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A Soil Moisture Monitoring Sensorweb Demonstration in the Context of Integrated Earth Sensing

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ABSTRACT

This paper describes work towards building an integrated Earth sensing capability, in particular the demonstration of a prototype in-situ sensorweb in autonomous remote operation in the context of soil moisture monitoring. A five-node prototype sensorweb was deployed and tested at Bratt's Lake Station in Saskatchewan. The sensorweb operated autonomously and standard meteorological parameters and soil moisture measurements were accessed remotely via satellite from the Integrated Earth Sensing Workstation (IESW) at the Canada Centre for Remote Sensing in Ottawa. The paper reports on the prototype sensorweb deployment in general and on soil moisture measurements in particular.

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

1. INTRODUCTION

Our monitoring requirements and responsibilities as nations and as members of the global community continue to multiply. We have some powerful science and technology tools at our disposal but it is not clear that we are using them effectively to tackle the issues before us. In many countries, government agencies in particular have long traditions of excellence in field data acquisition and more recently space-based observations of the Earth. However, such endeavours have been and largely remain resource-intensive activities. Innovative tools need to be developed to provide the time-critical and cost-effective monitoring of complex and dynamic systems essential to support effective decision-making.

The need to make better and more coordinated use of the resources available and planned for the future has led to efforts such as the Integrated Global Observing Strategy[b] (IGOS), which includes ocean, terrestrial and climate components as well as a variety of partnerships and prototype demonstration projects. IGOS is also a proponent of the Coordinated Enhanced Observing Period[c] (CEOP), which seeks to establish an integrated global observing system for the water cycle that responds to both scientific and social needs. Another initiative along these lines is the European program on Global Monitoring for Environment and Security[d] (GMES).

At the 2002 World Summit on Sustainable Development, the point was made that "… space-derived information generally needs to be combined with in-situ measurements and models to obtain a holistic picture of the Earth's environment. … There is no Sustainable Development without adequate information about the state of the Earth and its environment".[e] At the World Space Congress 2002, a Panel convened to explore "An Integrated Approach to Monitoring Planet Earth" noted that ground-based (in-situ) monitoring systems are inadequate by several orders of magnitude. The majority of space agencies represented on the Panel stated that an integrated approach to monitoring the Earth demands that the in-situ sensing be a funded part of the solution offered by space agencies. Indeed, the confluence

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[a] Canada Centre for Remote Sensing, 588 Booth Street, Ottawa, Ontario, Canada K1A 0Y7

[b] IGOS, http://www.igospartners.org

[c] CEOP, http://monsoon.t.u-tokyo.ac.jp/ceop/index.html

[d] GMES, http://gmes.jrc.it

[e] Josef Aschbacher, European Space Agency (ESA)

of advanced technologies for Earth-based sensorwebs[f g h], Earth science satellite webs[1, 2], and the power of the Internet will soon provide a kind of global virtual presence[3] or integrated Earth sensing[4, 5] (Figure 1).

As opposed to other distributed sensor networks, sensors in a sensorweb share information with each other and modify their behaviour based on collected data. In the in-situ context, a "sensorweb" consists of an autonomous wireless network of smart sensors[6] deployed to monitor and explore environments or, more succinctly, "a macro-instrument for coordinated sensing"[7]. A network of collaborating satellite platforms and sensors can be referred to as a satellite web or a sensorweb. The essential features in the satellite case are reconfigurable and interoperable satellite platforms and sensors that can decide amongst themselves when and how to acquire and downlink pertinent Earth imagery. With the capability of providing an ongoing virtual presence in remote locations, many sensorweb uses are being considered 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.

The work reported in this paper has been undertaken within the framework of a threefold effort to: (1) design and deploy sensorwebs for ground-based in-situ data acquisition, (2) develop methods to assimilate in-situ and remote sensing data into models that generate validated information products, and (3) facilitate the accessibility of in-situ sensor data and/or metadata from on-line geospatial data infrastructures. The focus of recent work has been on the first of these, in particular the deployment of prototype sensorwebs in the context of various Earth science applications, initially flood hazard and drought severity monitoring. The paper describes a prototype sensorweb and initial deployments as part of a Prototype Wireless Intelligent Sensorweb Experiment (ProWISE), including test and validation work at Bratt's Lake Station in Saskatchewan.

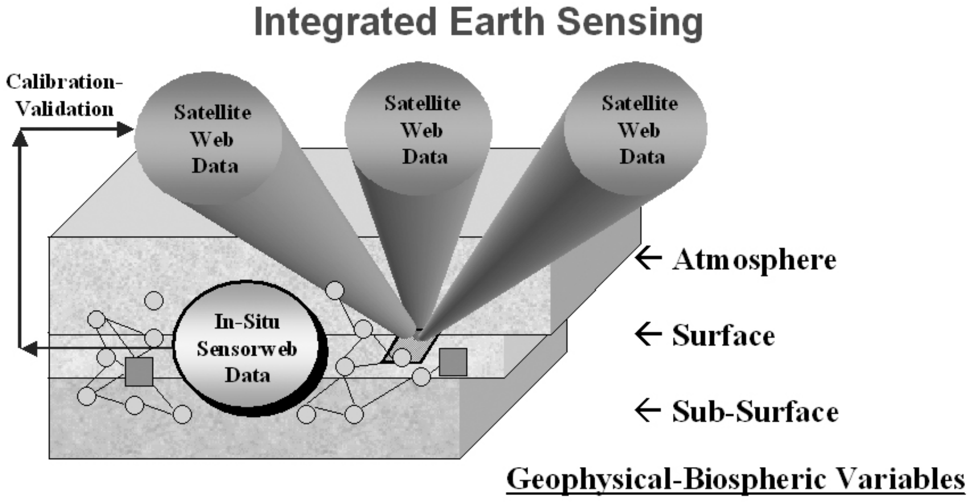

Figure 1. The integrated Earth sensing concept.

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[f] Pister, K.S.J., Kahn, J.M., and Boser, B.E. (1999) "Smart Dust: Wireless Networks of Millimeter-Scale Sensor Nodes", Highlight Article in *1999 Electronics Research Laboratory Research Summary*, Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720, 6 pp.

[g] Neil Gross, "The Earth Will Don an Electronic Skin", in "21 Ideas for the 21st Century", *BusinessWeek online*, August 30, 1999.

[h] Wireless sensor networks have been identified recently as one of ten emerging technologies that will change the world. Cf. Roush, W. (2003). "Wireless Sensor Networks", *Technology Review (MIT's Magazine of Innovation)*, 106(1): 36-37.

2. PROTOTYPE WIRELESS INTELLIGENT SENSORWEB EXPERIMENT (PROWISE)

The Prototype Wireless Intelligent Sensorweb Experiment (ProWISE) project has targeted the field deployment of a sensorweb with full inter-nodal connectivity and remote access and control. It has also been testing 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.

Early in 2002, a network of sensors purchased from Adcon[i] was deployed in various outdoor locations near Ottawa, Canada, to facilitate the debugging of data and communication protocol conversions between the microsensor/microcontroller packages and the satellite transceivers. Over time, the instrumentation has been augmented by the addition of various telecommunication devices, micro-controllers, and other sensors from various vendors. During the summer of 2002, a demonstration deployment was made at Bratt's Lake Station in Saskatchewan, Canada, in collaboration with Environment Canada's Meteorological Service of Canada (MSC). This field campaign included tests of the full remote access/control system through the Integrated Earth Sensing Workstation (IESW) in Ottawa.

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 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.

2.1 ProWISE sensors

Soil moisture: The Agrilink C-Probe has a dynamic range of 0-100 percent volumetric soil moisture (%VSM) and a resolution of 0.4 %VSM (8-bit A to D conversion). Its repeatability is ± 0.5 %.

Temperature and relative humidity: The SEN-R is a two-in-one sensor consisting of an accurate temperature and relative humidity sensor integrated in a meteorological housing, which uses natural air convection to minimize solar and ground radiation effects.

Solar radiation: The MS-020VM (GW730) pyranometer measures solar radiation (W/m^2) in the range of 400 to 700 nm. The sensor is cosine-corrected and has less than 0.5% temperature dependence over a 50°C range

Soil temperature: The RCI P 400 V temperature probe measures soil temperature at multiple depths. It is housed in a corrosion-resistant enclosure and can be inserted into the ground down to 30 cm.

Wind speed and direction: Due to its lightweight construction, the sensor package is compact and robust. The wind speed sensor consists of an AC generator and an integrated rectifier working without any contacts or brushes. Most external parts are made of highly resistant plastic and the sensor has a very low starting speed. The wind direction sensor is based on a precision potentiometer.

Leaf wetness: The leaf wetness sensor (LW730) works on the principle of electric conductivity, measuring in ten increments. The 30 by 40 mm sensor element is mounted on a holder for flexible installation.

Rain gauge: The Rain-O-Matic uses a unique self-emptying tipping spoon. The rain collector is made of Styrosund, which withstands harsh outdoor conditions, including heat, frost and UV radiation.

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[i] Adcon, http://www.adcon.at/adcon/english/welcome.htm

Node data storage and telecommunication: The A733 addWAVE is a robust Remote Telemetry Unit (RTU) for unattended year-round data storage and telecommunication featuring solar-powered wireless data transmission. It works as a transceiver that automatically collects a multitude of parameters from a given node and transmits them. It can be configured to receive and transmit parameters collected by other nodes in a large-scale network. The A733 provides secure data-transfer from remote location and can store up to 10 days of sensor data acquired every minute and averaged every 15 minutes.

Hub telemetry gateway: The telemetry gateway has two functionally separate units, the A840 central processing and data storage unit and an A440 wireless modem. The A840 controls a network of up to 200 Adcon RTUs. Data are retrieved automatically, temporarily stored in local memory, and delivered to a PC via serial or Ethernet interface. A built-in analogue V.34 modem allows for remote inquiry. Equipped with 16 MB onboard data storage, it is able to store 15-minute data from 200 stations for approximately 10 days. An internal battery ensures continuous operation preventing data loss during power outages. The A840 communicates with the A440 wireless modem via a serial RS-485 connection, which can be up to 30 meters in length. The A440 comes in an IP-65/67 housing and is compatible with any Adcon radio station.

3. SENSORWEB NETWORK OPERATION ISSUES

3.1 RF telemetry

The stations are operated remotely using wireless telemetry operating at a radio frequency of 464.6375 MHz with a bandwidth of 12.5 KHz for FM modulation as licensed by Industry Canada. In order to retrieve data from remote field stations, an Adcon A440 wireless radio modem and antenna can be attached to a tower on the roof of a building for the data telemetry base station. The modem would be connected by a coaxial cable to the A840 base station inside the building. The A440 modem has a potential range of 20 km. This telemetry network operates more-or-less continuously, polling data at 15-minutes intervals asynchronously from each station. Stations were routed through other stations where direct line-of-sight was not possible from the base station.

A number of factors determine the RF signal strength that is dynamic in time. Obstacles such as vegetation may attenuate the RF signal behaviour, which may be influenced by seasonal variation in leaf cover. The station masts could only be raised to 5 m without adding support in attempts to improve the RF response. If the RF signal strength decreased, the A840 would require multiple retries to retrieve the sensor data intact. The A840 usually makes two attempts during each polling period to contact a remote station A733 remote telemetry unit (RTU). The polling interval for retrieval of sensor data can be changed from every 15 minutes to every minute to increase the data recovery rate. This may be necessary to prevent loss of sensor data as the A733 RTUs can only store 10 days of data. The polling interval can be reduced only to the point where the battery level can support the extra RF traffic and it cannot be set at less than the time required by the A840 to retrieve data from all five stations.

3.2 Data outages

Data outages can occur at a station where the battery voltage drops below a specified threshold and the station becomes dormant. This also impacts recovery of data from stations routed through the affected station depending on the length of the outage. This situation occurs when cloudy conditions persist for several days such that the solar panel is unable to recharge the A733 battery. A solution in this case would be to double the number of solar panels at the ProWISE stations. A possible problem with this corrective action is the inability of the battery to fully discharge itself, requiring periodic deep cycling of the battery in a laboratory or replacement of the battery. In extreme conditions with extended absence of solar power, such as in the arctic, an alternate power source such as a large external battery would need to be used.

3.3 Station security

For most remote deployments, there is the risk of vandalism or theft despite the fact that the stations are often located some distance into a field. In addition, there is the potential for damage to cables by rodents and whole sensors by larger animals. While costly, spare cables, sensors and telecommunications equipment are a must for remote network deployments. One possible corrective measure aside from suspending cables off the ground is to house cables inside PVC pipes where possible.

3.4 Environmental concerns

In addition to potential damage from humans and animals, nature can still wreak havoc with high winds, hail, and frost. For example, several station masts were rotated, which required straightening and tightening of clamps. This can affect the performance of the solar panels as well as that of other sensors.

3.5 Data quality

Beyond the calibration of sensors, a number of operational factors sometime affect sensor performance and data quality despite implementation based following rigid installation and operation guidelines. Improper installation can result in faulty connections that can produce sensor data errors. Loosely fitting access tubes in the ground will alter the C-Probe soil moisture data. The rotation of a mast will bias the wind direction. Bird droppings and spider webs can affect the performance of the global radiation, leaf wetness and rain gauge sensors.

Unless they are inexpensive enough to be expendable, autonomous in-situ sensorwebs still require periodic inspections (even if only via visual inspection of sensor data in temporal plots) in order to address concerns such as those mentioned above.

4. CAPACITANCE SENSORS FOR SOIL MOISTURE

Capacitance sensors consist of a pair of electrodes (either an array of parallel spikes or circular metal rings) that form a capacitor with the soil acting as the dielectric. This capacitor works with an oscillator to form a tuned circuit and changes in soil water content are detected by changes in the operating frequency. Capacitance techniques have been documented[8, 9] for determining %VSM based on the permittivity of water versus air. Although well-defined relationships between relative permittivity and soil moisture content have been established[10], the effects of factors such as “bound water”, salinity and temperature are not well understood. The dielectric constant of free water at capacitance probe frequencies (<1000 MHz) is 80 and values for typical dry soil[8] are about 4. Capacitance sensors operating at lower frequencies (< 100 MHz) can detect bound water in fine-particle soils. This bound water is strongly attracted to the surface of soil particles and can constitute more than 10 percent soil moisture content and is not detected effectively by time-domain reflectometer (TDR) systems operating at frequencies > 250 MHz. Dielectric permittivity drops with the increase in soil water temperature, but bound water is released with increase in soil temperature, offsetting the initial decrease in permittivity[11]. Soil temperatures between 10 and 30 degrees C show the least amount of error for capacitance measurements in laboratory and field tests[12]. Physical models for specific soil types are still being developed and tested. Capacitance readings are most heavily influenced by air gaps in the soil volume nearest the electrodes, which is an issue with TDR and C-Probe sensors[9]. With all capacitance probes, calibration is necessary to deal with both the effects of the installation tube and the sensor’s response to water content. Subsequent raw frequency readings are usually scaled to fit a linear relationship. The assumption of a linear relationship for the non-linear curve between soil moisture and capacitance does not lead to significant errors[9]. Additional calibrations for specific soil types can handle the non-linear modelling appropriately.

The Agrilink C-Probe is housed inside a PVC access tube installed vertically into the soil. The C-Probe sensors function at frequencies in the range of 100-150 MHz. Capacitance measurements are made and converted into soil moisture content based on normalization. The normalization process involves calibration to 0 and 100 %VSM with an 8-bit resolution of 0.4 %VSM. This is done with 4-9 V input voltages and outputs in the range of 0-2.5 V measured using known quantities of air and water. Specific normalization formulae are proprietary to Agrilink, although it is likely that the relationship is linear and, as discussed above, not expected to lead to significant errors. The normalization procedure was retested and indicated a variance of ± 1 percent relative after a two-week period of inactivity.

For C-Probe sensor readings, 90 to 95 percent of the signal is measured within the first 0.65-1.3 cm of soil surrounding the access tube and over an estimated vertical extent of approximately 10 cm centred on the mid-point between the metal rings on each sensor. Thus, any air space between the access tube and the soil or any alteration of the soil surrounding a sensor caused by the installation of the access tube will result in a bias in %VSM. Care should be taken when installing access tubes into wet clay soils, which may shrink as they dry leaving air cavities beside the tube.

The raw %VSM data can be converted to calibrated %VSM by applying a calibration specific to soil type. Default calibration coefficients for standard soil types are provided in the cprobe.cal file that accompanies the addVANTAGE software. This calibration has to be invoked by the user in the C-Probe extension. Gravimetric soil moisture (GSM) and soil bulk densities should be computed from manual soil samples for the soil type surrounding each C-Probe sensor. Calibration coefficients computed from actual field data under diverse soil moisture conditions can be edited into the cprobe.cal file. If standard values are not available for the field in question, then reference samples should be taken when the C-Probe hole is augered or when the access tube is removed. However, this sample set would represent only a single soil moisture condition. An exception might occur where the soil type (bulk density) is constant throughout the vertical profile but the soil moisture varies from depth to depth. Depending on where the soil samples are taken with respect to the access tube, spatial variability in soil texture and moisture may result in ± 10-20 percent change in absolute %VSM. The conventional method for storing data from the C-Probe is through Adcon telemetry devices (A733 to A840) and storage in Adcon software (addVANTAGE).

According to the Adcon C-Probe software, programmable calibrations can be implemented for each soil type to match various ratios of air and water with specific soil characteristics. These post-calibrations fit the data collected to curves based on prototypical soil types (i.e., clays have greater soil water potentials and subsequent bound water). Very little background is provided on these calibrations and individual calibrations should be established specific to each soil type.

5. VALIDATION AT BRATT'S LAKE STATION

5.1 Study site

In order to validate data from the C-Probe sensors, soil moisture was measured during the 2002 field deployment at the Bratt's Lake Station (BLS) near Regina, Saskatchewan to coincide with %VSM calculated from soil core sampling measurements. It is located at 50˚12′10″N, 104˚58′15″W and encompasses 3.2 km^2 of flat prairie terrain at an elevation of 587 m above sea level (ASL). The BLS was developed to provide state-of-the-art measurements of surface radiation fluxes[13]. The BLS was chosen for the prototype sensorweb deployment because of the validation potential provided by existing soil core sampling done by BLS staff. The North Field and South Field sites, which are separated by 68 meters, have less than one meter in elevation difference and minimal surface undulations. The soil type for both sites, as with most of the BLS, is a black Chernozem. The high clay content of this soil type leads, in turn, to high water retention. The North Field had wheat, whereas the South Field was in its first year of fallow, a difference that can affect soil moisture.

Specific attributes of the soil that affect capacitance, such as salinity and temperature, have been considered and several assumptions were made in the deployment of the C-Probes. Although no salinity measurements were made, the soils of both fields were considered very low in salinity and optimal for cultivation practices. Therefore, it was assumed the capacitance measurements were not significantly affected by soil chemistry differences between the two sites. During the BLS deployment, the average soil temperature was 18.2 ºC and had a maximum of 22.6 ºC, which fits well within the range of minimal temperature influence on capacitance measurements[12]. Soil properties (such as swelling and shrinking clays) that produce air gaps, which can significantly alter C-Probe measurements, were also assumed not to be a factor based on qualitative observation prior to installation. The homogeneous field characteristics of the BLS sites were optimal for validation as very little spatial variability was expected between the soil core measurements and the C-Probe measurements.

5.2 Methods

Four C-Probes with Adcon A733 telemetry devices were installed at the Bratt's Lake Station (Figure 2). At each C-Probe location, %VSM readings were sampled at three depths every 15 minutes for the duration of the deployment. The nominal depths were 15 cm, 45 cm, and 75 cm, representing depth layers of 10-20 cm, 40-50 cm, and 70-80 cm, respectively, based on the C-Probe sensor zone of influence discussed earlier. An exception was C-Probe 18844, which was sampled at soil depths 0 cm, 30 cm, and 60 cm due to installation difficulties. The Adcon base station (A840 storage device) and wireless modem (A440) were installed on the instrumentation platform/trailer at BLS. A dedicated phone line was provided, which allowed dial-up access to the Integrated Earth Sensing Workstation (IESW) in Ottawa and data transfers from the A840 to the IESW. These transfers continued on a regular basis during the deployment period from July 15 to August 17, 2002.

Field installation errors such as disturbance and compaction of surrounding soil may have been introduced because of the difficulty in auguring the dense clays. Changes in the soil density and structure may have led to slight differences compared to the GSM core sampling method. Although care was taken to avoid such errors, they are not uncommon with in-situ methods that involve installation of sensing technologies with tubes or probes.

Figure 2. Adcon node 15263, with C-Probes 15262 and 18844 in the ground, deployed in the North Field at BLS.

5.3 Results

%VSM data from three C-Probes (ID numbers 15262, 18831, and 18854) were validated based on daily %VSM calculated from soil core samples taken from July 15 to August 16, 2002. The comparisons were made for the 10-20 cm depth range (hereafter called "sensor level 1"). Weekly core samples were also used to calculate %VSM for the 40-50 cm depth range ("sensor level 2") and the 70-80 cm depth range ("sensor level 3"), but the deployment period was too short to generate a meaningful amount of data to pursue validation analyses for these depths. For C-Probe 18844, %VSM data from sensor level 1 (0-5 cm depth range in this case) were compared to 0-5 cm daily %VSM calculated from core sampling.

The daily soil samples consist of five spatial replicates and mean data for each site, allowing local spatial sampling variability to be calculated. The time plot of C-Probe sensor level 1 %VSM data for all four C-Probes is shown in Figure 3. Increased variability is observed for C-Probe 18844 because the sensor is at the surface where soil moisture is known to vary rapidly when moisture is introduced. In general, soil properties can account for variations of ± 10-20 %VSM not withstanding measurement errors. The time plot of %VSM data for all three sensors on C-Probe 18854 is shown in Figure 4. Near surface changes in soil moisture are observed for sensor level 1.

5.4 Validation conclusions and recommendations

Correlations between C-Probe %VSM measurements and %VSM results from soil core sampling for sensor level 1 are shown Figure 5 for C-Probes 18831 and 18854. R^2 values are high, but the slopes and offsets indicate that there is a systematic effect between the two methods. The measurements made by the two very different techniques express different subsets of the parameters used in the physical definition of soil moisture. This systematic effect has not been completely taken into account in this validation analysis. Nevertheless, examination of absolute differences between the two methods (Figure 6) as well as variances in the soil core sampling method (Figure 7) indicates that the discrepancies are comparable to the local spatial sampling variance in the case of C-Probe 18831. The greater differences for C-Probe 18854 are likely due to its different placement (closer to the surface). Thus, the C-Probe data are generally valid within the range of local variability.

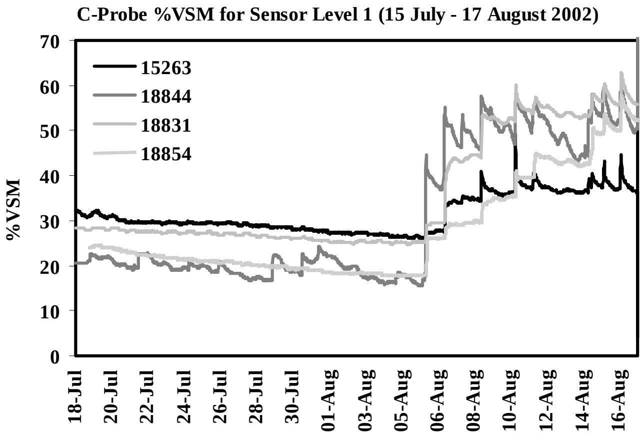

Figure 3. C-Probe data sets for sensor level 1.

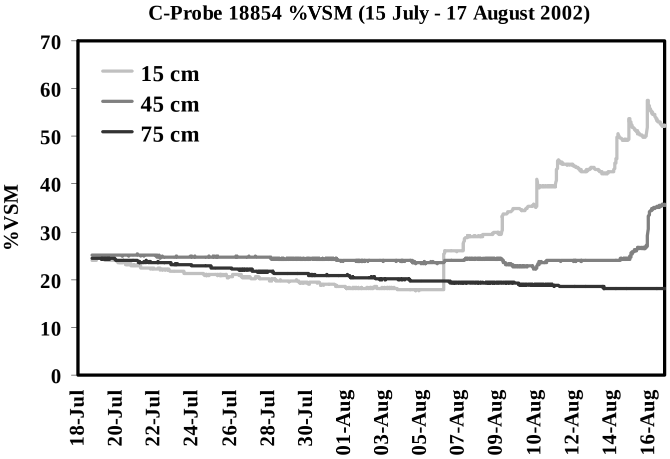

Figure 4. C-Probe 18854 data sets for all three sensor levels.

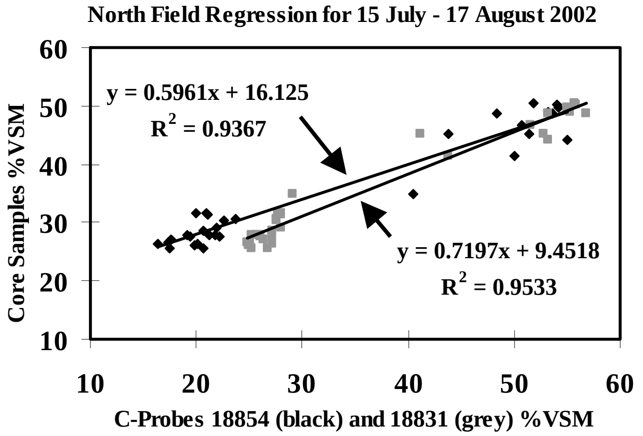

Figure 5. Correlation plot of core sample %VSM versus C-Probe %VSM for sensor level 1.

Figures 6 and 7 also indicate that significant amounts of water from rain events can increase variability in both C-Probe measurements and soil core sampling results, as demonstrated by the rain event of August 7, which affected both absolute differences and variability. Although the reasons for this are not understood, given that the soils of the study sites were flat and extremely homogeneous and hence not conducive to quick drainage, rain events appear to increase soil moisture measurement variability as much as 30 percent or more and should be considered in analysis of C-Probe measurements.

Several aspects of the C-Probe sensors require further validation. Although rain events and different soil saturation levels were measured, the deployment did not capture the full range of soil moisture levels. Due to the non-normal distributions of soil moisture values obtained from both C-Probes and soil core samples, true inferences could not be made from correlations that were calculated.

Insufficient soil core measurements at depths below 25 cm prevented validation of a large portion of the soil profile that the C-Probe can sense. Future studies hope to incorporate these depths and moisture ranges to have a more complete validation.

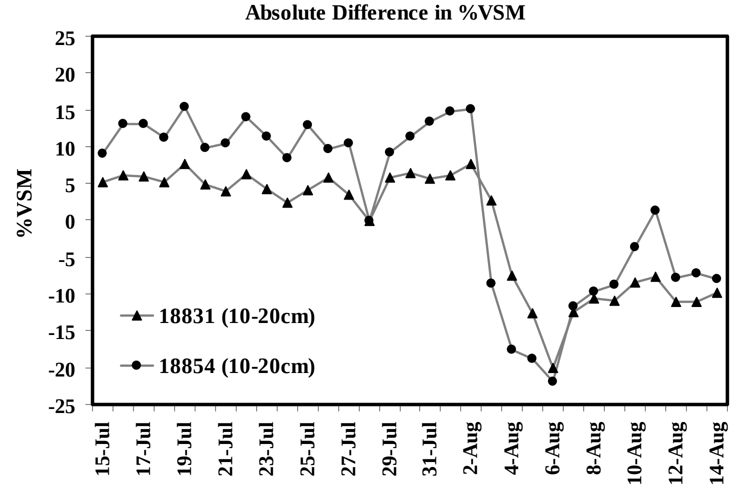

Figure 6. Absolute difference in %VSM between C-Probe measurements and results calculated from soil core samples.

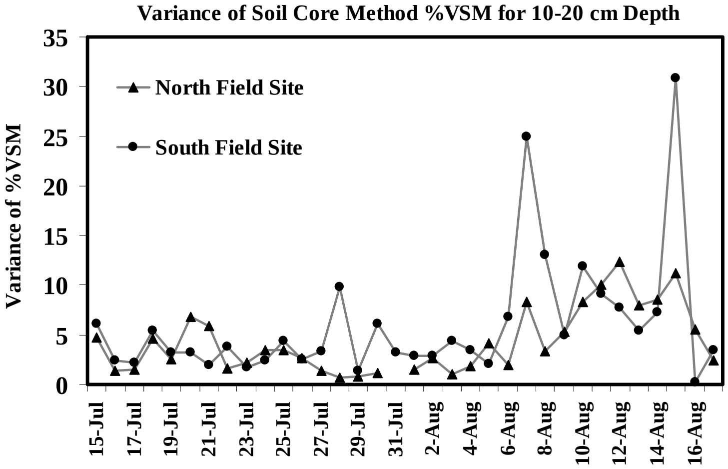

Figure 7. Variance in %VSM calculated from spatial soil core samples.

Based on the validation results and deployment observations, several suggestions can be made to improve future C-Probe deployments. When installed, C-Probes require auguring into the soil to the depth of the PVC installation tube. The augured soil should be stored and used as soil core method samples to measure actual volumetric soil moisture. This can give an initial idea of how valid the C-Probe is at time of installation as well as the different horizons, which may impact soil moisture changes at depth. If the C-Probes appear to have strange values at depth, this may indicate a faulty sensor or the presence of air gaps around the access tube generated during installation. Different C-Probes sensors should be tested in the same installation tube to see if similar results appear. This is a quick method to detect if sensors are faulty (may result from poor normalization or hardware damage). Otherwise, the PVC tube may need to be redeployed in a location with no air gaps.

6. CONCLUDING REMARKS

The Prototype Wireless Intelligent Sensorweb Experiment (ProWISE) successfully demonstrated a prototype soil moisture sensorweb in autonomous remote operation. The measurement suite consisted of several meteorological parameters but the focus of the deployment at Bratt's Lake Station was on soil moisture. Considering the many possible influences to the measurement of soil moisture by using capacitance, the results reinforce the strength of the relation between soil moisture and relative permittivity. The C-Probe demonstrated a high correlation (R^2 greater than 0.9) with independent estimates of soil moisture content under diverse soil moisture conditions over a period of five weeks. The inherent reliability of the system allows users to develop a high level of confidence in interpretation of the data for their specific applications. The challenge for soil moisture mapping over extended areas remains the high spatial sampling variability, which was confirmed by the measurements at the relatively homogeneous and flat Bratt's Lake Station location. This underscores the potential contribution that estimates based on satellite imagery can make.

Work currently underway[14] concerns the analysis of data from an augmented ProWISE sensorweb deployment from autumn 2002 through to the end of spring 2003. The objective of that study is to obtain soil moisture estimates for bare fields in the Red River Watershed in Manitoba, using Radarsat-1 Synthetic Aperture Radar (SAR) and Envisat Advanced SAR (ASAR) data, with ground validation based on soil moisture measurements from the ProWISE sensorweb and core samples, among other approaches. The next phase of the ProWISE development in 2004 will tackle smart internodal communication and heterogeneous sensorweb deployments involving many more sensor nodes.

Earth science sensorweb data have the potential to become an integral part of government policy and decision support domains. The work reported in this paper has taken an initial step towards demonstrating approaches to the time-critical and cost-effective monitoring of complex and dynamic systems. Nevertheless, much more needs to be done to provide a more solid basis for issue-specific decision support, including smaller, smarter and cheaper sensor systems for monitoring, the integration of time-critical in-situ sensor data and/or metadata into on-line geospatial data infrastructures, and the generation of validated data and information products derived from the fusion and assimilation of in-situ and remote sensing data into models. Ongoing challenges in such endeavours are the lack of resources to put in place capabilities for integrated assessment and the potential future shortfall of highly qualified science and technology personnel.

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