A Prototype VHF/UHF Tower Radar for Subsurface Sensing: System Description and Data Inversion Results

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Abstract - To nondestructively obtain the characteristics of a multilayered rough ground, a multifrequency polarimetric radar backscattering approach can be used. We have developed a tower-based prototype for the Microwave Observatory of Subcanopy and Subsurface (MOSS) mission concept. The tower radar makes backscattering measurements at VHF, UHF, and L-band frequencies. To focus the beam at various incidence angles within the beamwidth of the antenna, the tower is moved vertically and measurements made at each position. The signals are coherently summed to achieve focusing and image formation above and below the surface. This requires an estimate of wave velocity profiles throughout the imaged region. Traditionally, radar images are formed with the assumption that waves travel in free space. Here, however, the inhomogeneous profile needs to be calculated and used in image formation in the subsurface, hence providing a physically based approach to radar processing. To solve the inverse scattering problem for subsurface velocity profile simultaneously with radar focusing, we introduce a new method using two nested iterations. The inner loop is an inverse scattering algorithm that produces subsurface wave velocity for the layered medium given an estimate of the focused radar backscattering data. The outer loop uses the results of the velocity profile inversion and forms an updated backscattering coefficient image. The process continues until convergence is achieved. Numerical results will be shown using actual radar data acquired with the MOSS tower radar system and compared with in-situ measurements. Implications of this class of measurements for Earth and outer planetary exploration will be discussed.

I. INTRODUCTION

Knowledge of subsurface characteristics such as permittivity variations and layering structure could provide a breakthrough in many terrestrial and planetary science disciplines. For Earth science, knowledge of subsurface and subcanopy soil moisture layers can enable the estimation of vertical flow in the soil column linking surface hydrologic processes with that in the subsurface. For planetary science, determining the existence of subsurface water and ice is regarded as one of the most critical information needs for the study of the origins of the solar system. The subsurface in general can be described as several near-parallel layers with rough interfaces. Each homogenous rough layer can be defined by its average thickness, permittivity, and rms interface roughness assuming a known surface spectral distribution. As the number and depth of layers increase, the number of measurements needed to invert for the layer unknowns also increases, and deeper penetration capability would be required.

To nondestructively obtain the characteristics of the rough layers, a multifrequency polarimetric radar backscattering approach can be used. We have developed a tower-based prototype for the Microwave Observatory of Subcanopy and Subsurface (MOSS) mission concept. The tower radar makes backscattering measurements at VHF, UHF, and L-band frequencies. The radar is a pulsed CW system, which uses the same wideband antenna to transmit and receive the signals at all three frequencies. To focus the beam at various incidence angles within the beamwidth of the antenna, the tower is moved vertically and measurements made at each position. The signals are coherently summed to achieve focusing and image formation above and below the surface. This requires an estimate of wave velocity profiles throughout the imaged region. Traditionally, radar images are formed with the assumption that waves travel in free space. Here, however, the inhomogeneous profile needs to be calculated and used in image formation in the subsurface, hence providing a physically based approach to radar processing.

To solve the inverse scattering problem for subsurface velocity profile simultaneously with radar focusing, we introduce a new method using two nested iterations. The inner loop is an inverse scattering algorithm that produces subsurface wave velocity for the layered medium given an estimate of the focused radar backscattering data. The outer loop uses the results of the velocity profile inversion and forms an updated backscattering coefficient image. The process continues until convergence is achieved. Numerical results will be shown using actual radar data acquired with the MOSS tower radar system in Arizona, and compared with in-situ measurements. Implications of this class of measurements for Earth and outer planetary exploration will be discussed.

The tower radar is a system prototype for the conceptual Microwave Observatory of Subcanopy and Subsurface (MOSS) mission. The MOSS mission is a synthetic-aperture radar (SAR) Earth-orbiting system that underwent conceptual and technology development as part of the NASA Earth-Sun System Science Technology Office Instrument Incubator Program (IIP) for global observations of soil moisture under substantial vegetation canopies and at depths of down to several meters [1].

It consists of a synthetic aperture radar (SAR) operating simultaneously at two low frequencies, one in the UHF and the other in the VHF range. The mission scenario for MOSS is achieved from a sun-synchronous orbit of 1313 Km altitude, with a swath width of 340-430Km, incidence angle ranges of 17-30 degrees, resolution of 1 Km, and a 7-10 day exact repeat consistent with the temporal scale of variations of the subcanopy and subsurface soil moisture. Complementary to proposed soil moisture missions at L-band, which aim at retrieving the top surface soil moisture for low- or no-vegetation areas at 3-day sampling intervals, this mission optimizes the system design for under-vegetation and deep soil moisture, in addition to simultaneous measurement of the soil moisture at the top few centimeters. The tower-mounted mobile radar system presented here has been developed to produce several prototype science data set for MOSS. The tower radar operates at the same UHF and VHF bands as MOSS, with the addition of an L-band capability to simulate other possible future L-band radars in space.

II. TOWER RADAR SYSTEM DESCRIPTION AND FIELD EXPERIMENTS

To demonstrate the deep and subcanopy soil moisture products from the proposed UHF and VHF SAR instrument, we have developed a tower-mounted radar (Fig. 1). This system is a pulsed polarimetric radar, and uses a log-periodic antenna (LPA) on both transmit and receive. A fast T/R switch is used to change the operating mode of the antenna between pulses. The radar operates at VHF, UHF, and L-band. The LPA is a dual-polarized wide-band antenna covering the frequency range of 80-1200 MHz, with return loss of no worse than 10dB across the band. The antenna beamwidth is several tens of degrees wide in all principal planes, requiring a beam focusing scheme to allow proper correspondence of the data to scattering target locations. Our beam-focusing method consists of synthesizing a large effective aperture by moving the antenna (mounted on the tower) vertically such that the focused beam resolution cell is about 10m on the ground. The size of the synthetic aperture and sample spacing scale with wavelength. The antenna boresight is adjustable. The look angle of the focused beam can be controlled during post-processing, and is ideally in the 17-40 degree range to simulate the spaceborne system design.

The radar records the backscatter measurements at intervals allowed by the digital data collection system, typically 2-3 hours for each complete set of many vertical positions. The measurements demonstrate the temporal correlation between deep and subcanopy soil moisture and multifrequency radar data, thereby demonstrating wavelength-dependent radar penetration effectiveness for moisture observations. The same radar equipment can be transported to various sites for observations of these dependencies in different ecosystems.

Conventional synthetic aperture focusing techniques usually make the assumption that focusing phase compensation can be made using the carrier frequency phase. This procedure will not work for the MOSS processor due to the large percent bandwidth used for data collection. To overcome this limitation, we perform the focusing completely in the frequency domain. The receive data is Fourier transformed and near-field focusing phase compensation is performed by multiplying each frequency band by a phase factor exp[-2πift], where f is the carrier frequency corresponding to the Fourier transform frequency bin, and t is the round trip travel time from the antenna phase center to the center of volume cell (voxcell) being imaged. The calculation of the round trip travel includes ray bending effects to account for propagation within the soil, when subsurface voxcells are being imaged. Therefore, a soil moisture estimation algorithm needs to be embedded in the radar processing algorithm. The last step of the processing involves incoherently combining frequency bins to estimate the polarimetric Muller matrices and estimating the scattering cross section. The spectral content of a returned signal from a point target is given as:

$$E(\omega) = \frac{G\ \exp[-2i\omega r/c]W(\omega)H(\omega)\sigma(\omega)}{r^2}$$

Here, G is the two-way complex gain, W(ω) is the transmit pulse spectrum, H(ω) is the system frequency response, and σ(ω) is the (potentially frequency dependent) radar cross-section. For nominal field operation, it is necessary to characterize the parameters *G*, W(ω), and H(ω) as a function of time, and for each tower / antenna position. The three steps to obtain these terms in full are the internal calibration loop; the “passive,” or corner reflector calibration; and the “active,” or transponder calibration.

The internal calibration loop characterizes the entire system except for the antennas. It therefore gives W(ω), H(ω), and all of G excluding the complex antenna gain. Internal Calibration data are collected automatically at the beginning and end of every data take as detailed subsequently. The internal calibration drift can be monitored on-screen in real-time. To insure absolute amplitude calibration, 2.4m trihedral corner reflectors are used, whose theoretical scattering cross section is known. An active target, e.g., another antenna fed by the same signal generator as the radar, can be used for proper phase calibration as the radar antenna location is varied for aperture synthesis.

Since the transmit signal is switched to allow dual (T and R) operation of the antenna, the transmitted signal has a finite bandwidth determined by the switch transient characteristics. In our case, the effective bandwidth is 10-50 MHz, depending on the pulse width set at the beginning of each data collection.

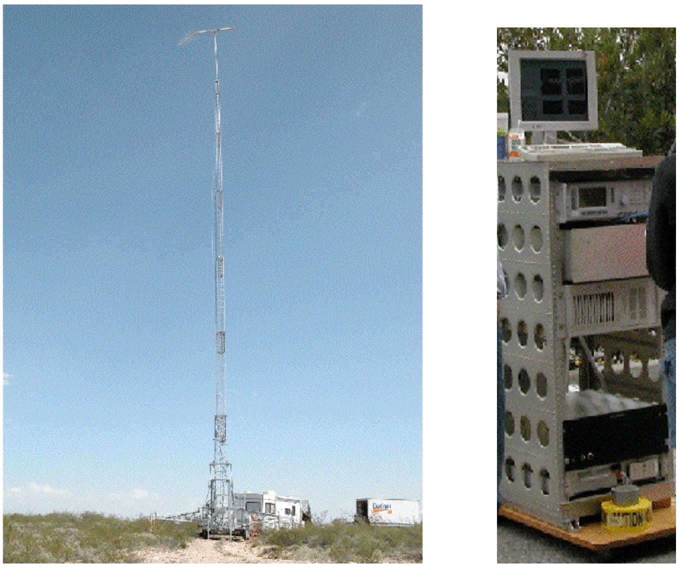

Figure 1. Left: Tower radar during field experiment in Arizona. At full extension, the tower is about 41m high. The antenna pointing can be adjusted full range as needed. The tower telescopes up and down, and can be towed horizontally for 2D coherent aperture synthesis. Right: tower radar RF/Digital equipment set.

III. PROCESING AND INVERSION RESULTS

The beam-focusing processor addresses a number of challenges for the tower radar. These include wide bandwidth coherent focusing, calibration, RFI removal, and soil moisture estimation. Note that due to the inherent penetration property of this radar, the processing and inversion algorithms have been integrated. Fig. 2 is a high-level flow chart of the interrelationship between the different data processing and estimation/inversion modules.

A new generation of soil moisture estimation algorithms has been developed and validated using the tower radar data. Here, the effects of soil penetration are being modeled and integrated into our previously developed forward and inverse scattering models for vegetation and soil characteristics. The soil is being modeled as a multilayered rough surface (Fig. 3) whose solution we have derived using an approximate and efficient analytical technique. Using a numerical solution, it is also possible to include various random scatterers such as rocks in the model.

The field locations included an arid/semiarid site in the Lucky Hills/Walnut Gulch watershed in Arizona and a dense forest site in Oregon. Deep soil moisture probes were installed at these sites. Fig. 4 shows an example of processed data taken in Arizona, while Fig.5 is the result of the soil moisture estimation for a two-layer soil model as derived in conjunction with data processing.

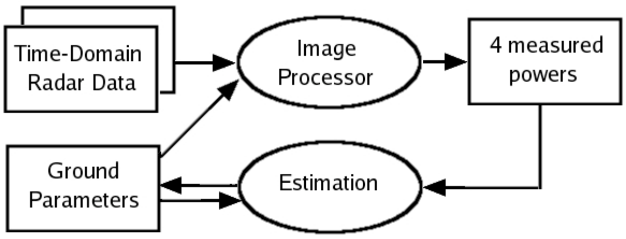

Figure 2. Tower radar processing and soil moisture estimation flow chart.

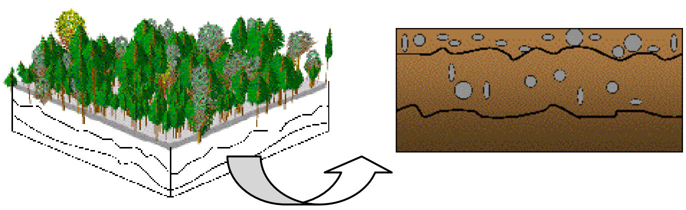

Figure 3. Layered medium model used in development of the new generation soil moisture estimation algorithms.

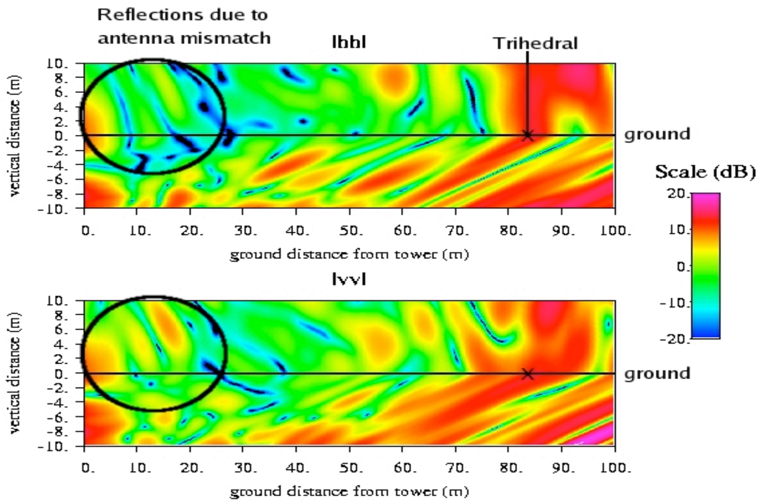

Figure 4.. Processed tower radar images at HH and VV polarizations, derived in conjunction with soil moisture estimation algorithms and the two-layer soil model.

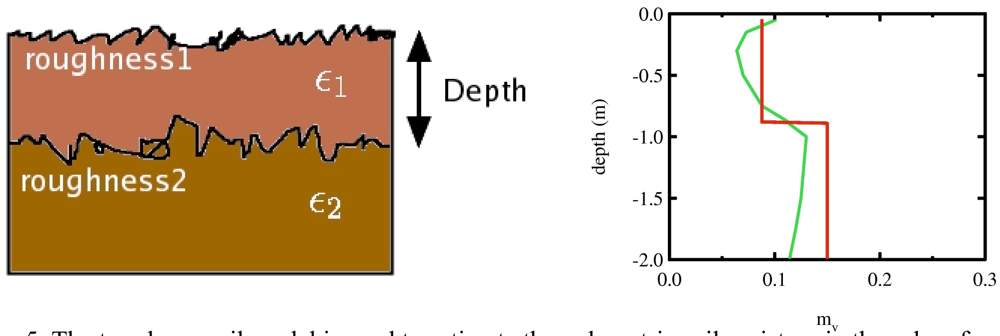

Figure 5. The two-layer soil model is used to estimate the volumetric soil moisture in the subsurface. This inversion algorithm is used iteratively with the coherent radar processor to converge on both the soil moisture results and the radar image. In the right-hand side figure, red is measured data, while green is estimated moisture.

IV. SUMMARY

To validate the MOSS mission measurement concept, a tower-based radar system was developed at VHF, UHF, and L-band frequencies. The radar is a pulsed continuous wave (CW) system, and uses a dual-polarized log-periodic antenna as both the transmitter and the receiver. Field experiments were carried out in both vegetated and nonvegetated surroundings, and soil moisture estimates were obtained from subsurface layers using radar processing and focusing algorithms combined with layered rough surface forward and scattering models. These experiments are the first of their kind in our knowledge, and have enabled us to retrieve multiple depth columns of soil moisture for the first time.

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