Towards Integrated Earth Sensing: From Space to In Situ

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Abstract

Significant advancements in Earth observation are expected to come about by developing more systematic capabilities for assimilating remote sensing observations and in-situ measurements for use in models, at relevant scales, to generate geophysical and biospheric information products. This paper provides an overview of the role of in-situ sensing in the context of integrated Earth sensing. The knowledge gleaned from integrated Earth sensing has the potential to empower managers and decision makers to act on critical climate, sustainable development, natural resource, and environmental issues. The paper describes a prototype wireless intelligent sensorweb deployed in a flood-forecasting context.

1 Introduction

" Man must rise above the atmosphere and beyond to fully
understand the world in which he lives". Socrates, 700 BC.

An early history of terrestrial remote sensing would be highlighted by a series of ideas and developments going back thousands of years, but primarily occupying the decades from the late nineteenth century through to the launch of the U.S. Earth Resources Technology Satellite (Landsat-1) in 1972 (Table 1). In many ways, the advent of Landsat marked the beginning of the modern era of satellite Earth observation. With the availability of direct broadcast data reception at ground stations around the world and the adaptation of image processing and pattern recognition tools, Landsat became the catalyst for the development of civilian remote sensing systems as we know them today. Landsat imagery continues to be the entry-level data type for many if not most users new to remote sensing technology and it occupies a very valuable niche in resource and environmental monitoring.

Today, space-based measurement systems provide unprecedented synoptic coverage of the Earth. Ironically, the extent to which data acquired by such systems can provide reliable and quantitative information depends critically on independent measurements and investigations carried out at the surface. Ground-based in-situ measurements make it possible to supplement and validate satellite sensor observations and there will always be parameters that are inaccessible from space. Indeed, over the next few years, the nature of remote and in-situ sensing and their relationship with the Internet will change drastically. Some analysts predict that trillions of sophisticated embedded measuring devices, each with sensors, a processor, a power supply, and a transmitter, will be networked together to provide an extensive monitoring system for the Earth[1].

In parallel to developments in the widespread deployment of electronic measuring devices, as well as developments in satellite telecommunications, the future of Earth observation satellites is exemplified by NASA's strategic Earth science vision for networks of satellite sensors, or satellite "sensorwebs". Much of the focus of these satellite sensorwebs over the next 25 years will be on improving predictions of Earth system changes, both short-term and long-term, with considerable priority given to severe weather phenomena and disaster events (NASA, 2000). These orbital sensor deployments will provide the robustness that an operational system requires by allowing many small, separate platforms working together intelligently and autonomously in reconfigurable and interoperable ways to accomplish what was formerly thought to require large, multi-sensor platforms largely controlled from the ground.

This paper presents the concept of integrated Earth sensing, whose goal is to make significant advancements in the practical use of Earth observation data by developing intelligent in-situ measurement capabilities that open new pathways towards the generation of quantitative geophysical and biospheric information products. The concept encompasses advanced technologies to design and deploy sensorwebs for ground-based in-situ data acquisition, develop methods to assimilate in-situ and remote sensing data into models that generate validated information products, and facilitate the accessibility of in-situ sensor data and/or metadata from on-line geospatial data infrastructures. The paper outlines early work on the first of these and describes a Prototype Wireless Intelligent Sensorweb Evaluation (ProWISE).

Table 1. Some milestones in the early history of remote sensing.

Epoch	Milestones
1839	Beginnings of photography.
1850-1860	Photography from balloons.
1909	Photography from airplanes.
1910-1920	Aerial reconnaissance (WW1).
1920-1930	Development / use of aerial photography & photogrammetry.
1930-1940	Development of radar.
1940-1950	Applications of non-visible spectrum (WW2).
1940-1950	Training on acquisition / interpretation of air photos (WW2).
1950-1960	Military research and development.
1960-1970	First use of term "remote sensing".
1960-1970	TIROS weather satellites.
1972	Launch of ERTS-1, renamed Landsat-1.

2 In-Situ and Proximal Sensing

In-situ sensing can be defined as a technology used to acquire information about an object when the distance between the object and the sensor is comparable to or smaller than any linear dimension of the sensor. A short dictionary-based definition for in-situ sensing could be "sensing in place". Because many measurements or observations are made from nearby locations that are

[1] Gross, N.: "The Earth Will Don An Electronic Skin", in "21 Ideas for the 21st Century", BusinessWeek online, August 30, 1999 issue.

not strictly speaking in-situ, the expression proximal sensing has been adopted in a variety of disciplines. A short dictionary-based definition could be "sensing from close range" (as in close-range photogrammetry, for example). For the present purposes and in practice, in-situ sensing is considered to encompass proximal sensing. Networks of in-situ sensors have been in place for decades in numerous contexts, perhaps the most prevalent being meteorological stations. These networks continue to evolve even as unattended sensor and wireless telecommunication technologies advance at a rapid pace and new uses are invented. It is becoming increasingly feasible to provide quality-controlled network-wide data to users via the Internet in near real time and information products from data fusion and assimilation into models within hours.

3 Integrated Earth Sensing

Satellite Earth observation sensors provide unique measurements of geophysical and biospheric variables globally and repetitively. These measurements are all the more critical because the Earth as a system changes constantly over a wide range of temporal and spatial scales. Nevertheless, it has long been recognized that ground data collection is an essential source of information even in surveys that rely heavily on remote sensing (Lee 1975; Justice and Townshend 1981; Teillet 1995). With the increasing availability of multiple satellite sensor systems, it is essential to provide ground-based benchmarks and cross-calibration standards on a continuous basis to ensure the self-consistency of information products generated from these multiple systems (Teillet et al. 2001a).

After thirty years of research and development and a notable under-utilisation of information products based on remote sensing by government agencies and resource developers, it is now widely acknowledged that pixel signals as measured by Earth observation sensors do not contain all of the information necessary to derive many of the geophysical and biospheric parameters required to address current issues of critical importance to citizens. Hence, a growing perspective today is that significant advancements in Earth observation are expected to come about only by developing more systematic capabilities for the fusion of remote sensing observations and in-situ measurements for assimilation with models, at relevant scales, to generate geophysical and biospheric information products. This integrated approach will include the specification and deployment of autonomous sensorwebs on the surface of the Earth in various application contexts. Projects should be undertaken to demonstrate the importance and impact of the fusion of in-situ measurements of quantities such as spectral reflectance, temperature, soil moisture, dielectric constant, etc., with remotely sensed pixel signals for use in relevant multi-scale models for the production of forecasts, yield estimates, or hazard potential, among many others.

4 Emerging Technologies

4.1 Wearable Computers

Field campaigns that take advantage of real-time data uplink and downlink to/from a common geospatial gateway from any point on Earth and at any given time will soon become commonplace. In years to come, in those cases where field research will still require a physical human presence, people will no longer have to carry computers, sensors and instruments to the field. They will be embedded or worn in clothes and other paraphernalia. Wearable computers and clothing-based multimedia computers are novel terms in our vocabulary and yet, today, these devices already exist (Mann 1997) and are capable of exchanging digital data, audio and video, as well as providing accurate viewpoints in real-time while processing and analysing field data. Wearable computers are currently being used operationally by utility companies and experimentally in the Houghton Mars Project, for example, which is a NASA-led international field research program dedicated to planning the exploration of the planet Mars.

4.2 Telepresence

Advances in video technology have opened the door to telepresence, the capability of being present in a real-time sensory way at locations remote from one's own physical location (Buxton 1997). Investigators undertaking field campaigns are able to communicate and exchange their results and ideas with colleagues at other locations in real-time. This contributes to standardization of measurement methodologies and protocols, remote technical support of instruments, lower-cost and wider participation in resource-intensive activities, university-level education, and training of highly qualified personnel (Teillet et al. 2001a). Following posted schedules, live webcasting and telepresence can provide experiment-oriented or pedagogical coverage of the in-situ measurement activities. Issues and controversies about measurements and methodologies can be featured during broadcasts.

4.3 WINS Technology, Sensor Pods, Sensorwebs, and Smart Dust

The automation of field mensuration is increasingly removing the operator from the field, particularly in hazardous environments. It is indeed becoming possible to remotely control and monitor field activities through the Internet. In particular, the converging technologies of sensors, micro-computers, and wireless telecommunications has led to new developments such as Wireless Integrated Network Sensors (WINS) (Asada et al. 1998) and intelligent networks of in-situ sensors, i.e., in-situ sensorwebs (Delin and Jackson 2000, 2001; Delin 2002).

WINS and related systems form the technology base for new monitoring and control capability for a wide variety of applications in sectors such as transportation, manufacturing, health care, environmental monitoring, and safety and security (Asada et al. 1998). WINS nodes are compact, low-power, and relatively inexpensive devices that combine sensing, signal processing, smart systems, and wireless networking.

As opposed to other distributed sensor networks, sensors in a sensorweb share information among themselves and modify their behaviour on the basis of collected data. In the in-situ sensing context, a sensorweb consists of wirelessly communicating, spatially distributed sensor pods that are deployed to monitor and explore environments (Figure 1). The pods serve as nodes in a communication chain or network that links up to base stations for wireless transmission to a user infrastructure. They can also have plug-in capability to handle data from other environmental sensors. With the capability of providing an ongoing virtual presence in remote locations, many sensorweb uses can be envisaged in the context of environmental monitoring. Sensorwebs could have as much impact on the uses of sensor technology as the Internet did on the uses of computer technology.

Already being investigated, the next step will be “Smart Dust” - sensing, computation, communication, and power in a cubic millimetre - deployed in large numbers with the ability to measure temperature, pressure, light, sound, humidity, magnetic field, and acceleration (Pister et al. 1999). Many uses are being considered, but an example would be forest fire detection, warning and monitoring. Quickly developed prototypes have been built using commercial-off-the-shelf (COTS) components. COTS Dust has the same functionality as Smart Dust, but the devices are a cubic inch in size instead (Hollar 2000).

4.4 Global Virtual Presence – Integrated Earth Sensing

An emerging perspective is that the advent of in-situ sensorwebs, Earth science satellite sensorwebs, and the Internet will provide a kind of global virtual presence, as described by NASA's Jet Propulsion Laboratory (JPL) or, alternatively, integrated Earth sensing. There is great potential for applying existing and emerging in-situ sensor technologies and networks in order to achieve the goals of resource and environmental monitoring activities. The criteria for success will be a dramatic increase in the efficiency of data collection and analysis, as well as the timely availability of data and derived information for decision-making.

5 A Framework for In-Situ Sensing Activities

Because numerous independently managed networks and archives of in-situ sensors and data currently exist, it will be important to focus activities carefully and leverage existing infrastructures wherever possible. The perspective that selected in-situ sensing networks can be a critical component of integrated Earth sensing is helpful in this regard. Thus, it is proposed that in-situ sensor measurement assimilation activities will initially fit within the following framework (Teillet et al. 2001b) (Figure 2). They should:

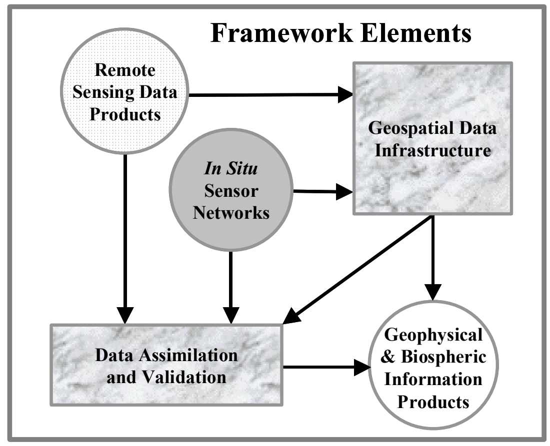
- Lead to the generation of information products that address clearly defined science and technology questions and/or user information requirements.
- Utilize in-situ sensor networks.
- Utilize remote sensing data products.
- Encompass data assimilation and validation components.
- Routinely provide in-situ data products and/or metadata on in-situ data holdings to a geospatial data infrastructure.

Complementary to current efforts towards an Integrated Global Observing Strategy[2] and Global Monitoring for Environment and Security[3], the integrated Earth sensing concept provides a framework for the research and development of advanced data acquisition and integration elements of environmental monitoring/information systems used for local, regional, or global decision-making. In-situ sensor measurement assimilation activities could focus as a priority on issue-driven science and technology activities such as the monitoring of remote environments, risk assessment and hazard mapping, and time-critical decision making (e.g., disaster and renewable resource information management).

[2] IGOS, http://www.igospartners.org/
[3] GMES, http://gmes.jrc.it/

Fig. 1. A sensor pod from the Jet Propulsion Laboratory (JPL) (Delin, 2002).

Fig. 2. Principal framework elements for in-situ measurement activities in the context of integrated Earth sensing.



6 Prototype Wireless Intelligent Sensorweb Evaluation

The main objective of the Prototype Wireless Intelligent Sensorweb Evaluation (ProWISE) involves the field deployment of a sensorweb with full inter-nodal connectivity and remote access and control. The project is also testing remote webcam operations and plans to demonstrate telepresence at remote field sites. These deployments do not yet take advantage of fully miniaturized systems but they utilize COTS technology and are taking place in real as opposed to controlled environments.

Early in 2002, a prototype network of sensors was deployed in various outdoor environments in the vicinity of Ottawa, Canada, to facilitate the debugging of data and communication protocol conversions between the microsensor/microcontroller packages and the satellite transceivers. During the summer of 2002, a test deployment was made at Bratt's Lake Atmospheric Radiation Observatory (BLARO) in Saskatchewan, Canada, in collaboration with Environment Canada's Meteorological Service of Canada (MSC). This field campaign included tests of the full access/control system through the Integrated Earth Sensing Workstation (IESW) in Ottawa. As shown in Figure 3, the initial sensorweb test configuration consists of a compact mast with sensors recording temperature, relative humidity, downwelling solar radiation, rainfall, wind direction, wind speed, leaf wetness as appropriate, soil temperature, and soil moisture (Figure 4). A more elaborate test deployment followed in autumn 2002 in the context of a flood forecasting application for the spring of 2003 in the Red River basin in Manitoba, Canada (Figure 5). The microspectrometer subsystems and related wireless telecommunications are still in the integration and testing phases.

The initial prototype sensorweb test-bed consists of five or six nodes and a base station. Different wireless telecommunication and telepresence strategies are being examined. Access and control are Internet web-enabled, remotely operated, and being tested from the individual nodes to the IESW in Ottawa as well as from the nodes to the base station and then to the IESW. Control of the microsensors is achieved through embedded systems specifically tailored to the geospatial application being investigated in the context of the framework discussed previously. Smart internodal communication is planned for the next phase of the ProWISE development. In that phase, the current style of nodes will likely become the base stations for local-area sensorwebs with the addition of several dozen smaller sensor nodes. Thus, hierarchically, there will be two levels to the in-situ sensorweb.

Fig. 3. Fully instrumented wireless station deployed in the Red River basin, Manitoba, Canada.

Fig. 4. Adcon soil moisture C-Probe.

Fig. 5. Prototype sensorweb deployment (five nodes and base station) in Red River flood forecasting context, Manitoba, Canada. Landsat-7 image width is approximately 45 km.

7 Concluding Remarks

The advanced technologies of today make it possible to develop integrated approaches to Earth sensing that encompass both remote and in-situ sensing. Integrated Earth sensing has the potential to significantly reduce the gap between partially validated information derived from remote sensing and quantitative geophysical and biospheric information needed to contribute to issues that society and policy-makers are striving to address. Such an effort will capitalize on the rapidly maturing technologies of micro-sensors and wireless telecommunications to expand the scope of remote sensing and make it more viable by providing solid underpinnings for the quality, robustness, and reliability of the information derived. It is from this perspective that integrated Earth sensing will help to make it possible for Earth observation technology to “cross the chasm” (Moore, 1991) and be adopted by mainstream users of technology.

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