A Low Cost Sensor to Quantify Spatial and Temporal Variability of Snow Packs

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ABSTRACT

A Wireless sensor that can measure the local density, wetness, temperature and snow grain size of a snow pack will be described. By minimizing the cost of replication of this instrument, sensor webs can be deployed that will characterize the considerable spatial variability of snow packs. By employing low power wireless technology, these sensors can monitor this spatial variability over time with minimal disturbance of the snow pack. Snow varies considerably vertically, due to variable accumulation from storms over the course of a winter season. Snow varies temporally, in response to forcings from atmospheric temperatures, insolation, and ground freeze-thaw state. Snow also varies horizontally, due to topography, vegetation variations, and from drifting. A low cost, easily replicated wireless sensor will allow the capture of many details of the evolution of the snow pack. The sensor will use a quarter wave open resonator operating around 900MHz to determine the snow density and liquid water content. An optical link spanning the length of the sensor will be used to quantify the snow grain size. The measurement set is completed with an electronic thermometer. The wireless design not only provides the greatest flexibility in deployment, but eliminates wires which are a path for anomalous heat and moisture transport to the sensor location. The communications link will employ UHF to insure maximum signal transmission even in a wet snow pack. Progress on the development of this sensor will be reported.

Keywords: Snow, Wireless, Microwave, Optics, Sensor.

INTRODUCTION

The U. S. National Research Council, in its Decadal Survey (2007), recommends that NASA conduct a Snow and Cold Lands Processes (SCLP) Mission to have a global understanding of the dynamics of the water reservoir that is the seasonal snow cover. The seasonal snow cover is important to the global climate, as the snow cover has a much higher albedo than the terrain it covers (Stone et al., 2002; Sun et al., 2004). The accumulation of wintertime snow is the primary source of water in many mountainous regions, such as California (Aguado, 1985). The melting of accumulated snow, under the right circumstances, can lead to catastrophic flooding (Marks et al.,

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These are a few examples of the importance of an understanding of the global snow cover dynamics to the understanding of this planet’s climate, and to the well-being of its inhabitants.

The SCLP mission’s science objectives, as stated in the Decadal Survey, are quantification of snow water equivalent (SWE), snow depth and snow wetness at 100 m spatial resolution and 3 to 15 day temporal resolution. The spatial resolution is driven by the effects of topography upon snow pack properties, and the temporal resolution is designed to capture changes in the snow accumulation and ablation over the course of a snow season. The seasonal snow cover is very dynamic, with substantial variations over short periods of time and over very short distances being quite common.

The SCLP satellite will use active and passive microwave sensors to make the measurements of SWE, snow depth and snow wetness. This choice of remote sensing technology is appropriate because microwaves have significant penetration into the snow pack, yet the microscopic structure of snow is of a characteristic size that snow has a significant spectral variation in the microwave region. Indeed, the fact that the shorter wavelengths experience more scatter darkening from the snow grains than longer wavelengths gives rise to the operational snow depth and SWE retrievals from passive microwave observations (eg. Goodison, 1989; Goitia et al., 2003; Chang et al., 1997; Singh and Gan, 2000).

These retrieval algorithms are empirical and trained on specific terrains, as the details of the snow pack, and the vegetation cover, are specific to each terrain. The extent of the applicability of these algorithms is not well understood because they are not tied to models of snow physics, but SWE rms errors relative to the training data are on the order of 2cm. While snow parameter retrieval algorithms have been established for a number of terrains (eg. Tait, 1998), the SCLP mission is intended to observe all the terrain types on Earth that are covered by a seasonal snow pack. The production of a comprehensive set of empirical relations between the snow ground truth and the remote sensing observables is limited by the ability to collect the ground truth. This research addresses the inadequacies of the current methods of snow pack ground truth data collection for SCLP validation by automating the in-situ collection of snow pack parameters critical to the SCLP mission.

The existing methods of ground-based collection of snow pack properties is spotty at best due to a scarcity of expensive, automated installations, resulting in spatial undersampling, or reliance upon skilled labor for the observations, often resulting in temporal undersampling. Many of the manual techniques summarized below are described in detail in (Greene et al., 2004).

Snow Depth. The most common observation of snow, namely the snow depth, is the simplest to perform. A calibrated measuring stick is inserted into the snow pack a prescribed number of times and the average depth is reported. An automated version of this measurement involves timing of a sonic pulse from a fixed location above the snow pack (eg. Campbell Scientific SR50A, MaxBotix MB7384, Judd Ultrasonic Depth Sensor), but this instrument does not perform spatial averaging.

Snow Water Equivalent. Arguably more important than snow depth, the snow water equivalent (SWE) is the depth of water that would result if the snow pack melted but did not run off or infiltrate the soil. Thus, it is the measure of future water availability. The manual measurement of SWE involves weighing core samples of the snow pack. While an individual sample is a relatively rapid measurement, the spatial variability of SWE requires many samples, and the field worker must carry some rather bulky equipment into often deep snow for this measurement. The SNOTEL and SCAN networks (Schaefer and Paetzold, 2000) are networks of about 1000 remote snow pillows across the U.S. that measure SWE automatically, but installations are expensive and not mobile. Gamma ray measurement (Offenbacher and Colbeck, 1991; Carroll, 2001) is a reliable method of mapping SWE from aircraft, but aircraft operations, and the instrument itself, make this measurement expensive.

Snow Moisture. The liquid water content of the snow is extremely difficult to measure due to the fact that the ice grains are made of the same material as the moisture. While knowledge of the moisture content of snow is important to understanding the thermodynamics of a snow pack, and to predicting short term runoff potential, it is of importance primarily due to the effect of moisture on the microwave remote sensing. The dielectric constant of liquid water is more than an order of magnitude larger than ice, and so the presence of liquid water in a snow pack constitutes a distinct remote sensing problem than that of dry snow. The most common ground truth method of snow
moisture measurement is categorical, depending, essentially, on the observer’s ability to make a snowball. Several electronic measurement techniques have been developed (Kendra et al., 1994; Sihvola and Tiuri, 1986; Nakata et al., 2005; Denoth, 1994), but most of them rely upon field personnel for operation. The only exception that is automated (Nakata et al., 2005) is an experimental prototype.

Stratigraphy. One method by which microscopic snow pack parameters, such as snow moisture, snow grain size and shape, and snow density, are measured is by stratigraphy. This is an extremely labor intensive operation, with a skilled observer completing only a few meters of snow depth, in a few snow pits, per day. The result, however, is a rather comprehensive picture of the vertical variations of the microscopic snow parameters over the entire depth of the snow column.

These methods are expensive, and because of the expense, they are incomplete in time and/or space. For example, snow pit stratigraphy is labor intensive, and it can only capture a single snapshot in time. However, cost is not the only issue. When the snow is melting, it can be very dynamic, and the stratigraphy procedures for complete characterization of the snow profile are likely too slow to faithfully capture the snapshot.

We are developing a method of obtaining snow pack data critical to the validation of the SCLP satellite which cuts the cost of data collection, and splits the difference between permanent installations (like the SNOTELs) which are very limited spatially but produce an excellent time series of data, and the expensive manual methods which are very flexible in terms of the sampling sites, but are limited in the overall volume of data generated by the availability of skilled labor. This system will produce the data needed for validation of SCLP’s derived science products, can be installed for as long as an entire snow season without maintenance, and a single installation can be spread out over an area of about 1 square kilometer to capture local terrain variations. The key to this approach is keeping the costs of reproducing the hardware to a minimum, which is possible due to the proliferation of wireless technology.

Our method uses a small, low power wireless sensor module that is embedded in the snow pack and collects data on the properties of the snow pack local to the sensor module. This data includes temperature, complex dielectric constant in the microwave portion of the spectrum, and optical transmissivity. The complex dielectric constant reveals the snow pack density and liquid water content (Kendra et al., 1994) while the optical transmission measurement reveals information about the snow grain size. These sensor modules then report their data back to a base station above the snow that is responsible for measurement scheduling and data archiving. The wireless communication between base station and sensor modules not only eases the set-up of the system, but the elimination of wires also prevents unnatural migration of heat and moisture to the observation points. Up to 128 sensor modules report to a single base station. Thus, this system can be deployed to report data over the course of a snow season, and the number of sensor modules means that spatial variability, either vertically in the snow pack or horizontally due to the terrain, can be measured.

The next section describes the sensor system components, followed by a section describing the science behind the individual snow pack parameter measurements. We next describe the engineering considerations in a section on the technical approach and a section on our perception of the technical challenges. We conclude with the status of the project.
Figure 1. A system configuration of the wireless snow pack monitoring instrument. A single base station on a fixed support above the snow pack controls and communicates with multiple sensor modules arrayed throughout the snow pack.

SYSTEM ARCHITECTURE

This project will develop a small, low-cost, low-power, wireless instrument suite for measuring the material characteristics of a very dynamic natural bulk material of great importance in many parts of the world: snow. The instrument will use commercially available electronic parts in two types of modules, which will be replicated, to make a comprehensive set of point measurements of the temperature, moisture, density, grain size and snow water equivalent of the snow pack. Figure 1 depicts one strategy for deploying these modules in a snow pack. These two types of modules are:

1. A sensor module.

   This module makes two unique measurements that quantify 4 local variables of the snow pack. First, it uses wireless transceiver technology not just to communicate but also to measure the complex dielectric constant of the medium immediately surrounding sensor module. Even when contaminated, a snow pack is composed overwhelmingly of air, liquid water and ice. Thus, knowledge of the complex dielectric constant permits the determination of snow density and moisture content. Second, an optical link across the external face of sensor module measures the optical extinction within the snow pack. Scattering dominates the extinction, and thus a transmission loss measurement quantifies the number of grain interfaces between a light emitting diode and a photodiode, both located on a single sensor module but separated by a few centimeters. Knowing the density from the radio frequency measurement, a mean grain size can be inferred. Finally, snow pack temperature will be obtained with an electronic thermometer. The components needed for this module are particularly inexpensive, and so a typical installation will have many of these sensor modules to capture the stratigraphy in several locations.

2. A base station.

   This module will serve as the master communication, control and data handling module for an installation of multiple sensor modules. It is the only module that must be installed above the snow pack. The base station will communicate wirelessly with each of the other modules using a star configuration, or other simple protocol appropriate for snow fields (eg. Kerkez et al., 2012). While the data collected in the initial deployment will be stored and periodically downloaded by an on-site operator, the base station(s) could be configured to relay the data from a remote location to a data
server connected to the Internet. The base station will also have an electronic thermometer to record local air temperature.

The wireless operational motif for this instrument is critical to its functionality. The absence of wires is important for observing the evolution of the snow pack over time: wires are a source of anomalous metamorphism, by being a conduit for heat and in some cases moisture. Together with their small size and low cost, the snow pack can be monitored vertically, horizontally and temporally by an array of sensor modules. Large regions can be monitored by a sensor web of base stations, with each base station communicating with its own sensor modules.

The major challenge to implantable sensors within the snow pack is keeping the introduction of foreign materials from locally altering the snow pack. The single most important parameter to control is power dissipation. Even modest heat dissipation, while it may not influence the temperature of the snow, will be sufficient to alter the local snow structure from the bulk characteristics, by encouraging the metamorphosis of the snow pack that results in the disappearance of small snow crystals and the growth of larger, rounder crystals. An additional advantage to the use of microwaves for moisture and density sensing is the fact that the sensor geometry can be made most sensitive at the part of the sensor most distant from the electronics. Thus, the measurement of moisture and density is removed from any modified snow adjacent to the sensor electronics. However, low power alone is not sufficient to prevent the sensor from altering its environment. A wireless communication link is critical, since wires can conduct heat at a much greater rate than snow. Careful packaging includes using materials which match the sensor albedo (in both shortwave and longwave) to the snow pack, and prevent wetting, which can lead to unrepresentative localized transport of liquid water. Even though existing products utilize microwave techniques for measuring soil moisture, none of those products are adequate for operation within a snow pack because of these considerations.

MEASUREMENT CONCEPT

We are developing a wireless implantable sensor for the automatic measurement of four variables that determine the thermal properties of a snow pack: the liquid water content, the snow density, mean grain size, and snow temperature. All of these variables will be measured locally to the sensor.

The temperature will be measured directly, as is currently done in many wireless sensor systems, by means of an appropriate circuit employing semiconductor junctions that have known temperature dependence. The LM60 series and LM234 series are examples of commercially available prepackaged circuits of this type. By comparing the temperature history of a vertical stack of sensor modules with the temperature recorded by the base station above the snow pack, the snow depth can be derived. The temperatures reported by the sensor modules above the snow pack will exhibit a much stronger correlation to base station temperature than the sensor modules buried in the snow pack.

The snow density and snow liquid moisture content will be inferred from a microwave measurement of the complex index of refraction. The real part of the complex index of refraction, \( n \), of a material describes the reduction in the speed of electromagnetic wave propagation in that material when compared to a vacuum. The imaginary part of the complex index of refraction, \( \kappa \), describes the rate at which energy in the electromagnetic wave is absorbed by the medium. The bulk complex index of refraction of snow, \( n_{\text{snow}} + j\kappa_{\text{snow}} \), is very nearly a linear combination of complex index of refractions of the constitutive materials of snow, namely air, ice, and water (Hallikainen et al., 1986):

\[
    n_{\text{snow}} + j\kappa_{\text{snow}} = v_{\text{air}} n_{\text{air}} + v_{\text{ice}} n_{\text{ice}} + v_{\text{water}} \left( n_{\text{water}} + j\kappa_{\text{water}} \right)
\]

where \( v_{\text{air}} \), \( v_{\text{ice}} \) and \( v_{\text{water}} \) describe the volume fractions of air, ice and water, respectively. Contaminants are typically so minor in concentration as to be negligible in terms of the bulk dielectric properties. In the microwave region of the spectrum, air and ice are essentially lossless, with \( n_{\text{air}}=1.000 \) and \( n_{\text{ice}}=1.775 \) (Ulaby et al., 1986). The complex index of refraction of water is a strong but well-known function of frequency and temperature (Klein and Swift, 1977; Meissner
Figure 2: Left: Measured results of a ring resonator from (Sarabandi and Li, 1997). Sand can be considered a proxy for ice, and moisture content (m_v) varied from no water added to 30% by volume. The resonant frequency decreases with an increase in n, and the half power bandwidth increases with an increase in κ. This qualitative behavior is consistent across all open microwave resonant circuits used in this manner, such as the magnetically coupled quarter wave coplanar stripline designed by the authors on the right.

and Wentz, 2004). Fortunately, in snow, the liquid water is always at 0°C, and the frequency is under control of the instrument. Thus, the volume fraction of liquid water is immediately available from the measurement of the imaginary part of the index of refraction of snow. The measurement of the real part of the index of refraction of snow, together with knowledge that snow is composed only of air, ice and water (that is, \( v_{air} + v_{ice} + v_{water} = 1 \)), yields the volume fractions of air and ice, from which the density is readily derived.

The measurement of the complex index of refraction (or dielectric constant, which is the square of the index of refraction) of snow has been demonstrated at microwave frequencies with several resonant circuit devices (Kendra et al., 1994; Sihvola and Tiuri, 1986; Nakata et al., 2005; Sarabandi and Li, 1997). While the geometry of the sensor in these examples varies significantly, the operational characteristics are very similar. The sensor forms a resonant structure, onto which a variable single frequency is coupled, and from which this frequency is coupled into a receiver to measure the relative magnitude. The real part of the index of refraction of the material in which the sensor is embedded lowers the resonant frequency from that when the sensor is in a vacuum. The imaginary part of the index of refraction lowers the coupling from input to output, which causes the half-power bandwidth of the resonant structure to increase. At frequencies below 1 GHz, the wavelength is sufficiently large that the microstructure (the size and shape of snow grains or moisture droplets) of the snow pack do not affect the measurements. Thus, simple measurements of the strength of the response of a resonator to a swept frequency are sufficient to characterize the complex index of refraction. Measurement of the spectral response of a resonant structure (Sarabandi and Li, 1997) for various materials, shown in Figure 2, demonstrates these principles. These resonators have many degrees of freedom to permit the design of appropriate sample volume, frequency range, dynamic range, and sensitivity to both the real and imaginary parts of the complex index of refraction.

We wish to emphasize here that the measurement of the complex dielectric constant is distinct from many existing capacitive soil sensors, and the no longer produced “Denoth meter” (Denoth, 1994) for snow, in which only the real part of the dielectric is measured. The measurement described here is a complex measurement, with two degrees of freedom from which both density and moisture can be retrieved.
Figure 3. Measured photocurrent over a 5mm optical link for sucrose sugar with grain size sorted by screen into four diameter ranges. The wavelength is 635nm; the bulk density is constant at 0.73g/cm$^3$. The best fit curve predicted by Bohren and Barkstrom (1974) is shown, but this model does not account for the effects of the cavity walls.

The snow grain size can be quantified with an optical link. Bohren and Barkstrom (1974) predict that light extinction should be proportional to snow density and inversely proportional to the square root of the grain diameter. An optical link that can measure extinction can be easily constructed from light emitting diodes (LEDs). Compared to reflectometry (e.g., Painter et al., 2007), which is subject to contact and surface issues, an optical link can make a more direct measurement of the grain size since the active area of measurement is between the optical elements. A forward biased LED will constitute a light source while a reversed biased LED constitutes a spectrally matched photodetector. Preliminary measurements show a sensitivity of an optical link made from LEDs spaced 5mm apart to the grain size of sucrose and sodium chloride (see Fig 3). Even though this cavity that we used does not conform to the requirements of the Bohren and Barkstrom model, we were able to observe the qualitative features predicted, namely that the extinction is a monotonic function of the number of refracting surfaces between the light source and the detector, and show that sufficient sensitivity for mean grain size retrieval is plausible.

The appropriate wavelength and spacing for the optical link will depend on various tradeoffs of ice properties, and performance and cost of available circuit components. LEDs come in various colors, permitting an evaluation not just of extinction, but also of the spectral gradient of the extinction, thus producing a more robust measurement (Mellor, 1970). At a snow density of 250 kg/m$^3$, the penetration depth of light at 1030nm ranges from 4.9 to 21 mm as the grain diameter increases from 100 to 2000um (Nolin and Dozier, 2000). Thus, LEDs mounted on the same PCB will permit a sensitive extinction measurement. We are evaluating if two colors are sufficient, if more colors are needed, or if a link including infrared would be more robust. Inside a snow pack, impurities in the liquid water, which can affect the losses, tend to be of very low concentration when compared to solutes in the soil.

The snow water equivalent will be obtained by integrating the density and moisture measurements over the vertical extent of the snow depth.

TARGET SPECIFICATIONS

The target range and resolution for the instrument are listed in Table 1. Durand, Kim and Margulis (2008) express a need for snow pack modeling accuracies of ±40kg/m$^3$ in snow density and ±45 um in snow grain diameter in order for these models to adequately predict remote sensing signatures of
snow. We will use these figures as our measurement objectives, so that this instrument can be used to validate those models. Kendra et al. (1994) were able to achieve overall moisture and density accuracies of 0.66% and 50 kg/m$^3$ with their proof-of-concept snow probe in a similar frequency band. Their snow density measurements were significantly more accurate for snow with less than 3% moisture than for wetter snow. Our very preliminary measurements of grain size (Fig. 3) indicate that the precision desired by (Durand et al., 2008) is achievable.

The sensor module will be designed to measure a snow pack volume of a few cubic centimeters. The strawman design has a microwave sensor head about 5cm long with a sensitive area about 1cm in diameter. This volume is appropriate for the instrument, as a smaller volume may be affected by the discreteness of the snow grains, especially if implanted where depth hoar develops. Larger volumes may not be able to distinguish some of the smaller features in the snow pack, most of which form in strata, such as ice lenses.

The snow water equivalent specifications will depend not only on the sensor module measurement performance, but also on the placement strategy of the sensor modules in the vertical direction. We will design a placement protocol that will meet or exceed the SCLP mission requirements (National Research Council, 2007).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid water content</td>
<td>0%</td>
<td>10%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Dry Snow Density</td>
<td>0 kg/m$^3$</td>
<td>600 kg/m$^3$</td>
<td>30 kg/m$^3$</td>
</tr>
<tr>
<td>Temperature</td>
<td>-40ºC</td>
<td>+40ºC</td>
<td>0.5ºC</td>
</tr>
<tr>
<td>Mean grain diameter</td>
<td>100um</td>
<td>2000um</td>
<td>40um</td>
</tr>
<tr>
<td>Snow Water Equivalent</td>
<td>1cm</td>
<td>20cm</td>
<td>2cm</td>
</tr>
<tr>
<td></td>
<td>20cm</td>
<td></td>
<td>10%</td>
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**TECHNICAL APPROACH**

Since the sensor modules will be the most common component, an emphasis will be made on producing a sensor module design that has low per unit cost while maintaining performance. The sensor module conceptual block diagram is shown in Figure 4. This concept employs a 150 ohm coplanar stripline configured as a quarter wave resonator, with an open circuit on the sensitive end, and a short circuit on the electronics end. Many other resonant structures are possible and will need to be investigated prior to prototyping. Commercially available products will be chosen for the implementation of the RF electronics, the wireless communications link, and the microcontroller for the sensor module. Texas Instruments manufactures a family of CMOS chips designed by Chipcon that are intended for wireless applications. The CC1000 appears to be a near perfect fit for this snow sensor application, and will be the central component in the strawman design used to define requirements and predict performance. The CC1000 is a radio transceiver with self-calibration of both frequency and transmit power. The radio transceiver operates over the range of 300MHz to 1000MHz. This frequency range is more than sufficient to provide for both the wireless data link and the measurement of the complex index of refraction. This chip will be coupled to the popular MSP430 microcontroller, also from Texas Instruments, for the command/control of the sensor module. This microcontroller comes in many configurations, including static memory up to 60kB, an 8 channel 12-bit analog-to-digital converter (ADC), and 48 individually configurable I/O lines. Both of these components have multiple low power (sleep) modes and are rated to work down to -40ºC.

Components for an early prototype of a sensor module that can measure snow density and wetness, and wirelessly report the measurement, has been designed and individually tested. These components include a CC1010 transceiver with a built in 8051 microcontroller, the PIN diode switch, a 150ohm quarter wave sensor, and the LTC5505 detector. For this project, the now-
obsolete CC1010 is replaced with the MSP430 and CC1000, but the other components have proven themselves to be useful for the sensor module (see Fig. 4).

The initial sensor module prototype will be as close to the operational sensor module as possible: constructed of a single printed circuit board, battery operated, sealed from moisture with a white plastic clamshell and waterproof coating. Once we demonstrate adequate operation of our design via several hand-built prototypes, we will fabricate about 100 units using commercial mass-assembly techniques so that unit-to-unit variance of measurement quality, power consumption, and wireless link performance can be evaluated. A modified sensor module can perform adequately as a base station tied to a PC via the MSP430 UART (serial) ports.

Considering the components listed above, it is expected that the sensor electronics should be able to fit in a box at most 2 cm high by 4 cm by 5 cm, with a sensor head extending from it about 5 cm long and 1 cm wide. Because the resulting measurement volume is small, roughly 5 cm long and 1 cm in diameter, high resolution measurements of spatial variability of the snow pack are possible. However, since any single point measurement, even over time, is unlikely to be representative of the snow pack as a whole, numerous sensors will be required in a single measurement site. This underscores the need to make the sensor relatively inexpensive to reproduce. In quantity, the most expensive commercially available components are the CC1000 and MSP430 chips, $5.25 each; the clamshell, $5.12; and the battery, $4.24. With commercial pick-and-place assembly of the printed circuit board, and manual packaging, we should be able to keep well under $100 per sensor module.

Since multiple sensor modules are required for meaningful measurements, the costs of an individual sensor module must be relatively low. However, we cannot at this time envision a per-unit cost so low that the sensor modules can be considered disposable after one snow season. Therefore, recovery of the sensor modules must be considered in their design. A white sensor clamshell case will help not only with thermal management during the snow season, but will help with sensor recovery after the conclusion of the snow season. Additional means of helping the recovery of sensors will be considered. For example, the LEDs used for snow grain size measurement can be made to flash upon a recovery command issued via the base station. Radio emissions can also be used for locating the sensor modules. With this mode of operation in mind, the sensor modules will be supplied with batteries that will last at least one snow season. Due to their excellent thermal properties, lithium batteries will be used. The clamshell can be opened and resealed for the replacement of the battery. During the summer, the owners of the sensors will be
responsible for some maintenance, including battery replacement, and thus reuse the sensor for many winters.

The base station will consist of hardware that is very similar to that of the sensor modules, connected with COTS sensor web hardware, such as a Libelium MeshLium module (http://www.libelium.com/). A CC1000 chip tuned to 915MHz communicates with the sensor modules, and a MSP430 microprocessor controls the base station. For data storage, we will employ a multi-gigabyte compact flash card. Serial ports unused on the sensor modules’ MSP430 will serve as an occasional communications link to a laptop for data dumps, and as the communications link to an L1-only GPS receiver. The GPS provides millisecond accurate timestamps for merging the resulting data from this instrument with other data sets. As the air temperature is an important component to determining whether a sensor module is above or below the snow pack surface, a temperature monitor will be included. The base station will also have the capacity to interface with an ultrasonic ranging sensor, such as the Campbell Scientific SR50A (http://www.campbellscientific.com/), so that the base station can directly monitor snow depth. Unlike the other modules under the snow surface, the power requirements of the base station are driven by power availability and operational duration, not by heat dissipation. As such, it will be designed to operate in remote areas by means of batteries recharged with a solar array. As the focus of this project is on the sensor modules, the full capability of the base station will not be developed. For example, while the capacity to include additional wireless channels for a sensor web of base stations will be designed into the base station, it will not be implemented, as this demonstration of the sensor module capabilities involves only one base station. In fact, as our preferred validation location includes 120VAC 60Hz power, we will design but not develop the battery and solar recharger. Daily snow depth measurements are made at our preferred validation location, so we will not include this measurement in our base station implementation, either.

TECHNICAL CHALLENGES

The following is a non-exhaustive list of the technical challenges associated with the sensor modules that we will address in this project.

Sensor Bandwidth

The volume of the sensitive region of the sensor is dependent on the geometry of the open resonant circuit, which, in turn, is dependent on the choice of operating frequency. The device will consist of a resonating quarter wave coplanar stripline that operates in the materials measurement band of 890 to 940 MHz reserved by FCC Part 15 Subpart 243, and/or at such low powers at other frequencies that no FCC license is required. However, the range of resonant frequencies for the open resonant circuit in snow shown in Figure 1 is substantial. The high bandwidth requirement can be traded off against sensitivity, as was done for the ring resonator circuit (Sarabandi and Li, 1997). The ring resonator accuracy was excellent because much of the reduction in sensitivity was overcome with an increase in the frequency accuracy of the support circuitry, when compared to (Kendra et al., 1994). The CC1000 and many other transceiver chips are capable of the needed accuracy. A probe that constitutes an extension of the PCB is desirable for ease of fabrication and the reduction in bandwidth. The probe shown in Fig. 2 is an ad-hoc “design”, with excess coupling from the input and output to the resonator, resulting in an insufficient resonator $Q$ for this application, but the fact that it works as well as it does is a testament to the robustness of the operational concept. An optimal probe design is currently being performed using EMAG Technologies’ EM-Cube CAE software.

Power Consumption

In order to insure meaningful measurements over the long term, power dissipation and packaging require careful consideration. The minimum thermal conductivity for snow can be considered to be 60 mW/m-K, for low-density (fresh) snow. Assuming also that all power dissipation occurs through the open resonator, and a temperature increase of snow should be limited to 0.1°C due to the sensor,
the maximum allowable average power dissipation for snow sensor suspended in the snow pack is on the order of 0.5 mW. This value for average power dissipation is quite achievable for a system intended to operate for months at a time, as will be discussed below. A Teflon clamshell enclosure, used for the electronics and the battery, provides a high albedo to prevent warming due to longwave or shortwave radiation. It also provides a thermal barrier and capacitance between the snow and the circuitry that occasionally consumes considerably more power than the maximum average limit. When active, the MSP430 microcontroller consumes about 1.2mW while the CC1000 transceiver consumes about 90mW of power when the transmitter is at full power. An LED will consume up to 60mW while it is briefly on. The duration of the measurement is dependent on the bandwidth to be swept, the frequency resolution needed, and the sampling rate of the MSP430 ADC. Measurements need not occur more frequently than every 5 minutes, so the average power consumption due to measurements would be on the order of 50 uW. This figure could be reduced significantly by abandoning the brute force search algorithm (frequency sweep) implied in this discussion for a more intelligent search for the resonant frequency. When in standby mode, the MSP430 consumes 6 uW and the CC1000 consumes 4 uW. The critical data that needs offloading are the timestamp, the settings for the frequencies corresponding to the resonance and the Q, the temperature, and optical detector outputs both with and without illumination. Leaving a generous margin for housekeeping data, this constitutes about 300 bits. For maximum distance transmission of this data, the transceiver on the chip consumes a maximum of about 90 mW of power, and can use a data rate as slow as 600 bps. Regardless of how often the data is actually offloaded, the data accumulates at a rate that will require an average of 300 uW to offload under these worst case calculations. In light of the above calculations, the objective of dissipating a maximum average power of 0.5 mW should be achievable. A battery with a derated capacity of 1200 mAh at freezing temperatures, corresponding to a lithium battery of 2/3 AA size, such as the Tadiran TL-3955/S, would be able to operate the device for about 8 months.

Wireless communications

The refractive index model in (1) predicts attenuation within the snow of about 9dB/m per percent of moisture at 915MHz, while the attenuation is only about 3dB/m per percent of moisture at 433MHz. Preliminary measurements of ours, and those of Stepanek and Claypool (1997), indicate that transmission of 915MHz communications signals through even very wet snow does not significantly impact the communications link when the receiver and transmitter are separated at a plot scale. Choosing to communicate at 433MHz while measuring the microwave dielectric near 900MHz will certainly eliminate any downtime due to significant wetness in very deep snow, but such a choice will require two separate oscillators. This will likely take the form of two separate transceiver chips. The CC1000 can operate at either of these frequencies, but not both in the same chip, due to the need for off-chip tuning components. Because we desire to keep the component costs for the sensor module low, and because we would like to leave open the option to utilize the communications channel losses for extended moisture measurements in the future, we will use the 915MHz communications band rather than the more robust 433MHz band, and suffer potential reporting delays when the snow is melting.

Calibration: microwave resonator

Techniques to calibrate microwave resonant structures with pure fluids of known dielectric are numerous (eg. Kendra et al., 1994; El-Rayes and Ulaby, 1987), but are based on the terminal impedance changes of an antenna embedded in a lossy dielectric (Deschamps, 1962). Even so, most calibrations for specific sensor geometries employ one or more ad-hoc corrections. We expect to have to do the same for the coplanar line quarter wave resonator. This process will be assisted with the use of CAE design software and with the use of an abundance of different calibration fluids to over-constrain the resonator response. Fluids of known complex dielectric constants that are compatible with this quarter-wave resonator include alcohols from methanol (Jordan et al., 1978), ethanol (Lou et al., 1997), up to octanol (Garg and Smyth, 1965), toluene (Lou et al., 1997), and pentanes (Sen et al., 1992) like hexane, heptane, and octane.
Figure 5. The University of Michigan meteorological deployment at CLPX in January 2004 (Hardy et al., 2008). The snow temperature array in the foreground consists of 15 thermistors, each mounted at the top of white-painted CPVC tubes cut to integral multiples of 10cm in length and mounted into a common base. Five of the thermistors are buried within the snow pack. The tower in the background contains the control hardware and other instruments.

Calibration: Optical measurements

The optical properties of ice, sucrose and sodium chloride are sufficiently similar that we can use these household products to calibrate the optical link. The materials can be separated into ranges of particle sizes by sieving the grains, and a particular grain size distribution can be approximated by mixing these different ranges in the appropriate ratios. Even if the model for extinction given by Bohren and Barkstrom (1974) is not appropriate, the data should be sufficient for an empirical fit.

System Validation

In the final winter of the project we will deploy the instrument at the University of Michigan Biological Station (UMBS) in Pellston, MI, near the “tip of the mitt” that is the lower peninsula of Michigan. The instrument will be installed in a protected, 100m diameter clearing in the forest in late October or early November, and removed once the snow has completely melted in April. We will install one base station on a tower to keep it above the snow pack (see Fig 5, background), and six “stacks” of 16 sensor modules.

We will then visit the site about ten times during the validation period to download data and characterize the snow pack using manual methods. We will measure the snow pack depth, weigh cores for SWE, and dig snow pits to measure the density, temperature, and grain size as a function of depth. Manual wetness measurements are categorical and therefore of limited value, but will be made nonetheless. During some of these visits, the snow pits will involve the extraction of a stack of sensor modules. Additional manual measurements will be made in the clearing to characterize the snow pack variability at this site. Between visits we will analyze the sensor modules’ data for consistency, availability, and accuracy.
The field work is weak on the validation of the snow moisture. Therefore, a cross comparison of the sensor modules to the Kendra snow probe (Kendra et al., 1994) will be performed for the snow moisture and density. This measurement will be performed on dry, moist, and wet sand as a proxy for snow.

**Deployment**

We envision the snow researcher using a GPS system at the time of deployment to cross list the module serial numbers with their locations. Techniques will need to be developed for deployment vertically in the snow pack. The most direct method is to deploy subsets of the full set of sensors over time, as the snow accumulates. Migration of the sensors within the snow pack due to compaction can be inferred from the density measurements.

However, since we cannot be present at the validation site for all of the expected snow accumulations, we will either pre-deploy the sensor modules on a structure that will suspend the sensor modules above the ground, or devise a structure for the automatic deployment of individual sensors as the snow accumulates. An example of the former method is shown in the foreground of Fig. 5. In this instance, thermistors are mounted at the top of a series of white-painted CPVC tubes, 10 to 150cm long in 10cm increments, to measure a snow temperature profile. For the sensor modules, we will create lightweight sensor holders made from a thermally insulating and hydrophobic material, such as polyethylene, for a one-time deployment of multiple sensors at various heights above ground in a single location. At present we envision a structure that resembles a white pine tree: a single, rigid trunk anchored to the ground with multiple horizontal limbs that are flexible to allow the snow to compress without dragging the sensor modules at the ends of the limbs through the snow pack. As evidenced by our experience with the data set from the configuration in the figure, sensors that are above the snow pack surface are easily distinguished from those within the snow pack by the correlation of the reported diurnal temperature variations with an independent record of air temperature readings.

**CONCLUSIONS**

This paper describes hardware that is currently under development at the University of Michigan to inexpensively quantify local snow pack parameters such as temperature, density, grain size and moisture. From many of these measurements, integrated quantities like snow depth and SWE can be derived. We have validated the individual measurement concepts and are currently engaged in the detailed design of the sensor circuits, keeping in mind the cost of replication.

The benefits of automated snow pack ground truth flow from the reduced cost of data acquisition. Lower costs mean longer term ground truth data collection, at more sites, than is currently possible. This will improve SCLP mission by capturing snow ground truth at more terrain types than is possible with current methods. Also, by deploying data collection instruments for a snow season or longer, a wide variety of snow conditions at an individual site can be observed. The result of this research will be a more robust validation of the SCLP science products than is possible with today’s technology.

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