Radar Remote Sensing of SWE Combining Dual Ku, X, C and L Band.

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ABSTRACT

With the advent of current and future multifrequency radar systems such as Sentinel-1 (C band), NISAR (L band) and TSMM (Dual Ku band), we leverage the frequency response of snow to these multiple frequencies to study various properties of snow e.g., SWE, snow wetness. In this work,

1. In the volume scattering approach to retrieve SWE for snow with small to moderate depths, we use
   i. X band and High Ku band in SnowGlobe, and
   ii. The dual Ku band for TSMM.
2. We use C band to retrieve deep snow depth SWE using co- and cross-pol volume scattering of snow.
3. We use L band for two purposes,
   i. To find the rough soil surface rms height and soil moisture below the snowpack.
   ii. To find the percentage of snow wetness in the snowpack by leveraging the attenuation of rough surface scattering due to the snow wetness at L band.
4. We study single pass interferometry at dual Ku band to enhance the dual Ku band SWE retrieval by adding the additional phase information.
5. By combining a data-fusion time series of L and Ku band, we show the retrieval of SWE and snow wetness.

Dual Ku Band SWE Retrieval: 2 Measurables in 2 Parameters

- The SnowGlobe algorithm is based on the parameterized bi-continuous DMRT equations of a one-layer model for co-polarized X band and Ku band. It has been successfully applied to retrieve SWE at X and high Ku band with minimal prior information and without the need of any priors on grain size nor scattering albedo.
- We adapt the approach of parametrization and algebraic inversion algorithm to the TSMM mission for dual Ku band of 13.6 GHz and 17.2 GHz. A preliminary dual Ku band parameterized model at co-pol is given below-

$$\sigma_{VV}^{13} = -1.6 + 1\left(0.75\cos\theta_t\,\omega_{13}\left[1-\exp\left(\frac{-SWE}{4683(1-\omega_{13})\cos\theta_t}\right)\right]\right)$$

$$\sigma_{VV}^{17} = 0.05 + 1.12\left(0.75\cos\theta_t\left(\frac{\omega_{13}}{0.32\omega_{13}-0.69}\right)\left[1-\exp\left(-\frac{2}{\cos\theta_t}\left(1.84\left(\frac{SWE}{4683(1-\omega_{13})}\right)^{0.97}\right)\right)\right]\right)$$

- Figure 1 show that this parameterized dual Ku algorithm is validated against one year of NoSREx tower series data.

Future-

- Improve the algorithm by including cross-polarization.
- Including cross polarization, we will have a total of 4 measurements: co-pol and cross pol of low Ku band and high Ku band.

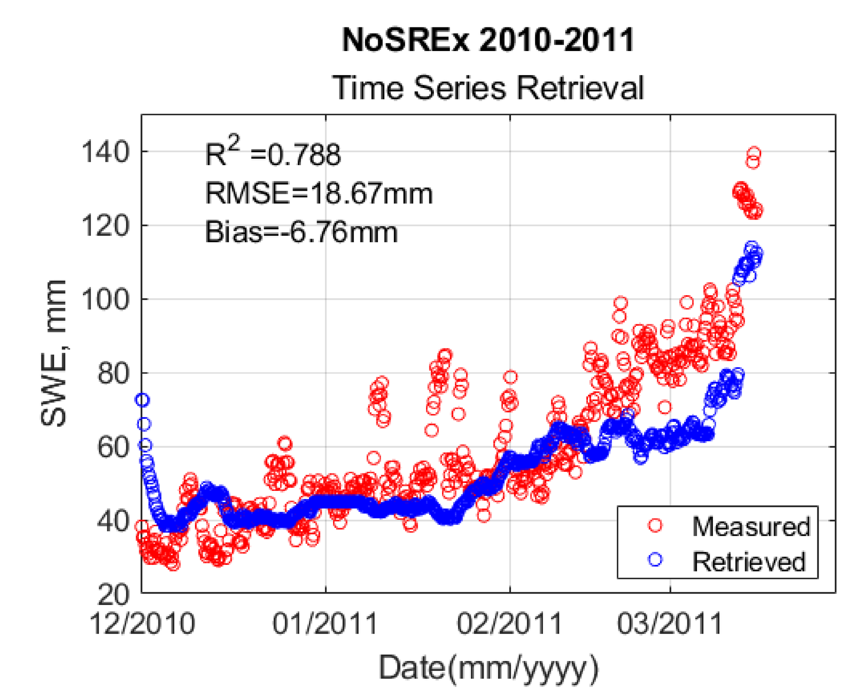

Figure 1: *Dual Ku band retrieval of NoSREx time series data.*

- Figure 2: We will use a two-layer model of snow: upper layer and lower layer to have a total of 4 parameters: scattering albedo of upper layer, SWE of upper layer, scattering albedo of lower layer and SWE of lower layer.

Figure 2: *Two-layer model for SWE retrieval. Layer 1 and layer 2 consists of individual parameters of SWE, ω and density.*

- We will develop the algebraic inversion of 4 measurements and 4 parameters so that prior information are reduced to a minimum.

L Band: Retrieving Roughness and Snow Wetness

Retrieving Roughness rms height and soil moistures below the snow

- To enhance the volume scattering retrieval algorithm, the roughness radar scattering needs be subtracted.
- We perform NMM3D full wave simulations of rough surface scattering at L band.
- Figure 3: We use a time series retrieval algorithm like the one proposed for the (SMAP) mission to retrieve rms height and soil moisture.

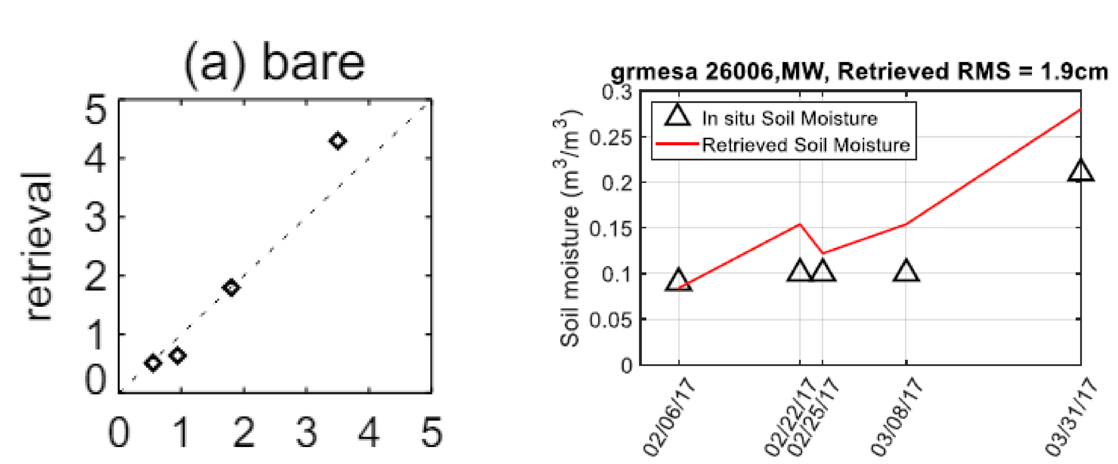

Figure 3: *Rms height and soil moisture retrieval based on SMAP retrieval algorithm.*

L Band: Retrieving Roughness and Snow Wetness

Retrieving Snow Wetness

- When the snow is wet, the L band backscattering from the rough soil surface will be attenuated due to the wetness.
- The absorption due to wet snow at L-band is only small to moderate so that rough surface scattering is significant enough to be still detected at L-band.
- Figure 4: We use full wave simulations to calculate the effective permittivity (real and imaginary parts) of tri-continuous media.

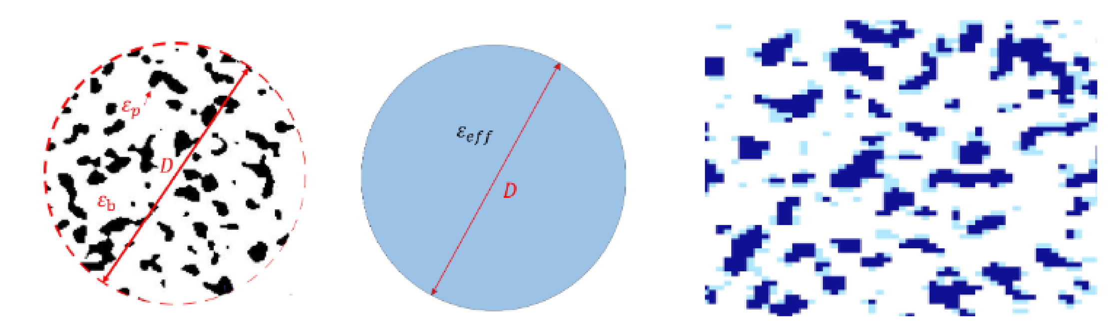

Figure 4: *Full wave simulations to find ε_{eff} (left and middle) of tri-continuous media (right)*

- The backscattering coefficient at L-band is given by-

$\sigma_0 = \sigma^{rs} e^{-2\kappa_a d \sec\theta_t}$,

- As the wetness in snow increases, the absorption coefficient, $\kappa_a = 2k_0\left|\mathrm{Im}\left\{\sqrt{\varepsilon_{eff}}\right\}\right|$ increases. As κ_a increases, the exponential term decreases, reducing the overall observed signal σ_0 at L Band.

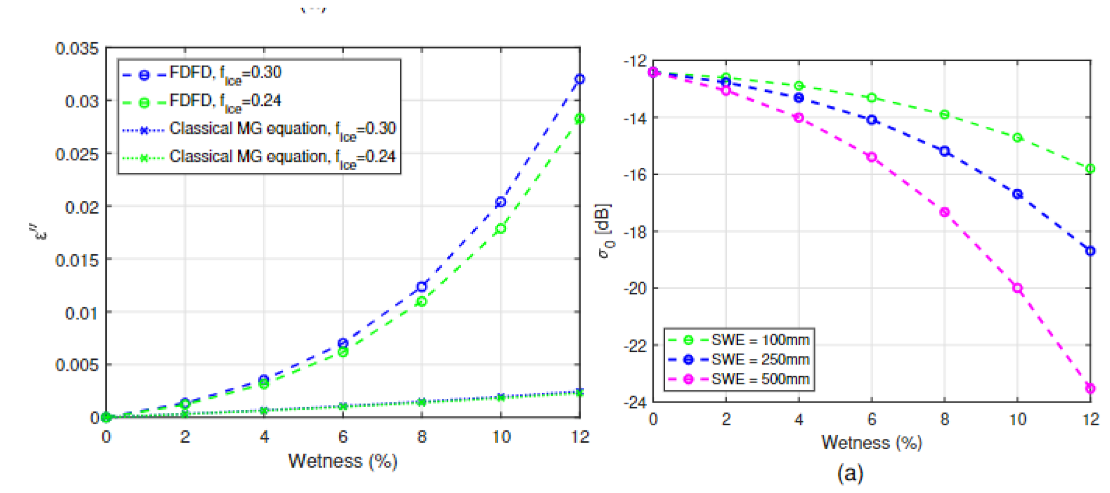

Figure 5: *Absorption of wet snow (left) and backscatter verses snow wetness for different SWE (right).*

- Figure 5: are simulation results. We estimate that for SWE less than 500 mm, snow wetness can be estimated to 12% using L band backscattering.

Dual Ku Band Single Pass Interferometry

- The purpose is the use of interferometric phase for retrieval of SWE.
- We use first order scattering of the bi-continuous DMRT model to calculate the interferometric phase at Ku band.
- In the calculation of interferometric phase, we include rough surface scattering in addition to volume scattering. The first order scattering with combined volume and surface scattering using bi-continuous media is given by-
- $$\gamma = e^{jk\phi_0} e^{-j\beta d}\frac{\int_0^d P e^{\left(\frac{2\kappa_e}{\cos\theta_t}(z-d)\right)} e^{j\beta z} dz + \sigma^{surf} e^{-\frac{2\kappa_e}{\cos\theta_t}d}}{\int_0^d P e^{\left(\frac{2\kappa_e}{\cos\theta_t}(z-d)\right)} dz + \sigma^{surf} e^{-\frac{2\kappa_e}{\cos\theta_t}d}}$$

- Figure 6: Results of interferometric phase combining volume scattering and surface scattering, as a function of snow depth.
- In future, we will use full wave simulations of layered snowpacks to calculate interferometric phase.

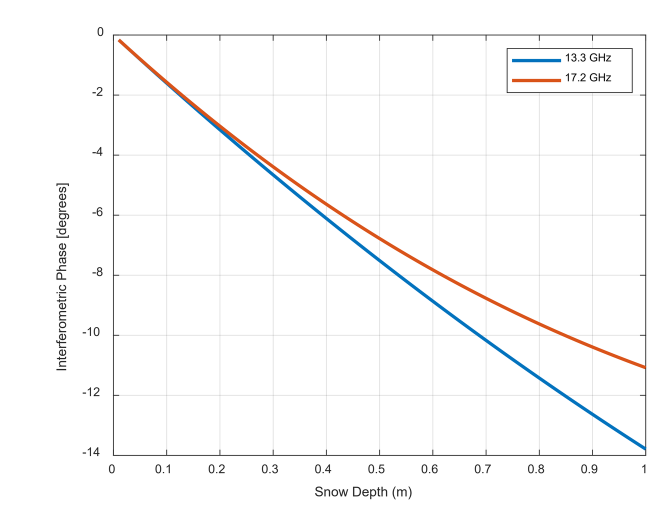

Figure 6: *Interferometric phase ($\Delta\phi$) vs depth for combined volume and surface scattering.*

Data fusion of Time Series of Dual Ku Band and L Band for Retrieval of Snow Properties

- One example is to use dual Ku band time series in conjunction with L band time series to infer both SWE and snow wetness.
- By using dual Ku band SWE algorithm, SWE is determined. When wetness occurs, L band backscatter depends on both snow wetness and SWE. Since SWE has been determined previously from Ku band, thus the snow wetness can be inferred.

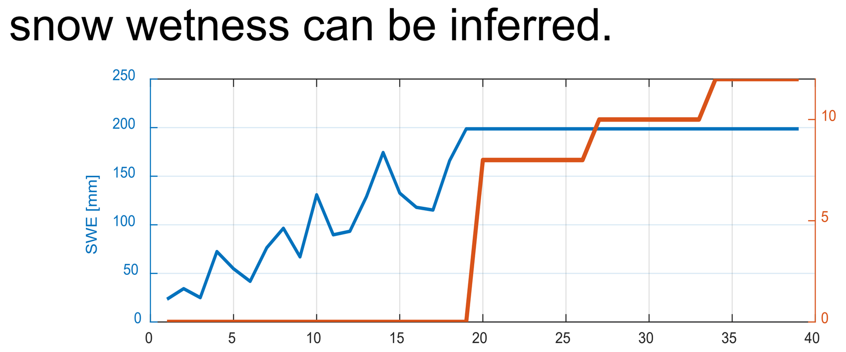

Figure 7: *Model simulation at dual Ku and L band using hypothetical time series wet snow. Simulation contains both volume and surface scattering.*

- Figure 7 are results of data fusion of dual Ku band and L band. Dual Ku band will be used to retrieve dry SWE and during wet snow, Ku band will be used to detect the wet snow onset, and the L band will be used to retrieve snow wetness.

C Band Analysis of Deep Snow, Roughness and Snow Wetness

- For detailed C band analysis, please find the poster by **Firoz Borah** titled "**C Band Sentinel 1 Remote Sensing Of SWE with Roughness Effects And Snow Wetness.**" in the appropriate poster board.