ENERGY, MINES AND RESOURCES CANADA

CANADA CENTRE FOR REMOTE SENSING

RESOURCE INFORMATION SYSTEMS UTILIZING REMOTE SENSING DATA

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SUMMARY

The need for better information about the physical environment to assist management of earth resources is placing new demands on resource information systems. These intensifying requirements are coming at a time of rapidly evolving information technologies for which these needs are in part a driving force and in part a receptive beneficiary. This report is a background document on some aspects of past and present resource information systems. It also discusses factors considered important in the development of new systems which are anticipated in the longer term to involve networks of data bases and information extraction facilities. The end-to-end information system concept is considered important, that is, a balanced, integrated system in which all phases from data acquisition through information use for resource management are well planned and developed so there are no weak links and information needs are satisfied. Although much of the report is approached from the point of view of a remote sensing emphasis, this is not without merit. Repetitive multiscale spatial and spectral remotely sensed data on dynamic environmental phenomena will be a major contributer to resource information systems in future, providing 1-, 2- and 3- dimensional observations. The issues discussed in the report, though of necessity incompletely, are important for Canada, and substantial contributions have and continue to be made here in development of suitable approaches and technologies. The Canada Geographic Information System which is a starting point in the report for discussion of computerized geographic resource information systems, was developed to handle the Canada Land Inventory information base for land use and economic planning in rural Canada and was one of the first digital geographic information systems developed worldwide. The most recent work discussed is a standard format for the transfer of geocoded information in spatial data polygon files devised and adopted by four major

Canadian federal government geographic data base operators.* This facilitates exchange between data bases, and the computer tape format is compatible with a family of formats adopted by the various Landsat station operators for Landsat-D.

The report is divided into two parts: the first part deals with information technologies both in an historical perspective and with some considerations for future networked-systems; the second part considers a number of applications in resource management and environmental monitoring assisted by remotely sensed data, and some considerations of associated information requirements and information extraction system requirements.

The technology section reviews characteristics of computerized geographic information systems including several federal government geodata bases, and data processing, management and storage considerations of systems with remote sensing inputs. A number of issues are discussed including: factors affecting the acceptability, flexibility, capability, compatibility, and utility of conventional geographic systems such as differences in storage structure influencing data exchange, problems of handling large quantities of data, and costs of update and interrogation; the benefits of compatibilities of systems such that data collection/duplication is minimized and information synergism maximized; the desirability of extensive system preplanning because of often complex organizational factors and the need for flexibility and adaptability; some costs associated with information systems and analysis facilities; the need for analytical and modelling capabilities to derive information from spatial and associated attribute data; and the desirability of

* "Standard Format For the Transfer of Geocoded Polygon Data", D.G. Goodenough et al, CCRS Research Report 79-3, December 1979.

sharing of data, of hardware and software and of expertise. Because of the benefit of sharing, and because of the increasing demands for timeliness of data and information products, communications technologies will have increasing importance for resource information systems, and possible costs and systems designs are discussed. While many conventional geographic information systems have been used for policy and planning purposes, resource information systems which will accept remote sensing inputs are increasingly needed for day-to-day management purposes. Image based information systems are reviewed, and some functional requirements of image analysis and information extraction facilities discussed.

The second part of the report, on applications, especially involves attempting to identify many of the data sets both archival and near real time that are desirable and may have to be handled by an information system to satisfy user requirements. It also reviews some of the applications of remote sensing data, particularly Landsat data to resource and environmental problems, and their use in some modelling activities.

Rapidly changing technology complicates prescription of resource information system design but makes ongoing interagency planning necessary to minimize costs and maximize the information available to the resource manager.

RESOURCE INFORMATION SYSTEMS UTILIZING REMOTE SENSING DATA

This report was prepared as a background document to consideration of regional resource information systems that would utilize satellite remote sensing data as one important data input. Much of the information was collected in 1979 and developments in the field are occurring quite rapidly.

PART A

RESOURCE INFORMATION SYSTEMS

PART B

Applications Utilizing Remote Sensing Data: Some Considerations of User Data and Information Requirements and of Information Extraction System Requirements

1. Computerized Geographic Information Systems

1.1 History

A geographic information system has been defined as a "computer system for storing and processing mappable data so that both the data and its location can be retrieved".* Geographic information systems differ from object oriented information systems, which include scientific or statistically oriented information systems and management information systems, by the addition of locational identifiers. This feature adds to the complexity of machine handling of the data and has made for slower development relative to generalized object oriented data base management systems.

Geographic information systems began to appear in North America in the 1960s as a result of two principal driving forces. Developments in computer technology permitted data to be stored, retrieved, manipulated and displayed. Computer availability became widespread and costs decreased. A second factor was the desire for a centralized data bank which would permit manipulation and integration of one or more types of data required to fulfill user information needs.

The trend toward information system development accelerated in the early 1970s. Power has made a survey of many of the U.S. systems and shown a rough chronology of their development (Figure 1).* Her studies show that systems have developed at all government levels - national, regional, state, county and municipal. Differences of concern at these levels are reflected in systems design, for example geocoding grid size. Many of her study findings are applicable to information systems generally including those in Canada. Some observations particularly worth noting include:

- Information systems at present are incompatible among each other in hardware and software, even between pairs of systems using the same computer type and the same programming language and operating system.
- Although by the time of the study (1975) some new systems were buying sections of software from existing systems, converting the purchased software to run on a different computer is not a trivial problem.
- Systems which have failed have usually done so because of organizational problems, eg. inadequate time or money, lack of institutional commitment to the system's maintenance, insufficient marketing to provide a base of users.

* "A Computerized Geographic Information System: An Assessment of Important Factors in their Design, Operation and Success", M.A. Power, Centre for Development Technology, Washington University, St. Louis, Mo., December, 1975.

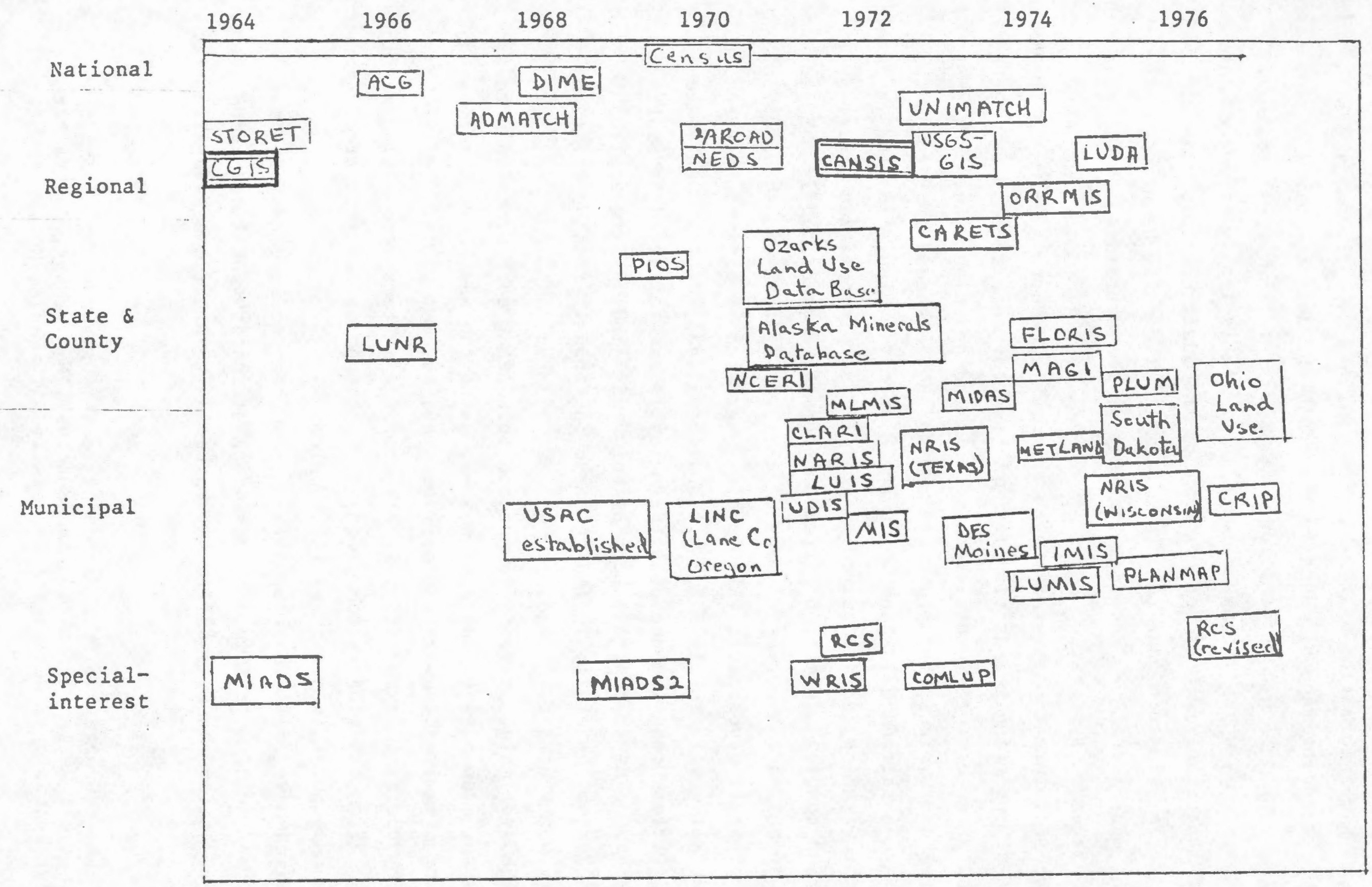

Figure 1. A rough chronology of some North American information systems. Adapted from Power, M.A., M.S. thesis Washington University, 1975. Includes CGIS and CANSIS.

- Many systems suffer from inadequate determination of user needs so that the system is not satisfactory to agencies it was intended to serve. The scale of many information systems is wrong for many programs. Most systems are not yet used as the chief information source for decisions. A major design error has been to underestimate or overestimate the level of complexity necessary for the proposed system to accomplish its tasks eg. some have overemphasis on technical design.
- Although natural resource systems and socioeconomic systems have developed almost independently throughout most of their history, nearly all new systems are concerned with the incorporation of both socioeconomic and natural resource data.
- There are a number of social barriers to innovation which have hindered acceptance and use of geographic information systems eg. fear of agencies that their original goals and mandates will be subverted.
- A major problem in data production has been digitization of input data.
- A shortcoming of many systems has been their use to produce single items for data display rather than to provide quantified data for valuable decisions.

Power notes that "The computerized geographic information systems which have been built to date have fallen short of their potential as a storage and analysis tool, although several are operating successfully."

The Canada Geographic Information System was one of the first systems in North America. It was developed to facilitate use of data gathered by the Canada Land Inventory (CLI). The role of the CLI was that of an information base for land use and economic planning in rural Canada.* The inventory was of a "reconnaissance" type and focussed on "areas of major concern" rather than exclusively local problems.* The CLI coverages concern resources rather than sociological factors, and the capability coverages which are derived variables depending on interpretation of raw data refer to the physical capability of the land to support varying levels of intensity of activity or use. A computerized information system was seen as a method of handling and analysing large volumes of data in a timely and efficient manner so that the potential utility of the data would be realized. The incorporation into CGIS of socioeconomic data, and remote access to the system by terminals in other provinces represent important features in the trends of geographic information systems.

* "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins, D.F. Marble, UNESCO press, 1976.

The major problem experienced with the CGIS development resulted from the pioneering nature of the development. Some geographic information system developments have been characterized by designer independence (failure to take advantage of experience gained or transferable software resulting from other developments), and from inadequate design review which could have identified shortcomings such as improper grid cell size to satisfy user needs. Basic problems have sometimes centered on geocoding and georeferencing methods limiting the system application and compatibility with other systems.

With the availability of satellite data in computer compatible form, and with developments permitting other data to be input more readily to these systems, a major bottleneck will be alleviated and more attention can be focussed on efficient processing and storage.

Computerized geographic information systems have some commonality in objectives with the less complex object-oriented data base management systems. Objectives of data base technology include: making an integrated collection of data available to a wide variety of users; centralizing control of the data base to make data administration more efficient; provision for quality and integrity of the data. The major objective is to make data sharing possible. In general, the data base as well as programs, processes and simulation models are available to a wide range of users. Data sharing reduces average costs with individual users paying only for their share. Centralized data definition facilitates control of data duplication which usually entails some storage inefficiency. If a distributed system is used, and the data is entered at many locations, it may well be efficient to store it near the entry port.

1.2 Topological Information Systems

One of the two basic types of physical storage characteristics of geographically oriented data is irregular cells or linearly encoded data. The second map encoding scheme is grid encoding discussed in section 1.3. In the former structure, aerial data consist of nodes and line segments forming closed regions or polygons; linear form data consist of nodes and connecting line segments; and point form data consist of nodes. The organization of the encoded nodes and line segments is generally handled through lists.* Disjoint pieces and inclusions are usually allowed.

There are several advantages to this type of data structure. Data encoding experiments have shown either coarse or fine (ie. more points to define the area) polygons are significantly more accurate in area measurements than grid-based systems.+ The latter systems also tend to underestimate or lose linear features when two data variables are overlaid. This data structure has been found to be advantageous in terms of computer storage requirements in describing: regions that are large and uniform such as county boundaries; ie. regions that are large in area in comparison with the basic data cell size; regions that have irregular shape; and linear features.

There are also several disadvantages to this structure. Access time is slow compared with a raster structure in which the disc sector where the required data is stored can be computed in one operation. File merging is also slow.

If the user requires several types of information about a point for which he specified UTM coordinates, the system must do a search of each set of polygons calculating a "point-in-polygon" test function on polygon vertices. The search of the set of land use polygons for example for the geographic point of interest can be very time consuming. In overlaying one map on another, information systems such as the Polygon Information Overlay System (PIOS) of the Comprehensive Planning Organization and the County of San Diego, Calif, use a point-in-polygon routine, comparing polygons from one map with vertices of the other polygons point by point, and determining overlapping areas.+ Polygon overlay is difficult for large files. The cost of file merging usually grows as the product of the number of polygons, and also depends on their complexity. The computer time associated with operation with large files therefore

* "Remote Sensing and Geographically Based Information Systems", R.C. Cicone, Proceedings of the 11th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, July 1977.

\+ "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins, and D.F. Marble, UNESCO press, 1977.

can make polygon overlay expensive. Other problems which have been indicated are:[†] the high costs of getting the data into the system; considerable computational expense associated with file editing; and complex topological architectures to achieve efficient data extraction from any given area. It is expected that further development of algorithms and data structures will simplify polygon manipulation. Special processing may assist in handling polygon data by permitting operations to be executed on several paths simultaneously rather than sequentially. Proponents believe that the final product of spatial analysis should be the main consideration, and that topological systems will offer more effective geographic representation than gridded systems.[**]

For large number of overlays, substantial errors can arise in the polygon overlay process, dependent on classification accuracy. For example, if a polygon unit has some non-uniformity within it, the classification accuracy may be reduced and the error magnified with multiple overlays. It has been noted that if a randomly chosen point in a polygon is 95% likely to belong to the class to which the entire polygon was assigned, the likelihood that 5 desired attributes for a 5 polygon overlay will be found in the intersection of the five units is only $(0.95)^5$ or 0.77.[*] If two polygons to be overlaid, are near the system's resolution limit, the small intersection area is susceptible to error.

One 1968 study comparing costs of polygon storage with irregular grid storage (computer storage by ownership blocks) found for the parcel file 48.7 more man hours required per square mile and a total preparation cost of $175 versus $125 for polygon storage (37% of the latter cost was for computer time compared with 3% for the parcel file). Comparison of system costs are difficult, however, as evident from a data encoding experiment involving overlay of land use and census tract maps of a 7.5 x 7.5 minute area reported by Tomlinson et al.[+] This compared several grid and polygon systems but each system was

+ "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins and D.F. Marble, UNESCO Press, 1977.

* "Remote Sensing and Geographically Based Information Systems", R.C. Cicone, Proceedings of the 11th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, July 1977.

** "Topological Information Systems for Geographic Representation", N.R. Chrisman, 2nd International Symposium on Computer Assisted Cartography, Reston, Virginia, Sept.

† "IBIS: A geographic information system based on digital image processing and image raster data type", N.A. Bryant and A.L. Zobrist, Proc. Symposium on Machine Processing of Remotely Sensed Data, Purdue University, W. Lafayette, Ind., June 1976.

designed for a purpose and a geographic scale different from those assigned for the experiment. The experiment showed the high cost of the labour-intensive input stages in all cases, and of overlay when data is in polygon form. The authors stress the requirement for overall system efficiency in establishing a data base including both digitizing and subsequent handling of the data resulting from the digitizing.

There are a variety of linear encoding techniques such as chain/node encoding, location lists and point dictionaries. Consequently, although polygon data storage structures are used in most geographic data bases in Canada, they are generally incompatible. Generally little transfer of data has taken place between different data bases. After software has been developed and tested, transfer between two data bases could be routine with processing time (and therefore continuing costs of data transfer) dependent on complexity, eg. the polygon structure may be full of pointers. The cost would be a function of the system used for conversion eg. the conversion could go much faster if all elements could be kept in the computer memory and the procedure was not input-output bound. Dueker has outlined alternative ways of encoding geographic data.† For example, each line segment may be encoded twice because it is part of two polygons.

Conversion between the two basic data storage structures (line and grid encoding) is possible but for both types of operations is time consuming (and therefore costly). Conversion from polygon to grid format is simpler. It has been done for example to overlay Agriculture Canada Cansis polygon data on Landsat data. JPL have a set of routines to convert polygon data files described by x.y coordinates to digital image descriptions of regions ie. to a VICAR (Video Image Communication and Retrieval) record format. A routine scribes lines into an image file by setting the boundaries of polygons to a particular grayscale value. Array arithmetic may subsequently be performed on a pair of images. Conversion from raster to polygon format can be time consuming. An operator that will work quickly on polygon edges is required, and subsequent editing may be required to ensure polygon closure.

Polygon encoding results in closed, homogeneous regions. When complex patterns are present, fairly high costs may be associated with the multiplicity of coordinate points required to describe perimeters. A serious problem of

†"A Framework for Encoding Spatial Data", K.J. Dueker, Geographic Analysis, Vol. 4 (1972), p. 98.

accuracy of representation can arise with polygon encoding. Many geographic phenomena eg. changes in soil types are not discrete and do not have distinct boundaries. Representing the character and intensity of a phenomenon as homogenous throughout a discrete polygon may be misleading.* Tomlinson notes that this fault is inherent in any map production (Accuracy of representation is a strength of the raster-type image based system).

Data capture in the polygon encoding method may be done by a line-following digitizer, scanner or other input device, and the accuracy of the stored data is limited only by the quality of the source material rather than being inherent in the coding technique (note the comments of the preceding paragraph however). Manual digitization (using a cursor) can lead to errors particularly due to operator fatigue, and require extensive editing. Automatic line following devices depend on a good quality of map input and additional costs may be incurred in map preparations. Input costs using this method may be small (as little as $100/map sheet using laser-optical technology).+ The cost comparison of methods used to convert geographic data to machine readable form depend on the magnitude of the data being encoded. Dueker concludes that a drum scanner mode is best when the geographic data are densely distributed on imagery and there are many images to be processed. For gross or less dense patterns point digitizing is most feasible.†

† "A Framework for Encoding Spatial Data", K.J. Dueker, Geographical Analysis, Vol. 4, p. 98, 1972.

+ "Program on State Agency Remote Sensing Data Management (SARSDAM)", L.F. Eastwood and E.O. Gotway, Final Report prepared for NASA Marshall Space Flight Center, May 19, 1978.

* "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins and D.F. Marble, UNESCO Press, 1976.

1.3 Grid Cell Information Systems

In this structure, polygons are replaced by a set of uniform regions, usually squares. Within each cell data may be recorded as a number, an identification (eg. farmland) or a set of percentages (eg. 50% farmland, 50% forested).

An irregular grid structure may be used involving a non-rectangular line pattern with a census block for example, used as a cell. Cells can be stored in an array (rather than a list) permitting an efficient way of data retrieval ie. access through coordinate referencing. Therefore grid systems have advantages of simplicity in computer program design, improved retrieval speed, and storage compactness. They facilitate crosstabulation of variables encoded within a particular cell. Grid systems are supported by the technologies of satellites, raster scanners and special purpose computers.

Grid structures include three encoding techniques:* sequential - Data values are entered into cell after cell along rows or columns; compact sequential - repeating data values are not stored for each cell, but stored along with a length attribute; complete coding - each data value has a locational vector associated with it.

Grid encoding is accomplished by overlaying an arbitrary grid on a source map, categorizing selected attributes of each cell in a matrix, and storing in a matrix form. For example, in the Land Use and Natural Resources System in New York, a scaled acetate grid is placed over a map and the most prevalent feature value in each cell is recorded by hand. The acetate then becomes a source document for keypunching. A chief disadvantage is high labour cost.

Other Data Storage Types

Non spatial, list oriented data such as statistical characterization of a particular layer of geographic data may be integrally related to the processing of geographic data, and be another data storage structure type. These data may be managed in associated flat files. Tables of aggregated statistical information form another integral part of the geographic data base.*

The grid structure has several disadvantages. Update of data files is costly because of the manual effort required. The fit to the data is not generally as good, as provided by line encoding. The resolution of the system is limited by the cell size rather than by the accuracy of the data set described. Data is aggregated ie. the number or extent of line or point features can be tabulated

* "Remote Sensing and Geographically Based Information Systems", R.C. Cicone, Proceedings of the 11th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, July 1977.

for each cell but their locations cannot; in the overlay process different characteristics associated with a line or point cannot be overlaid for areas smaller than a cell.

1.4 Further Comments on Data Structure

When working in an operational mode involving large data volumes, data storage and organization strongly influence costs of data handling and query. "A well-thought-out and optimized logical and physical structuring of the data may mean the difference between the success and failure of a large project."* The trend in Canada has been to the polygon form of data structure and Table 1 lists an inventory of position related data files in the federal government in 1975. Many computerized systems for handling spatial data have been developed internationally. For example, Power has examined the history and operation of two dozen systems in the U.S. As of early 1976, more than 50 system activities in the U.S. Geological Survey were specifically concerned with gathering and handling spatial information in the fields of geology, geography, topography and water resources.* Most existing systems are not compatible with one another leading to a suggestion that there could be advantage in creating (in the U.S.) fusion centres where data from diverse sources and structures could be combined. While most seem to agree with the desirability of building interfaces to facilitate smooth interchange between systems, impediments are seen to standardization. These include not only problems of sunk investments and individuality of approach of specific agencies, but also concerns that certain types of data fall naturally into certain types of structures and significant efficiencies may be lost in imposing less suitable structures. While future computer architectures and data base management systems may permit a greater flexibility in the way data is stored and handled, it is apparent that where new systems are being developed interagency preplanning could result in system compatibilities which would facilitate data sharing. The capabilities of systems may differ considerably so that, for example, data digitized for input, retrieval and display for one system may require considerable editing to provide suitable input to another system in which data is overlaid, analysed, etc. Data capture includes not only the initial conversion to digital form, but also placing the data in the required structure in logically correct data files. The digitizer coordinate frame of reference is defined by the map projection

* "GIRAS: A Geographic Information Retrieval and Analysis System for Handling Land Use and Land Cover Data", W.B. Mitchell, S.C. Guptill, K.E. Anderson, R.G. Fegeas and C.A. Hallam, U.S. Geological Survey Professional Paper # 1059, 1977.

Table

Inventory of Position-Related Data Files

Name	Agency	Type of Data
1. CANSIS Canadian Soil Information System	Agriculture Canada	Detailed Soil Information
2. National Position Control Survey	E.M.R. Geodetic Survey	Survey Control
3. Auto Cartography	E.M.R. Map Production Directorate	Topographic Maps, Grids and Projections
4. Hydrographic Data Base	Environment Canada Canada Hydrographic Service	Nautical Chart Data
5. Military Geographic Information Documentation	Dept. of Defence	Topographic Features of Military Significance
6. Geochemical Analysis System	E.M.R.	Field and Lab Data Relevant to Exploration and Geochemistry Chemical Data of Trace Elements of Mineral Potential
7. Regional Geological Field Data	E.M.R.	Geological Observations
8. Geomathematical Regional Geology Mineral Resource Estimates File	E.M.R.	Regional Geology Mineral Deposits
9. CANMINDEX	E.M.R. Geological Survey	Mineral Occurrence File
10. Moly File	E.M.R. Geological Survey	Date of Occurrences of Molybdenum and Related Elements
11. Mineral Deposits File	E.M.R. Geological Survey	Mineral Deposits
12. BA, SR, F, Deposits of Canada	E.M.R. Geological Survey	Barium, Strontium and Flourine Deposits
13. URE-1	E.M.R. Geological Survey	Uranium and Thorium Data from Boreholes
14. MINDEP	E.M.R. Geological Survey	Mineral Occurrences
15. MANIFILE	E.M.R. Geological Survey	Mineral Deposits
16. Geophysical Data	E.M.R. Geological Survey	High Resolution Aeromagnetic Data
17. Mackenzie Valley Geotechnical Data Bank	E.M.R. Geological Survey	Geotechnical Bore Hole Data
18. Urban Geology Automated Information System	E.M.R. Geological Survey	Geotechnical Data

19. NCC Data Bank	National Capital Commission	Cadastral, Socioeconomic and Topographic Data
20. Canadian Geographic Reference System	Environment Canada Lands Directorate	Data Base Including Series of Coverages Showing Aspects of the Land by Shape and Location of Facets with Associate Descriptive Data
21. FUNDY	Environment Canada Forest Management Institute	Land and Forest Inventory Data
22. PUKASKWA	Environment Canada Forest Management Institute	Land and Forest Inventory Data
23. National Gravity Control Station File	E.M.R., Gravity and Geodynamics Div. Earth Physics Br.	Digital Data and Station Descriptions for Gravity Reference Stations
24. National Gravity Anomaly File	E.M.R., Gravity and Geodynamics Div. Earth Physics Br.	Free Air and Bouguer Gravity Anomaly Data
25. Vector Geomagnetic Field in Canada	E.M.R., Div. of Geomagnetism Earth Physics Br.	Observations of Earth Magnetic Data
26. Canadian Epi-Centres File	E.M.R., Div. of Seismology & Geothermal Studies, Earth Physics Br.	Data, Time, Location and Magnitude of all Known Earthquakes in Canada & Immediately Adjacent Regions
27. Temperature & Thermal Properties of the Earth's Crust	E.M.R., Div. of Seismology & Geothermal Studies Earth Physics Br.	Temperature & Thermal Properties of Rocks and Geological Data
28. Geothermal Data File for Permafrost Regions of Canada	E.M.R., Div. of Seismology & Geothermal Studies Earth Physics Br.	Underground Temperatures & Calculated Equilibrium Temperatures
29. Landsat, Computer Compatible Tape	E.M.R., CCRS	Digital Data of 100 nm Images of Canada

and the digitization of selected control points with known geographic coordinates. Discussion of data structures in polygon-type systems below provides an indication of differences in data organization that are characteristic of these systems.

One of the largest U.S. systems, The Geographic Information Retrieval and Analysis System (GIRAS) of USGS provides systematic and comprehensive collection and analysis of land use and land cover data on a nation wide basis.* In the system many more polygons are involved for land use and land cover than for other overlays which include political units, census county subdivisions, hydrologic units, federal land and state ownership boundaries. Digitizer coordinates are reduced in the editing process, for example, from 0.78 million (input coordinates) to 0.13 million (output coordinates) as an average of selected samples of land use and cover map quadrangles. The data structure is described as "the latest in a series of evolving structures used to represent digital land use data." Common boundaries or arcs defined by a series of x,y coordinate pairs are digitized only once and linked to form polygons. A map may be segmented for more economical processing, and retrieval of data subsets. There are several related files. For example, the polygon record contains a pointer to the subfile assigning arcs to polygons, which, in turn, points to those arcs comprising the polygon. There are record points to coordinate strings describing that arc. An arc contains the attribute codes left and right of the arc. Data once converted to digital form by a digitizing device go through several steps to produce the specific file required by the GIRAS system, eg. conversion to specific format, elimination of points according to spatial tolerance specified for the system, edit and error detection, etc.

Polygon to grid conversion in most geographic information systems is time consuming. The point-in-polygon search routine involves determining if the centre of a grid cell is within a specified polygon. In GIRAS, the intersection points between each horizontal scan line of the grid system and the arc are calculated, and the arc's attribute data used to decide the categories of cells along that scan line. Mitchell et al note that the GIRAS 1 production system was not designed to support the capture, editing, and correction of large and complex data sets, or handle the advanced manipulative or analytic desires of many users. As a result system improvements have been made. Such limitations in handling large

* "GIRAS: A Geographic Information Retrieval and Analysis System for Handling Land Use and Land Cover Data", W.B. Mitchell, S.C. Guptill, K.E. Anderson, R.G. Fegeas and C.A. Hallam, U.S. Geological Survey Professional Paper # 1059, 1977.

data volumes and high update frequencies, and in providing a wide range of manipulation and analytical capabilities are characteristic of most conventional geographic information systems.

Various digitizing devices and their corresponding software produce outputs ranging from lists of x-y coordinates to complex data base structures. Some polygon digitizing methods involve digitizing each line twice instead of once as noted for GIRAS. Procedures for data reduction, transfer of digitizer coordinate data to desired coordinate systems, and creation of final data base format also vary. A compact notation for segment storage in CGIS can reduce by at least an order of magnitude storage requirements which would be, if stored in the x,y coordinate system output form, on average 200,000 bytes per map sheet for boundary data alone.* Once data are in the final data base format, costs of manipulating and retrieval are dependent on data structure and organization (number of pointers, etc.), and some operations may be very costly or impossible. Dueker notes that independent decisions regarding one element of an information system, such as input or storage, force decisions pertaining to another element say retrieval or output, that may be contrary to the purpose of the system.† A total systems approach is required with the starting point being specification of the types of query desired.

Dueker has discussed several alternative methods of encoding geographic data including: areas encoded as polygons made up as a sequence of points, areas encoded as being contiguous to other areas, line segments encoded in relationship to their endpoints and their contiguity to areas, etc. The five case studies chosen by Tomlinson et al to represent the various methods of encoding graphic data, also illustrate a range of capabilities in geographic information systems.+ For example, the Minnesota Land Management Information System using 40 acre grid cells is oriented to data input, retrieval and mapping rather than statistical analysis or modelling. The small grid, Oak Ridge Regional Modelling Information System is primarily oriented to the digitization, storage and display of geographical information but was developed together with a land use model and has several

+ "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins, and D.F. Marble, UNESCO Press, 1977.

† "A Framework for Encoding Spatial Data", K.J. Dueker, Geographical Analysis, Vol. 4, 1978.

* "Canada Geographic Information System", Lands Directorate, Environment Canada, 1974.

analysis and output capabilities. Many systems have statistical analysis capability and some (eg. GIRAS) carry along ancillary data such as polygon area and perimeter in the data structure to facilitate data retrieval and analysis. The extensive capabilities of the five polygon CGIS system are discussed in section 1.6. System incompatibilities restricting data exchange which have been reported in other countries, also apply in Canada. Kloosterman notes "The diverse nature of the computer hardware industry and the specificity of software packages pose a problem for soil information systems. This threatens to restrict transfer of information between systems and results in considerable duplication of efforts."+

There are several steps in data base creation which may vary for different systems, resulting in stages at which data could be readily transferred with varying economies according to overall compatibility. Fisher notes that for CGIS the cost of converting the map image (scanner output) to a list of xy vertices is less than 10% of the total cost of putting a map into the Data Base.†

Procedures of data reduction and creation of final data base format may result in data generalization. This would be particularly true for coarse grid formats but could also apply to some polygon formats. Some agencies may wish to work from a "master" set of x,y vertices retaining as much accuracy as allowed by the source map. An information system may be required to handle both hard data, ie. site specific soils or other type of sampling data, as well as map data. Preservation of data quality is particularly important for the former. Computerized methods of handling data are permitting retention of much primary data. For manual handling of soils data, Kloosterman notes "In most cases, the volume of data collected in a project was so immense that it required preclassification and grouping at very early stages of data collection...Computer-oriented data management...permits the scientist to maintain contact with basic data, up to the point of publication, thereby precluding the necessity of early data classification. This capacity facilitates the sorting and summarizing of data in a variety of ways at different times as maps, summaries or tables..." While the optimized final data base format of, for example, a land management agency involved in land evaluation, planning and management may be different than an environmental agency, there may be a level in the data collection and

† T. Fisher, Lands Directorate, Department of Environment, personal communication.

+ "Role of Computer Information Systems in Soil Science", P. Kloosterman, Applications of Geographic Information Processing, 2nd Symposium Workshop of National Capital Geographic Information Processing Group, U. of Ottawa, April 1977.

data base creation procedures at which data transfer is most readily accomplished.

Some Canadian experiences in exchanging spatial systems technology have been summarized by Yan et al.* Recommendations are made for data transfer when systems already exist. Use of standardized interchange formats are considered the most suitable because of reduced software development efforts.*

* "Exchanging Spatial Systems Technology: Related Issues and a Case Study", J. Yan, S. Witiuk and T. Fisher, Applications of Geographic Information Processing, 2nd Symposium Workshop of the National Capital Geographic Information Processing Group, U. of Ottawa, April 1977.

1.5 Other Considerations in the Development and Utilization of Geographic Information Systems

Because of the stimulus of increasing volumes of spatial data and the search to determine and satisfy necessary and sufficient data and information needs of users, geographic information systems are receiving considerable attention. A number of considerations which have been brought forward at conferences and in the literature are discussed below.

Peuguet distinguishes between a data base management system (DBMS) and a geographic information system (GIS).* A geographic information system is defined as a data base management system with the addition of analytical capabilities which permit derivation of information from both the spatial data and its associated attribute data. The DBMS is the middleman between a collection of data and users of that data, and is defined as an integrated software package designed to manage data of various types for all phases of input, data editing, updating, retrieval, and output by a number of users.

A map is a simple data base management system. It is a structured file with data organized so that a human can determine the nature of entities and the relationships of interest. Some computer-based systems just provide users with the same information available from paper maps. Humans have limited effectiveness in scanning many map sheets or examining some complex features; and information extraction from maps when large data volumes are involved may be costly. Computer-based systems also allow display of spatial data, but relationships between entities may be explicitly defined in the file or calculated within the DBMS.

While the remote sensing community are attempting to obtain a clear understanding of the operational needs and constraints of users, the community concerned with geographic information systems are now wrestling with the same problems. The underutilization of many GIS's may in part be due to a lack of serious questions of this nature in the past. Berry notes that "---there is a need for activity which will probe more thoroughly than it has in the past the real information and graphics needs of planners involved in the day to day planning process.---And I suspect that as with all new technologies the opportunity will reside not in providing better ways of doing the things that are being done right now,---but in providing a different way of doing new things that in turn will enable practicing planners to function better."+ It may be noted that he

* "Raster Data Handling in Geographic Information Systems", D.J. Peuguet, ibid, vol. 2.

\+ Keynote address, B.J.L. Berry, in First International Advanced Study Symposium on Topological Data Structures for Geographical Information Systems, Harvard Papers on Geographic Information Systems, G. Dutton ed., 1978.

makes reference to planners. Although many conventional geographic information systems have been developed to meet planning needs, GIS development is also needed to meet day-to-day management requirements and to meet forecasting requirements. It is also required to meet needs at the local level. Berry notes "---there are other potentialities in the technology---the move from the global to local---the move to much greater flexibility, to much greater ability for individuals to have access, to have control, to be able to experiment, to develop applications systems and data systems that are adapted to individual needs of individual users---."* This requirement for flexibility and decentralization will influence system design and choice of data structure. Flexibility is required to allow data bases to grow and evolve in complexity in order to avoid obsolescence. Some of the functions of a system and the way they are performed will change as the system is used and users become more sophisticated. As well as accessing specific types of data, some users will want a "browse" capability in a geographic information system. There is likely to be a tradeoff between GIS operational efficiency and types of query permitted.

Often polygon data (eg. a soils map) represents a generalization of field observations ie. grouping and classification of data at very early stages of a data collection. The generalization reduces the bulk of primary data, but loses details and may constrain the analytic process which is used. The generalization process usually organizes the thematic content categorically, and use of mathematical operations on the data requires proper assignment of "value" or "utility" functions to the categorized data. User requirements are central to the question of generalization, and the consequences of loss of detail. Decisions as to the generalization process affect the level of detail of field observations. They also could significantly impact the design of a DBMS for a particular application.

The question of generalization is central in data base development. Map data is often needed at a large number of scales and levels of detail. In practice, hierarchical relationship both locationally and descriptively of levels of description is rare. Overlay of different thematic descriptions can give false conclusions if the thematic description is a generalization of a spatial complex which is appropriate for the whole but not for the part.† Storage in a single data base of levels of description which do not constitute a true

* Keynote Address, B.J.L. Berry, ibid, Vol. 1.

† "Future Directions", B.G. Cook, ibid, vol. 1, p. 103.

hierarchy can give problems. For example, it has been indicated that in Britain, three scales of data bases - 1:10,000, 1:25,000 and 1:250,000 may be better than one general data base.[+] In filling out the levels of description, usually the coarser and more generalized are considered first, with some parts filled out later at a finer scale.

Although there is concern about the need for compatibility of data bases to facilitate data transfer, and possibly some standardization of data structure, questions with regard to types of query desired are the starting point. The consequences of lack of standardization and particularly of the inability to come to grips with some of the underlying methodological problems of handling spatial data have been widely recognized. The redundancy and conflicting effort in data base development without a common base of standards and procedures, has been noted, leading to "immense spillovers" and sometimes results which are impossible to merge with the work of others.[*] Access to different data bases required for analysis is a minimum requirement. With regard to non-optimized data structures to satisfy queries that will be made, Tomlinson notes that "When large commitments of funds and staff have been made in building a specific data organization, it is difficult to reverse the process. There will be a natural tendency to work with the data bases that have been created, rather than to reorganize them. This will limit the number of queries that can be economically answered from the data, and therein lies the constraint that poor data structures place on future investigation."[†]

The structure and content of data in geographic information systems influences the specific questions or analyses undertaken, and there are considerable uncertainties about structures that should be utilized. It has been argued that the type of data structure chosen is conditioned by what one perceives phenomena are really like.[**] The physical and logical structure of the data base also influence costs of data access and manipulation. The spatial relationships of entities (point, linear and area entities) are of concern to Tomlinson and he notes that "There is no clear

† "Difficulties Inherent in Organizing Earth Data in a Storage Form Suitable for Query", R.F. Tomlinson, Proc. AUTO-CARTO III, San Francisco, 1978.

* "Keynote Address, B.J.L. Berry, ibid, Vol. 1.

** "Concepts of Space as a Guide to Cartographic Structures", N.R. Chrisman

\+ "Geographic Information Systems as Models", D.W. Rhind, ibid Vol. 1, p. 93.

understanding of the relative applicability of the various types of data structure inherent in existing data base management systems to the problem of specifying spatial relationships---there are substantial methodological deficiencies in defining spatial relationships themselves."* The principle of DBMS's is to organize data so that paths are established to retrieve the entities required, and also to specify the relationships between entities adequately so that: they are explicitly determined and retrievable, readily determined by human observation and interaction through use of data display, or calculable within the DBMS. The types of questions asked and spatial relationships influence the logical schemas used to organize spatial data. The replacement of path tracing methods which maximize use of sequential processing computers, with pattern analysis, and sequential processes with array processes (raster processing) may lead to more effective DBMS's. Peuguet has argued that geographic information systems employing only raster methods must be developed because of increasing raster-to-vector and vector-to-raster conversions and computational costs, and the raster-mode algorithms now available.+ Peuguet shows that raster oriented techniques exist to perform almost all the required capabilities of a geographic information system, with the time dimension ie. selective update of spatial data the only deficiency. Employment of raster-only systems is a controversial issue at present and in the absence of concensus everyone agrees on the need for transferability. Raster-to-vector conversion can be carried out if required,# as can the reverse. The question is one of efficiency associated with those operations.

Hierarchical storage methods have been proposed for both raster and polygon data to minimize search time.‡ These methods (eg. use of nests of squares) allow access via location to raster or irregular (point sets or polygon) data. Interfacing of vector and grid representations is also possible using these methods. If raster storage is used, vectorization to extract nodes or polygons may be done at a specified level of detail.

‡ ibid, p. 33.

"Extraction of Topological Information from Digital Images", A. Rosenfield, ibid, vol. 1, p. 41.

+ "Raster Data Handling in Geographic Information Systems", D.J. Peuguet, ibid, Vol. 2.

* "Difficulties Inherent in Organizing Earth Data in a Storage Format Suitable for Query", R.F. Tomlinson, Proceedings of AUTOCARTO III, San Francisco, 1978.

The existence of both spatial and non-spatial data in DBMS's presents special management problems. Non-spatial data lends itself to sequential computer processing. Efficient algorithms exist for processing such data eg. application of mathematical and statistical models. Processing ease makes it desirable to store such data in basic form. Non-spatial data can be related to spatial data (points, lines, areas) through an identifier. Spatial data are mappable data which permit computation of relationships such as distance, area, length adjacency, and connectedness. Spatial trends bringing an independence and predictability of adjacent data values may exist and spatial analysis techniques may involve trend surface analysis or spatial autocorrelation methods.* Such spatial analysis techniques will be addressed more and more in future in image processing. Processing times associated with spatial data may make it desirable to retain some analysis results (eg. area calculation) as part of the data base. A combination of the two data types is required to focus analysis on a particular area, to produce quantitative maps showing raw data or model product value, distributions, or impose spatial relationships on statistical analysis. It has been suggested that the differences between the two data structures may necessitate different physical and logical structures.*

Although some GIS software has been transferred from one computer to another, availability and transferability has generally been low. After considerable experience, Reed notes that "Invariably, I have found GIS software and documentation at best mediocre---".+

Computer graphics are an integral part of geographic information systems assisting in the analysis and providing a communications medium by which a problem solution or alternative solutions may be presented to a resource manager, planner, government official, etc., some of whom may not be knowledgeable in computer operations. Geographical concepts such as gradients, spatial relationships, relative magnitudes, densities, movements etc. can be communicated. Computer graphics have been an essential part of most natural resource and urban analysis systems in which data are extracted from files for display or information products are displayed. A range of applications have been utilized including special types of thematic mapping such as distortion of conventional cartographic

+ "GIS Software Portability/Transportability: Problems and Recommendations", C.N. Reed, ibid, Vol. 2.

* "Spatial Analysis in a Data Base Environment", K.E. Anderson, ibid, Vol. 2.

projections to study functional rather than metric space relationships (ie. functional rather than physical distance between points), and distortion of area replacing physical area by some areal quality such as population. The trend is to more interactive capabilities to assist analysis and to display intermediate processing steps, and to more quantitative forms of analysis involving modelling and simulation. Urban analysis systems with modelling and graphics capabilities have been used to display alternatives to planners, and to provide information for engineers and managers as well.* Natural resource analysis systems have provided a wide range of data-base query and modelling capabilities to regional, natural resource or land use planners, including implications of alternative land use patterns and associated environmental impact. Environmental analysis systems eg. air and water quality seek quantitative solutions and require good models, appropriate boundary conditions, and determination of geographical relationships between the data. Large volumes of primary data may be involved in these studies, and interactive graphics facilitate investigation of patterns and handling of these data volumes. Computer graphics play "a dominant role in reducing the impedance of the interface between user and data."* The human facility for determining spatial relationships between entities in photographs and displays is considerable. Graphics developments including stereoviewing take advantage of this. Interactive graphics where rapid response is required place demands on the data bases and file organizations utilized that are much more severe than for batch systems.

The utility of raster data structure as an internal storage structure is discussed further in section1.6. The structure provides considerable flexibility in data processing including handling a wide range of input and output scales.

* "Computer Graphics in Urban and Environmental Systems", R.L. Phillips, Proceedings of the IEEE, Vol. 62, No. 4, April 1974.

1.6 Generalized Geographic Information Systems

The preceding sections outline a variety of data structures and incompatible information systems. These problems have stimulated the concept of a generalized geographic information system.* The concept is one of a centralized data bank and the user is supplied with a very high-level language interface. Generalized computerized systems may have the advantage of increased flexibility and the disadvantage of decreased operational efficiency in carrying out particular tasks. Cicone notes that in the computerized geographic information system developments to date much duplication of effort has taken place in the development phase since the user has not been able to take advantage of the fact that there is a commonality to the data sets and data processing algorithms required. On the other hand, in reference to data-base management systems, Fry and Sibley point out that "The benefits of a generalized approach can be summarized as the elimination of program duplication and the amortization of one-time development costs over many applications of the program."+

In the generalized information system concept, the same skeleton system and supportive software would be supplied commercially to any user employing geographically oriented data, and specific modules which are independent of data storage would be developed for particular applications, ie. application programs would be independent of data storage.* A principal characteristic of the proposed system is that interfaces are provided so that data may be viewed independent of storage characteristics, eg. a data layer stored in polygon format may be accessed as if it were in grid cells. Although certain layers of information fall naturally into grid or linearly encoded data structures, the optimum system could handle both by providing an interface between layers. Another requirement of a generalized information system is to manipulate non-spatial or object oriented data. (A spatial information system is just an object oriented system with an added attribute - location identifiers.) This data could include statistical characterization of a particular layer of geographical data. The non-spatial data may result from special processing functions within the geographic information system, eg. generation of sets of mean vectors and covariance matrices representing the statistical composition of a remotely sensed layer. Such statistics become integral elements of the data base. Data base growth as a

* "Remote Sensing and Geographically Based Information Systems", R.C. Cicone, Proceedings of the 11th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, July 1977.

\+ "Evolution of Data-Base Management Systems", Computing Surveys, Vol. 8, March 1976.

result of processing must be supported by the system. The particular applications program may result in new layers of spatial information being generated, which are maintained by the data base management subsystem. The design should not restrict processing functions (ie. it should permit upwards compatible, modular growth so the scope of applicability is not limited). Data preprocessing may include an analytical transformation of the data such as, in the case of remote sensing data, creation of a new data layer from compression of the data into fewer dimensions with axes oriented in the direction of the principal components. Data processing includes feature extraction within and between layers of data, and inference modelling (a mathematical model is used with the data information content to project changes that may occur). Other desirable objectives of a geographic information system include fulfillment of cross-level and cross-functional information requirements. Retrieval functions include retrieval based on nominal data characteristics, coordinal data designation and relational techniques. Requirement for a data resolution different than that available may necessitate resampling. Data acquisition tasks associated with geographic information systems include determining existing data sources and new measurement requirements, establishing sampling strategies, and determining data computer compatibility.

2. Canadian Geo-data Bases

Several digital geodata bases have been developed within the federal government. Four of the largest of these are discussed briefly in section 2.1 to 2.4. A listing of position related data files was given in Table 1. The remaining subsections discuss issues related to data flow between agencies and developing provincial interest in digital geodata bases.

2.1 National Topographic Data Base

A digital topographic data base can give the flexibility and capability of providing not only simple graphic products but also of satisfying user requirements for sophisticated terrain analysis.* The National Topographic data base aims at eventual complete coverage of Canada at a scale of 1:50,000. Digital mapping technology is close to a limited production stage and production processes will be converted to digital methods over the next few years. A task force report considering the advantages of the technology and its current rate of adoption by Europe and the U.S. Defence Mapping Agency, concluded that digital technology will move rapidly to dominate future surveys and mapping activities.* The digital mapping system uses magnetic tape files to store digital map detail obtained from aerial photography and related survey data.

Input to the topographic data base will come from three sources.

a) Manual digitization - Graphic materials may be produced manually by plotting from aerial photographs in stereoscopic instruments. The graphical output from photogrammetric plotting may be digitized by manual tracing.

b) Direct digitization on stereo - plotting instruments - The analogue information contained in aerial photography may be converted to digital form directly in a photogrammetric plotting instrument fitted with devices which encode its motions. Through use of an interactive data collection and edit system, an operator can interact with the data and edit the contents of the manuscript tape. Positional accuracy is high, ie. digital information used in compilation of topographical maps at 1:50,000 scale can be used to produce graphics at 1:10,000 scale to standard map accuracies.+

c) Contours derived by analytical interpolation from a digital terrain model produced with the Gestalt photomapper. This produces digital terrain models directly, and accurate contours are produced by means of computer programs.

* "Report of the Task Force on National Surveying and Mapping", Department of Energy, Mines and Resources, 1978.

+ "Digital Mapping and Automated Cartography at the Department of Energy, Mines and Resources", M.E.H. Young, Third Annual Meeting of the National Capital Geographic Information Processing Group, Carleton University, May 12, 1978.

Since contours generally change little through subsequent map revisions, they may be advantageously generated as a separate compilation process. The data base file is the position or manuscript file with all features expressed in their true position without regard to cartographic symbolization.

The digital manuscript or position file is used to produce a cartographic tape or representation file, which is employed for the production of the necessary graphics for publishing the map. In this cartographic processing stage, linework is generalized, feature symbols are introduced, etc.

Automatic plotters which produce conventional maps rapidly and accurately to selected scales without manual drafting are directed by programs using data stored in the digital files.

Digital mapping includes derivation and storage of thematic information such as land registration, rights-of-way, geological features, etc. Developing data manipulation capabilities permit derivation for example of slopes and areas from the stored data. Stored map information may be retrieved by separate categories (eg. roads) and sub-areas.

Map information stored at 1:50,000 scale would be output at 1:10,000 scale and have standard map accuracy for that scale of map. It would, however, be lacking in content (eg. display of all buildings) usual for maps of that scale. Output at larger scale is readily accomplished. Some data massaging would be required to go to smaller scale eg. 1:250,000.

Digital mapping at 1:50,000 can be done using graphic products at larger scales eg. 1:20,000 at less cost than compilation from new photography. If a digital product at the larger scale were available the cost would be even less although methods of generalization to the smaller scale would be necessary.

At present, the operational time and costs of digital mapping are believed to be comparable to conventional mapping (automated cartography has high initial costs with several millions of dollars already invested by Surveys and Mapping Branch).

2.1.1 Relationship with the Provinces

It is logical that the federal government should concentrate on topographic mapping scales of 1:50,000 and smaller and that provincial activities should focus on larger scale mapping. Provincial requirements are causing growing activities at the larger scales and every province is conducting or planning to conduct its own mapping program at 1:20,000 and larger scales. Most of the provincial work is contracted out to industry. It would be desirable to utilize map information obtained by the provinces to update the smaller scale federal maps. Digital mapping at 1:50,000 scale could be done at much less cost (than using new photography) if provincial digital mapping at 1:20,000 for example, was available. However, it requires the adoption of standards for the communication of data.

The provinces generally have a high interest in digital mapping systems and would like to see a national topographic data base that would accommodate the needs of many users. A recommendation that "As early as possible, Topographical Survey create mechanisms for the formulation of standards for digital mapping, including the storage and retrieval of digital map data, involving federal, provincial and municipal governments, the universities and the private sector" has been made.*

A complicating factor in federal-provincial system uniformity could be the use of more than one map reference system. National mapping and that of several provinces is based on the UTM projection and grid reference system while other provinces use different systems. Standardization on one map reference system would be advantageous.

2.1.2 National Geographic Mapping

This includes the creation and updating of a geographic data base for Canada, the production of a National Atlas based on selected thematic maps depicting the physical, historical and socio-economic aspects of Canadian geography and the provision of geographic information of national scope to the federal government. A task force report* found, with regard to the National Atlas, that the problems with the current program included the fact that information in traditional cartographic products is often out of date because of the slow (and expensive) production process. Also some other federal agencies have created their own data collection agencies and are producing thematic maps. These maps use a wide variety of geographical referencing systems. The principal task force recommendation was that "By the year 1983, Geographical Services Directorate shift to a new program based on new concepts, ideas and formats, using digital technology to treat data and produce thematic maps that could be delivered at user's request, or be assembled in folio or book form." The difficulties of

+ "Report of the Task Force on National Surveying and Mapping", Study Conducted by the Department of Energy, Mines and Resources, May 1978.

creating the data base management systems needed to cope with the files and data banks used in the production of these maps was recognized. The report recommended that Phase 1 of this plan implementation should include contracting out development of the software necessary to overlay sets of disciplinary data and explicit historical trends. The report also recommended that the Geographical Services Directorate computerize the geographical names data base.

Summary

This section indicates the general shift to digital technology favoured and recommended by the Task Force on National Surveying and Mapping for most of the activities of the Surveys and Mapping Branch of the Department of Energy, Mines and Resources. As indicated, progress in this direction has been made. Standardization of systems has been noted as of major importance.

2.1.3 Relationship of Topographic Data Bases and Image Based Information Systems

Some Landsat-derived information such as new transportation routes and offshore shoals and islands has been used in topographic map revision. Small segments of an image have been examined in the plotting process with many ground control points utilized to improve positional accuracy. This procedure of producing a graphical product and manual digitizing to update a data base is likely to continue with Landsat-type satellites in order to achieve high positional accuracy.

Topographic data bases contain valuable information for overlay in image based information systems. Relief information is of particular interest. Digital terrain models (DTM) give elevation data in a raster (ie. grid or matrix) format so that an elevation number for a Landsat pixel can be obtained. Digital terrain models may be determined in two ways. Contours printed on existing maps may be manually digitized to produce digital vector files. Software for producing DTM's is available from Surveys and Mapping Branch, EMR, and processing costs per 1:50,000 map sheet are in the order of $100 to $200. Alternatively, the Gestalt Photomapper (one of which is used at Topographical Survey) automatically produces DTM's. The point density is high - for example at a photo scale of 1:55,000, the digital terrain model gives elevations in a grid pattern at 10m intervals (point density in a grid at 0.181mm intervals at photo scale). This instrument is particularly effective in northern areas but not so effective when man made structures such as bridges are present. The technique requires 2 1/2 to 4 days to produce one 1:50,000 digitized map sheet. The "pixel" elevation value could be used with Landsat data in a classification or other process: also contours may be generated from the DTM's and displayed on an output map product.

While elevation contours are present on all graphic products for 1:50,000 mapping in southern Canada and may be converted to DTM's, a digital terrain model will exist for every new northern 1:50,000 map that is produced using the Gestalt Photomapper.

Other data available in topographic data bases may also be overlayed in imaged based systems, including for example land registration, rights-of-way, geological features, census inventories, transportation routes etc. Landsat based photomaps with highway networks displayed have been produced for example.

2.2 Canada Geographic Information System (CGIS) - Lands Directorate, Environment Canada

The CGIS is a computer system, designed: to collect and store data from maps and statistical tables in a readily analysable form, to permit comparison of data for given regions (compare coverages) and correlation of selected socio-economic or other related data, and to permit output in map or statistical form.* The data structure used is a fine polygon structure with an identifier for each polygon. The system has the potential, not yet implemented, to store data for points or for lines and to interface that with data for areas. Polygon data can be automatically converted to any size of grid cell summary at any time.

The system can input map data in the UTM projection at scales from 1:370 to 1:1,000,000, and output maps at any scale in the UTM on Lambert projections. The major portion of the data base is at a scale of 1:250,000 and 1:50,000. Input procedures involve manuscript preparation (including manual procedures of scribing and extraction of descriptive data), digitizing, scanning, editing and verification of descriptive data. Polygon boundaries are input using a digitizer table, or automatically using an optical drum scanner. Polygon descriptive data includes classification, area, and location of centroid. The cost of converting the map image (scanner output) to a list of x,y vertices is less than 10% of the total cost of inputting a map to the data base. Map preparation, correction of cartographic errors and creation of the final data base format are all more expensive operations. Total input costs vary with map complexity but range from an average figure of about $500 per map to $800 for a dense land use map.

Up to 8 coverages can be overlaid simultaneously, and the composite output from one overlay operation can be input to another creating more layers. Cross tabulations between coverages can be made, eg. land use by census area. New coverages can be analysed in the same manner, as the original ones. There are 8 CLI coverages in the data base including land use, drainage areas, and the capability for agriculture, forestry, ungulates, recreation, waterfowl, and sports fish. In addition to numerous special studies, other major coverages include shoreline, census enumeration areas and administrative boundaries. CGIS have also developed routines to utilize Statistics Canada summary tapes. At present approximately 3000 maps are in the data base including coverage of the bottom third of Canada for 10 different themes. Although CLI data are presently limited

* "The Canadian Geographic Information System, CGIS Overview", W.A. Switzer, February, 1977.

in scope, CGIS could code data describing all of Canada. Updating of the data base is accomplished by using the overlay facility to superimpose the map of the change polygons on the original map. There is no good standard to measure overlay accuracy but it is generally within about 3%.

Data may be output as maps, tables, or digitally so that it can be further processed by the user. A grid can be superimposed on the polygon data and tabulations produced giving the percent composition of each cell. The cost of interrogating the data base is highly variable depending on the creation of a composite data base and overlay of coverages of interest. Costs could range from $100 for a single coverage product of an area to $40,000 for a 5-coverage overlay of the whole CLI area. Output sets of polygons can be overlaid manually (1 sheet on top of another) or different colour pens for each set of polygons or colour separations may be used. The user can specify a particular geographic area such as an arbitrary circle (eg. 10 miles around Ottawa), an area unit of any shape or size, an administrative unit (county, province, parish), an arbitrary figure, polygons, grid systems, a single **point** or series of points.

The CGIS system to date (not including the cost of CLI data acquisition) has cost in the order of $10 million. The major application is production of national statistics such as agricultural capability intersected with land use. From its inception, the computerized system was seen as a method that would save time and effort in handling massive amounts of data collected in the CLI program and make data available to land use planning by the federal and provincial governments.

The planning process was seen as involving analysing information to determine land capabilities, comparison with current population distributions and incomes, and development of government programs to achieve an efficient pattern of land use.*

The addition of other files to the data base in addition to CLI data, has enhanced the utility of CLI data by making it possible to aggregate data for specific areas eg. areas of Class 1 agricultural land in a particlar area, and to compare physical and socio-economic characteristics. Users of CLI data have been listed as planners, engineering firms, individuals, conservation authorities, and a variety of users in private, municipal, provincial, and federal agencies.*

The CGIS is designed for use on an IBM S/360/370 computer equipped with the usual peripheral equipment. It is written in PL/1 with assembler language routines to perform some functions. There are remote terminals for on-line

* "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins, D.F. Marble, the UNESCO Press, 1976.

operation now in Halifax and Alberta. Costs of interrogation are the same as noted above plus communication charges.

Manuscript map data is used as input to the CGIS at present. No aerial photography data is used as direct input now. Elevation information is currently not included in the data base.

To the extent that remotely sensed data improves the accuracy and currentness of information in the data base on which decisions are made, it will assist the objectives of the CGIS. Potential CGIS applications include land use conflict analysis, long-range land requirement forecasting, comparison of land capabilities with social and economic demands under different policy assumptions, environmental impact studies, location of public service facilities and land use monitoring to assess changes.*

Delays and difficulties were experienced during the development phase of CGIS as has been the case with some other geographic information systems. "Developers underestimated not only the problems but the costs of system development. However, these problems are not unique to CGIS.*

* "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins, D.F. Marble, the UNESCO Press, 1976.

2.3 Soils Data Base - Agriculture Canada

A soil information system has been described as a data management service acting as a vehicle for dissemination of information to other disciplines and providing a channel for interfacing to other systems (many information systems have fallen short of this objective). It requires a high degree of standardization by those contributing data to the system and those expecting data from it. *Kloosterman notes that the full potential of computer-assisted data handling is not yet being exploited in part because current concepts of soil data handling "remain entrenched in the approaches developed when all data were handled manually." This early stage of development of digital data management in soils and other resource related areas makes integrated planning feasible for optimized intra- and interagency information systems, which are also designed to accept new types of remotely sensed data as it becomes available.

Work in the Canada soil information system (CANSIS) began in 1971. The CANSIS data base uses a polygon data structure. Manuscript maps are digitized manually for input to the data base. The data is input at the scale of the map - for example, some are at 1:250,000 and many are at larger scales ie. 1:50,000 or 1:20,000. About 4-5 man days are typically required per map sheet. Digitizing is done as part of the normal map production process with a scriber-cursor enabling an operator to scribe and digitize his map at the same time. The digitizers are driven by a PDP 11/10 mini computer controller. Processing is done at Agriculture Canada on an IBM 370 computer with CPU costs per map sheet in the order of $20. There is limited capability for scale change of the output product (up to a factor of 2). Some statistical information is available eg. area data.

Detailed soil maps include boundaries drawn according to slope, topography, texture and materials. Some generalization is possible in the data base so that an output thematic product could be produced on the basis of a subset of these characteristics.

At present soils departments in the provinces send soil survey maps to Ottawa for input to the data base. The provinces use only graphic products. Manitoba Soils Survey have acquired the CANSIS software and will create their own data base. Startup costs including digitizing table and minicomputer would be in the order

* "Role of Computer Information Systems in Soil Science", B. Kloosterman, Applications of Geographic Information Processing, U. of Ottawa, April, 1977.

of $50,000. It will then be possible to input their data directly into the CANSIS data base.

The users of the system are primarily soils survey personnel although other agencies eg. Parks Canada have made use of the data. There are at present about 300 maps in the data base. In addition to map information, CANSIS contains "hard" or point data. Field and laboratory data resulting from soils surveys, and fertility and yield experiments, are recorded in soil data files. Data may be used for further statistical analysis such as correlation and regression analysis, and statistical summaries are used to help survey staff define mapping units and soil series.*

A part of the CANSIS data base under development is the soil performance/ management file which brings together information related to the performance of identifiable soil units, ie. productivity under specific conditions. The data is keyed by geographic location and includes information on site, treatment, climate, soil (chemical and physical analysis) and crop (development and yield data). Data of varying quality and extent are being obtained from a variety of sources. These include in order of decreasing quality: experimental plots (perhaps one or two in a region), variety trials (fairly sparse), certified seed growers (also sparse coverage), soil tests, crop insurance surveys and farm surveys (these three provide fairly comprehensive coverage amounting to about 50% in western Canada.

The objectives of this file are to provide a research tool for scientists doing land evaluation and soils surveys, and to provide performance data to provincial agencies setting recommendations for fertilizer management practices. Agencies doing soil testing would provide to farmers recommendations which could be adjusted on the basis of data in their data base.

At present data is being compiled. Software has not yet been developed to produce output products.

<u>Relationship of Soils Data Base and Image Based Information Systems</u>

Soils maps are digitized and input to the CANSIS data base. Current Landsat MSS data can assist in producing soil maps by delineating soil landscape patterns, that is outlining broad land systems. Land systems are recurring patterns of slope, topography, texture and materials. High resolution satellite data in the 20-30 meter range should satisfy many soil mapping requirements. Thirty meter resolution should permit discrimination of prairie knolls and depressions. Eroded knolls and wind eroded prairie areas give rise to brighter tones on present

* "Role of Computer Information Systems in Soil Science", B. Kloosterman, Applications of Geographic Information Processing, U. of Ottawa, April, 1977.

Landsat MSS data, and the high resolution data should permit much better discrimination of these eroded areas and delineation of boundaries of different soil landscape patterns. Eroded knolls have distinct signatures.

Some overlaying of digital soils data in an image based system has already been accomplished. Polygon soil boundaries from the CANSIS data base have been coverted to grid format and overlaid on reformatted Landsat data (rectified and resampled).* Registration is within one pixel. The thematic overlay data has information on slope, topography, texture and materials. Within the zonal boundaries thereby delineated on the imagery, one can determine signatures of fallow land or various crops, and examine the tonal patterns of wind eroded plains or eroded knolls. Slope information is very important in agriculture and this is already contained in the soils information.

The next desirable step is to overlay legal land survey boundaries. This has several advantages including assisting ground checking and relating to other data including land assessment, crop insurance, yield and soil testing data.

It is important to note that the soils data (texture, materials, etc.) is <u>baseline data</u>. The cropping patterns observed by Landsat which will show variations from week to week and year to year will be influenced by this basic soil data. For example, saline areas may not show up in a particular year when there is a lot of precipitation to wash the salts down. In another year these may be readily indicated by the cropping pattern. Inference of causes of other observed cropping variations in a particular year eg. moisture stress, plant disease, insect damage, weeds, will also be assisted by this basic information on materials, slope, texture and topography. Some of these conditions depend on meteorological factors eg. observation of salinity depends on moisture, hence the requirement to tie in meteorological data with the resource monitoring data. Field work would usually be coupled in with satellite-observed patterns indicating problem areas or important zonal boundaries but the latter would be reduced, and the requirement for aerial photography may be eliminated in many cases by adequate resolution satellite data.

Changes in extent or amount of land degradation occur at varying rates according to specific conditions (eg. soil type and slope). For example, severe erosion could be caused by thunderstorm activity. Resolutions of 20-30m should be adequate for detecting some of these changes. If better resolution was available

* J. Shields, Agriculture Canada, personal communication.

(10m) it could be utilized in this erosion-monitoring application and for monitoring saline areas. Detection of areas of land degradation should be facilitated by higher resolution Landsat data overlaid with the type of thematic data (slope, soils) indicated above.

The possible benefits of improved farm management have been discussed previously.* Realization depends not only on adequate information integration but also on an adequate extension service to communicate effectively to the individual farmer how he can improve his production and conserve his land. Some of the suggestions for sustained yield, for example, longer cropping rotations and withdrawal from the practice of frequently leaving fields fallow, require persuasion of the individual farmer including both communication and proof. Landsat data can contribute to the proof for example through buildup of a historical data base over time showing crop type and crop and land condition on a field by field basis.

* "Applications and Potential Benefits of Landsat-D", A. McQuillan, CCRS Research Report, 1978.

2.4 Census Division Data Base - Statistics Canada

The pyramidal pictorial structure below shows the different geographical statistical areas of census data.*

Canada

(subprovincial regions) -63 SPR- — PR (Provincial Areas) -12

(federal electoral districts) -282 FED- — CD (Census Division) -260

— CSD (Census Subdivision) -5,546

Domain of the Geographic Master File

(census metropolitan areas) CMA-

(census agglomeration) CA-

(census tracts) -2,685 CT-

(urban area) UA-

Domain of Geocoding

EA (Enumeration Area) -35,154

(city blocks) BLKS -

(block faces) BF-

(single address) 8 million SA

Definitions:

EA - The enumeration area is the basic census data collection unit and the building block of the geostatistical areas. EA's may be used to aggregate data to all statistical areas. An EA may include up to 375 households and always includes less than 100 farms. An EA never cuts across any area recognized by the census.

CSD - The census subdivision whenever possible corresponds to a municipality. It corresponds to a township in rural southern Ontario, but not in the prairie provinces. CSD's are constantly subject to territorial or designation changes. All CSD's will aggregate to CD.

CD - The census division may or may not have legal status depending on the province concerned. In Newfoundland, Manitoba, Saskatchewan and Alberta, the term describes geostatistical areas that have been created as an equivalent for counties. The CD code permits the aggregation of data for Provinces and Subprovincial Regions (except in parts of Quebec).

CT - The census tracts are stable building blocks for urban communities with population 50,000 or over. The census tract population must be

* Information obtained in personal interview with P. Hubert, Statistics Canada.

between 2500 and 8000 except for census tracts in the central business district, in industrial areas, or in peripheral rural or urban areas which may have either a lower or a higher population. The area must be as homogeneous as possible in terms of economic status and social living conditions.

CMA/CA - These are geostatistical areas created by Statistics Canada. Census metropolitan areas (CMA) are defined as the main labour market area of an urbanized core (or continuous built-up area) having 100,000 or more population. They contain whole municipalities. A census agglomeration area (CA) is a geostatistical area comprised of at least two adjacent municipal entities. These entities must be at least partly urban and belong to an urbanized core having a population of 2000 or more.

SPR - The subprovincial region (formerly called Economic Region) is a statistical unit consisting of a group of census divisions (except Quebec), and intended to make possible the tabulation of data for comparable units throughout Canada.

FED- Federal Electoral Districts are non-permanent geostatistical units established by parliament, and may cut across all geostatistical areas except provinces and enumeration areas.

Socioeconomic data collected by Statistics Canada may be obtained for the geostatistical units indicated on the pyramid above. Special data-base searches which can cost several hundred dollars depending on complexity of cross tabulations and geographic areas are required for some user requests. A number of census user summary tape files are available at a cost of $55 per tape. These contain data pertaining to demographic, housing, household, family and economic characteristics and are available at the enumeration area, census subdivision and census tract geographic levels.* Examples of enumeration area user summary tape files corresponding to these characteristics include:

- demographic - population by mother tongue by sex; dwelling (household and housing)
- occupied private dwellings by tenure by structural type;
- family - families by family structure by age groupings of children at home;
- economic - population 15 years and over by labour force activity by level of schooling by sex.

* "1976 Census User Summary Tape and Microfiche, Content of Tables", Statistics Canada, September 1978.

Boundary data is available in machine readable form for the geostatistical units except for the enumeration areas. The CGIS which wanted socioeconomic data at the enumeration area level in their data base, digitized, EA boundaries from Statistics Canada map manuscripts on which these units were delineated. Statistics Canada have used these boundary tapes in production of a series of thematic maps. Some minor interfacing difficulties had to be overcome. Data is sometimes required at a finer level than enumeration areas particularly for urban areas. Although in rural areas this is the smallest unit, and is a function of density ranging in size from about five to ten square miles in southern Ontario to one to three hundred square miles in the prairie provinces, data is available for smaller units for 131 municipalities representing about 51% of the national population. An enumeration area represents about 2 or 3 city blocks, but for these municipalities data is stored at the block face level (one side of a block face between two intersections), and x,y coordinates are attached to census data at this level. This permits a greater flexibility in the use of data for urban applications, eg. census data could be provided on the basis of wards. Availability of data at the block face level provides more accurate data for many applications than extrapolation from the enumeration area. About 10 of these municipalities provide, on a continuing basis, updated geographic information to Statistics Canada (eg. new streets). It is expected that information of this nature will be obtained from more municipalities in future. This information goes toward preparation for the next census (eg. boundaries of enumeration areas).

Information obtained from other levels of government in addition to the municipal geographic changes noted above include information from the provinces on changes in census subdivisions.

Several geographic files are available from Statistics Canada. These include:

1976 Street Index - links address ranges to enumeration areas. The data consists of street name, type and direction, odd and even address ranges; the latter includes municipality, federal electoral district, enumeration area and census tract. Street index generally cover urban centres having 20,000 or more in population.

1976 Geography Tape File - assigns each enumeration area to all higher geographic levels by code and name for Canada. It includes EA centroids (in both U.T.M. and latitude, longitude coordinates), the standard geographic codes, the land area, the population and household counts.

1971 - 1976 Enumeration Area Conversion File - establishes correspondence at the enumeration area level in light of the large number of changes in enumeration area boundaries in 1976 vs 1971 and the small degree of correspondence users may obtain in comparing data at the EA level.

1976 Enumeration Area Centroid File - gives the province, federal electoral district and enumeration area codes associated with the UTM coordinates of the enumeration area centroid and the population count.

Although the Census Division currently use Surveys and Mapping topographic maps to delineate geographic areas they expect to use eventually digital products from S&M automated cartography.

There are changes in the boundaries of some geostatistical areas from census to census. For example, there were 35,154 EAs delineated in Canada for the 1976 census compared to 42,533 EAs for the 1971 census. An updating of these boundaries would therefore be required every census in an information system overlaying socioeconomic with other types of data.

Satellite data of <u>adequate spatial resolution</u> could assist the census division in terms of drawing urban boundaries (at present a very time consuming task) and providing urban physical information (eg. streets) between censuses. The census division are interested in areas of rapid growth in preparation for the next census (eg. new enumeration areas).

By providing data at the block face level for urban areas (subject to some confidentiality limitations) and at the enumeration area level for rural areas, Statistics Canada have been moving towards a greater flexibility in terms of availability of census data and therefore in terms of satisfying a wide range of user requirements involving a variety of geographic areas and cross tabulations.[*] For example, data can be aggregated by school district, police district, etc. - in short, for whatever geostatistical or administrative area required. It is expected there will be a greater integration of socioeconomic data with other forms of data in future.[*] This has already taken place with the Canadian Geographic Information System and one would anticipate that this social and economic data would provide a vital input to provincial land use and environmental information systems. Considerable cost has been incurred in the data collection phase (in the order of $40 million) and a principal objective is to make the data available for a wide range of applications. It is important to note the time scale associated with collection of this data (in comparison for example with changing environmental conditions) ie. socioeconomic information update at 5-year intervals with some geographic boundary updating at that time.

Socioeconomic data is collected at one point in time (every 5 years) and a particular geography corresponds to that data. While the Census Division of

* "Quelques aspects de la géographie au recensement du Canada; Lier, aujourd'hui et demain", D.J. Hubert, présenté au congrès sur la méthodologie de l'aménagement et du développement, 45 e congrès annuel de l'association canadienne-francaise pour l'avancement des sciences, Trois-Rivières, mai 1977.

Statistics Canada are interested in changes in geography in preparation for the next census, at the local level planners may be interested in making use of new data for example on roads and buildings to assess trends and perform extrapolations from data of the previous census. Satellite data which could provide updated information could assist at the local level in this interim period.

2.5 Current Developments and Trends to Digital Resource Information Systems

Developments are occurring at the provincial level which make a study of computerized geographic information systems important at this time. These include on the one hand a progressive maturity of several types of technology, including data acquisition, processing and analysis and information system technologies, and on the other a requirement for better resource management and conservation.

A great deal of information is currently being digitized within several departments of the federal government, as well as some by industry. Some of this involves once off applications and/or small, single purpose files. As systems have evolved to complex, multi file, multi-purpose systems, management teams involving disciplinary scientists, system designers, computer programmers and clerical staff have been put together.* Data base developments within federal agencies have taken place largely independently of one another, with the result that there is at present little interchange between them. (As already noted, however, geostatistical area boundaries have been exchanged between Census and the Lands Directorate.+) If this situation were to develop at the provincial level as well, it would represent a serious handicap.

Provincial interest in digital information systems is currently high. For provincial agencies working closely with their federal counterparts, there may be tendencies to adopt a similar data base structure although as noted above the latter are generally incompatible. For example, Manitoba Soils Survey have acquired the CANSIS software and will use that for their soils data base. A committee of federal and provincial surveys and mapping agencies has been formed to consider standards for topographic data bases. These two examples indicate some movement toward standardization in data collection and organization between federal and provincial departments with similar interest. Even if this ideal were to be achieved, it would not at all guarantee comparability between data collected by various agencies for

+ "Exchanging Spatial Systems Technology: Related Issues and a Case Study", J. Yan, S. Witiuk and T. Fisher, Applications of Geographic Information Processing, 2nd Symposium of the National Capital Geographic Information Processing Group, U. of Ottawa, April 1977.

* "Concepts, Objectives and Structure of the Canada Soil Information System", J. Dumanski et al, Can. J. Soil Science, Vol. 55, 1975, p. 181-187 and "Role of Computer Information Systems in Soil Science", B. Kloosterman, Applications of Geographic Information Processing, D.M. Douglas, U. of Ottawa, April 1977.

a particular region. This ability to correlate information is most crucial at the local level for management purposes. There is some evidence of such inability to correlate information at the local level extending to digital information systems. A study on information management in the Maritimes found with regard to computer applications for information handling that* "despite commonality of interests, the sharing of systems, techniques or even experience between governments has not developed naturally to any extent---The development of information systems generally has proceeded independently in the three governments resulting in duplication of effort---incompatibilities now exist between government installations which impede the exchange of programs and data files." The trend in the two examples noted above to look to federal agencies as models in constructing data bases may result from agencies perceiving more benefits in structuring systems this way (by discipline) than striving for compatibility with other systems at their own government level.

The difficulties in convincing agencies to change structures or to develop software to reformat data for use by other agencies is illustrated by the difficulties experienced by the federal Interdepartmental Committee on Geographic Information Systems. Formed in 1975 to facilitate the transfer of computer based geographic data within the federal government and to encourage cooperation and information exchange, the committee disbanded after 1 1/2 years after failing to make progress towards standardization for the exchange of geographic information. A subsequently formed Spatial Data Transfer Committee has produced a draft document outlining a standard format for the interchange of spatially encoded data in the form of polygon chains. The unwillingness of agencies to change the structure of established systems is understandable, particularly since large development costs were associated with some. The need for preplanning is therefore apparent.

Remote Sensing Data and the Problem of Data Flow Between Agencies

With the rapidly expanding data volumes from satellites and other data collection platforms, and the expanding developments of computerized geographic information systems, there is a requirement for standards which will facilitate data exchange at the international, national, local and system level and permit merging of multi-source data.

The Canada Centre for Remote Sensing acquires remotely sensed data and makes

* "Final Report to the Land Use Planning Sub-Committee on the Land Use Planning Information Project", W.R. Trenholm and P. Wood, April 1, 1974, N.B. Dept. of Agriculture.

it available to users. It is therefore concerned that the data may be in a form which is readily usable, and can be input smoothly and at low cost into existing user information systems. In-house research into analysis methodology requires a smooth data flow in the reverse direction - that is that various types of data collected by users be readily incorporated into an image-based information system.

CCRS has been involved in studies both at the national and international levels to develop methods of smooth data flow between agencies. Documents have been prepared for the requirements of a general user CCT format family, and for a proposed general structure which could meet most of the expressed needs and be adopted internationally. A principal requirement of the structure is that it be well suited to the presentation of cellular image type data such as that available from Landsat. Other data types which must be handled include: profile data (eg. traces from airborne profiling sensors); alphanumeric, numerical or logical linear list; and polygon or chain structure data. Accommodation of polygon data would facilitate the use of remote sensing information in updating many existing geodata based systems. A Canadian federal government interdepartmental "Spatial Data Transfer Committee"* has the objective of developing a standard format for interchange of spatially encoded data in the form of polygon chains. Such exchange would serve to reduce duplication of data collection costs. Data transfer would be accomplished by production of a computer tape in standard format by the donor agency. Most existing data bases in Canada use the polygon chain structure for storage of ground class information. In order for them to assimilate readily the inherently gridded remotely sensed data, conversion to this standard format is required. One software package is used by each agency to read and write data in this standard format. The incorporation of remotely sensed data in geodata based systems would therefore be accomplished with minimum impact on existing software systems. Although conversion of polygon data to cellular form is readily accomplished, the reverse process of converting continum cellular data (eg. Landsat data) to a series of steps, outlining of homographic areas and converting to polygon lists, is much more complex. Data base structures using the gridded approach also need to be supported by providers of image products. Among the specialized products required to be accommodated in a standard CCT

* Committee composed of representatives from Statistics Canada, Lands Directorate of Environment Canada, Agriculture Canada and Canada Centre for Remote Sensing.

format are multi-temporal, pseudo-imagery, mixed data imagery, mixed sensor imagery, mosaic data, subscene data, thematic map data, various projections and various pixel or ordering schemes such as byte interleaved by line, byte interleaved by pixel, byte interleaved by pixel pairs and band sequential.* Multi-scenes from different sources are to be accommodated as well as cross references between data bases and scenes.

Other Considerations in Development of Digital Information Systems

While remote sensing technology is in a state of rapid development there are other factors encouraging development of geographic information systems. Agencies, government and private are in a transition phase to digital information systems. On the applications-pull side are pressures for improved management and protection of resources and environment requiring better information for decision making. Another factor is the trend to metrification. This is causing many government agencies to examine their information products, and it provides a logical break point for conversion to a new type of information system. Because of these pressures and the inclination to "jump on the bandwagon" thoughtful consideration may not be given to questions of centralization vs decentralization, education at various levels, security of information, or impending technology changes which could make a system obsolete. Other potential problems include: possibility of proliferation of systems which are incompatible (between provinces and between departments in one government); the possibility of becoming locked (because of large resource investments) into a system which does not really satisfy requirements in an effective way-or which may unnecessarily fail to satisfy other values such as human fulfillment. Information system development is costly and the history is characterized by a multiplicity of "individual" system designs. Most serious costs are not so much the up-front cost if the system fails to permit optimum information to be obtained for decision making. High costs of data acquisition relative to overall costs are intensifying requirements to avoid any duplication of acquisition and any unnecessary acquisition particualrly of ground data. Sharing of digital data bases facilitates this.

A major consideration in design of an information system for management purposes is the increasing availability of "real-time" environmental observations. Although this paper has emphasized earth resource and meteorological satellite data, improved communications, selective data acquisition and the existence of a computerized information management system can influence the types of data

* "User Computer Compatible Tape Format Family Requirements", prepared by the Canada Centre for Remote Sensing for the Landsat Ground Station Operators Working Group.

acquired including their timeliness, accuracy and reliability. Data can be collected by in situ sensors and relayed by satellite and other methods to central locations. Aircraft may obtain more selective data, ie. more frequent coverage of a particular location than provided by satellite or a special type of data acquisition, guided by satellite reconnaissance data. If a proper information system were in place it would facilitate tapping a dimension of data acquisition underutilized in the past, namely individual "observors of opportunity" eg. farmers and other private citizens, aircraft on other missions, etc. Site specific observations are of value for such monitoring as disease spore and insect counts, water and air quality sampling, ground moisture and snow measurements, etc. As systems can become overloaded with data of varying quality, emphasis is on selective acquisition of quality data.

Planning of regional geographic information systems require careful consideration as to real user requirements, the extent to which the system will be used, and realistic development costs. The CGIS under development since 1965 has not yet achieved its potential widespread utility although its use has been increasing and remote terminals should further expand that. It has a valuable data base and powerful information overlay capability. Acceptance as well as development takes time. Tomlinson notes* "Developers underestimated not only the problems but the costs of system development. However these problems are not unique to CGIS." He also notes that "There are just as many problems,and possibly more, on the management side of implementing an information system as there are on the technical side".

In developing an information system to satisfy user needs, much consideration must be given to the space and time scales of the information requirements. Often a high level of information detail is required by provincial and municipal governments in carrying out their management responsibilities. A study in the Maritimes noted that "---there is an inverse relationship between the demand for increased detail and the availability of information."** The study found a stronger information base for large area (province wide) information than for small areas. For example, the CLI maps at a scale of 1:250,000 provide reconnaissance level information capable of satisfying only some of the planning and management objectives. Information also showed a high variability in quality from one area

**"Final Report on the Land Use Planning Sub-committee on the Land Use Planning Information Project", W.R. Trenholm and P. Wood, April 1, 1974. New Brunswick Dept. of Agriculture.

* "Computer handling of geographical data", R.F. Tomlinson, H.W. Calkins and D.F. Marble, UNESCO Press, 1976.

to another (as well as availability). Provision of an information system framework in which this sporadic data is imbedded would assist in highlighting geographic information deficiencies as well as facilitate standardization.

The development of many geographic information systems has been driven by land-use planning requirements. Requirements for information updates in these systems may be keyed to changes in urban areas. For example, an annual update of information in urban and urban fringe areas and less frequent updates elsewhere may be adequate for satisfying land use planning requirements. However, for day-to-day management of water, resources, crops and forests, the time scales for information updates are much shorter. An information system to satisfy these requirements usually requires that large volumes of data be handled quickly and inexpensively.

3. Remote Sensing Data Management and Processing

3.1 History of Environmental Data Acquisition

Throughout history, ground methods have been used to collect data on resources and the environment. The cost of collecting data by this method forced a high degree of selectivity in sites where data was acquired and necessitated use of sampling methods. For dynamic distributed phenomena, models were developed which made use of a time series of point observations. For example, in hydrology point observations of temperature, precipitation, evaporation and snow water equivalent were made, and input to regression models; and in meteorology point measurements were made of such parameters as temperature, pressure, relative humidity, and wind velocity, and input to forecast models.

Aircraft photography permitted earth resource observations to be carried out over large areas ie. it filled in the spatial dimensions. Methodologies were developed for timber and other resource inventories usually employing combined aircraft and ground measurement methods, and gradually gained acceptance. Many map products were produced such as soils maps, vegetation maps, biophysical surveys and land use maps. In addition to these interpreted products, the "raw" photographic data continued to be in demand by investigators for many applications. Costs associated with airphoto acquisition and information updates made repeat coverages and map revisions usually infrequent. Aircraft costs also limited the extent to which two and three dimensional data on dynamic distributed phenomena, such as snow cover, were acquired.

The repetitive nature of satellite coverage, which provides a time dimension to earth observations, makes this an ideal platform for monitoring. Extensive use has been made of both polar orbiting and geostationary satellites in monitoring dynamic weather conditions. Landsat has similarly demonstrated the ability to monitor changing earth resource conditions. Landsat has similarly demonstrated the ability to monitor changing earth resource conditions. The satellite platform has facilitated the ability to compare emittance data and reflectance data (including that obtained in spectral regions outside the range of normal photography) acquired at different times and at different locations. To date, Landsat data has seen some use both for mapping and monitoring applications. Among the first successful monitoring applications were those where there were spatial changes in features with distinctive spectral characteristics, eg. ice and snow monitoring. However, use of the data for some monitoring applications has undoubtedly not received a thorough test using a suitable information system in an operational environment. Satellite data is available in computer compatible form. Its integration with complimentary data in computerized environmental information systems should therefore be facilitated.

3.2 <u>Earth Resource Satellite Program</u>

In the case of remote sensing technology, a new era of international interest and participation is beginning, stemming largely from the success of the Landsat program. Polar orbiting satellites are global data acquisition systems. Several space agencies now have planned earth resource satellite programs so that more frequent ground coverage from a system of satellites is probable in future. Infrequency of coverage aggravated by cloud cover has been an impediment to some operational Landsat applications.

The Landsat program and airborne remote sensing programs have provided a much better understanding of the extent to which user needs can be satisfied by remote sensing and where changes or additions to present satellite data acquisition would be advantageous. Many future satellites will be characterized by improved sensor spatial resolution. Other planned changes include added spectral channels, narrower bands in some spectral regions, better radiometric resolution, and addition of new sensors such as synthetic aperture radar and rain radar.

The increased numbers of satellites and much higher data volumes expected from sensors on-board each satellite makes planning of end-to-end systems necessary. Ground data handling and analysis and data archival will require careful planning and evaluation so that available data may be selectively acquired and utilized to meet user requirements in an optimum way.

The new capabilities of obtaining information from space come at a time when there is a high level of consciousness of the need for information which will help in conserving resources, protecting the land base, preserving environmental quality, etc. The availability of the data will help to generate an awareness of its need.

Some of the planned satellite programs and expected developments within the next decade which will influence requirements for information management are outlined below.

New Programs

Significant developments are expected for the visible and infrared spectral regions within the next decade. NASA plans to launch the experimental satellite Landsat-D, representing the "second generation" in spaceborne earth resources sensors, in 1981. In addition to carrying an MSS similar to those of the first three Landsats, it will have a Thematic Mapper. This sensor will have finer spatial resolution, more bands with narrower and better defined spectral responses, higher radiometric accuracy and resolution, more sophisticated inflight calibration techniques, and greater geometric fidelity.* Spectral bands are described in Table 1. The increased instrument sensitivity -256 gray levels vs 64 for MSS- is equivalent to going from about 2% precision to 0.5% precision.+ From the data management point of view, the TM pixel size $(30m)^2$ as compared to the MSS pixel size $(80m)^2$, will have a big impact. The thermal infrared channel however will have $(120m)^2$ pixel size. Table 2 compares the spatial resolution of the sensor on Landsat-3, Landsat-D and SPOT (a French satellite planned for 1984 launch).

A third generation in the development of visible and infrared sensor technology will come from solid-state array technology (pushbroom scan arrays) which permits performance improvements over MSS and TM electromechanical scanner technology.+ The advantages of line arrays include precise geometric positioning of the detectors, very high sensitivity and favourable signal-to-noise ratio with small lightweight optics, low power consumption and no moving optics. For the 0.4 to 1.1 um spectral region, current technology would permit spatial resolution of 10m and spectral bands as narrow as 20 nm. For comparison purposes, the TM will cover spectral ranges 70 nm or more wide. Extension of the spectral response into the 5 um and 8 to 14 um regions is planned for the next four years. Offset pointing would permit stereographic imaging for topographic mapping and two to five day return coverage from one satellite. It is anticipated that this sensor with all the TM bands could be utilized by 1988. The potential 10m resolution of multispectral data and the potential for narrow spectral bands which may be desired, for example, for water quality studies, will greatly increase data handling requirements if that data is acquired.

+ "Remote Sensing Using Solid-State Array Technology", L.L. Thompson, Photogrammetric Engineering and Remote Sensing, Vol. 45, January 1979, p. 47.

* "Development of the Thematic Mapper", O. Weinstein, .LR. Linstrom and J.C. Bremer

Table 1

Thematic Mapper Spectral Passbands

Band	Spectral Range (um)	Basic Primary Rationale for Vegetation	Principal Applications
1	0.45-0.52	Sensitivity to chlorophyll and carotinoid concentrations	Coastal water mapping Soil/vegetation differentiation Deciduous/coniferous differentiation
2	0.52-0.60	Slight sensitivity to chlorophyll plus green region characteristics	Green reflectance by healthy vegetation
3	0.63-0.69	Sensitivity to chlorophyll	Chlorophyll absorption for plant species differentiation
4	0.76-0.90	Sensitivity to vegetational density or biomass	Biomass surveys Water body delineation
5	1.55-1.75	Sensitivity to water in plant leaves	Vegetation moisture measurement Snow/cloud discrimination
6	2.08-2.35	Sensitivity to water in plant leaves	Hydrothermal mapping
7	10.4-12.5	Thermal properties	Plant heat stress measurement Other thermal mapping

Table 2

Sensor	Spatial Resolution	Resampled Pixel Size	Resampled Pixel Area
Landsat MSS	79 m	$(50m)^2$	0.62 acre$\left(\frac{1}{1.6}\right)$
Landsat TM	30 m	$(25m)^2$	0.15 acre$\left(\frac{1}{6.5}\right)$
SPOT HRV	20 m multispectral	$(12.5m)^2$	0.039 acre$\left(\frac{1}{26}\right)$
	10 m panchromatic		
	10 m	$(10m)^2$	0.025 acre$\left(\frac{1}{40}\right)$

Developments in sensor technology in other parts of the electromagnetic spectrum are also anticipated. In the microwave region the number of microwave radiometer channels is forecast to grow eventually to 30 covering up to 300 GHz, and spatial resolution in the shuttle era is expected to improve by well over an order of magnitude. Active radars are expected to be further developed and see operational use.

In addition to the U.S. and French satellites noted above, Japan will launch MOS-1 (Marine Observation Satellite) in 1983, carrying a visible and near infrared radiometer with Landsat MSS spectral bands and 50m resolution. The development plan of the Japanese Earth Observation Satellite program includes MOS-2 and 3 in 1985 and 1989, and LOS-1 and 2 (Land Observation Satellites) in 1987 and 1991. Studies for a European Remote Sensing Program are underway by the European Space Agency. Two satellite systems, LASS (Land Applications Satellite System) and COMSS (Coastal Ocean Monitoring Satellite System) are being considered, with a proposed first satellite launch in the 1985-86 time period. Among satellite programs under consideration in the U.S., are included both satellites which would monitor a variety of land, meteorological and oceanographic conditions, and programs which would be tailored to a particular application.

The trend is towards not only acquiring these new types of data but also to new procedures in acquiring and handling "old" types of data. Satellite monitoring is permitting increasing selectivity in airborne and ground data acquisition resulting in improved efficiencies in those procedures of data gathering somewhat analogous to radio-dispatched taxi operations. Aerial photographs and interpreted map products made using photographic and other information sources are being digitized and input to information systems. The Gestalt Photomapper automatically produces digital terrain models. The point density is high; for example at a photo scale of 1:55,000, the digital terrain model gives elevations in a grid pattern at 10m intervals.

Two points emerge, in the discussion in this section, as of particular importance to monitoring of earth resources and environment. It is evident therefore that national and international earth satellite observation programs will produce frequent multispectral two (or three) dimensional data which will constitute a major driving force in future environmental information systems. In addition, as the spatial resolution of the data increases to 30m (Landsat-D), to 20m (SPOT), and possibly to 10m, the utility of the data for monitoring at the local level improves.

3.3 Preprocessing

Geometric Correction Using CCRS Digital Correction System (DICS)

Resampling of Landsat data to square pixels with DICS will assist in image analysis. Landsat MSS data is resampled to produce 50m pixels. It is planned to use 25m Landsat-D TM pixels. SPOT multispectral data acquired at 20m resolution and panchromatic data at 10m resolution could be produced as 25m or 12.5m pixels. At 25m some information would be thrown away. The main disadvantage of going to 12.5m is the increased amount of data to be handled. This represents 4 times more than 25m data and 2.5 times more than 20m data. The advantage is that the combination of the 10m panchromatic data with the 20m multispectral data should improve the spatial information content over the multispectral data alone. Similar spatial information improvements would be expected from combining high resolution airborne data with satellite data, or Seasat-type SAR data with Landsat MSS data. Airborne MSS data could be produced or air photo products scanned with a microdensitometer to produce a pixel size which would nest with square pixels of the above sizes. It may also be noted that the Canadian Seasat SAR processor will produce a pixel size of 12.5m.

The extent to which radiometric accuracy is degraded by resampling is dependent on the resampling algorithm. The DICS system oversamples at 50m (pixel size 57 x 79m) and uses 16 point interpolation (ie. 8 pixels on each side to perform the pixel interpolation). It is believed that the information loss is very small using this method (and a small problem compared with haze, sun angle, and other considerations).

Image analysis is facilitated by the DICS output format. Auxiliary information provided includes the northing of every line and the easting of the first and last pixel of every line. The easting of any pixel in between may be computed. In the CIAS one can request that the cursor be moved over a pixel with a particular designated northing and easting. The ability to determine the northing and easting of any pixel in a Landsat frame facilitates the merging of other data. For example, relating a particular point measurement at a given northing and easting to a particular pixel in a frame should be easy. If one wishes to work with a particular block of data, in one operation, one can compute the disc sector where that data is stored.

The DICS system could also be used to resample meteorological satellite data. NOAA data has a lot of distortion so that working close to nadir is desirable. The resolution is 1 km, therefore 50m Landsat MSS data will nest with it. NOAA and Landsat data could be rectified to the UTM projection independently and then superimposed.

Ground control points from 1:50,000 scale maps (where available) are used with DICS. About 20-30 points per Landsat image are used. The method is based on rubber sheet registration. Eventually data from Surveys and Mapping automated cartography will be used.

The spatial information contributed by combining with multispectral satellite data high resolution airborne data (eg. radar, photographic or MSS data) or high resolution satellite data (eg. SPOT panchromatic data) can increase the power and efficiency of processing. Higham et al note that the set of regions, nodes and corners can be used to control operations on the underlying image.* These topological characteristics vary less in time than most other features and can provide ready made "nuclei" for clustering making multispectral classification more efficient.

* "Multispectral Scanning Systems and Their Potential Application to Earth Resources Surveys", A.D. Higham et al, prepared for ESRO under ESTEC contract No 167372.

3.4 History of Image Processing

Landsat MSS data has been a major driving force in the development of image processing capabilities. At the beginning of the decade, before Landsat, in laboratories such as LARS (Laboratory for Applications of Remote Sensing, Purdue University), and JPL (Image Processing Laboratory at Jet Propulsion Laboratory), image processing involved single job, batch oriented programs with no interactive image displays.

During the early years that MSS data was available, agencies operated in a research mode developing flexible interactive systems. General purpose computers were usually used with operations carried out in software. Recently the desire to move toward operational applications has stimulated efforts to develop systems capable of handling large data volumes with high throughput rates. This trend together with the trend to more complex applications will continue.

Although general purpose computers provided operational flexibility, their low throughput rates stimulated a move to use of special purpose hardware processors. For example, at CCRS, use of a software image processing system including an interactive multispectral analyser display on a medium size computer (PDP-10) was found to be too slow to meet ongoing requirements. General purpose computers such as IBM 360/75 or minicomputers still perform key functions in most image processing systems. Brabston and Taber note "In nearly all large scale, pipelined systems there will exist a need for a process controller. Due to the complexity of this scheduler and the need to control the various peripherals, a general purpose computer will normally form the heart of the system. This computer may also be well suited for interacting with operators and users via displays or terminals. In addition it may perform some complex, low throughput special processing such as the generation of the grid of geometric correction locations or radiometric correction tables from scene statistics."*

General purpose computers or minicomputers are still used by some agencies for Landsat image processing where a research mode of operation is employed or data volumes are limited. Basic pattern recognition functions are available in PDP-11 software. Benson et al note that the USDA Application Test System (described in Section 3.7) can be scaled down and include compatible display systems

* "Design of Pipelined Systems for Landsat Image Processing", D.C. Brabston and J.E. Taber.

comprising a single colour unit, three refresh memories and a single graphics channel.* A PDP-11 (without an array processor) may be used. Although flexibility and capability for modification are usually considered characteristics of software image processing systems, Goodenough notes "Our experience has been that software systems of hundreds of programs developed a rigidity comparable to systems with hardware processors."+

A general purpose computer is not well suited for processing that deals with pixels on an individual basis. Throughput requirements have stimulated development of pipeline and array hardware processors. A pipeline system may be used for special processing of Landsat image data, including geometric and radiometric correction, image enhancement and high speed data reformatting. An array processor may be used for high speed array processing applications such as classification with the maximum likelihood decision rule or carrying out two-dimensional fast Fourier transforms. Section 3.4.1 indicates that array processors have been interfaced to both large general purpose computers (eg. IBM 360/75) and minicomputers with large decreases in processing times. The minicomputer-array processor combination leads to an inexpensive system with good throughput capability.

The complexity of image processing applications has undergone considerable evolution during the years of the Landsat program. One trend is toward more attention to spatial information. Although with coarse resolution MSS data, more information for target identification is contained in the spectral information content, the future trend to better satellite data resolution, and to more utilization of airborne data in combined data sets, will give further impetus to spatial processing. For example, Laver and Thaman in a study of information content of simulated space photographs found that at ground resolutions of 50 feet or better, information could be obtained on shape, size, texture, and shadow characteristics within vegetation types.** Algorithms will have to be developed to utilize this information. Balston has expressed the view that spatial processing is the single most important aspect of image processing.+ Clearly

** "Information Content of Simulated Space Photographs as a Function of Various Levels of Image Resolution", D.T. Lauer and R.R. Thaman, Proceedings of the 7th International Symposium on Remote Sensing, Ann Arbor, May 1971.

* "An Application Processing for Imagery Data", J.L. Benson et al, Proceedings of an International Conference on Earth Observation from Space and Management of Planetary Resources, Toulouse, March 6-11, 1978.

+ "Programming Hardware for Remote Sensing Image Analysis", D.G. Goodenough, AFIPS-Conference Proceedings, Vol. 47, AFIPS Press.

++ "An Image Analysis System for Earth Resources Surveys", D.M. Balston, Systems Technology, April 1978.

much use of texture and shape information is made by a good photointerpreter in interpreting an image. Balston also believes that since texture is an extremely variable feature, different ways of measuring it will be required for different images.

A second trend has been towards merging of multiple data sets taken from various sources, at different times, possibly for different purposes. The trend to merging multisource, multitemporal remotely sensed data with auxilliary data and with non-imaging data bases, although begun, will be developed much more fully in future. The image based information system concept is discussed in Section 3.6.

3.4.1 Review of Several Image Processing Systems

There has been an evolution in computer-assisted analysis of satellite data since the beginning of the Landsat program from use of general purpose computers such as IBM/360 operated in a batch oriented environment, to the use of interactive analysis using array processor-minicomputer combinations. This section reviews some of these developments and important characteristics of several image processing systems.

Atmospheric and Oceanographic Information Processing System (AOPIS)*

This experimental system is one of the most versatile and powerful developed to date. While some other systems are faster or capable of handling larger data volumes, this system includes many of the elements particularly system integration features desirable in an environmental information system. The system includes: capabilities for both meteorological and earth resources analysis; integration of several computers, storage media and analysis terminals; capability for input of multitemporal, multisource data sets; capability of analysing very rapidly changing meteorological data; and interfacing with a remote computing facility.

The system consists of a central PDP-11/70 to which two image analysis terminals used primarily for meteorological applications are interfaced. A second PDP-11/70 processor is dedicated to deriving atmospheric temperature and humidity profiles from GOES data, and shares a disc with the central processor. The disc permits sounding data to be incorporated into severe storms analyses conducted on the central processor. AOIPS also includes a modified Image 100 system with an interactive image analysis terminal, and a PDP-11/45 computer. The terminal is interfaced to the AOIPS central PDP-11/70 through a shared disc unit. A remotely located IBM S/360/91 computer communicates with the AOIPS PDP-11/70 computer through a 4800 bit-per-second telephone link. A high density digital tape (HDDT) unit interfaced to the PDP-11/70 provides storage of 1.4×10^{10} bits per 7200-foot reel of tape. It is planned that HDDT's will provide the primary medium for meteorological satellite data in future. Data inputs to the system include CCT's of satellite and aircraft MSS data and related digital ancillary data such as digital topographic data, point measurement data and boundary maps required to carry out specific information extraction operations. The link with the remote IBM computer permits AOIPS users to carry out large computational jobs such as a variety of weather, climate, and earth resources modelling activities on the high speed IBM machine and to display and analyse the results of these

* "AOIPS - An Interactive Image Processing System", P.A. Bracken, J.T. Dalton, J.J. Quann, J.B. Billingsley, AFIPS Conference Proceedings, Anaheim, June 5, 1978.

computations on the AOIPS. Other features of the system of note include:

- the two terminals used for meteorological applications provide time lapsed display of up to ten TV sized images in a movie loop presentation. Each terminal can use up to 10 refresh memories to support data analysis operations.
- the video disc connected to the 3 analysis terminals can store 600, 512 by 512 images which may be recorded from or played back to the TV monitors of the terminals.
- the Image 100 is designed to process image data, particularly Landsat data, and performs enhancement and multispectral analysis classification.
- software has been developed to compute cloud height and the displacement of selected clouds in a series of time lapsed digital images. It produces analyses of the computed wind fields and displays images overlayed with plots and data contours of analysis parameters.

The use of the system for meteorological applications is of particular interest. Wind vector fields have been measured from a time series of GOES data and used as inputs to equations that derived the meteorological parameters of divergence and deformation. The magnitudes of these dynamic parameters are numerically and spatially associated with the development of hail producing thunderstorms.

Parameters related to atmospheric convection intensity such as cloud top temperature and height and rate of vertical growth of a thunderstorm can be identified from analysis of GOES infrared data. Thunderstorm intensity and the occurrence of severe weather are highly correlated with the intensity of atmospheric convection.

AOIPS system capabilities include analysis of the dynamics of rapidly forming storm cells, generation of precipitation estimates from digital imagery and determination of temperature profiles of selected clouds.

Although considerable information extraction has been achieved, plans are for providing capabilities for registering image and non-image data from multiple sources and establishing integrated data bases.

Jet Propulsion Laboratory (JPL)

Image Processing Capability

Applications of an image based information system developed at JPL are described in Section 3.5. The JPL image processing laboratory system has been reported to consist of an IBM 360/65 central computer with a megabyte of memory and 900 m bytes of on-line disc storage. A PDP 11/40 computer is interfaced to the IBM computer and supports several interactive terminals and display systems.*

* "Elements of an Image Based Information System", A.L. Zobrist, Proceedings of the Caltech JPL Conference on Image Processing, Pasadena, Calif. Nov. 3-5, 1976.

The interactive image display systems are used to perform precise registration of non-imaging and imaging data bases. For example, Census Bureau tabular files containing the geographical location of vertices may contain errors resulting in failure of tract boundary lines to meet at vertices or generation of erroneous tract boundary lines. This produces an erroneous district image when the tabular data is converted to image format. The census data may be edited through use of the interactive display system with graphics overlay capability.

Plessey Image Analysis System

The system was designed to support three types of processing:+ software processing on a host mini-computer; interactive processing using a fast hardware processor; and special hardware processing intermediate in speed and complexity. The central element of the system is a modular digital image store using charge coupled device technology and comprising 16 channels each providing an image of 512 x 512 pixels. Image processing software on the host minicomputer includes routines for image correction, classification, image filtering such as edge enhancement, spatial feature extraction, and image transformations. File housekeeping permits information to be maintained about an image concerning, for example, the processing it has undergone, its source, and its statistical parameters. The interactive processor is a modular pipeline processor. Interactive functions which may be performed include image ratioing, intensity normalization, contrast enhancement, colour enhancement, level slicing, contouring, multispectral classification, area measurement, and statistical evaluation. Intensity normalization is a process involving dividing the intensity in each band by the overall intensity of the image. It is derived by first using a vector unit to sum the intensities of all bands and storing this sum in a spare store channel. Ratio units are then used to provide the desired quotients. An interaction control processor which includes a small minicomputer, undertakes the tasks of interpreting and executing operator commands and calculating and specifying real-time control signals. The user can implement commands which provide a sequence of images on the display (useful for time-lapse photography). This processor can be used for the storage of successful processing parameters for subsequent recall later.

Extensions to the system through special hardware processors are planned so

+ "An Image Analysis System for Earth Resource Surveys", D.M. Balston, Systems Technology, April 1978.

that processes which already may exist in software may be extended to use on large data sets. These include rectification, complex classification and spatial processing. A texture analysis facility is likely to be re-programmable to permit flexibility in use. Spatial processors of increasing complexity are planned starting with a two-dimensional filtering module, continuing with a texture analysis module and leading to shape recognition modules.

The system has been designed to have considerable flexibility, both in terms of its modularity and the comprehensive nature of the processing. It is controlled and constrained by a small computer.

The possible use of a remote terminal comprising a three-channel store, colour monitor and visual display unit has been considered. Provided the interpreter does not wish to use the interactive nature of the commands, he could do image classification and spatial processing and use the full range of software on the host computer. A fully interactive system could be developed.

CCRS Image Analysis System (CIAS)

The CIAS consists of two minicomputer subsystems. One subsystem used for all image analysis contains a minicomputer and two hardware processors - a pipeline processor and an array processor. It consists of a PDP-11/70 minicomputer with 256K 16-bit words of core memory; a modified Image 100 interactive pipeline processing system, and an Image Analysis (IAP) array processor which provides a parallel processing path in the subsystem. The PDP 11/70 controls all interfaces and therefore indirectly all data transfers within the system. Prior to the development of the IAP most of the system time was devoted to the maximum likelihood classification of large images* in the PDP-11/70. This is one of the IAP's main functions, along with the calculation of two-dimensional fast Fourier transforms (making available interactive operations in the spatial frequency domain) and selection of pixels from disc images and transfer to and from the Image 100 memory. Processing times for maximum likelihood classification are: for a 512 x 512 segment, 4 channels, 32 classes - 12 seconds; and for a 2048 x 2048 pixel segment 11 channels 32 classes - 20 minutes. The IAP can function either independently of the Image 100 processor or in combination with it to use the ratioing and matrix multiplication hardware. The IAP can also perform fast table look-up useful for radiometric and atmospheric corrections, image enhancements, and other

* "Programming Hardware for Remote Sensing Image Analysis", D.G. Goodenough, AFIPS-Conference Proceedings, Vol. 47, AFIPS Press.

image intensity manipulations. It can reformat data simultaneously as they are moved from one memory to another. Unsupervised classification is carried out by determining the vector distribution for a selected area, clustering the distribution in the PDP 11/70 and loading the generated statistics into the IAP where classification is carried out on the whole image stored on disc.

Training area selection, ground control points, and other map information may be input directly to the IMAGE 100 subsystem from a digitizing tablet.

The second minicomputer subsystem includes a PDP-11/40 minicomputer and a PDS flatbed color read/write precision microdensitometer. This system may be used to digitize colour aerial photographs and provide a file for subsequent analysis, or to write such a file onto colour film.

Multitasking software is used to make full use of the multiple processing capabilities of the system. Program menus, discussed in detail by Goodenough[+] are presented to the operator for selection. The system has a wide range of programs. For example, a principal component enhancement is available with the first eigenvector assigned to brightness, the second to the ratio red/green, and the third to the ratio blue/yellow. A video filtering program results in passage of either a high or low spatial frequency image. Spatial feature generation such as gradients or segments are generated and can be merged into the image files as additional channels.

The primary CIAS output products are: computer compatible tapes for input to PDS color-write microdensitometer (high resolution), CCRS electron beam image recorder (medium resolution), color strip film recorder (low resolution) and grid structured geographic data bases; tables providing summaries of spectral and spatial statistics by class and measurements of class areas; and approximate maps of class distributions including single class or multiple class representations and photographs of CRT displays.

ARIES System

ARIES is a digital image processing system built by DIPIX for the Canadian Forestry Service. It consists of a computer subsystem (utilizing a DEC PDP 11/40 minicomputer), an image processing and display subsystem, and an image recorder subsystem. Recently an array processor has been added to increase processing power.

+ "The Canada Centre for Remote Sensing's Image Analysis System CIAS", D. Goodenough, 4th Canadian Symposium on Remote Sensing, Quebec City, May 16-18, 1977.

Digital images entered into the system are stored on an 88 m byte disc. The Image Recorder subsystem is a Dicomed D 47 precision CRT device, with attachments for 70 um roll film or Polaroid chips. It has a 4K by 4K addressable image area. Colour images are made by writing red, green and blue images in succession. A full colour, full resolution image takes approximately 20 minutes.

Data may be displayed with 8 bit resolution, of which seven are assigned to the basic image allowing 128 separate colours. The eighth is used for overwriting with training boundaries etc. The image may be panned and zoomed and boundaries of arbitrary shapes may be written or erased. A set of preprocessing programs allows spectral bands to be summed, differenced, ratioed, contrast stretched, spatially sharpened or spatially averaged, radiometrically corrected, etc. Image enhancement programs permit image data to be mapped into an axes system corresponding to the principal components of a selected set of image data. Statistical measures of data within arbitrarily generated boundaries can be calculated and used as inputs to image enhancement or classification programs.

Low Cost Digital Processing Systems

The information extraction facilities described in this section have all included powerful image processing capabilities and are systems costing $0.5 million or greater. There is a whole spectrum of system options available to the user depending on his budget, the data volumes to be analysed, the time within which the analysis must be performed, the complexity of the analysis to be carried out, and the output, and the output products required. This large range of options complicates reliable cost estimations of establishing a network of information extraction facilities to satisfy potential satellite data user agency requirements.

Stand alone Landsat digital processing systems with costs as low as $20,000 have been described in the literature.* One prototype system costing $18,000 includes a Data General CPU (Noral 3/12w/32kw), 1.2 m byte floppy disc, cartridge tape drives, Data General console and printer, and appropriate software to process Landsat data. Addition of an interactive colour display, used for the location and analysis of sample training fields for maximum likelihood classification, would increase costs by at least $10,000. Refresh memory requirements, color resolution and cost are determined by the number of grey shades allotted to each of the three color guns. This system was designed to provide products that would feed into state's information retrieval systems.

* "Low-cost Landsat Digital Processing System for State and Local Information Systems", N.J. Hooper, G.W. Spann, N.L. Faust, Proceedings of the Thirteenth International Symposium on Remote Sensing of Environment, Ann Arbor, April 23, 1979.

Image Analysis Systems with Remote Image Display Terminals

Section 4 outlines in detail the use of remote interactive image display terminals connected to a host image analysis facility. Non-interactive display terminals may also be used which display results of processing operations carried out in batch mode on a remote computer. Data may be transferred on a network (eg. Datapac) or transferred physically (by CCT) to a storage medium at the display. Some applications require extensive visual interpretation, and this method permits several files to be called up for viewing at the display without tying up the remote computer during the human interpretation procedure. Agriculture Canada use this method and have a DEC 11/34 combined with Norpac display (system cost about $50,000) for local viewing. Cost of extracting 5 mile by 6 mile agricultural segments of interest from source tapes is variable depending on its location and may cost up to $150.

Examples of Networked Image Analysis Systems

The EDITOR software system is an interactive file management and image processing system and an interactive data analysis system for processing of Landsat data. It was developed at the University of Illinois in collaboration with USGS/D1, NASA/AMES and USDA/SRS. It runs on TENEX, and for large data sets on the ILLIAC-IV, linked using the ARPA network. Some preprocessing functions such as image geometric correction are performed on general purpose computers off line from EDITOR in batch mode.* An x-y coordinate digitizer is used to digitize agricultural ground-truth boundaries. EDITOR and the digitizer routines are used with dial-up telephone line terminals so that input and output are limited to 300 baud or about 10 line pairs per second. The only hardware required to access the EDITOR system is a keyboard send-receive terminal with acoustic coupler and a telephone link to a TENEX system on the ARPA network.

* "An Interactive System for Agricultural Acreage Estimates Using Landsat Data", M. Ozga, W.E. Donovan, C.P. Gleason, 1977 Machine Processing of Remotely Sensed Data, Purdue 1977.

3.4.2 The LACIE Program as an Example of a Large Remote Sensing Data Management - Image Processing Project

The objectives of the LACIE program are very different than those associated with regional environmental information systems. The LACIE program is a proof of concept experiment concerned with worldwide agricultural monitoring. It therefore involves a discipline oriented, global information system. Because of the vast geographic area involved, the program relies on appropriate sampling strategies. In spite of these fundamental differences from regional information systems, there are several components of the program of particular relevance. LACIE involves: processing and analysis of large volumes of multitemporal, multisource data; combining data sets; and developing and utilizing several types of crop models. It has been a focal point for development of a range of methodologies and techniques. Since it has been an experimental rather than operational program, its characteristics (eg. maintaining flexibility, making use of existing equipment in some instances, etc.), have reflected that. It is of value to consider some of the procedures adopted for system integration and the methods and trends established by the program. Some image processing developments associated with the LACIE program are considered first.

Illiac IV - ARPA Network Analysis of Landsat Data

The Illiac IV is a high speed parallel processing computer capable of execution rates for suitably parallel problems of 200 MIPS.* It is an array of 64 general purpose computers with each of these processing elements executing the identical instruction on different data items. The system may be accessed through the ARPA (Advanced Research Projects Agency) Communications Network which permits users throughout the U.S. to have access to computational power which might not otherwise be available to them. The Illiac IV has been used in a batch processing mode for multispectral classification of Landsat data. In preparing for a batch run, an interactive PDP-10 program named EDITOR is used which facilitates the training or clustering activities that precede classification. EDITOR is a PDP-10 Landsat imagery analysis system (available at 2 locations many miles from the Illiac IV) providing an ARPA network interface to classification procedures on the Illiac IV. The ARPA network is also used to connect graphics data digitizing equipment to the interactive PDP-10 computers. The equipment may be linked to the PDP-10 systems via dial-up telephone line connection to ARPA network node facilities. The digitizing equipment is used to digitize field, tract and segment

* "Digital Processing of Landsat Imagery on Illiac IV', R.M. Hord

boundaries recorded on photos. SRS (Statistical Reporting Service) ground sample data collected according to statistical sampling criteria may be therefore used as ground truth information for Illiac IV classification training. Landsat image files and SRS ground truth data are geographically registered. The EDITOR software system is used for small-scale analyses of SRS area segment data. The Illiac IV, addressed through the EDITOR system, is used for specific large-scale Landsat image analyses functions.

The ILLIAC IV throughput is very high. Less than 80 seconds were required for classification of 4.9 million pixels.* Execution times are about two orders of magnitude faster than with an IBM 360/67.

The method is of particular interest as it involves extensive use of communications technology and of a remote powerful image analysis facility.

Use of the STARAN Parallel Processor in the LACIE Program

During the early years of the LACIE program at Houston, Landsat data analysis was carried out on IBM 360/75 computers. Some operations, particularly clustering and classification were expensive users of computing resources. The requirements for high data throughput resulted in a change in the processing system to include a parallel processor. A special purpose processor (SPP) was added as slave to a host IBM 360/75 computer.+ For the two array SPP system, 512 independent data streams can be processed simultaneously. It is used for pattern recognition tasks including statistics, iterative clustering, adaptive clustering (involving grouping of similar measurement vectors), maximum likelihood classification, and mixture density classification. These algorithms all have an inherent parallelism resulting from a particular computation being performed on all pixels in an image. Performance gains over the 360/75 stand-alone system depend on the specific conditions. For example, for an adaptive/iterative clustering benchmark exercise, the time requirement was 1/57 of the stand-alone system. For a LACIE segment, performance improvements up to 15 to 1 were usually experienced. Performance improvements for mixture density classification were about 13 to 1 for a full Landsat frame, and up to about 7 to 1 for a LACIE 5 x 6 mile segment. Performance gains for statistical processing may reach about 3 to 1 for large fields and large channel set jobs. Generally, principal limitations on throughput with the SPP are the retrieval function from image storage, except for complex jobs, for example,

* "Illinois Crop Acreage Estimation Experiment", R. Ray and H. Huddleston, Machine Processing of Remotely Sensed Data, Purdue U., June 1976.

\+ "Application of a Parallel Processing Computer in LACIE", S. Ruben et al

12 channels and 20 classes when it becomes CPU bound. Direct access to the imagery on the storage disc would improve throughput. Application program processing is initiated from the host side of the interface unit. Management of the LACIE data base with 4.2 billion bytes of disc storage, and the complex software needed to interface between the user and application software required retention of the IBM host computer. The SPP provides a research oriented system, programmable, and useful for exploring new approaches to image processing.

USDA Application Processing System - The Application Test System (ATS) was implemented to test and evaluate LACIE and LACIE-like inputs, technology, and techniques in an application environment.

The ATS system was designed to utilize off-the-shelf components, to be able to accommodate new technology developments through modular change, to facilitate ease of utilization, and to have system transferability characteristics.

At the centre of the system is a PDP-11/70 minicomputer complemented by two 300 megabyte discs which provide storage for image processing and data base functions and a programmable array processor. The ATS is capable of incorporating five analyst stations. The system is expandable upwards. The mainframe core storage may be increased from 512 kilobytes to 4 megabytes, and an additional 600 megabytes of disc storage can be added without additional controllers. Performance times include: 512 x 512 pixel, 4 channel, 8 class run in 57.8 seconds and 117 x 196 pixel, 4 channel 30 cluster run in 16 seconds.

The Integrated Multivariate Data Analysis and Classification System (IMDACS) operates on the 11/70 providing the user with the capability to select and execute interactively via a terminal the major processing functions such as cluster, stats, image and class. A unified file structure facilitates communication between the processors. For example, statistics files can be built by either the statistics processor or the clustering processor. The files can be used to initialize either clustering or supervised classification processes.*

An Integrated Data Base Management System implemented on the PDP-11/70 provides system capabilities for supporting non-imagery data processing functions and for providing ancillary data support for image processing.

USDA plan to add a data acquisition system to extract and register sample segments from full frame Landsat data on high density digital tapes.

LACIE-Related System Developments

Several features in the evolution of data processing systems in support of LACIE may be highlighted. These include:

* "An Application Processing System for Imagery Data", J.L. Benson et al. Proceedings of an International Conference on Earth Observation from Space and Management of Planetary Resources, Toulouse, March 6-11, 1978.

- earth resources interactive processing system (ERIPS) data base design considerations. The data base was required to store 4 acquisitions for 3840 sites and 16 acquisitions for 960 sites. The resulting 30,720 acquisitions required an image base of 2.9 billion bytes. In addition the fields data base required 85.7 million bytes and the history data base 3.9 million. The ERIPS mass data base contains 4.2 billion bytes for imagery, history and training.
- The ERIPS system supports both interactive users and a batch production mode of operation. Menus permit users at all levels of experience to interact with the computer. The system would be improved if more terminals (more than the two at present) with more local intelligence (eg. local editing capability) were supported.*
- A link was established between Goddard Space Flight Centre and JSC, Houston.
- The requirement to process large volumes of data impacted both pixel processing (resulting in use of programmable peripheral high-speed processing capability) and data management ie. manipulation of and traffic control for many large data sets. It is anticipated that the high data volumes from future satellites may require system reorganization to exploit peripheral processors in the solution of data management problems, eg. free the 360/75 from traffic control and allow the array processor more direct access to the data bases.
- Performance comparisons have been made between the general purpose IBM 360/STARAN array processor combination and the minicomputer PDP 11/70/AP 120 pipeline processor. For example, for a 512 x 512 maximum likelihood 4 channel, 8 class run, the former combination gave 41 seconds and the second 56 seconds.
- Future system trends are expected to include: significant increases in processing volumes resulting from mutual registration of different sensors and higher sensor data volumes; analysis flow trends to more complex data uses; requirement that the central processor support a number of remote and local terminals as more analysts need access to the data.
- Other features of the LACIE system evolution include: terminal access to meteorology data; computerized yield and crop calendars; interactive production estimates; and correlated data sets. Future system requirements include multiyear data retention, multicrop analysis and data base integration. Plans include implementing a climatic early warning system and versatile soil moisture budget.
- The planned USDA data processing system will include host computers (for

* "Briefing Materials for Technical Presentations", The LACIE Symposium, Johnson Space Centre, October 1978.

historical data, evaluation data, report data), a data base computer (for yield analysis, aggregation and reporting), an acquisition computer (handling MSS and meteorology data) and analyst computers (projected 3 each supporting 3 analyst stations).

- a multicrop information system is required to accommodate the following data categories - crop samples, digital imagery, classification data (fields, dots, class maps, masks), meteorological data (station, grid cell - full cell = 25 x 25 N Mi), agronomic data (soils, cropping practices), crop assessment reports, historical data (area, yield, production, meteorological), status data.

Ground Management System to Support Image Analysis

Relating ground truth data to Landsat digital imagery is an important step in image analysis. In LACIE, for segments on which intensive analysis is carried out, a one-to-one correspondence is developed between a ground-truth image and the corresponding Landsat digital image. Coiner and Ungar have designed a computerized geographic information system for management of ground truth data.* It involves construction of a digital ground truth array so that direct pixel by pixel comparison may be made between classification obtained from aircraft and degraded to Thematic Mapper resolution. Fields were plotted from aerial photography onto a grid defined by the MSS data. Each field boundary was plotted and each field or non-agricultural area to be considered in the ground truth was assigned a number. Each field number in the array was associated with a specific LACIE field number (LACIE Inventory data provided part of the ground truth used). The ground truth array files were corrected, rectified and reformatted to conform to specific classification and display tasks. Separate files were created for training areas.

Construction of a ground truth file or data channel for the area of interest permitted study of figure-of-merit related classification problems.

* "Ground Truth Management System to Support Multispectral Scanner (MSS) Digital Analysis", J.C. Coiner and S.G. Ungar.

3.5 Integration and Processing of Spatial Data Sets

When spatial data sets are converted to registered image-like data sets, powerful analytical methods may be developed and utilized in analysis of these data. Already powerful image processing methods exist to manipulate and analyse image type data, for example, to enhance, filter, transform, classify, perform change detection, do statistical analyses, etc., and extensive development of new techniques is certain in future.

Advantage of these methods may be taken by non-satellite spatial data. For example, Anuta has used clustering techniques with geophysical data - 3 gamma ray channels and a magnetic anomaly channel - and related the results to geology units from a digitized geology map channel.*

When multiple image data sets are overlayed, memory and computer core limitations restrict the useable image size for processing. Methods may be used to reduce the data to be analysed including: feature selection - choice of the best subset of a set of channels to carry out a classification; preprocessing to reduce the dimensionality of the data set. A principal component transformation involves a rotation of an n-dimensional data space such that the first component lies along the direction of maximum variance; ie. maximum correlation, of the dimensions.* The remaining components contain a monotonically decreasing amount of variance in the data sets, so that the first few principal components usually contain all the information of the full set of original data channels.

3.5.1 Image Based Information Systems

Image based information systems, ie geographic information systems based on digital image processing and image raster data type have been developed.+ To date the JPL system has been used primarily for land use types of applications.

In essence an image based system involves converting other geographic information to fit Landsat imagery. Therefore, it may properly be called a Landsat-based information system. It operates on the basis that images of thematic maps or taken from remote sensing platforms can be converted to a raster scan, and that existing tabular and graphically formatted geocoded data sets can be referenced to a raster scan.+ The raster scan is equivalent to an ultra-fine mesh grid cell data set. Digital image processing techniques are required to interface the existing

\+ "IBIS: A Geographic Information System Based on Digital Image Processing and Image Raster Datatype", N.A. Bryant and A.L. Zobrist, Proceedings of the LARS Symposium on Machine Processing of Remotely Sensed Data, June 1976.

* "Computer-Assisted Analysis Techniques for Remote Sensing Data Interpretation", P.E. Anuta, Geophysics, Vol. 42, April 1977, p. 468.

data sets with the new data.

An underlying philosophy of this approach is that it may be easier and less costly to convert the user's information for example, a polygon file, which in general will contain fewer bits than an image, to fit a Landsat image than to try to make Landsat data fit the user's system. It has been noted, for example, that the County Boundary DIME (Dual Independent Map Encoding) File for all of the U.S. contains only about 50,000 latitude/longitude pairs compared with 3×10^7 pixels in a single Landsat image. In most systems spatial data are compactly stored in some abstract form eg. areas partitioned by type or class into polygon regions.

Powerful image processing capabilities are required for this information system. The method requires adequate image-to-image registration so that images of different scale, rotation or map projection can be superimposed precisely enough. Such registration is readily carried out in the CCRS CIAS using the Landsat digital products from the digital image correction system (DICS). The correction process involves image overlay which requires resampling of radiometric values. An image processing system can be converted to an image based information system by adding capabilities to permit merging of other spatially referenced data. The JPL design team recognized the need to interface different data types, and the requirement for the system to interface with mathematical and statistical programs which could be used to aid in the analysis of spatially oriented data.

It is important to merge tabular, eg. weather data, graphical, eg. elevation contours, and image eg. land use data in geographic information systems. Image data must be registered to spatially referenced tabular data, with pixels aligned with records. A tabular - to - raster conversion interface permitting interfacing of tabular data bases with a 2 dimensional data base of registered images, is needed. Software is required to incorporate 2-dimensional and tabular data sets to raster formats. The image data type provides a general representation for spatially distributed data. Although customarily the value stored in each cell represents a shade of grey, the value can be a datum for the area corresponding to that cell. There are several data types possible: the pixel value may identify a point (or line), the nearest set of points (or lines), or the distance to the nearest set of points (or lines); the pixel value may be a record pointer to a tabular record which applies to the pixel geographic area (eg. population statistics); the pixel value may represent a physical variable such as sediment load, soil moisture, elevation, crop yield, precipitation, etc; the pixel value may be a numerical identifier for the district which includes that pixel area, eg. administrative district, census district etc.; the pixel value may be a numerical identifier for land use or land cover or for any other area classification scheme. The system must handle images composed of words of varying length. For example, while image processing systems usually handle 256 grey levels, elevation maps can require 15000 pixel values. In the image representation, data for a geographical point can be accessed by position in the image matrix. In the raster format, x,y coordinates are recognized by their position in the scan, so that the system should permit rapid incorporation and comparison of data sets.

In the JPL system a data interface has been provided between different data types so that results of processing can be stored. For example, a tabular file resulting from processing an image may be interfaced to other tabular files. Tabular data can be kept in its natural state of aggregation in the working data base and cross tabulated to whatever districting is needed.* Existing geographic information systems have computational steps such as polygon overlay, aggregation and cross tabulation. Image processing analogues are required in the image based information systems. In the JPL approach, for the polygon overlay operation in which areas of intersection of polygons are obtained, a two-image histogramming operation is used. Cross tabulation factors may be modified by a density estimate of the variable being cross tabulated.

There are several advantages to this image-based approach. In cases where information must be updated frequently and Landsat is used as a monitoring tool, conversion of information to polygon format for input to polygon-based systems can become costly, particularly when there are numerous small polygons in the classified image. The economics of going to an image based system or converting products to existing polygon structures would depend on update frequency. Some of the information available in existing information management systems is very helpful in Landsat data analysis. For example, elevation contour information in some cases would improve classification accuracy. In future systems one will want to merge such supportive information together with historical data (the situation at the time of a previous analysis) to improve the performance of an image-based system. Advantages of an image based system include rapid incorporation of data sets (a problem with previous methods), rapid comparison of data sets (difficult with polygon systems) and adaptation to various scales by resampling the raster scans.+

+ "Integration of Socioeconomic Data and Remotely Sensed Imagery for Land Use Applications", N.A. Bryant, Second Annual William T. Pecora Memorial Symposium, Sioux Falls, South Dakota, October 25, 1976.

* "Elements of an Image Based Information System", A.L. Zobrist, Proceedings of the Caltech/JPL Conference on Image Processing, Pasadena, California, Nov. 3-5, 1976.

In section 1 some of the drawbacks of polygon and grid cell geocoding procedures were noted. A major disadvantage is that most require sequential computations applied to tabular data strings.* Therefore, formatting or processing inherently two-dimensional data is costly. High costs of updating some elements of a data base can result in some information being out-dated thereby affecting the utility of the information system. High costs of manual encoding of grid cell input files has limited the spatial resolution used. File editing and computer software architecture costs have been major problems with polygon systems. The costs of getting data, particularly land use data, into both types of system have been high. This is where the major part of costs has been incurred. Although Landsat data is computer compatible, and provides cost savings for some types of map production, there have been difficulties in interfacing it with existing geographic information systems.+

The raster scan data base format facilitates cost effective interrogation of areas of interest.* A region of interest can be accessed from a major file by generating a raster scan data plane outlining the area as a binary mask. By image multiplication, the information processor would be presented with data only from the defined area. Cross referencing of data planes would also be facilitiated.

It has been noted that a large number of image processing and data manipulation capabilities are needed for a basic image based information capability. However, a powerful and general information system can be developed. Several types of 2-dimensional data can be put in the raster scan format. Scanning microdensitometers may be used to scan photographs of thematic maps or aerial photo transparencies.

Scanning devices are used to measure and record digitally the optical density of points in photographic images. Although the resulting data bases may be large because of the raster format, the algorithms required to process the data can be relatively simple and can often be used on relatively small computers. This is in contrast with small data bases resulting from recording in digital form the Cartesian coordinates of points defining airphoto polygon boundaries. Often complicated computer algorithms requiring the use of large computers are needed to process the polygons defined in this way. Scanners such as the CIAS flatbed microdensitometers are controlled by a minicomputer to permit real time manipulation of the digitized density data.

* "Design Criteria for a Multiple Input Land Use System", F.C. Billingsley and N.A. Bryant, Proc. NASA Earth Resources Symposium, Houston, Texas, June 1975, NASA TM X-58168.

+ "Program on Earth Observation Data Management Systems (EODMS), L.F. Eastwood et al, Final Report for Goddard Space Flight Centre, Dec. 31, 1976.

Underwood and Aggorwal have used a three-color film scanner for the digitization of aerial photographs of agriculture using Ektachrome infrared film and computer analysis to detect the presence of insect infestations in citrus trees.*

3.5.2 Example Applications of the JPL Image Based System

1. Tabulation of land use in transportation zones within administrative districts -**

The procedures used involved digitizing the district map, editing the resulting polygon file, converting the polygon district file to an image, registering districts to a classified Landsat image (thematic classification) and painting each of the traffic zones in the administrative district image with a unique gray scale value. Each location of the 2 image overlay corresponds to a pair of pixels, one representing a district and the other a thematic class. Polygon overlay therefore involves summing the number of pixels of each thematic class (different land uses) for each of the colors in the administrative image (different transportation zones) resulting in a table of acreage and percentage of each type of land use for each zone. A tabular file is produced which can be interfaced to other tabular files. In a related application involving census data already in digital form, the digitizing and editing steps are replaced by a tape handling routine which converts the census tape contents to the image based information system polygon file format.

2. Allocation of population statistics to traffic zones on the basis of land use -

This is an extension of the method described above, involving cross tabulation. Population statistics are available by census tracts. They may be allocated to traffic zones by assuming an equal distribution of population over both kinds of districts. This application involves a better distribution method - that of allocating census tract population statistics to traffic zones in proportion to the residential land use. Residential land use may be used as a distribution coefficient to make other more accurate assessments, for example, more precise mapping of environmental pollution impacts.+

3. A further potential application is monitoring land use changes for a two year period to help update decennial census statistics and predict growth trends.+

** "IBIS: A Geographic Information System Based on Digital Image Processing and Image Raster Datatype", N.A. Bryant and A.L. Zobrist, Proceedings of the LARS Symposium on Machine Processing of Remotely Sensed Data, June 29, 1976.

+ "Tabular Data Base Construction and Analysis from Thematic Classified Landsat Imagery of Portland Oregon, 1977 Machine Processing of Remotely Sensed Data Symposium, Purdue U. June 1977.

* "Interactive Computer Analysis of Aerial Color Infrared Photographs", S.A. Underwood and J.K. Aggorwal, Computer Graphics and Image Processing 6, 1, Feb. 1977.

4. Another application of the JPL image based geographic information system has been the integration and analysis of geophysical data using image processing techniques. Gravity and magnetic values were converted to an image processing format, with magnetic data in gammas and gravity data in milligals converted to a new set of data numbers with range 0 to 255. Several types of display, manipulation and analysis were used. Various data types (ie. total, vertical, east horizontal and north horizontal magnetic components, and gravity) were assigned to each of three colour planes to produce colour imagery. Data correlation resulted in colour superposition. Principal component or eigennector images were produced. Any three principal components of an n component multispectral scene can be individually contrast enhanced and colour composited for display. The individual components are uncorrelated so that the display generally contains a full range of colour. Relationships between two variables such as gravity and magnetics may be obtained through use of 2-dimensional frequency of occurrence histogram programs.

Synthetic aperture radar data (Seasat, L, and X band airborne) has also been integrated with other data types in this image based information system using image processing techniques.

3.5.3 Other Image-Based Systems

A number of data sets have been converted to Landsat compatible image-like data sets to permit analysis with a general purpose IBM computer.* The techniques have been applied to geophysics problems by converting topographic and geophysical variables to an image-form. The method involves digitizing, transforming to a uniform grid-cell format, and registering a wide variety of map data types. For geophysical studies, 20 variables were digitized and registered to produce a 20 channel data file.* Data types registered included: digital (Landsat MSS), film (side-looking radar, aircraft thermal IR scanner imagery, colour aerial photography, colour infrared aerial photography), and graphic contour and polygon maps. The latter included geology maps (polygon type), and six geophysical maps plus topographic maps (all in the form of manually or machine generated contours). The geophysical data included gamma-ray radiation (thorium, uranium, potassium, potassium/thorium ratio), 500-ft elevation magnetics (magnetic anomaly measurement) and induced electromagnetics (conductivity of subsurface).

Landsat data was already in digital form. Film sources were digitized on a rotating drum microdensitometer. The data was preprocessed to put in a form suitable

* "Computer-Assisted Analysis Techniques for Remote Sensing Data Interpretation", P.E. Anuta, Geophysics, Vol. 42, April 1977, p. 468.

for registration. Geophysical and geology maps were manually digitized using a coordinate digitizing table. Contour data was interpolated to a uniform grid by using a linear combination of six nearest contour data points. Polygon to grid conversion for the geology map data was found to be relatively easier, and required that careful records be kept defining the area contents on either side of a boundary.

The 20 channel data file produced by registration formed the basic input to a multivariate geophysical data study. A main objective was to evaluate the different data sources in order to select the best possible subset to be used in further surveys.

Production of image-like data files including both MSS and non-MSS data has been done for other applications as well. Topographic data has been gridded and registered with Landsat MSS data to assist forest and snowcover mapping.+ Slope and aspect, of utility in these applications, may be computed from the elevation channel.

+ "The Decision Tree Classifier Design and Potential", Proc. Symposium on Machine Processing of Remotely Sensed Data, H. Hauska and P. Swain, Purdue U. 1975.

3.6 Some Considerations in the Design of Remote Sensing Information Extraction Systems

The purpose of the data processing system is determined by the needs of the user, and the interface with the user requires priority consideration in system design. While these needs must be identified at the outset, it is possible that they will change and evolve with time. A degree of system flexibility and adaptability is required to accommodate changing requirements.

Many of the data processing systems developed to-date have been primarily for remote sensing research. This can lead to different tradeoffs in throughput, reliability, accuracy, flexibility and accessibility than optimized operational systems. Flexibility is of priority importance in the research phase, while efficiency, simplicity and the ability to detect and correct errors are very important for operational purposes. The degree of centralization desirable both for processing of the remotely sensed data and merging with ancillary data is also affected. While the overall system is very centralized at the sensor end, decentralization occurs downstream toward the user. Economics of scale resulting from processing large quantities of data favour decentralization as far downstream as possible. Some preprocessing such as geometric and radiometric corrections will therefore be required by almost all users. Groups of users may require further specialized processing such as image enhancement, data compression or registration of multiple data sets which could cost-effectively be performed at a common location, possibly at the next branch point in the data distribution tree. With regard to merging with ancillary data, Tomlinson notes "Repeated efforts must have been expended by innumerable users in many research centers to orient the Landsat data spatially and stretch them numerically to overlay a standard topographic map. This---is typical of the multiplication of overbend costs that occurs when data are provided to many users in forms that are not amenable to query."[+]

In order to fulfill the purpose of the data processing system to provide information to satisfy user needs, special attention must be given to output products and the analyst interface with the processing system. The user (consumer of information) and analyst may be different people, particularly for operational systems. The analyst, by means of the system's interactive capability, needs to view the raw data, to view results of various processing operations, and be provided with periodic status reports, ie. intermediate analysis results. Analysis results produced by the system are potentially data for a further round of processing, and must be accessible. For example, the analyst may wish to retain classification

+ "Difficulties inherent in organizing earth data in a storage form suitable for query", R.F. Tomlinson results in the computer system so that he may access and manipulate them interactively. Storage requirements for analysis results depend on the volume-rate of results generation, the period of time required to retain the results on-line, and the ease and speed of results retrieval. Typical system output products include maps, photographs, tables and magnetic tapes. Production of tabular summaries may require statistical analysis of classification results. Under the stimulus of remote sensing requirements, output devices are improving, including mechanical hardcopy devices (eg. ink jet plotters, electrostatic printer/plotter), electronic hardcopy devices (eg. electron-and laser-beam recorders, CRTs), interactive devices (eg. CRT's, typewriter/teletype), and storage devices (eg. digital magnetic tape, film recorders). Cost, quality of product, versatility, reliability, and speed of production are important decision factors.

System complexity requires careful consideration in terms of the purpose of the data processing system. The types of remote sensing data processing operations are increasing, and for operational use it may be desirable to be restrictive in the interest of efficiency and simplicity. Algorithms are generally selected in terms of efficiency and ability to provide the required information. Complexity is tailored to the problem at hand and quality of data available. There is a hierarchy of algorithm complexities for analysis on a spectral basis, including first order statistical models in which each class is represented by a single, deterministic curve of response versus wavelength, and second order statistical models in which discrimination is based not only on the average separation between data sets in n-dimensional space, but also on the shape of these distributions. Complexity may be extended to include information contained in the spatial and temporal variations in the data. Pattern recognition methodology may be extended beyond only spectral features to include spectral/spatial/temporal features as well. Algorithms may be developed which make use of the spatial variations within objects, or the size and shape of objects and of the distribution of sizes and shapes within regions. There are statistical dependencies between the spectral responses of neighbouring pixels. Complex algorithms may be difficult to use from the data analyst standpoint.

Landgrebe has described a potentially powerful complex hierarchical classification procedure whereby a classifier reaches a final decision on a picture element by making decisions at successive nodes in an information tree.[+] He lists

+ "Useful Information from Multispectral Image Data: Another Look", D.A. Landgrebe, in Remote Sensing: The Quantitative Approach, P.H. Swain and S.H. Davis, McGraw Hill Company, 1978.

advantages including: potentially improved accuracy by reducing illogical misclassifications at a particular level; reduction in the number of alternative classes at each node, permitting fine tuning of the feature set; and possible changes in the processing algorithm at each node, eg. classification of multispectral data at one node and another operation on ancillary data at another node, or the same operation performed on temporally separated data sets at two nodes with classification at one node conditioned upon classification at the earlier node. Improved information extraction and reduced computation time have been demonstrated with algorithms using this approach.

It is important to note that although pattern recognition has evolved as the principal quantitative remote sensing technique and has been incorporated in most remote sensing data processing systems, other quantitative analysis methods such as statistical methods (correlation analysis, regression analysis) may be used.

The addition of ancillary data to remotely sensed data increases the dimensionality of the data. Generally complexities of information extraction as well as information content are increased. Ancillary data is used to derive classifier training statistics. Mean recognition accuracy and therefore classification accuracy increases with number of training samples, although a greater number of spectral bands and/or signal-to-noise ratio are required to achieve it.[+]

Data dimensionality is also increased through use of multitemporal data. Complexity of information extraction and training sample requirements are also increased. It has been noted that more spatial resolution, more spectral bands and more temporal observations may decrease classification accuracy.[+] Generally at least a larger number of training samples are required to adequately estimate higher-dimensional statistics. Therefore a greater amount of reference data may be required to extract the increased information which the data contains.

In spite of significant advances in data processing, human participation in processing is expected to continue to be important. Human interaction impacts the point at which decentralization is desirable (automatic processing and centralization are possible in the preprocessing phase). Pattern recognition analysis for example utilizes an interactive approach involving an iterative combination of man and machine operations including definition of a list of classes, location of training data, computation of class statistics, and scene classification by

+ "Useful Information from Multispectral Image Data: Another Look", D.A. Landgrebe, in Remote Sensing: The Quantitative Approach, P.H. Swain and S.H. Davis, McGraw Hill Company, 1978.

a supervised pattern recognition algorithm. Swain and Davis emphasize the importance of the human role in being aware of the relationships between reference data and remote sensing data, and in drawing from available data making use of experience to make critical decisions.* Data integration and machine processing methods are rapidly evolving which modify the role of the human in the system. There is therefore a spectrum of levels of human participation in remote sensing analysis ranging from purely manual (photointerpretation) through interpretation of machine enhanced imagery to interactive analysis methods which develop as data merging methods, processing hardware technology and powerful algorithms are developed.

Interactive facility requires that operations be easily performed and images rapidly displayed after operation so that an evaluation of the applied processing may be made.

Interaction may be required at each processing step to evaluate results and make modifications as necessary. Steps could include digital filtering, textural analysis, clustering, image enhancement, classification, etc. For data analysis at the local level, the requirements of interactivity and flexibility may be more important than ability to process large data sets. Some forms of interactive information transfer would require only low data rates to an analyst terminal. For example, an image processing system would supply the analyst with interpretation aids (eg. histograms), additional (non-image) information about the processing, system messages and tutorial information.**

An analyst may want to perform a sequence of operations on data for a particular area, each requiring interaction and evaluation. Kourtz found that Taylor enhancements of Landsat data produced a higher credibility with users of forest fuel map products than computer produced classifications.+ Multitemporal interpretation aids have been produced by compressing the multitemporal spectral variation of an image into a three-dimensional image. For example, in agriculture principal component greenness transformations have been used to provide information about phenological growth patterns of crops.+ The transformation maps each of n multitemporal acquisitions onto the greenness axis and then compresses these n

** "DIBIAS-The Digital Image Processing System at DFVLR System Design and Applications", P. Haberacker, Proceedings of an International Conference on Earth Observation from Space and Management of Planetary Resources, Toulouse, March 1978.

* "Useful Information from Multispectral Image Data: Another Look", D.A. Landgrebe, in Remote Sensing: The Quantitative Approach, P.H. Swain and S.M. Davis, McGraw Hill Company, 1978.

+ "Principal Component Greenness Transformation in Multitemporal Agricultural Landsat Data", R.A. Abotteen, Twelfth International Symposium on Remote Sensing of Environment, Manila, April 1978.

greenness channels into three new channels using a linear combination (ie. 1st three principal components) of the n green channels. Small grain and non-small grain crops can be distinguished multitemporally in the greenness direction.

Decisions regarding purchase of stand alone or time-shared data processing capabilities or purchase of services depend on several factors including initial and ongoing cost factors, the number of times the system will be used, timeliness and format requirements, volume of data to be analyzed, quality of results required, and in particular the ability to provide the user with the products required. One of the principal issues involved in information management particularly where satellite data is involved is the question of use at a particular location of raw or interpreted (derived) data. This impacts communications, storage and data handling methods and costs, and is relevant to the "choke factor" discussed by Keller and Frippel.*

* "AIDS: An Advanced Integrated Data System Concept", D.W. Keller and G.G. Frippel, Proceedings of the 13th International Symposium on Remote Sensing of Environment, Ann Arbor, April 1979.

3.7 Spatial Data Storage and Management Considerations

Data volumes stored in conventional geographic information systems are small compared with potential raw satellite image data volumes. Tomlinson quotes potential data volumes of several US programs including:* 6.8×10^7 x,y coordinate pairs in the Land Use Mapping and Data Project involving 359 map sheets at a scale of 1:250,000 (this is 39% of the number of topographic maps at this scale covering all of Canada); 2.8×10^9 x,y coordinate pairs at 12 points per inch and 4.1×10^{10} at 175 points per inch for the entire 7.5 minute 1:24,000 topographic series; and 5×10^{10} bits (1977) total in over 50 USGS data bases. In comparison, an MSS image contains 4.4×10^8 bits (50 m resampling), a TM image 2.7×10^9 bits (25 m resampling) and a SPOT image (resampled at 12.5 m) 7×10^9. The latter figures become 1.2×10^{11}, 7.4×10^{11} and 1.9×10^{12} for one complete US coverage (no overlap or sidelap).

In spite of the large data volumes, costs of image processing and preprocessing are reasonable in comparison with costs of manipulating much less dense polygon data volumes in geographic information systems. Advantage has been taken of parallel processing techniques, for example, a 1976 publication quotes results of a data encoding test on 49.8 square mile area in which two data sets - a land use (1:100,000 scale) and a census tract source map were utilized.+ For the coarse polygon system used in the test, ie. the San Diego Comprehensive Planning Organization's Polygon Information Overlay System, the cost for overlay of one data set upon another was $88 ie. $1.77 per square mile for the test area. Cost estimates made for 7-band Thematic Mapper data include preprocessing (geometric correction to put in a form for overlay) are $0.058 per square mile, and analysis (classification) about $0.24 per square mile. The image raster structure lends itself to methods of rapid overlay and analysis.

Data base management systems of conventional geographic information systems have been used successfully with spatial and aspatial data where the spatial data is point source data. In this case the locational data may be treated essentially as spatial values. For example, the Groundwater Site Inventory File in the U.S. National Water Data Storage and Retrieval System contains inventory data describing the location, geohydrologic characteristics, construction and production histories, and field measurements for approximately 250,000 groundwater sites. The locational

+ "Computer Handling of Geographical Data", R.F. Tomlinson, H.W. Calkins, D.F. Marble, UNESCO Press, 1976.

* "Difficulties Inherent in Organizing Earth Data in a Storage Form Suitable for Query", R.F. Tomlinson, Proceedings of AUTO CARTO III, San Francisco, 1978.

information consists of groundwater site location coordinates and is amenable to plotting, contouring, and statistical analysis.

4. Communications Networks for Transfer of Resource Information and Remotely Sensed Data

4.1 History

For many years the weather service has used networks to transmit information quickly to regional offices. This rapid transmission was necessary because of the time scales being dealt with. It has permitted complex numerical weather prediction models to be run centrally at the Canadian Meteorological Centre (CMC) computer in Montreal with results communicated to offices along the network. The AES synoptic network which provides real-time hourly observations consists of 318 stations across Canada. Hourly, or in some cases, 3-hourly measurements of temperature and 6-hour accumulations of precipitation are recorded at these stations and then transmitted via teletype to central weather offices and the CMC computer.* Meteorological satellite data is also acquired and distributed in real or near real time to all major weather centres across Canada. Very High Resolution Radiometer (VHRR) visual and thermal infrared data is obtained from the High Resolution Picture Transmission System on the polar orbiting NOAA weather satellite. The NOAA data are digitized, computer processed to compress data and remove panoramic distortion and to add annotations and geographical outlines, and facsimiled over voice quality national meteorological land line circuits to weather centres.+ VHRR data, processed to enhance ice detail, is also facsimiled by dial-up telephone to Ice Forecasting Central in Ottawa. Data from Tiros-N, which replaces the NOAA series in 1979, comes from the Advanced Very High Resolution Radiometer, Operational and Vertical Sounds, and an onboard data collection system, in digital form. Visual Infrared Spin Scan Radiometer data from the geostationary meteorological satellite GOES, is sectorized at the Satellite Data Laboratory in Toronto. Half hourly sectors at selected resolution, enhancement and location are to be facsimiled over the meteorological network in real time to weather centres in the Maritimes, Quebec, Ontario and Manitoba. Similar acquisition and distribution is planned for western Canada.

+ "Remote Sensing of Satellite Data for the Atmospheric Environment Service", C.I. Taggart, Ontario Association for Remote Sensing Newsletter, Vol. 3, No. 1, March 1979.

* "Meteorological Inputs for Hydrological Models", R.G. Lawford, paper prepared for the IWD Technical Workshop on Modelling Activities Related to Flood Damage Reduction, May 23-25, 1979, Hull, Quebec.

4.2 Transmission of Raw Satellite Remote Sensing Data to Regional User Agencies

There are several communications links between satellite receiving centres and ultimate users which require detailed examination. Broadcast of raw satellite data to regional agencies involves one-way data transmission, but data information flow between agencies in a province or interactive image analysis discussed in Section 4.3 may involve 2-way data flow. Frequently, a high speed data link is required in one direction only.

If satellite data is acquired by direct readout at Canadian ground stations and preprocessed there, the first link would involve transmission to regional agencies. According to timeliness and cost considerations, this could be done by CCT, by satellite or landline link at moderate or slow transmission rate, or in real time by satellite link. Tables I and II estimate some upper bound data volumes if all data acquired for a province, eg. British Columbia, were broadcast to a regional centre. Broadcast data could be read out simultaneously by several agencies within a province, or a central agency could receive data for the province and rebroadcast it as required to other agencies. While some selectivity in terms of cloud free data and coverage requirements is probable in both cases, the scenario of transmission of sectorized data to a regional centre at a moderate rate from which good quality selected data is retransmitted probably at a slower rate to other agencies within the province has advantages. Ground terminal, tape recorder or disc drive, and computer costs would be less for multiple stations for a slower transmission rate, and data handling would be reduced as the regional centre would pass on only data useful to local and regional agencies. The total number of Landsat coverages per year at present with an 18-day repeat cycle is 20.3 (descending passes) and would increase to 122 (plus sidelap) if 6 satellites were in operation.

Space Segment Costs:

The data volume values of Table II apply to broadcast to one province and have been sized according to the B.C. requirements shown in Table I. While data volumes for one province are too small to justify a dedicated satellite channel and therefore only partial channel or occasional full channel use are needed, requirements by several provinces including both data broadcast and interactive image analysis may in the long term fully utilize a channel. Other options are suggested in Section 4.4 however.

Data may be broadcast at high data rate (eg. 60 Mb/s) via satellite for a short time (Table III), at medium data rates eg. 1.544 Mb/sec via satellite (Table IV), or at low data rates continuously (Tables I, II, IV and VI) via landline or satellite. Satellite transmission is economical for long distance high volume transmission as seen in Tables III and IV. For example, occasional use of a full Anik channel (and therefore fast 60 Mb/s data transmission) to transmit all raw satellite data of B.C. to that province would cost $23.9 to $91.3 thousand annually for the space segment transmission of data from one Landsat satellite (thematic mapper data) and $78.9 to $164.3 thousand for a six-satellite system, depending on the degree of channel sharing possible. Costs for dedicated use of a partial satellite channel (1.544 Mb/sec) are similar as shown in Table IV, ie. about $25,000 (or less with extensive sharing) to $125,000 for data from one satellite and $82,000 to $125,000 for data from 6 Landsat-D type satellites. While the former rate has advantages in faster transmission of data, the latter requires less costly ground station facilities. Broadcast data could be transmitted to one or several agencies within a province. These space segment costs even at current rates are reasonable. In addition, they are expected to decrease by one-third or more in time. A U.S. study shows the cost of leasing a wide-band transponder channel will decrease by two-thirds during the next 20 years.*

Ground Terminal Costs:

Costs of data broadcast to several agencies within a province will depend on ground receive terminal costs. Lease rates quoted in Table V are for high quality and reliability terminals. It will probably be possible for individual agencies to own receive only terminals by 1985. With adequate numbers of such terminals, specifically designed for remote sensing requirements, purchase cost by that time for ground stations capable of being used with full Anik channel bandwidth could be in the order of $40,000 per receive station. This is based on the order of magnitude cost reduction in TV receive-only terminals in a 5-year period, and a $30,000 capital cost of a receive terminal suitable for the purpose under consideration although not up to Telesat's standards. More conservative estimates put the projected cost of these terminals at $75,000. Commercial estimates of present costs run to $400,000 if terminals were purchased rather than leased. If a partial satellite channel is used, receive terminal costs could be

* "Research and Development", Department of Communications, 1977-78.

substantially reduced. One judgement of cost for a 5 Mb/s channel was for ground terminal costs about 1/3 those for full channel capacity, ie. about $25,000. For slower transmission rates in the order of 1 Mb/s, development of direct broadcast TV terminals and their low cost due to large volume sales, could influence costs of receive terminals with digital modems for the lower transmission rates to give costs considerably lower than present estimates of $15,000. The ground terminal costs noted should be within reach of many agencies and there could be several receive stations within a city. An important cost consideration is the equipment required in handling the high data rates associated with full space segment channel bandwidths. This requires special tape recorders or disc drives and computers and could result in additional costs over low data rate channels in the order of $100,000.

Uplink costs are more expensive, and in 1985 it may still be necessary to contract with a common carrier for data uplink. One informed opinion is that transmit terminal capital costs will be not more than $235,000 at that time, and lease rates $75,000 per year. Present commercial rates are much higher with estimates of transmit terminal lease costs of $235,000 per year and purchase costs (if permitted) in the order of $0.5 million. Terminal purchase cost variations according to full or partial channel use are only minor in comparison with those for receive stations. One judgement estimated purchase cost differences of about $50,000 for transmit-receive terminals utilizing 50 Mb/s channel capabilities versus 5 Mb/s channel capabilities.

The above transmit and receive terminal costs and space segment costs (Tables III, IV) indicate that real time raw satellite data transmission is probably economically feasible from one location to multiple locations throughout the country. However, uplink costs suggest that transmission from multiple locations to other locations must be examined closely. This would be the case for satellite data relay from a central facility in a province to several other agencies. It would also apply for linkage of a host image analysis facility to several remote terminals. However, for example, if 10 terminals were involved, shared uplink costs could eventually be in the order of $7,500 each per year.

Discussion

At present, receipt of digital image data of the same scene by several agencies requires rewriting the data on several CCTs for distribution at a cost to the user of $200/CCT. Utilization of satellite broadcast would allow multiple users to read out the data and retain their own data bank. Local storage and analysis becomes more feasible as storage and processing costs decrease.

Options for multiuse and multiagency sharing of a partial communications satellite channel are discussed further in Section 4.4.

Table 1

Transmission Requirements for Broadcast of Raw Satellite MSS Data to Provincial Agencies

Number of Satellites	Province	Approximate number of scenes per repeat cycle	Scenes per day (ascending and descending)	Scenes per day (descending passes only)	Total data volume ‡ (descending passes) -bits/sec	Continuous transmission rate required (k bits/sec)
1-Landsat-3 MSS sensor (18 day repeat cycle)	B.C.	97	10.8	5.4	2.37×10^9	27.4
	Ontario	90	10	5	2.19×10^9	25.3
	Sask.	62	6.9	3.4	1.49×10^9	17.2
6-Landsat-3 MSS sensor (3 day repeat cycle)	B.C.	97	64.8	32.4	1.42×10^{10}	164
	Ontario	90	60.0	30.0	1.31×10^{10}	152
	Sask.	62	41.4	20.7	0.89×10^{10}	103

Table 11

Satellite Data Broadcast Transmission Required for Several Satellite Sensor Acquisitions of British Columbia

Satellite Sensor	Data Volume per 185 km x 185lKM scene ‡ (bits)	Approximate Daily Volume for full coverage of B.C. (descending passes only)	Continuous transmission rate required for descending passes (k bits/sec)ǂ
1 - satellite			
MSS	0.438×10^9	2.4×10^9	27.4
TM	2.66×10^9	$^{*}14.6 \times 10^9$	166
HRV	7.00×10^9 (2.94×10^9 for single pass 120 km swath width)	$^{+}24 \times 10^9$	270
6 satellites TM		88×10^9	10^3

‡ Volumes given represent the output from the CCRS Digital Image Correction System (DICS) with MSS data resampled at 50 m, TM data at 25 m and HRV data at 12.5 m. Data volumes per MSS scene for example for the uncorrected data would be 0.243×10^9 bits.

* Approximate figure. Although the swath width is the same as Landsat-3 MSS, ground track spacing is slightly larger (170 km vs 150 km at equator), but repeat cycle is shorter (16 vs 18 days).

\+ Very rough estimate at present because of significantly different track spacing, swath width and repeat cycle.

ǂ These values represent transmission of all raw satellite data. Since some selectivity according to image quality before broadcast to regions is likely, these represent upperbound values for descending satellite passes.

Table III A

Part Time Communication Satellite Full Channel Transmission of Raw Remote Sensing Satellite Data of British Columbia

Satellite	Channel Capacity (M bits/sec)	Time to Transmit One Full Scene** (seconds)			Time to Transmit TM Imagery to B.C. (1 satellite)		Time to Transmit Imagery to B.C. (6 satellites)	
		MSS	TM	HRV	Daily (minutes)	Annually (hours)	Daily (minutes)	Annually (hours)
ANIK	62	7.1	42.9	47.4	3.9	23.9	23.4	143.4
ANIK-C (1981)	90	4.9	29.6	32.7	2.7	16.4	16.2	98.7

Table III B

Communications Satellite Costs to Broadcast Thematic Mapper Data of British Columbia

Satellite		Space Segment Cost to Transmit TM Data to B.C. Annually (one satellite)		Space Segment Cost to Transmit TM Data to B.C. Annually (6 satellites)++	
		Full Cost* (000$)	Shared Cost (000$)	Full Cost‡ (000 $)	Shared Cost+ (000 $)
Anik (full channel capacity)	(1)	91.3	23.9	164.3	78.9
	(2)	67.5	23.9		

** Refers to 185 km swath width for MSS and TM data, and 120 km swath for HRV data.

++ Data acquired annually by six Landsat-D type satellites.

* Uses rate of (1) $250 per quarter hours for 100 hour use annually and (2) possible $185 per 10 minutes for 50 hour use annually, $170/10 minutes for 100 hour use annually.

\+ Uses rate of $137.50 per quarter hour for 1000 hr use annually. The 143 hours required for broadcast to B.C. represents about 1/7 of 1000 hours. The assumption is sharing demand is such that not more than 14.3% of broadcast time is taken up in transmission to B.C. If this rate applied, but B.C. were required to pay 20% of the cost due to insufficient demand for sharing elsewhere in Canada, the annual cost to B.C. would be $110,000.

‡ Uses suggested rate of $150/10 minute ($450/30 minute daily). Shared costs indicate that broadcast is made of data of other provinces in Canada as well so that, for example, transmission to B.C. might be for 3.9 minutes within a 15 minute period and elsewhere for the remainder.

Table IV

Communications Times and Costs in Tramsmitting Satellite Data of British Columbia to that Province

Mode of Transmisison	Channel Capacity	Time to transmit one 1000x1000 scene-full resolution		Time to transmit one full scene -minutes (hours)		
		MSS	TM	MSS	TM	HRV
Anik	1.544Mb/s (partial satellite channel capacity)	15.4 sec	31.1 sec	4.7 (.08)	28.7 (.48)	31.7 (.53)
Dataroute	50 kb/s	8 min	16 min	146 (2.4)	887 (14.8)	980 (16.3)

Mode of Transmission	Time to transmit TM imagery to B.C. (1 satellite) hours		Time to transmit TM imagery to B.C. (6 satellties) hours		Space Segment Cost to transmit TM Imagery to B.C. annually (one satellite)* (000$)		Space Segment Cost to transmit TM imagery to B.C. annually (6 satellites) (000$)	
	Daily	Yearly	Daily	Yearly	Dedicated	Shared †	Dedicated	Shared
Anik (1.544 Mb/s channel)	2.6	958.7	15.6	5,752	125	13.7 (11% of channel usage) 25 (20% of channel usage) 41.6 (33.3% of channel usage)	125	82.3 (66% of channel usage)
+Dataroute	81		487					

* Suggested rates of $125,000/yr. for dedicated 1.544 Mb channel available for 8,760 hours.

N.B. + Dataroute rates eg. Ottawa-Vancouver (1976) were $17,719 for 24 hours and $8,179 (9.00 pm - 6.45 am) making this prohibitively expensive for these data volumes.

† Three values for data broadcast costs to B.C. are given depending on the demand by other regions of Canada for shared use of the channel. It is unlikely that broadcast costs of other regions would occupy 89% of the channel time therefore the first value is unreasonably low unless the channel were used for other purposes such as interactive image analysis.

Table V

Rates for Anik provided by Telesat

Protected Channel (62 Mb/s)	current rate $2.1 million/yr.	
(Guaranteed service)	possible eventual rate $1.5 million/yr.	
Occasional Use (62 Mb/s)	100 hour yearly use	$1000/hr.
(can be pre-empted)	1000 hour yearly use	$137.50/quarter hour
	3000 hour yearly use	$105.25/quarter hour

Purchase cost transmit terminal - $500,000, Receive terminal - $400,000

Lease Rate Transmit terminal Anik - $165,000/yr., Anik C - $235,000/yr.

Lease Rate Receive terminal Anik - $125,000/yr., Anik C - $160,000/yr.

Table VI

Landsat Satellite Data Transmission Costs by Landline

Transmission Mode	Transmission Rate	Time to Transmit One Full Scene (hours)		No. of Frame Equivalents /year		Cost transmission Ottawa to Vancouver	Cost/yr. & no. of TM frames	Cost for 1107 TM frames annually
		MSS	TM	MSS	TM			
Datapac	9K baud	13.5	81.9	640	105.5	$0.47/million bits	$133,570 (106)	$1.7 million
Dataroute	230K baud	0.53	3.2	6714	1106.8	$480,000/yr	$480,000 (1107)	$0.48 million

4.3 Use of Interactive Remote Image Analysis Terminals

Present Technology

Within the provinces there are several types of agencies or "levels" at which information extraction capabilities are required. These levels are illustrated in Figure 1. For analysis of remotely sensed data, user interaction will be required at increasingly more geographical locations as the data becomes utilized in routine management operations. Therefore while initially remote sensing information extraction activities may be carried out at an analysis facility located at a regional multidisciplinary centre, eventually user interactive capabilities may be desirable at private agencies, discipline oriented government agencies and then at local branches of those agencies. There is some evidence of this already beginning to occur. In British Columbia where there is no regional multidisciplinary analysis facility, several agencies are considering acquiring image analysis capabilities. A terminal permitting display of local data and input of data to the network will eventually be required in field offices. Therefore, eventually the requirement for interaction (input, display) at the system extremities (field office, farm) will be high. Other users requiring access to information extraction facilities include universities, industry and municipal governments.

Questions of centralization vs decentralization are complex. In the short term factors favouring centralization include high cost of transmission of raw data and increasing volumes of that data, and trends to integration of multisource data and resulting complexity of data handling and information extraction facilities. The latter require high equipment costs, high maintenance costs and a critical mass of expertise. However, users want a strong interactive capability in the information extraction and applications modelling phases. This factor combined with decreasing processing and storage costs tends to favour increasing decentralization particularly in the longer term operational phase.

The degree of centralization will be influenced by the timeliness of information requirements. When data sets from multiple satellite coverages must be handled in near real time, expensive communications links and information extraction facilities will generally be required. These costs of processing and communicating large data volumes may require a higher degree of centralization in hydrometeorology for example, than for forestry agencies which maintain inventories and set allowable cuts, for which less frequent updates and fewer ancillary data sets are required.

The high cost of data acquisition and interactive information extraction makes

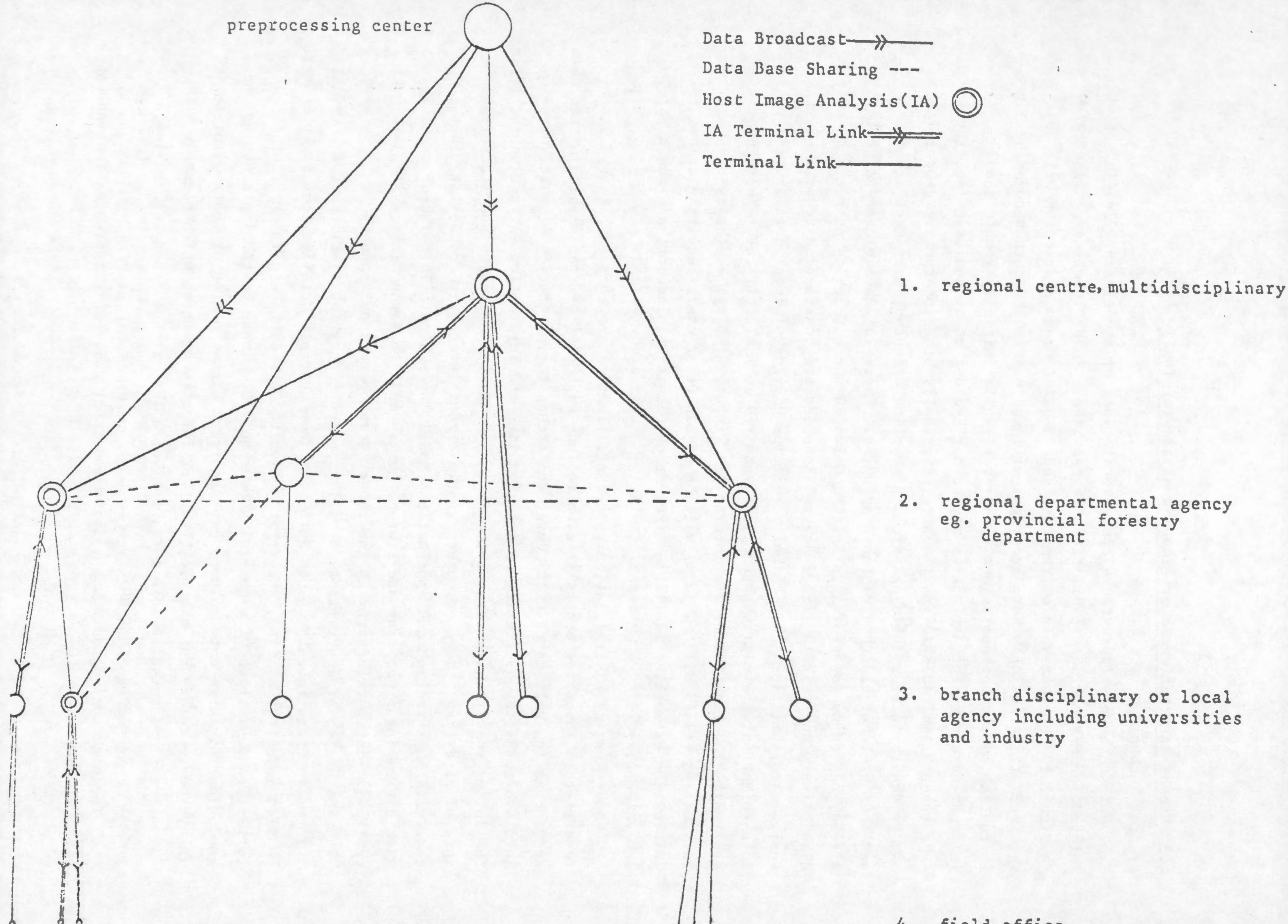
preprocessing center
Data Broadcast
Data Base Sharing ---
Host Image Analysis(IA)
IA Terminal Link
Terminal Link
1. regional centre, multidisciplinary
2. regional departmental agency eg. provincial forestry department
3. branch disciplinary or local agency including universities and industry
4. field office

FIGURE 1

the concept of sharing data bases and some facilities attractive in both the short and long term. The use of remote interactive terminals connected by communications links to information extraction facilities will continue to grow. Their use with non-spatial data are well established. Also, remote terminals have been used to display spatial data including Landsat data and data from geographic information systems (CGIS). Where dense spatial data is to be analyzed (image data), considerations of remote interactive terminals versus use of independent information extraction facilities require considerations of information timeliness, complexity of extraction operations, and cost.

DIPIX have proposed linking remote interactive image analysis terminals to a central host image analysis facility via DATAPAC common carrier packet switching network and examined capabilities and costs.[+] Capabilities could be expandable from initially an interactive display at the end of a long line to an analysis system, through increasing front end processing and storage capabilities, to an eventual stand-alone system if desired.

Current costs of a "baseline" stand alone system which includes an array processor, suitable image storage capability, and Dichomed image recorder are about $400,000. Suitable image recorders have about $100,000 minimum cost. In addition, annual operating, maintenance and analyst support costs have been found for the ARIES system to be $100,000 minimum, with actual costs probably 10-15% greater. It is important to note the experience of DIPIX and the use of ARIES by forestry personnel, in that technical expertise was required in initial training of discipline-oriented personnel, for system maintenance, and for user assistance in most exploratory work. Experience showed the requirement that an analyst be available. For a system involving remote terminals, this would indicate that method of logical support should "be on call if not on line". This requirement is not surprising in the experimental and development phases of a new system, and considering the growing complexity of information management systems often will be required in the operational phases. Kourtz has noted that "In the old days, new developments and corresponding applications, say in the aerial photography - timber inventory field, came about by the determination of a few highly motivated users who could see how to improve existing methods and procedures. However, today the complexity of digital processing insures that the developers and users are two distinct groups".[*] The need for a team approach and critical mass of expertise is central to the technology transfer problem.

+ "IMAGENET - An Image Analysis Network", P.R. Pearl, Machine Processing of Remotely Sensed Data, Purdue University, June 27-29, 1979.

* "An Insight into the Problems of Landsat Technology Transfer in Forestry", P. Kourtz, paper presented at 1979 CACRS meeting.

The DIPIX Imagenet proposal rests on the consideration that, rather than having a slow stand alone image analysis facility possibly with a marginal quality output device and incurring substantial ongoing operating, maintenance and personnel assistance costs, complex operations including processing and outputting would be done centrally. The remote terminal would be inexpensive, some data communications cost proportional to usage would be incurred, central data processing would be very fast (in contrast to medium capability stand alone systems) although a delay which could be in the order of minutes depending on the communications link would be required to transmit a screen full of data to the terminal. Outputting would also be done centrally, which could be a handicap if an information product was required quickly. Assistance from an analyst viewing the same data could be available centrally for several interactive terminals. This would ensure that each user had access to methodological support if and when required, but permit sharing of that support with several other users.

The requirement for user interactive image display units is well established in analysis procedures involving remotely sensed data. Considering early studies in a batch oriented environment, NASA's staff noted that even simple image processing operations took from days to weeks to produce desired results and required numerous manual, error prone steps. Operations requiring a high degree of human interaction with the image data during the information extraction were not practical in this mode.[*] For operational usage, the need for timeliness, reliability and flexibility requires use of interactive image analysis terminals. Improving spatial information content in satellite data will increase this need. Ragan and Salmonson note that thematic mapper 30 m resolution may allow much more extensive use of airphoto interpretation techniques.[+]

In the Imagenet concept, commands entered at the remote terminals would initiate and control image processing tasks, within the host image analysis system. No analysis would be done locally in a baseline capability system, although local capabilities could be developed if required. Raw or processed image data of full or partial resolution or in a compressed form would be transmitted to the remote terminal for interpretation and evaluation. A microprocessor would be used by the colour image display terminal for data packing, control of network data transfers and operator control and display functions. Point and area identifiers would be interactively generated at the terminal and transmitted to the

* "AOIPS - An Interactive Image Processing System", P.A. Bracken, J.T. Dalton, J.J. Quann and J.B. Billingsley, National Computer Conference Proceedings, AFIPS Press, June 5, 1978.

\+ "The Definition of Hydrologic Model Parameters Using Remote Sensing Techniques", R.M. Ragan and V.V. Salmonson host system. Training (signature development) would be done on small areas and the signatures transmitted via Datapac or other link for large area classification. Statistics generation would be done at the host facility. Radiometric manipulations (look up table enhancements) of the displayed image could be done locally, eg. enhance a small area at full colour resolution, and the look-up tables read back to the host facility for manipulations on a large area. In the evaluation phase a small area at full resolution could be viewed, or alternatively a larger area at reduced radiometric resolution (ie. 2 or 3 bits from 3 bands). Image size would be constrained by the size of the video memory at the terminal.

The capability of image analysis could be developed if desired at a remote terminal. Rapid microprocessor developments are reducing costs of processors on which image analysis software can be implemented. Adequate disk storage would be required. An array processor and recording capability could be added as required. The cost of mass-produced array processors may eventually go as low as $10,000. The initial baseline capability would provide an interactive capability at the user's location, and facilitate training in use of the new technology. System evolution to predominantly local analysis could improve timeliness (eg. data available on disk at the site possibly transmitted the previous night). A network tie to the original host facility may be broken or retained for special analysis. A local image record capability is very attractive but at $100,000 or more capital cost plus maintenance it may be more expensive than the rest of the terminal.

As satellite data volumes increase and operational applications are developed the number of interactive displays required by multiple users will grow rapidly. In fact the main problems that will result from the high data volumes of Landsat-D are seen by some to be not just in processing where considerable capability exists, but in other areas such as how to display the data, what to do with it after classification, etc. Minimization of movement of raw data by terrestrial communications lines will be required to keep costs down. A particular satellite coverage may be required by several users in several locations. Multiple coverages will often be required in a particular analysis. If storage of multiple coverages of dense image data sets can be centralized to minimize communications costs, and information extraction procedures carried out at the storage site (also on part to minimize communications costs) and still permit the remote user to input auxilliary data, control the extraction procedures, and adequately evaluate the results quickly (perhaps only a subset of the total area, or a fraction of the volume of the original raw data) there are cost advantages. There are significant differences however, between satellite communications where ground terminal costs dominate, and data volume dependent land line communications. These are discussed further below and in the next section.

It is important that evaluation be possible at various stages in the information extraction (processing) procedures. While integration of multi-temporal, multisource data may be required in the information extraction process, evaluation of derived products or intermediate processing steps may involve transmission to a terminal of a greatly reduced data volume for a particular area. For example, in a particualr classification it would be quite reasonable, especially when 7 band TM data becomes available, to use 10 or more input channels of different spectral and spatial channels, and biomass windows.

In the remote terminal concept outlined here the initial capital and fixed annual costs for the terminal are relatively small in comparison with stand alone systems ($\sim$10%). Costs are strongly influenced by data communications costs which depend on the extent to which the terminal is used if costs are shared with other communication channel users. This provides particular benefit where heavy use of the terminal is not required for example, by universities, industry or outlying government offices.

It has been noted above that while communications costs are incurred in the system involving remote terminals, the amount of raw or analysed data transferred may be small in comparison with that used in a particular analysis task. In comparing for example a 10 terminal system within a province with 10 stand alone systems, the additional costs of providing raw data (particularly satellite data) to the 10 independent systems and storing it locally may exceed the network communications costs in the multiterminal interactive system. Firstly, it will likely be desirable to keep a provincial satellite data bank (even if many stand alone systems are used) in order to satisfy requirements of a multiplicity of small users such as industries, municipalities, etc. In that case provision of pre-processed raw data from these centres to stand alone facilities would involve either production of CCTs for those facilities (reproduction costs at least $50 per tape containing one MSS image plus $20 for the tape. A time delay would be experienced by this method), or transmission via a communications channel of the full amount of raw data used by each facility.

Transmission could be by landline with volume dependent charges exceeding those for transfer of analysed data in an interactive image analysis system. If satellite communications were used, because of the dominance of ground terminal costs, the cost of broadcasting data to several stand alone facilities would be slightly higher but not very different from use of satellite communications for interactive analysis.

Alternatively, if the option is to communicate raw data coming into a province directly to a number of stand alone facilities rather than a central facility, since more than one facility may require the same CCT costs for raw data will be higher. These higher costs can result from data volume dependent charges if landline transmission is used, or from receive station and associated tape recorder and computer costs if satellite communications are used.

It may be noted that already some forestry users of satellite data have expressed interest in land line transmission of digital data as an alternative to CCTs. Foresters have been in the forefront in making use of the digital data in Canada. Convenience as well as timeliness are the reasons. Other potential operational users with much more serious timeliness requirements (eg. streamflow forecasting) will eventually demand use of such communications channels if the data is to be useful to them.

As technology advances decrease image processing throughput times and as higher resolution satellite data results in more human "photointerpretation", the amount of human interaction time spent in viewing image enhancements and evaluating results at various stages of processing is likely to increase relative to actual machine processing times. Many interactive display terminals will be required. A time-sharing mode is favoured by which an individual analyst does not tie up an image processing facility. Image transmission costs below suggest it may become as important to share common data bases as facilities.

There are strong advantages to having immediate access to the complete scene to be analysed so that subareas for intensive study may be correctly and quickly selected. Storage capacity and communications costs may deter this at a remote terminal. Availability of a hardcopy product of the raw satellite data may be sufficient to provide the required scene overview. A user may tolerate a short delay in acquiring a subscene at a terminal if it is the correct one, but he would be quickly frustrated by trial and error delays in selecting the appropriate study area.

Table VII presents some order of magnitude comparative costs of independent systems versus terminals network-linked to a central facility. The network approach is expected to increase in cost attractiveness with number of terminals, eg. 4 more desirable, than 2, although there will be an upper limit which a host can effectively support. Sharing facilitates use of special purpose high throughput processing, information extraction and information product output. The costs of the image analysis facilities are nearer the lower end of a range of costs of capable systems required to handle the high resolution data of Landsat-D, SPOT and follow-on satellites. Those data volumes ensure the requirement for large peripheral storage, array processors and high quality output devices. For example, suggested potential improvements to the ARIES system to improve throughput include faster tape drives for more rapid data entry, more core memory to allow larger programs to co-exist without the delays of swapping to and from disk, and a second large image disk to facilitate a new operator preparing to come on while the previous operator was still working.* Clearly a time shared system would have to give careful consideration to disk storage requirements of multiple users, as well as array processors and shared output devices.

Table VII

Approximate Comparative Costs of Providing Image Analysis Capabilities at 10 Locations within a Region

	Independent Systems	Remote Terminals Networked to Central Analysis Facility
Capital Costs	\$500,000x10 = \$5 million	\$70,000x9+1.5-2.0 million = \$2.1 - 2.6 million
Operating Cost (maintenance + software and methodological support)	\$100,000x10 = \$1,000 k	\$5,000x9+\$200,000 to \$300,000
Communications Costs	Costs of transporting raw data to independent sites.	Costs of Datapac, satellite or alternative communications links.

The above figures indicate large capital costs associated with independent analysis systems. Large volumes of raw data (multiple passes) must be acquired at each location on CCT's or by land line, and large storage capabilities are needed. The host image analysis facility would include a lot of peripheral storage, a good output device and suitable array processing capability.

In the Imagenet concept, the time required to transmit an image through the network can be appreciable. The time effect may be reduced by several methods including:* reducing the number of bits per pixel eg. 2 or 3 bits from 3 bands; transferring only a segment of an image at full resolution; transmission of a second image while displaying the first image undisturbed; transmission of an image through the network with decrease in information content with time (permitting early image manipulation); use of data compression by data coding prior to transmission and decoding at the remote terminal eg. transmitting labelled pixels and the Look-Up-Table required for decoding.

Transmittance times for image segments may be acceptable: assuming a rate of

* DIPIX staff, personal communication.

9000 Baud during image transfer, it would require about 3.7 minutes to transfer $2x10^6$ bits, for example a 505 line x 506 pixel 8 bit (single band) segment or 252 lines x 253 pixels 32 bit (four band) segment. However, transmittance times for segments making up a full 4 band Landsat frame ($13.7x10^6$ pixels from DICS) containing $438x10^6$ bits would require about 13.5 hours. A full 7 band TM image would be much worse ie. $54.8x10^6$ pixels for visible and near IR bands and $3.4x10^6$ for 100 m thermal IR pixels giving a total of $2657x10^6$ bits and a transmission time of 81.9 hours. The data volume would increase to $7x10^9$ bits for 4-band 12 m resolution data of the same size. Currently envisaged remote terminals would be limited in video memory to about 4 to 8 million bits. DIPIX consider that reasonable analysis conditions could involve transmitting 10 two million bit images per hour for evaluation. Total transmission costs between two locations include a variable data volume dependent component and a fixed monthly station charge of $417.

The Datapac communications limitations on the area that can be analysed at the host and evaluated at the terminal depend on the data transmitted to the terminal for evaluation, eg. whether transmission involves only change information, only selected segments for evaluation of the total area, full or reduced resolution, etc. For example, if local evaluation involved transfer of 10 per hour, 50 per day two million bit images, with each segment of 252 lines by 253 pixels and 32 bits, approximately 3000 square miles of Landsat MSS data could be evaluated daily.

Because of the volume dependent component of Datapac charges, costs can escalate rapidly for transmission of dense data such as image data. Also rates per kilopac of data transmitted vary widely with the stations involved with rates between Toronto and Montreal or Ottawa. For example, near the low end of the cost range while those in mountainous B.C. are at the upper end.

Table VII provides some sample representative costs for transmission of full Landsat scenes of raw data from potential regional center locations to agencies where independent image analysis or interactive terminals could be located.

Table VIII provides Datapac network costs for interactive image analysis for a number of host and associated remote terminal locations across Canada. Communications costs are given for 2 plausible scenarios of 10,000 and 24,000 image segment transmissions annually, each of 2 million bits (the former representing for example 10 segments for each of 5 hours daily and 200 days annually). However, segment transmission could be less than 10,000 annually.

Several observations may be made from the tables. Considering first Table VIII:

Table VIII

Datapac Costs for Transmission of Frames of Raw Landsat Data+

Location of Regional Centre	Location of agency to which data is transmitted	Cost for Each Normal Kilopac of Data Transmitted ie for each image of $2x10^6$ bits($)†	Cost to transmit MSS imagery One scene($)	Cost to transmit MSS imagery 100 scenes* ($÷1000)	Cost to transmit TM imagery One scene($)	Cost to transmit TM imagery 100 scenes* ($÷1000)
Quebec City	Montreal	0.31	68	6.8	412	41.2
Toronto	Sault Ste. Marie	4.03	883	88.3	5,356	535.6
Toronto	Toronto	0.15	33	3.3	199	19.9
Winnipeg	Brandon	1.47	322	32.2	1,954	195.4
Regina	Winnipeg	0.50	110	11.0	665	66.5
Edmonton	Lethbridge	0.96	210	21.0	1,276	127.6
Edmonton	Calgary	0.33	72	7.2	439	43.9
Vancouver	Prince George	4.38	959	95.9	5,821	582.1
Vancovuer	Kamloops	2.40	526	52.6	3,190	319.0
Halifax	Charlottetown	1.91	418	41.8	2,538	253.8
Halifax	Fredericton	0.75	164	16.4	997	99.7
X	Y_1	0.15-1.0	33-219	3.3-21.9	199-1,329	19.9-132.9
X	Y_2	1.0-2.0	219-438	21.9-43.8	1,329-2,658	132.9-265.8
X	Y_3	2.0-3.0	438-657	43.8-65.7	2,658-3,987	265.8-398.7
X	Y_4	3.0-5.0	657-1095	65.7-110	3,987-6,645	398.7-664.5

Time to transmit one MSS 4-band scene = 13.5 hours.

Time to transmit one TM 7-band scene = 81.9 hours.

+ Costs do not include monthly station charges, but only volume dependent costs.

* For example about 2 scene equivalents per week year round.

† Source: Datapac Network Rates June 1977.

1. One full MSS scene would require 13.5 hours or "overnight" to transmit. In the same period about 1/6th of a TM image could be transmitted. This timeliness could be improved upon by physical transport of tapes within a city such as Toronto, and in many cases between cities eg. Quebec City to Montreal, Toronto to Ottawa, etc.
2. High costs are discouraging to this form of data transportation. For example, within Ontario costs for one MSS scene, which could be stored on one high density cartridge, range from \$33 within Toronto to \$883 for transmission from Toronto to Sault Ste. Marie. Less costly alternatives eg. courier usually exist even when Datapac rates are at the low end of their range such as \$70 for transmission of one MSS scene between Toronto and Ottawa. Minor improvements in timeliness between distant locations would rarely justify the large cost increases for this form of transportation.
3. Where small data volumes are transferred on a daily basis, Datapac transmission becomes a little more favourable. However, there is a fixed station charge which for 250 working days is equivalent to about \$20 per day. Therefore for one scene-equivalent transmitted between Toronto and Ottawa per week, the average daily cost would be \$34.
4. If Datapac could be used by an agency in communication of several types of data including small image data volumes, so that effectively fixed station costs would be shared among several users, the cost attractiveness of Datapac vs alternatives could improve. Trends to digital information systems are likely to increase the transfer between agencies of ancillary data in digital form.
5. The large data volumes of Landsat-D TM generally make costs of Datapac transmission of raw data prohibitive. Transmission times also become very long (81.9 hours per full TM scene).
6. Some of the sample costs, eg. \$7200 for transmission of 100 scenes annually from Edmonton to Calgary plus \$5000 station charges, are competitive or attractive with respect to satellite broadcast. Communication satellite broadcast has better timeliness and becomes more cost attractive for larger data volumes such as will be the case when TM data becomes available, particularly because of costs associated with ground stations. In both cases if timeliness is not critical, physical transport of tapes must be considered since cartridge costs may be only several dollars and courier costs between major cities could be \$25 - \$30 or less. The attractiveness of network transmission of digital data relative to transport of tapes will improve in future.

Table IX

Datapac Costs for Interactive Image Analysis †

Province	No. of Stations in Prov.	Host Location	Terminal Location	Rate for each Normal Kilo-pac of Data Transmitted($)	Scenario 1* ($ ÷1000 per year)	Scenario 2+ ($÷1000 per year)
British Columbia	7	Vancouver	Prince George	4.38	48.8	110.1
			Kelowna	2.53	30.3	65.7
			Kamloops	2.40	29.0	63.6
			Victoria	0.64	11.4	20.4
Alberta	5	Edmonton	Medicine Hat	2.61	31.1	67.6
			Red Deer	1.66	21.6	44.8
			Lethbridge	0.96	14.6	28.0
			Calgary	0.33	8.3	12.9
Sask.	3	Regina	Moose Jaw	1.02	15.2	29.5
			Saskatoon	1.01	15.1	29.2
			Winnipeg	0.50	10.0	17.0
Manitoba	2	Winnipeg	Brandon	1.47	19.7	40.3
Ontario	22	Toronto	Ottawa	0.32	8.2	12.7
			Sault Ste. Marie	4.03	45.3	101.7
			Toronto	0.15	6.5	8.6
Quebec	7	Quebec City	Sherbrooke	0.84	13.4	25.2
			Montreal	0.31	8.1	12.4
New Brunswick	3	Halifax	Moncton	0.87	13.7	25.9
			Fredericton	0.75	12.5	23.0
Nova Scotia	2	Halifax	Sidney	2.88	33.8	74.1
Prince Edward Island	1	Halifax	Charlottetown	1.91	24.1	50.8
Newfoundland	1	Halifax	St. John's	0.65	11.5	20.6
Province Z		X	Y_1	0.15-1.0	6.5-15.0	8.6-29.0
			Y_2	1.0-2.0	15.0-25.0	29.0-53.0
			Y_3	2.0-3.0	25.0-35.0	53.0-77.0
			Y_4	3.0-5.0	35.0-55.0	77.0-125.0

† Datapac Rates and Station Locations Source: Datapac Network Rates, June 1977.

* Involves conservative scenario of total annual transmission of 10,000 2 million bit images (eg. 10 per hour, 5 hours/day, 200 days/yr, each image requiring about 3.7 minutes for transmission).

+ Assumes 24,000, 2 million bit images annually (eg. 10 per hour, 8 hours/day, 300 days/year).

With regard to Table IX:

1. There are a limited number of locations for which Datapac service is provided, and not all cities are served in which are located provincial agencies involved in resource and environmental management. Costs tend to be higher in western Canada, particularly in British Columbia.
2. Communications costs vary widely. For example, using Scenario 1 which involves moderate remote terminal usage, annual costs are about $8,000 for terminals in Montreal linked to a host in Quebec City, in Calgary to one in Edmonton, or in Ottawa to one in Toronto. These costs are still only about $1000 per month with the more intensive usage of Scenario 2. However, the corresponding Scenario 1 cost is $45,300 for a terminal in Sault Ste. Marie linked to a host facility in Toronto.
3. Transmission time for one 2 million bit segment is 3.7 minutes. While transmission times are appreciable, this may be a necessary inconvenience in order to afford interactive image analysis. The necessity to transmit data can be alleviated by acquiring tapes of desired raw data for display at the remote terminal. Areas for analysis at the host can be selected and some local analysis may be carried out using that data. A high degree of selectivity in data transmitted from host to terminal could be developed with this mode of operation. Decreasing storage and processing costs will improve the capabilities which may be implemented locally.
4. Landline transmission is of particular advantage where there are a small number of remote terminals interacting with a host facility, eg. 2 or 3. This would occur for example if an agriculture department analysis facility had terminals at two or three branch locations. Or an analysis facility could have several local work stations and one or two terminals at only one remote location. This provides an advantage over satellite communications (Table XI) which rely on multiple terminal sharing of uplink and space segment costs to keep data transmission costs down. However, response times using Datapac are not as favourable as for typical satellite communications channels as outlined in Table XI. Datapac communications, where rates are low, bring relatively low cost, potentially powerful analysis capabilities particularly to agencies which are not heavy users of analysis capabilities and where therefore data volume transfers are not excessively heavy.
5. Heavy remote terminal use as in Scenario 2 brings Datapac costs in many cases comparable with or higher than the satellite communications costs of Table XI,

plus the slower response inconvenience. Clearly, each region will have to be examined as to location of remote sensing user agencies, alternative forms of communication services to those locations, requirement for ancillary digital data transmission, and intensity of use of analysis capabilities and required sophistication, because communications are such a prominent system cost consideration. The degree of centralization will be influenced. For example, high alternative communications costs in B.C. make a centralized, multiterminal analysis facilities with satellite communications look attractive.

6. Datapac costs between provincial capitals are relatively low ie. less than $1.00 per kilopac in most instances. Rates between capitals in adjacent provinces are low, for example Winnipeg to Regina - $0.50, and Regina to Edmonton $0.56. Therefore, from a present landline communication cost standpoint, regional centres involving more than one province, eg. the western grain growing area, are not discouraged. The existence of good landline links between provincial capitals may be of value if regional centres with host analysis facilities are located there, and uplink randomly into a shared satellite channel.
7. Utilization of a remote terminal to a host analysis facility is usually economically more attractive within a city than when satellite (or alternative) data relay is required to a more distant site. Total communications costs by land line (co-ax or fibre) of $5k to $12k/yr (sec.4.5) are likely to be less than satellite space segment costs alone, and large costs are associated with uplink and receive terminals.

Transmission of Preprocessed Data to Regional Centers by Datapac

For completeness, costs of transmission of preprocessed Landsat data as an example from Ottawa to Vancouver by Datapac are given in Table IXB Costs are excessively high and this type of data communication is not likely to be used. Higher capacity dedicated communications links could be used, for example, 230 kilo baud Dataroute communications links capable of transmitting about 3 TM frames per day. However, costs in the order of $480,000 per year (night rates) or $40,000 per month are also excessive for provincial agencies. This represents a cost per TM frame of about $443 with continuous transmission.

Table IX B

Cost transmission Ottawa to Vancouver	\$0.94 per 2 million bit segment
Time to transmit 2 million bits	3.7 minutes
Time to transmit 4-band MSS frame of 438×10^6 bits	13.7 hours
Time to transmit 7-band TM frame of $2,657 \times 10^6$ bits	81.9 hours
Number of MSS frame equivalents per day; per month; per year	1.75; 53.3; 640
Number of TM frame equivalents per day; per month; per year	0.3; 8.8; 106
Cost per frame for transmission-MSS; TM	\$206; \$1260
Cost per square mile for transmission	\$0.016
Cost per year, continuous transmission ie. 106 TM frames or 640 MSS frames	\$133,570
Cost per year for transmission of 5 MSS frames daily	\$380,880
- of 5 TM frames daily (Table 1)	\$2.3 million

Communications Between Field Offices and Agencies with Image Analysis Capabilities

The third communications link to be considered is the one at the system extremities linking the field office, farmer, observor of opportunity, etc. with an agency having image analysis capability, either a terminal to a remote host facility or an independent facility. A video link to a low-cost display (or TV) in the field office would be desirable so that image data could be viewed at the field office. Data, probably usually only point source, would be input at the field office. Although input of attribute data should not be difficult, locational identification would be more complex. For example, a forest ranger who observes disease outbreak has to have a method of inputting that information into the system with locational accuracy. A method of interacting with an image on a screen to tag a particular location may be required.

For rural communications, it is expected to be possible to run a broad band glass fibre to a rural telephone subscriber for the same cost as conventional copper pairs. Field trials of a fibre optics distribution system to bring services including interactive data signals and TV into homes from a central distribution point are underway in Elie, Manitoba.

For more remote locations eg. forestry or rangeland offices, microwave or satellite methods would be required. Satellites are presently being utilized for data relay of sensor point source data such as stream flow and precipitation observations. For image transmission, roof top earth terminals would be utilized at field offices.

4.4 Options for Multi-Use, Multi-Agency Sharing of a Satellite Communications Channel

Satellite communications have advantages in transmitting high data rates over long distances. Multi-agency use, and sharing of transponder and space segment costs can result in reduced individual user costs. Tables X and XI discuss cost advantages of sharing partial satellite channels both nationally and regionally for preprocessed data broadcast and/or rebroadcast and for interactive image analysis.

Nationally Shared Partial Satellite Channel for Data Broadcast, Data Rebroadcast and Interactive Image Analysis

TABLE X A

Cost of Nationally Shared Satellite Communications

Time Frame	Space Segment Capacity in Mb/s (cost)	Transmission time for full TM scene	Daily Broadcast to 6 Regions (5 scenes per region) 1 satellite descending passes	Daily Broadcast Time	Space Segment Cost (per region) per yr.	6-way shared transponder cost (per region) per yr.
Short term (to 1983)	1.544 ($125,000 /yr.)	28.7 min.	30 scenes	14.35 hrs.	$12,500* 20,800‡	$27,500+ 11,700 ++
	5.0 ($405,000 /yr.)	8.86 min.	30 scenes	4.43 hrs.	$12,500* 67,500‡	$27,500+ 11,700 ++

** This estimate is for a cost increase above that for 1.544 Mb/s proportional to the bandwidth increase. It is conservatively high and space segment costs will be slightly lower than those indicated.

* Cost taken as proportional to broadcast time.

‡ Channel dedicated to this broadcast.

\+ Uses quoted cost of $165,000/yr.

++ Uses potential future cost figure of $70,000/yr.

TABLE X B

Space Segment Capacity Mb/s	No. of scenes rebroadcast per region daily	Total re-broadcast time for 6 regions daily	Total time for broadcast and rebroadcast daily	Space Segment rebroadcast cost, 3 agencies per region/yr	Rebroadcast 3-way shared transmit cost/year**
1.544	0.5	1.44 hours	15.8 hours	$417*	$55,000+
				$2,800‡	$23,300 ++
1.544	0	0	14.35 hours		0
5.0	0.5 to 2	0.45 to 1.77 hours	4.88 to 6.2 hours	$420*	$55,000+
				$18,350‡	$23,300 ++

+ Uses quoted cost of $165,000/yr.

++ Uses potential cost figure of $70,000/yr.

* Cost taken as proportional to broadcast time.

‡ Remaining channel time not used for broadcast charged to rebroadcast.

**These figures drop if interactive image analysis also carried out.

TABLE X C

Space Segment Capacity	Channel Time Available for Inter-Active Image Analysis	Time required to transmit 10 512x512 images per hour	Number of terminals accommodated	Shared space segment cost (yearly) per region	Shared uplink image analysis terminals plus rebroadcast to 3 others
1.544	8.21 hrs.	1.37 min.	Maximum 20 at once**	$1,100 (40 way sharing)	$18,300+ $7,800 ++ (6 image analysis terminals)
1.544	9.65 (no re-broadcast) hours	1.37 min.	Maximum 20 at once ***	$2,500	$27,500+ 11,700 ++ (no rebroadcast)
5.0	19.1 to 17.8 hours	0.422 min.	Maximum 60 nationwide	$5,400 to 5,000 $6,750 ‡	$12,700+ 5,400 ++ (10 image analysis ter-minals)

** For example, 20 in east for 4 hours (eg. 7,7,6 terminals for 3 regions) and 20 in west for 4 hours.

***For example, 20 in east for 4.5 hours then 20 in west for 4.5 hours.

+ Uses quoted figure of $165,000/yr.

++ Uses estimated potential cost figure of $70,000/yr.

‡ Cost for each of 60 terminals if channel dedicated solely to interactive analysis.

Considering Table X

1. A dedicated partial satellite channel could be used to satisfy comprehensive remote sensing requirements nationally, including data broadcast from a central preprocessing facility to the regions, rebroadcast from a centre within each region where data selection is carried out, and interactive image analysis within the regions. In this table 6 regions are considered including one each in British Columbia, Ontario and Quebec, two in the Prairie Provinces and one in the Maritime Provinces. With present Landsat coverage, each region has in the order of 90 scenes per repeat coverage and 5 scenes per day. Because of the widely varying coverage frequency requirements throughout the territories, they have not been included. However, some daily broadcast to these areas, for example, showing ice conditions in selected Arctic areas, could be required if satellite broadcast were carried out operationally.
2. In the short term a 1.544 Mb/s channel (or possibly even 1 Mb/s channel) would satisfy data broadcast requirements. The former would have some excess capacity for other purposes (see, however, the comments made in point 10). As data volumes increased due to increased numbers of resource satellites, broader channel bandwidths could be utilized. Although there may be some problems in data broadcasting around the clock, the lower data rates mean less expensive receiving station equipment. Several agencies rather than just a regional centre may be able to afford receive equipment. Differences in overall ground station and data handling equipment capital costs between full satellite channel rates of 60 Mb/s and partial rates of 1.544 Mb/s could easily exceed $150,000.
3. If a 1.544 Mb/s channel were adopted both for data broadcast from a central facility, and for data rebroadcast and interactive image analysis within a region, the same receive equipment could be used by an agency to receive "real time" raw data from a national centre and selected raw data and/or analysed data from a regional centre.
4. A dedicated 1.544 Mb/s channel for data broadcast nationally would have an annual 6-way shared space segment cost of $20,800 and uplink cost of $27,500 at present rates. These may eventually reduce to $14,900 and $11,700 respectively on the basis of estimates of possible eventual cost reductions from $2.1 million to $1.5 million for a full satellite channel and from $165,000 down to $70,000 per year for transmit terminal costs.

5. It is evident in Table X that there would be only limited excess capacity at 1.544 Mb/s for interactive image analysis after data broadcast if all 6 regions acquired raw data. Possibly not all would receive data via this mode in the short term (eg. some receiving tapes) thereby freeing more capacity. In Table X C it is clear that annual shared transponder costs dominate space segment costs eg. $27,500 vs $2,500 where no channel capacity is used for rebroadcast of raw data. Only about 4.5 hours maximum of interactive image analysis per day would be possible under this scenario.
6. The higher 5 Mb/s transmission rates make much more channel capacity available for interactive image analysis. Interacting terminals could be used for extensive periods each day (eg. 18 rather than 4 hours), and more terminals could share transmit terminal costs. The example of ten interactive terminals linked to each of 6 regional centre host facilities would involve space segment costs of $6,750 per agency (or less if some raw data broadcast was carried out) plus shared uplink costs of $16,500 which could in future drop to $7,000 per agency.
7. High transmit terminal costs mean that high data rate transfer could occur from host image analysis to remote terminal but would not be provided in the reverse direction in general because of the high costs associated with a transmit-receive terminal at the remote analysis terminal.
8. Because of the possibility of sharing transmit terminal costs, the dominant present cost is the receive terminal cost. It is anticipated that in the near future, in particular for production of multiple copies of receive terminals, that uplink costs will be the dominant cost factor especially for the lower data transmission rates.
9. Although Table X includes the possibility of interactive image analysis, the daily broadcast time of 14.35 hours at 1.544 Mb/s is a lower bound time requirement for 30 scenes daily. The corresponding broadcast time for a 1 Mb/s channel capacity is 22.2 hours daily. In an operational mode some provision would be made for problems arising, and therefore a dedicated 1.544 Mb/s channel for only national data broadcast is a reasonable possibility.

Note 10. Although the higher data rate could handle national requirements, the alternative of a low data rate (1.544 Mb/s) for national broadcast and dedicated low data rate links, either 1 to 1.54 Mb/s apace segment channels or land line for regional use (rebroadcast and interactive image analysis) have attractive advantages.

Regionally Shared Partial Satellite Channel for Data Rebroadcast and Interactive Image Analysis

Table XI Costs of Regionally Shared Satellite Communications

Time Frame	Space Segment Capacity Mb/s (and cost/yr)	Transmission Time to re-broadcast one full TM scene	No. of scenes rebroadcast daily	Time for rebroadcast daily	Space Segment Cost per each of n agencies per region /yr	Rebroadcast n-way shared transmit cost/yr.
Short term (to 1983)	1.544 ($125,000)	28.7 min.	0.5 to 2	0.24 to 0.96 hrs.	$417(n=3)* $208(n=6) $41,000 (n=3)+ 20,800 (n=6)	$55,000(n=3)‡ 27,000(n=6) 23,300(n=3)‡‡ 11,700(n=6)
Long range (after 1987)	1.544 ($125,000)	28.7 min.	5 to 8	2.4 to 3.8 hrs.	$4,200 to 6,600(n=3)* $2,100 to 3,300(n=6) $41,000(n=3)+ 20,800(n=6)	as above
Long range	1.0 ($100,000)**	44.3 min.	5 to 8	3.7 to 5.9 hrs.	$5,100 to 8,200(n=3)* $2,600 to 4,100(n=6) 33,300(n=3)+ 16,700(n=6)	as above
Long range	30 ($1,100,000)	1.5 min.	30 to 48 nationally	0.75 to 1.19 hrs.	$1,900 to 3,000(n=3)* $950 to 1,500(n=6) $61,100(n=3)+ 30,600(n=6)	as above

* Cost allocated according to channel time utilized.

\+ Cost if channel dedicated to rebroadcast only.

‡ Uses quoted cost of $165,000/yr.

‡‡ Uses potential future cost figure of $70,000/yr.

**A rate slightly less than that for 1.544 Mb/s is estimated.

Table XI ct'd

Space Segment Capacity Mb/s and cost/yr.	Channel time available for interactive image analysis	Time required to transmit 10 512x512 images per hour	Number of terminals accommodated per region	n-way shared space segment cost yearly	n-way shared uplink costs
1.544 ($125,000)	23.8 to 23.0 hours (short term)	1.37 minutes	10 to 20	$11,900 to 12,400* (n=10) 6,000 to 6,200 (n=20) $12,500 (n=10)+ 6,300 (n=20)	$16,500‡ (n=10)** 12,700 (n=13) 7,000‡‡ (n=10) 5,400‡‡ (n=13)
1.0 (100,000)	20.3 to 18.1 hours (long term)	2.1 minutes	10	$7,500 to 8,500* $10,000+	as above
30 ($1.1 million)	22.8 to 23.3 hours	0.07 minutes	60 to 120 nationwide	$17,400 to 17,800* (n=60) $8,700 to 8,900* (n=120) 18,300 (n=60)+ 9,200 (n=120)+	as above

* Cost allocated according to channel time utilized.

\+ Cost if channel dedicated to interactive analysis only.

** Includes 10 interactive image analysis terminals and data rebroadcast to 3 other stations with stand-alone image analysis capabilities.

‡ Uses quoted cost of $165,000/yr.

‡‡ Uses potential future cost figure of $70,000/yr.

Discussion of Table XI

1. If a regional centre has the capability of transmitting for example in a 1 or 1.544 Mb/s channel to regional agencies and the latter have appropriate receive terminals, both raw remote sensing data and analysed data for evaluation at an interactive terminal may be transmitted. An agency investing in receiving equipment to receive data communicated by satellite might well invest an additional $50,000 or so for an analysis terminal to interact with a powerful host image analysis facility even though it may have some local image analysis capability.
2. Raw data rebroadcast, even with a 1 Mb/s channel and 6 resource satellites acquiring data, is seen not to put a heavy load on the communications satellite channel capacity, eg. less than 6 hours transmission time for 8 scenes per day over a 1 Mb/s link. This can be done at off-hours leaving considerable capability for interactive image analysis.
3. Low satellite data transmission rates eg. 1 or 1.544 Mb/s are very suitable for regional purposes. Relatively lower receiving terminal and associated handling costs put costs within range of more agencies so more terminals can share both uplink costs and possibly host image analysis costs. This results in lower operating hosts per agency.
4. For a scenario involving a regional centre broadcasting preprocessed data to 3 agencies and providing host image analysis capabilities for 10 others, yearly time-shared space segment costs in the short term would be about $420 per agency for raw data broadcast and $11,900 for interactive analysis, and shared transponder costs for each of the 13 agencies would be about $12,700 at current rates and potentially $5,400 in future. When receive terminals can be purchased for several thousand dollars and interactive image analysis terminals for possibly $50,000, the capability for interactive analysis should be within range of many agencies.
5. A high data rate channel, such as the 30 Mb/s rate given, can provide much faster response in interactive image analysis without great increases in space segment costs, provided a sufficiently large number of agencies participate. However, high receive terminal and associated data handling costs will keep costs out of range of many agencies.
6. A dedicated 1 Mb/s channel could be utilized strictly for interactive image analysis. For example, for 10 agencies interacting with a regional centre, annual present space segment costs per agency would be $10,000 and transmit costs $16,500. Both could drop in future to $7,100 and $7,000 respectively.

7. Use of a dedicated 1Mb/s channel for only raw data broadcast involves substantial present space segment costs in the order of $16,700 and uplink costs of $27,000 for transmission to 6 agencies, and double those costs for 3.
8. The cost of augmenting a host facility to accommodate another terminal (provided it has expansion capability), purchase of a terminal and satellite data receive capabilities is less than most stand-alone image analysis systems. Terminals provide access to extended analysis capabilities and data bases.
9. Communications satellite considerations support the concept of a considerable degree of centralization in terms of site(s) from which raw data is broadcast within a region and/or where host image analysis facilities are located. A single site for redistribution of raw data is preferable from a communications satellite viewpoint, possibly with a co-located host image analysis facility. The effect of sharing transponder costs is seen, for example, by costs per receive station of about $55,000 for 3 receive stations, $27,500 for 6 and $16,500 for 10 with possible future reductions to $23,300, $11,700 and $7,000 respectively. A scenario therefore with 10 remote terminals to a regional centre facility and 3 and 2 terminals linked to two regional disciplinary agencies would give annual uplink costs in the order of $16,500, $55,000 and $83,000. Where a small number of remote terminals were involved, alternative communication links eg. Datapac could be utilized to keep costs down (see 4-3), or stand-alone analysis facilities could be more cost-effective.
10. The importance of communications on the centralization issue has a geographic dependence. Alternatives to satellite methods, particularly landline, between centres of interest can be reasonable in cost in some areas for example in Ontario and very expensive in others, for example in British Columbia. High alternative costs make stand alone analysis facilities or multi-terminal (more than 5) facilities using satellite communications more favourable.
11. Tables X and XI both consider 1.544 Mb/s rates as this is now a standard transmission rate in major Canadian cities.
12. Although present regulations require leasing or receive terminals and contracting with common carriers for uplink, it is posssible that within 5 years receive terminals could be purchased. If transmit terminals could also be purchased, one estimate of potential cost was $235,000. Therefore, for example, 10 agencies having remote terminals to a central facility could share capital costs at $23,500 each.
13. Table XI assumes rebroadcast of 0.5 to 2 scenes out of a total of 5 incoming scenes daily. This is selected cloud-free data required by agencies with receive capability. In the table, transmit costs are shared between 3, 6 or 13 agencies the latter including 3 agencies with stand alone image analysis capabilities and 10 with interactive terminals. This is considered a "medium-term" scenario. In the long term as receive terminals, storage and display costs decrease

more agencies will wish to receive and display data locally. Moreover, broadcasts from a central agency may include not only raw data, but some standard change or enhancement products. For example, a forester with a display in a field office could be directed to identify change on the basis of such information products, and communicate his findings to a parent agency with analysis capability either local or remote. Since the time required for broadcast of one TM scene is 28.7 minutes at 1.544 Mb/s, several scenes a day of special information products could be communicated if required without significantly affecting interactive image analysis activities. All shared costs decrease with increases in participating agencies, with transmit costs at present rates for 25-way sharing dropping to about $6,600 annually.

An alternative to central production of special enhanced or other information products is limited processing capabilities associated with display capabilities even at nodes near network extremities. Raw satellite data would still be required by these agencies who would share in satellite communications costs.

14. Although a high data rate link is desirable for transmission of image data from host to terminal, the opposite communication flow will usually be by low speed terrestrial links.
15. Although a multi-interactive analysis terminal approach is favoured by satellite communications, development work is required to assess the terminal loading that a host facility can effectively support in an operational environment.
16. Use of 1.544 Mb/s rates throughout the system both for national and regional transmissions would provide an advantage of compatibility with existing intracity lines.
17. Research and development is required in remote terminal-host interactive image analysis. By providing raw data to both locations so that terminals at both locations can view the scene image, methods may be developed to reduce the data needed to be transmitted so that only interactions, changes, etc. are transmitted.

4.5 Data Rate Communications Links within a City

Dedicated terrestrial high data rate links between agencies within a city or over ralatively short distances could use co-axial cable, copper pairs, microwave links or fibre optics. Co-axial cable has higher immunity to noise than twisted pairs, ie. about 10^{-9} vs 10^{-5} or lower (ie. 1 bit error in 10^5).

Datapac and Dataroute have errors in the order of 10^{-6}. Optical fibers have very high quality transmission. Microwave links have reliability problems (fading).

Linking up agencies to shared trunk lines whether they be LD1 lines (1.544 Mb/sec), co-axial cable or, in 5 to 10 years, fibre optics, requires installation of dedicated local loops. Installation costs of the latter might vary from as low as $1000 per mile for twisted pairs where existing conduits are used to over $25,000 per mile for cable where there is no line now. Co-axial cable links for broadband transmission, requiring repeaters and special terminal equipment are expensive. A tentative quotation for a dedicated leased 5 MHz video channel between CCRS and CRC, Shirley Bay (25 to 30 miles) was $1454/month. Considerable new outlay ($0.5 million or about $17,000 per mile on average) would be involved to extend existing lines and lay in existing conduits although considerable rebuilding would be necessary. The installation cost per mile for new line would exceed $17,000 as several miles of line exist in the downtown area. If conduits do not exist and trenching is required, those costs exceed $5,000/mile. The economic feasibility of laying a line such as the CCRS-CRC line depends on the overall demand for services, and in this case the line will not be laid at this time. Twenty seven video channels were planned for the line. The alternative cost for a microwave link from CCRS to downtown to CRC was quoted as $2350 per month ($28,000/yr). If an individual user had to shoulder much of the installation cost to extend a service to his location, the costs noted above are considerable. The general demand for this type of service is increasing. It may be anticipated that a lease cost for a high quality video channel to another agency within a major city could therefore be in the order of $1000 per month. Although many variables are involved, Bell Canada staff provided an approximate channel lease rate estimate of $20 per quarter mile per month for a video channel. Channel lease cost would therefore be in the order of $400/month ($4,800/yr.) for a 5 mile line and $1000 ($12,000/yr.) for 12.5 mile.

Transmission quality and bandwidth will increase with fibre optics, and real costs and therefore lease rates should be less given their capacity and cost of installation. Fibre optics should impact the cost of local communications. It is expected that within a few years it will be possible to run a glass fibre to a subscriber for the same cost as copper pairs. Considering the bandwidths possible, transmission costs especially for these high data rate applications should be less. Transmission rates of 50 Mb/sec (current trials) to several hundred megabits/sec (in future) can be expected, with switching probable ie. packets of

50 Mb image data (1000 x 1000 pixel, full resolution data) could be transmitted.*

In experimental trials at London, Ontario 300 Mb/s rates are used for each fibre, with repeaters spaced at 4 km separation.+ Comparable co-ax repeater spacings are 1 km. Trials in Japan have achieved fibre optics transmission at 33 M bits over 50 km distances without repeaters. Transmission at 50 Mb/s over a 10 km distance without repeaters is therefore quite probable in the 1985 time frame. Transmission quality is high with error bit rate of about 10^{-9} to 10^{-11}.

For digital transmission at high bit rates, fibre optics is a favourable method. Costs to pull fibre have been estimated at $5-6k per km compared with about $10 k for co-axial cable.+ Early cost comparisons with alternatives, showed fibre to be economically favourable above 6 Mb/s rates and costs of the new technology have decreased since that time. The factors above point to fibre optics as the transmission method for high bit rate digital transmission over relatively short distances.

It is likely that beyond 1985, requirements for urban high data rate transmission will be satisfied more and more by fibre optics, and feasibility of providing this service and cost to a user in a particular location will depend on trunk lines already installed and the dedicated local loop required to patch into existing lines. The high capacity trunk lines, even for this high data rate application, would be shared. An "average" channel lease rate of $400-1000 per month is used in the analysis. This assumes an adequate demand for wide bandwidth services. It may be high when fibre optics networks develop extensively. The figure applies to high data rate transmission between agencies within a major city. Satellite transmission costs are used for data transmission between cities. Alternative high data rate and landline costs are very expensive, and microwave costs are quite expensive (eg. $28,200/yr. given above for 25 mile communication).

+ K. Hill, Communications Research Centre, private communication.

4.6 Impact of Integrated Information-Communication Systems on Resource Information Networks

Present technology trends are to a synthesis of communications and information systems. In the past several years networks of computers and large time shared information systems have been constructed which are dependent on communications networks. The trend to integration of information systems and communication systems is beneficial to the user, who now has to overcome interface problems with respect to the compatibility of communications and information technology. It has been suggested that eventually the two systems may become a fully integrated comprehensive information-communication system with completely digital transmission which would be reached through a single multi-purpose apparatus available to everyone.* "The long range prospect is one of a completely digital transmission and computer switched telecommunications network that will be far more reliable and more economical than the present electro-mechanical network."+

Hiltz and Turoff note that "...the key technological advances have to do with decreasing the cost and increasing the reliability of existing technology, more than with making new breakthroughs. These key changes in the economics of computer mediated communications-information systems will occur within the next decade."** Their book on computer conferencing, ie. systems that use the computer to mediate communication among human beings, forecasts price reductions in computers and terminals as industry pursues the mass public market. Accompanying communications cost reductions are likely as a public need for digital communications is recognized as opposed to current business-use-only assumptions. Policy and regulatory decisions are expected to be major factors. Decreasing computer and communications network costs are therefore expected to stimulate widespread use of computer-mediated communications systems over the next decade.

There are several driving forces which may influence proliferation of these systems. One is saving of energy and time. This may occur in many areas of society whether it be industry workers performing their work using computer and communications technologies at locations closer to their homes, or resource managers carrying out their responsibilities at a local office rather than commuting

** "Information and Communication: Is there a System?", J.C. Cohen et al, NATO Symposium on Telecommunications, Plenum Press, 1978.

* "The Network Nation: Human Communication Via Computer", S.R. Hiltz and M. Turoff, Addison-Wesley Publishing Co., Reading, Mass. 1978.

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to other locations. The trend to an information based society recognizes the economic and other values of information, and the importance of access to information for decision making.

An important concept in computer networking is that of a switchboard computer which communicates with other computers and facilitates resource sharing and network transparency from a user point of view. This concept is being incorporated in an Electronic Information Exchange System (EIES) for Scientific Research Communities sponsored by the U.S. National Science Foundation.* A microprocessor (referred to as Hal) has been programmed to engage in the computer conference system with the same powers of interaction as any human member, and with tasks including the following: it may enter EIES and receive or send messages or retrieve and enter items into the other components of the system; it may exercise certain analysis routines or generate display graphics from data provided by other EIES members, and return the results to them; it may phone other computers and select data from existing data bases or obtain the results of a model to send back to any designated group of EIES users; it may drop off and pick up communication items from other conference and message systems. The microprocessor facilitates bringing together and utilizing many differing computer resources. "An individual knowledgeable about a particular computerized information resource now becomes ... the transponder for the group as a whole. That is, only one member of the group need be familiar with a particular computer model or data base. That person can utilize Hal as an agent to obtain information and/or data from the resource for the benefit of the group as a whole. The result is a mechanism for the group to produce a collective wisdom or knowledge base. As a result...the EIES system is a communication system that is inseparable from the capabilities we normally ascribe to a computer system." The user therefore sees a multitude of services as one system. The potential of these technologies for an integrated but decentralized resource information system is evident.

A major advantage of information networks is the sharing of capabilities, both expertise and data processing and analysis. Networks that will make available to scientists any resource stored on a computer should result in a greater participation, for example, by university scientists in environmental modelling as they could have access to data and much better analysis tools. This will permit bringing human resources more effectively to bear on resource and environmental problems. It will permit bringing group expertise together in new research areas,

* "The Network Nation: Human Communication Via Computer", S.R. Hiltz and M. Turoff, Addison-Wesley Publishing Company, 1978.

to provide collective intelligence and judgements in the evaluation of complex problems. In modelling and simulation studies, computerized conferencing may help in the formative process, in execution of a simulation, and in the evaluation and assessments. In the formative phase there is opportunity to provide interfaces between modellers and decision makers, and a range of data processing capabilities is available to specify model assumptions and structures easier. Because of the difficulties in applying analytical techniques to real-world decision processes that take into account all relevant factors, conferencing can assist in simulation. Finally it assists in evaluating the results of the model. Several advantages of group collective intelligence have been listed * including: improved performance (eg. accuracy) through redundancy ie. checks on output; pooling of information unique to individuals; partitioning of work; stimulation of new or different intra-individual ideas; and intra-individual motivation. The ability of two or more individuals to interact in resource and environmental analysis and decision making should frequently improve the quality (accuracy, completeness, timeliness) of results obtained.

As data processing costs decrease and labour costs increase, the requirement is more for human optimization than for most efficient machine use. These trends are against centralization of computers in an organization and general purpose computers which perform all tasks. These practices tend to drive up software and people costs which are now the majority of total costs of computer systems. Decreasing computing costs mean that is is not necessary for computers to work at full capacity. Software development is required to provide capabilities more directly suited to the requirements of the end user.

* "Group Performance", J. Davis, Addison-Wesley Publishing Company, Reading, Mass., 1969.

5 Some Functional Requirements Considerations

Operational resource management problems influence applications division activities including image analysis research and development. Identification of those problems and the potential assistance of remote sensing methods in solving them, is required in assessing the requirements of an information extraction facility.

Previous CIAS-related activity led the way in Canada in terms of achieving a strong capability in image analysis. A new information system for research and development is required to utilize effectively new data from second generation earth resources satellites and to satisfy new evolving requirements in information extraction capabilities. The demands that image analysis capabilities will face in the 1980s include:

1. New types, rates and quality of satellite data:

Stereographic multispectral data will be available by 1984, and microwave data from satellite-borne synthetic aperture radar and from higher resolution microwave radiometers than previously utilized could be available by 1985. Data volumes from LANDSAT-D and SPOT will be an order of magnitude greater than present MSS volumes. Spatial resolutions of 30 m (LANDSAT-D TM), and 10 m panchromatic and 20 multispectral (SPOT HRV), and improved spatial and spectral resolution represent substantial improvements in data quality.

The prospect of increased numbers of satellites and therefore increased number of coverages by the mid 80's, of a greater number of spectral channels per coverage, and of greater data volumes per spectral channel need to be addressed in assessing throughput requirements, as well as the size of geographic area to be covered in different applications.

2. The need to incorporate a spectrum of data integration techniques:

This includes

(a) Combining multitemporal coverages from a specific satellite eg use of several biowindows in crop production studies.

(b) Combining multitemporal coverages with historical data, eg in crop production studies for yield accuracy improvement, or in regeneration study to provide a time sequence of regrowth from cutover to the present.

(c) Integrating archival data of areal, linear or point source form with satellite imagery. For example, this would include digitized soil maps and digital terrain models.

(d) Combining data from different remote sensing sources. This includes (i) combining aircraft and satellite data. Aircraft data could include multispectral scanner data, digitized photographic data, microwave radar data, and other image and line profile data. Aircraft data will generally be high resolution data. (ii) Merging of satellite data with satellite data. This includes merging high resolution with high resolution data eg Seasat-type SAR and Landsat MSS data, and merging high resolution with low resolution data eg MSS with ICEX-type microwave radiometer data or GOES, TIROS, or HCMM data. It can also include merging satellite data of different time scales as well as different space scales.

Because of the incremental nature of information provided in a particular spectral region, a major requirement will be that of combining data from several regions including possibly, visible, microwave and thermal IR channels for such applications as snow monitoring, soil moisture estimations, and vegetation condition monitoring.

(e) Integrating point source reference data with remote sensing data in a monitoring mode. This includes combining a high temporal point source sampling rate (and limited spatial sampling) eg from data buoys or hydrologic data collection platforms with satellite data of limited temporal sampling (but comprehensive spatial coverage).

(f) Integrating boundary data such as administrative district data, ownership boundary data etc. with satellite data so that socioeconomic and administrative information may be merged with environmental and land use information.

3. Greater complexity in analysis algorithms and in modelling capabilities:

Spatial processing, which some consider the single most important aspect of image processing, is of growing importance because of improved satellite resolution and use of airborne data in combined data sets. Filtering, texture analysis, and shape recognition capabilities require development.

The use of high resolution airborne data to supplement the spatial and spectral information content of satellite data, and of more frequent (eg GOES) or more reliable (ie microwave) satellite data or more frequent point source data to supplement the temporal information content of satellite data, requires development of new analysis and modelling capabilities. Models may be required to correlate and interpolate in space as well as forecast in time. Much development is required, for example in hydrology, in modelling and analysis capability to integrate effectively point source and areal data in monitoring and forecast modes.

4. Networking of image analysis facilities and data bases:

Individuals at or near the extremities of environmental information distribution systems such as forest rangers, scientists or observers in field offices, farmers, etc. may have detailed local site specific information. It may be desirable at these levels of the distribution system, or at least at branches of government departments concerned with resources and the environment, to have the ability to evaluate image data on a display terminal, to have a mechanism to input their special information and informed judgements, and in some instances to carry out analysis locally. Remote interactive terminals linked to information processing facilities are needed when access is required to more powerful analysis capability than available locally or to a data bank which would be too costly to transfer and store locally (eg considerable costs may be incurred in transmission of satellite data).

In development of a sophisticated information extraction facility, consideration should be given to remote users including those who may have some independent analysis capability.

5. Requirement for a spectrum of output products:
In an operational environment, a variety of output products will usually be required. Information extracted through data processing may be aggregated at various levels (eg aggregated statistical information). Information utility depends on its availability in the form required by the user. A system whose development is concerned with its utility ultimately in an operational environment, must give strong consideration to this aspect.

6. Interface with geographic information systems:
There is an immediate requirement for image analysis sytems to provide output products to existing polygon or grid structured information systems. Because of the costs of update, data overlay, and interrogation, these systems have generally been developed and utilized for policy and planning purposes. Research is required into geographic information systems for day-to-day operational resource management applications, which include an image analysis system as one component of a linked information system involving multisource inputs and modelling capabilities. (Dynamic models include for example hydrologic, forest fire, crop yield, crop disease and weed spread, water and air quality.)

Because a particular spectral band of remotely sensed data generally provides only incremental information, its ultimate utility in resource management operations depends on data and information integration. Multisource, multitemporal, multispectral and multispatial data may be required to give a <u>convergence of evidence</u> providing adequate information for decision making.

A pioneering image analysis facility should provide experience in various merging and analysis operations clarifying which could readily be incorporated in less expensive stand alone systems, and which would best be incorporated in a centralized system possibly with remote access capability and/or large on-line data base storage.

Anticipated User Requirements

6. Forestry

In addition to analysis techniques that have been prominent in remote sensing related forestry research to date, including use of multitemporal multispectral data in cover type and condition analysis and use of selected airphoto and ground sampling in multistage sampling analysis, several other important techniques have begun to be used or will be used in future. These include: merging of other baseline data particularly topographic and soils data with forest cover data; integration with forestry data of climatic (inventory analysis) and weather (forest protection studies, fire and disease spread models) data, the latter involving use of meteorological satellite data; and development of algorithms to utilize increased spatial information in higher resolution satellite data. A forestry study involving degradion of the spatial resolution of aerial photography found that at a ground resolution of about 15 meters there was a jump in information content with detail added on shape, size, texture and shadow characteristics within each vegetation type.*

6.1 Forest Inventory Requirements -

Benefit estimates indicate that a conservative estimate of the additional value of an accurate forest inventory in Canada just to industry would be $25 to $38 million annually. Canada has 806 million acres (i.e. 1.26 million square miles) of forest land. Inventories that have been made show geographic inconsistencies (particularly from one province to another) and are often out of date by 10 to 20 years. In several provinces, allowable cut determinations are based on both firm and shaky data resulting in a lack of confidence in the data. Two levels of forest inventory for Canada may be considered - a regional inventory for forest areas which are not economically viable (particularly northern areas), and a more intensive inventory for those areas suitable for harvest. The areas involved are about 475,000 and 785,000 square miles respectively, the latter including some areas that may be allocated to wood production in future.

Multistage sampling methods using satellite and selected airborne and ground data have been found to be cost effective. Landsat data is used in the precise stratification of the forest area, permitting selection and location of sample units. For timber volume inventories the success of the technique, particularly in complex structured areas, is expected by many to be improved with Landsat-D data. The success of the method has also been found to sensitively depend on the ability to relate accurately geographically the satellite airphoto and ground data (i.e. a sampling requirement is the ability to get into the pixel being sampled).

* "Information Content of Simulated Space Photographs as a Function of Various Levels of Image Resolution" D.T. Lauer, R.R. Thaman, Proceedings of the 7th International Symposium on Remote Sensing, Ann Arbor, May 1971.

Inherent limitations in the spectral and spatial information content of Landsat MSS data leading to often unsatisfactory species-specific forest cover classification accuracies should be reduced as noted in the opening paragraph by development and utilization of spatial analysis techniques which take advantage of new high resolution satellite data. (Also Landsat-D spectral bands have been chosen to give improved vegetation discrimination.) Classification accuracies have also been found to be improved by exploiting ecological preferences of species. Forest cover is determined by topography, soils and climate. Since the type and density of forests are affected by the slope and aspect of the surface, and by elevation-related variations in precipitation and solar radiation, it is helpful to include these types of collateral information in the analysis method. For example, one study found species-specific classification accuracies to be increased by 27% through use of topographic (elevation, slope, aspect) information. Likewise specific types of soils and climate would affect the probability of occurrence of particular species, and could be incorporated in the analysis procedure. Site quality, watershed, cultural, and ownership data are also valuable ancillary data. These types of reference data merged with Landsat data provide more efficient stratification, improved classifications, more detailed summary output and more accurate and specific forest inventories.

Although the applicability of Landsat data for regional inventories has been demonstrated in several cases, its utility for detailed inventories for management purposes requires much more investigation. In producing a baseline inventory using satellite data in combination with other information, considerable airborne and ground data are necessary to achieve high accuracies. Once established, however, considering the forestry characteristic time-constants and the satellite change detection information (identifying gradual or abrupt change), subsequent supportive information should be much more selective in terms of site and type. Satellite data should provide a large contribution to the continued accuracy of an inventory once established.

Economic factors and environmental constraints are increasing the value of forest inventories to industry. Some of their requirements are as follows:

- accurate location of new logging edges and area of cutovers. These are required to satisfy government regulations and/or to upgrade their own inventory.
- location and acreage of burns, blow down, disease or disease vulnerable areas. Company operations in a particular area are limited by access, so a lead time is required for road building. Knowledge of incipient disease or vulnerable timber may influence logging plans so that stands are harvested before they

become decadent. Similarly early detection of fire and blow down areas may enable a company to salvage timber there before it becomes too decadent. Alternatively, the information may flag planners to avoid these areas in planning road networks for harvest operations.

- location of transportation routes, seismic lines, pipelines, well sites, rights of way, other cultural data.
- knowledge of varying terrain types and the accompanying timber growth. This is required for road planning and long range equipment development and acquisition strategies.
- knowledge by location of wood volume, species, age, condition, maturity. Confidence in investment and company expansion, optimized road network layout from a construction and haulage point of view, and harvesting strategy according to species marketability are all dependent on accurate inventory information.

It may be noted that while some forest inventory data requirements (eg age, maturity) may be better satisfied by satellite data as an historical data bank is developed, other requirements could be modified to be satisfied by satellite data. Perceived user needs are often influenced by the data that is available. For example, Washington Department of Natural Resources have noted that in their inventory studies a subjective definition of old growth as trees greater than 96 years of age was used. A redefinition to 135 years where marked spectral differences exist would have resulted in a more accurate stratification of the study area.

6.2 Forest Protection -

Because of the high costs associated with "crisis" forest protection, methods are sought which will minimize the requirements for this, and make response more timely and effective when control is necessary. Forest fire damage and control costs total at least \$100 million annually in a \$30 million/\$70 million ratio. Disease damage and control costs are more difficult to estimate (budworm spray cost ∼\$30 million in 1976 and damage of multimillion dollar value).

Information required in forest fire control includes

- forest fuel maps depicting slash, disease, burns, blow downs, tree species etc. This helps determine how rapidly the fire will spread. Information on the value of the timber (type, age, volume, maturity, condition, etc.) aids in fire fighting priorities.
- other cover type information including location, age and condition of roads, and the proximity and accessibility of water which can act as a barrier to fire spread and be used in control.
- terrain information. This is of assistance to ground crews, and topography is an important parameter in fire spread models. Topography influences local wind conditions and therefore moisture and fire spread.

- forest fuel moisture. Factors which influence this include amount of winter snowfall, time of snowmelt, time and volume of spring and summer rainfall, rate of evaporation and evapotranspiration.
- meteorological data. Accurate weather information is the key to anticipating severe forest fire situations, and intensifying reconnaissance as well as control preparations.

When a fire is in progress, monitoring its location in the presence of smoke by using sensors operating in the thermal infrared spectral region is required for control.

Because of the time required to plan and execute management decisions, (eg build a road in to salvage timber, or even to launch a spray program), early detection of disease outbreak is important. Once outbreak is detected, local monitoring can be intensified for example to delineate area and extent of infestation, survival over winter and dispersal. Remote sensing methods may be capable of either showing host conditions favourable for outbreak (eg moisture or other stress conditions), or host stress conditions once initial buildup has occurred but before there is significant dispersal. Delineation of disease areas before significant spreading permits cost effective selective control eg controlled burn, cutting, selective chemicals.

In addressing forest disease problems, the need for proper forest management is becoming increasingly recognized. For example in the spruce budworm problem, once host conditions become favourable eg balsam fir reaches an age of perhaps 45 years (note: dependent on climate and site conditions), the "stage is set" for an outbreak and risk increases as the fir ages. Spraying may only delay the problem. Also the effects of increasing human intervention, particularly in suppressing forest fires, are not fully understood and may in some cases aggravate forest disease problems. An objective of satellite monitoring where that information on dynamic vegetation and moisture conditions is combined with archival and selected ancillary sampling data, is to provide a better understanding of natural and human intervention cause-effect relationships so that management practices may be adjusted accordingly. In the case of spruce budworm, a remote sensing overview detecting areas of outbreak and followed up by ground sampling, could help answer questions related to the existence and size of epicenters, whether such epicenters may occur "simultaneously" in several regions according to weather conditions and other factors, and vital questions with regard to population buildup and dispersal.

In addition to detection and identification of disease and disease-susceptible areas, the same basic information as for forest fire protection (ie tree types and condition, moisture, climate and weather information, terrain information, etc.) are required for disease and insect protection.

At present, visual observation from light aircraft is the principle method used to delineate diseased areas to determine where spraying should be carried out. This method and sometimes aerial photography are used to direct salvage operations. The requirement is delineation of areas of various levels of severity of infestation. Satellite data of improved spectral and spatial resolution and observing conditions at the right time may be adequate for this purpose.

6.3 Regeneration, Site Quality, and Classification -

Regeneration, which is central to forest planning and management, is receiving more attention because of identified threats to timber supply in some regions. Site specific information is needed therefore a great deal of ancillary information is required with satellite data. Baseline data requirements for an ecological understanding include landform, soils, water, vegetation and climate. An ecological classification is required when prescribing site preparation treatments, selecting tree species, defining seed collection zones and prescribing management action to preserve site quality such as fertilization or irrigation.

Monitoring following human and natural disturbances including logging, clear-cutting, fire, pests, grazing or browsing assists management practices including how to increase stand yield, to minimize disease occurrence or to influence a particular succession pattern. It is required to assess the adequacy and rate of natural or artificial regeneration, to determine species and competition, to assess site preparation and effects of application of herbicides and insecticides. Monitoring the effects of disturbances assists in understanding the ecology of a region. The seasonal timing of data acquisition will usually be important. Satellite resolution improvements will assist in monitoring earlier growth stages, but considerable ancillary data will be required.

Natural resource management in large areas must be based on long term ecological planning which presupposes a knowledge of the dynamics of the ecosystems involved. Repetitive monitoring should assist in more effectively incorporating the "time dimension" in ecosystem descriptions and prediction of impact effects. An ecological classificiaton should be applicable for wildlife and range considerations, assist in decision making at site specific levels, and assist planning at broader levels. Resource conflicts are becoming more important. Evaluation of forests for potential other than fibre production includes estimates of tolerance to recreational activities.

Vegetation helps in recognizing and delineating ecologically meaningful units. The nature and importance of factors controlling the vegetation pattern change with scale. eg

- scales $\geq$ 1:500,000; controlling factors include regional relief, range of parent material and regional climate (snow cover, precipitation, temperature, etc.)
- scales of 1:50,000 to 1:250,000; factors include fertility, texture and depth of parent material, range of moisture regimes and microclimate. Satellite resolution improvements can permit recognition of new units with different environmental controlling factors. It may be desirable in an information system to generalize or aggregate up from one level to another eg from a detailed site specific classification to a regional classification.

Interfacing with Forestry Data Bases-

"The greatest need now is the cooperation of public and private agencies in developing a comprehensive data base. A cooperative data base will be cost-effective because one series of classifications and one storage of the data base will serve a multitude of users."* The need is to proceed by an iterative and convergent approach, to develop a data base with products at required levels of processing and aggregation to be used in management decision making.

* "Forest Inventory with Landsat, Phase II, Washington Forest Productivity Study", R.A. Harding, R.B. Scott, State of Washington Dept. of Natural Resources, April 1978.

7. Agriculture

Remote sensing may be used in agricultural applications to assist in production estimates at a regional, national, or global level (primarily using sampling techniques), or for providing information on a field by field basis. The former is useful for production and marketing decisions while the latter is useful for farm and land management decisions.

The U.S. LACIE experiment is the foremost example of a complex information extraction facility to provide information on a large area basis. It provides information on the wheat growing regions of 8 major wheat growing countries. Sampling techniques are used. Because of the large area over which information is required and the dynamic and complex nature of the application under investigation, many techniques have been developed in fast and complex information extraction, and management of very large data bases and their interface with information extraction facilities. A related and similarly imposing problem would be development of a domestic crop and land information and management system utilizing monitoring techniques. The need for such a system may increase as food prices rise, environmentally-appropriate agriculture is stressed, and fine-tuned management decisions to achieve objectives of sustained or increased production become more complex. Comprehensive monitoring of national farmland areas would present information systems with severe challenges. This section outlines some of the information requirements of both global crop production forecast systems and national farm information systems to provide a perspective of information management requirements.

Although the LACIE program has achieved a significant level of maturity towards an operational forecast system, efforts to obtain high accuracies and to provide suitable information products to users will likely lead to increased complexity in information management. A JPL study notes that a complex mix of systems will probably be required including: data acquisition over extended spectral regions out into the microwave region; a variety of spatial resolutions; and better cloud-free coverage at critical times. These same requirements are evident in the section on farm management. Information extraction facilities will require modification to accommodate new spectral regions, a range of spatial scales, and increased coverages. (The requirement to accommodate a wide range of spatial scales down to high levels of detail should be more severe for domestic agricultural applications.)

The total area of occupied farmland in Canada is about 170 million acres, of which about 109 million acres are improved land. Other acreages of interest include:

Total crop acreage $\simeq$ 70 million acres

Total prairie crop acreage $\simeq$ 55 million acres

Total prairie wheat acreage $\simeq$ 27 million acres

Total prairie oats and barley $\simeq$ 16 million acres

Total fallow acreage $\simeq$ 27 million acres

Total prairie fallow $\simeq$ 26.5 million acres

Total Canadian potatoes $\simeq$ 0.3 million acres

Total Canadian tame hay $\simeq$ 13 million acres

Total Ontario corn for grain $\simeq$ 1.5 million acres

7.1 Applications of Remote Sensing in Crop Production Estimates

Potential benefit studies have estimated benefits of global wheat forecasting as possibly several tens of $ million annually. Barley and oilseeds are other large export products. The value of the 1978 rapeseed crop was about $1 billion.

China and USSR have a combined wheat acreage of about 230 million acres compared with 27 million acres in Canada and 53 million acres in the U.S. Wheat production estimates for large grain producing countries, particularly China and USSR are currently very inaccurate. Forecast estimates for other grains and oilseeds are generally poorer than for wheat. Development of a global crop information system initially for wheat would be expected to assist in providing generally improved information on crops worldwide. The process of obtaining detailed information on such parameters as soil-moisture and meteorological conditions favourable or unfavourable for wheat production, could assist in forecasting production of other crops.

In addition to information required for the annual marketing of grains, information is required to assess the grain growing potential of developing countries. This would assist long range planning (eg influence decisions to develop high protein crop

(i) Global Wheat Production

The emphasis in the U.S. LACIE program has been on more timely and accurate estimates of foreign wheat area, yield and production on a scheduled basis throughout the growing season. The data processing system in support of the LACIE program was originally scoped at 4800 segment capacity, each 5 X 6 mile in size, from 8 countries. A 14-day segment throughput was specified including 5 days for acquisition and extraction, 4 days preprocessing and 5 days analyst processing. (The nominal LACIE processing time for all phases without backlogs was approximately 30 days. The average throughput time including backlogs in Phase III was 50 days.)

Specifications for the LACIE ERIPS (Earth Resources Interactive Processing System) data base included: sufficient size to store 4 acquisitions for 3840 sites, 16 acquisitions for 960 sites making a total of 30,720 acquisitions. Of the data bases on-line during a support period the image data base had the most severe requirements of 2.9 billion bytes (94,790 bytes/acgn, for 30,720 acgn's), the fields data base had requirements for 85.7 million bytes (17,860 bytes/site X 4800 sites), the history data base for 3.9 million bytes and the process control data base for 280,000 bytes.

Global production estimates involve use of multiple data sets and of modelling techniques. A data base for a worldwide multicrop information system would include:+ crop samples, digital imagery (Landsat and variable format), classification data (fields, dots, class maps, masks), meteorological data (both daily and monthly station and grid cell data), agronomic data (soils, cropping practices), historical data (meteorological, agricultural production), crop assessment, and status data. Models used in production estimates include phenological models for calculating dates of crop development events based on in-season environmental conditions (agrometeorological data such as temperature, day length, precipitation, wheat type, etc.); and yield models which include monthly weather variables for a region calculated as the departure from their long term averages. Variables include precipitation, temperature, degree days above 90^{o}F and potential evapotranspiration. Models are under development which use daily weather variables, a versatile soil moisture budget (for improved estimate of plant available water), and combined Landsat and Metsat data. Objectives of new yield models include increased capability to utilize additional information sources such as soil surveys, nitrogen use models, pest models, soil moisture models and crop calendar models. Data bases therefore would include soil fertility, soil moisture, crop calendar, insect and disease damage, spectral reflectance and radiance and observations. Variables in crop starter models include average daily temperature, total daily precipitation, and the time difference between the normal planting date and the actual date.

A variety of crop-weather models using different designs and/or input variables have been developed and applied. Baier notes that their usefulness is limited by uncertainties in the meteorological modelling process.* Also if too many weather

* "Information Requirements for Regional and Global Operational Systems in Agricultural Meteorology" Earth Observation Systems for Resource Management and Environmental Control, Plenum Press, New York, 1977.

+"Briefing Materials for Technical Presentations" The LACIE Symposium, L.B. Johnson Space Centre, October 1978.

variables are used in multiple regression analysis, the coefficients become unstable. The models may contain primary meteorological input data or derived data. Primary meteorological data include precipitation, maximum and minimum air temperatures, relative humidity, solar radiation, sunshine or cloud cover, and wind. Derived or agrometeorological data developed from primary data include potential and actual evapotranspiration, soil moisture, heat units and their derivations, and indices of heat, cold or moisture stress. In addition to meteorological data, astronomical data such as daylength or solar radiation at the top of the atmosphere may be needed.

The major application of Landsat data to date has been in the acreage component of production. Crop types are differentiated using spectral data and data related to the phenological cycle (crop calendar data). The improved texture information provided by Landsat-D and SPOT may aid in crop differentiation. From Landsat-type satellites an assessment of current crop conditions on a large area can be obtained for known soil/climatic regions. An early indication of deviations from average conditions for a particular date can be determined which complements and verifies results from weather based growth equations.* Research has shown significant Landsat-yield correlations that are crop calendar dependent. However, combined agrometeorological-spectral yield models require further development.

The two primary environmental determinants of crop yield are temperature and moisture. Idso et al have developed a stress degree day concept which makes possible crop yield estimates from remotely acquired crop canopy temperatures and auxiliary air temperature measurements obtained during the period from head emergence to the cessation of head growth.+ They believe the method in combination with LACIE-type acreage estimates, could form the basis of a system for the remote surveillance of crop production.

(ii) Domestic Production Estimate

Current statistical results may be adequate at the national level (because of cancelling out of errors) but quite inaccurate at the local level. Improvements may be possible even at the national level. For example, optimistic estimates of achievable performance in the U.S. where considerable historical data exists, are for yield accuracies of 98% and for acreage estimate error reductions down to about 1% even at the state level.

+ "Remote Sensing of Crop Yields", S.B. Idso, R.D. Jackson, R.J. Reginato, Science, Vol 196, April 1, 1977.

* "Information Requirements for Regional and Global Operational Systems in Agricultural Meteorology", W. Baier, Earth Observation Systems for Resource Management and Environmental Control, D.J. Clough and L.W. Morley eds, Plenum Press, 1977.

Higher resolution satellite data should extend the applicability of the data to smaller fields and special crops such as potatoes.

It may be noted that difficulties have been experienced with current satellite data in separating some important crops such as barley and spring wheat. Although resolution improvements will help, good discrimination may require acquiring data within a particular period at 2 or more closely spaced dates (assuming satellite data is eventually available to provide this). This requires adequate data processing capacity during those peak periods.

Monitoring yield reductions caused by such production reducing factors as fertilizer deficiencies, insect damage, moisture deficiencies, damage by climate, and crop diseases would assist local production estimates. (This would also be of benefit to local planning for operations related to crop harvest and protection.)

Crop production depends on the water budget. Water supply inventories coupled with water demand estimates and water application practices are important in the efficient prediction of crop yield. Water supply requires information on precipitation, ground water and surface water. Water demand requires information on crop area by species, climate time and crop phenology to estimate crop use of water with time the rates of evapotranspiration, and presence and efficiency of irrigation. Thermal remote sensing data has applicability in surveys of irrigated areas and as input to models for predicting potential evapotranspiration. Crops require an adequate water supply which depends on the stage in the growing season. If the required water supply is not available, reductions in total yield can be predicted.

7.2 Improved Farm Management

7.2.1 Crop Management

The rather coarse resolution of Landsat MSS has been suitable for monitoring the "integrated" response of crops on a field by field basis (for large simply-structured fields), and thus useful for broad scale inventory and monitoring applications including crop identification and acreage estimates. Improved resolution should facilitate monitoring crop conditions within fields. In most cases the farmer is on site and has considerable knowledge about his fields and how they respond to specific management practices and weather conditions. However, a regional crop information and management system could gain acceptance as the weather service has, as a supplementary source of information for decision making. Communications improvements (eg note the fiber optics test project in Eley, Manitoba) as well as information acquisition and integration improvements could stimulate development of such a system. Management requirements at the individual farm level should therefore be considered.

In the short term for farm management, information is needed which will assist in planting, fertilizing, cultivation, spraying and harvesting decisions. Sound decisions generally result from farming experience and "normal" weather conditions. Unfamiliar conditions whether due to anomalous weather behaviour, extreme insect or disease events, or different cropping patterns, cause more problems and supplementary information may be needed. Management action as a result of early growing season information could include chemical application or addition of fertilizer to yield-retarded or damage-susceptible patches.

For longer term management, a thorough analysis of crops of the previous year, eg of stress conditions, of yield per field, of yield variations within fields, of disease and weed areas, of moisture excesses and deficiencies, can all influence management actions. Similar information acquired over several years influences long range management plans. A farmer may not have a full perspective of patterns and boundaries of such conditions, although he generally has considerable information about his fields, particularly overall productivity and extreme low production areas. Management actions for example could involve drainage or irrigation, fertilizer or herbicide application to selected areas, or changed crop or tillage practice.

Some requirements related to crop management include:

(i) Land Management for Sustained or Increased Crop Production - This is discussed in section (2).

(ii) Information to assist short term management decisions - Decisions on planting, fertilizing, and harvesting are heavily dependent on weather information.

Soil moisture is so important to crop development, vigor and susceptibility to damaging agents that an updated account of soil moisture would be a valuable feature of a crop information system. Some management actions eg a decision to apply fertilizer in a particular concentration, would be influenced by this.

(II) Crop Protection

Annual prairie cereal crop losses include: for weeds in the order of 15 to 20% ($475 to $635 million value); for insects and disease in the order of 7.2 and 12% for wheat, 6.9 and 7.5% for barley and 5 and 6% for oats. There is a requirement for early damage detection or alerting of "state of vulnerability" (the latter dependent on such factors as crop variety and growth stage, soil conditions, moisture levels etc.). Satellite data could be used either for direct monitoring of the existence and progress of damage conditions, or as an input to a predictive model (with meteorological, soil moisture, and other variables) which would assist in deployment of other forms of tactical surveillance such as ground sampling of insect population counts or disease spore data.

- Weed damage - Current weed surveys to assess the abundance and distribution of weeds and to assess yield losses, rely on sampling methods. More appropriate sampling and expansion factors would be of assistance to these methods. Although satellite data will be limited in direct detection to very heavily infested areas, it could provide input to weed spread models which include several information inputs - weed counts, soil conditions (moisture, temperature), and weather conditions. Management decision models which influence decisions to selectively spray, cultivate or rotate crops would include these environmental factors, cost and effectiveness of various control methods, and value of crops.
- Insect damage - Benefits would come from early detection of infestation, detection of conditions favourable to outbreak of infestation, and development of management practices to reduce the probability of outbreak. Early detection requires frequent surveillance when weather and crop conditions are appropriate for outbreak to occur. For example, grasshopper damage tends to occur in dry weather, and aphid damage under humid conditions. Reliable 3 day monitoring would be required for grasshopper monitoring, and daily coverage for fleabeetles and aphids. A detection system could involve meteorological satellite data and ancillary data (other weather data, processed information products eg crop type and model outputs eg soil moisture data, and crop development data) to provide an alarm of favourable conditions, followed by intensive surveillance including selected high resolution satellite data, aircraft data (if satellite data was not frequent enough or of high enough quality),

and ancillary data (eg insect population counts, information on insecticide applications). The functional requirements of an information extraction facility are therefore(1) a 2 level approach with strategic general surveillance of a region directing selected tactical monitoring and(2) the need for timely, cost effective access to selected segments in an image data base and the associated ancillary data. Environmental monitoring should provide a better understanding of how insect cycles and behaviour patterns depend on environmental conditions and cultural practices, and assist development of outbreak and spread predictive models. Yearly monitoring of regions showing where outbreaks occur, the cultural practices (crop rotation, insecticides, etc.) which have been followed in those areas of outbreak, and the weather conditions that have prevailed, will aid understanding of both perennial and cyclical outbreaks, and provide guidance to farmers in their cultural practices and "state of preparedness".

- Disease damage - Information requirements are similar to those for insect damage. Where outbreak occurs and immediate control measures are necessary, potential remote sensing applications include delineation of disease focii, updating of progressive disease boundary limits, and input to disease spread models. Utility of the data will depend on coverage frequency and resolution. Multitemporal data will be useful in monitoring development of stress conditions, and differentiating stress and non-stress areas. It is anticipated that Landsat-D will facilitate detection of stress areas down to 1/2 acre and that new spectral bands and improved quantization will assist detection of stress conditions. Delineation of affected and vulnerable areas will permit more effective ground sampling.

  The effectiveness of short term management practices is dependent on environmental conditions. Information on relevant conditions is required before undertaking control measures. For example the effectiveness of spray for rust control in wheat is weather dependent. Most effective management actions for disease control require a longer planning horizon. These include preventative methods, genetic methods, biological control, cultural and physical methods. For example if root rot is determined as the cause of a monitored stress condition, management procedures could involve application of a heavier amount of fertilizer to the delineated affected area the following spring, or change to forage or other crop.
- Other stress causes - Crop stress caused by frost, fire and floods are expected to be detected by Landsat-D. Detection of moisture stress and nutrient deficiency will depend on spatial extent and availability of adequate collateral data.

The individual farmer makes several management decisions which help to determine the vulnerability of his crops to stress factors. These include type of crop, time of planting, seed purity, cultivation practice, amount and kind of fertilizer, chemical applications, irrigation, drainage, time of harvesting. Information on these practices (in combination with archival and reconnaissance level information) helps determine the intensity of local surveillance required. USDA are implementing an alarm application that will alert the remote sensing analyst to unusual events including preseason soil moisture, drought, late/early freezes, maximum air temperature, minimum air temperature, lodging/harvest problems, planting soil temperature, excessive precipitation and insects/disease/erosion. Threshold values are specific for each grid cell, crop type and crop biological growth stage.

7.2.2 Land Management

Although weather factors will always cause fluctuations in yield from year to year, the magnitude of these fluctuations can be kept to a minimum by optimized management practices. Conservation of a healthy land base is a principal consideration. Since a farmer has many fixed production costs, a 5% yield increase may be the difference between profit and loss for his operation.

One requirement is for the delineation of patterns and boundaries of several conditions within fields including soil type and texture, soil nutrients, soil salinity, soil erosion (wind and water) and soil moisture. Delineation of homogeneous areas within a field is required for collection of representative soil sampling or selective analysis. Considerable collateral information is required with satellite data to detect, identify and quantify these soil conditions. (The ability to detect and identify these conditions is very dependent on spatial resolution, and will improve as data of 30 m (Landsat-D), 20 m (SPOT HRV) and 10 m (SPOT panchromatic) becomes available.) They are discussed more fully below.

(i) Soil salinity - Salinity is mainly caused by excess water whose source is usually located upslope and outside the affected area itself. It causes deterioration of physical structure and growth and yield reduction. Requirements are for detection and delineation (possibly through monitoring of crop stress) and identification of cause which may require an understanding of regional hydrology. The source could be too much irrigation or inadequate drainage in the case of irrigated lands, irrigation canal seepage, or precipitation in excess of crop use, trapped water, or summer fallowing. Management could involve providing soil drainage or using proper agronomic practices such as growing salt tolerant crops. High resolution satellite data and collateral data (eg on irrigation practices) may permit detection of saline areas. Increases in crop canopy temperature and lack of vegetation growth can be indications of salinity. Information requirements include topography, soil color, permeability and ponding.

Correction of a soil salinity problem may require drainage of excess groundwater. Thermal inertia monitoring can show water-saturated areas. Where water tables are within the capillary fringe, cool regions may be associated with high summer surface evaporation (with surface salt accumulation), and crop damage in cultivated regions. Salinity problems may go undiagnosed while easy corrective measures are still possible. This could happen where an entire field is nearly uniformly affected.

(ii) Soil nutrient deficiency - It is expected that operational application of satellite data may be possible in fields with relatively homogeneous materials where good collateral information exists on soil types, fertilizers applied, soil pH etc.[1]

1. The document "Landsat Follow-on: A Report by the Applications Survey Groups", NASA Technical Memorandum 33-803, Jet Propulsion Laboratory, Dec. 15, 1976 provides much valuable information on agricultural requirements.

(iii) Soil erosion - Soil erosion can produce a double loss - the loss from a source site of productive surface soil, and damage at the deposition site down-wind or downstream from the source. Detection of the source of water erosion could therefore be direct, or indirect by tracing sediment loading in rivers to its origin. Water erosion is a positive growth feedback process resulting in loss of organic matter and plant nutrients, deterioration of soil structure, decreased moisture infiltration and retention, and increased runoff and further erosion. Information requirements for soil erosion investigation include surface roughness; occurrence and distribution of vegetative cover; both growing and crop residue; soil physical properties including texture, slope and infiltration capacity; and soil moisture. Ancillary data is therefore required. Vegetation reduces runoff velocity, increases infiltration time, binds soil particles together, provides habitat for biotic life thereby increasing soil permeability, and absorbs the impact of rainfall. While actual erosion may be difficult to assess, potential erosion areas associated with changes in vegetative cover should be readily identified by satellite data.

(iv) Soil type - Satellite data has been used to assist stratification. Aircraft MSS experiments give optimism that satellite resolution improvements will permit better recognition of soil types and therefore better sample site selection. Soil classification information needs include geologic materials, and soil permeability including topography, subsoil, and plant type. Soil suitability for growing a particular crop depends on soil texture, depth, water-holding capacity, drainage, salinity, organic matter content, acidity, topography and climate.

(v) Water Excesses and Deficiencies - Irrigation Management and Drainage

The total amount of precipitation, its distribution in space and time, and soil retention influence water excesses and deficiencies. The amount of water retained by the soil depends on the soil type, the current state of its physical structure, its present organic matter content, and current cropping and tillage practices. Drought is a major problem in the prairies, and crop yields and the utility of fertilizers are both dependent on soil moisture. Occurrence of wind erosion is also dependent on drought conditions. Excess water in local areas can cause water logging, salinity and alkalinity which require appropriate cropping, tillage and/or drainage. Frequency of occurrence of floods in some agricultural areas has been increasing due to decreased water holding capability and weather conditions.

Drought area information requirements include monitoring surface water, soil moisture, wind erosion, and vegetation conditions. Drought areas tend to be warmer than normal regions with vegetation infrared reflectance reduced. Information requirements for assessing irrigation potential of an acre include soil type, topography, texture, drainage conditions, salinity, and availability of water.

Irrigation scheduling requires information on soil moisture conditions. It is expected that remote sensing monitoring of surface emittance calibrated by ground measurements will be very useful.

Satellite imagery acquired immediately after a rainstorm can show where ponding occurs because of soil impermeability. Floodplain zones may be delineated by monitoring snowmelt runoff, and runoff following storms.

(vi) Soil Restoration and Crop Rotation

Benefits of fertilizer application depend on scheduling. Application timing depends on knowledge of when the particular crop needs the nutrients, and when sufficient moisture will be present so the fertilizer may be used effectively.

Ecologically-appropriate conservation involves crop rotation and nutrient recycling (eg clover can add 150 lbs of nitrogen per acre per year to the soil, plus organic matter). Appropriate cropping practices may increase water storage at the site, benefiting crops there and reducing both erosion and downstream problems. Monitoring crop rotation and other management practices and relating them in an information system to baseline data (eg soils, relief), crop production and meteorological data should provide valuable insights into short and long term economic and environmental benefits of site-specific management practices.

7.3 Other Agricultural Applications

Assessment of Crop Damage

Remote sensing methods may be used to assist in crop damage assessment. Weather-caused damage includes frost, drought, excessive moisture, hail, wind and winterkill. In most instances, crop insurance agencies make liability assessments after harvest when production is known. Remote sensing methods provide an objective method of assessment while the crop is standing in the field. They are most attractive for damage assessment in 1) cases where the damage boundaries are poorly delineated, or there is a variation of damage intensity throughout the affected area. Frost and hail damage for example are difficult to assess without an aerial perspective. 2) cases where it is desired to follow up the initial inventory with a monitoring program to assess the effectiveness of control measures. 3) cases where assessment is normally otherwise done after harvest and may be primarily determined by the farmer's biased assessment of his loss. 4) less accessible areas eg areas of excessive moisture, forage in more remote areas, etc. Although aircraft visual and photographic methods have been used for crop damage assessment, resolution inadequacies have retarded the use of satellite data for this application to date. Assessment using high resolution satellite data would involve image analysis of the damage area and supplementary information provided by the farmer or inspector.

8. Hydrology

Hydrologic studies may require complex information extraction capabilities. The reasons for this include: (1) Land, water and atmospheric phenomena and their relationships are involved. (2) The data banks involved contain sets of data that must be updated with different update frequencies. The spectrum ranges from "archival" data (eg. soils, topography) to "real time" data requirements (eg. weather, streamflow, water quality). (3) The information extraction facility must deal with data not only of a range of time scales, but also a range of space scales, eg. weather data (obtained in part from meteorological satellite data) will be on a coarser scale than land and water data. (4) Water in all its phases may be involved in a particular study. Phenomena of interest could include ice in lakes and rivers, permafrost, snow, surface water, groundwater, precipitation, evaporation, infiltration, evapotranspiration, etc. (5) Water flow data are defined with a directional flow relationship (ie. direction as well as locational identifiers are important). External hydrologic models using differential equations are used to analyse streamflow. Analysis results may be reconverted to a spatial format for final display and integration with other spatial data. (6) Because of the range of parameters involved in hydrologic studies, the number of data sets required will often be large. Problems with direct observation of parameters such as vegetation and soil moisture and snow water equivalent using a single spectral channel may be assisted by merging data from several channels. It should be noted that while present Landsat spectral channels are favourable for vegetation monitoring, the thermal and microwave regions contain much information for hydrologic cycle studies. Thermal infrared remote sensing is particularly effective in monitoring liquid water and/or its effects on the environment. Microwave methods provide reliable data. The interactions between water and the environment are complex necessitating merging of multiple remote sensing and ancillary data sets.

The sections below separate data requirements (remote sensing and ancillary data) for hydrologic planning and real time management.

8.1 Hydrologic Planning Models

Planning models are used to estimate the magnitude and duration of peak runoff flows. The information is used in the sizing and design of waterworks.

Planning models require quantitative physiographic and hydrologic information. As for other hydrology purposes, many different models exist with different inputs. The data that is available influences the model that is used. Models have been structured to take advantage of the capabilities of Landsat data. As other forms of useful hydrologic data become available, for example, remotely sensed data in the microwave region, new models may be developed (if the models that have now been developed to take remote sensing inputs are inadequate). Peak flow has been identified to be primarily governed by precipitation, infiltration and surface flow - both overland and in the channel, except for special circumstances.* The drivers for these processes include:

overland flow - slope, surface friction, drainage density and pattern

infiltration - soil permeabilities, soil moisture capacity, and antecedent soil moisture

rainfall - regional and seasonal, and recurrence statistics.

Remote sensing methods have potential of providing quantitative information on the overland flow components listed and antecedent soil moisture. (Meteorological satellite data also has potential for precipitation measurements.) Among the features of one specific peak outflow rate model* are a rainfall spatial correlation factor to convert point rainfall to its areal equivalent, and an infiltration equation relating infiltration rate to maturity of cover, average vegetative cover and soil moisture capacity. It is important that the model measure the physiographic and hydrologic (eg. surface cover, soil moisture) characteristics which exist during the critical season (eg. spring flood period). Landsat data has been used in physiographic basin measurements (watershed area, overland flow length, drainage density, channel dimensions), surface cover identification and classification, and soils classification (using considerable ancillary data).

A watershed runoff prediction model developed by USDA SCS generates runoff curve numbers based upon the type, density and spatial distribution of soil and vegetation cover. Soil moisture is also involved. The SCS defines 4 soil types ranging from low to high runoff potential. Computer generated vegetation maps using Landsat data with species type and density identification generalized to a level compatible with the data, were found to compare well and give similar runoff calculations to ground survey vegetation maps. Storm runoff predictions are used in California to delineate flood plain boundaries which affect building standards for commercial and residential structures; to establish building standards for specialized flood control facilities such as dams, debris basins, spreading ponds, etc., and to provide baseline data for flood insurance.

Land use information is a key factor in determining the response of a watershed to precipitation. It is used in hydrologic engineering planning models in combination with other watershed physical characteristics such as topography, soil class, land slope and erosion index, to assess the flood hazard, general damage potential and environmental status of watersheds. The model is calibrated to reflect

* "The Application of Remote Sensing to the Development and Formulation of Hydrologic Planning Models", P.A. Castruccio et al. Ecosystems International Inc., Gambrills, Maryland, 1976.

the hydrologic consequences of an existing land cover pattern. Analysis methods are used to determine the hydrologic, economic and environmental impacts of land use change (ie. alternative land use patterns). Hydrologic impacts are determined by basin response characteristics (ability to retain moisture related to amount of impervious cover and land surface management methods). Economic impact is determined by the size, density and type of structures which affect the damage potential in urban areas. More detailed land use information is required in urban areas for economic and environmental analysis, than for hydrologic analysis. Landsat digital data has been found to be useful in combination with ancillary data (digitized map data including watershed boundary data and road network data, ground data and aerial photograph data) in land use classification for hydrologic planning purposes.

Where many years of historical data are available from a well-designed rainfall - streamflow monitoring network, a statistical model may be used to describe quantities and timing of runoff. These models are usually structured so that remote sensing has little or no application. Hydrologic models using map and land cover data may be used where there is an absence or minimal amount of local streamflow data. These may be very oriented to remote sensing inputs, for example, regression models using stream levels rather than areas obtained from maps. Comparisons have been made between conventional and Landsat-based models in gaged watershed.

One application of STORM (Storage Treatment, Overflow Runoff Models) to examine the impact of a number of flood alternatives used input data based on Landsat data and then input data consisting of 52 years of hourly precipitation data. Similar results were obtained. Among features of models that have been pointed out are: that the input parameters of many models are presently overdefined in terms of the sensitivity and accuracy of the model; that questions with regard to input data arise because of limitations in the nature of the process being simulated; and that because of processing constraints simplification may have had to be made even to an imperfect understanding of a process.[+]

+ " The Definition of Hydrologic Model Parameters Using Remote Sensing Techniques"
R.M. Ragan and U.U. Salomonson

The applicability of the present Landsat data to forestry planning requirements where the data requirements are more general (than for management) has been noted. An interesting hydrology application has been a simulation study to show distribution of runoff and pollution loadings in an area with excellent data base but multiple sub-jurisdictions. A new Landsat based data management system was found to be preferable to consolidating existing data of different formats, map scales and levels of currency.

In addition to having now some remote sensing data of watershed conditions which could improve runoff estimates, particularly in ungaged watersheds, development of computer-based models requiring land cover inputs is being stimulated by emphasis on environemntal concerns and water demand conflicts. The user may wish to evaluate the water quality (as well as hydrologic) consequences of a change in land cover and use a calibrated model in this analysis. The spatial quality distribution as well as quantity has been determined from interfacing Landsat-based cover data with digital files containing soil, slope and rainfall.

8.2 Management of Water Resources

One of the principle requirements in water management is accurate forecasting of water flow volumes and timing. Such forecasts are needed in hydroelectric power generation, irrigation, flood control, water supply, navigation, and recreation. Largest annual benefits are to hydroelectric power generation where the value of energy generation is increasing rapidly. Remote sensing benefits with appropriate data acquisition could eventually be several $ million annually, for this application. Potential flood damages are increasing as areas are built up (estimated Lower Fraser River damage from the probable maximum flood is $500 million - 1972 $ and total Canada losses in 1974 were $72 million). Until recent years, most measurements were point source, and predictive models have been developed over the years to be compatible with the data that was available. In the index method of forecasting seasonal runoff, correlations of historical records of runoff are used with indices of important determinants of runoff for the area. There are terms in the regression equation which include data inputs such as fall, winter and spring precipitation (possibly 3 terms), base flow, evaporation temperature, snow water equivalent and glacier melt. The accuracy of the seasonal forecast increases as the season progresses-for example on January 1 the fall precipitation is known but historical values are used for winter precipitation. Index methods have a number of disadvantages including requirement for lengthy river discharge records to establish reliable records. Values tend to be biased toward the mean so that events of most interest are poorly represented. Inherent limits to accuracy cannot be overcome by adding more snow courses or increasing the number of indices. Seasonal runoff forecasts for which index methods are presently used rely on detailed observations of snowpack water equivalents measured at a certain date and point. It is hoped that eventually statistical methods may be eliminated and replaced with deterministic methods which try to assimilate the actual physical processes. These reduce the length of record required. These require improved inputs in terms of timeliness, reliability, density and quality.

Water budget methods are used operationally in short term runoff forecasting. These may include either primary or derived variables. Data inputs may include snow pack (snow cover, snowline elevation, snow water equivalent), soil moisture, evaporation, temperature maxima and minima, precipitation, precipitation interception (leaves, branches, etc.), transpiration, freezing level, and ground water storage.

Since models must be compatible with their data base, model development is required to accept remotely sensed data of new forms and frequencies. Data integration is required in modelling these streamflow processes. Since these are not unique data sets, forecast accuracy may be improved by having independent sets of data.

Short term runoff forecasting requires reliable availability of data in near-real time. At present, information is scarce from high elevations, remote or unpopulated areas. Automated remote stations using data transmission methods are beginning to be used and will provide complementary data to broad area satellite coverage.

The interplay of runoff model and data errors make assessment of the relative contribution of various input parameters eg. soil moisture, snow line etc., difficult. Sensitivity studies to determine the importance of improved accuracy in a particular variable are model dependent. Many errors contribute to the total forecast error and some cancel each other. The table below indicates reported significance of hydrological variables in forecasting seasonal runoff.* The significance percentages indicate in broad terms what percentage of the variability accounted for by a multiple regression equation is attributable to a particular variable.

* Soil Conservation Service, National Engineering Handbook, Section 22, Snow Survey and Water Supply Forecasting

Table 1

Variable	Significance	Percent
Snow water equivalent	Very high	60-90
Temperature	Moderate high	10-25
Precipitation		
Fall	Moderate	5-20
Winter	Moderate high	30-60
Spring	Moderate high	10-25
Wind	Moderate	5-20
Radiation	Moderate	5-15
Relative humidity	Moderate	5-10
Streamflow (antecedent)	Moderate	5-15
Baseflow	Moderate	5-15
Soil Moisture	Moderate	5-10

It is evident that snow water equivalent is a dominant variable in areas of heavy snowfall. Extensive studies have been made on monitoring snowpack by satellite and aircraft methods. Table 2 lists satellite requirements for monitoring snowpack. Image resolution requirements are more severe for small watersheds or for mountainous areas where snow-line elevation changes occur rapidly over short horizontal distances. Considerable research on the applications of NOAA VHRR and Landsat data have been carried out and experiments have been conducted to integrate aerial surveys and hydrologic data from earth-based sensors. Aerial surveys include measurements of snow water equivalent by γ techniques (line profile), snow-line data in mountainous regions, snow cover observations, aerial observation of depth markers and airborne radiometric snow gauges. Ancillary data may be desirable for these surveys including slope, variation in terrain, aspect, vegetation. Several ground based methods of measuring snow water equivalent or snow depth at a point (eg. snow samplers, snow pressure pillows) are utilized. For satellite snowpack monitoring, meteorological satellite data has the advantage of being available on a daily basis (cloud cover permitting) although its resolution is coarse. Maps showing percentage snow cover for selected basins are now produced on a routine basis from NOAA imagery by NESS. The more detailed Landsat data can be used as a method of checking and calibrating meteorological satellite data. Although Landsat-surveyed mountain snowpacks have shown more detail than aerial survey snow charts in comparative studies in some areas in the U.S., forest cover is a complicating factor in Canada. Landsat-observed snow cover has been used in statistical regression models for seasonal volume flow, and as an input to a computerized simulation model providing short term and seasonal forecasts.[*] The greatest potential for water supply forecasting is in improving forecast accuracy and in expanding forecast services during the period of snow melt. Snowcover extent is an important variable for forecast purposes once the main snowmelt season begins. Snow mapping may be done by photointerpretive means, and AES are examining digital snow cover analysis methods.

Studies on passive microwave remote sensing of snow parameters have shown promising results. The penetration depth varies greatly with snow parameters and depths in dry powder snow to 23m at low frequency (4.9 Ghz) have been

* "Landsat Derived Snow cover as an Input Variable for Snowmelt Runoff Forecasting in South Central Colorado", Shafer, B.A. et al, W.T. Pecora Symposium, June 1979.

Table 2

Hydrological element	Description	Resolution A	B	C	Accuracy	Frequency
Snow						
Snowline	Line separating a region of $<50\%$ snow cover from a region of $>50\%$ snow cover	30	100	1000	-	daily
Snow cover	Percentage of specified area covered by snow	300	1000	10,000	($\pm5\%$ of snow area)	daily
Water equivalent	Depth of water contained in a vertical column of unit cross section	100	300	1000	±2 mm if <2 cm	daily
Free water content	Equivalent depth of all the water in the liquid phase contained in a vertical column of unit cross section	100	300	1000	$\pm10\%$ if >2 cm	
Snow-surface temperature	Equivalent radiating temperature at the top of the snow pack surface	100	300	1000	$+1^{\circ}$C	6-hourly
Surface albedo	Ratio of reflected to incident energy over specified λ range	100	300	1000	5%	6-hourly
Groundwater Detection						
Acquifer mapping	Area where ground-water found	100	100	100	-	5 years
Location of springs	Existence of ground-water	30	30	30	-	5 years
Location of Discharge to	Existence of ground-water					
a) rivers		30	30	30	-	weekly
b) lakes		100	100	100	-	weekly
Groundwater Level	Elevation of the piezo-metric surface of an acquifer at a certain location and time	300	1000	1000		daily
Soil Type		100	1000	1000	-	5 years

Source: "Informal Planning Meeting on the Satellite Applications in Hydrology" World Meteorological Organization, Geneva, October 25-27, 1976 found.* The seasonal development of the snow pack may be monitored by surveying the diurnal variations weekly, or more frequently to determine the moisture content of the uppermost snow layers or the accumulation rate of fresh snow. Higher resolution radiometer data available in the 1980s will increase the utility of this method.

Net solar radiation is the key parameter in earth surface energy-balance equations utilized in hydrological modelling.+ Remote sensing methods using physiographic and climatic variable data have been developed to give timely location specific solar radiation estimates on a watershed or subwatershed basis.+ Climatic variables used in the system include: cloud cover (the transmitted radiation depends on type, height, density, and amount of clouds. Cloud cover may be estimated from NOAA or GOES data); daylength (obtained from standard meteorological tables); temperature (values can be estimated from NOAA satellite, thermal data, or from spatial interpolation of ground station point temperature data, or from thermal aerial imagery); albedo (albedo is influenced by the nature of a surface and its moisture content at a particular time.) It may be determined by Landsat and/or NOAA data; and total incoming radiation (values may be obtained by standard meteorological data). Slope, aspect, and elevation are also used in solar radiation estimates. Model outputs can be maps of net shortwave radiation, net longwave radiation and net solar radiation.

Evapotranspiration (water loss to the atmosphere, ie. the combined evaporation from all surfaces and the transpiration of plants) is one of the main components of the water budget. Remote sensing-assisted methods using locational, physiographic and climatic data have been used to estimate and map potential daily evapotranspiration.† Physiographic data used include hydrologic land use, elevation, slope and aspect. Computer assisted classification of satellite and aircraft multispectral data was used for hydrologic land use. Climatic data inputs included solar radiation (output from model discussed above), soil moisture, depth to water table, river discharge,

† "Use of Landsat and Environmental Satellite Data in Evapotranspiration Estimation from a Wildland Area", S. Khorram and H. Gregory Smith, 13 International Symposium on Remote Sensing and Environment, Ann Arbor, April 1979.

+ "A Solar Energy Estimation Procedure Using Remote Sensing Techniques", S. Khorram, Proc. Sixth Annual Remote Sensing of Earth Resources Conference, the University of Tennessee Space Institute, Tullahoma, 1977.

* "Passive Microwave Remote Sensing of Snow-Review of a Long term Measuring Campaign" R. Hofer and C. Maltzler, Satellite Hydrology, The Proceedings of the 5th Annual W.T. Pecora Symposium, Sioux Falls, June 10, 1979.

precipitation, evaporation, transpiration, air temperature, dewpoint/frost point, wind direction and velocity, incoming solar and net radiation, temperature, specific conductance, dissolved oxygen, PH and turbidity.

In addition to its utility in regional watershed models, remotely sensed data can play a major role in large-scale hydrologic models. A large scale ground hydrologic model, coupled with an atmospheric general circulation model, has been developed which calculates the heat and moisture fluxes across the atmosphere-land interface and changes in water storage in various horizontal zones on and below the ground surface. Several model variables including fraction of bare soil and vegetated surface, ground temperature, and albedo of the land surface are within the capability of remote sensing techniques. Some information on soil moisture, and potential and actual evapotranspiration which provide the major moisture coupling between the atmosphere and the land surface, is obtainable from remote sensing. Time- and spatially-dependent properties of the soil such as soil conductivity, moisture transfer coefficient and soil specific heat are beyond remote sensing; however, indirect qualitative inference of some of these properties may be possible through correlations of plant-soil remotely-sensed scenes and in situ measurements.*

*"Modelling the Terrestrial Hydrology for the Global Atmosphere; The Future Role of Satellite Data", J.D. Lin, P. Bock and J.J. Alfano, Satellite Hydrology, June 11, 1979.

Point source hydrologic data has been transmitted in digital form by various communications channels in hydromet networks. These methods include satellite relay of data from remote sites. This has been demonstrated to be economical. The data collection platform network began with the Landsat program. About 30 DCPs were deployed, and they demonstrated that near real time data can be collected reliably using satellites.* Parameters transmitted include water level, water velocity, air temperature, precipitation, and ice condition. The GOES geostationary satellite is also now used for data relay. TIROS-N will be used in future for sites where use of GOES is not feasible (eg. northern and mountainous areas). A combination of GOES and TIROS-N should meet many operational requirements. For example, in Quebec a system consisting initially of 35 automatic stations (and 135 in 1982) and relying on the GOES satellite, will collect, treat and transmit hydrologic and meteorological data in real time beginning in 1979.

Network transmission of weather, hydrology and ice information described above has involved transmission of a time series of point observations by land line and satellite, and of relatively low resolution image data by low data rate land line. Transmission of mappable land-related data has not occurred to a great extent for several reasons. Information on slowly varying mappable phenomena has been displayed in graphic form on maps and a need that would justify costs for digitizing and information transmission has not been recognized. The amount of land-related data in digital form has been limited by the high costs of acquiring or putting data in this form.

* "Retransmission of Hydrometric Data in Canada", R.A. Halliday and I.A. Reid, Final Report to Canada Centre for Remote Sensing, April 1978.

9. Water Quality Monitoring

9.1 Filling in the 4-Dimensional Data Base

Conventional water quality measurements have provided measurements at specific geographic locations, sometimes in a vertical profile and sometimes with frequent time sampling. High costs have discouraged dense spatial sampling in most instances and virtually prohibited simultaneous sampling at a number of locations. However, parameter values may change spatially, gradually or abruptly. Information on horizontal distribution is required for most parameters. Methods are needed to determine values at intermediate locations between point measurements and to predict water quality changes with time.

Passive sensors are presently used on satellites and provide data which is an integrated response (vertically) of the water body. This must be merged with field point sample data which may be depth integrating or may be collected at the surface or other specific level. Care must be taken to ensure compatibility of the two types of measurement. The user requirement could be for information on the integrated effect eg total sediment load in the water column, or for level specific information eg concentration of pollutant near water intakes. Sediment, chlorophyll and some pollutants may exhibit vertical inhomogeneity while others such as dissolved nutrients etc. have fairly homogeneous distribution throughout the water column and measurements made at a particular level are applicable throughout. Satellite data has advantages of synoptic coverage, repetitive coverage and depth integration. Field samples may not have been collected during adverse weather or at favourable times, and repetitive satellite coverage helps fill in this time dimension. Costly mistakes have resulted from not acquiring field sample data at the appropriate time.
The multi level sampling required for remote sensing data calibration in vertically non-homogeneous water bodies involves only minor additional effort at each site compared with single sample collection. Remote sensing data can then help fill in the 3-D distribution picture. Models which take advantage of relationships with ancillary parameters eg those providing information on vertical mixing such as turbulence might be used. Aerial inhomogeneities in sediment load or other constituents which often occur in large water bodies, resulting in gradients within a pixel and lower radiance give underestimates of pollution measurements. Improved spatial resolution will help with this problem.

Horizontal distribution and vertical profile data are required for temperature anomalies, pH, and BOD. In addition to these parameters, also needed are: total concentration in the water column, sources, and sinks, required for dissolved oxygen, nutrients and dissolved solids (K, Mg, Cd, CO_3, SO_4, PO_4, plus common ions) with chemical nature required for the latter two as well; total concentration in the water column and in the bottom sediment required for pesticides, coliform bacteria, and heavy metals; and concentration in the bottom sediment, half-life, element species/isotope and level of radioactivity required for radioactive nuclides. Areal extent information is required about petroleum, phytoplankton, zooplankton and algae. Location, thickness and chemical properties are required for petroleum, and spatial distribution, concentration and species are needed to satisfy data requirements for the other three. Data requirements for suspended particles include concentration, turbidity, composition of suspended material, total mass in column, particle size spectrum and sedimentation rate.

Conventional models used in water quality studies for estimation or prediction often have a limited data base to work with because of the cost of sampling at multiple spatial points. The quality of the input data is dependent on the location of the monitoring site. In order to maximize the complementary contribution of satellite synoptic and repetitive coverage to monitoring, estimation and prediction, attempts have been made to quantify distribution patterns obtained remotely in order to associate the pattern with other environmental factors and to construct a model. In order to describe and analyze the macroscopic characteristics of the two dimensional distribution pattern, Fourier Transformation methods have been used.* Lower order Fourier coefficients (0-4th order) were found to be adequate to describe chlorophyll and temperature distributions. By correlating the extracted features of remotely sensed patterns (ie the Fourier coefficients) with the corresponding data on the ground in a statistical model, and calculating regression coefficients, it should be possible to <u>estimate</u> the Fourier coefficients only from the ground data and reconstruct the distribution from the coefficients by the inverse transformation. Obtaining the distribution from ground data in this way is useful when weather conditions do not permit remote sensing data acquisition. This has been used successfully for air pollution studies. A statistical model which correlates the distribution pattern Fourier coefficients with external conditions(ie meteorological conditions etc.) is used to <u>predict</u> the distribution only from the external conditions. The method depends on how well the features of the pattern

* "Quantitative Description and Analysis of Remotely Sensed Water Quality Distribution", Y. Yasuoka, Y. Jikura and T. Miyazaki

are correlated with the other environmental factors (eg meteorological conditions).

9.2 Remote Sensing of Water Quality

Because of temporal changes of water quality in three spatial dimensions (ie a 4-D modelling problem), extensive data is required for assessment and prediction. Both surface and volume effects (as well as path radiance and atmospheric attenuation) contribute to the spectral signal monitored by Landsat, Nimbus G, or airborne scanners or spectrometers. The variables which affect satellite-measured energy levels include surface roughness, floating plants and other materials on the water surface, water colour, water turbidity, spectral influence of suspended particles including phytoplankton and zooplankton, internal water reflections and scattering, vegetation, reflectance of bottom sediments, specular reflection of skylight from the water surface, atmospheric effects (which are particularly important in water quality studies) including water vapour content, aerosols and molecular content, and sun elevation angle and time of year. Unscrambling the contribution to the total signal from this mix of contributers may be difficult. Remote sensing methods may not correlate with water sampling results because of incompatibility with or inadequacies in the latter. In turbidity measurements, for example, most water samples will not have been collected by depth integrating samplers giving errors if vertical mixing is poor. Illustrative examples have been given where field water samples collected at one depth have not been representative of conditions throughout the water column and therefore disagreed with remote sensing integrating techniques.[†] Remote sensing methods have been successful in detecting pollution sources previously undetected, possibly because of settling to lower levels than where field samples were taken. Secchi depth is not necessarily a consistent and reliable index of water turbidity, and a remote measurement may be a more accurate representation of average, near surface turbidity.[*] Some development work has been done on models to describe water quality and biological productivity.

Studies of remotely sensed energy flux and water turbidity have given correlation coefficients typically in the 0.7 to 0.9 range.[*] Multiple regression techniques have been used to determine the correlation between various field measurements and remotely sensed data. Several studies have demonstrated the feasibility of measuring Secchi disc transparency using MSS data.[+] Turbidity can be a measure or index of sediment and plankton concentration. The remotely sensed measurement depends on concentration of silt, particle size and reflectance of the particles. Since differences in

† "Assessment of Aquatic Environment by Remote Sensing", M.S. Adams, F.L. Scarpace, J.P. Scherz, W.J. Woelkerling, Institute for Environmental Studies Report # 84, University of Wisconsin-Madison, September 1977.

* "Satellite Surveillance of Physical Water-Quality Characteristics", G.K. Moore

+ List of references in "Landsat Follow-on: A report by the Applications Survey Groups", NASA Technical Memorandum 33-803, Jet Propulsion Laboratory, Dec. 15, 1976.

remote flux due to atmospheric aerosal alone can be greater than between concentrations of 10 and 100 mg/L of suspended silt (MSS band 5, particle diameter 0.02 mm), atmospheric corrections must be applied. Techniques using the remote data itself including band ratioing, and calibration using dark reflective objects in the scene have been used. It is possible that methods using meteorological satellite data could be developed in future.

Although a mix of factors can complicate interpretation of satellite data in water quality applications, this is not necessarily the case with, for example, changes in turbidity of reservoirs and estuaries usually caused by suspended sediment concentration changes, and in inland lakes by changes in phytoplankton content during summer months. Remotely sensed data provides patterns which can be correlated with field point samples to provide quantitative estimates.

Inferences about lake circulation can be made from turbidity plumes and turbidity related patterns observable on MSS imagery. This is of assistance in locating sampling sites and in study of water transport phenomena.

Turbidity and suspended sediment are often well correlated. Good suspended sediment estimates have been obtained using Landsat and limited field sampling both in inland[*] and salt water bodies.[+] Improved spatial resolution of future satellites will permit the technique to be used in narrower rivers. Satellite data could therefore be more useful in sediment transport and lake and reservoir filling studies. Turbidity may be an index to concentrations of certain constituents since suspended clay particles can carry micro-organisms, cations, anions and organic compounds including pesticides and heavy metals. Therefore while some chemical constituents affect water colours, remote measurement of colourless chemical constituents must come indirectly from a correlation of the remote signal with the distribution of ions sorbed on suspended particles or constituents used in the growth processes of phytoplankton.

Alfoldi et al[†] have developed a chromaticity analysis technique for measurement of turbidity, secchi disc depth, and chlorophyll. The technique has been applied primarily to suspended solid analysis since present Landsat data is more sensitive to those variations than other water quality situations (Satellite data which is more suitable for water quality studies in terms of location and width of spectral bands, radiometric and spatial resolution is expected in future.) The method involves a

* "Quantitative Water Quality with Landsat and Skylab",H.L. Yarger and J.R. McCauley, Proceedings of the NASA Earth Resources Survey Symposium, Houston, June 9, 1975.

\+ "Assessment and Classification of Selected Illinois Lakes through the Application of Space Technology", D.J. Schaeffer, R.P. Clarke, D.F. Sefton, and D.M.P. Boland Satellite Hydrology, Fifth Annual William T. Pecora Symposium,Sioux Falls, June 1979.

† "Progress Toward a Landsat Water Quality Monitoring System", T.T. Alfoldi and J.C. Munday Jr., Proc. of the Fourth Can. Symp. on Remote Sensing, Quebec City, 1977, p. 325; "Verification and Application of a System for Automated Multidate Landsat Measurement of Suspended Sediment" J.C. Munday, T.T. Alfoldi and C.L. Amos, Fifth Annual William T. Pecora Symp. on Satellite Hydrology, Sioux Falls, S.D. June 11, 1979.

radiance normalization preprocessing technique in which MSS bands 4, 5, and 6 radiances are normalized to eliminate brightness information and emphasize hue (related to type and concentration of water constituents) and saturation. Satellite data acquired at different times can have variations in atmospheric attenuation, path radiance, sun angle elevation, and extraneous factors in surface reflectance (eg white cap). Surface calibration sampling may not be feasible for every scene, and this technique involves automatic pixel-by-pixel adjustment of atmospheric variations, permitting reference calibration data from one or more dates to be extrapolated spatially to other regions and temporally to other dates. An automated system for quantitative suspended sediment concentrations has been developed, with correlation between satellite and surface data for combined data sets of 96%, and absolute error of the calibrated satellite measurements of 44% of S over the range $L < S < 1000$ mg/l. Data inputs include water sample data of suspended sediment concentration, chlorophyll a, grain properties and selective water absorbance. Suspended sediment distributions over a complete Landsat scene lacking surface data can be mapped in less than 3 hours with an interactive system. Suspended sediment contour maps produced for varying conditions of weather, season and tide have been used to study the distribution, transport and disposition of Bay of Fundy suspended sediment, and to initialize and calibrate a numerical model predicting siltation effects after a barrage has been constructed across the tidal flow in the proposed Fundy Tidal Project. For this specific project, the model predicts no significant sedimentation during the power project lifetime.

In estuaries, lakes, and reservoirs, satellite remote sensing may be used for repeated evaluation of productivity because of the relationship of optical turbidity to plankton type, size, shape, form and distribution. Phytoplankton production has been related in models to chlorophyll concentration and ambient light. MSS data has been found to be correlated well with chloropyll a in lakes where inorganic sediments have not masked its presence.* Chlorophyll a can be used as an index of eutrophication since chlorophyll is a component of suspended algae ie phytoplankton. The TM visible bands (particularly the new blue band) are expected to improve this capability. Several studies of lake eutrophication have been made using Landsat digital-data assisted methods. MSS data has been used with contact sensed data to develop regression models which provide relative estimates of total organic nitrogen, total phosphorus, multivariate trophic indices and chlorophyll a. The estimates can be used to develop lake trophic state rankings and groupings, although they

* "Quantitative Water Quality with Landsat and Skylab", H.L. Yarger and J.R. McCauley, Proceedings of the NASA Earth Resources Symposium, Houston, June 9, 1975.

are not as accurate as field measurements of trophic indicator values at a given lake location.

MSS data has been used for differentiation of broad categories of lake contaminants in Lake Superior.* The data was found useful in sampling site categorization used in determining chemical loading and in testing numerical models for simulation of contaminant dispersion. The MSS data permits monitoring of large scale phenomena which reflect both the transport and dispersion processes taking place. MSS data obtained on consecutive days was used to monitor turbidity plumes and to determine their spreading rate. Results of a model using the actual wind conditions were compared with observed plume dynamics. Model results showed many of the structural features displayed in the observed plume. A principal objective was to determine how the runoff plumes disperse in the lake under various wind conditions in relation to the location of municipal water intakes. (Drinking water may be affected by the overflow of municipal sewer systems and snow melt runoff.) Remote sensing data by itself was limited in coverage frequency and to identification of only the relatively high concentration of tracer contaminants, hence the complementary use of a dispersion model. Quantitative projected contaminant concentrations verified by remote sensing data were determined. The distribution of total phosphorus for the spring runoff was determined using a relationship between total phosphorus, turbidity and Landsat Band 5. Sufficient statistical data was available in the measurements for cross-correlation of turbidity with total phosphorus, total organic nitrogen, SiO_2 and SO_4. For aquatic biomass estimates, as for other biomass calculations involving use of remote sensing, stratified sampling methods may be used in ground truth collection.

Surface biomass concentrations caused by algae, macrophytes or a combination of these types have been studied with MSS data. Multitemporal data is useful in studying lake characteristics. Lake bottom effects which present a noise factor in satellite classification, can be studied by analysing spring imagery when lakes are clear and free of algae and bottoms are most apparent. Lakes are classified on the basis of their trophic state. An oligotrophic lake does not have enough nutrients to sustain significant algal growth, so that the backscattered energy flux may be fairly uniform from spring through summer. Highly eutrophic lakes will have high backscattered signal in August because of heavy algal growths. Using multi-spectral techniques, it is possible in many cases to separate algae, macrophytes

* "Use of Remote Sensing in Determination of Chemical Loading of Lake Superior due to Spring Runoff", G.J. Oman and M. Sydor, Canadian Journal of Spectroscopy, Vol 23, March/April 1978.

(large aquatic plants), sand bottom, humic material, red clay etc.+ Different macrophytes, or macrophytes at different depths give different spectral responses which may be separable depending on the spectral channels used. Time of data acquisition for lake classification is important, with maximum differentiation in backscattering caused by nutrients in different lakes during the last part of August to the first week in September.+ This coincides with the minimum amount of dissolved oxygen and maximum temperature.

The large area coverage of Landsat MSS data has permitted comparing the trophic state of one lake with that of another for which field samples were taken.* Chlorophyll a is correlated with total phosphorus and with MSS data. Phosphorus is usually the limiting factor for algal growth. Algae form when nitrogen and phosphorus flow into a lake, interact with sunlight and remain for a sufficient period of time.

Other Remote Sensing Methods of Acquiring Water Quality Data

Thermal data acquired by airborne infrared linescanners and line profiling radiometers and from satellites such as Landsat-D, Tiros N, and HCMM is used often in combination with field data in monitoring water temperature patterns. Studies of surface circulation (location of current boundaries) can aid in constructing erosion-preventative structures and in planning for waste disposal. Airborne data has been used to study the discharge of warm cooling water from power stations and industries. Heat disperses in the horizontal and vertical directions according to a number of factors including water currents, turbulent diffusion, wind, heat transmission to the air, and tidal cycles and salt intrusion in estuaries. The temperature distribution may be homogeneous vertically or exhibit stratification, and sensors at several depths are required to determine this and for operational monitoring if stratification exists. Baseline data could be used in plant construction impact models. Discharge operational data could be input to aquatic environment models with output of these influencing operations.

Because of the complex mix of variables involved in water quality studies, use of airborne sensors acquiring selected spectral data is probable in priority areas to augment and/or improve accuracy of satellite coverage. Remote detection of dissolved constituents is possible in narrow wavelength bands. The CCRS line profiling multichannel analyser (OMA) has 500 spectral channels and can be used to analyze shapes of absorption spectra of different constituents. It may be used as

* + "Assessment of Aquatic Environment by Remote Sensing", M.S. Adams, F.L. Scarpace, J.D. Scherz and W.J. Woelkerling, Institute for Environmental Studies, Report # 84, University of Wisconsin-Madison, Sept. 1977.

Frannhofer line discriminator to detect dissolved luminescent materials such as organic wastes. Laser Roman spectroscopy which is constituent-specific has been used experimentally in oil slick and other studies. Experiments are being carried out in Lake Ontario using ship-acquired optical measurements and water quality samples, an airborne line profiling 4-channel photometer (MPPH), airborne 10-channel imaging multispectral scanner, and Nimbus 7 coastal zone mapper data to monitor chlorophyll and suspended solids concentrations and possibly dissolved organic materials (by MSS). A major component of this work is applying atmospheric corrections by a model utilizing atmospheric transmission albedo and sun angle data. Ground-acquired atmospheric transmissions are used in the corrections. An eventual operational system would be expected to include satellite data plus selected airborne profiles and field sampling and require merging of these data types. Bathymetry measurements from satellite or aircraft also may require ancillary aircraft data on water quality parameters to account for their influence.

Good correlation (0.986) has been obtained between MPPH photometer remote sensing estimates of chlorophyll-a concentrations and field measurements for the Kawartha Lakes region. The Nimbus 7 CZ CS is the first satellite sensor designed for water quality measurement (chloropyll-a and suspended solids concentration).

Although there are some "standard" data types collected for water quality evaluation, and established biological methods used, deficiencies may arise for several reasons including: scarcity of data particularly in remote areas; excessive delays in data acquisition; and difficulty in determining the overall effect of multiple interacting factors. Satellites play a role in timely data acquisition from all areas, remote or otherwise, providing some physical and biological information by sensing. A second role is played by data relay from data collection platforms (DCP) at selected locations. There are numerous interacting factors in complex aquatic systems and meaningful data on biological impact is needed. Since biological systems are integrators of the environment in which they are immersed, appropriate biological monitoring is indicative of environmental conditions. Remote sensing contributes in assessing biological response to water quality changes for example, by monitoring the presence and condition of algae and macrophytes. If fish behaviour is to be used as a measure of biological response, in situ methods are required. In situ measurements of fish breathing rates have been used to detect stressful conditions caused by water quality fluctuations.*

* "Biological Water Quality Monitoring from Remote Stations and NASA GOES Satellite", E.L. Morgan et al.

Aquatic plant response to environmental changes would generally have different time scales than fish response, and the detectable response due to particular physical/chemical changes might be very different.

Site specific physical/chemical data collection and biological monitoring has been carried out and interfaced with a DCP for GOES data transmission.* Physical data transmitted simultaneously with fish breathing data included dissolved oxygen, temperature, hydrogen ion concentration, conductance and oxygen-reduction potential. This type of biological response monitoring network (involving breathing rates) provides a quick indication of particular types of water quality fluctuations. It therefore provides an "alert" just as satellite data can for other types of biological response or changes in observed physical conditions. A total information system could include physical/chemical data from both manned and unmanned stations, as well as data inputs from several methods of biological monitoring. Data bases would therefore include accepted "standard" physical/chemical data sets as well as biological data (possibly not as "standard" in form with a less uniform approach to comprehensive data collection and some of which could be obtained from model outputs). The monitoring described above provides "instantaneous" information on certain water quality changes through comparison with normal breath rates while monitoring methods involving aggregation of data over a period of time may be required to determine biological response in some cases. Selected airborne coverage may be desirable to monitor changes in biological community structure and species composition due to water quality changes.

9.3 Estuarine Management and Water Quality

Estuaries are used for many purposes including fishing, aquaculture, recreation, harbours, and sewage and waste disposal. Knowledge of the 3-dimensional circulation dynamics is basic to an understanding of diffusion and flushing processes. Many factors are at play including estuarine bathymetry and configuration, upland discharge, tidal components, coastal currents offshore, salinity, nature of salt water/fresh water interface, temperature, and wind. Three dimensional modelling is required for estuarine circulation, environmental monitoring and pollution studies, and requires detailed surveys to provide adequate input data. Because of river flow, tides, and the mixing of fresh and salt water, estuaries exhibit changing conditions. Satellite data may be used in monitoring estuarine circulation, in the development of models, and in verifying model performance. Information needs include:

* "Biological Water Quality Monitoring from Remote Stations and NASA GOES Satellite" E.L. Morgan et al.

- basic data on bathymetry and basin geometry (part of which could be provided by the blue and near IR band respectively of Landsat-D), shoreline morphology, and depth to bedrock. Estuary bottom mapping may involve a combination of techniques such as sonic soundings, airborne laser and photography methods, and satellite data. The latter could be useful where changes due to sediment deposition occur.
- Aerial extent at high and low tide, and flooding. Remote sensing methods are applicable. For flood mapping, weather conditions may dictate use of SAR data overlayed on baseline data.
- Monitoring of circulation, current patterns, tidal flushing, thermal and salinity distribution, could involve merging of several types of remotely sensed data including TM data (observation of natural traces such as turbidity, temperature patterns and foam and debris lines), meteorological satellite data (more frequent though less detailed temperature distribution information), and SAR imagery for surface condition information (roughness, possibly current, temperature, and surface wind information). This data will complement field measurements and assist in locating instruments to measure current, temperature/salinity etc. Circulation patterns are 3-dimensional and the amount of ancillary data required is situation specific depending on stratification or homogeneity, mixing etc. TM thermal data is expected to provide a means to chart surface salinity patterns under varying tidal and upland water discharge.*
- Monitoring physical, chemical, and biological conditions of fresh water flow and estuaries, monitoring pollutants, sediment, diffusion and dispersion. Field sampling must be merged with remotely sensed data. Dye-diffusion or dye-emitting drifters and airborne monitoring may be used to calculate pollution dispersion and circulation patterns.
- Prediction and monitoring impact of human activities such as channel dredging, fill placement, harbour deepening, prediction of response to natural changes such as storms and floods; defining schedules for channel/harbour maintenance on hydraulic, chemical and biological system, determination of optimum location and shape of disposal sites and siting of sewage outfalls; estimation of sedimentation rates in harbours.
- establish cause-effect relationships between multiple conditions eg turbidity and surface winds, nutrient level changes associated with variations in river flow, effect of inflow water condition changes on abundance and species of estuarine fauna.

* "Landsat Follow-on: A Report by the Applications Survey Groups", Jet Propulsion Lab, NASA Technical Memorandum 33-803, Dec. 15, 1976.

The information requirements above demonstrate the need for merging of multisource data and the use of models to take advantage of interrelationships and to describe complex and rapidly changing processes.

A combination of satellite and airborne platforms and in situ sensors on DCPs would be ideal for monitoring estuary and coastal processes. Aircraft can provide more frequent and/or selective coverage than satellites. Requirements for data coverage (and therefore data handling) are situation specific. Guidelines have been given as daily coverage for chlorophyll, municipal and industrial effluents and oil monitoring, twice daily for suspended sediment, and 48 hours for thermal effluent.[*] TM spatial resolution is considered necessary for suspended sediment and industrial effluent monitoring, with coarser MSS-type resolutions for the others.[*] Considerable data volumes are also acquired by aircraft, and radiance data are usually more difficult to analyse. Munday et al has noted advantages of synoptic techniques over conventional data acquisition and models which fail to provide information on fine structure of circulation involving fronts and convergence zones, often do not take wind effects into account, and usually do not give simultaneous study of circulation at alternate sites which could be involved in a particular project.[+] Several parameters of interest in estuarine dynamics eg wind and currents are vector quantities so that speed and direction attributes must be stored in a data base. Particular wind and tide data give rise to specific circulation patterns. Prediction of movement of spilled oil, and planning of cleanup operations require surface circulation information.[+] Slick trajectory maps and current vector maps depend on tidal phase and wind vectors.

Remote sensing data has applicability in changing estuarine and coastal areas where, due to wave and current action, sandbars, shoals, and islands are undergoing processes of formation, accretion, erosion, submergence, reformation and migration.[+]

9.4 Land Use and Water Quality

Water quality management depends on land use and land management. Water quality problems arise from point and non-point pollution sources. Some information requirements include:

Monitoring Agricultural Land Management Practices -

Runoff from agricultural land is a major non-point pollution source. For example in rural Ontario 70 to 100% of the sediment load has been attributed to rainfall and runoff induced erosion on cropland, grassland, and woodlands, and

+ "Applications of Remote Sensing to Estuarine Management", J.C. Munday et al, Virginia Institute of Marine Science, Annual Report # 5, June 1977.

* "Comparison Capabilities and Costs of Dedicated Airplane and Spacecraft Missions for Remote Water Monitoring of U.S. Coastal Zones", W.L. Darnell, NASA Technical Memorandum 74046, December 1977.

0 to 30% to streambank erosion. Water quality depends on natural factors of land resource including soil characteristics, land use, hydrology and topography, and weather (snow melt, precipitation), and on land-owner management practices such as method of tillage, fertilizer application, pesticide and herbicide applications, irrigation and drainage and management of livestock and livestock wastes. These parameters would be included in a comprehensive data base. Remedial measures which would reduce sediment and nutrient loadings are site specific because of localized variations in pollution sources, soil properties and landscapes, cropping systems and active pollutant contributing areas. For example, high unit-area loads were found where fine-textured soils were involved.

Factors identified in the PLUARG study which contribute to water quality problems, and which would indicate information needs required for prediction of contribution and recommendation of remedial measures include:*

- degree of intensive cultivation. Progressively greater erosion potential was found for permanent pasture, pasture, small grains, corn in rotation, continuous corn, white beans, some horticultural crops and plowed land.
- susceptibility to erosion which occurs particularly during the snowmelt and spring runoff period. Management techniques are possible which either reduce soil erodibility (eg maintaining soil structure by increasing organic matter content or by minimum tillage), or reduce impact of rainfall (eg mulch or cover crops).
- practices near drainage systems. Tillage operations near stream banks and livestock access to these areas during periods of high soil moisture contribute to streambank slumping.
- fertilizer and manure enrichment of soils in frequently hydrologically active areas. Identification of these areas is required. Sediments from these areas carry nutrients into streams.
- non-optimum management practices to minimize nutrient entry to streams. Optimum timing of fertilizer application, matching rates of application to crop needs, fall cover-cropping, and incorporation of organic residues of a high C/N ratio help reduce losses.

Remedial measures which reduce soil erosion and storm water runoff would reduce pesticide entry into water. Crop rotation can control some insects.

Pollutants of a non-agricultural origin can affect water quality in agricultural watersheds, including industrial organic contaminants and heavy metals from atmospheric fallout and pesticides from spraying of road sides.

* "Agricultural Watershed Studies, International Reference Group on Great Lakes Pollution from Land Use Activities", Summary Report, May 1, 1978.

Point Source Pollution Abatement -

Remotely sensed data can contribute to an integrated information set in the planning stages of some facilities with potential impact on water quality, and monitor pollutant entry and dispersion in some instances. Requirements on detail will continue to make airborne data needed in most cases.

Multiple data sets are required in planning of location and size of public sewage treatment plants and collection systems including environmental capability data (soils, geology, water resource, topography), land use data, and trend population growth maps. For example, a land resource information system in Toledo, Ohio uses a 4 hectare grid cell system and 1:50,000 photography as source data. Similar environmental data to that noted above is required to guide rural development into areas where soils and conditions are suitable for home sewage systems.

In the case of agricultural point-sources, including manure storage, livestock feeding areas, silos, the degree of siting separation necessary to protect water quality depends on soil type, slope and other site specific features.

There are many other point sources of pollution such as pulp and paper mills, power plants, canneries, industries, etc. Point source monitoring is effective in most cases.

9.5 Forestry Changes and Management Practices

Soil losses due to erosion are generally much lower for forested than for cultivated lands. Just as for agricultural lands, erosion in forested areas will be affected by rainfall, slope, soil moisture, and soil erodibility parameters, therefore these data would be included in an information system. Information is required on natural and man-made changes in the forests which affect water quality. Natural changes include fire and blowdown. Management practices which can affect water quality include logging, road construction, irrigation and drainage, fertilization, pesticides and herbicides and site preparation for regeneration (scarification, controlled burns). Management is expected to become more "intensive" in future, with the resulting possibility of greater impact on water quality from site preparation and improvement. Of interest is man's impact on the natural rates and processes of erosion and effects on water nutrient levels and temperature. Harvesting of trees along streams can result in higher temperatures, and falling trees into streams or dragging logs through them may cause blockages, channel changes and oxygen depletion from decomposing organic material.* Scheduling operations to avoid susceptible soils in wet weather can strongly reduce impact.

In addition to the activities noted above, non-renewable resource development (including seismic lines and pipelines) and route development (including

* "Forest Management in Canada, Volume 1", F.L.C. Reed & Associates, Ltd., Forest Management Report FMR-X-102, January 1978.

transmission line, highway and railroad construction) can influence stream sediment loading.

9.6 Rangeland Management

Rangeland fires can increase susceptibility to erosion. Access of livestock to streams during high soil moisture periods eg in the period after snowmelt provides a minor contribution to sediment loading, and herbicide application along streambanks may result in its entry to waterways.

10. Ecological Classification

Classification has been defined as the grouping of objects into classes on the basis of properties or relationships they have in common. Several classification systems have been developed in Canada to provide land information based on three concepts:* pedological, developed for soil surveys; phytosociological, developed for determination of forest site classes; and physiographic, developed for determination of forest sites and for multipurpose land classification.+ These concepts have contributed to the development of the hierarchically structured biophysical land classification system, an integrated approach to environmental inventory, based on the recognition of landscape characteristics as an ecological framework for the evaluation of natural resources. The Canada Committee Ecological (Biophysical) Land Classification is responsible for coordinating the continued development of a Canadian Land Classification System.

Aircraft photography has traditionally been used to provide much of the data for these surveys, and undoubtedly has influenced the nature of the classification systems used in the past and continuing to be developed. Satellite data is relatively new and attempts have been made to use it in existing classification systems. The four levels of the Biophysical Land Classification are: land region, areas of land characterized by distinctive regional climate as expressed by vegetation, and mapped at scales of 1:1 million to 1:3 million; land district characterized by distinctive patterns of relief, geology, and associated vegetation and mapped at 1:250,000 to 1:1,000,000 land system characterized by a recurring pattern of landforms, soils, and vegetation and mapped at 1:100,000 to 1:250,000; and land type characterized by a fairly homogeneous combination of soil texture, drainage and a succession of vegetation and mapped at 1:10,000 to 1:50,000. Satellite data has been used for mapping at the 2 small scale levels and information equivalent to the land system level has been obtained in certain cases eg rangeland studies.*

As satellite data with a range of resolutions from 80 m down to possibly 10 m becomes available, the range of classification levels which can be mapped will increase and the nested hierarchy of resolutions available can be related to the hierarchical structure of an appropriate classification system. Because of the

+ "Land Classification as a Base for Integrated Inventories of Renewable Resources", P. Gimbarzevsky, Proc. Workshop: Integrated Inventories of Renewable Natural Resources, Tucson, Arizona, January 1978.

* "Remote Sensing as a Tool in Ecological Classification", P.A. Murtha

monitoring capability of satellites, it seems certain that a classification system will eventually be used which makes use of that data fully. Initial steps toward remote sensing compatible classification systems have been taken,* which should in future develop more towards satellite compatible ecological classification systems. The original classification and inventory establish the baseline to which the updated inventory (monitoring) is referred.

* "Remote Sensing as a Tool in Ecological Classification", P.A. Murtha

11. Land Use Mapping, Land Development Planning, and Natural Resource Inventories

11.1 Introduction

The section above has focussed on land use (including internal farm land use ie whether row crops, forage crops, etc. are being grown or whether fields are in fallow), and on land management practices which potentially affect water quality. Monitoring possibly several times annually and at appropriate times is required to obtain the desired information. In land use-water quality studies, manual densitometry and color additive viewing of Landsat data has been found to have only limited capability for monitoring land use and land use change. Manual densitometry provided discrimination between wholly forested watersheds and partially surface mined watersheds but little else in one investigation, while color additive viewing showed promise in land use recognition and change monitoring but was limited to large-area analysis and changes such as large area logging or farming or surface mining activity.* For most land use and management monitoring and evaluation of relationships between land use and water quality, digital methods facilitating data integration and analysis will be required. Timely data is often needed.

Comprehensive land resource data is needed for land planning and policy decisions. A range of levels of detail is required by agencies involved in these decisions. Previous studies have identified the variety of products which now exist. "The user, for example a resource planner, must go to many different sources to obtain the information he needs (if in fact it exists). He will often find it confusing that the information he can obtain is available only at different scales and it may be impossible to synthesise or obtain a true appreciation of the information that does exist."+ Information products for example in water quality, soils, land-use, transportation, recreation, etc. may be in different scales, with differing terminology and accuracy. Land development and resource management planning decisions are complex today because of often conflicting environmental, social, economic and administrative factors. Satellite data provide a systematic input to land resource data systems and can assist in integrating and inter-relating other data sets.

Land resource information systems have been found to be helpful in identifying potential problem areas and evaluating alternative solutions.† Graphic displays and output products are required to communicate information to public policy decision makers.

† "Development of an Integrated Data Base for Land Use and Water Quality Planning", J. Adams and C. VanSchayk

+ "Benefits of Remote Sensing in Canadian Northern Resource Development", A. McQuillan, CCRS Report 75-6AX, January 1975.

* "Remote Sensing of Effects of Land Use Practices on Water Quality", D.H. Graves et al, University of Kentucky Research Foundation, Department of Forestry, NASA contract No. NAS8-31006.

The space and time scales of information products required are variable, with most intensive demands generally in urban areas. Planning is now seen as a continuous process that needs regular information on how a planning area performs. Comprehensive land development planning in urban and urban fringe areas involves consideration of water quality, recreation, housing, waste disposal, transportation, commercial development etc., so that agencies interested in land use data (as well as basic land resource data including soil characteristics, topography, hydrology, geology data) include planning agencies, engineering offices, waste disposal offices, environmental protection agencies, transportation agencies, zoning offices, parks and recreation offices, public health agencies, municipal planning offices, housing development agencies, etc. Resource inventory and land use data required in rural areas includes inventory data on agricultural lands, rangelands, forested areas, surface water, wetland and base ground (eg. rock, sand). In wilderness areas, mapping is required of geology, climate, landforms, soils, vegetation and hydrology (some features eg. permafrost and peatlands are particularly important in these areas).

There are several areal aggregations of land use change required including census tracts, enumeration districts, ownership, traffic zones, counties, and other zoning usually expressed in terms of a single type of use. Environmental information systems provide breakdown by natural regions, ie physiographic regions based on landforms, soils, climate and hydrology. Such natural areas provide meaningful management areas particularly where water-related concerns (sewage systems, runoff abatement, etc.) are prominent.

11.2 Use of Digital Data in Land Use/Land Cover Studies

Numerous investigations of land use/land cover and land use change have been made for urban, regional and wilderness areas using Landsat data and digital analysis methods. For example, one urban-regional land use change study used 4-band MSS data to classify an area into single family residential, commercial-industrial-multifamily, cleared land, forested, open space, and water.* This map was then combined with a land-use change map for the urban-rural fringe zone rural area showing only areas where changes had occurred since a previous date so that areas of change could be categorized. The latter was obtained by ratioing only 1 band of data (Band 5) for the two dates. Special processing ie noise reduction algorithms and spatial filtering techniques may be used to improve this change map. Verification involved overlay of satellite data with aircraft data and field checking, and operational use would involve use of change maps in the directing of ground checking operations.

* "Urban and Regional Land Use Change Detected by Using Landsat Data", W.J. Todd, Jour. Research U.S. Geol. Survey, Vol. 5, No. 5, Sept.-Oct. 1977.

A European study of computer aided extraction of land-use information from Landsat image data concluded that for larger areas of homogeneous land-use in central Europe, acceptable classification accuracies are obtained for land-use inventories.*

A land-use and land cover classification system developed for use with remotely sensed data by U.S. Geological Survey has classification according to urban or built-up land, agricultural land, rangeland, forestland, water, wetland, barren land, tundra and perennial snow or ice, with 2 to 7 sub-categories for each level. Land cover analysis using computer analysis of Landsat data has been one of the major applications of Landsat. A review of several major U.S. studies of land use effects and incorporation of the data into information systems has been made.#

Rubec and Thie have used Landsat digital data interpretation for mapping and summarizing land use/land cover types in rural Manitoba at a fairly large scale - 1:50,000+. Monitoring of land use change over a 4-year period was accomplished by classifying two sets of land use data (4 years apart) and then comparing them on a class by class basis to determine amount, location, and nature of differences in classification (and therefore in land use). The study concluded that Landsat data is quite useful for synoptic summarization of land use/cover in the study area. Although comprehensive automated land use monitoring was troubled by problems with spectral classification and data registration, the authors believe that this monitoring of some land use classes, such as wooded cover, agriculture land and water, will soon form an important component in a national land use monitoring program.+ This program could involve monitoring a series of sampling sites of selected representative or critical areas. Operational programs will be assisted by interfacing with cultural and other ancillary data, better registration, and better data (eg Landsat D). "Conventional" and expensive monitoring methods of using aerial photo interpreted land use maps and the Canada Land Data System for change detection also have some inaccuracies with errors due to line drawing, photointerpreter inexperience, etc.

In studies to determine the suitability of Landsat MSS data for operationally updating CLI land use data, Schubert found that most CLI classes can be mapped automatically at 1:250,000 scale.‡ Accuracies of 80% or greater were found in mapping grazing land, wetlands, barren ground, water bodies and croplands. Pastureland,

* "Evaluation of Landsat Image Data for Land-Use Mapping", W. Kirchhof et al, Int. Astronautical Federation Cong, Dubrovnik, Yugoslavia, Oct. 1, 1978, Pergamon Press

"Remote Sensing of Environmental Impact of Land Use Activities", C.K. Paul, Proc. 11th Int. Symp. on Remote Sensing of the Environment, Ann Arbor, April 25, 1977.

+ "Land Use Monitoring with Landsat Digital Data in Southwestern Manitoba", C.D. Rubec and J. Thie, Proc. 5th Canadian Symposium on Remote Sensing, Aug. 28, 1979.

‡ "Computer Processing of Landsat Data as a Means of Mapping Land Use for the Canada Land Inventory", J.S. Schubert, CLI Report No. 13, Lands Directorate, Environment Canada, Ottawa.

woodland and urban areas were less satisfactorily mapped.

11.3 Merging of Land Use and Archival Data

In addition to ancillary data acquired at about the same time as the Landsat data, which assists in land use classification, and archival historical data providing "first guess" information; it may be desirable to merge ancillary data such as soils, geologic, and topographic data with land use data. Many government functions are directly or intimately related to land-use and cover patterns, and land-use maps provide data for assessing spatial relations and proportions of land in various classes. Land planning and zoning requires integration of other information with land-use. The CGIS, for example, combines land capability with land-use data. Detailed soils data are very important to land planning, and merging of soils and land use data shows the spatial relations of land-use classes to soil characteristics. One study has used computer maps of eight soil interpretations indicating soil limitations for dwellings with basements, septic tank absorption fields, sewage lagoons, shallow excavations, area sanitary landfill, trench sanitary landfill, local roads and streets, and suitability as a source of road fill.[+] Both soil mapping units and land use data were digitized at the 2.5 acre cell level and assigned to a cellular grid system referenced to ground coordinates. Merging of the 2 data sets provides a quantitative basis for planning and zoning eg what areas are suitable for basement-type dwellings. High altitude aircraft data was used in this study.

11.4 Information Products on Land Use Change

Numerous provincial and local agencies have interest in land use change and development patterns in urban-rural areas, and many have responsibilities for land and resource management. There is some interest in land use and environmental concerns at the federal level as well. Agencies with interest include, for example, conservation authorities, agriculture agencies, transportation and communication agencies, environment and environmental protection agencies, health service agencies, natural resource (eg water, forestry, fish and wildlife) agencies, surveys and mapping agencies, park service, housing and urban development agencies, regional planning agencies, and municipal governments. The variety in type and extent of involvement results in a variety of information product requirements in terms of accuracy, frequency of update information required, level of spatial detail, required and geographic specifity of that data, and types of data aggregations (more detail and accuracy again generally required at the local level). The increased

+ "Interpretation of Land-Use Data and Soil Survey Data", T.L. Cox, Photogrammetric Engineering and Remote Sensing, September 1977.

requirements of detail, accuracy, timeliness, and completeness of data at the local level necessitate the ability to accurately, quickly, and cost-effectively overlay and merge multisource data, and therefore put strong demands on geographic information systems and inter-system compatibility.

Considering the varying level of generalizations of spatial detail, and aggregations of tabular data on acreages, housing, population, etc., a flexible "system" is needed to provide required detail at local levels and more generalized data when required by other levels of government.

In view of the considerations above, the following products are desirable as output of an information extraction facility which includes image analysis capability:

- the ability to provide directly, or to input digital data to a geographic information system which provides data at multiple scales and levels of generalization on land use and land use change. The ability to change map projection for different base maps is also desirable.
- hard copy products (colour, black and white) showing land use change areas and type of change involved. Transparent overlays showing these features may also be useful.
- aggregate tabulations of total area of change, area by various change categories, area of total change or change by category within specific administrative boundaries or zones or within specific geographic areas. Tabulations of the number and size of change areas may also be useful.

In agreement with the frequent requirement for more spatial and temporal detail at the local level, multicounty or municipal maps may be prepared with tabular aggregations at smaller units as input to planning models.

11.5 Land Use Impact Assessment

Land use data is relevant to many government functions. For example, many population projection models employ a census base plus a population rate of change based on land use changes. Population and land use changes may in turn be related to environmental quality. An extensive Central Atlantic Regional Ecological Test Site (CARETS) project investigated land use environmental impacts, including impact of land use on air quality.* Land use maps were overlaid with 2.5 km grids in built-up areas, and 5 and 10 km grids in less urbanized areas. Percent of land uses in each cell were converted to emission rates based on tons emitted per day of various residential, commercial, and industrial use types. Air quality maintenance areas may be established in which various land use alternatives and strategies for controlling rates of emission can be considered. Other investigations

* "Remote Sensing of Environmental Impact of Land Use Activities", C.K. Paul, Proc. 11th International Symposium on Remote Sensing of the Environment, Ann Arbor, April 11, 1977.

associated with the project included applications of the land use data products to the study of coastal environmental processes, and certain climatological impacts of land use patterns, including the urban "heat island".+

Land use planning includes consideration of effects of land use change on the environment. Impact assessment is based on information about past, current and possible future land use patterns and the effects of these changes on the environment. This requires monitoring of land use change and analysis of effects of those changes. If there is a good and continually developing understanding of relationships between land use and environmental quality, monitoring of land use changes and trends can provide warnings so that environmental effects can be anticipated, detected early if they arise, and minimized. The development of indices of land use practice relating intensity of land use and environmental stress to help assure that the carrying capacity of the land is not exceeded, has been suggested.† Some types of environmental stress monitoring are very amenable to remote sensing.

Land use change and population growth are related and these affect the environment. Changes in land use and corresponding population changes can result in:

- damage to environmentally sensitive areas. These include for example areas with limited carrying capacity (eg thin soil mantle), areas important in the food chain (eg wetlands), areas acting as absorptive biological buffers (eg areas which reduce impact of non-point source pollutants or mitigate changes in microclimate), areas close to surface water or ground water which might become polluted, etc.*
- changes in air, water, noise, solid waste or pesticides pollution. These can result from many factors such as large commuting distances, development of improper sites (eg housing with septic tanks in unsuitable soil, development in flood plains, poor choice of site for industry, or waste disposal, development over groundwater recharge zones lowering the groundwater and possibly contaminating the acquifer as well as influencing ground subsidence), and poor land use patterns (affecting quantity and quality of runoff, amount of groundwater available to dilute discharge of pollutants, etc.).

It is important to emphasize the importance of site selection for development, whether it be a transporation route in the tundra or waste disposal site in populated areas. Although more non-environmental ancillary data will be required

+ "Remote Sensing and Land Use Impact Assessment", T.H. Pierce, J.R. Gustafson, J. Kontsandreas, 12th Int. Symp. on Remote Sensing of Env., Manila, April 20, 1978.

+ "The Land Use and Land Cover Map and Data Program of the U.S. Geological Survey: an Overview," J.L. Place, Remote Sensing of the Electromagnetic Spectrum, Vol 4, Oct. 1977.

† "Remote Sensing and Land Use Impact Assessment", T.H. Pierce, J.R. Gustafson, J. Kontsandreas, 12 Int. Symposium on Remote Sensing of Environment, Manila,

in the latter decision, both require a multistage approach to focus in on alternative sites for detailed study. Without this approach, optimum site(s) may be missed, with all the attendant increased costs of maintenance, pollution control, etc. Not always will detailed baseline data be available when a project is considered (CLI data or "raw" data may be the only data available) but a geographic information system should be able to handle this site specific data. Assessment-modelling systems can use this information system to forecast the implications of alternative development scenarios on environmental and socioeconomic characteristics.

It has been noted that "quality assurance is needed in the remote sensing of land use impacts to win the confidence of program managers and decision makers. Currently standards and procedures in remote sensing are not uniform and are often difficult to defend under legal scrutiny".* In order to satisfy this quality criterion, increasing use can be expected of digital analysis of satellite data corrected for atmospheric and other varying conditions. The systematic coverage provided and quality control can reduce errors and ambiguities. A major problem of updating land use maps in the past has been cost of aerial photography for entire regions of interest. Photography may be acquired for specific purposes for specific geographic areas but regular coverage of entire areas for land use planning purposes is not likely to be available except possibly for large urban areas.

11.6 Other Remote Sensing Data

High resolution satellite and airborne synthetic aperture radar data also has applicability for land use monitoring, although cost may limit its use. Only in exceptional cases would cloud cover be severe enough to prevent data acquisition by alternative methods within acceptable time limits. Seasat data has shown excellent capability for monitoring some drainage features and certain types of cultural features. Studies with airborne SLAR have found forest vegetation a potential complicating factor, concealing some features and reducing clarity and homogeneity of others.+

Land Use Planning

Land use planning involves designing a unified development plan. It must consider the spatial relationships of all land uses. There are dynamic and complex interactions among air, water, land, biomass and cultural resources. Distinctions have been made in types of planning including:** physical planning which

** "Spatial Land-Use Inventory, Modelling and Projection/Denver Metropolitan Area, with Inputs from Existing Maps, Airphotos, and Landsat Imagery", C. Tom, L.D. Miller and J.W. Christenson, NASA Memorandum 79710, August 1978.

* "Remote Sensing and Land Use Impact Assessment", T.J. Pierce, J.R. Gustafson, J. Kontsandreas. 12th Int. Symp. on Remote Sensing of Environment, Manila, Philippines, April 20, 1978.

+ "Land-Use Analysis of Radar Imagery", F.M. Henderson, Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 3, March 1979.

emphasizes functioning of cities in an economic and engineering sense; advance planning which addresses problems of blight, obsolescence, suburbanization, and sprawl; and social planning which comprises a socioeconomic, political and physical approach to development and functioning of the urban community, addressing human and social considerations.

A spatial land-use inventory, modelling and projection study has been carried out by Tom et al for the Denver metropolitan area.* Ancillary map data was overlayed on a Landsat multispectral data base, land-use change prediction models were created and tested and land uses mapped. A digital landscape model ie. a multivariate, multitemporal mathematical model was developed with overlayed inputs of: existing maps including topographic, vegetation, soils, geologic, and transportation; socioeconomic data including census tract maps of population, family count, housing, and car ownership; and remote sensing imagery including photointerpreted and computer pattern classified satellite and aircraft images. Computed outputs included slope and aspect planes, socioeconomic density planes, minimum-distance planes, transportation access planes, solar-radiation planes, and Landsat transformations. Computer techniques in land-use modelling provided predictive simulations and display of the spatial behaviour of the landscape to natural or man-induced alteration and control. Model outputs included future land-use scenarios, site development plans, power plant site comparisons, zoning alternatives and other applications to economics, hydrology, planning, energy, etc.

Topographic slope and aspect data planes were input to a digital spectroirradiance model to compute a near-instantaneous incoming solar radiation or insulation data plane. The landscape model provided a method of interrelating in a common format data collected with diverse techniques and map scales by a wide assortment of public and private organizations. A model variable was one overlay of spatially registered data in a common cellular network. Ten acre square cells were used as prediction units. The landscape model included thirty-four map variables divided into land-use, physiographic, socioeconomic and transportation submodels, the latter three being regulating components of the landscape. Other variables pertinent to landscape modelling could include utilities service, domestic water supply, land ownership and parcel size, land values, soils, and zoning regulations. Projections for future land use were based on observations of changes in the area in the recent past.

* "Spatial Land-Use Inventory, Modelling and Projection/Denver Metropolitan Area, with Inputs from Existing Maps, Airphotos, and Landsat Imagery", C. Tom, L.D. Miller and J.W. Christenson, NASA Memorandum 79710, August 1978.

Data components of a natural-resource inventory data system for improving land planning include spatial data to specify: climate, demography, economics, geology, land use, minerals, population, recreation, soils, topography, vegetation, water and wildlife.

12. Wetlands

Requirements are for wetland mapping, inventory, and monitoring. Wetlands, particularly those with diversity of character, are many times more valuable from the standpoint of biological production than farm, forest or range.* They are regions of constantly fluctuating ecological conditions. Airborne remote sensing has been used extensively in wetland studies. Wetlands have been described as hydrologically active areas of water storage and discharge, sediment and nutrient filtration, and erosional buffering. The present Landsat data is hindered in wetland applications by resolution, and it is anticipated that TM data will be much more suited to updating inventories, monitoring and evaluating wetlands, both coastal and inland. While MSS data may be used for regional overall land use and land cover mapping, often a more detailed classification is desirable for wetland inventory in southern more complex areas of Canada.

Wetlands are definable in terms of hydrology, soils and vegetation. Because of water level fluctuations, and often gradual change in vegetation, soil or topography, the boundary of a wetland or wetland class is difficult to map. Any single measurement, aerial or ground, provides boundary information for one particular time. Aerial data from several dates are needed to identify wetland types and to determine hydrologic/vegetative boundaries.

Wetland baseline information for resource management may be required for several purposes including:* legislative or regulatory requirements; location of seasonally inundated and permanently flooded areas; decision on sites for agricultural, residential, or industrial development; wildlife management and habitat acquisition; and development of wildlife and recreational opportunities. The value of wetlands as flood buffer areas, pollution removal systems, sanctuaries, nurseries for commercially important fish and shellfish; and urban green space has now been recognized.† In wilderness areas, the information could be required in connection with transportation route location, non-renewable resource development, and hydropower development projects.

Digital satellite data has been found to be promising for mapping and classifying habitat types in northern large and extensively occurring wetland areas

† "Wetland Classification on the Alaska North Slope", J.W. Morrow and V. Carter, Proceedings of the 5th Canadian Symposium on Remote Sensing, Victoria, August 1978.

* "Three Approaches to the Classification and Mapping of Inland Wetlands", P.T. Gammon, D. Malone, P.D. Brooks, V. Carter, 11th International Symposium on Remote Sensing of Environment, Ann Arbor, April 25-29, 1977.

in Canada.[+] Digital analysis of satellite data of the Peace-Athabasca Delta region classified eight major habitat types including turbid open water, less turbid open water with emergent aquatic vegetation, flooded fen, immature fen/sparsely vegetated mudflats, immature fen/fen, low shrub/fen, tall shrub/mixed forest and coniferous forest. Textural colour patterns of the automated classification results were analysed to delineate hydrologic-vegetation units. The study using 1975 Landsat data (with colour infrared photography to compare results) identified significant habitat differences from maps of the area prepared when water levels were high in preceeding years. The results indicated the likelihood of providing a current habitat type map of the area, and detecting and monitoring environmental change.

A study of several sites in Alaska found that digital Landsat data could classify wetlands into 10 classes and 23 subclasses according to a hierarchical scheme based primarily on vegetation, soils and hydrology.[*] Digital analysis of this data was found to be a valid inventory technique where conventional aerial photo interpretation techniques cannot be used. Major classes separated included forested wetland, scrub/shrub wetland, emergent wetland, moss/lichen wetland, aquatic bed, reef, rocky shore, unconsolidated shore, unconsolidated bottom and rock bottom.

Wetland habitat mapping has been found to be more successful in one study, by combining soils and other ancillary data with Landsat data.[‡] Combined soils and spectral data permitted differentiation of some similar wetland and upland types, and enabled additional wetland types to be differentiated from non-wetlands.

In aerial photographic studies of wetlands, seasonal photography has sometimes been used because of natural water fluctuations, seasonal growth of emergent aquatic vegetation and continuous tree cover.[†] For example, one study used coverage acquired in February (high water, leaves-off), October (late growing season), and November (low water, leaves off).

† "Three Approaches to the Classification of Inland Wetlands", P.T. Gammon, D. Malone, P.D. Brooks, V. Carter, Proc. 11th International Symposium on Remote Sensing of Environment, Ann Arbor, April 25-29, 1977.

‡ "Using Landsat MSS Data with Soils Information to Identify Wetland Habitats", C.L. Ernst and R.M. Hoffer, Satellite Hydrology Symposium Sioux Falls, South Dakota, June 11, 1979.

* "Wetland Classification on the Alaskan North Slope", J.W. Morrow and J. Carter, Proceedings of the 5th Canadian Symposium on Remote Sensing, August 1978.

\+ See "Wetland Mapping and Environmental Monitoring", G.M. Wickware, Proceedings of the 5th Canadian Symposium on Remote Sensing, Victoria, August 1978, and references therein.

Ancillary data which has been found useful in evaluating wetlands includes topographic data, drainage patterns of surrounding area, cultural features, and water stage data.[+] Data used in verifying classifications have included aircraft and helicopter surveys, vegetation maps, topographic maps, and field reports.[‡] Because of the dynamic nature of wetlands, correlation between Landsat data and some types of ancillary data is affected by time spread between acquisition times of the various types of data. Near coincident acquisition is desirable. The increased spectral resolution of skylab MSS was found to permit categorization of complex areas, such as the Florida Green Swamp.[‡] TM data should therefore be more appropriate for complex-structured areas.

A common problem in natural resource inventories has been lack of adequate standard classification systems. The existence of this problem for U.S. wetlands has been pointed out, with its resulting incompatibility of maps and inventory products, which exhibit different scales, formats, minimum mapping units and classes and do not allow for valid comparisons of acreage, wetland type, or vegetative composition on a regional or national basis.[++] A new system has been designed to group ecologically similar habitats so that value judgements can be made; to furnish units for inventory and mapping and to provide uniformity in concepts and terminology. For wetland inventories as well as biophysical surveys, there is some flexibility in adopting a classification system, and one may be adopted which uses remote sensing data as a primary source of input data.

Scales used in wetland mapping are variable. Carter reports mapping of wetland boundary dynamics and vegetation at scales of 1:24,000 and 1:100,000 in several U.S. states, using color infrared photographs.[+] She notes that management requirements and legal considerations for wetlands necessitate great accuracy in boundary placement and map scales of 1:24,000 or larger.[++] The Peace River-Athabasca Delta Landsat data classifications were compared with those using photo interpretation

+ "Applications of Remotely Sensed Data to Wetland Studies", V. Carter, COSPAR: Space Research Volume XVII, 19th plenary meeting, Philadelphia, PA, June 14-19, 1976.

++ "Coastal Wetlands: The Present and Future Role of Remote Sensing", V. Carter, 11th International Symposium on Remote Sensing of Environment, April 25-29, 1977.

‡ "An Analysis and Comparison of Landsat-1, Skylab (S-192) and Aircraft Data for Delineation of Land-Water Cover Types of the Green Swamp, Florida", A.L. Higer et al, U.S. Geological Survey, Water Resources Division, Miami, Florida, Nov. 1975.

+ "Three Approaches to the Classification of Inland Wetlands", P.T. Gammon, D. Malone, P.D. Brooks, V. Carter, Proceedings 11th International Symposium on Remote Sensing of Environment, Ann Arbor, April 25-29, 1979.

techniques on 1:100,000 scale color infrared photographs.

Although biophysical surveys and many mapping applications benefit from reduced field surveys made possible by remotely sensed data, the reduction is particularly important for wetlands because of the difficulty in getting this data, and because of the need for timely output information for decision making. Ground data is hard to obtain because of poor wetland trafficability, lack of topography preventing overview of an area, and large amounts of frequently tall vegetation.[‡]

Satellite data has been used to monitor large-scale coastal wetland alterations (dredge disposal, canal construction, road building) and to classify marshes by salinity type. While the data has been found useful for large, vegetated coastal marshes, a spatial resolution of 1/4 ha or less is felt necessary for interface with inventories at all levels.[#] It has been reported that Texas plan to map natural vegetation associations for the state at 1:250,000 using Landsat digital data.[#] Generally coastal wetland inventory map scales are at scales of 1:24,000, 1:100,000, 1:250,000 and 1:500,000 in the U.S.

Three dimensional data is required for wetlands. Submerged aquatic vegetation which shifts in position and abundance from year to year is a problem for wetland mappers, and turbidity in coastal waters restricts remote sensing techniques of monitoring.

Environmental monitoring of coastal wetlands is required to examine seasonal and long term succession in wetlands and to examine how they are affected by such factors as salinity changes, sediment buildup, flooding, drainage and land use effects. A better basic understanding of these hydrologically active areas is needed, requiring for example relating physical parameters with vegetation distribution. An information system would require acquisition of multiple data types to establish these relationships, followed by ongoing monitoring of several variables to identify changes occurring. In addition to the above natural exogenous factors information on ecological impact of practices such as herbicide treatment of vegetation, and the effects on it (ie photosynthesis and productivity) and on biological populations is required.

In addition to those parameters discussed above, water quality measurements of pH, dissolved solids, and sediments are needed.

"Coastal Wetlands: The Present and Future Role of Remote Sensing", V. Carter, 11th International Symposium on Remote Sensing of Environment, Ann Arbor, April 25-29, 1977.

‡ "Wetland Inventory and Condition Evaluation Techniques", N. Roller and J. Colwell, IV Pecora Symposium, Sioux Falls, October 10-12, 1978.

13. Fish and Wildlife

Fish and wildlife agencies require information on the status of populations, and on the amount, extent and condition of their habitat. An extremely wide range of information products is required both on land and water habitat and their seasonal and long term changes. Information product requirements vary over a wide range of space and time scales, and analysis requirements also vary from simple photointerpretive methods to multisource data integration and digital analysis. Sampling strategies, whereby reconnaissance level data is used to direct more detailed surveys, are frequently used to reduce data gathering costs. Many information products produced by other agencies, eg forestry maps, ice and snow cover maps, water quality data etc., are of use to fish and wildlife agencies, and their requirements are often for analysed products, ie where several types of data have been merged and processed to produce an information product, which become one input to population or behaviour models. Much information related to "human habitat condition assessment" ie land, water and air environmental quality, is required in these studies. It is therefore important that wildlife agencies can acquire information from other environmental and resource agencies, sometimes in a very timely manner. Moreover since wildlife species are "integrators" of the environment conditions they are exposed to, wildlife agencies can provide valuable feedback information to agencies concerned with environmental quality. These factors clearly establish the requirement for adequate communications capabilities.

Seasonal changes are a major factor in wildlife behaviour and filling in this time dimension particularly with information on the hydrologic cycle (weather, ice snow and water) has been a major contribution of satellite data. Vegetation conditions are a major determinant of wildlife habitat, and satellite data has geographically broadened the information base particularly through the use of multistage approaches.

- All wildlife species require an adequate food supply, cover, and supply of water, so that population control may be accomplished by management of these habitat factors. The information requirements of wildlife managers that remote sensing data can help satisfy have been listed as:*
- the amount, distribution, and accessibility of suitable habitat types classified according to ecologically appropriate classes and to animal populations expected to occupy them.
- habitat condition and factors related to determination of the habitat's carrying capacity (eg. food supply and its quality in relation to what the habitat is

* "Remote Sensing Applications to Wildlife Management and Habitat Control", D.M. Carneggie, The use of remote sensing in conservation development and management of the natural resources of the state of Alaska, Dept. of Economic Development, State of Alaska.

potentially capable of producing).

- the ecological characteristics of each kind of biological community identified as "habitat" (eg. species composition, plant distribution, plant succession, vegetation-soil-moisture relationships, environmental factors, water distribution, etc.)
- identification of special management problems associated with diverse habitat types, eg. undesirable plants, loss of plant vigor due to pollutants, detrimental effects of other land use activities,
- animal census data including kind of animal and numbers utilizing a given habitat, distribution and migration, and season of use of a habitat.

Information requirements therefore range from a regional overview of habitat provided by satellite data, to large scale photography (eg. 1:2000-1:5000) for animal census and evaluation of habitat components, to ground surveys for determining quantity of available forage. Timing of data acquisition for a particular phenomena of interest is often critical. For example, often snow or ice-free areas are of importance for feeding or resting. Flooding, snowmelt and ice freeze-up and breakup are important periods for some wildlife. Information on the distribution and availability of fresh water supplies for water flow habitat, drinking, fish spawning, etc. requires data gathering at particular times. Timing of data acquisition for vegetation studies will generally be more critical for detailed ecosystem studies where individual plant species are separated on the basis of phenological stage of development, than for regional wetland habitat classification.

Several types of remotely sensed data have been found useful for wildlife studies. Water temperature, important to aquatic life, may be monitored by thermal IR methods. This data has also been used for day-night animal population counts. Ice and wave data obtained by radar (possibly in combination with ancillary data) could be valuable in marine mammal studies. In this case, as in many others, the wildlife agency might be a secondary user, with the high cost of data acquisition and processing borne by a "primary" user agency.

The concept of acquiring comprehensive baseline data, then using satellite reconnaissance level data as an alarm to significant habitat changes ie deviations of vegetation or hydrology-related phenomena (snow, ice, water levels, water quality), from "normal" conditions, is central to wildlife management and environmental impact studies.

Detailed wildlife habitat studies have usually made use of high resolution images, with characteristics such as size, tone or colour, shape, pattern and texture useful in detecting and discriminating features of interest. Features of interest would include for example vegetation species composition, surface phenomena, including litter and soil crust characteristics, rockiness, nature of humus layer, presence of disturbances (erosion), and moisture regimes.[*] Further measurement of vegetation parameters would include plant density, plant cover, plant height and frequency. Data on these parameters may be obtained from photos by visual or photogrammetric means, or from ground sampling plots located from the photos.

The three requirements for wildlife subsistence (and therefore management) ie food, cover and water supply all vary with time of year, underlining the importance of sequential coverage for this application. Considering food supply, temporal coverage permits monitoring the rate of forage development, assessing the time of availability of the forage, and predicting, with the aid of climatic information, the green feed period.[*] Weather and human activities are exogenous influences on all three of these subsistence requirements. Simulation models can be used to predict influence of changes in either of these driving factors, and to choose between alternative management strategies. Clearly any improvements in forecasting these exogenous factors are desirable. A data base would contain records of both types of factors, including ancillary data related to each.

Landsat data has been used extensively with supportive data in studies of wildlife habitat. Ancillary climate and topographic data is useful in classifying cover type and because of its influence on wildlife behaviour. Several derived data elements are very important for wildlife.[+] These include edge (length of interface between two vegetative/surface types or snow or ice boundaries), interspersion (heterogeneity of vegetation/surface feature types), and distance to nearest cover, water, food, etc.

In Arctic areas, monitoring of ice and snow rate of disappearance from traditional nesting grounds of Arctic geese by NOAA and Landsat data has been successful and
‡nesting success each year. This information is needed for the establishmen
of cost effective.‡ This is the principle environmental determinant of regulations
governing daily and seasonal limits, times and lengths of seasons, harvest quotas,

‡ "Remote Sensing Oceanographic and Terrestrial Information Systems", A.K. McQuillan, J.C. Henein, L.W. Morley and D.J. Clough, Proceedings of the 1st Conference on the Economics of Remote Sensing Information Systems, San Jose, January 1977.

+ "Remote Sensing Applications to Wildlife Management in the U.S. Fish and Wildlife Service", A.D. Marmelstein

* "Remote Sensing Applications to Wildlife Management and Habitat Control", D.M. Carneggie, Alaska Remote Sensing Symposium, Anchorage, 1969.

and other limitations for hunters of waterfowl. Supporting information includes distribution of populations among available nesting areas, breeding behaviour, breeding population size, age structure, and migration affinities of fall flights into various flyways and harvest areas, etc.[+] Because nesting sites are required within a critical two or three week period, this is one wildlife application where satellite SAR data may be required to obtain data in the presence of cloud cover that is common at this time of year.

Ice conditions are of major importance to several types of marine mammals. Polar bears are extremely dependent on sea ice for their food. They concentrate in areas where leads form frequently since they are the areas where seals congregate because of easy access to air. Satellite data can indicate the time during breakup when bears can no longer use the ice for their offshore movements. Many whales found in the Arctic are migratory, arriving in open water through leads in the spring and departing in open water in the fall. Multistage approaches have been used in studies of the harp seal on its whelping grounds off the east coast. Satellite data provides an overview of ice conditions, and aircraft sensors operating in the visible and ultraviolet regions determine the extent of the seal herd and the distribution of seals on the ice. The approach permits understanding of habitat-seal distribution relationships, and selection of appropriate survey sampling techniques to provide the best estimates of pup population for a given year.[‡]

Requirements for storing and merging of multiple types of detailed data in data bases and information extraction facilities are generally more stringent (in terms of varieties of data) in the research phase than in the operational monitoring phase. In the former, analysis of wildlife behaviour involves investigating the effect of many factors to find their relative importance and derive interrelationships. Behaviour is influenced not only by environmental conditions (some of which may be monitored remotely) but also by other factors such as social behaviour and circadian rhythms.[++] (Radio telemetry may be used

++ "Synergistic Remote Sensing of Walrus and Walrus Habitat", G.C. Ray and D. Wartgok, Workshop on Remote Sensing of Wildlife, Quebec City, November 1975.

‡ "Remote Sensing and Ecosystem Management", D.M. Lavigne, N.A. Oritsland, and A. Falconer, Norsk Polarinstitutt, Oslo, 1977.

\+ "Remote Sensing Applications to Wildlife Management in the US Fish and Wildlife Service", A.D. Marmelstein in the study of circadian rhythms). Ray and Wartgok††† describe the use of instruments sensing throughout the electromagnetic spectrum including active devices (SLAR and laser profilometer) and passive devices (cameras, thermal scanners and microwave radiometers) to provide "convergent" evidence of walrus populations, thermal energetics, and habitat conditions including ice distribution, thickness, type, age. Even in the research phase, multisensor or modelling techniques which will permit zooming in on wildlife in their habitat are required. In the case of marine mammals with ice as a natural habitat for example, not only can weather change the condition of the habitat, eg. snow cover or temperature, but can shift it spatially.

The synergistic effect of multiple data sources is important in contributing to a more in-depth understanding of ecological principles and wildlife behaviour. Diversity has been listed as one of the five fundamental parameters describing ecological processes, and if a species is eliminated (a factor tending to reduced overall stability), it is important to an understanding of life-support systems in general, to understand those factors which in an integrated fashion contributed to a cataclysmic threshold crossing. Once relationships have been established, ongoing operational monitoring of a limited number of parameters indicative of key ecosystem conditions will often be adequate.

The narrow time window dependent on season and meteorological conditions during which data on habitat may be collected has been noted above. Meteorological data is important both for scheduling and interpreting some types of data acquisition on wildlife population and thermal energetics. Precipitation, winds and ambient temperature can affect temperature difference between an animal and its environment, and therefore affect its detectability.*

Frequent satellite coverage in specific areas at specific times of the year is a common requirement for wildlife studies. Dynamic summer conditions in the Arctic require multiple coverages, including data to schedule detailed surveys. The desirability of daily Landsat coverage of water bodies along waterfowl migration routes at appropriate times of the year has been noted.*

Considerable use has been made of satellite and airborne data in assessing

* "Remote Sensing and Ecosystem Management", D.M. Lavigne, A.A. Oritsland and A. Falconer, Norsk Polarinstitutt, Oslo, 1977.

††† "Synergistic Remote Sensing of Walrus and Walrus Habitat", G.C. Ray and D. Wartgok, Workshop on Remote Sensing of Wildlife, Quebec City, November 1975.

terrestrial and aquatic ecosystems in northern Canada where survey costs are high and available data is limited. For example, Lavigne and Falconer[*+] have discussed the role of Landsat in outlining natural habitat regions, and compared the information content of the data with the Arctic Ecology Map Series which outlines sensitive and critical areas for various species but has nonuniform quality because of nonuniform data availability. Studies of several Arctic areas with Landsat showed a diversity of habitats and "appear to offer a clearer delineation than that provided by the Arctic ecology map series." They point out that the final printed product is a compromise between the knowledge of what exists and the limitations of scale, and therefore clarity in the final product. They discuss utility of Landsat for identifying and outlining habitat of the lesser snow goose and grizzly bear, for studying the dynamics of fish populations as they migrate out of the Mackenzie Delta with spring breakup and return before fall freeze-up, and for studying lakes in which Arctic char are found and the relationship of these lakes to each other and to the ocean, vegetation, and geology of the area. It has been noted, following studies of beluga whales by aerial photos, that once the type of estuary where they gather is understood, satellite imagery can be used to locate all suitable estuaries along a coast.

Digital Landsat data analysis has provided most of the information required in vegetation mapping of large areas of Alaska for moose habitat assessment.[‡] Map products at 1:250,000 scale and with 12 classes were produced. Landsat-based analysis of vegetation types provide potential caribou range assessments which must be supplemented and modified using climatological data on snow depth, windpacking of snow cover, and formation of ice crusts. Deep snow affects survival rates of species such as moose through lack of food and increased losses to predators. Wildfires are an important factor in habitat creation.

It is important to note that the wildlife manager's requirement for cover type information will generally be different from that of other users. In wildlife habitat inventory data gathering in more populated areas, natural areas will be classified more intensively than agriculture or urban areas, with detailed plant association patterns shown. For example, detailed vegetation-type maps have been produced in Texas, including average height and canopy cover of dominant plant

‡ "Use of Landsat Imagery for Wildlife Habitat Mapping in Northwest and East Central Alaska", A. LaPerriere, Alaska Coop. Wildlife Research Unit, University of Alaska, NASA contract NAS5-20415.

+ "A role for Landsat data in the ecological mapping of the Canadian Arctic", D.M. Lavigne and A. Falconer, Symposium on Machine Processing of Remotely Sensed Data, Purdue University, June 21-23, 1977.

* "Remote Sensing and Ecosystem Management", D.M. Lavigne, N.A. Oritsland and A. Falconer, Norsk Polarinstitutt, Oslo, 1977.

species at specified locations.+ Digital analysis of Landsat data was supported by information from other vegetation studies, district biologists, aerial photography, topographic maps, county highway maps, and previously documented maps containing information related to changes in land use, vegetation, soil types and range sites. Output information products of classification are base maps (scale 1:126,000) used for delineating species management unites. The wildlife resources within each unit will be administered according to appropriate management treatments necessary to produce sustained yields of wildlife resources. The units become stratification guides for population modelling studies where management alternatives are examined with respect to various factors influencing populations.+ The importance of spatial distribution of cover types as an indicator of habitat quality is well recognized. Not only is presence and abundance of principal vegetation and terrain cover types in supplying food and cover important, but spatial distribution and accessibility in relation to seasonal and daily radius of activity, respectively of wildlife are as well. Models of habitat quality have been developed to numerically estimate quality with edges (boundary between two cover types), which are superior as habitat and which may be determined by aerial observations, a key parameter.[†]

The procedure of collecting baseline data, then monitoring change is well established in population dynamics and environmental impact studies. Changes in relative abundance and spatial distribution of key cover types and corresponding population changes are required. As data analysis and integration methods evolve, studies will make effective use of archived aerial photographs and previous fragmentary results, in combination with current data. The present spectral and spatial resolution of Landsat data has made it suitable for regional analysis, but for most development projects more detailed data is required prior to construction, for impact assessment and for reclamation assessment. Some of these more detailed requirements will be satisfied by future satellite data. Comparisons have been made of interpretation detail and accuracy using colour infrared aerial photography and three types of analysis, including manual photointerpretation of raw data, photointerpretation of density-sliced photography, and computer classification of

†"Quantitative Evaluation of Deer Habitat", N.E.G. Roller, IV Pecora Symposium, Sioux Falls, October 10-12, 1978.

\+ "Wildlife Management by Habitat Units - A Preliminary Plan of Action", C.D. Frentress and R.G. Frye, Proceedings of NASA Earth Resources Survey Symposium, Houston, June 1975.

scanner-digitized photographic data.* Analogue image density analysis gave unsatisfactory results. The study concluded that "The general impression at this point in our analysis is that the subjective judgement of human interpreters familiar with the area involved remains a critical factor which is difficult, if not impossible, to duplicate with computer assisted analysis".* This suggests the need not only for man-machine interactive capabilities in automated analysis, but the desirability of advanced graphics capability including stereo viewing. Some photointerpretation specialists have developed an enormous facility through prolonged experience for extracting information using only black and white photography in large part because of relief information in stereo pairs. In somewhat the same way that sensors permit extension of measurement space beyond the limited human visual part of the electromagnetic spectrum, advanced graphics may permit taking advantage of human photointerpretive abilities extending applications beyond just terrain topographic studies to other applications where the third dimension represents another type of information. Such visual displays can also often facilitate communication of various types of information or management alternatives to policy makers more effectively than numerical data.

Several studies of waterfowl habitat have been made using digital remote sensing data.+‡ Waterfowl habitat quality depends on both water conditions and the terrain conditions of the surrounding wetlands and upland cover types.+ The Environmental Research Institute of Michigan+ have developed a habitat quality model which accounts for both water conditions and terrain factors. Water conditions considered are pond number, area and size-class, distribution, while terrain characteristics evaluated include presence of spatial arrangement of certain terrain types. A level slice of band 7 MSS data was used to generate a map of ponds, and adjusted by data from aircraft survey transects which provided a sample approximately one percent of the total area. This double sample technique was

‡ "Documenting A 10-Year Change in Land Use and Waterfowl Habitat from Digitized Aerial Photomaps", G.D. Adams and G.C. Gentle, Proceedings of the 5th Canadian Symposium on Remote Sensing, Victoria, 1978.

+ "Quantitative Evaluation of Habitat Conditions for Effective Waterfowl Management by Computer Manipulation of Landsat Classified Data", J.E. Colwell et al, 12th International Symposium on Remote Sensing of Environment, Manila, Philippines, April 20-26, 1978.

* "Remote Sensing Applications to Wildlife Management in the U.S. Fish and Wildlife Service", A.D. Marmelstein

necessary because MSS, while providing large area coverage, does not have adequate spatial resolution to detect small ponds. In attempting to evaluate habitat quality, the study area was gridded into sections of 1 square mile for section by section evaluation. This corresponds approximately to the home range of some waterfowl. The procedure imposes an artificial grid system on the natural characteristics of the study area, but also characterizes habitat on the basis of readily definable land ownership and management units.*

Because of the wide variety of types of wildlife and their characteristic habitats, home ranges and migration routes, the number of information products required and different aggregations of basin data could be numerous. In the above study while a map of general land characteristics and significant waterfowl habitat requirements were produced, it is noted that aggregations for example, for different species of waterfowl or of all depressions could be produced if desired by the resource manager.* Landsat data (like an aerial photograph) may be processed and analysed for a specific purpose in an optimum way. The sufficiency of information products which a wildlife agency obtains from other agencies (eg. forest inventory, snow cover maps, etc.) in satisfying its requirements naturally depend on specific objectives, but for detailed habitat and population dynamics studies, and particularly those of a research nature, requirements for specific types of land, water, and meteorological data (as well as non-environmental data) and special integrations and processing of that data, can be demanding and necessitate access not only to several data bases but also to a powerful information extraction facility.

"Quantitative Evaluation of Habitat Conditions for Effective Waterfowl Management by Computer Manipulation of Landsat Classified Data", J.E. Colwell, N.E.G. Roller, D.L. Rebel, E.A. Work, 12th International Symposium on Remote Sensing of Environment, Manila, Philippines, April 20-26, 1978.

* "Wetland Inventory and Condition Evaluation Techniques", N.E.G. Roller andJ.E. Colwell, IV Pecora Symposium, Sioux Falls, South Dakota, 1978.

14. Air Quality Monitoring

Air pollution may be monitored by remote sensing devices using either direct methods (active or passive sensors with suitable characteristics) or indirect methods (eg effect of pollutants on vegetation).

14.1 Effects of Air Pollution on Vegetation

Vegetation is a sensitive indicator of several types of air pollution. Plants are susceptible to air oxidants, including sulphur dioxide, ozone, flourides, nitrous dioxide, peroxacetyl nitrate and copper oxides which cause foliage discolouration.* Susceptibility to damage varies with species, stage of growth and exposure time and is affected by air temperature, humidity, light intensity, air circulation and water supply. Topography affects air circulation and therefore the concentration of pollutants in certain areas. Intensity of industrialization and urbanization influences amounts of pollutants emitted. These data would be included in the data base of a system using vegetation as a pollution indicator, or to predict potential damage to vegetation from various pollution levels.

Sulphur dioxide affects chlorophyll a and b pigments, detectable remotely because of loss of reflectance at infrared wavelengths. Tone, texture, size, and shape are used in photointerpretation studies of damaged vegetation. Levels between 0.1 and 1.0 ppm have often been found to cause damage such as reduction in yield of crops or leaf blotching.* The feasibility of Landsat monitoring of large forest areas damaged by sulphur dioxide fumes has been demonstrated in Canada.+

Smoke and dust affect the light energy available for photosynthesis around towns and industrial sites by reducing light intensity (particularly UV) and hours of bright sunshine, and by the blackening of leaves by dust particles. Air quality and meteorological measurements, assisted by use of infrared line scanners and radiometers showing for example areas of fresh cold air, have been used in aid of regional planning to promote improved air quality in highly populated areas.*

Necrosis of plants and defoliation of some trees is common at high ozone levels. Some pollutants can be concentrated in the food chain (just as for water pollution). For example, when flourides are deposited on pastureland, the grass concentrates the pollutant resulting in poisoning of grazing animals.*

Detailed air-oxidant damage inventories have already become part of forest management plans in East Germany which experiences high annual damage. In less

+ "SO_2 Damage to Forests Recorded by ERTS-1", P.A. Murtha, Proceedings of the 3rd ERTS-1 Symposium, Volume 1, Section A, Goddard Space Flight Center, Washington, 1973.

* "Monitoring Environmental Pollution by Remote Sensing", P.A. Vass and J.L. Van Genderen

heavily populated areas, such monitoring could occasionally assist local planning as well as keeping inventories accurate. Potential uses of the remote sensing information include:* (a) determination of the pollution source. Consistent prevailing winds may establish identifiable patterns. (b) siting of air quality sampling stations. Some would be located in vegetation damage areas indicative of high pollution concentration. (c) input to air quality models. These usually determine pollution concentration within a given geographic area. (d) monitoring of vegetation damage in successive years to assess pollution control successes. (e) economic evaluation of vegetation damage. Sampling methods may be used.

14.2 Direct Detection of Air Pollutants

Specific air pollutants may, in principle, be monitored from satellite or aircraft platforms provided sensors are employed which are tuned to the usually narrow absorption bands of these constituents. Some air quality studies have been carried out using coarse resolution meteorological satellite data and relatively higher spatial resolution Landsat data. The coarse resolution data from geostationary satellites provides smog and haze information and a time series of frequent observations on airborne particulate matter both natural and man-made, including smoke plumes, blowing dust and airborne volcanic material.† Landsat data may be used for defining the location, extent, source and diffusion characteristics of smoke plumes. A Landsat image provides an aerial perspective at one instant of time, which can assist air particulate concentration sampling, provide geometric and diffusion information, complement statistical data obtained by aggregating ground sampling measurements over time, and permit comparisons of 2 or more plumes within an image under particular meteorological conditions.

Plumes are affected by many factors including stack height, exit velocity, emission temperature, advection (wind velocity), turbulent diffusion, and topography. Remote sensing in both air and water studies provides circulation information much needed for modelling. Landsat data may provide useful information about the turbulent structure of the atmosphere and the way it affects pollutant dispersal.+ Statistical models describe a "time averaged" distribution of plume particles but

† "Monitoring Air Quality from Satellites", F.C. Parmenter, Proceedings 4th Joint Conference on Sensing of Environmental Pollutants, American Chemical Society, 1978.

+ "Remote Sensing of Pollutant Plumes from Landsat", P. Brimblecombe, A. Armstrong, T. Davies, Journal of the British Interplanetary Society, Vol. 31, No. 1, January 1978

* "Applications of Remote Sensing to Vegetation Injury Caused by Air Pollution", D.R. Williams

instantaneous departures from regular distributions (ie Gaussian where particles move randomly and independent of each other) may provide important information on atmospheric structure. Densitometric measurements of Landsat images have provided information on lateral diffusion profiles and smoke plume height, lateral diffusion coefficients and plume particulate concentration. Digital analysis of Landsat data has been used to quantitatively establish the lateral and transverse extent (and diffusion) of the plume, as well as its source and geographical location.* Advantage may be taken of the difference in reflectance/absorption characteristics in the different MSS bands, and of multitemporal differences eg use of two images of the same area at the same time of the year, one with and one without a smoke plume. Contrast stretching, band ratioing and density slicing all may assist analysis.

Many airborne and ground based remote sensing techniques have been developed. Satellite platforms will eventually be used for some of them. Air pollutants that are important and that may be monitored remotely include particles/opacity, SO_2, NO_2, CO, light hydrocarbons, HCL, HF, NH_3, NOx, H_2S, HNO_3, O_3 and vinyl chloride; and eventually heavy hydrocarbons, SOx, some specific trace elements and chlorinated hydrocarbons.[+] Passive remote sensing devices including correlation instruments, vidicons and aircraft photographic techniques are useful for direct observation of hot plumes and indirect observation of complex sources through perimeter monitoring. Active laser devices including Lidar, differential absorption and laser Doppler velocimeter are required for direct observation of cool plumes. The use of satellite platforms, for example, for correlation spectrometric techniques could permit large area monitoring of long term buildup of pollution, interaction between sources of air pollution and the oceans, and development of predictive models for pollution forecasts.[†] A comprehensive air quality monitoring system could include measurements of air pollution from satellite, aircraft, and ground stations, meteorological data from ground stations and satellite platforms, and vegetation damage and water quality data by remote and surface methods. Ground-based measurement methods may include manual, automatic, extractive, point or integrated sampling or remote measurement. Spatial resolution requirements for atmospheric studies will in many cases be coarser than that available for surface features from high resolution satellites.

† "Satellite Monitoring of Atmospheric Gases", A.R. Barringer and J.H. Davies, Journal of the British Interplanetary Society, Vol. 30, 1977.

+ "Legal Aspects of Remote Sensing and Air Enforcement", M. Griggs and C.B. Ludwig, APCA Journal, Vol. 28, No. 2, February 1978.

* "Satellite Remote Sensing for Smoke Plume Definition", T.T. Alfoldi, Proceedings 4th Joint Conference on Sensing of Environmental Pollutants, American Chemical Society, 1978.

estimated

Air pollution dispersion models generally use a mix of measured, and assumed parameters. With suitable monitoring devices, particularly remote sensing devices providing range resolution, actual measurements may be available for most or all of the important parameters. For example, it has been noted that dispersion from point sources is usually modelled with some type of Gaussian dispersion formulation, using estimates for plume centerline height-of-rise (estimated with empirical formulas from heat flux, momentum flux, stack height, effluent and ambient temperature, stability, and vertical wind profile), crosswind and vertical dispersion coefficients, atmospheric stability, mixing depth, and mean wind velocity.* Remote methods could provide actual measurements of plume centerline heights, centerline concentrations, vertical and horizontal dispersion coefficients and transport winds.

Aerial surveys assist in design of contact monitoring networks, and plant site selection as well as plume tracking. Advantages of remote methods include rapid response, unannounced and non-interfering monitoring.

* "Remote Sensing of Air Pollutants", J.A. Eckert and R.B. Evans

15. Energy- and Mineral-Related Applications

Energy and mineral resources are of major interest to the provinces. Mapping and environmental monitoring data which will assist in exploration, project development (including transportation infrastructure) and environmental impact assessment become a valuable input to land information and management systems. The contribution of satellite data in petroleum and mineral exploration activities has been examined in detail in a JPL study* and is summarized here. Much of the analysis of satellite data and its merging with other information sources to assist exploration objectives has been done by industry staff. Development of powerful analysis techniques can provide advantage to a company in this competitive field.

15.1 Geologic Mapping: Geologic mapping involves mapping of the geometry and composition of the earth's surface materials. Geologic maps are fundamental to a comprehension and efficient exploration and hazard assessment program. Since the level of mapping detail required is related to the detail of exploration or environmental study, satellite data must be augmented by airborne and other data depending on end use. Very detailed mapping is required for selection of drill or mine sites and delineation of site hazards, more general mapping to select areas for seismic work, sampling or soils studies, and regional mapping to identify petroleum or mineral areas. Rock type information in geologic mapping requires data on mineral composition, elemental composition and properties, subsurface extent, density, texture, color, temperature and thermal inertia, and erosion patterns.

It will be possible to produce geologic maps at a scale of 1:100,000 using Landsat-D data. Although the Landsat MSS bands have permitted improved geologic mapping, the new TM bands (combined with improved spatial resolution) are expected to augment present capabilities in several ways. In the 1.6 uTM band there is a greater range of reflectance of surface materials than for MSS bands facilitating class separation and mapping of rock types, even with 50% vegetation aerial coverage. For geobotanical purposes the band will provide a capability to measure vegetation stress by reflecting the underlying soil composition in addition to other factors. Distinctions between some rock types on the basis of mineralogically related density differences and different moisture retention which influence thermal inertia may be observed in the thermal IR

* "Landsat Follow-On: A Report by the Applications Survey Groups" NASA Technical Memorandum 33-803, prepared by Jet Propulsion Lab, Dec. 15, 1976.

region. (Information improvements may be obtained by combining TM and other data such as HCMM or airborne data to give day-night coverage.) The TM 30m resolution will facilitate mapping of: - geomorphic (landform) features including permafrost, glacial features, and fluvial features such as drainage boundaries, alluvial fans, flood plain levees, abandoned meanders and stream terraces. Overall geomorphic mapping needs include data on drumlins, eskers, kames, moraines, ridges, trenches, braided streams, meanders, levees, bars, beaches, reefs, cusps, banks, pengoes, beaded streams. Shadows help in highlighting these features from remote sensing platforms.

-structural features including folds and fractures. Structural mapping of linear, curvilinear and circular features has been a major application.+ Tonal differences, shadows and drainage and texture have highlighted folds, faults and lithologic differences. The 30m resolution should permit delineation and analysis of large scale lineament fine structure and of shorter linears. Structural mapping and short linear study directed to location of areas of detailed study, sampling, geophysics and drilling will benefit from repeated views noting surface changes (denudation, fault offset, etc.).

-circular features providing guides to mineral, oil and gas or saline deposits or providing indicators of high temperature activity nearer the surface than elsewhere and therefore possible sources of geothermal power;

-orthophotomaps at a scale of 1:100,000 which graphically represent landforms and cultural features and are useful in regional structural analysis. Characteristic shapes or tones in the imagery and linear patterns associated with ridges, streams, shores and property lines provide information on morphologic, hydrologic and cultural features. Many previously unknown linear, curvilinear and circular features identified using MSS data are being investigated by conventional and geophysical methods with ground investigations including basic research into fracture pattern geometry and brittle deformation as well as indicators of mineral and petroleum deposits.

The availability in the 1980s of satellite stereocoverage (eg. SPOT) is expected to augment the satellite data information content on form and texture of the terrain substantially. Digital analysis methods which utilize shape and texture of information will continue to be developed. SAR data acquired from satellite and airborne platforms can be merged with visible and IR data as new channels in analysis. Experiments using digitized geophysical map

+ "Landsat Follow-On: A Report by the Applications Survey Groups" NASA Technical Memorandum 33-803, Dec. 15, 1976.

data as channel inputs with MSS data in classification studies have been carried out.*

15.2 Exploration

Exploration activities characteristically involve utilization of many technical methods. Savings in unnecessary exploration and development efforts and new discoveries result from effective application of these technologies. Satellite data has been found to complement and aid in the interpretation of aeromagnetic and gravity data, and to assist decisions with respect to application of more expensive exploration techniques (field reconnaissance). A good deal of the early analysis involved photointerpretive methods, but trends are to digital analysis and much of the work done by industry is unpublished. Landsat applications in petroleum exploration have included identification of major structural features within sedimentary basins, locating areas for geologic mapping and outcrop sampling, locating geophysical reconnaissance surveys, preparation of base maps to provide trafficability and access information to seismic crews to assist pipeline routing studies and to aid aircraft navigators and field parties. Landsat-D data may assist in detection of certain surface alterations indicative of hydrocarbons.

Information on tectonic features required in mineral exploration requires data on drainage patterns, vegetative cover, faults and joints, surface temperature anomalies, tonal features, and presence, attitude and orientation of planar structures. Satellite data through spatial patterns of reflectance, spatial texture and temporal reflectance change provides information on areas of different vegetation populations, seasonal growth and decay patterns, and vegetation vigor, stress, patterns and textures. Spatial resolution improvements will improve texture mapping.

Satellite data is used in mineral exploration to assist in determining surface materials composition, identifying igneous intrusions and impact structures that may be associated with mineral deposits, identifying structural features such as faults, shear zones, joints and other fractures which influence deposits, identifying erosional and depositional features, and studying vegetation where it is an indicator of underlying geologic terrain, of heavy metals in groundwater or of nutrient deficient parent rocks. Digital techniques may be used to facilitate discrimination of surface materials composition and to enhance surface textural features. Surface pattern and topography aid in

* "Computer Assisted Analysis Techniques for Remote Sensing Data Interpretation" P.E. Anuta, Geophysics, Vol. 42, April 1977, p 468.

identifying erosional and depositional features. In addition to expected advantages of the new TM bands, it may be desirable to utilize other remotely sensed data, for example multi-thermal airborne scanner channels to separate compositional and temperature differences of silicates and other geologic targets.

Digital analysis used in Athabasca Tar Sands studies provided better definition of the extent of surface outcrops.* Overall information on location, distribution and capacity of mineral deposits requires data on subsurface extent, geochemical patterns, density, trace element content, radioactivity, magnetic anomalies, tonal features, texture, temperature and thermal inertia, color indicators, spectral properties and vegetative cover.

15.3 Environmental Geology

Satellite data may be used with multisource ancillary data to assess geologic hazards (earthquakes, landslides, cave-ins, sinkholes, volcanic eruptions), earth materials for engineering usage, and environmental impact in order to assist in selection and evaluation of sites for engineering structures. Sited investigations associated with energy projects include nuclear and other power plant sites, gas compressor sites, dams, waste disposal sites, other engineering structures including transportation routes (pipelines, transmission lines, bridges, highways, railways), towns, buildings and airports could be part of the infrastructure established with energy development projects.

Airborne data has been used extensively in environmental geology applications. Improvements in satellite data will increase its utility for discrimination and identification of soil and rock types and vegetative cover, landform analysis, linear delineation and recognition of potential hazards such as landslides and sinkholes. Active and inactive faults present hazards for engineering structures, - inactive zones because fault breccia zones are usually highly permeable to fluids moving parallel to the fault. Applicability of satellite data for fault and cross-strike lineament identification will be improved with TM data. Other applications expected to benefit include identification of larger landslides (>1 km across), location of trends along which unstable ground may be concentrated, identification of smaller sinks, and observation of alignment of sink holes in limestone terrain indicating areas where sinks are likely to be encountered. Ancillary airborne and other data will continue to be needed in these studies. Stereo coverage is useful in most instances. Satellite data

* Baker, R.N. and Smith, A.F., General Electric Company, IEEE Symposium on Adaptive Processing, Houston, Texas, December, 1975.

spatial resolution improvements to 10m would assist some applications such as landslide detection.

Considering overall information needs to assess several geologic hazards, these include:

- earthquake hazards and damage which require information on location of active faults, subject to ground failure, and water saturated surficial units. Associated data requirements include linear mapping, topographic indicators of recent movement eg. offset drainage and groundwater barriers, seismicity (assisted by DCPs), regional soil mapping, position and depth of ground water table, unstable slopes, and porosity of soil or rock units.
- landslides requiring information on active and recent slides and areas susceptible to sliding or instability. Data requirements include geologic formations or structural features which may localize, eg. linears, or lead to unstable ground, topographic expression such as scars or hummocky topography, and soil and vegetative differences (possibly satellite detectable) which indicate disruption of groundwater flow.
- cave-ins (mines, underground excavations) require information on surface cracking, faults, tunnel routes, and limestone topography. Vegetation and moisture discontinuities associated with surface cracking require local observations, but linear and sink hole alignment data requirements may be satisfied in part by satellite data.
- differential settling caused by poorly consolidated, porous surficial units requires data on porosity indicated by vegetation and moisture discontinuities and possibly thermal inertia signatures.

Location of construction materials strongly influences cost of engineering structures and may influence route selection in materials-scarce regions such as northern Canada.* Differentiation of soil and rock type may be assisted by analysis of landform, drainage pattern, vegetation and spectral response utilizing remote sensing data. The physical properties characterizing construction materials include porosity, permeability, grain size, bearing capacity, shear strength and planes of weakness.

Other factors influencing engineering site selection include subsurface water, drainage and soil erosion. Subsurface water information requirements include soil moisture content, water table elevation, aquifer location and direction of groundwater migration related to pollution considerations. Data contributing

* "Applications of Satellite Thermal Infrared Measurements to Earth Resources Studies" J. Cihlar and A. McQuillan, Can. J. of Remote Sensing, April 1978.

to satisfaction of these requirements include data on springs and seepage areas, lake bottom springs (revealed by thermal plumes), sand-and-gravel discrimination from clays and moisture (use of thermal inertia methods), and vegetation distribution. Drainage and soil erosion information requirements include information on the topographic drainage system, consolidation of surficial units influencing erodability, and areas of past or present sedimentation. Data required on the regional pattern of streams and ridges is only partially satisfied by satellite data ie only major topographic features are detectable. Thermal inertia methods may provide information on porosity influencing erodability. Deltas, fans, sedimentary plumes, sediment load in lakes and streams are indicative of natural and construction related sedimentation. Spatial and spectral data improvements will increase satellite data utility to observe major features.

15.4 Engineering Surveys and Construction

Construction in northern Canada is particularly susceptible to water-related problems. About one-half of Canada lies in the permafrost regions. Accurate mapping and typing permafrost can have large construction and subsequent maintenance benefits. Permafrost is a subsurface phenomenon and interpreting its presence or absence and its nature to a depth of 1.5 to 2 meters requires understanding the relationships between permafrost and landform, relief, vegetation, drainage conditions and drainage flow, soil and climate, all of which can be used as indicators. Multisource data is helpful in providing convergence of evidence, including stereo coverage, thermal infrared data,[+] radar and MSS data. Vegetation reflects drainage conditions particularly in organic terrain and in the Arctic and subArctic. Based on vegetation, permafrost can be delineated and degradation and aggredation assessed. Landsat data has been found to be useful for typing of permafrost in Arctic and subArctic environments, where vegetation differences are significant indicators.[*] Colour infrared photography with advantages of greater detail than MSS data and relief information, has given high mapping accuracies in both the discontinuous and continuous permafrost zones (95-99% in organic terrain in Manitoba studies using imagery at scales of 1:120,000). This photography has also proved useful in assessing peatland which is also a major factor in northern route construction. Vegetation patterns are closely correlated with peat landform patterns and are distinctive. Canada has 278 million acres of peatland. Peat is difficult material to drain and usually

+ "Application of Satellite Thermal Infrared Measurements to Earth Resources Studies" J. Cihlar and A. McQuillan, Can. J. of Remote Sensing, April 1978.

obtains its strength from the surface mat of partially dried organic matter.

Many problems associated with influence of soil and drainage conditions on northern construction could be discussed.+ For example fine grained soils susceptible to intensive frost action should be avoided. Obstruction of surface or underground natural drainage cause water to accumulate on the surface and freeze. Road fill interfering with natural drainage can cause erosion of the grade, and standing water causes thawing of the underlying permafrost.

Data needed to satisfy information requirements for soil classification, profile and capability include mineral composition, organic content, color, granularity, layering, chemical composition, porosity and permeability, acidity, density, mechanical properties, moisture, vegetative cover and land use.

Satellite data can affect the four main factors that affect route location (and therefore design and construction costs) including soil strength, quantities of earth works, drainage requirements and construction materials.* The imagery provides an overall view of regional relationships indicating the interrelationships between climate, landforms, geology, vegetation and cultural features, and provides a geomorphological framework for study of individual component landforms and a common base for comparison of analysis prepared by investigators of various disciplines in a coordinated planning effort.* It provides distributions and spatial relationships for regional surveys which include soil mapping (including variations in moisture condition and therefore strength), terrain classification, engineering materials location, drainage characteristics, and particular engineering problems such as slope stability. Seasonal coverage in areas where water, frost, snow and ice can present problems can be valuable in avoiding major construction and maintenance problem areas.

Satellite imagery is most useful for the planning and feasibility stages of an engineering survey such as preparation of regional maps or reconnaissance whereby areas can be selected for more detailed study by aerial or ground methods. Effective surveys for construction projects involve an integration of survey techniques including satellite radar and other sensor data for regional information, and airborne photography and other sensor data and ground data for detailed information. The requirement both to discriminate and relate features will result in increasing use of digital enhancement and analysis methods. Regional surveys in the northern parts of the provinces and the territories have often been done in connection with development projects, and comprehensive resource inventories do not exist in many areas. The imagery may be used for regional surveys as a means of storing information as part of a national data bank.

* "The Use of Satellite Imagery for Highway Engineering in Overseas Countries" T.E. Beaumont and P.J. Beavers, Journal of the British Interplanetary Society, Vol. 31, January 1978.

16. Meteorology

16.1 Visible and Infrared Satellite Methods

Rainfall estimates, both statistical and real time are required for a variety of resource management and planning purposes. Estimation methods using digital infrared geosynchronous satellite imagery have been developed for use at southern latitudes (below about 60^{o}N) where satellite coverage is available. Techniques are based on the fact that active convective regions of rainfall are brighter and colder on the satellite image than non-precipitating regions. A technique used at the National Hurricane and Experimental Meteorology Laboratory, Florida uses time histories of convective clouds from a sequence of satellite images. The inferred rainfall is calculated for every image during the cloud's lifecycle and is proportional to cloud top temperature. Estimation of rainfall over an area (80^{o} longitude x 40^{o} latitude) for 24 hours at a temporal resolution of one hour required 50 minutes CPU time on a CDC6600 and about 3.5 million characters storage*[1] (storage depends on number of clouds). Successful rainfall estimates have been made over fairly large areas (15,585 Km^2 in Montana) by determining cloud histories and rain volumes, and adjusting satellite based estimates by comparison with results over a small sub-area (~ 12% of total area) where a network of rain gauges and good ground reference results were available. It has been suggested that when a real time iterative version of the methods is developed, it can be used to monitor convective rainfall over large areas for flash flood identification and warning.*[2]

A technique for estimating convective rainfall which compares changes in two consecutive GOES satellite pictures, both IR and high resolution visible, has been applied in real time to major flash-flood producing thunderstorms.*[3] The technique involves identifying the active portion of the convective system, making a "first guess" initial rainfall estimate using enhanced IR alone, and examining successive pairs of high-resolution visible and enhanced IR to determine a factor to be added to the "first guess" which indicates heavier rainfall. Imagery signatures associated with heavier rainfall include very cold tops, rapidly expanding thunderstorm anvils, overshooting tops, thunderstorm mergers, and merging convective cloud lines. The heavy rain is usually

*[1&2] "Rain Estimation over several areas of the Globe using Satellite Imagery" W.L. Woodley, C.G. Griffith and J.A. Augustine, Satellite Hydrography, Sioux Falls, June, 1979

*[3] "A satellite-derived technique for Estimating Rainfall from Thunderstorms and Hurricanes" R.A. Scofield and V.V. Oliver, Satellite Hydrology, Sioux Falls, June, 1979

concentrated in an area less than 10 miles in width. The technique has been applied in Mississippi and works well for short-lived isolated thunderstorms that produce heavy rain due to large updrafts. Rainfall estimates for thunderstorms embedded in slow-moving large-clustered thunderstorms must be amplified. A large area becomes saturated to a great height and storms in the cluster interior have rainfall rates much greater than for isolated thunderstorms. Other indicators of rainfall intensity are:*[1] decaying clouds produce little or no rainfall; clouds with cold tops that are becoming warmer produce little or no rainfall; most of the significant rainfall occurs in the up-wind portion (anvil) of a convective system. Enhanced infrared imagery with colour shadings set to represent various temperature ranges of reflected surfaces are used in many of these studies.

Some experimenters have used film loops of GOES images to assist analysis. In work by Ingraham et al in Venezuela, 300 mb charts were not available for establishing the direction of winds aloft.* For the determination of the upwind and downwind sections of the anvil tops, reliance was placed on the motion of visually identifiable anvils in surrounding regions. Twenty four hour, 16 mm film loops prepared from the individual images were used, projected onto a large scale map outline of the area. GOES imagery in the visual and enhanced infrared modes were used to compute half hourly amounts of preciptations in these studies. The indices for identification of convection are based on the fact that the presence of active and deep convective systems can be ascertained by the localized aspect of convective clouds, their growth and their vertical development.*[2]

Barrett has developed a cloud indexing, aerial statistics approach giving results on both a daily and monthly basis.*[3] Satellite viewed clouds are ascribed indices relating to their degree of cover, and to the probabilities and intensities of associated rain. These cloud based rainfall estimation indices are correlated with rainfall observations by regression techniques. Raingauge data providing relatively accurate, continuous point source data is combined with the more complete satellite spatial distribution information. The region is subdivided into regular grid squares (or cells) with size related to the scale of the study region and the resolution of available

*1 "Use of GOES Imageries to Determine Storm Rainfall Amounts and ArealExtents in Data - Deficient Regions" J.D. Jolly, ibid

*2 "Preliminary Rainfall Estimates in Venezuela and Colombia from GOES Satellite Images" D. Ingraham, J. Amorocho, M. Guilarte, and M. Escalona

3 "Monitoring Precipitation: A global strategy for the 1980's" E.C. Barrett and/or anticipated satellite imagery. Satcells (for which rainfall estimates are made using satellite cloud evidence) are allocated to the scatter of gacells (which contain dependable gauges) on the basis of climatic similarity, and the regression analysis for each gacell serves as the basis for estimations of rainfall at related satcells. At high latitudes where there are low winter illumination level and polar orbiting satellites must be used, estimation systems based on infrared data are required. The arrays of cloud top temperatures require processing to permit differentiation between cloud types since cloud identification has been necessary for cloud indexing methods.[1] Cloud type is represented by cloud brightness and texture to-gether. Barrett notes development requirements including the incorporation of physical models of cloud behaviour onto cloud indexing algorithms, and the need for interdigitation of satellite and conventional data and automation to produce cloud type maps.

Experiments of Whitney and Herman have found several variables derivable from satellites and conventional data to be related to areal-averaged rainfall.*[2] These include IR-temperature gradients in the direction of tropospheric shear, ratio of IR temperature to the laplacian of IR temperature, upwind (relative to high-level wind) portion of the low-level moist tongue, and low-level dewpoint advection.

16.2 Microwave Methods

A direct approach to rainfall estimation utilizes microwave radiation which emanates not from the upper surfaces or layers of cloud but from embedded areas of rain. Passive microwave methods have been particularly effective in rainfall estimates over ocean backgrounds which appear "cold" at microwave wavelengths. Experiments over land using vertical channels at 37 and 85 GHz have been reported as successful in rain detection and estimates of its amount with accuracies to better than ±5 mm/hr. across the range from 0 to 25 mm/hr.*[3] These channels provide data under a wide range of conditions except for those with supercooled water or substantial snow amounts above the rain layer. The presence of rain causes a decrease in microwave brightness temperatures (cooling greater with increasing rain rate) relative to the background at frequencies

*[1] "Applications of Satellite Data in Mapping Rainfall for the Solution of Associated Problems in Regions of Sparce Conventional Observations" E.C. Barrett.

*[2] "A statistical Approach to Rainfall Estimation Using Geostationary Satellite Data" L.F. Whitney and L.D. Herman, Satellite Hydrology, Sioux Falls, June 1979.

*[3] "The Estimation of Rain Rate Over Land from Spaceborne Passive Microwave Sensors" M.G. Fowler, H.K. Burke, K.R. Hardy and N.K.

greater than 30 GHz. Direct appraoches initially yield maps of instantaneous rainfall intensity. Not all are convinced that passive microwave methods give meaningful results.*1

Microwave radar can be used for three dimensional mapping of precipitation and ground based radar has been valuable for mesoscale observations. Advantages of ground based weather radar measurements over rain gauges have been identified as: areal nature of coverage, good resolution (2 x 2 Km squares), coverage possible in remote areas where rain gauges are not easily accessible, and frequent recording of data with easy transmission to users on a real time basis. Snowfall can also be measured and precipitation followed. Disadvantages include cost of hardware, reduction in accuracy at specific points compared with rain gauges, and much more data processing required before areal precipitiation measurements are achieved. Without a dense network of rain gauges with telemetry throughout a basin, cells of heavy precipitation may go undetected. Radar methods have resulted in improvements in hydrologic predictions particularly where localized thunderstorms are involved.*2 Satellites having a meteorological radar on board which would increase radar coverage to the synoptic scale have not yet been launched. While geostationary satellite platforms present the possibility of frequent large area radar coverage, limited coverage and low sampling rates of polar orbiting satellites limit the value of these for mesoscale forecasting. The combination of a broad swath width passive device and narrower swath width radar providing good vertical resolution and volume quantification could be effective. As an example of a possible space radar, the rain radar proposed for Seasat-B had vertical resolution 1-3 Km, horizontal resolution 1-10 Km, and swath width 1500 Km.

16.3 Weather Radar-Weather Satellite System

The advantages listed above of weather radar over gauges, particularly aerial coverage and ease of data transmission suggest advantages of combining radar and satellite data for forecast and accumulated precipitation estimates. Satellite data would permit through delineation of raw areas on the visible and IR imagery extrapolation of rainfall data beyond the 250 Km radius useable with radar to large scale regional coverage. AES plan, as a prototype to operational systems that could be used in regional forecast centers, to employ a processor to overlay data from two radars (McGill and Woodbridge) over GOES satellite

*1 J. Austin, McGill University, personal communication.

*2 "Hydrological Applications of Calibrated Radar Precipitation Measurements" J.E. Corrie and N. Kouwen.

imagery. In the planned system, satellite data are remapped onto a conical projection in a cartesian format, on a regular 8 Km x 8 Km grid and radar data are remapped into an array (8 Km x 8 Km or possibly finer) which can be overlaid with the map used for the satellite imagery and the set of images stored on disc. Satellite data are analysed using a 2 dimensional classification scheme. The images are compared in the areas where there is radar coverage and a map produced showing clear, cloudy and rain areas in the area of satellite coverage plus intensity of rain within radar range. A sequence of such images may then be used to produce a short range forecast (2 to 3 hours). The scheme involves division of previous maps and the current image into 16 subareas and use of a pattern recognition method to produce forecast images. The images are combined with appropriate interpolation across boundaries to produce a forecast map. Sections of interest may be sent on low grade lines (telephone) to regions for display on standard colour TV monitors. Planned transmission is for pictures consisting of a 245 x 192 individual 8 bit element. A 300 baud line is therefore suitable.

Other map products which could be produced include; accumulated rainfall (integrated rain and probability over a period of more than 6 hours) cloud heights, and upper air wind displays eg at 200, 700 and 1000 millibars. An eventual operating system may involve several radars linked to a central processor where satellite data is received and processed. The present radar analysis and forecast methods involve conversion of weather radar data to cartesian maps at constant altitude, and hourly production of digital arrays which may be compared in a pattern recognition procedure so that mean translation velocity of the rain system may be estimated and extrapolated while conserving the present pattern configuration. It is planned that a forecast from the radar-satellite system be produced hourly. Precipitation estimates outside the radar range are expected to have considerably reduced accuracy. Although the radar will give good information on the translation velocity of the rain system within its range, satellite data will augment this upwind of the radar. It is planned to integrate raingauge data eventually into the system. Accumulated precipitation charts would include these point data.

Although the main objective of the technique is short range forecasts up to 3 hours (and therefore applicable to thunderstorm activity), it is expected that some improvement in accuracy of the NWP forecasts (for general precipitation) for longer periods (eg 6 hours) would result from incorporation of this data. The radar site would receive from the central processing facility both the short range forecast using the radar-satellite methods, and longer range (eg 12, 24, or 48 hour) NWP forecast data.

Accurate short range forecasts would have value in several resource management applications where there is a capability of rapid reaction. Good communications are required and this technique is designed to use TV monitors (eg utilizing cable TV, Teledon, Vista). Data from this integrated system like data from weather radar will be compatible with and feed into flood warning systems. Other applications could include aid to forest fire control and detection scheduling, and assistance to some crop management practices (fertilizer or chemical spray application) where longer range NWP forecasts could be improved and timely action could be taken.

Rain radar on a geostationary satellite providing data at almost 20 minute intervals would be useful for this type of short range forecasting GOES data for general purposes is limited to below 65°N and for this application to about 60°N.

Radars used in this system have associated computers, and preprocessed data is transmitted to the central processor. There are several such radar in Ontario and Quebec (Carp, London, Quebec City, McGill and Woodbridge).

The suitability of 300 baud lines for transmission of satellite maps with radar overlays is an important consideration.

The cost of weather radars depends on the range required. For example, one radar with about 200 Km effective range cost $750,000. It is estimated that a reasonable radar for resource-type applications (eg hydrology information for forestry) with about 100 Km range would cost $100,000.*[1] Radar may be competitive with multiple remote stations costing $15,000-$20,000 each.

A multistage method is needed for accumulated precipitation with raingauges calibrating radar which in turn calibrate satellite data. A radar with 100 mile radius would need at least 2 or 3 rain gauges telemetering data preferably every hour to keep the radar accumulation estimates over a period of time on track. (These quantitative precipitation estimates might be provided to a customer every 24 hours or even every hour eg to forest fire agencies.) The number of radars required together with satellite data is uncertain. Ballpark figures suggested included 1 or more per GOES image sector, and about 6 of the $100,000 variety for Ontario.*[2]

Precipitation forecasts provided from NWP models are generally fairly poor for 12 hours but as good as they will get for 24 hours. There is a gap between the 0-3 hour "image forecasting" methods using radar

*[1&2]

J. Austin, McGill University and D. Butler, Goodwood Data System, personal communication.

and satellite inputs, and the fairly reliable 24 hour NWP forecasts using synoptic inputs. Methods which will give 6 and 12 hour forecasts may evolve from a combination of the two. The image forecasting methods can provide some types of data to the NWP models eg area of precipitation, height and motion of clouds, if the latter can assimilate them. The problem of updating NWP models with high resolution data is in the research stage. Forecasts in this time range could be useful in deciding to spray for forest (eg spruce budworm) or crop disease, decisions to shut down logging operations, etc. The accuracy of present NWP precipitation forecasts are unknown.*[1] A coarse grid is used and checking with gauges difficult.

Interference with microwave communications would rule out some weather radar sites.

16.4 Other Considerations

A major problem at northern latitudes is coverage frequencies of polar satellites. It has been noted that microwave data from polar satellites such as NIMBUS G (twice daily coverage) is insufficient to measure precipitation from smaller-scale (<200 Km) weather systems (Cumulus clouds have lifetimes on the order of 30 minutes). It may be sufficient for larger-scale systems (cloud clusters, tropical storms and hurricanes have lifetimes of several days). Where geosynchronous data is available, it gives reasonable estimates for the small-scale systems and for frozgen precipitates and often poorer results for the large-scale systems.

Two aspects of satellite-assisted rainfall estimations require further discussion - the applicability of the techniques over land where a rain gauge network now exists, and increasing use of computer automated methods. Woodley et al suggest that their computer-automated method using GOES thermal infrared imagery could be used by agricultural users in day-to-day monitoring of precipitation over major crop-growing areas to identify areas of precipitation excess and deficiency and to project crop production.*[2] The technique is seen as a method both for flood warning and providing continuing data for river forecasting and planning data for hydroelectric power developments. It is suitable for large areas ($>10^7$ Km^2) down to individual clouds.

The computer-automated technique in use at the National Hurricane and Experimental Meteorology Laboratory uses

*[1] J. Austin, McGill University and D. Butler, Goodwood Data System, personal communication.

*[2] "Rain Estimation Over Several Areas of the Globe Using Satellite Imagery" W.L. Woodley, C.G. Griffith, J.A. Augustine, Satellite Hydrology, Sioux Falls, June 1979.

programs which navigate the digital imagery, isolate and track clouds, group clouds by segments and make rain calculations, and map rainfall at the surface of the earth. Apportionment of the rainfall at the earth's surface is made according to cloud top temperature but the key to the technique is its use of convection cloud histories. A large computer is presently required to generate the rain estimates.

A powerful NASA information extraction facility is used for a broad range of meteorological applications.*[1] System developments recognize that meteorological investigations require access to registered data sets derived from multiple sources of image and non-image data. Therefore in the Atmospheric and Oceanographic Information Processing system (ADIPS) capabilities under development include the ability to register, combine, display and analyse GOES and NIMBUS satellite data, ground based radar image data, and surface ancilliary data. A second interactive minicomputer based image processing system, the Visible Infrared Spin Scan Radiometer Atmospheric Sounder system (VAS) will be used to extract temperature and humidity profiles from GOES-D data after launch in 1980. A shared disc between the PDP-11/70 processors of the two systems will provide the means of incorporating sounding data into severe storms analyses conducted on the AOIPS. With the present AOIPS system, cloud motions between spatially registered images are measured and wind vector fields derived. Uniformly gridded wind vector fields are generated from wind fields derived from satellite imagery, and from these are derived divergence, vorticity and other parameters associated with wind fields. Also derived are cloud heights, cloud temperature profiles, cloud growth rates and precipitation estimates. The resulting information is combined with other meteorological information for input to storm models and further analyses. Outputs include TV displays and hard copy products of images overlayed with plots and data contours of analysis parameters. For example for one severe local storm system, wind fields were calculated using GOES data taken at 5 minutes intervals, and parameters giving divergence, vorticity and deformation of wind fields were derived (using equations with wind vectors as inputs) and overlayed on the satellite imagery. The magnitude of these dynamic parameters were numerically and spatially associated with development of a hail producing thunderstorm.*[2] In the present system, a remote IBM S/360/91 computer is used for some modelling activities. Planned future developments include developing capabilities for multispectral analysis of severe storm data, applying multispectral classification techniques to severe storm analysis, and establishing integrated data bases for

*1&2 "Meteorological Image Processing Applications" P.A. Bracken, J.T. Dalton, A.F. Hasler and R.F. Adler, Thirteenth Symposium on Remote Sensing, Ann Arbor, April 1979 storage, comparison and correlation of multisource/multitime image and non image data.*1 For meteorological applications, an interactive system is required which will allow a user to take full advantage in a timely fashion of data which often has rapidly decaying value.

*1 "AOIPS - An Interactive Image Processing System" P.A. Bracken, J.F. Dalton, J.J. Quann, J.B. Billingsley, 1978 National Computer Conference, AFIPS Press, June 1978.