# DUAL-LOW-FREQUENCY RADAR FOR SOIL MOISTURE UNDER VEGETATION AND AT-DEPTH

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## ABSTRACT

To address a key science research topic for the global water and energy cycle, namely measuring soil moisture under substantial vegetation canopies and to useful depths, we have developed a concept for a synthetic aperture radar (SAR) system operating simultaneously at UHF and VHF frequencies. We are currently prototyping key technology items that enable this concept under the NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP). This presentation describes the technological challenges and innovations we are addressing to enable the implementation of this instrument and its integration into a future Earth-orbiting mission.

## INTRODUCTION

Simultaneous estimation of deep (order 0.1 to 1 m) and shallow (order 0.01 to 0.1 m) soil moisture at spatial resolutions on the order of 1 km could provide a major breakthrough for estimation of vertical flow in the soil column linking surface hydrologic processes with that in the subsurface. The key controlling variable of the hydrologic partitioning over terrestrial surfaces is soil moisture and its profile within the root-zone. Surface moisture and its variation are controlled by surface soil evaporation and runoff. Deeper moisture and its variation are strongly related to drainage and transpiration by deep-rooted grasses and trees. The difference between the two reservoirs characterizes the soil moisture gradient, which undergoes frequent reversals in response to wetting and drying periods. Measurements with repeat intervals corresponding to storm and interstorm intervals (~3-7 days) allow adequate sampling of the moisture gradient dynamics, which in turn allows the estimation of fluxes. This science data product distinguishes the measurement set being developed here from that of any other existing, planned, or proposed mission.

To penetrate vegetation, soil surface, and deep soil, lower-frequency microwaves are needed due to their ability to travel through significant vegetation canopies and through soil without losing needed information content. Although passive microwaves have been widely used in several past, present, and planned radiometer systems, they are best for retrieving surface soil moisture in no- or low-vegetation areas (e.g., [1] – many other references exist). In the presence of vegetation and to penetrate into deeper soil, a radar is needed to achieve the required resolutions at lower frequencies with reasonable antenna sizes.

## MISSION CONCEPT AND CHALLENGES

To address this key science research topic of measuring soil moisture under substantial vegetation canopies and to useful depths, we have developed a concept for a synthetic aperture radar (SAR) system operating simultaneously at UHF and VHF frequencies. We are currently prototyping key technology items that enable this concept under the NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP). This presentation provides an overview of the technological challenges and innovations that will enable the implementation of this instrument and its integration into a future Earth –orbiting mission. The instrument operates at the two low frequencies of 435 MHz (UHF, P-band) and 118 MHz (VHF) to enable vegetation and deep soil penetration. The future mission scenario is achieved from a sun-synchronous orbit of 1313 Km altitude, with a swath width of 430Km, small and shallow incidence angle range (17-30 degrees), resolution of 1 Km, and a 7-day exact repeat consistent with the temporal scale of variations of the subcanopy and subsurface soil moisture. The principal hardware technology needed to realize such spaceborne mission is a large and lightweight antenna with dimensions of 30m by 11m at VHF and 30m by 2.8m at UHF. This antenna is prohibitively massive with current technology. Our proposed antenna concept utilizes a lightweight 30-m mesh reflector antenna fed symmetrically by a single feed structure with highly shaped beams operating simultaneously at two frequencies. The key technology item to be addressed here is the design and prototyping of the dual-low-

frequency antenna feed that would achieve the required performance. Other technological challenges include the development of accurate soil moisture estimation algorithms and the mitigation of ionospheric effects at the low frequencies considered. There are also some operational challenges such as obtaining spectrum bands in which to operate. Each of these challenges and our approach to solving them is introduced below.

## LARGE LOW-MASS ANTENNA

To achieve adequate spatial and temporal sampling resolutions, our design requires a 30-m long antenna with variable widths for each of the two operating frequencies. With current technology, this would be prohibitively massive for a spaceborne mission. Our antenna concept utilizes a lightweight 30-m mesh reflector antenna fed symmetrically by a single feed structure operating simultaneously at two low frequencies, synthesizing rectangular effective apertures on the reflector. This is the key hardware technology item under development. The 30-m reflector antenna is an extension of the already-demonstrated 12-m Astro-mesh reflector [2]. At VHF, the effective illuminated reflector aperture is 11m, whereas at UHF it is 2.8m. To achieve such under-illumination of the reflector antenna, a dual-stack patch array is utilized whose number of elements and their amplitude weighting at each frequency are designed to optimize the synthesized pattern on the reflector. Preliminary analyses of this concept have been developed in [3]. The array dimensions are roughly 4.7m by 1.5m by 10cm. The combined mass of the reflector and array are projected to be an order of magnitude lower than if the same aperture sizes were to be implemented with patch array antennas. This concept is illustrated in Figure 1.

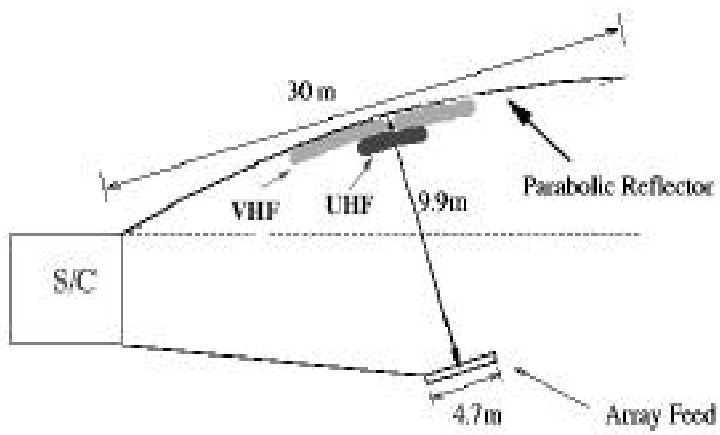


Figure 1. Subillumination of a 30-m reflector by dual-frequency feed araray

## SOIL MOISTURE ESTIMATION ALGORITHMS

Estimation methods for soil moisture under substantial vegetation and to 2 meters or more below surface with sufficient accuracy are essential in maximizing scientific return of a prospective mission. In principle, such estimation is possible from a dual frequency polarimetric SAR dataset in the UHF and VHF range. However, the details of such retrievals are complex and require detailed sensitivity analyses and product demonstrations with actual data. Our field experiments with a simple tower-based radar will provide such dataset to be used to demonstrate the achievable soil moisture products and their accuracies. The tower radar will be operated at a number of field locations representing various vegetation and moisture conditions. Retrieval of under-canopy and deep soil moisture from low-frequency radar data involves (1) characterizing the vegetation cover and its interaction with soil, and (2) modeling the soil as a multilayered medium with random boundaries and varying dielectric constants.

The scattering interactions of vegetation with the underlying soil have been studied and characterized using a number of numerical forest scattering models. The observed radar backscatter would contain the “double-bounce” interactions between the ground and the vegetation volume (crown layer of a forest stand, or leafy part of crops or bushy vegetation) or stems (tree trunks or taller crop stalks), as well as a direct ground signal, only if the frequency is low enough to penetrate through the vegetation layer and back to the sensor without significant loss of intensity. As shown by Moghaddam et al. In [4] in a tall boreal forest stand, at least two frequencies and multiple polarizations are needed to

solve the inverse problem of calculating soil moisture (dielectric constant) by separating the canopy and soil contributions. In that work, L- and P-band airborne SAR data were used, and soil moisture estimates to within 4% (volumetric) of ground measurements were obtained. The change detection accuracy was about 1%. Having the lower VHF frequency replacing, or in addition to, L-band is anticipated to further improve the soil moisture estimation results. The algorithm to demonstrate science products in conjunction with the ground test data in this project will be fine-tuned to (a) include more diverse vegetation conditions, and (b) include a multilayer soil model.

## PROTOTYPE SCIENCE DATA SET

To validate the mission concept and test the estimation algorithms, we will conduct a ground campaign whereby radar data at P-band and VHF will be collected at several test sites instrumented with deep soil moisture probes. Such complete data set does not currently exist. The radar itself will be a simple switched waveform system utilizing readily available off-the-shelf components. The signal source sequentially generates VHF and P- band signals which are transmitted using one set of broad-band log-periodic antennas, switched between transmit and receive modes. Operationally the radar will be mounted on a tower or crane structure looking down over the experiment site, and moved vertically and horizontally to construct a synthetic aperture. The backscattered returns are from an area approximately 50m in azimuth x 10m in range and are temporally averaged to reduce thermal noise. A switching network enables switching between the V- and H polarized transmit and receive modes of the antenna allowing for a fully polarimetric collection. The radar will record backscatter measurements at intervals in accordance with the ground-truth schedule. The result will be a comprehensive data set illustrating the temporal correlation between in-situ measurements and multifrequency radar data, thereby demonstrating wavelength-dependent radar penetration effectiveness for moisture observations. The same radar equipment will be transported to various sites, the timing of which will be determined to optimize the observations at each site.

## REMOVAL OF IONOSPHERIC EFFECTS

At the low frequencies considered here, the attenuation and Faraday polarization rotations caused by the ionosphere could be detrimental to the performance of a spaceborne radar if untreated. The ionosphere is a dispersive medium that induces the following effects on the radar signal: 1) group delay; 2) attenuation, 3) pulse dispersion, 4) Faraday rotation, 5) defocusing of the synthetic aperture. We show methods of overcoming these problems through optimizing system design and post-processing methods that include taking advantage of the fully polarimetric scattering matrix, optimizing local orbit crossing times for least ionospheric activity, and modeling and removing ionospheric effects using electron content data available from other ancillary measurements.

## SPECTRUM MANAGEMENT

A persistent concern with operating a radar at low frequencies is the radio frequency spectrum limitations imposed by various spectrum management agencies such the FCC and the NTIA in the United States. Most of the electromagnetic spectrum in the 100 MHz to 1 GHz range is currently allocated for military or civilian applications such as television, radio, and mobile communications. The Working Party 7C will be considering active allocations in the 420-470 MHz region in its 2003 agenda, and allocation of a 6 MHz bandwidth seems to be increasingly probable in that timeframe. In the VHF range, there may be similar possibilities for an experimental license in the aeronautical radionavigation band at 108-117.975 MHz. Given the very small pulse duty cycle in our design (1% or less), we anticipate a favorable consideration. We will be approaching this current impediment systematically, starting with securing a “stage 1” NTIA review for operation on a non-interference basis.

## REFERENCES


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