A Framework for *In-Situ* Sensor Measurement Assimilation in Remote Sensing Applications

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Abstract

An In-Situ *Sensor Measurement Assimilation Program is being established at the Canada Centre for Remote Sensing. This paper highlights the goals and general framework of this new, strategic initiative. The* in-situ *sensing framework is illustrated conceptually in the context of three remote sensing applications. The paper also looks ahead to the use of sensor webs and sensor pods, as technology moves towards the concept of a global virtual presence.*

Introduction

Remote sensing can be defined as a group of techniques 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 group of techniques 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 comparable 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 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. However, these networks continue to evolve as unattended sensor and wireless telecommunication technologies advance at a rapid pace and new applications 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 assimilation into models within hours.

Satellite Earth observation sensors provide unique measurements of geophysical 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). Indeed, a common perspective today is that significant advancements in Earth observation are expected to come about only by developing more systematic capabilities for assimilating remote sensing observations and *in-situ* measurements for use in models, at relevant scales, to generate terrestrial information products. Such capabilities can provide essential validated information for decision making if they involve interagency cooperation, common data processing standards, and timely access to data and information products on a long-term basis.

Given the increasing importance of *in-situ* data and their assimilation into models that also use remote sensing data, the Canada Centre for Remote Sensing (CCRS) has initiated an *In-Situ* Sensor Measurement Assimilation Program (ISSMAP). This paper describes ISSMAP in general as well as the five-element framework to which selected project activities will be expected to conform. Conceptual data flow charts are presented to illustrate how information products can be developed in the context of watershed management, crop productivity and risk mapping, and in-land water quality monitoring. The paper also looks ahead to the use of sensor webs and sensor pods, as technology moves towards the concept of a global virtual presence.

ISSMAP Goals

The goals for the overall program, currently in a definition phase at CCRS, are as follows. For selected biospheric applications, ISSMAP will collaborate with other agencies, the private sector and universities to:

- Develop / adapt and demonstrate advanced sensor, telecommunication, and processing technologies and systems for *in-situ* sensor data acquisition.

- Facilitate the development and demonstration of applications that assimilate *in-situ* and remote sensing data into models to generate validated information products.

- Ensure the integration of *in-situ* sensor data and/or metadata into on-line geospatial data infrastructures.

ISSMAP Framework

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. ISSMAP activities must:

- Generate terrestrial information products that address clearly defined science questions and/or user information requirements.

- Utilize *in-situ* sensing data products.

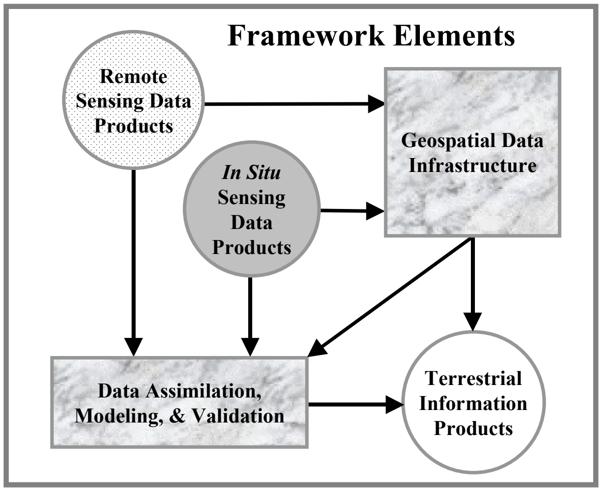
- Utilize remote sensing data products.

- Encompass data assimilation, modeling, and validation components.

- Routinely provide *in-situ* data products and/or metadata on *in-situ* data holdings to a geospatial data infrastructure.

In addition to these five key elements (portrayed in Figure 1), priority will be given to *in-situ* data acquisition technologies that leverage existing automated networks, operate in an unattended

Figure 1. Principal framework elements required for consideration by the in-situ *sensor measurement assimilation program.*



manner, use wireless telecommunications, use centralized or common methods for data processing, and establish standards or data sets for validation and measurement protocols.

Applications Development Examples

The conceptual data flow charts in Figures 2-4 illustrate the ISSMAP concept using examples taken from three applications development contexts. These cases conform to the ISSMAP framework in that they integrate and assimilate *in-situ* and remotely sensed data into models to generate value-added information products, address specific user information requirements, and provide data from an automated *in-situ* network to a geospatial data archive.

Watershed Management

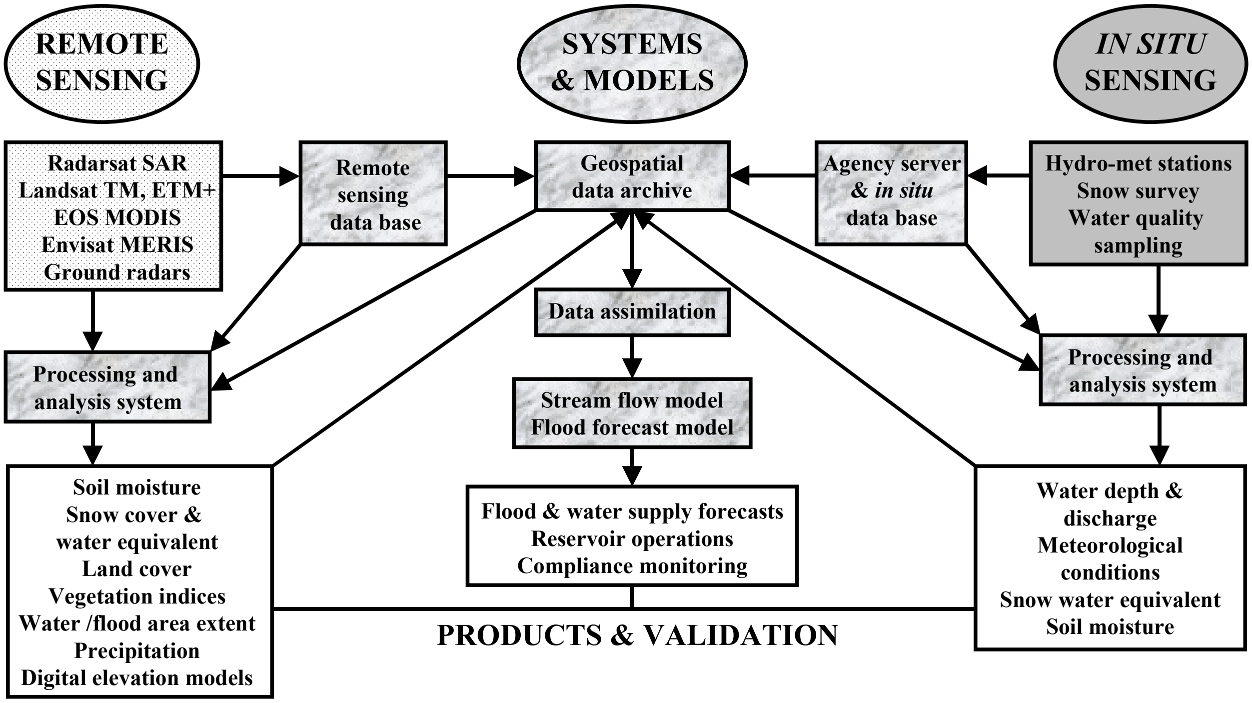
Information is needed to guide day-to-day operational decisions for reservoir operations, flood and water supply forecasting, and compliance monitoring. Much of this information is involved in predicting the response of a watershed to precipitation or snowmelt runoff. Since actual point measurements of the runoff generated across a watershed are impractical, reliance is placed on measuring a variety of factors that affect runoff. While this approach is indirect, it does have the advantage of providing predictive capabilities. The response of a watershed to runoff conditions is of primary interest. Dams and reservoirs are manipulated to achieve a variety of objectives. Warnings may be issued to residents in flood-susceptible areas so that precautionary measures can be taken. Reservoir levels, ice conditions, fish spawn and wildlife nesting activities are monitored at critical times so that appropriate action can be taken by dam operators to protect habitat or prevent shoreline damage.

Hydrologic modelers typically process and manage point data, such as precipitation series from meteorological stations. They also occasionally complete spatial interpolations on point data from multiple stations to produce average values for input into lumped models. There are several thousand sites in Canada where hydrologic parameters such as river and lake level, precipitation, temperature and basic water quality are monitored by direct contact sensors and the data are telemetered essentially continuously through battery-operated low-power transmitters. The data are used for real-time monitoring for environmental disaster surveillance and/or resource management with the prime hydrologic purposes being for flood warning systems and reservoir regulation. Although telephone (cellular and landline) and radio systems are used, there are many areas of Canada where telemetry by satellite transponder is the only option.

Distributed hydrologic models typically use multiple gridded spatial datasets for input and this often requires interpolation and merging of point, spatial (gridded) and occasionally linear (flight survey) data. Topographic and drainage characteristics such as surface slope, orientation, roughness and river length are usually also estimated using digital topographic data commonly available from Federal or Provincial/State Government sources. The satellite derived hydrologic data of most significance would be land cover, snow cover and water equivalent, soil moisture, and evaporation indicators such as leaf stress and area. As well as the integration tools being available, the data also must be available in near real-time within minutes or hours, presumably via the Internet. These data sets can be large and often require specialized Geographic Information Systems (GIS) for efficient processing and management. Figure 2 presents the conceptual data flow for watershed management.

The next major improvement in hydrological modelling, and the improved disaster surveillance and resource management that would come from it, will be in the integration of near real-time *in-situ*, imagery and spatial data digitally into the day-to-day operation of the watershed model. Currently, there is great interest in hydrology in integrating the continuous ground-based weather radar precipitation measurements into the

Figure 2. In-situ *sensor measurement assimilation for watershed management.*



watershed models. Although there is some work in this area, it is not yet widely used operationally.

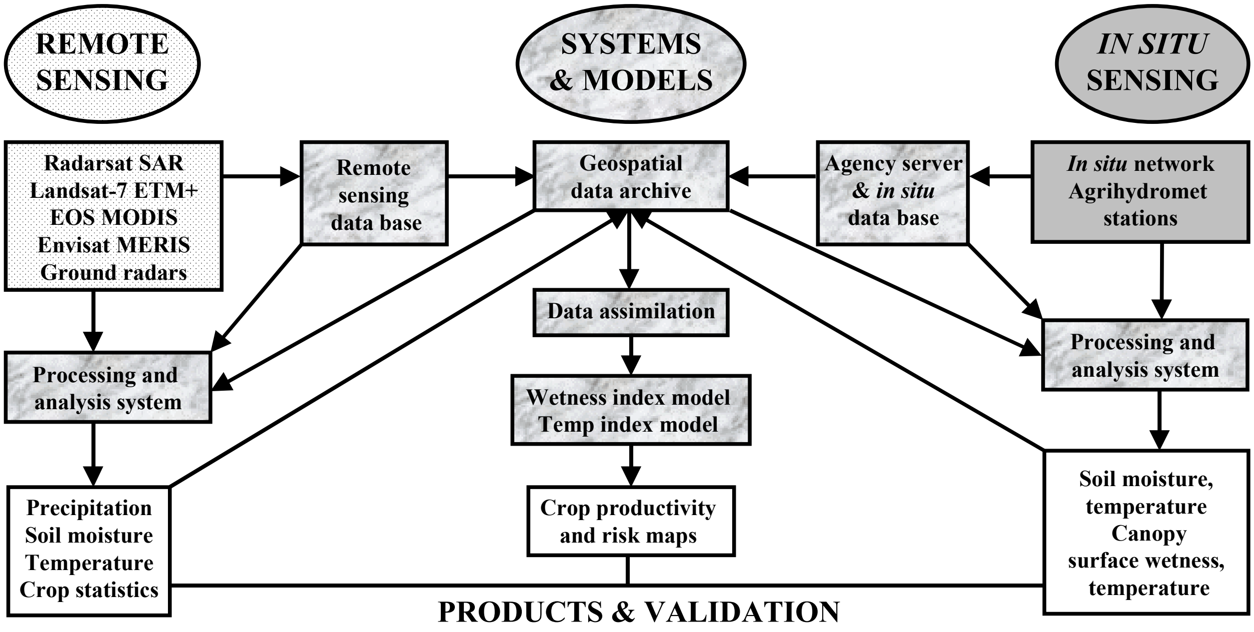
Crop Productivity and Risk Mapping

Physical properties of the soil and crop canopy, specifically moisture and temperature, are key parameters in determining crop productivity. These parameters are also essential in establishing the risk of crop infestations. Models exist to predict crop productivity and the risk of infestation. However, in order to provide accurate predictions, these models require frequent information on soil and canopy conditions, throughout the growing season. *In-situ* sensors capable of measuring moisture and temperature are available and automatic data loggers allow data acquisition at selected temporal intervals. Nevertheless, even within the context of an *in-situ* network, these sensors cannot provide the spatial coverage required to map productivity and risk at the field, local, and regional scales. In contrast, remote sensors provide adequate spatial coverage, but products derived from these sensors still rely heavily on ground data for information extraction, as well as model calibration and product validation. The integration of *in-situ* data with remote sensing products (Figure 3) has the potential to provide the information required by crop prediction models for the generation of productivity and risk maps. Such maps can provide critical information, particularly for local producers, marketing agencies, and agricultural service providers.

In-Land Water Quality Monitoring

Water quality definitions depend on jurisdiction and purpose (environmental health, industrial process consumption, drinking water supply, etc.). Most of them imply a certain combination of physico-chemical parameters (pH, temperature, etc.) and biochemical composition of water (salinity and concentrations of other naturally occurring inorganic and organic substances such

Figure 3. In-situ *sensor measurement assimilation for crop productivity and risk mapping.*

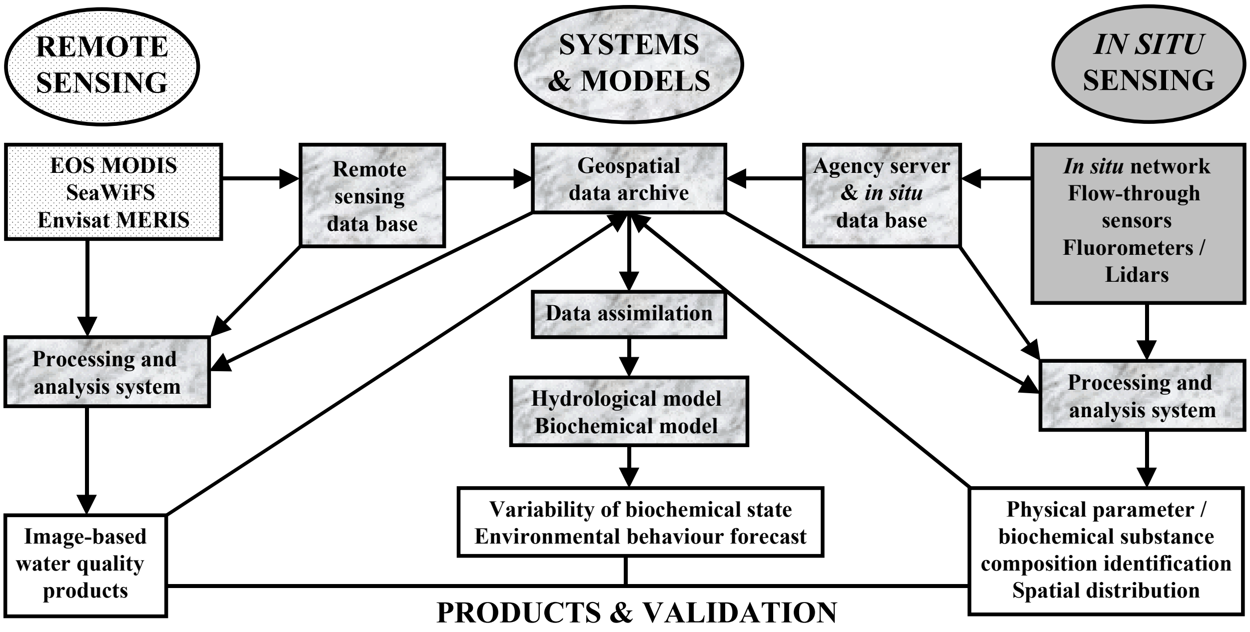


as alkali metals and their compounds, dissolved organic matter, chlorophyll pigments, as well as harmful inorganic and organic contaminants, etc.). Today's physical, electro-chemical and electro-optical sensors are capable of providing continuous delivery of real-time data *in-situ*. As in other application areas, the CCRS *in-situ* data assimilation activities will concentrate on developing procedures for direct water quality data supply and their incorporation into validation of remotely sensed data. The following two examples outline some of the challenges in the implementation of the conceptual data flow chart shown in Figure 4 for the assimilation of water quality data.

Firstly, water temperature and its trends are important indicators of health and changes of aquatic environments (natural cycles, thermal pollution, etc.). All remote methods of sensing water surface temperature are based on radiative measurements (i. e. the measurable parameter is the spectral density of radiation intensity reflected from water surface in a certain electromagnetic range) yielding radiative temperatures in non-equilibrium that are then converted to thermodynamic temperatures using appropriate models. *In-situ* sensors measuring temperature directly or indirectly will be in thermodynamic equilibrium with the measured target. Measurable parameters in this case will be degree of expansion, electrical charge or current, sensor surface adsorption rate, etc. Intense modeling / sensor adaptation / data transmission / acquisition system development work will be required for both the direct *in-situ* data supply and *in-situ* validation of remote sensing.

Secondly, water quality / stress assessments rely greatly on measurements of bio-chemical composition of water. Satellite remote sensing based on measurements of water colour, while providing large-area coverage, can only observe dramatic changes in water composition (e.g. intense eutrophication, algal blooms, substantial oils spills, etc.). Modern *in-situ* analytical instruments such as improved multi-wavelength lidars and fluorometers (Dudelzak et al., 2001a,b), immersible mass-spectrometers, and other devices can detect changes in water molecular and

Figure 4. In-situ *sensor measurement assimilation for in-land water quality monitoring.*



elemental composition at trace levels and thus at the earliest stages of stress. The availability of such *in-situ* data would not only help directly monitor critical areas but would also provide quantitative validation of remote sensing.

Towards a Global Virtual Presence: Sensor Pods and Sensor Webs

This paper defines a framework to help guide a new initiative to advance the use of *in-situ* measurements in the context of remote sensing applications. Looking ahead to where this strategic initiative can lead, one can identify innovative technologies that will be important for ISSMAP to investigate. In particular, the emerging technology of sensor webs and sensor pods holds considerable promise for *in-situ* sensing. A sensor web is a wireless network of independent sensor pods deployed to monitor parameters of interest (Delin and Jackson, 2000, 2001). 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.

Each sensor pod is capable of acquiring data and transmitting these data on to neighbouring pods. Thus, the pods serve as nodes in a communication chain or network that links up to base stations for transmission to a user infrastructure. Each pod includes a battery, a microcomputer, a GPS receiver, and wireless communication equipment. Sensor pods with these capabilities are intended to be communication pods primarily, although they can have plug-in capability to handle data from other environmental sensors. More specialised sensor pods achieve additional functionality by housing other instruments and in most cases a digital camera.

The goal is to use sensor pods that are relatively inexpensive, easy to deploy, and robust enough to withstand a wide variety of weather conditions and *in-situ* circumstances. Developmental versions of sensor pods range in size from a few centimetres to a few decimetres. The sensor web concept has become possible because of advances in wireless telecommunications technology, inexpensive microsensors, improved signal-to-noise ratio in CMOS detectors, application-specific integrated circuits, and low power consumption.

Apart from providing local storage and connectivity to the Internet, key base stations could also include more elaborate equipment to facilitate live web-casting and telepresence. It is anticipated that such capabilities, in combination with periodic field visits, will facilitate many activities, including the following areas of fundamental importance.

- Standardization of measurement methodologies and protocols.
- Improved international coordination of calibration and validation activities.
- Innovation through a higher degree of networking and synergy.
- Remote technical support of instrumentation.
- Lower-cost and wider participation in resource-intensive activities.
- Education and training of highly qualified personnel.
- Greater promotion and visibility of the critical role of *in-situ* sensing and calibration and validation.

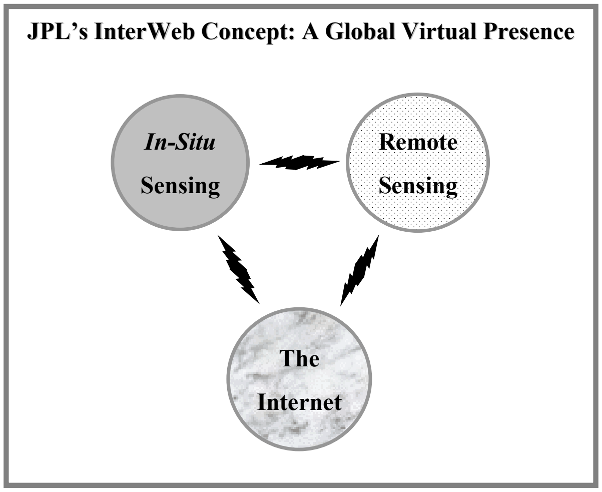
Delin and Jackson (2000, 2001) state that the key insight about sensor webs is that "a node can be a web itself, which leads to an "interweb" concept of linked webs". From this perspective, they see the advent of *in-situ* sensor webs, together with NASA's Earth science vision of satellite sensor webs (NASA, 2000) and the Internet, as providing a kind of global virtual presence (Figure 5).

Concluding Remarks

This paper reports on a new program being established at CCRS towards the increased use of advanced *in-situ* measurement technologies and assimilation in remote sensing applications. In collaboration with interested partners, the program will focus on advanced technologies for *in-situ* data acquisition, remote sensing applications involving data assimilation and modelling, and integration of *in-situ* data into geospatial data infrastructures. Emphasis will be placed on activities that conform to the five-element framework presented in the paper, centred on: terrestrial information products; remote sensing; *in-situ* sensing; data assimilation, modelling and validation; and geospatial data infrastructure.

The paper outlines applications development examples, including conceptual data flow charts, in the areas of watershed management, crop productivity and risk mapping, and in-land water quality monitoring. The innovative technologies of sensor pods and sensor webs are also noted as being the leading edge of the emerging perspective of an InterWeb or a global virtual presence, as described by Delin and Jackson (2000, 2001).

Figure 5. Schematic diagram of the Jet Propulsion Laboratory's (JPL) InterWeb concept, adapted from Delin and Jackson (2000).



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> "In the next century, planet earth will don an electronic skin. It will use the Internet as a scaffold to support and transmit sensations. This skin is already being stitched together. It consists of millions of embedded electronic measuring devices: thermostats, pressure gauges, pollution detectors, cameras, microphones, glucose sensors, EKGs, electroencephalographs. These will probe and monitor cities and endangered species, the atmosphere, our ships, highways and fleets of trucks, our conversations, our bodies -- even our dreams."
> (Neil Gross, "The Earth Will Don An Electronic Skin", in "21 Ideas for the 21st Century", BusinessWeek online, August 30, 1999 issue. See also http://www.businessweek.com/1999/99_35/b3644001.htm)