GeoComp - n, an advanced system for generating products from coarse and medium resolution optical satellite data.

Part 1: System characterisation

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Résumé

Le Centre canadien de télédétection (CCT) utilise depuis 1992 le Système de géocodage et de composition (GeoComp) pour le traitement des données de la série des satellites porteurs de radiomètres perfectionnés à très haut pouvoir de résolution (AVHRR) de la National Oceanic and Atmospheric Administration (NOAA) des États-Unis. Le système GeoComp (Robertson et coll., 1992) a été conçu pour produire des images composées multidates systématiques utilisables en cartographie couvrant de grandes étendues et ne comportant que peu ou pas de nuages. Une révision du système original a été proposée en 1995 afin d'en améliorer la conception en fonction de l'expérience acquise à l'exploitation pour y intégrer de nombreux progrès réalisés en matière de matériel informatique et pour introduire des produits à valeur ajoutée résultant de recherches effectuées d'après des produits du GeoComp. Le nouveau système a été désigné GeoComp-n pour «nouvelle génération» de processeurs GeoComp. Parmi les améliorations techniques intégrées au GeoComp, mentionnons une architecture de système modulaire, une GUI entièrement fonctionnelle et un format de produit de données réorganisé. Le système a été livré dans sa version initiale en mars 1999, la validation des couches de données a été complétée en juillet 1999 et le système a été utilisé de manière opérationnelle au Centre de télédétection du Manitoba à compter de 2000. Dans cette communication et dans celle qui l'accompagne, nous décrivons le nouveau système et la gamme étendue de produits qu'il permet de générer.

Abstract

The Canada Centre for Remote Sensing (CCRS) Geocoding and Compositing system (GeoComp) has been processing the Advanced Very High Resolution Radiometer (AVHRR) data from the United States National Oceanic and Atmospheric Administration (NOAA) series of satellites since 1992. GeoComp (Robertson et al., 1992) has been designed to produce systematic, map-compatible, multi-date composite images over large areas and with reduced or no cloud content. A revision of the original system was proposed in 1995 to improve the design based on the experience gained from the system's operation, to incorporate the many advances in computer hardware, and to introduce value-added products resulting from the research that employed GeoComp products. The new system was called GeoComp-n for the "next generation" of GeoComp processors. Technical improvements designed into GeoComp-n include a modular system architecture, a fully functional operator GUI and a revamped data product format. The initial version of the system was delivered in March 1999, the validation of the data layers was completed in July 1999, and the system has been used operationally at the Manitoba Centre for Remote Sensing starting in 2000. In this and the accompanying paper, we describe the new system and the wide range of products that are generated through its operation.

Background and Introduction

In the mid-1980s, the global scientific and policy communities were becoming increasingly more aware of the pervasive and growing environmental changes. In the policy domain, the Bruntland Report (Bruntland, 1987) for the first time articulated the global environmental policy agenda. In the scientific community, the International Council of Scientific Unions began preparation of a science program that later became known as the International Geosphere-Biosphere Programme, IGBP (IGBP, 1990). The term 'global change' became a frequent word in both science and policy contexts, and eventually resulted in far-reaching deliberations and decisions reached at the Global Conference on Environment and Development in Rio de Janeiro (United Nations, 1993).

In the course of these discussions, 'global change' became synonymous with processes that take place over large areas, vary with the spatial scales (from landscape to global), typically have large temporal variability (from diurnal to centuries) and may be of natural or anthropogenic origin. It also became obvious that the traditional in-situ observation methods are unable to cope with the demand for data that are needed to develop and run models of the various processes and their interactions. For example, the vast majority of ecological studies were (and in many cases still are) conducted at the plot or stand scale (Gosz, 1999).

Among the various domains of the earth system, the biosphere plays a key role because of its numerous interactions with the physical and chemical environments, its capability for rapid feedback, and its importance to the economic and social well being of humankind at local and regional levels. Thus, the biosphere and its interactions with the environment are important targets for global change studies. It is especially critical in a resource-based country such as Canada where agriculture and forestry support a significant part of the national economy. In addition, given the vast biogeographic scope of Canada's ecosystems, it was argued at the time (Cihlar, 1987) that Canadian remote sensing efforts should supplement global monitoring programs of other space agencies by providing more detailed monitoring at the national level.

The above policy and science considerations have pointed to the need for an observation method that is capable of gathering data daily on the terrestrial biosphere over large areas. Through very rapid development following the launch of the Earth Resources Technology Satellite (ERTS-1) in 1972, earth observation science and technology reached a stage where it could be considered as a credible alternative. However, the Landsat-based strategy was not appropriate in this context because of infrequent coverage, excessive data volume in relation to the data processing methods and technology, and a data policy that rendered the access impractical for large-area applications. Fortunately, the pioneer work of Tucker, Holben and colleagues (Tucker, Gatlin and Schneider, 1983; Gatlin, Sullivan and Tucker, 1984; Holben, 1986) illustrated the great potential of meteorological sensors for biospheric studies. The key sensor of interest, the Advanced Very High Resolution Radiometer (AVHRR), although designed for atmospheric observations and weather forecasting, also had the two most important spectral bands for vegetation studies: red and near infrared.

The national need for information on vegetation dynamics and the capability offered by the NOAA AVHRR led to a decision to establish a national-scale data collection and processing program for Canada. While there were AVHRR mapping initiatives abroad including the United States Geological Survey (USGS) Global 1 km AVHRR (G1KA) data set (http://edcdaac.usgs.gov/1KM/1kmhomepage.html) (Teillet et al., 2000), Pathfinder AVHRR Land (PAL) data set (http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/LAND_BIO/GLBDST_Data.html) (Lovell and Graetz, 2001) and the Global Inventory Monitoring and Modeling Systems (GIMMS) data set (Zhou et al., 2001); none of them produced 1-km maps over Canada or provided the radiometric and geometric accuracy in the data processing demanded by CCRS. Nor was the software used to generate these data sets commercially available. The Canadian program benefited from an ongoing use of AVHRR data to estimate crop yields in the Prairie Provinces (Glick, Benci and Brown, 1983; Prout et al., 1986), but it required the build-up of more substantial infrastructure as well as a supporting research program. The most important elements of the infrastructure were a systematic data acquisition campaign and a computer system for the standardized processing of daily data. To achieve the latter, a Geocoding and Compositing System – GeoComp (Robertson et al., 1992) - was built on the occasion of Canada's participation in the International Space Year.

GeoComp employed the best hardware and software technology available at the time. In its geometric processing, it drew heavily on the Multi-Observational Satellite Image Correction System (MOSAICS) heritage (Friedel and Fisher, 1987), and it required special array processors to achieve the required throughput. Over the years, GeoComp produced 10-day composites of AVHRR data during the growing season. GeoComp provided the first-ever portrait of the Canadian landmass in its spatial richness and temporal variability, both within a growing season and over the years. The data in turn became the foundation for research into inversion algorithms, higher-level products, as well as the characteristics and functioning of Canada's terrestrial biosphere (Cihlar et al., 2002b).

Based on the lessons learned through the operation of the GeoComp system, a proposal was made to CCRS management to develop a next-generation system (Cihlar, Li and Chen, 1995a). The issues to be dealt with included both basic processing and the generation of higher-level products. The processing components included noisy line detection, calibration, geocoding, compositing, atmospheric and bi-directional reflectance corrections, identification and removal of residual clouds, and the generation of higher-level products. In 1997, a formal request for proposals was issued by CCRS for the development of the next generation of GeoComp, dubbed GeoComp-n (CCRS, 1997). This new system was developed under contract with a Canadian industrial partner, PCI Geomatics of Richmond Hill, Ontario.

In this paper, we describe the system overview with respect to the design philosophy and basic structure of the system, the basic data processing, the GeoComp-n products available, the operational implementation used by CCRS, and planned future improvements.

System Overview

GeoComp-n is a fully integrated software package providing end-to-end processing of AVHRR data. It supports four primary functions: AVHRR data input, pre-processing, geocoding and resampling, and composite product generation. An overview of the system functionality is shown in Figure 1. The GeoComp-n software package is designed to run on industry standard commercial off-the-shelf hardware. This flexibility allows the software to operate on a wide variety of platforms depending on the users' processing requirements. It is built on top of the PCI Geomatics EASI/PACE software package that provides much of the core image processing functionality. This modularity should also allow for easy upgrades to support new sensors as the data become available.

A robust graphical user interface (GUI) has been designed to assist the operator in data entry, setting parameters, monitoring the status of system processes and generation of products. All user interface elements include context-sensitive help. A "Product Definition Wizard" is built into the system to assist the user in defining all aspects of a product. The numerous options available for a particular product type are then saved in a product definition file for re-use, assuring consistency of the resulting products. All or any subset of these product layers may be produced; where any product dependencies are transparent to the user. Various databases are required for system operation and product generation. GeoComp-n can generate geocoded and composite products in any of the map projections supported by EASI/PACE.

All processing is carried out in batch mode where the operator can submit several geocoding and compositing jobs for sequential execution. Optional built-in checkpoints in the process also permit the operator to review the results at various stages of processing. The desired checkpoints are triggered by conditions specified by the operator, such as having an insufficient number of ground control points in the case of very cloudy imagery.

For ease of data access and for maximum portability to other image processing systems, the output products are created as flat raster binary image (.img) files. The data layers are typically scaled into a 16-bit unsigned integer. Extensive standardised metadata describing the products, including the algorithm and processing parameters, are contained in a text file associated with each binary image file. This is a major departure from the Committee on Earth Observations Satellites (CEOS) format (Murphy, 1990) traditionally used to output CCRS satellite products. The CEOS format is very rigid in that ancillary and image data are encoded in a pre-defined format in specific file and record locations. The ancillary data are not necessarily text readable. Modification or addition of parameter records and inclusion of unlimited descriptive text isn't normally permitted.

The original GeoComp system produced top-of-atmosphere (TOA) radiance in the five bands, Normalized Difference Vegetation Index (NDVI) computed from TOA reflectance, solar zenith angle, satellite zenith angle, relative azimuth angle and the selected pixel date for each pixel in the composite. In addition to the 10 bands generated by the original GeoComp system, many new data layers can also be generated for a composite product. Some of the new data layers are improved operational products while others are advanced experimental products based on the research undertaken by the Environmental Monitoring Section at CCRS (Cihlar et al., 2002b).

The original GeoComp system operated on a Digital VAX platform with specialized hardware and software. For example, resampling was carried out on a set of array processors to maximize throughput, which required custom software. The operator controlled the system through a command-line interface and although batch-mode processing was used, operation of the system was an operator-intensive procedure. By using commercial-off-the-shelf hardware and software components, GeoComp-n has built-in flexibility to incorporate advances in both hardware and software with a minimum of effort.

System Databases

GeoComp-n employs various databases for system operation and product generation. The system data file (systemdata.aux) contains the default directory names for most of the input and output activities. The master product type definition file (masterproddef.aux) contains database pathnames, pathnames for auxiliary (.aux) files with product coefficients and various processing parameters, and is used as the template for user-defined product definition files. The radiometric calibration coefficient auxiliary file (nominally named radcal.aux) must be updated regularly as it contains both time- and satellite-dependant parameters. Annual updates for this file will be available from CCRS before the growing season.

The product coefficient auxiliary file (nominally named productcoeff.aux) contains product processing parameters and scaling coefficients. It is populated with reasonable default values, but any of these may be altered for custom product definitions. The system includes the template files for the master and product layer metadata files.

Other databases used by GeoComp-n include the ground control point (GCP) image chip database, digital elevation model (DEM), land cover map of Canada (includes a water mask), and seasonal NDVI database for cloud removal. All auxiliary database files supplied with the system are plain text files and can be edited by the user.

Composite Product Format

Composite products are generated using an innovative product format specification in which each product layer is stored on disk as a flat raster file, with no header or extra information within the file. All composite product layers are contained within a single subdirectory, whose name identifies the composite product uniquely by date, and are linked to a PCIDSK format (.pix) file for easy viewing in ImageWorks. These composite products may then be archived and/or backed up to other media using any number of third-party archiving software packages such as WinZip, tar and Windows Backup available under Windows NT.

An associated product metadata (.mdf) file describing the algorithm and processing parameters used is generated from a template (.mdft) file for each product layer and incorporates real-time processing parameters. The metadata files are fully commented plain-text files that use the ParameterName=value format. Two master metadata (.imdf) files that describe the list of input scenes, general processing parameters and databases used to generate the composite product as a whole are also generated.
This output format is a major departure from the CEOS format traditionally used for CCRS satellite products (Murphy, 1990). This format was selected for maximum portability among image processing systems and so that the metadata are in a human-readable format.

GeoComp-n has the capability to optionally generate browse imagery and catalogue update files (CUFs) of the composite products for cataloguing purposes. These files are compatible with the CCRS Earth Observation Catalogue (CEOCat) database. They should be searchable in CEOCat by the end of 2002. The browse imagery is generated in Joint Photographic Experts Group (JPEG) format consisting of three operator-specified channels of the 1 km resolution data at an operator-specified reduced spatial resolution.

Basic Data Processing

The basic data processing chain consists of four steps: AVHRR data input, data pre-processing, geocoding and resampling, and composite product generation. These steps are illustrated in the data flow diagram in Figure 1 and described below.

AVHRR Data Input

GeoComp-n was specifically designed to handle the High Resolution Picture Transmission (HRPT) or Local Area Coverage (LAC) AVHRR data with a nominal ground resolution of 1.1 km at nadir. Input data formats supported include CEOS format AVHRR data produced by the CCRS NOAA AVHRR Transcription and Archive System (NATAS) at the Prince Albert Satellite Station (PASS) or Level 1B (L1B) data produced by any number of commercial AVHRR receiving systems. Details on NATAS can be found on the web site http://ceocat.ccrs.nrcan.gc.ca/guides/avhrr/ch4.html. The data can be read from Exabyte tape, CD-ROM or downloaded over the network to a local disk system.

Data Pre-processing

The pre-processing options are contained in a product type definition file, with many of the processing parameters defined in auxiliary or database files.

Typically, L1B data from the NOAA Selective Active Archive (SAA) are missing scan lines as blank lines are dropped. As GeoComp-n requires all the scan lines for geocoding, the option exists to replace the missing lines with blank lines or data from adjoining lines.

An additional concern is the presence of noisy pixels/lines from orbits received near the horizon. Noisy lines can be detected using header information supplied with the raw image files and/or automatically using simple heuristics. The line replacement algorithm can replace a noisy scan line with the line below or above, or by the average of the two if the scan line is not at the beginning or end of the file. If the user chooses not to replace bad lines then the remaining noisy pixels/lines are entered into a Quality Control (QC) bit mask as noisy pixels/lines (0=bad or missing pixel, 1=clear or good pixel).

An optional, albeit crude, cloud detection algorithm using raw count thresholds can also be applied to identify obvious cloudy pixels that are then entered into the QC mask. A pixel is considered to be cloudy if the following relation is true: channel 1/channel 2 > threshold 1 and channel 1 > threshold 2.

The raw data can then be calibrated to top-of-atmosphere (TOA) radiance using onboard calibration data for the thermal channels or calibration parameters provided in the radiometric calibration coefficient file for the visible and near-infrared channels. The output of the pre-processing is a PCIDSK format file containing the raw or calibrated radiance data for AVHRR channels 1 to 5. The radiance data in the pre-processed product file are scaled using coefficients provided in the radiometric calibration coefficient auxiliary file. Calibration can be disabled such that the pre-processed file will contain raw digital numbers.

Strictly speaking, the orbit model determination can be considered part of the geocoding process. However, chip matching, as described in the next section, is carried out in the pre-processing phase so that a pre-processed file on the disk contains a fully determined orbit model.

Geocoding and Resampling

An orbit model refinement process is employed in geocoding where the satellite position and attitude are modelled and refined using GCPs that are automatically matched against an image chip database using image correlation. Sub-pixel accuracy can be achieved routinely with little or no operator involvement, provided that sufficient cloud-free areas are present in the imagery. In compliance with the design specifications, "the absolute 2-dimensional residual error for 1 km resolution geocoded products shall be 0.55 +/- 0.07 % RMSE of the IFOV, or better; that is, 95% of geocoded AVHRR products shall have a measured absolute 2-dimensional error of 750 m or less". Even in the absence of ground control where the algorithm could not find a minimum, operator-specified number of GCPs, the system can proceed with geocoding using the systematic ephemeris information supplied with the data, or input after the fact from the TIROS Bulletin United States (TBUS) ephemeris information retrieved from the Internet at the NOAA National Environmental Satellite, Data and Information Service (NESDIS) web site at: http://psbsgi1.nesdis.noaa.gov:8080/EBB/ml/nicexp.html. An absolute geometric accuracy of <3 km can be achieved for pixels near nadir by using the orbit model determination alone with reliable ephemeris data in the absence of significant solar activity. Unfortunately, sporadic solar storms since August 2000 have degraded the quality of the ephemeris data.

GeoComp-n is supplied with an image chip database covering Canada. The chip database consists of small (64x64 pixel) geocoded image chips from summer images. These have been derived from precision geocoded Landsat Multi-Spectral Sensor (MSS) or Thematic Mapper (TM) data, and Marine Observation Satellite-1 (MOS-1) Multi-spectral Electronic Self-Scanning Radiometer (MESSR) data. These data have been resampled to 1 km resolution by modelling the modulation transfer function of the AVHRR sensor. In addition, image chips may also be derived from precision geocoded AVHRR data. The image chip database can be augmented by chips from other high-resolution satellite data sources or for other geographic regions.

Optionally, geocoding incorporates terrain correction to produce ortho-rectified products. The default DEM used for this process is the GTOPO30 Global DEM, with a spatial resolution of 30" in latitude and longitude, produced by the USGS at the Earth Resources Observation Systems (EROS) Data Centre (EDC) web site: http://edcdaac.usgs.gov/gtopo30/gtopo30.html. While radiometric resampling may employ a variety of algorithms; the damped Kaiser method (Kaiser, 1974) is typically applied to maintain maximum radiometric fidelity and geometric accuracy. While AVHRR data are resampled to 1 km resolution; the raw pixels at extreme satellite zenith angles (>60º) can have a ground resolution of >5 km. The selection of near-nadir pixels for compositing will help constrain the spatial resolution of the composite pixels.

GeoComp-n supports a wide selection of map projections. The default projection used for continental scale products is the Lambert Conic Conformal (LCC) projection. The output of the geocoding phase consists of a PCIDSK format file containing the raw or calibrated radiance data for AVHRR channels 1 to 5, the solar zenith and azimuth angles, and the satellite zenith and azimuth angles. The radiance layers in the precision geocoded product file are scaled using coefficients provided in the radiometric calibration auxiliary file. The angle channels in the precision geocoded product file are scaled using coefficients provided in the product coefficient auxiliary file.

Composite Product Generation

To create composites, a set of overlapping geocoded full swath images is selected and each output pixel in the composite is chosen based on a pixel selection criterion. Composites may be created for any geographic area, as defined by the operator in the product definition file. The system supports maximum NDVI or minimum satellite zenith angle as the selection criteria, the choice depending on the type of information to be extracted from the composite. With maximum NDVI, the least cloudy or contaminated pixels are assembled from a series of images collected over several days. While NDVI may be computed from any of the channel 1 and 2 radiance or reflectance products (see below), the TOA reflectance–based NDVI is typically used for pixel selection. When using the minimum viewing angle as the selection criteria, pixels are selected based on their proximity to nadir. Pixels selected closer to nadir have reduced atmospheric effects and footprint size. Pixels may also be masked out from the final composite product by a water mask or by setting a maximum satellite zenith angle.

Product layers and their associated metadata files are generated according to the options requested by the operator in the product type definition file. The product layers are scaled according to scaling coefficients provided in the product coefficient auxiliary file.

GeoComp-n products

So far, only AVHRR data products (specifically for NOAA 14) have been defined. However, the system is modular enough that it could conceptually be modified to handle other similar data types such as SPOT Vegetation (VGT) or TERRA Moderate-resolution Imaging Spectroradiometer (MODIS) data, provided that the input formats are compatible and that the current processing algorithms are appropriate for these data. GeoComp-n products form a series consisting of: top-of-the-atmosphere (TOA) radiance or reflectance and ancillary products (collectively known as the basic products), surface reflectance products, and higher-level products. Standardised and detailed metadata files accompany all GeoComp-n composite products. A complete list of available product layers is given in Table 1. The algorithmic details for all products listed below are given in Cihlar et al. (2002b).

Basic Products

Top-of-the-atmosphere (TOA) radiance - The data in all five AVHRR channels are converted from raw counts to TOA radiance by applying radiometric calibration coefficients. The method varies according to the type of data. Because of post-launch sensor degradation and the absence of onboard calibration for AVHRR channels 1 and 2, time-dependent calibration coefficients have been derived from vicarious calibration data. Examples of these composite products are shown in Figures 2 and 3. Radiometric calibration of channels 1 and 2 uses the piece-wise linear calibration coefficients as recommended by

CCRS (http://www.ccrs.nrcan.gc.ca/ccrs/tekrd/rd/ana/calval/noaa14e.html). The method is described in Cihlar and Teillet (1995b), and the coefficients are maintained in an auxiliary database file. The thermal data in AVHRR channels 3, 4 and 5 are converted to TOA radiance using onboard calibration data. The telemetry data include space counts, blackbody counts and platinum resistance thermistors (PRT) values. These are used to compute gain and intercept calibration coefficients to convert raw counts to TOA radiance. The thermal calibration method is described in Kidwell (1998). Note that the daytime radiance for AVHRR channel 3 includes reflected solar irradiance in addition to the thermal emissive component.

TOA reflectance - The TOA radiance data for channels 1 and 2 are converted to TOA reflectance using the method described in Teillet and Holben (1994).

TOA brightness temperature - By using the inverse of the Planck function with the appropriate central wave numbers, the TOA radiance for channels 3, 4 and 5 can be converted to TOA brightness temperature in degrees Kelvin (Planet, 1988). Examples of these products for channels 3 and 4 are shown in Figures 4 and 5, respectively. Channels 4 and 5 are very similar. Note the very high temperatures in the southern prairies. This effect is due to the high temperature of bare or sparsely vegetated soil.

Normalized Differential Vegetation Index (NDVI) - NDVI is computed from visible and near infrared channels (channels 1 and 2 of AVHRR):

$$NDVI = \frac{channel2 - channel1}{channel2 + channel1},$$

where the channel values may represent TOA radiance, TOA reflectance or surface reflectance as described below.

Viewing geometry channels – Five viewing geometry channels are defined. The satellite (viewing) zenith angle is specified as a number between 0 and 90 degrees from nadir. The satellite azimuth angle is given as a number between 0 and 360 degrees clockwise from the North Pole. The same conventions apply to the solar zenith and azimuth angle channels. The relative azimuth angle is computed as the angle between the satellite azimuth angle and solar azimuth angle going clockwise. All angles are given in degrees. The relative azimuth angle product (Figure 6) is dominated by values around either 0 degrees (back-scatter) or 180 degrees (forward scatter). A discontinuity is observed where pixels in the composite came from the nadir region of an orbit where the relative azimuth angle quickly changes. The solar zenith angle (Figure 7) appears relatively uniform with an expected increase towards the North Pole since the NOAA satellite is in a sun-synchronous orbit. The satellite zenith angle (Figure 8) has more variation in the 0 to 67 degree range and the pattern is indicative of which pixels were selected for inclusion in the composite.

Relative date - The relative date is the number of days since January 1, 1970 (typical baseline used for time functions by most computer languages) of the scene used. This also ensures continuity with the convention used in the original GeoComp system.

Input scene map – The input scene map lists the scene number used in the composite where the scene numbers are indexed in the input scene list metadata file. An example of this product layer is shown in Figure 9. In this image, one can see how the cloud-free areas are assembled from the set of swaths used as input. For the most part, these are medium-scale contiguous areas; although, there are many cases where pixels are mixed at the individual pixel scale, reflecting the wide variation in cloud conditions expected over the course of 10 days. Pixels included from the last orbit in the composite period because of persistent cloud or surface contamination may be suspect. Composite pixels in the Arctic may typically originate from the last scene acquired during the composite period.

Pixel count - The pixel count contains the number of geocoded scenes available for compositing at a given pixel location in the composite map. An example of this product is shown in Figure 10. The large number of pixels available in the North is due to the overlap of many scenes in this area as the satellite crosses the North Pole while still within the reception circle. The discontinuity evident on Baffin Island is due to the limit of the reception circle for the receiving station in Eastern Canada. The apparent banding in the composite image is due to the satellite orbit precession that results in a slightly shifted orbit position from day-to-day.

QC pixel mask - The quality control (QC) mask is derived from the noisy pixel data described in the pre-processing description.

Residual geometric error map - The geometric error map is an attempt to estimate the geometric (registration) error (magnitude and direction represented as separate layers) for any given pixel in a composite product. For a given geometrically corrected scene the ground control point (GCP) errors are used to compute, via the Kriging technique (Denman and Freeland, 1985; Deutsch and Journel 1992), an error surface which may then be composited into the final product. The errors are represented in magnitude (meters) and direction (0 to 360 degrees clockwise from the North Pole) of the residual error at each point. The concept for this product, which has yet to be evaluated for its usefulness, is to assist in analysing any geometric anomalies that might be observed in the composite product. An example of this product is shown in Figures 11 and 12. The geometric error magnitude ranges from 300 to 4000 m while the direction ranges from 0 to 270 degrees. The compositing of adjacent orbits results in a patchwork of geometric error magnitudes and directions sometimes observed as a linear discontinuity. The large errors observed in Figure 11 in northern Alberta may indicate that the pixels used in the one day composite originated from an orbit that was very cloudy and didn't have a sufficient number of GCPs uniformly distributed across the image. The error directions are typically observed in the north-south direction as the orbit model using ephemeris data places the image close to the correct longitudinal position. Where there is good GCP control, we expect to see a geometric error magnitude of 1000 m or less with the direction of the error vectors randomly distributed.

Surface Reflectance Products

Atmospherically corrected reflectance - The TOA reflectance is converted to surface reflectance by applying the Simplified Method for Atmospheric Correction (SMAC) radiative transfer code (Rahman and Dedieu, 1994). This atmospheric correction using parameterization of geometry and nominal atmospheric parameter values is applied after geocoding and compositing.

Normalized BRDF-corrected surface reflectance - The modified BRDF model by Roujean (Latifovic, Cihlar and Chen, 2002) was applied to AVHRR composite data from 1993 to 1996 processed with the original GeoComp software to derive BRDF correction coefficients for individual land cover types. The land cover map was developed from a classification of the mean seasonal NDVI (computed from BRDF-corrected surface reflectance) for 10-day AVHRR composites during the 1995 growing season (Cihlar et al., 1999a). The 31 land cover classes were reduced to 14 classes for the BRDF correction of surface reflectance to a nadir-view with a constant solar zenith angle of 45^{o}.

Normalized Difference Vegetation Index (NDVI) - NDVI may also be computed from either surface reflectance product as described above.

Higher-Level Products

Pixel contamination mask - The Cloud Elimination from Composites using Albedo and NDVI Trend (CECANT) (Cihlar, 1996) was developed to identify contaminated pixels where the surface vegetation, bare soil, rock or open water is obscured by clouds, partial (sub-pixel) clouds, cloud shadows, smoke or other heavy aerosols, and snow or ice. This procedure was designed to process a complete year (growing season) of composite images. It uses channel 1 surface reflectance as a coarse filter for definitely contaminated pixels and the seasonal trajectory of the NDVI curve (computed from the surface reflectance) as a fine filter for partly contaminated pixels. The CECANT-derived contamination mask is needed by several higher-level products. A near real time version of CECANT was developed by Cihlar et al. (1999b) and will be implemented in GeoComp-n.

Surface temperature - The land surface temperature in degrees Kelvin is determined using the split window method of Coll et al. (1994) for brightness temperatures in channels 4 and 5 and a separate accounting for atmospheric attenuation and soil emissivity (Cihlar, Chen and Li., 1997a; Cihlar et al., 1997b).

Leaf area index - The leaf area index (LAI) is derived from an empirical relationship with NDVI according to land cover type (Chen et al., 2002). Landsat 5 TM data from across Canada were used in the validation of the LAI model. LAI is unitless and can have values in the range of 0 to 10 (indicating very lush, dense vegetation).

Instantaneous FPAR - the instantaneous fraction of photosynthetically active radiation (FPAR) absorbed by the surface is computed from an empirical relationship that relies on the LAI, a land cover dependent correction factor and the solar zenith angle (Cihlar et al., 2002b).

Daily Mean FPAR - The daily mean FPAR absorbed by the surface is computed from an empirical relationship that relies on the LAI, a land cover dependent correction factor and the pixel latitude for the solar zenith angle at solar noon (Cihlar et al., 2002b).

Instantaneous APAR - The instantaneous absorbed photosynthetically active radiation (APAR) is the radiation absorbed by the vegetation canopy (Li and Moreau, 1996). The maximum instantaneous APAR value is 544 Wm^{-2} (nominal value for incident solar radiation between 400 nm and 700 nm at the top of the atmosphere for mean sun-earth distance of 1 astronomical unit).

Daily Total APAR - The daily total APAR is determined as the integral of APAR values during daylight (sunrise to sunset). For simplification, an estimation of the integral is made with the mean solar zenith angle, where the TOA albedo is assumed to be constant for the day. The daily total APAR is given in units of kilo-Watts-Seconds per m^2 or kilo-Joules per m^2.

Composite Mean APAR - The composite mean APAR is computed from the sum of all observed (clear and cloudy) daily total APAR values (computed per scene) during the composite period divided by the number of scenes at each pixel. The composite mean APAR is given in units of kilo-Watts-Seconds per m^2 or kilo-Joules m^2.

Fire mask - An algorithm developed by CCRS (Li, Nadon and Cihlar, 2000a) allows the mapping of hotspot pixels for forest fires on a daily basis, which are aggregated in a binary image layer for a multi-date composite; thus, retaining all hotspot pixels during the composite period. A land cover map is used to mask out non-forest pixels. A number of visible and thermal channel threshold tests are used to eliminate false alarms.

PAR albedo - Photosynthetically active radiation (PAR) surface albedo is required to compute green APAR for vegetation growth models (Cihlar et al., 2002b). Currently, the complete PAR albedo algorithm is implemented in GeoComp-n; however, the calculation is slow due to the computation of a look-up table (LUT). It is planned to move the BRDF integration outside of the algorithm and to create a permanent LUT file on disk to speed up the process.

Operational Implementation

NOAA AVHRR data for the Canadian landmass are received at PASS in Saskatchewan, where they are formatted into raw data products in NATAS. The browse imagery and CUFs from NATAS are transmitted to CEOCat by file transfer protocol (FTP) on a daily basis. The NATAS products are electronically transferred by FTP to a file server at CCRS typically within two hours of satellite overpass time. The products are received in a compressed (.zip) file format to optimize use of the Internet bandwidth. They then pass through an automated quality control check and, if successful, are made available to authorized users including the Manitoba Remote Sensing Centre (MRSC). Approximately 140 orbits per month are received, with up to 6 weeks of the most recent NATAS data being stored on-line at any one time.

PASS cannot acquire AVHRR data for the extreme eastern part of Canada (Nova Scotia and Newfoundland) where the satellite is out of the reception circle for PASS. A Memorandum of Understanding has been signed with Fisheries and Oceans Canada (FOC) to receive East Coast data at their Mont Joli (in Quebec) satellite receiving station and to electronically send the data to PASS for processing in NATAS.

In 1999 and 2000, three main GeoComp production systems have been used, one at MRSC (for operational products) and two at CCRS (one for fire monitoring and the other for scientific research).

Manitoba Remote Sensing Centre Products

An operational facility at MRSC in Winnipeg generates composite products on a routine basis for CCRS and assorted composites for MRSC clients by subscription. Raw NATAS data, which were previously delivered on Exabyte tapes, are now downloaded electronically from the CCRS FTP server. These data are imported into the GeoComp-n system, pre-processed and geocoded, converted into composite products, and shipped on Exabyte tapes and CD-ROMs or delivered electronically. Daily and 10-day composite products are produced by MRSC for CCRS during the growing season, April 11th (or April 1st starting in 2000) to October 31st. For the 10-day products, the composite periods for any given month are from the 1st to 10th, 11th to 20th and 21st to end of the month. The image layers included in single day and multi-day composite product bundles are shown in Table 1. For comparison, the basic product set generated by the original GeoComp system prior to 1999 is also included in the table. The 10-day composite products are used in ecological studies at Parks Canada (Wilmshurst, Tuckwell and Naughten, 2000). Seven-day composite products are produced for spring wheat yield prediction by Statistics Canada (Reichert, Nixon and Dobbins, 1998).

While MRSC is generating many of the data layers in the 10-day composite products for CCRS near real time, the basic composite bundle consisting of radiance data for the five AVHRR channels and ancillary channels is used as input to the Atmosphere, Bi-directional and Contamination Corrections of CCRS version 2 (ABC3V2) software system (Cihlar et al., 2002a). Historical GeoComp-n data older than two years will be re-processed in ABC3V2 and made public on the Natural Resources Canada GeoConnections Discovery Portal (http://ceonet.ccrs.nrcan.gc.ca/). Since ABC3V2 can only be used in post-season processing, many of its refinements have yet to be implemented for the near real time operation of GeoComp-n. However, some versions of these algorithms are becoming available such as CECANT and will be implemented in the future.

Fire Processing

One GeoComp-n production system has been used at CCRS to produce daily fire maps of Canada. The production system consists of a 2x350MHz NT workstation with a 500GB Redundant Array of Independent Disks (RAID) disk tower. Raw data are downloaded from the NATAS data file server, imported into GeoComp-n, geocoded using a nearest neighbour resampling algorithm and composited into daily products. The composite product is used by a customised fire detection algorithm (Li, Nadon and Cihlar, 2000a; Li et al, 2000b) to detect the hotspots and produce a map of active fires for Canada. A daily colour Tagged Image File Format (TIFF) image of the composite is also produced with the fire hotspots overlaid on the image. Both the TIFF image and the fire map are sent electronically to the Canadian Forestry Service (CFS) in Edmonton where they are imported into a geographic information system (GIS), overlain with map information and made available to forest fire managers via an Internet based system (http://fms.nofc.cfs.nrcan.gc.ca/FireM3/). Four to six scenes per day are processed, the last scene being received at about 10 p.m. local time and the final products being completed before midnight. The system is also used as a research tool for developing fire and smoke detection algorithms.

Future Improvements

GeoComp-n needs about 5.5 minutes to import, 5 minutes to calibrate and 45 minutes to resample an AVHRR orbit containing 5700 lines using a standard 16-point damped sin x/x resampling function on a 450MHz NT PC. Since CPU speed is the main limitation of the geocoding speed, continuing advances in faster CPUs will alleviate this problem. By way of contrast, input-output was the main limitation in the original GeoComp system, especially the data transport to and from the two specialized array processors that performed the resampling. With the advent of large capacity RAID systems, disk space is becoming less of an issue for the large number of scenes being geocoded and data layers being generated for the composite products. Typical disk requirements are such that one month’s worth of data consumes approximately 110 gigabytes of disk space if all the intermediate products (raw, pre-processed and geocoded) remain on-line.

At the present time, input of the raw data for geocoding is controlled by the operator using a GUI. This can be tedious and slow, particularly when reprocessing several hundred raw scenes. A series of Practical Extraction and Report Language (Perl) scripts, which are layered on top of the GeoComp-n software, have been written to automate the import of raw data, geocoding and compositing processes. These scripts have been employed in the fire production system at CCRS.

When high-resolution mosaics of North America become available, the GCP chip database will be augmented to include more GCPs along the entire orbit, especially in the western United States where clouds are less frequent. This should lead to a significant improvement in the success and speed of the image chip matching algorithm.

It is intended to continue implementing GeoComp-n upgrades as new and revised algorithms become available, new satellites come on-line, and the system configuration and user interface are optimized. For example, an expanded fire mapping algorithm is nearing completion, which will take into account improved scaling of thermal radiance data and the increased radiance range of AVHRR/3 channel 3B (3.4 um) onboard NOAA 16.

Conclusion

The GeoComp-n system has been designed to increase ease and flexibility of different inputs or products, to provide greater reliability and efficiency in operation and to easily accommodate new and growing processing requirements. These objectives have been successfully met. The modular design philosophy and the close interaction between software engineers, science users and system operators have been shown to be the essential ingredients. GeoComp-n (commercially available from PCI Geomatics) can deliver geometric and radiometric accuracies in composite products unprecedented in operational AVHRR data processing software. At the present time, GeoComp-n supports a broad spectrum of operational and experimental products from AVHRR data, but expansion to other data types and new products should be straightforward once their characteristics are established and the required algorithms defined. This represents a significant advance in processing capability for coarse to medium resolution optical satellite data for Canada, and also has strong potential for use in other parts of the world. In particular, the higher-level product algorithms are being developed and validated for use in boreal and temperate ecosystems present in Canada. The high degree of automation and flexibility in GeoComp-n should be adequate to meet the requirements (ranging from scientific to practical applications) of a wide variety of users including forest fire management agencies, crop forecasting and assessment agencies, crop insurance companies, forestry industries, and government environmental agencies.

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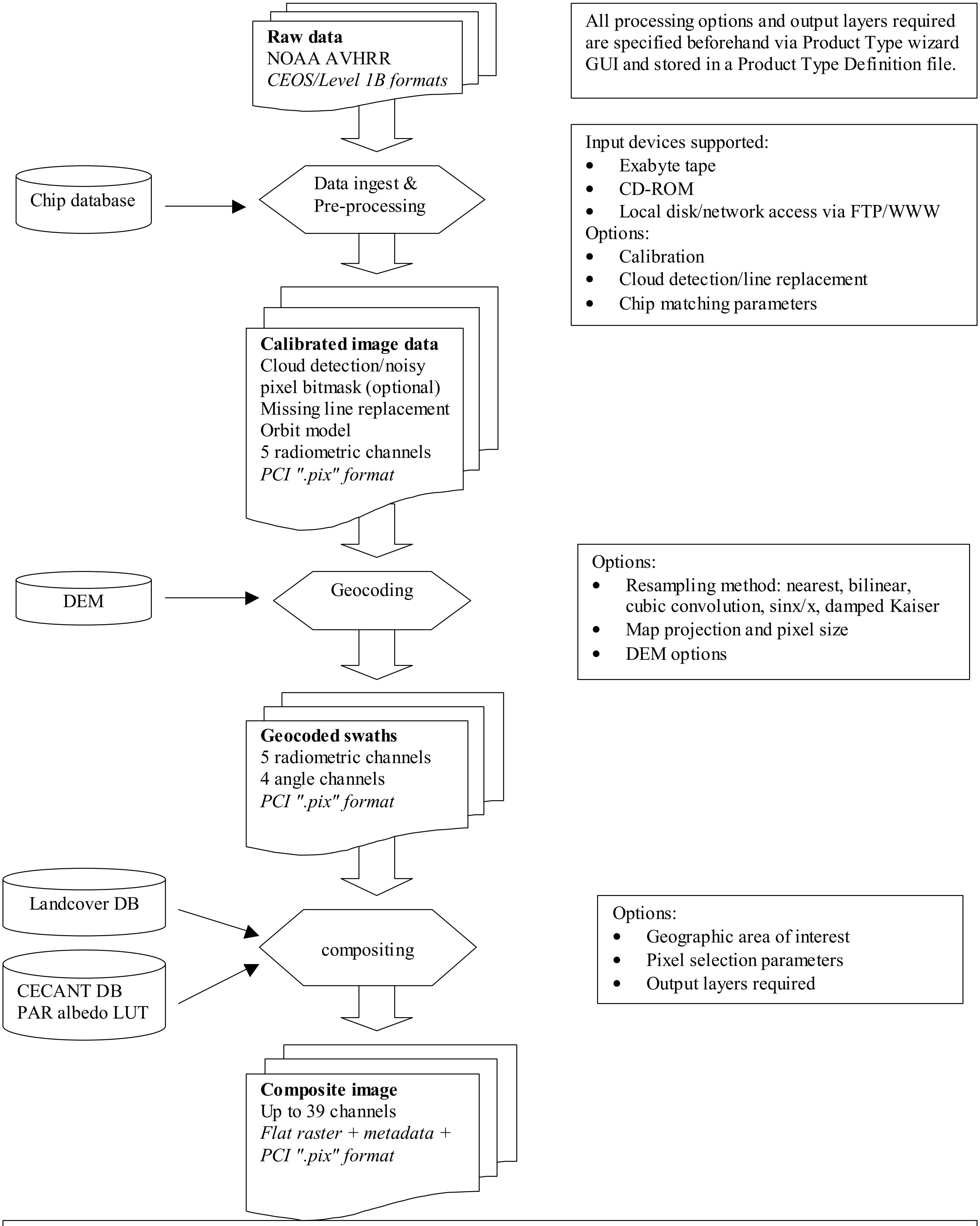

All processing options and output layers required are specified beforehand via Product Type wizard GUI and stored in a Product Type Definition file.

Input devices supported:
- Exabyte tape
- CD-ROM
- Local disk/network access via FTP/WWW

Options:
- Calibration
- Cloud detection/line replacement
- Chip matching parameters

Options:
- Resampling method: nearest, bilinear, cubic convolution, sinx/x, damped Kaiser
- Map projection and pixel size
- DEM options

Options:
- Geographic area of interest
- Pixel selection parameters
- Output layers required

Figure 1 - GeoComp-n data flow diagram

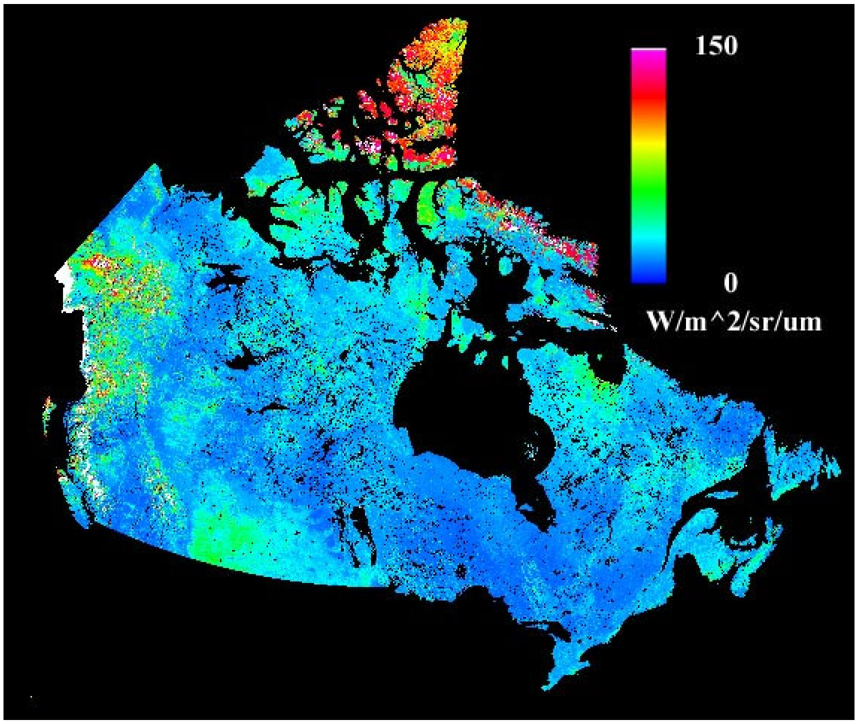

Figure 2 - Channel 1 TOA radiance product for the period August 11-20, 2000

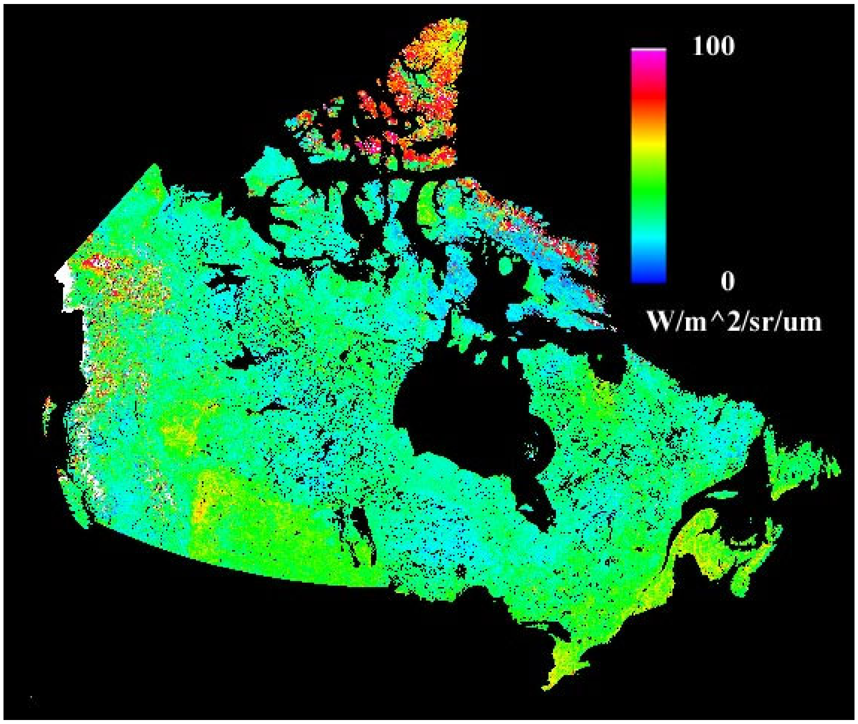

Figure 3 - Channel 2 TOA radiance product for the period August 11-20, 2000

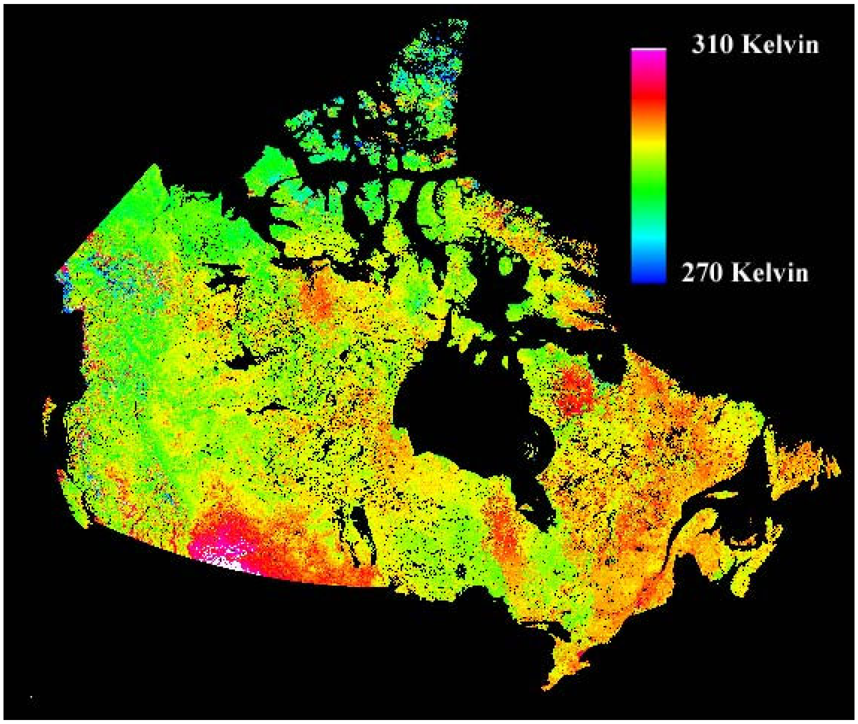

Figure 4 - Channel 3 TOA brightness temperature product for the period August 11-20, 2000

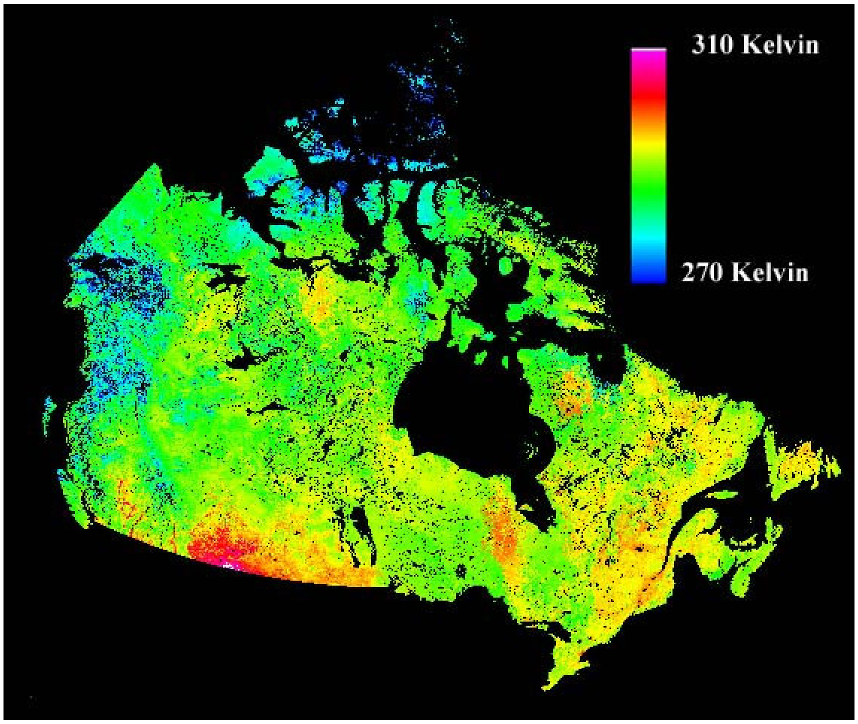

Figure 5 - Channel 4 TOA brightness temperature product for the period August 11-20, 2000

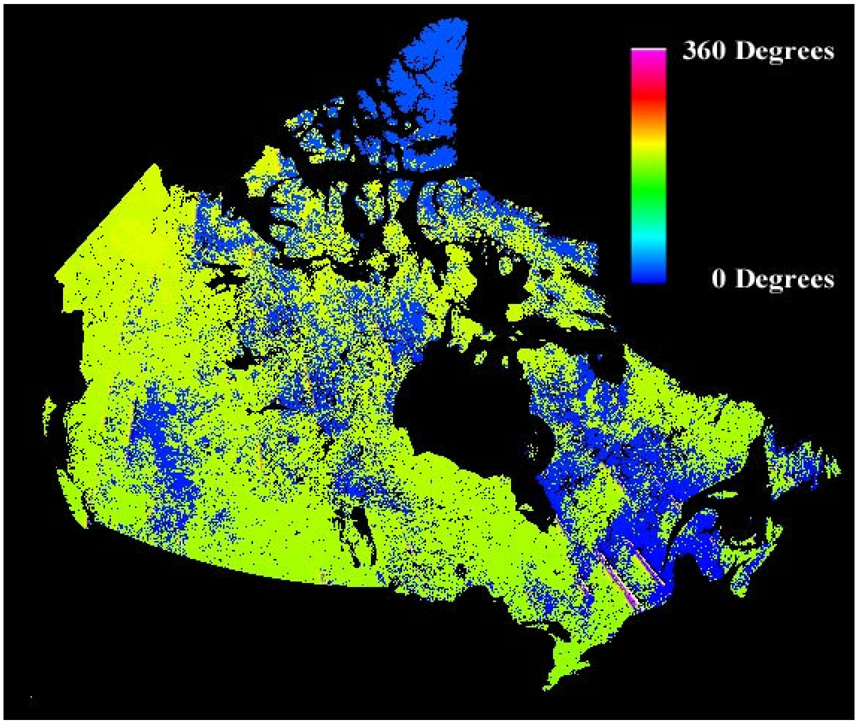

Figure 6 - Relative azimuth product for the period August 11-20, 2000.

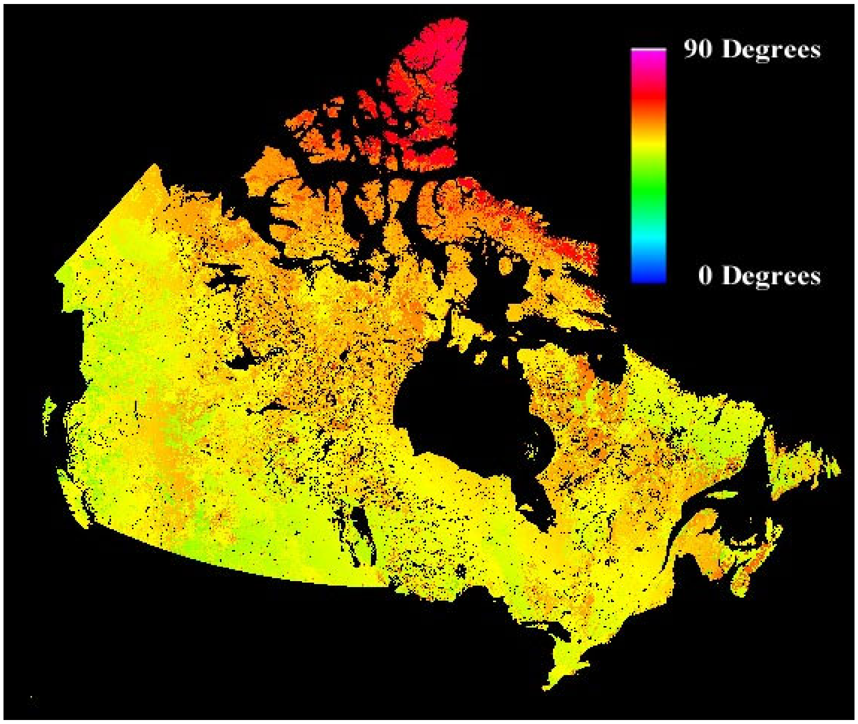

Figure 7 - Solar zenith angle product for the period August 11-20, 2000

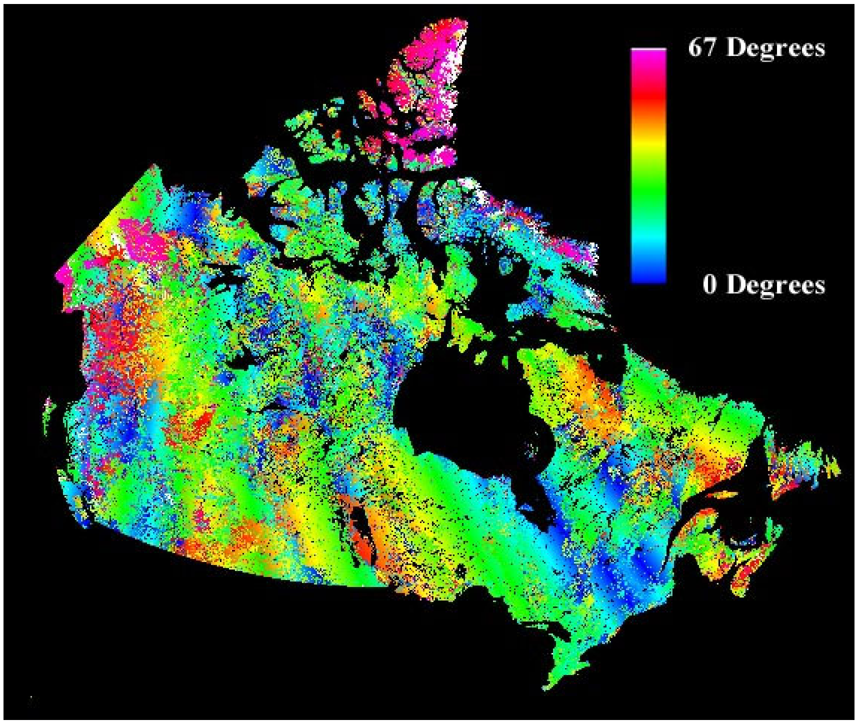

Figure 8 - Satellite zenith angle product for the period August 11-20, 2000

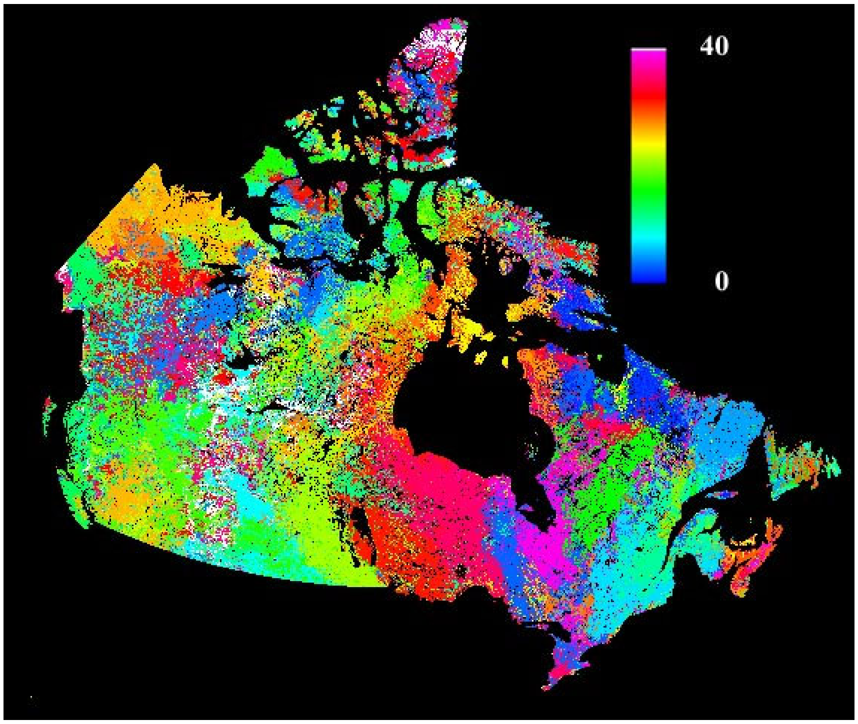

Figure 9 - Input scene map product for the period August 11-20, 2000

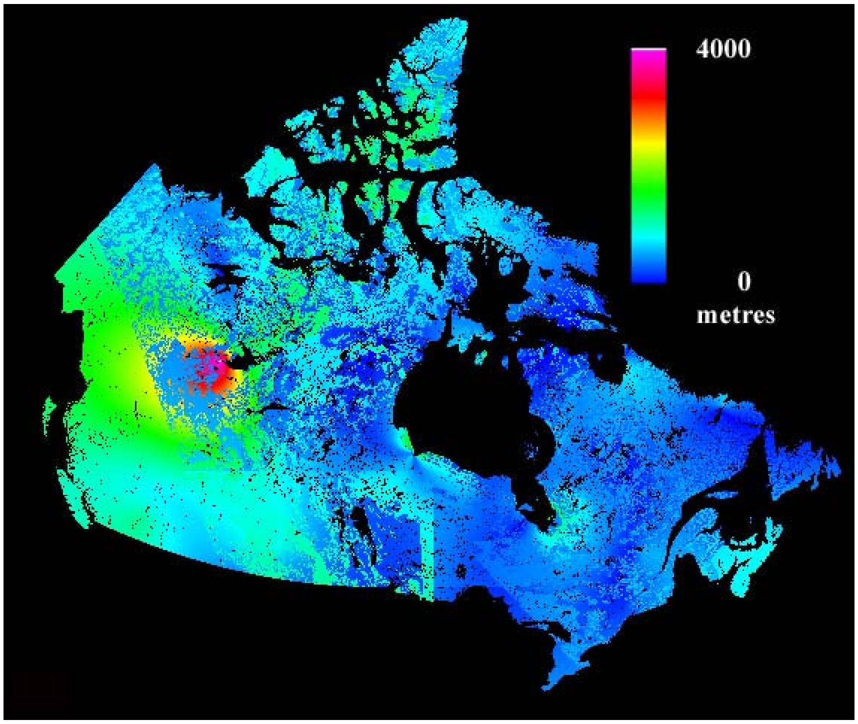

Figure 10 - Pixel count product for the period August 11-20, 2000

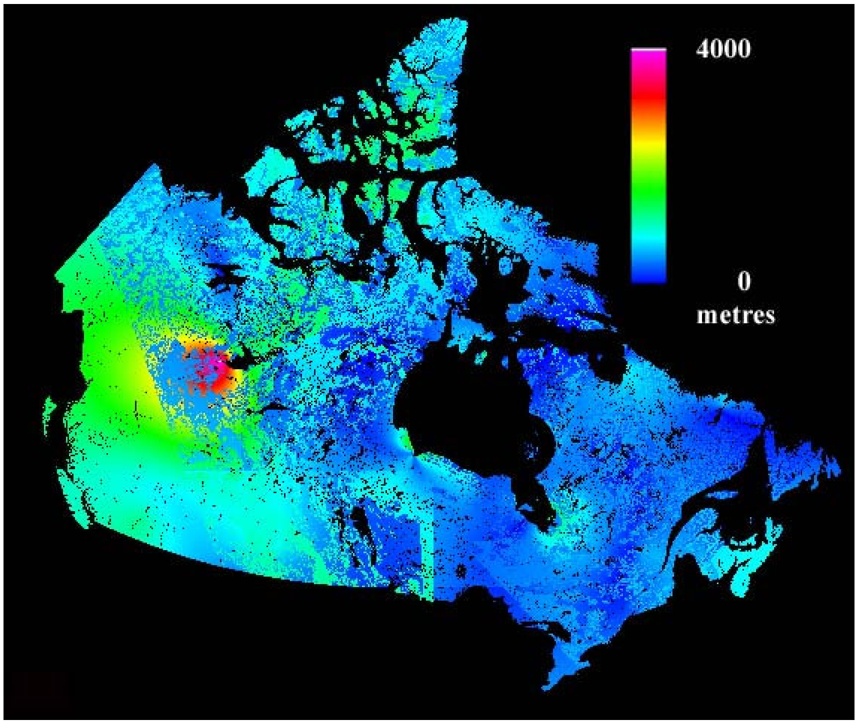

Figure 11 - Geometric error magnitude product for August 8, 2000

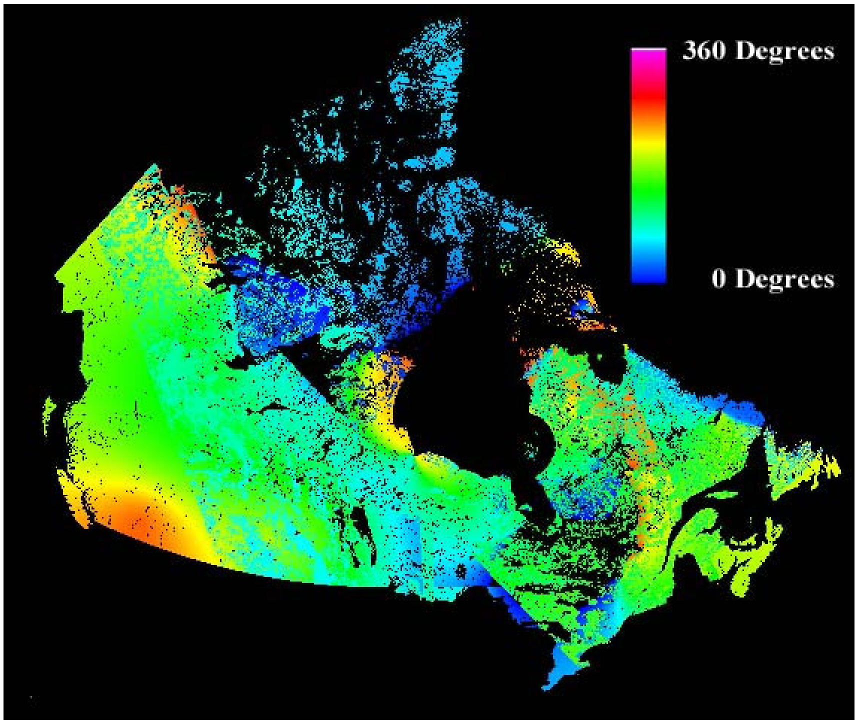

Figure 12 - Geometric error direction product for August 8, 2000.

Table 1 - Composite product bundles

Disk file identifier*	**Geocoded scenes**	**Basic set (pre-1999)**	**Single Day composite set**	**Multi-Day composite set**	**Bits per pixel**	**Units**	**Description**
Basic products							
B01_RATOA	X	X	X	X	16	W/m^2/sr/um	Calibrated radiance at top-of-atmosphere
B01_RETOA			X	X	16	Reflectance factor	Top-of-atmosphere reflectance
B02_RATOA	X	X	X	X	16	W/m^2/sr/um	Calibrated radiance at top-of-atmosphere
B02_RETOA			X	X	16	Reflectance factor	Top-of-atmosphere reflectance
B03_RATOA	X	X	X	X	16	mW/m^2/sr/cm-1	Calibrated radiance at top-of-atmosphere
B03_BTTOA			X	X	16	Degrees K	Top-of-atmosphere brightness temperature
B04_RATOA	X	X	X	X	16	mW/m^2/sr/cm-1	Calibrated radiance at top-of-atmosphere
B04_BTTOA			X	X	16	Degrees K	Top-of-atmosphere brightness temperature
B05_RATOA	X	X	X	X	16	mW/m^2/sr/cm-1	Calibrated radiance at top-of-atmosphere
B05_BTTOA			X	X	16	Degrees K	Top-of-atmosphere brightness temperature
NDVI_RATOA					16	Ratio	NDVI computed from RATOA
NDVI_RETOA		X	X	X	16	Ratio	NDVI computed from RETOA
SATELLITE_ZENITH	X	X	X	X	16	Degrees	Satellite zenith angle
SATELLITE_AZIMUTH	X		X	X	16	Degrees	Satellite azimuth angle
SUN_ZENITH	X	X	X	X	16	Degrees	Solar zenith angle
SUN_AZIMUTH	X		X	X	16	Degrees	Solar azimuth angle
REL_AZIMUTH		X	X	X	16	Degrees	Relative azimuth angle
REL_DATE		X		X	16	Days	Relative date (days since 1-JAN-1970)
INPUT_SCENE_MAP			X	X	8	None	Input scene map
PIXEL_COUNT			X	X	8	None	Pixel count
QC_PIXEL_MASK			X	X	8	None	Pixel QC mask
GEO_ERROR_R				X	16	Metres	Residual geometric error magnitude
GEO_ERROR_THETA				X	16	Degrees	Residual geometric error direction
Surface reflectance products							
B01_RESUR_SMAC				X	16	Reflectance factor	Surface reflectance, SMAC-corrected
B02_RESUR_SMAC				X	16	Reflectance factor	Surface reflectance, SMAC-corrected
B01_RESUR_BRDF				X	16	Reflectance factor	Surface reflectance, BRDF-corrected
B02_RESUR_BRDF				X	16	Reflectance factor	Surface reflectance, BRDF-corrected
NDVI_RESUR_SMAC				X	16	Ratio	NDVI computed from SMAC
NDVI_RESUR_BRDF				X	16	Ratio	NDVI computed from BRDF
Higher level products							
SURFACE_TEMP			X	X	16	Degrees K	Surface temperature
LAI			X	X	16	m^2/m^2	Leaf area index
FPAR_INST				X	8	Percentage	Instantaneous FPAR
FPAR_DAYMEAN			X		8	Percentage	Daily mean FPAR
APAR_DAYTOTAL			X		16	kJ/m^2	Daily total APAR
APAR_INST			X		16	W/m^2	Instantaneous APAR
APAR_COMPMEAN				X	16	kJ/m^2	Composite average APAR
APAR_TOTAL				X	32	kJ/m^2	Sum of daily total APAR
FIRE_MASK			X		8	Probability (binary)	Fire mask

PAR_ALBEDO				X	16	Factor	PAR surface albedo
CECANT				X	16	None	Cloud/snow/ice mask

***Bxx-YYZZZ-KLMN**: B: AVHRR channel; xx=AVHRR channel no.; YY: RA (radiance), RE (reflectance) or BT (brightness temperature); ZZZ: TOA (top-of-the-atmosphere) or SUR (surface); KLMN: SMAC (atmospheric correction only) or BRDF (atmospheric and bi-directional corrections)