A Soil Moisture Sensorweb for Use in Flood Forecasting Applications

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ABSTRACT

This paper describes work towards building an integrated Earth sensing capability and focuses on the demonstration of a prototype in-situ sensorweb in remote operation in support of flood forecasting. A five-node sensorweb was deployed in the Roseau River Sub-Basin of the Red River Watershed in Manitoba, Canada in September 2002 and remained there throughout the flood season until the end of June 2003. The sensorweb operated autonomously, with soil moisture measurements and standard meteorological parameters accessed remotely via land line and/or satellite from the Integrated Earth Sensing Workstation (IESW) at the Canada Centre for Remote Sensing (CCRS) in Ottawa. Independent soil moisture data were acquired from actual grab samples and field-portable sensors on the days of RADARSAT and Envisat Synthetic Aperture Radar (SAR) data acquisitions. The in-situ data were used to help generate spatial soil moisture estimates from the remotely sensed SAR data for use in a hydrological model for flood forecasting.

Keywords: in-situ sensing, radar remote sensing, sensorwebs, soil moisture, flood forecasting.

1. INTRODUCTION

Efforts are under way towards building an integrated Earth sensing capability that encompasses both remote and in-situ sensing. Initial work has focused on the demonstration of in-situ sensorwebs in autonomous remote operation in the context of flood hazard, groundwater monitoring and drought severity monitoring applications. A prototype sensorweb was deployed in the Roseau River Sub-Basin of the Red River Watershed in Manitoba, Canada in September 2002 and remained there throughout the flood season until the end of June 2003. It consisted of five nodes and a base station distributed across an area of approximately 50 km in length. The sensorweb operated autonomously and provided soil temperature and soil moisture measurements plus standard meteorological parameters remotely via land line and/or satellite modem to the Integrated Earth Sensing Workstation (IESW) at the Canada Centre for Remote Sensing (CCRS) in Ottawa. C-band Synthetic Aperture Radar (SAR) data were acquired from the RADARSAT-1 SAR (HH polarization) and the Envisat Advanced SAR (ASAR) (HH, VV, and HH/VV polarizations) instruments. Coincident ground data were collected on selected satellite overpass days. The in-situ data were used to help generate spatial soil moisture estimates from the SAR image data for use in the WATFLOOD hydrological model for flood hazard monitoring. A heterogeneous in-situ sensorweb is also being developed for deployment in Alberta, Canada to support drought severity monitoring. Another in-situ sensorweb is currently deployed in Ontario, Canada to support groundwater monitoring on the Oak Ridges Moraine which is the principal aquifer for the city of Toronto (population near 5 million). This paper discusses integrated Earth sensing and sensorwebs, and reports on the prototype in-situ sensorweb demonstration in Manitoba and on plans for the heterogeneous sensorweb development.

2. FLOOD HAZARD MONITORING AND SOIL MOISTURE

There are significant urban populations and infrastructures that are vulnerable to flooding in the Red River Watershed. Consequently, there are ongoing studies to enhance the flood protection infrastructure at Winnipeg, Manitoba, a city of

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some 600,000 citizens. Integrated Earth sensing activities that encompass both remote and ground-based (in-situ) sensing[1, 2, 3] will contribute to enhanced flood mitigation, flood forecasting and emergency planning along the Red River, where there exists the potential for multi-million dollar flood disasters. The in-situ sensorweb work described in this paper is part of an effort to produce hazard and infrastructure assessments and improve real-time monitoring capabilities that will contribute to reducing the impacts and costs of flood disasters, and improve decision-making during flood emergencies[4].

Soil moisture is a key geophysical variable that plays a significant role in land surface-atmosphere processes and an important input parameter for a variety of hydrological and climatological models. The amount of moisture held in the soil is dependent on a number of site characteristics, including the amount of precipitation, air and soil temperatures, soil texture, topographic slope and aspect, and land cover. It contributes to information used for flood hazard monitoring and, in conjunction with Snow Water Equivalent, to predict the amount of spring melt. There has been considerable interest in the possibility of using both passive microwave and active radar imaging sensors from satellite platforms to estimate and monitor soil moisture over large areas[5, 6, 7, 8, 9]. Radar imagery is ideal for mapping soil moisture due to the sensitivity of backscatter to the dielectric constant and the ability to image through cloud cover. It is the strong relationship between the dielectric constant and radar backscatter that enables measurements of soil moisture. Currently available satellite radar imagery is at C-band, which can be used to detect soil moisture in the surface layer (0-5 cm). More specifically, for bare soils without vegetation cover, a linear relationship exists between volumetric surface soil moisture, surface roughness, and C-Band SAR backscatter[10]. Once this relationship is established with the help of ground-based (in-situ) measurements, it can be used to produce maps of soil moisture estimates from large areas. Modelling is required to allow for dependence on surface roughness, which in turn depends on soil texture, topography and farming practice and can change with time as wind and water erode the soil surface[10]. Modeling is also required to estimate soil moisture below the surface layer.

While soil moisture data from in-situ sensors cannot provide wide-area coverage, they do provide continuous and real-time data at specific locations and provide reference data for satellite-based retrievals. Strictly speaking, it is not currently feasible for point measurements to validate satellite-based estimates with high accuracy. However, the advent of miniature autonomous sensors[12, 13] is expected to help considerably in this regard by making it possible over time to increase the number of deployed in-situ sensors by several orders of magnitude.

Experiments are in progress to obtain soil moisture estimates for fallow fields in the Roseau River Sub-Basin, part of the Red River Watershed, using RADARSAT-1 SAR)and Envisat ASAR data. Dual-polarization images from a single SAR or Envisat-RADARSAT combinations are being used to minimize the effect of surface roughness on radar soil moisture estimates. Radar-derived soil moisture estimate maps are being prepared for input to watershed modeling (WATFLOOD model). Ground validation is based on soil moisture measurements from the in-situ sensorweb and soil core samples, as well as other approaches.

3. PROTOTYPE IN-SITU SENSORWEB FOR ENVIRONMENTAL MONITORING

In the context of integrated Earth sensing, the Prototype Wireless Intelligent Sensorweb Experiment (ProWISE) at CCRS has targeted the field deployment of a sensorweb with full inter-nodal connectivity and remote access and control[1, 2, 3]. It has also made it possible to test remote webcam operations and demonstrated telepresence at remote field sites. These deployments do not yet take advantage of fully miniaturized systems but they utilize commercial-off-the-shelf (COTS) technology and are taking place in real application environments.

The initial prototype sensorweb test-bed consists of five nodes and a base station. Each node has 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. Visible and near-infrared microspectrometer subsystems and related wireless telecommunications are currently in the integration and testing phases. Different wireless telecommunication and telepresence strategies have been 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. Smart internodal communication is planned for the next phase of the ProWISE development.

4. ROSEAU RIVER BASIN DEPLOYMENT 2002-2003

The five-node ProWISE sensorweb was deployed in the Roseau River Sub-Basin from autumn 2002 to spring 2003. It operated autonomously with standard meteorological parameters and soil moisture measurements being acquired every 15 minutes and accessed remotely from the IESW in Ottawa, Ontario. The station locations were selected based on successful RF range testing and to complement the satellite soil moisture mapping of fallow fields identified by extensive discussions with farmers.

The sensorweb monitored soil moisture and other agrometeorological parameters. Initially, the soil moisture data collected by the C-Probes were transmitted with the other sensor data via the Adcon A733 wireless radio modems to the Adcon A840 data storage unit and gateway situated in the Shevchenko School in Vita, Manitoba. These data were then transmitted via a modem connection by a land line to the IESW. The C-Probe terrestrial wireless link to the A840 was replaced by a Vistar MT-2000 satellite link for trial periods (Figure 1). This advance put each soil moisture sensor from each individual node "on the air" in real time and constitutes an important step in demonstrating different aspects of sensorweb deployment. As well, an attempt will soon be made to replace the A840 modem connection with a Globalstar satcom connection operating at the sensorweb hub with the implementation of a stand-alone solar power solution.

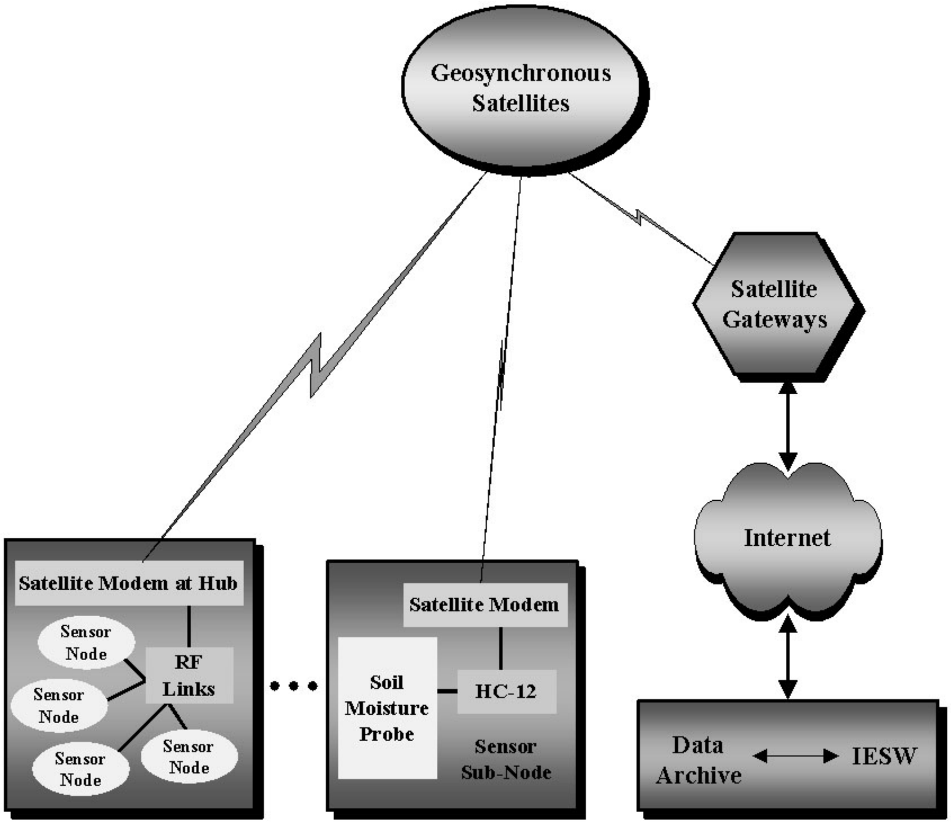


Figure 1. Logical data flow of the deployment configuration and satellite telecommunication routing between the sensor nodes in the field and the Integrated Earth Sensing Workstation (IESW) in Ottawa. The sensorweb hub may at times use a land line instead.

The soil moisture device at each ProWISE node is an Agrilink C-Probe, which can have up to six capacitance sensors (three are currently used) located down to one metre in depth. Each of these sensors measures Percent Volumetric Soil Moisture (%VSM) with a precision of 0.4% for a depth interval of 10 cm. Output signals are normalized using known quantities of air and water, and formulae proprietary to Agrilink. Post-measurement calibration methods are available for specific soil types (e.g., clay versus sand) or can be user-created from laboratory or test site measurements.

With the permission of local farmers, the five ProWISE nodes were located between Dominion City and Vita (Figure 2, Table 1) to continuously monitor environmental conditions such as air temperature, relative humidity, wind speed and direction, solar radiation, leaf wetness, soil moisture, and soil temperature. The sensor configuration was the same at all sites and is illustrated for the Reimer site in Figure 3.

With respect to sensor heights, the global radiation (GR730) sensor and anemometer were at the same height above ground level (AGL), and the air temperature (Sen-R), relative humidity (Sen-R) and the wetness (LW730) sensors were at the same height AGL (Table 2).

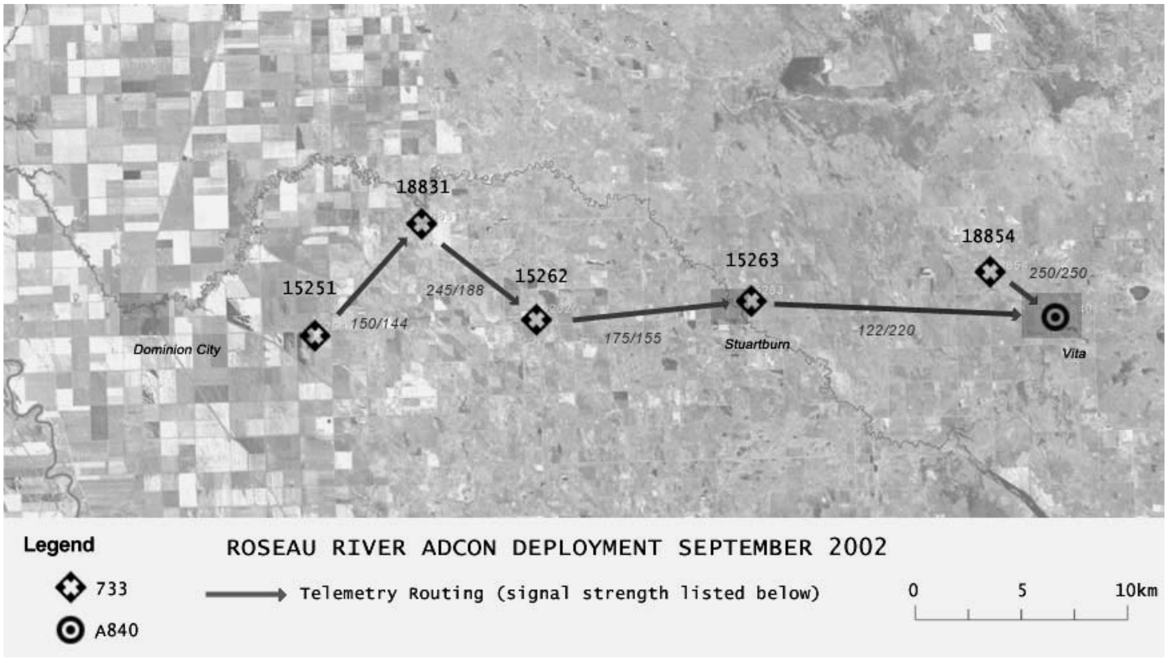


Figure 2. ProWISE sensorweb node map for the Roseau River deployment.

Station Name	Node ID	Longitude (UTM Zone 14)	Latitude (UTM Zone 14)	Elevation ASL (m)	Soil Type
Roseau 1 - Kirkpatrick	15251	642489.5016	5443794.599	221	Rego Humic Gleysol
Roseau 2 - Reimer	15262	653128.9157	5444655.251	255	Orthic Dark Gray Chernozem
Roseau 3 - Dyck	15263	663159.8914	5445527.73	265	Gleyed Dark Gray Chernozem
Roseau 4 - Palmer	18831	647836.0106	5449058.053	229	Gleyed Rego Black Chernozem
Roseau 5 - Smook	18854	674736.9301	5446690.187	275	Gleyed Dark Gray Chernozem
Roseau Hub - Shevchenko	A840	677730.4318	5444517.911	273	Rego Humic Gleysol

Table 1. ProWISE sensorweb geographic data.

Figure 3. Reimer station (node 15262).

Station Name	Node ID	C-Probe Sensor Depths (cm)	Rain Sensor Height AGL (m)	Sen-R Sensor Height AGL (m)	GR730 Sensor Height AGL (m)
Roseau 1-Kirkpatrick	15251	10, 40, 70	0.94	1.47	2.36
Roseau 2-Reimer	15262	10, 40, 70	1.04	1.52	2.31
Roseau 3-Dyck	15263	10, 40, 70	0.86	1.45	2.29
Roseau 4-Palmer	18831	10, 40, 70	0.91	1.45	2.34
Roseau 5-Smook	18854	10, 40, 70	0.91	1.37	2.36

Table 2. ProWISE sensor heights and depths.

5. SOIL MOISTURE SAMPLING METHODOLOGY

The elements of the soil moisture sampling program included: 1) deploying three Campbell Scientific monitoring stations in each of the three distinctive areas of the Roseau sub-basin according to soil type and land use; 2) deploying five ProWISE sensorweb nodes to obtain a better spatial distribution to monitor environmental conditions; 3) locating appropriate soil moisture sampling sites throughout the basin for sampling in autumn 2002 and spring 2003; and 4) conducting soil moisture sampling on satellite image acquisitions days.

5.1 Field selection

Radar backscatter from agricultural fields is strongly affected by soil moisture, vegetation cover, vegetation moisture, crop residue and the presence of tillage. Given these constraints, only bare agricultural fields were selected as potential candidates for soil sampling. In order to quantify soil moisture using radar image data, the following criteria were applied for field selection: three to four sites per soil type, good site distribution across the basin, proximity to roads to minimize travel time on sampling days, large enough fields to obtain a reasonable backscatter average from the radar image data (minimum size of 100 RADARSAT SAR samples), homogeneous sites with a minimum amount of crop residue or weeds (none preferred), and smooth fields with no tillage (if possible).

Site pre-selection was carried out using Landsat Thematic Mapper (TM) images to find agricultural areas with potential fallow fields and then driving around and talking to farmers. Once potential sites were located, the owners were identified using Regional Municipality (RM) maps and permission was obtained from each owner for sampling. GPS points were taken from the four corners of the chosen fields and flagged stakes used to delimit sampling areas. Digital photographs and notes were recorded regarding general field conditions, residue cover, weed cover, tillage, presence of rocks, etc.

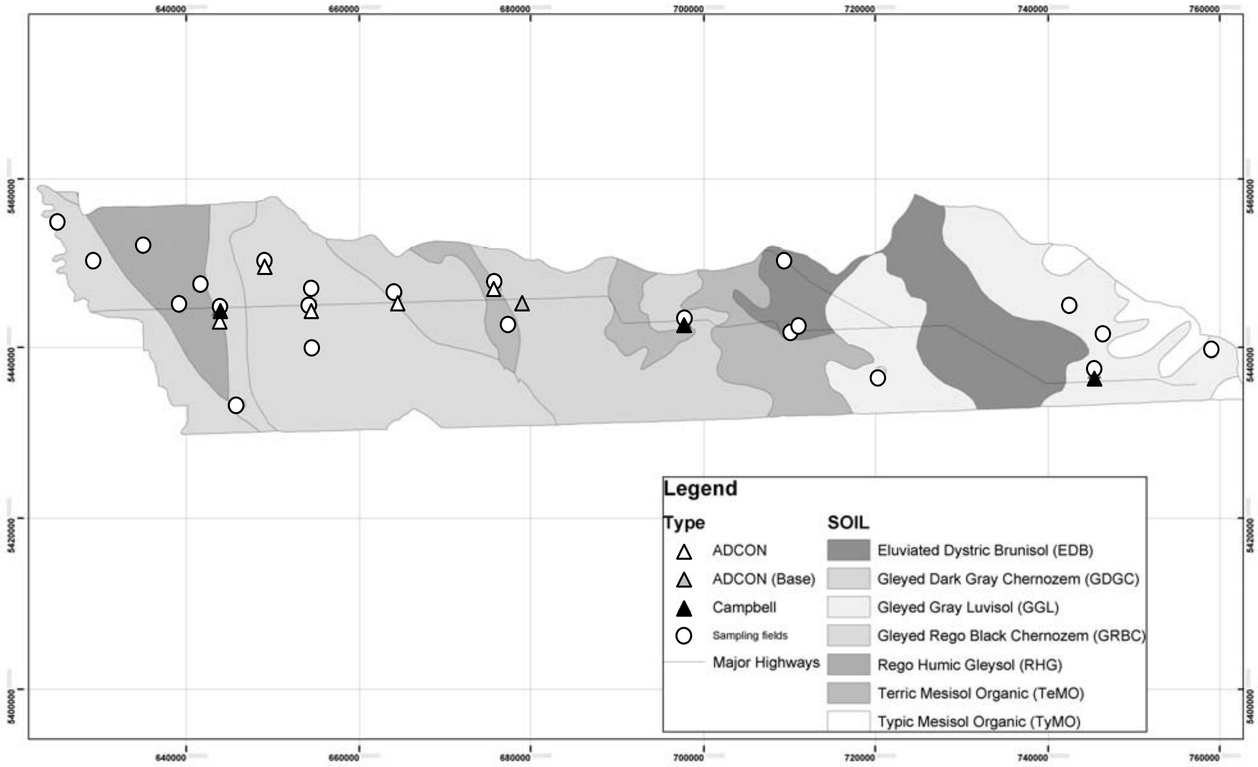


Figure 4: Sampling sites and monitoring station location in the Roseau basin in relation to soil types.

5.2 Sensor locations

The Campbell Scientific stations and ProWISE sensorweb nodes were located in the selected fallow fields (Figure 4). Permission was obtained from the farmers before installing the instrumentation. Ideally, the sensor locations should be evenly distributed across the basin, which extends across approximately 150 km. The Landsat TM images from the Roseau River sub-basin indicated that there are three main areas across the basin based on land use, which itself reflects soil type. The area to the East is dominated by wetlands, bogs and forest, the central area is dominated by pasture land, mixed forest and some agricultural fields, and the Western area of the basin is dominated by agricultural land. A Campbell Scientific station was installed in each of the three areas. The original idea was to distribute the five ProWISE nodes to augment spatial coverage of the basin. However, RF telemetry considerations limited the distribution of the ProWISE nodes to the Eastern portion of the basin, providing improved spatial distribution in that area.

5.3 Surface roughness measurements

Surface roughness parameters (root-mean square (RMS) height and correlation length) were obtained at a minimum of three sites per field using a SRM-200 surface roughness meter[14]. Measurements were made at each site during each satellite overpass acquisition series, typically two to three weeks apart. This was necessary because surface roughness continuously changes during spring and autumn because of agricultural activities and the effects of wind and rain.

The surface roughness instrument consists of a tripod mounted with a camera, projector and flash. The tripod is draped with a shroud to create a portable darkroom (Figure 5). The flash is mounted on a projector, which projects a rectangle of illumination (50 mm by 100 mm) on the ground. The camera takes oblique photographs of the illuminated ground within this rectangle. The photographs are subsequently scanned and software used to calculate the RMS height and correlation length[14]. The long axis of the projected rectangle is oriented parallel to the radar beam direction to measure roughness in the SAR look direction. The look direction is approximately 70 degrees for the ERS-2 and Envisat SARs and 78 degrees for the RADARSAT SAR. In order to minimize manipulations, the surface roughness instrument was oriented to measure roughness along a look direction of 74 degrees with respect to true North.

Figure 5: Surface roughness device.

5.4 Satellite acquisitions and coincident in-situ sampling

C-band SAR data were acquired from the RADARSAT-1 SAR (HH polarization) and the Envisat ASAR (HH, VV, and HH/VV polarisations). The Envisat ASAR dual polarisation mode (HH/VV) was the preferred acquisition mode, but it only became available as of February 2003 (Figure 6). The RADARSAT W1 beam mode (150 km swath) was selected for this study because this swath covers the full basin. Other RADARSAT-1 SAR standard beam modes (S1 to S5) and Envisat ASAR beam modes (IS1 to IS4) were also selected but only partially covered the basin. All images were acquired on ascending passes (evening overpasses). Ascending passes were chosen instead of the descending passes in early morning to avoid the effect of morning dew on the ground. Overpass time over southern Manitoba for any RADARSAT or Envisat acquisition on ascending passes is approximately 00:02:45 Coordinated Universal Time (UTC) and 04:00:00 UTC, respectively. For field validation, the satellite acquisition times were adjusted to local time.

Soil moisture measurements are ideally taken within a four-hour window (i.e., plus or minus two hours) of a satellite acquisition. Because of the large size of the Roseau sub-basin (150 km East to West) and the limited sampling staff (three teams of two individuals each), the window was extended to six hours (plus or minus three hours) for some acquisitions (e.g., RADARSAT W1 beam mode) to allow time for the teams to collect data across the full sub-basin. Sampling time was also limited by the availability of daylight. Climatic constraints were taken into consideration to achieve unbiased sampling results; soil sampling was not undertaken during periods of intense rainfall, prolonged freezing, and snow cover. Prior to sampling, a transect was established along the longer axis of each field to maximize coverage using the flagged corners as a guide. Five sampling stations were established along the transect to measure soil moisture and additional parameters. These sites were a minimum of 5 m apart and within the same type of micro-terrain. In addition to the documentation of the general site descriptions, the following measurements were taken at sites along the transect:

- GPS readings at selected locations.
- Chain length measurements at selected locations to obtain a qualitative measure of surface roughness (extra measurement for backup only).

- Soil moisture readings with a portable Time Domain Reflectometry (TDR) soil moisture probe at five locations per sampling site. Readings at each location were taken in replicates of three within a one-metre radius. This resulted in a total of 15 soil moisture samples from each sampling site (Figure 7).
- Soil grab samples (three replicates) were taken using a 5 cm ring. Once a correlation was established between TDR and soil samples, only TDR readings (as described above) were taken in a given field for subsequent satellite acquisitions. The soil moisture determination consisted of weighing each sample before and after desiccation, which consisted of 'baking' the samples for 24 hours at a temperature of 100 degrees C. The soil analyses were carried out at the National Water Resources Institute (NWRI) in Saskatoon.

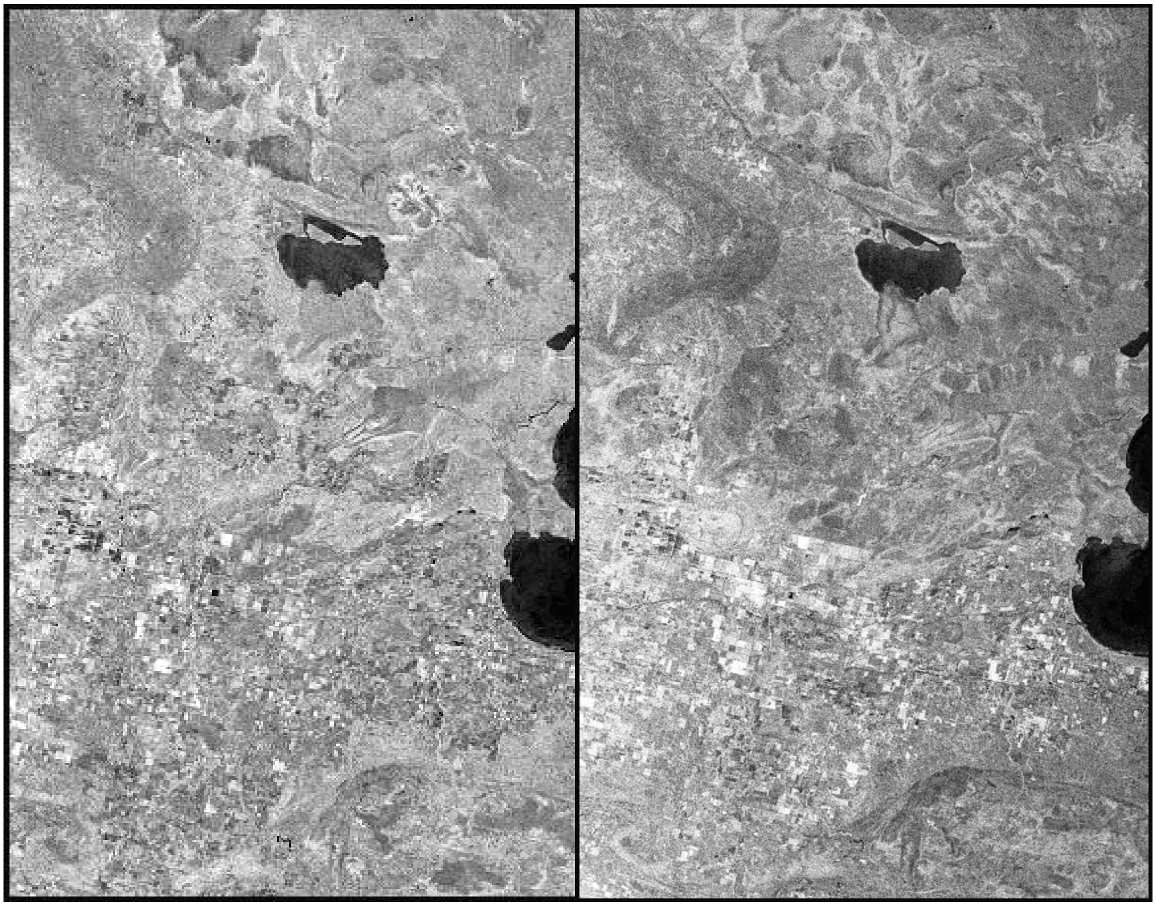
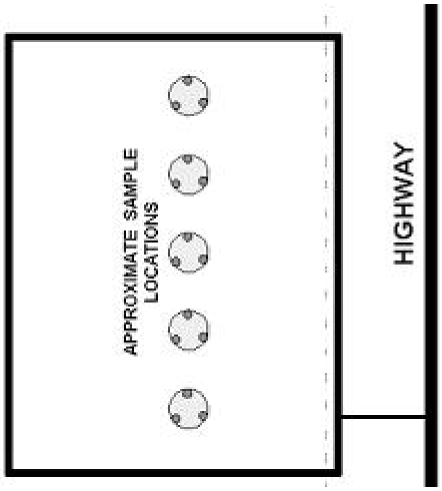


Figure 6. SAR imagery of the Roseau River Sub-Basin: RADARSAT SAR C- HH, beam S1, ascending pass, 17 April 2003 (left) and Envisat ASAR C- HH/VV, beam IS1, ascending pass, 15 April 2003 (right).
RADARSAT data © Canadian Space Agency.
Envisat data © European Space Agency.

Figure 7: Example of field sampling transect for soil moisture measurements.



6. SOIL MOISTURE SENSORWEB RESULTS

The acquisition of datasets by the various ProWISE sensor nodes in a variety of environmental conditions throughout the season will allow an evaluation of the performance specifications of each component. It required leaving the sensorweb deployed at the Roseau River basin for a significant period of time (autumn of 2002 to the end of the flood season in June 2003). The meteorological data are currently being compared to Environment Canada (NWRI) data collected by their Campbell Scientific (CS) equipment where stations are co-located. The C-Probe soil moisture data were compared to soil moisture measurements taken by continuously functioning Aquaflex sensors buried at 7.7 cm, grab soil sampling for gravimetric soil moisture (GSM) measurements, and CS TDR soil moisture readings taken during the days of SAR satellite image acquisition.

The C-probe soil moisture measurements were compared with values obtained with a TDR (Figure 8). The TDR readings are typically taken in the top 5 cm to calibrate satellite C-band radar data that typically measure the top 5 cm. While the effective zone of influence for TDR readings is 4 to 8 cm, negligible contributions may come from a zone 10 to 20 cm along the TDR probe. In terms of validating TDR data against GSM samples, the TDR capacitance readings are in response to the “bulk” soil water only[15]. GSM samples are often dried for 24 hours at 105 degrees C, which drives off both “bulk” and “bound” water thus introducing a systematic bias. Some concern exists that GSM sampling may measure the crystalline water in addition to the “bulk” and “bound” water measured by the C-Probe or the “bulk” water measured by the TDR.

In addition to the field soil moisture sampling carried out in the autumn of 2002, some TDR data were collected for the top 5 cm at the ProWISE C-Probe locations for comparisons. In the spring of 2003, TDR and soil core samples were also taken in the vicinity of the C-Probes at depths of 0 to 6, 7 to 13, 17 to 23, and 37 to 43 cm to match the C-Probe sensor depths. The soil core samples will be processed by NWRI into GSM and soil bulk density values that will permit CCRS to calibrate the C-Probe sensor data from raw to calibrated %VSM. Ideally, the soil samples should be acquired from the material removed during installation of the access tube for the C-Probe to minimize spatial variability errors. As well, to promote additional confidence in the normalization of sensors and the proper performance of the C-Probes, test readings for all C-Probes should be made in a common access tube under static soil moisture conditions.

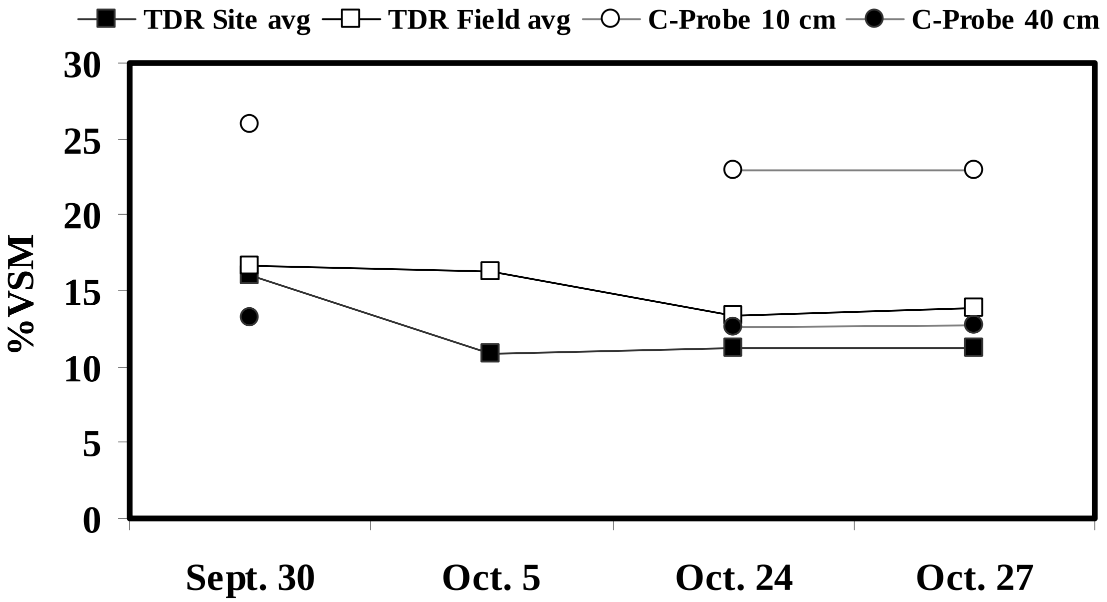


Figure 8. Comparison of soil moisture data from C-Probes and TDRs at the Smook Station, autumn 2002.

Figure 9. Wet soil at Dyck site,
Roseau River Sub-Basin, Manitoba

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A time series (March 2-12, 2003) of the C-Probe soil moisture data and air and soil temperature data collected by the ProWISE station at the Smook site is shown in Figure 10.

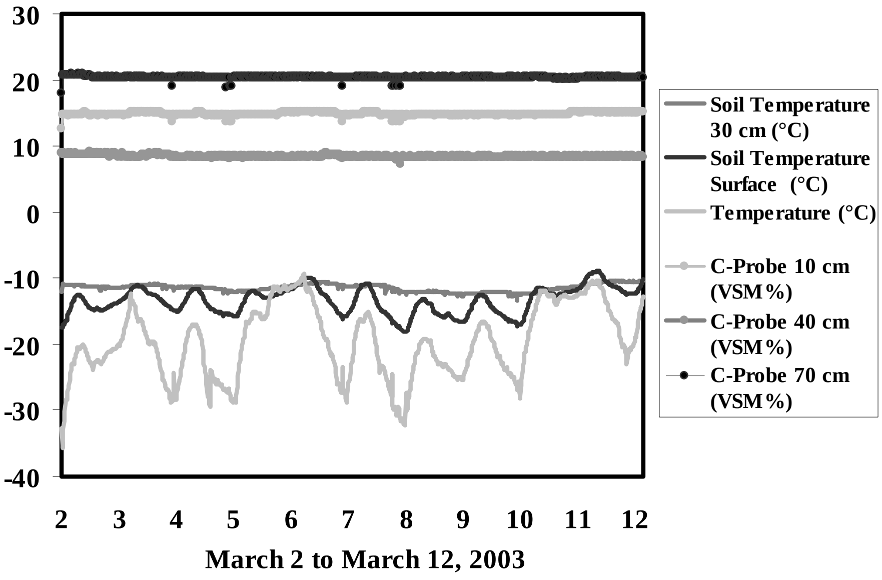

Figure 10. C-Probe and temperature profiles for the Smook fallow site (March 2-12, 2003).

7. CONCLUDING REMARKS

Efforts are under way at the Canada Centre for Remote Sensing (CCRS) towards building an integrated Earth sensing capability that encompasses both remote and in-situ sensing. Initial work has focused on the demonstration of an in-situ sensorweb in autonomous remote operation in the context of flood hazard monitoring. A prototype sensorweb consisting of five nodes and a base station was successfully deployed in the Roseau River Sub-Basin of the Red River Watershed in Manitoba, Canada in September 2002 and remained there throughout the flood season until the end of June 2003. The sensorweb operated autonomously and provided soil temperature and soil moisture measurements plus standard meteorological parameters remotely via land line and/or satellite to the Integrated Earth Sensing Workstation (IESW) at CCRS in Ottawa. Independent soil moisture data were acquired from actual grab samples and field-portable sensors on the days of RADARSAT SAR (HH polarization) and Envisat ASAR (HH, VV, and HH/VV polarisations) data acquisitions. The in-situ data were used to help generate spatial soil moisture estimates from the SAR image data for use in the WATFLOOD hydrological model for flood hazard monitoring.

An in-situ sensorweb is currently deployed in Ontario, Canada to support groundwater monitoring on the Oak Ridges Moraine which is the principal aquifer for the city of Toronto (population near 5 million). A heterogeneous in-situ sensorweb is also being developed by CCRS for deployment in Alberta, Canada to support drought severity monitoring.

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