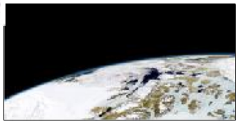
# Toward and Autonomous Ground-based RF Facility to Monitor Snow and Ice in Remote Regions



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## 1. Introduction

The ability to acquire quantitative measurements of changes in glaciers and snow accumulation in cold regions and at high elevations is critical to understand current climate. About one billion people across the world depend directly on mountain snow for freshwater resources, including the western US. Besides water resources management, snow and ice information is essential for a wide-range of socio-economic activities from maintenance and operations of lifeline infrastructure at high latitudes, management of ecosystem services in mountainous regions, and disaster preparedness and warning (e.g. avalanches, highway icing, rapid melt flash-floods and ice dams).

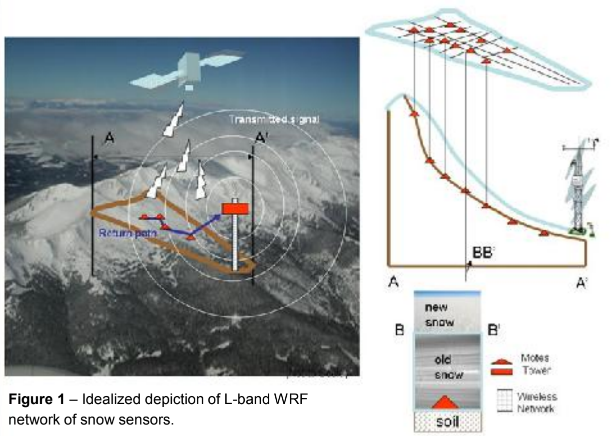


**Figure 1** – Idealized depiction of L-band WRF network of snow sensors.

An autonomous platform consisting of nested wireless networks of RF sensors to monitor the evolution of snow wetness, snow depth and snow bulk density, through accumulation, metamorphosis and melting phases in remote regions is being developed at Duke University. Specifically, a prototype TX-RX L-band sensor (Kang and Barros 2010) demonstrated capacity to detect snow wetness exceeding 25% (well above the 5-8% of current technology). In addition, exploratory tests during snowfall events suggest that the same measurement principle could be useful to monitor solid precipitation accumulation during snow or ice storms at both L and S bands. The new measurement system was deployed for the first time during the GCPEX campaign January-March 2012 in Ontario, Canada.

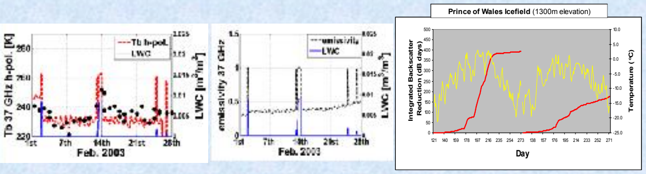


**Figure 2** – Sensitivity of microwave brightness temperatures (left, SSMI) and snowpack radiometric properties (center, modeled, Kang and Barros 2011a-b) and backscatter (right, QuikSCAT, courtesy S. Yueh, JPL) to the presence of melt water.

Currently, satellite-based remote sensing provides the only means to monitor snow and ice over large-scale regions, and remote regions in particular. Whereas satellite-based observations provide reasonable estimates of snow covered area, the same is not true for the internal structure and composition of snow and ice layers and snow water content due to high spatial heterogeneity that cannot be resolved at the remote-sensing measurement scale. Ultimately, deployment of the facility we envision in extreme environments can provide ground-based validation data (in research mode) and monitoring data (in data assimilation mode) to improve the utility and quality of satellite-based retrievals of subgrid-scale wetness and microstructure.

## 2. Full System Testing

The first generation of the L-band TX-RX system sensor to monitor the temporal evolution of surface snow and ice in regions of complex terrain was designed, fabricated, and tested under laboratory conditions at Duke University to establish proof-of-concept. Five snow modes were fabricated.

Each sensor operates at 39 discrete frequencies (39 channels) in the 1.00-1.76 GHz frequency range (0.02 GHz increments), although only a limited number of channels (< 10) are actually used for snow water equivalent retrieval.

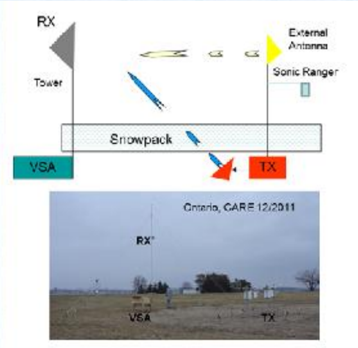


**Figure 3** – Experimental set-up of TX_RX snow modes in the laboratory and during GCPEX, in Ontario, Canada during the 2011-2012 winter.

Kang and Barros (2010) determined that the range 1-1.2 GHz was the best functional range across all five snow mode replicates. The snowpack was modeled in the laboratory using layers of Regicell foam (a non-polar plastic, radiometrically inert in the 1-1.4 GHz range) with different densities (and porosities) as the dielectric host (R10, R30 and R60, where the numerical index indicates the number of air bubbles per cubic inch corresponding to 88%, 42%, and 7% porosity respectively). The water equivalent was modeled by adding varying water depths to the foam, thus in terms of liquid water content up to 25% volumetric water content, which is the typical maximum water holding capacity of snow.

Data analysis using R10 foam are presented in Figs. 4 and 5. The snow mode algorithm extracts time-varying amplitude changes and phase shifts at different frequencies, which are the primary parameters in the SWE estimation algorithm. For each frequency channel ω in the 1.0-1.4 GHz interval, at each measurement time we have two signals: Tair (t) = Aair exp (jωt+φair) and Tmedium (t)= Amedium exp (jωt+φmedium). The amplitudes Amedium and Aair, and thus the attenuation ΔA can be extracted directly from the measurements, and the phase difference Δφ can be estimated by manipulating (Tair/Tmedium). Attenuation is expressed in dB.

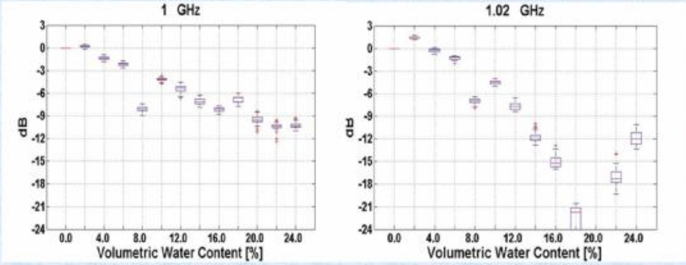


**Figure 4** – Amplitude attenuation curves as a function of volumetric water content (VWC) for sensor T1 using R10 in two selected frequency channels.

Figure 4 shows that as expected amplitude decreases monotonically with volumetric water content up to 20% VWC. At VWC=8% there is the effect of the intrinsic frequency of the model snowpack geometry (common in similar experiments). Around 20 % VWC there is a cavity resonance effect that is due solely to the confined Plexiglas box we must use in the laboratory to water . This effect should not be present under field conditions. This premise is being examined for the GCPEX field experiments.

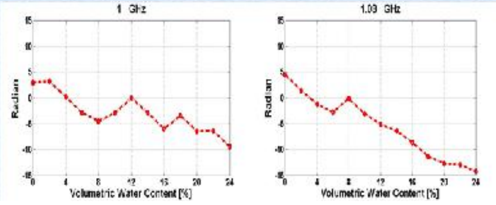


**Figure 5** – Phase shift curves as a function of volumetric water content (VWC) for sensor T1 using R10 in two selected frequency channels.

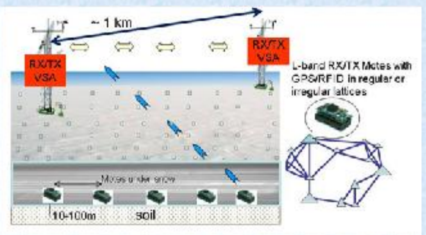
Figure 5 shows the phase shift curves for the same same laboratory conditions as in Fig. 4.

Note that the phase angles are un-wrapped in order to change absolute jumps ≥ π to their 2*π complements to obtain the monotonic trends as a function of VWC.

Currently, we are working on the verification of the algorithm to relates amplitude attenuation and phase shift to dielectric changes in order to estimate VWC from snowpacks in realistic field conditions without using empirical calibration from laboratory experiments such as the ones described here.

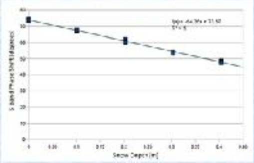
## 3. Next Generation Technology

**Scalability** - A 1"x2" module that incorporates a 3 axis accelerometer, and gyroscope, and a wireless system on a chip processor. The antenna is near edge of the PCB. A simple printed circuit board dipole antenna for this RF module has also been designed. This module contains components that cost less than $20. We have obtained quotes of a few thousand dollars to fabricate and assemble 100 of these boards. That leads to an estimated cost of less than $25/mote cost for 100 mote PCBs. The battery and case will add to the cost, bringing the total cost per module to less than $50 according to current estimates.



**Field-Scale RF Autonomous Facility** -The network comprehends two RX/TX towers equipped with VSAs and data storage and transmission capabilities, and one hundred snow motes to be distributed on the ground surface in wireless lattices with mote-to-mote distances ranging from 10 to 100m with higher density clusters embedded within a regular grid at 100 m resolution.

To preserve the quality and independence of the data, the motes will operate in the L-band for amplitude and phase measurements, and in S-Band for phase measurements and for mote-to-mote communications



**Combined L-S Functionality** – Preliminary tests using phase-shift measurements in S-band indicate show robust behavior to extend snow mode measurement capabilities to **include snow depth in addition to snow wetness.** This capability enables full characterization of snowpack physical and hydrological properties.

## 4. Conclusions and Further Work

- The measurement concept was demonstrated under laboratory conditions. Multi-frequency analysis in terms of amplitude and phase changes is needed to interpret the response from increasing water volumes. A physically-based algorithm for SWE retrieval is being tested to guarantee measurement reliability and reproducibility without calibration under various snow regimes.
- Field experiments are required to establish performance baseline and strategies for operations and maintenance of hive networks in extreme environments.
- Technical readiness exists to address challenges that stem from large-scale deployment in remote rugged environments: scalability (miniaturization, power management, and long-term performance), sensor network protocol design (network management, in-network computation and routing), and generalization of observing algorithms

**References**

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