Project Final Report

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Project Summary

The cryosphere is a major component of the hydrosphere and interacts significantly with the global climate system, the geosphere, and the biosphere. Measurement of the amount of water stored in the snow pack and forecasting the rate of melt are thus essential for managing water supply and flood control systems. Snow hydrologists are confronted with the dual problems of estimating both the quantity of water held by seasonal snow packs and time of snow melt. Monitoring these snow parameters is essential for one of the objectives of the Earth Science Enterprise—understanding of the global hydrologic cycle. Measuring spatially distributed snow properties, such as snow water equivalence (SWE) and wetness, from space is a key component for improvement of our understanding of coupled atmosphere-surface processes.

Through the GWEC project, we have significantly advanced our understandings and improved modeling capabilities of the microwave signatures in response to snow and under-ground properties. The major accomplishments include:

- We have newly developed the improved microwave models that can be used to simulate backscattering and emission signals for snow covered terrain with validation in comparison of the ground experimental data. The improvements include 1) the multi-scattering modeling capability for snow pack volume scattering and emission, 2) the Advanced Integral Equation Model development for better description of under-ground backscattering and emission signals.
- We have established two radar backscattering coefficient databases, one for wet snow and the other for dry snow, for the wide ranges of snow properties (density, depth, grain size, and wetness) and under-ground soil roughness and dielectric properties (soil moisture and frozen/thaw conditions). Each database includes the sensor parameters of the multi-frequency (L, C, X, and Ku Bands) and multi-polarizations

(VV, HH, and VH). Using CLPX experiment radar data and through the lookup table approach, snow properties can be more accurately interpreted by the investigators.

- We have carried out the concept studies to support a satellite mission CLPP for monitoring snow water equivalence and snow wetness from space through the numerical simulations of the radar backscattering response to snow properties at the frequency range of C-band to Ku-band. Through the simulated data, we have developed the concept algorithms include: 1) inversion model development for snow water equivalence retrieval, and 2) inversion model development for snow wetness retrieval.

During the project, we have actively participated CLPX experiment in Colorado in Feb., 2002 and played an important role in AIRSAR acquisition planning, conducting field experiments, and AIRSAR data analyses. Following sections give the extended summaries of our achievements during this project. The detailed documents can be found in the selected hard copies of the manuscripts.

Microwave modeling improvements

Theoretical modeling efforts have significantly improved in recent years. The commonly used models -- Small Perturbation Model, Physical Optical Model and Geometric Optical Model -- have been recognized with the limitations since each model can be only applied to certain roughness conditions. In physical model developments, the Integral Equation Model (IEM) has demonstrated a much wider application range for surface roughness conditions (Fung, 1994). Recently, Chen et al. (2003) extended the original IEM and developed the Advanced Integral Equation Model (AIEM). The improvements were mainly done by removing some weak assumptions in the original IEM model development. They include

1. the complementary field coefficients were re-derived to keep the absolute phase terms in the surface Green's function and its gradient, leading to more complete expressions of the multiple scattering (Chen et al., 2000) and single scattering terms (Chen et al., 2003).

2. In calculation of the bistatic scattering coefficient of randomly dielectric rough surfaces, the Fresnel reflection coefficients are usually assumed to be either at the incident angle or the specular angle in the low- and high-frequency range respectively. However, these two

considerations are only applicable to their respective regions of validity. A physical-based transition function that naturally connects these two approximations was proposed by Wu et al. (2001) and was included in the new version of the AIEM model (Chen et al., 2003).

The comparisons of AIEM with a three-dimensional Monte Carlo model [19,20] simulated data (Chen et al., 2003) and the experiment data [18] showed a significant improvement in accuracy over the original IEM model, especially for the very rough surface conditions or high frequencies. It allows more accurate calculation of surface emission signals over a wide range of surface dielectric, roughness, and sensor frequencies.

We have evaluated the microwave snow pack volume scattering and emission models. During the past studies, we commonly use the sphere to approximate the ice particles in modeling microwave signals of snow pack. We found that this approximation can describe both backscattering of co-polarizations in active and emission in passive signals reasonable well. However, it is poorly predicts of the cross-polarization signal in radar. Through the evaluations of the effects of the different particle shapes on the backscattering coefficients of the cross-polarization and compared with the experiments data (CLPX-02) and the several semi-empirical models, we found that the relationships between the co-polarized and cross-polarized signals are well controlled by the optical thickness and can be described as:

- For dry snow, cross-pol = co-pol/3 (optically thin);
- For wet snow, cross-pol = a*(co-pol)^b (optically thick);

Above results provide a physical basis to decompose the scattering contributions of the surface and volume scattering terms and make the inversion algorithm to be much more simplified.

In order to evaluate the feasibility of using multi-polarization Ku-band measurements to estimate SWE, we have updated our first-order dense medium polarimetric backscattering radiative transfer model (Shi and Dozier, 2000) to the multi-scattering model using the Matrix Doubling technique (Fung, 1994). In this way, the cross polarization signals of snow covered terrain can be simulated. We have incorporated these recent new developments in each scattering and emission component of our microwave radiative transfer models, improving our capability to simulate backscattering and emission signatures for snow-covered terrain. This radiative transfer model uses the Matrix Doubling method that includes all multi-scattering components so that the backscattering and emission signals can be accurately simulated. The major characteristics of this model are:

1. Dense Media Model for volume scattering and emission components of microwave interactions within snowpack. The near-field effect is evaluated by modifying snow extinction properties (Tsang et al., 1992). It allows use of different shapes of scatters with Raleigh scattering phase functions for sphere, Raleigh scattering phase function for spheroid, and Mie scattering phase function for sphere;
2. Advanced Integral Equation Model (AIEM) for surface scattering and emission components at air-snow and snow-ground interfaces (Wu. Te al., 2001 and Chen et al., 2003);
3. Bistatic AIEM model (Chen et al., 2003) is used for the boundary conditions for Radiative Transfer Equations so that the volume-surface interaction scattering terms can be simulated.

Using field snow and underlying-ground validation measurements, Jiang et al., (2004) showed good agreement between this model and microwave measurements. This model will be used as the basis for our development of a quantitative microwave-based retrieval algorithm of snow pack properties.

Microwave signature database simulations

We will establish a database covering the most common snow properties (density, depth, grain size, temperature, and wetness) and underlying soil surface properties (roughness and dielectric constant). Applying the microwave radiative transfer model, we will generate simulated backscatter and emissivity signatures for these canonical snowpacks for several possible sensor configurations. The simulated data will be used to carry out sensitivity and characterization analyses, including an assessment of frequency and polarization dependence of each of the model's scattering and emission components (surface scattering/emission, snow volume, and their interactions), as well as the quantitative inversion algorithm development and testing. Currently, we have finished the simulated database for C-band and two Ku-bands at 30° incidence. Through the proposed investigation, we will complete the simulated database of a range of frequencies from C-band to Ku-band for the optimal sensor parameter selection and a range of incidence angle to a take into account the terrain surface orientations that result in a different incidences.

The success of many applications, especially for hydrological modeling and predictions, depend heavily on measurements from space. However, the currently planned suite of sensors on the EOS platforms do not provide the capability to monitor these important snow properties, and requirements for future SARs were not driven by these applications.

Concept Development for Supporting Snow Satellite Mission

As part of NASA's pre-mission and feasibility studies, NASA's Cold Land Processes Working Group has identified a combined active/passive microwave sensor configuration as a viable configuration for a potential satellite mission designed specifically to measure snow properties (SWE and wetness). This system incorporates a dual-frequency (possible range C- to Ku-bands) and dual-polarization (VV and VH) Synthetic Aperture Radar (SAR) system to provide backscatter measurements at 100 meter spatial resolution, together with a dual-frequency (Ku- and Ka-band) and dual-polarization (V and H) radiometer system that would provide brightness temperature at 4-7 km spatial resolution. Both instruments utilize the same incidence angle with a possible range of 20° to 35°. The selection of this configuration was based on 1) the science requirements for spatial and temporal resolution, 2) low risk and low cost instrument considerations, and 3) snow parameters (snow water equivalence and snow wetness) retrieval capabilities. The correspondence of snow parameters retrieval capability to instrument design was based on known sensitivities of radar backscattering and brightness temperature to snow properties. The development of robust quantitative retrieval algorithms is a critical component to development of any snow satellite mission.

Through GWEC project, we carried out the concept study to identify the sensor parameters suitable for microwave remote sensing-based retrieval of snow pack properties with possible range C- to Ku-bands. We have accomplished the part of it evaluation and developed the corresponding quantitative retrieval algorithms under certain frequency considerations. They include 1) a dual-frequency (1.25 GHz and 13.4 GHz) and dual polarization (VV and VH) technique for retrieval SWE (Shi, 2003), 2) a dual-frequency (13.4 GHz and 17 GHz) and dual polarization (VV and VH) technique for retrieval SWE (Shi, 2004), and 3) a dual-frequency (5.3 GHz and 13.4 GHz) and dual polarization (VV and VH) technique for retrieval snow wetness

(Shi and Jiang, 2004). The details for estimation of SWE under the first sensor configuration (1.25 GHz and 13.4 GHz) can be found in (Shi et al., 2003) and has been reported in the previous progress report. Therefore, this study will not be reported here. In comparisons of the accuracy and complexity of the algorithms between 1) and 2), the second sensor configuration with two Ku-band (13.4 GHz and 17 GHz) provides a much simple and a better accuracy than that the first sensor configuration (1.25 GHz and 13.4 GHz).

Selection of the optimal frequency

The complexity of the relationship between snow properties and the radar backscattering signal render an empirical approach to the measurement of SWE impossible. The correlation between SWE and backscattering for a given incidence angle and polarization can be positive, negative, or nonexistent. Our sensitivity analyses indicated that the C-band SAR measurements will be affected mainly by the ground surface properties. The parts of the signal that comes from a typical snow pack at C-band are about 30 % and 15 % for HH and VV polarization, respectively. The C-band measurements are expected mainly sensitive to under-ground surface condition. At X-band it about 60% of the signal comes from the typical snow pack. Thus we expect that the measurement is much more sensitive to snow pack and that the requirement for estimation of the ground backscattering component is less severe. However, we do expect that the signal from new snow pack (characterized as small grain size) is quite weak and the estimation of snow water equivalence might have the similar problems.

It is clear that two critical capabilities of the radar instrument are required for monitoring snow water equivalence globally. First, the radar signal can penetrate the natural snow packs so that the snow depth information can be obtained from the measurements. Secondly, the radar signal from snow pack itself has to be large enough to provide the first-order information for snow pack itself. In order to select the optimal sensor parameters, we have carried out the numerical simulations on the frequency dependence of snow extinction properties. Figure 1 shows the frequency dependence of penetration depth in (A) and the volume scattering albedo in (B). The solid line was generated by using a new snow pack parameters (low density and small grain size). It represents a weak snow pack signal or a low-limit case. The dotted line was from the old snow pack parameters (high density and large grain size). It represents a strong snow pack signal or an up-limit case. The penetration depths and albedo are about 0.5 (old snow) to 10 (new snow) meters and 0.1 (new snow) to 0.7 (old snow) at Ku-band (13-19 GHz), respectively. Therefore, we expect that Ku-band instrument has capability to penetrate the most of natural dry snow cover globally and provide much more sensitive to snow pack itself than those by X-band and C-band. However, the measurements will run into the penetration problem at the frequency higher than 20 GHz. It indicates that the optimal sensor frequency for estimation of SWE is Ku-band.

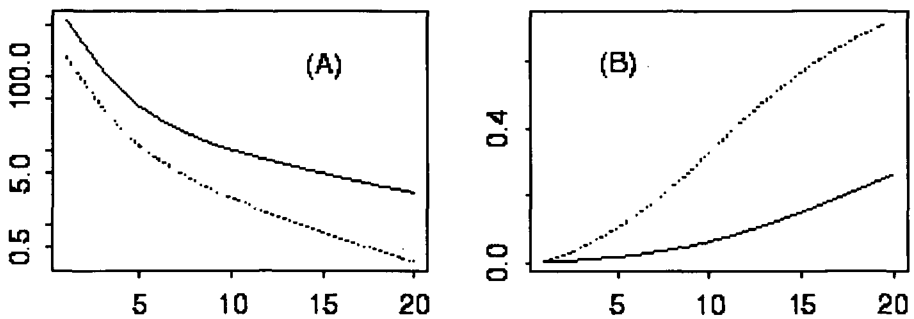

Figure 1. Frequency (x-axis in GHz) dependence of snow extinction properties of the penetration depth in m (A) and the volume scattering albedo in (B).

Concept development of a physically-based algorithm to estimate snow water equivalence from dual-frequency and dual-polarization radar measurements

As demonstrated in (Shi and Dozier, 2000b), the complex relationships between radar backscattering and SWE make it implausible to characterize the parameters from the limited field experiment measurements for estimating snow depth or water equivalence from SAR measurement. A general backscattering model can be written as a four component model with the scattering components – the surface scattering from the air-snow interface, the direct volume scattering from snowpack, the interaction term between snow and underground, and the surface scattering from snow-underground interface:

$$\sigma_{pq}^{t} = \sigma_{pq}^{a} + \sigma_{pq}^{v} + \sigma_{pq}^{gv} + T_{pq}^{2} \cdot \exp[-2\kappa_e d/\mu_r] \cdot \sigma_{pq}^{g} \qquad (1)$$

In considerations of each backscattering component from dry snow cover Eq (1) for the SWE algorithm development, the backscattering signals from the air-snow interface are generally considered as the "noise" since they are typically very small in comparison with the other scattering contributions and have no information on SWE. Its effect on retrieval snow properties can be reduced by using the signal generated by the typical and snow density and roughness parameters (Shi & Dozier, 2000b). The backscattering signals generated by the snow-ground interface do have the SWE information. However, these signals are difficult to be used to estimate snow water equivalence since they are affected by both snow and ground properties and their complexity in its formula description (involving double integration). On the other hand, both direct volume and ground surface backscattering components provide the direct information on snow water equivalence and the other snow properties. The former can be described as a function of the optical thickness (τ – a product of the snow extinction coefficient and snow depth) and the volume scattering albedo (ω – a function of the snow particle size, size variation, stickiness, and temperature). The later provides the snow pack attenuation properties through the optical thickness if the magnitudes the backscattering signals at the snow-ground interface can be estimated. These two scattering components are the major scattering sources from the dry snow cover and commonly represented as a "cloud model" (Ulaby et al., 1986). However, the ω and τ are positively correlated to the direct volume backscattering signals. The τ is negatively correlated to the underground surface backscattering signals. In other words, the effects of SWE in these two scattering components are in an opposite way and make the difficulty in characterizing the effects of SWE. It is clear that SWE can be muck accurately estimated if we could separate these two scattering signals. In this investigation, we developed a new concept and the corresponding techniques for the quantitative SWE retrieval under the CLP sensor configurations. They involve 3 tasks:

1. How well we can decompose the direct volume and surface backscattering signals from the radar measurements separately?
2. How to use the direct volume backscattering signals to estimate SWE?
3. How to use the surface backscattering signals to estimate SWE?

We have carried out the analyses and the initial concept study using the simulated data at the Ku-bands (13.4 GHz and 17 GHz) and 30° incidence. The results are very encouraged. **Fig 1** shows the relationships between the depolarization factor - $\sigma^t_{vh} / \sigma^t_{VV}$ (as x-axis) and the direct volume scattering contribution - $\sigma^v_{VV}/\sigma^t_{VV}$ (top) and the under ground surface scattering contribution - $\sigma^s_{VV}/\sigma^t_{VV}$ (bottom). The left and right columns are for 13.4 and 17 GHz, respectively. They indicate that the depolarization factor is proportional to the volume scattering and inversely relates the surface scattering contribution. It is because the backscattering signals of the cross-polarization from the surface scattering component is, generally, very weak. The dominant scattering source is the volume scattering. Based on these relationships, we have developed a technique to estimate the direct volume and surface scattering components, separately. For this dataset, the RMSE for estimated σ_{VV}^{V} and σ_{VV}^{S} at 17 GHz are 0.21 and 0.18 dB, respectively. They indicate the scattering contributions of the volume and surface components can be well estimated.

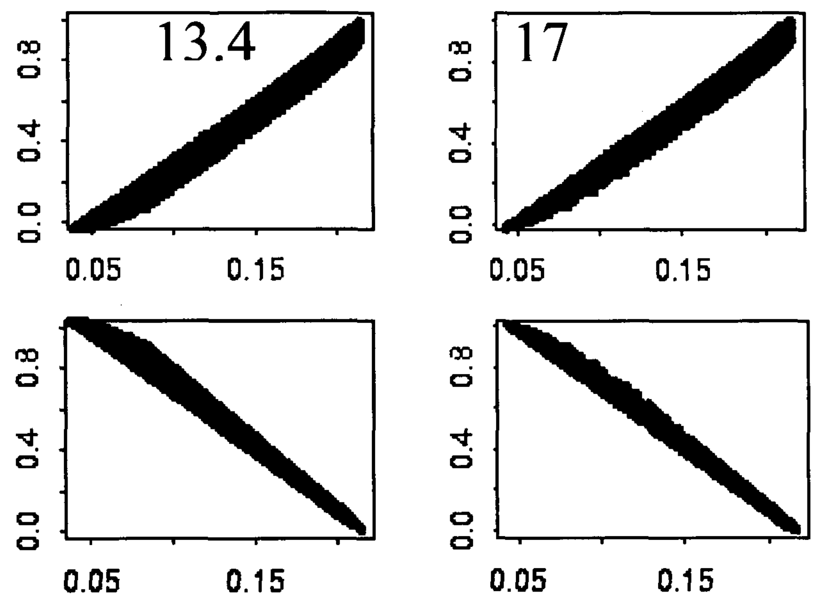

Fig. 1 the relationship between the depolarization factor (as x-axis) and the direct volume scattering contribution (top) and the underground surface scattering contribution (bottom). The left and right columns are for 13.4 and 17 GHz, respectively.

As an indication of the first-order direct volume backscattering model (Shi 2004), the ratio of the direct volume backscattering signals from two frequencies can be written as a function of snow optical thickness at the corresponding frequencies. In this way, the effects of snow volume scattering albedo can be minimized so that the optical thickness of snow pack can be estimated. **Fig 2** (left) shows the relationships between the volume scattering ratio from two frequency 13.4 and 17 GHz (x-axis) and the optical thickness difference $\tau(17) - \tau(13.4)$ in corresponding frequencies (y-axis). As we can see, they are directly correlated and we can use the estimated volume scattering ratio and this relationship to infer the snow optical thickness difference. **Fig 2** (right) shows the high correlation between the snow optical thickness difference at 17 and 13.4 GHz (x-axis) and that at 17 GHz (y-axis). This is because all snow extinction properties including albedo, extinction, scattering, absorption coefficients are all highly correlated between these parameters at different frequencies. Therefore, we can estimate snow optical thickness at each frequency from the estimated optical thickness difference.

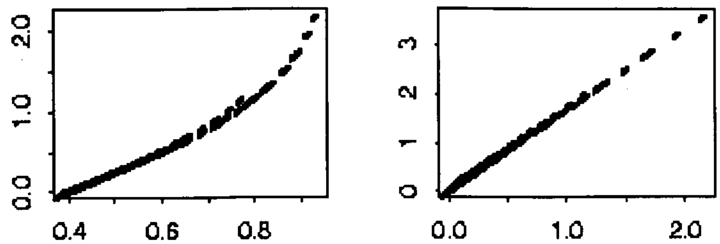

Fig. 2 The relationships between the volume scattering ratio from two frequency 13.4 and 17 GHz (x-axis) and the optical thickness difference in corresponding frequencies (y-axis) at left and the relationship between the snow optical thickness difference at 17 and 13.4 GHz (x-axis) and that at 17 GHz (y-axis) at right.

However, the relationship between the optical thickness and SWE is affected not only by SWE but also by the other snow extinction properties that resulted from the different snow grain size, density, and temperature. To estimate SWE from the optical thickness information requires knowing, at least, one of the extinction properties. With the estimated τ, then, the volume scattering albedo ω at each frequency can be estimated using the direct volume scattering model. We have developed a technique to estimate SWE by using the optical thickness and the volume scattering albedo from two frequencies (Shi 2004). This technique uses 1) the absorption part of the optical thickness to minimize the effects of snow particle sizes, 2) the snow density effects is linearly related to absorption coefficient, and 3) the ratio $\kappa_a(13.4)/\kappa_a(17)$ depends mainly on snow temperature. It allows separating SWE from the optical thickness τ.

This concept for using direct volume backscattering signals from two different frequencies to estimate SWE holds much potential since each step (decomposing of scattering components, using the volume scattering ratio to estimate the optical thickness, and estimating SWE from the optical thickness) are all strongly supported by physical principles. This is also much simpler than existing techniques since it does not require background measurements of underlying ground surface before snowfall. The details of this concept study can be found in (Shi, 2004).

Concept development of a physically-based algorithm to estimate snow wetness with dual-frequency radar measurements

Radar backscattering from wet snow cover is mainly from the scattering sources: 1) volume scattering from snowpack and 2) surface scattering at air-snow interface. The actual relationships between radar measurements and snow wetness depend on which scattering component is the dominant scattering source. If the volume scattering is dominant scattering source, the radar measurements will show a negative correlation to snow wetness. However, the radar measurements will have a positive correlation to snow wetness if the surface scattering is dominant scattering source. This complexity of the relationship between the backscattering and snow wetness makes it unrealistic to develop an empirical relation between the radar signal and field measurements. It is clear that the separation of the surface and volume backscattering signals in radar measurements from wet snow cover is a key issue in developing a reliable snow wetness retrieval algorithm.

Using our simulated radar backscattering database for the dual frequency C-band 5.3 GHz and Ku-band 13.4 GHz and the dual-polarization (VV and HV) at 30° incidence, we have carried out a concept study and developed a snow wetness retrieval algorithm (Shi and Jiang 2004). The newly developed algorithm mainly involved two steps: 1) decomposing the surface and volume scattering signals using depolarization factor, and 2) using each scattering component (surface or volume backscattering signals) to estimate snow wetness.

In analyses of our simulated database for C-band and Ku-band at 30° incidence, it is found that the depolarization factor is proportional to the direct volume scattering contribution and inversely relates the surface scattering contribution in total backscattering signals in both C-band and Ku-band. Similar to the dry snow cases, it is because the cross polarization signals are mainly generated by the volume scattering term. The cross polarization signals from surface scattering are, generally, very small. With these relations, each scattering contribution in the total backscattering signals can be estimated. The estimation accuracies (in RMSE) for the surface scattering components from this dataset were 0.27 dB and 0.35 dB for C-band and Ku-band, respectively.

The algorithm development for using surface scattering signals is based on the relationship of the reflectivity and the surface roughness parameters at two frequencies. We, first, used the relation of the reflectivity at these two frequencies to estimate the surface roughness ratio $Sr_{vv}(C)/Sr_{vv}(Ku)$. Then this estimation was used to separate the surface roughness into three regions. Finally, the algorithms for each roughness region were applied to estimate the reflectivity at C-band which can be further used to estimate snow wetness.

The algorithm development for using the volume scattering signals is based on that the ratio of the volume scattering coefficients from two frequencies in Rayleigh scattering region is a constant. We demonstrated that snow wetness can be derived from the first-order radiative transfer model using two frequency volume backscattering signals at VV polarization. details of this concept study can be found in (Shi and Jiang, 2004).

Publication List

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