Research Note

Towards Integrated Earth Sensing: Advanced Technologies for In Situ Sensing in the Context of Earth Observation

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Summary

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. It also defines a framework for taking advantage of intelligent sensor webs based on the converging technologies of micro-sensors, computers, and wireless telecommunications in support of critical activities such as the monitoring of remote environments, risk assessment and hazard mapping, and renewable resource information management. 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.

Introduction

With the advent of remote sensing technology, particularly weather satellites to begin with and images of the globe taken from Earth orbit and beyond, our thinking about the planet we live on has taken on a global perspective that was not possible in the past. In the middle to late twentieth century, we began to study general/global circulation models, global change, Earth system science, sustainable development, etc., as well as environmental concerns such as global warming, ozone depletion, deforestation, desertification, wide-spread pollution of land, sea, and air. Perhaps these investigations and concerns are early signs of a form of collective global awareness, what Teilhard de Chardin (1956) called the “noosphere”, but they are undoubtedly a tardy re-awakening to what aboriginal peoples have known for thousands of years concerning nature as a system.

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. 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, a revolution is taking place. 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 and a transmitter, will be networked together to provide an extensive monitoring system for the Earth (Gross, N.: “The Earth Will Don An Electronic Skin”, in “21 Ideas for the 21st Century”, BusinessWeek online, August 30, 1999 issue).

In parallel to developments in the widespread deployment of electronic measuring devices, as well as those in satellite telecommunications, the future of Earth observation satellites is exemplified by NASA’s strategic Earth science vision for networks of satellite sensors, or "sensor webs". Much of the focus of these satellite sensor webs 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 to accomplish what was formerly thought to require large, multi-sensor platforms.

Earth observation agencies in particular need to develop new data acquisition strategies and systems for integrated Earth sensing to monitor remote environments, hazards and disasters, and natural resources using remote and in situ measurements. Innovative approaches to ground station networks and high-speed data flows will be important aspects of this new perspective.

This paper describes a new initiative towards integrated Earth sensing, with the goal of making 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 focus is on advanced technologies to: design and deploy intelligent sensor networks for in situ data acquisition; develop methods to integrate in situ and remote sensing data into models that generate validated information products; facilitate the accessibility of in situ sensor data and/or metadata from on-line geospatial data infrastructures.

Definitions

Remote sensing can be defined as a technology used to acquire information about an object by detecting energy reflected or emitted by that object when the distance between the object and the sensor is much greater than any linear dimension of the sensor. A short, dictionary-based definition could be that remote sensing is "sensing from a great distance". For the present purposes and in practice, it is the gathering of data about the Earth and environment by satellite sensors.

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 sensing could be "sensing in place". Because many measurements or observations are made from nearby locations that are not strictly speaking in situ, the expression **proximal sensing** has been adopted in a wide 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 a variety of contexts, perhaps the most prevalent being meteorological stations. These networks continue to evolve as unattended sensor and wireless telecommunication technologies advance at a rapid pace and new applications are invented (Teillet et al., 2001). 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 assimilation into models within hours.

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 (Pettinger, 1971; 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.

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 all citizens. 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 use in models, at relevant scales, to generate geophysical and biospheric information products. The fusion process involves gathering remote sensing and in situ measurements and placing them self-consistently in the same physical reference frame. Such an integrated Earth sensing capability can provide essential validated information for decision making if it involves interagency cooperation, common data processing standards, and timely access to data and information products on a long-term basis.

Looking Back

In the past, the main tools for field campaigns were pencil and paper, a shovel, a ruler and a spyglass (Figure 1). At the end of the 19th and beginning of the 20th century, the technical revolution of that era created new sensors and instruments that drastically changed and improved field techniques. Meteorological, climatological and oceanographic field research was known to be the most advanced, employing the leading instruments of the time. There were thermometers and barometers, wind measurement devices and stream gauges, bathymeters and pyranometers, to name a few. The data records were still kept on paper, often on strip-chart recorders.

In the middle of the 20th century, data were still carried from the field in the form of written notes and then manually entered into computers that had limited storage capacity and processing power. With the arrival of the digital era, scientists and engineers, assisted by computer technologies, adopted new means of measuring, recording and analysing field data. A new generation of digital sensors and instruments came to replace the old analogue ones, creating an incredible flood of data. In some instances, the sensors and instruments were no longer carried to and from the field but were instead connected to data loggers in the field. This opened up opportunities for field work automation. The data loggers recorded measurements at programmed intervals and the data became readily available when the data logger was connected to a computer.

Networks of unattended meteorological and hydrological stations (hydrometric stations) with analogue sensors were developed and deployed for weather forecasting, climatological modeling, and agricultural and hydrological applications. The stations were irregularly distributed, mainly in urban areas and to a lesser extent on agricultural lands. Remote areas were not necessarily covered unless they were being monitored for military purposes. Operators had to visit each site to collect the data or eventually transmit the data to a central location via RF and/or telephone communications. Various hydrometeorological services around the globe processed the data by hand and eventually by computer and generated paper maps on demand.

At present, there are numerous operational automated and semi-automated meteorological, weather forecast, climatological and environmental monitoring networks. Many of them are centralized sensor networks where data collected at stations are transmitted to a central location. Typically, these stations consist of towers equipped with various sensors and instruments allowing measurements to be recorded by data loggers. The data loggers, equipped with RF or cellular-capable devices, transmit the measurements to a central facility where the data quality is verified. Then the data are made available through the Internet to customers. The end user community encompasses farmers, weather forecasting agencies, researchers, university groups, and schools, among many other constituencies.

Looking Ahead

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 the coming years, 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 data, voice and video, as well as providing accurate viewpoints in real-time while processing and analyzing field data. Wearable computers are currently being used operationally by utility companies and experimentally in the Houghton Mars Project, for example, a NASA-led international field research program dedicated to planning the exploration of the planet Mars.

Advances in video technology have opened the door for 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 will be able to communicate and exchange their results and ideas with colleagues at other locations in real-time. This will contribute 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.

Following posted schedules, live webcasting and telepresence will provide experiment-oriented or pedagogical coverage of the in situ measurement activities. Issues concerning different measurement methodologies can be featured during broadcasts.

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, computers, and telecommunications have created the new instrument concept of intelligent sensor webs (Delin and Jackson, 2000, 2001). As opposed to other centralized sensor networks, sensors in a sensor web share information among themselves and modify their behavior on the basis of collected data. In the in situ sensing context, a sensor web consists of wirelessly communicating, spatially distributed sensor pods that are deployed to monitor and explore environments (Figure 2). 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 sensor web applications can be envisaged in the context of environmental monitoring. Sensor webs 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 millimeter - deployed in large numbers with the ability to measure variables such as temperature, pressure, light, sound, humidity, magnetic field, and acceleration (Pister et al., 1999). Many applications are being considered, but an example would be forest fire 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).

An emerging perspective is that the advent of in situ sensor webs, Earth science satellite sensor webs, and the Internet will provide a kind of global virtual presence, as described by NASA's Jet Propulsion Laboratory (JPL) (Figure 3) 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 Canadian 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.

The In Situ Sensor Measurement Assimilation Program (ISSMAP)

Given the increasing importance of in situ sensor data and their assimilation into models that also use remote sensing data, the Canada Centre for Remote Sensing (CCRS) is committed to an In Situ Sensor Measurement Assimilation Program (ISSMAP), to be led by the Data Acquisition Division of CCRS. ISSMAP's 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 information products. This will involve the specification and deployment of unattended intelligent sensor webs in various application contexts to demonstrate the importance and impact of the fusion of in situ measurements of quantities such as spectral reflectance, soil moisture, dielectric constant, stream flow rates, evapotranspiration, with remotely sensed pixel signals for use in relevant multi-scale models for the production of forecasts, yields, or hazard potential, among many others. ISSMAP's objective is to collaborate with partners to carry out relevant issue-driven demonstrations of the integrated Earth sensing approach, initially developing specific prototype sensor web applications that will include a web-enabled control and data processing facility that is also integrated into on-line geospatial data infrastructures.

Because many independently managed networks and archives of in situ sensors and data currently exist in Canada and elsewhere, it will be important to focus activities carefully and leverage existing infrastructures wherever possible. It is proposed that selected ISSMAP activities conform to the following framework (Figure 4). ISSMAP activities must:

- Lead to the generation of biospheric 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.

ISSMAP will focus on issue-driven science and technology activities such as the monitoring of remote environments (e.g., Canada's North), risk assessment and hazard mapping, and time-critical decision making (e.g., disaster and renewable resource information management). As an example, Figure 5 illustrates the ISSMAP framework in the context of watershed management. Primary outputs and contributions of ISSMAP will be robust unattended sensor networks, approaches to data assimilation, and scaled integration into geospatial databases. The program will encompass external collaborations, leveraged funding opportunities, and CCRS projects to develop in situ measurement and assimilation capabilities in the Canadian Earth observation context. Complementary to current efforts towards an Integrated Global Observing Strategy (IGOS, http://www.igospartners.org/), ISSMAP will demonstrate some advanced data acquisition and integration aspects of a typical environmental monitoring/information system for regional decision-making.

Closing the Gap

The advanced technologies of today make it possible to develop integrated approaches to Earth sensing that encompass both remote and in situ sensing. An in situ sensing program 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 Canada is striving to address. The In Situ Sensor Measurement Assimilation Program – ISSMAP - will capitalise on the rapidly maturing technologies of micro-sensors and 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 from satellite-based Earth sensing. It is from this perspective that integrated Earth sensing will help to make it possible for Earth observation technology to "cross the chasm" and be adopted by mainstream users of technology (Moore, 1991).

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Figure Captions

Figure 1: Drawing from Sir William Logan’s field journal.

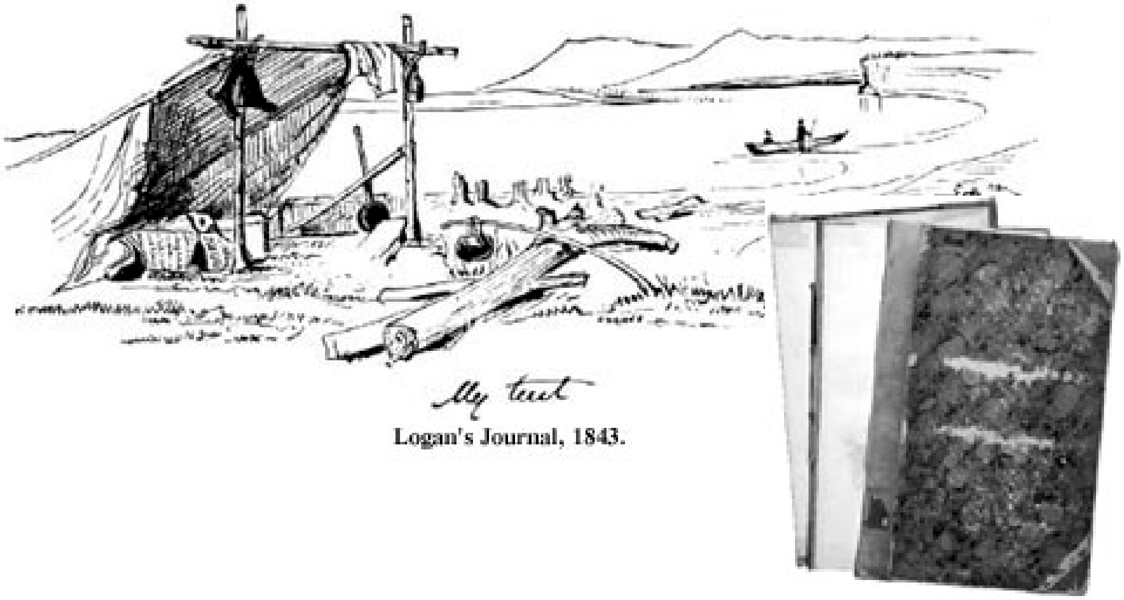
Figure 2: A sensor pod from the Jet Propulsion Laboratory (JPL).

Figure 3: Schematic diagram adapted from JPL’s InterWeb concept (Delin and Jackson, 2001).

Figure 4: Principal framework elements for the In Situ Sensor Measurement Assimilation Program (ISSMAP).

Figure 5: Example of the ISSMAP framework in the context of watershed management (Teillet et al., 2001).

Figure 1: Drawing from Sir William Logan's field journal.



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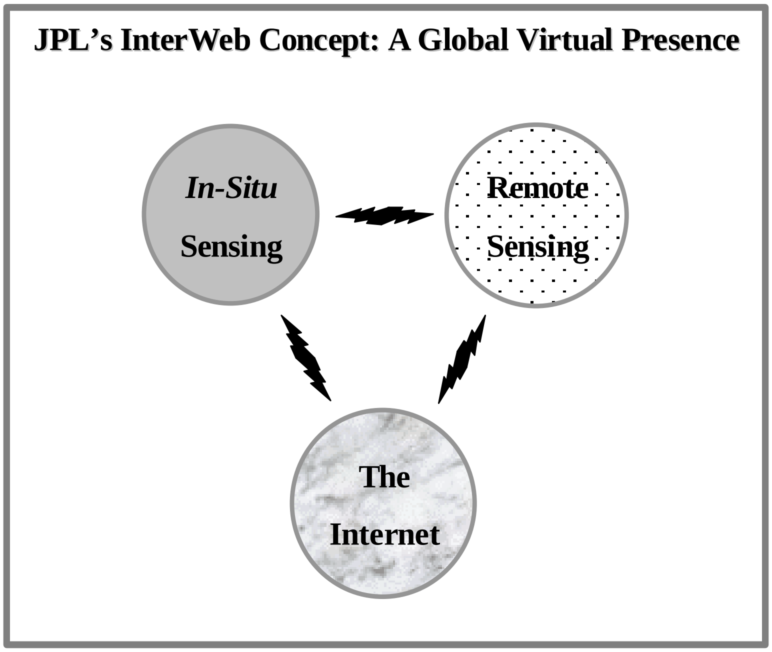
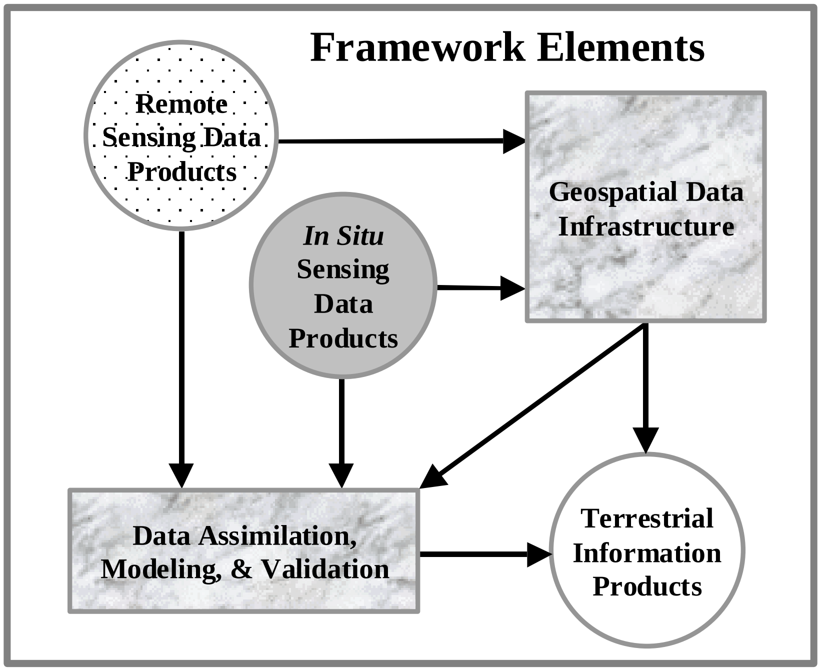


Figure 4: Principal framework elements for the In Situ Sensor Measurement Assimilation Program (ISSMAP).



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