Microwave Observatory of Subcanopy and Subsurface (MOSS) IIP: Final Results and Next Steps

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***Abstract* – The microwave observatory of subcanopy and subsurface (MOSS) project has been supported under the ESTO IIP to develop technologies for a SAR mission that provides global observations of soil moisture under substantial vegetation canopies and at useful depths. This VHF/UHF polarimetric SAR is designed to provide 7-10 day repeat observations of soil moisture under substantial vegetation canopies and at depths reaching 1-5 meters, at 1 Km resolution. Due to the rapid repeat cycle, the required swath width is 300-400 Km, which must be realized by a 30m long antenna. Conventional array implementations would result in a mass of over 4000 Kg, whereas with the technology proposed and demonstrated in this project, the total antenna mass becomes about 400 kg. This antenna concept is implemented by a dual-stack patch array feed illuminating a 30m mesh reflector to synthesize the required long rectangular apertures and achieve the wide swath. This feed system was designed, and a prototype built and demonstrated. Initially, a scaled version was built and tested, which was also integrated with a scaled reflector antenna for demonstration of the overall antenna system. The full-size low frequency feed was also built and its performance successfully demonstrated. The technology was therefore taken to TRL 5-6 from 3. Other components of this project were the demonstration of the science data and products, which was achieved through a tower-based VHF/UHF radar. Experimental data were generated for deep penetration in the Arizona desert, as well as for forest penetration in a dense forest in Oregon. The soil moisture products were demonstrated and in so doing, a novel integrated inversion-processing algorithm was developed. This presentation will cover the projects accomplishment and suggest some possible next steps to realize this concept as an Earth orbiting mission.**

I. INTRODUCTION

Microwave Observatory of Subcanopy and Subsurface (MOSS) is a synthetic-aperture radar (SAR) Earth-orbiting system under 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. Several challenges exist for implementing such a system, which were studied and matured under this IIP project. These include the design of a large aperture antenna and prototyping of its feed system, development of a prototype science data set, development of soil moisture estimation algorithms, frequency interference analyses, correction of ionospheric effects, and evaluation of the impacts of MOSS products on global water and energy balance and Carbon cycle studies.

The required repeat observation period of 7-10 days imposes a requirement on the instrument's swath width and hence the antenna size. Specifically, both frequencies require an antenna length of at least 30m, while each requires a different antenna width (wider at VHF, proportional to wavelength). Using conventional phased array technologies, the two antennas, even with a shared-aperture architecture, would have a mass in excess of 4000 kg, rendering the mission unfeasible. The concept proposed by MOSS was to synthesize the two different antenna widths on a single parabolic mesh reflector of 30-m diameter by subilluminating the reflector surface with a dual-frequency stacked patch microstrip array feed. The resulting total antenna system mass is one order of magnitude lower than the conventional approach while carrying significantly lower risk than other antenna concepts such as inflatables. MOSS has prototyped this antenna feed system to show the feasibility of the overall concept.

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.

A tower-mounted mobile radar system 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. During the next two years, this radar will be operated at several diverse locations that encompass arid/semiarid, temperate, and boreal climates with various soil types and vegetation covers. The soil moisture products derived from this system will be used to show the anticipated range and quality of MOSS products and their utility in global climate studies. Water and energy balance, as well as Carbon cycle, modeling is an integral part of this project and is being carried out to assess the impact of prospective MOSS data products. Other important aspects of this project are the correction for ionospheric effects (manifested in signal attenuation, polarization rotation, and reduction of coherence within the synthetic aperture) and analysis of frequency interference from and to other systems operating in the same frequencies.

II. SAR SYSTEM DESIGN

A preliminary design for a radar system capable of simultaneously meeting all of the measurement requirements mentioned above was performed early in the project [2]. The system parameters are summarized in Table 1. The pulse repetition frequency (PRF) was maximized to lower the azimuth ambiguities to a reasonable level but is still low enough to achieve a swath width that fulfills the revisit time requirements. A long (140us) pulse length is used for both systems enabling a relatively low transmit power of 2kW. To assess the performance of the proposed system, an echo simulator was written that incorporates a Bragg rough-surface soil backscattering model. Also incorporated are modeled E- and H-plane antenna patterns at both frequencies that take into account the effects of blockage and enable us to calculate the azimuth and range ambiguities.

Table 1. Summary of SAR system design parameters

Parameter	**UHF**	**VHF**
Altitude	1313 km	1313 km
Swath Width	346 km	346 km
Antenna Width	2.8m	11m
Antenna Length	30m	30m
Center Frequency	435 MHz	137 MHz
Bandwidth	1 MHz	1 MHz
No.Looks/1km (min.)	54	40
Peak Power (1 channel)	2kW	2 kW
Pulse Length	140usec	140usec
Duty Cycle (2 channel)	13%	13%
Avg. Power (2 channel)	255W	255W
PRF (1 channel)	455Hz	455Hz
Processing Bandwidth	137Hz	182Hz
Data Rate (dual channel)	1.7Mbps	1.7Mbps
Incidence Angle Range	16-32	16-32
Azimuth Ambiguities	-18dB	-20dB

III. ANTENNA DESIGN

The SAR system design for achieving the required wide swath indicated that the antenna length at both frequencies has to be at least 30m, while the width has to be 11m at VHF and 2.8m at UHF. Such an antenna, if implemented with state-of-the-art array technology, would have a mass of about 4000 kg, resulting in an unfeasible mission. Our antenna design synthesizes the same size apertures by subilluminating a 30-m mesh reflector symmetrically fed with a dual-stacked patch array. Figure 1 shows the reflector geometry and the radiating currents synthesized on its surface. The resulting mass of the reflector, feed array, and support structures is estimated to be less than 500 kg.

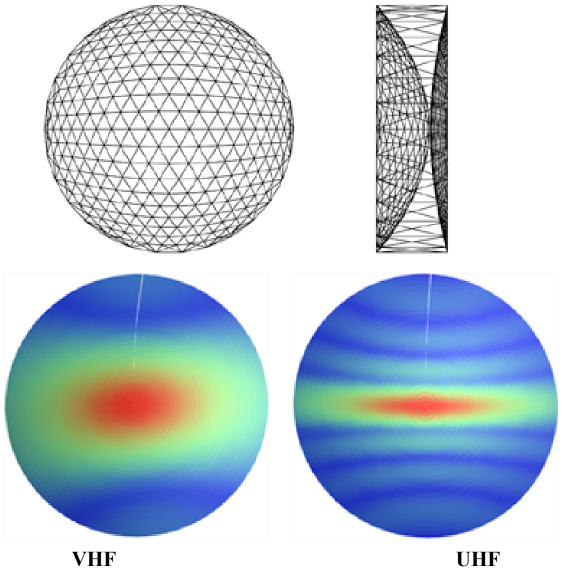

Figure 1. Top: front and side view of the Astro-mesh reflector antenna aperture schematic (Courtesy TRW-Astro). Bottom: synthesized currents on the reflector, generated by the dual-frequency feed array in Figure 2.

Figure 2 shows the nominal feed array design [3]. Each of the UHF and VHF arrays have honeycomb substrates with dielectric constant very close to that of air. Three microstrip power-dividing networks deliver power to each of the two patches on each UHF subarray, as shown in Figure 3. A three-way Wilkinson power divider for each frequency and each polarization is used to equally divide the input power to and combine the received power from each subarray. Each patch is fed from two locations corresponding to vertical and horizontal polarizations. A prototype of the feed has been designed, fabricated, and successfully tested. The TRL for this technology has thus been elevated to 5-6.

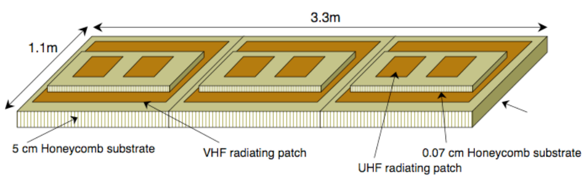

Figure 2. Feed array schematic, showing the dual stacked patch UHF and VHF arrays.

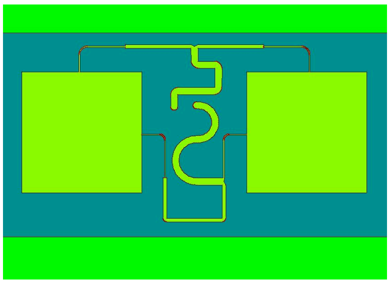

Figure 3. Microstrip power divider schematic for each UHF subarray. The feed points at the start of each line are fed through a circular opening through the VHF patch below.

For testing the concept initially, the dual-frequency feed element was built at the scaled frequencies of L-band and S-band, roughly a factor of 10 higher than the actual frequencies (Figure 4). A feeding configuration using thin coaxial lines was used to deliver power to each patch as opposed to a stripline [4]. The radiation pattern of this scaled frequency array is shown in Figure 5.

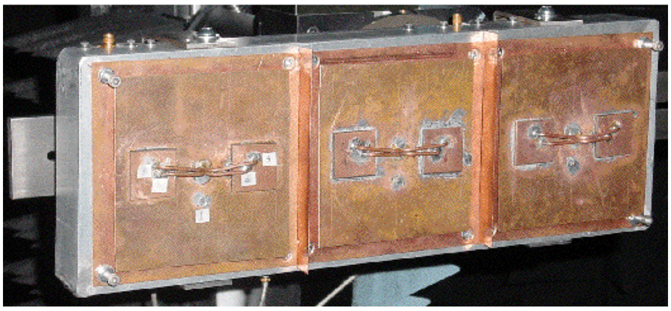

Figure 4. L/S band scaled frequency feed array, built using thin coaxial feed lines.

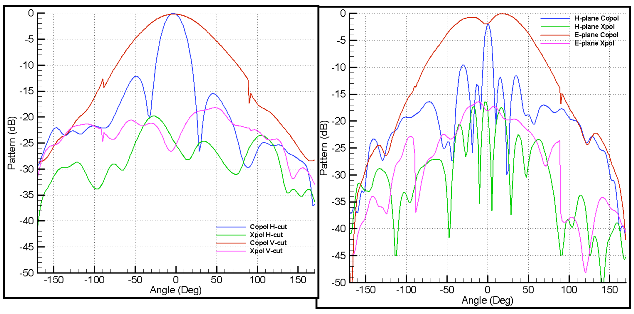

Figure 5. Sample measured radiation patterns for the scaled feed array. Left: lower frequency, H-port (along-array). Right: higher frequency, H-port.

Using an existing 3.65m reflector antenna, the full-up feed+reflector antenna system performance was also evaluated and used to validate the end-to-end antenna system concept. The overall radiation patterns measured are shown in Figure 6, confirming the theoretically calculated patterns.

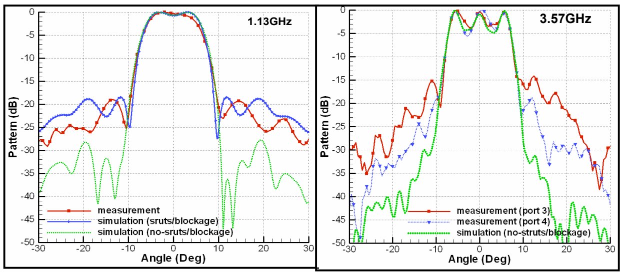

Figure 6. Sample measured radiation patterns for the scaled reflector feed by the scaled feed array. Left: lower frequency. Right: Upper frequency.

The full-scale feed array was constructed using the design and dimensions shown in Figures 2 and 3. Two preprototypes were built initially with nominal design parameters and the honeycomb substrates. Using the actual measurements, the dimensions were then slightly modified to achieve the desired performance. The final array design reflects this optimized set of dimensions. Figure 7 shows the completed array from the front side.

Figure 7. Completed full-scale VHF-UHF feed array

To hold the structure together, a CAD model of the array was generated and a mechanical support structure was designed and built, as shown in Figure 8.

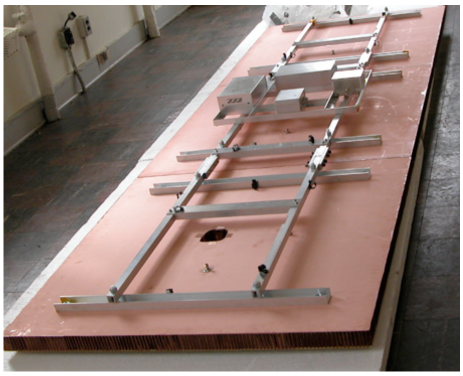

Figure 8. Mechanical support structure on the back of the array. This structure is also used to attach the four 3-way power dividers

The feed antenna was extensively tested for S-parameters, radiation pattern, and gain. The latter two were performed at an outdoor ground reflection antenna range using standard gain calibration. To reduce the backlobes in the radiation pattern at VHF where the ground plane is relatively small, copper walls were installed around all the elements. Sample results for the radiation pattern and gain are shown in Figure 9, validating the performance of the feed. The TRL for this technology has hence been advanced to 5-6.

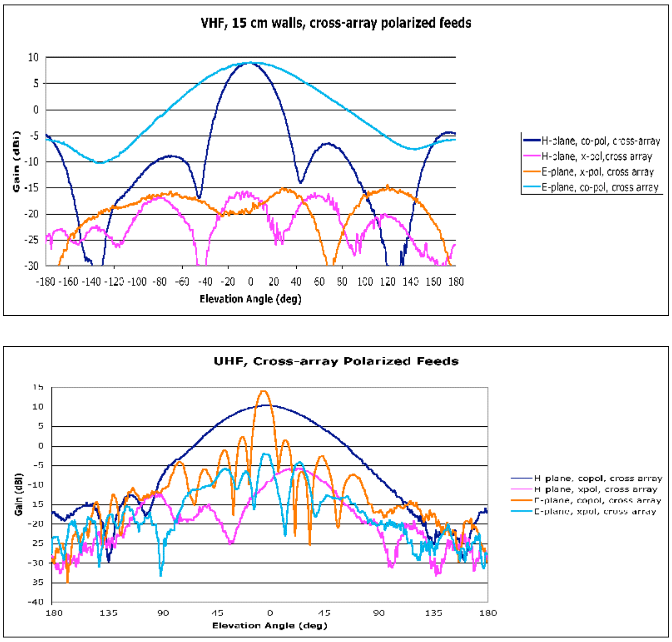

Figure 9. Sample measured pattern and gain for the UHF-VHF feed array. Top: VHF, cross-array polarized. Bottom: UHF, cross-array polarized.

IV. TOWER RADAR 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 (Figure 6). 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.

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 about 30 MHz.

Figure 10. 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.

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. Figure 11 is a high-level flow chart of the interrelationship between the different data processing and estimation/inversion modules.

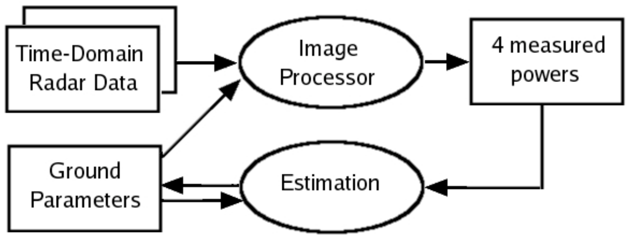

Figure 11. Tower radar processing and soil moisture estimation flow chart. .

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 (Figure 12) 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.

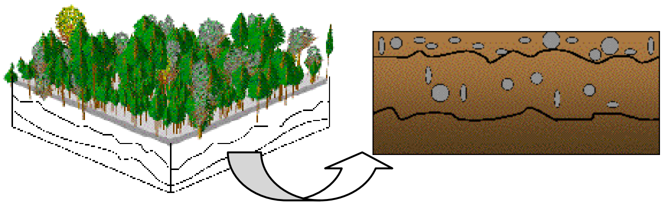

Figure 12. Layered medium model used in development of the new generation soil moisture estimation algorithms.

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. Figure 13 shows an example of processed data taken in Arizona, while Figure 14 is the result of the soil moisture estimation for a two-layer soil model as derived in conjunction with data processing.

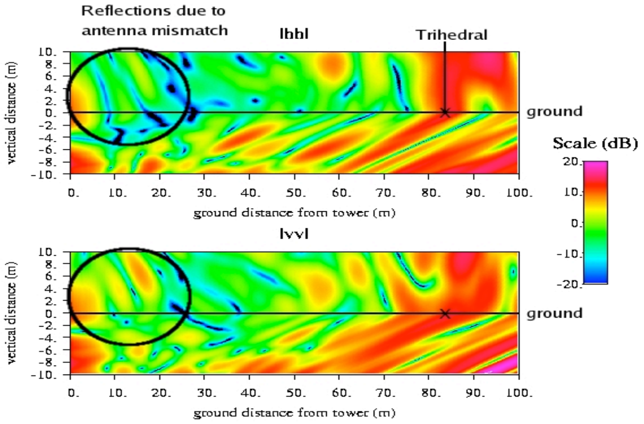

Figure 13. Processed towr radar images at HH and VV polarizations, derived in conjunction with soil moisture estimation algorithms and the two-layer soil model.

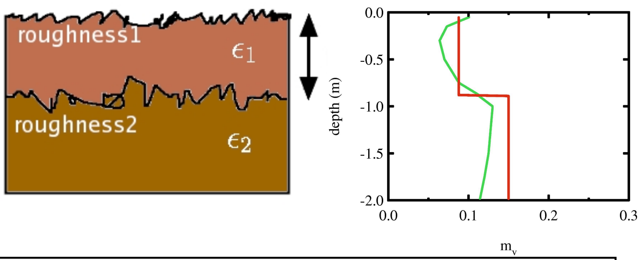

Figure 14. The two-layer soil model is used to estimate the volumetric soil moisture in the subsurface. This inversion algorithm is used iteratively with the coherent radar processor to converge on both the soil moisture results and the radar image. In the right-hand side figure, red is measured data, while green is estimated moisture.

V. MESH REFLECTOR AND SPACECRAFT DESIGN

The advent of light mesh-type reflector surfaces has made it possible to launch and deploy large antennas in space at a much more reasonable cost than the significantly heavier antennas of the same size. An example of such a surface is the Astro-mesh by TRW/Astro (now Northrop Grumman) [7]. To study the mechanical and spacecraft design issues for MOSS, TRW/Astro has performed detailed analyses related to the packaging, launch, deployment, and operations of the MOSS instrument. Figure 15 depicts a candidate mechanical design for the 30-m reflector, spacecraft, feed, and booms.

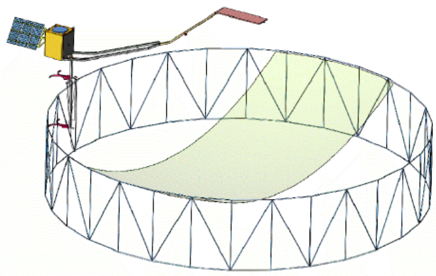

Figure 15. Candidate mechanical design for the 30-m reflector, spacecraft, feed, and booms

Some highlights of the analyses results are:

- Although the desired effective aperture shape for MOSS is rectangular (30m by 11m at VHF and 30m by 2.8m at UHF), synthesizing this aperture on a parabolic mesh reflector is significantly preferred to a cylindrical mesh aperture from mass, packaging, and risk points of view. This confirms the appropriateness of our original concept.
- An F/D of 0.45, as selected to achieve science requirements for swath width, results in a package size in the optimum range. The package size is approximately 6.6 m long and 1m in diameter.
- The 30m antenna is not deemed to pose a major risk item for the mission. The technology has been demonstrated, e.g., on the 12m Thuraya antenna.
- The launch vehicle will be at least a Delta-III class.
- Two spacecraft options have been considered, each with its own advantages. Preliminary candidate deployment mechanisms for each case have been studied. In both cases, placing the spacecraft within the non-illuminated antenna aperture provides the shortest mast length for the deployed antenna and feed. A possible scenario is depicted in Figure 10.
- The propulsion, electrical, and attitude control subsystems do not have stringent requirements, and can be accommodated with existing technology. The on-orbit delta-V requirements for the MOSS mission can be accommodated with a simplified version of a baseline dual-mode, pressure regulated, bi-prop propulsion subsystem The 1313km 6am/6pm orbit has no eclipse, and hence batteries are only needed during launch and prior to solar panel deployment. The range of pointing requirements under

consideration for the MOSS mission (1.0 deg required, 0.5 or 0.25 deg desired) can all be supported by a simple earth-sensor and sun-sensor attitude reference system.

- The low data rate of the MOSS instrument allows a rather low demand on the solid state recorder and the downlink systems.
- The mass of the reflector, boom, all mechanisms, and the dual-frequency feed is estimated to be less than 500kg.

VI. SUMMARY

The MOSS project has studied various design, technology, and scientific challenges for implementation of a UHF/VHF polarimetric SAR mission for global observations of deep and undercanopy soil moisture. The final results on various aspects of the project are given in this paper. In addition to the topics noted in previous sections of this paper, ionospheric effects and impact on the study of global water and energy cycle will also be discussed at the presentation.

The antenna feed technology, which was the principal technology under development, has been advanced to TRL 5-6. It has been shown that there are no significant technology issues outstanding for realizing this mission. Certain aspects of the antenna technology, such as the integration of the full-scale feed with the 30-m reflector may still need to be advanced to TRL 6 before a flight mission can be initiated. Further investment also needs to be made in maturing the processing and inversion algorithms in the new integrated framework.

ACKNOWLEDGEMENTS

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REFERENCES

[1] M. Moghaddam, E. Rodriguez, D. Moller, and Y. Rahmat-Samii, NASA Tech Brief: "Dual low-frequency radar for soil moisture under vegetation and at-depth." (To Appear, 2003).

[2] Moller, Rodriguez, Moghaddam, and Hoffman, "A Dual-low-frequency Radar for Sub-canopy and Deep Soil-moisture Measurements," Big Sky Conference, March 2003.

[3] Huang, J., Y. Rahmat-Samii, and M. Moghaddam, "A VHF/UHF dual-band dual-polarized microstrip array," presented at *PIERS'2003*, 1/2003 (invited).

[4] Keerti S. Kona and Yahya Rahmat-Samii, "Design and Analysis of a Novel Probe-feeding method for Stacked Microstrip Patch Antennas," *IEEE AP-S Int. Symp.*,Columbus, Ohio, June 2003.

[5] Rodriguez, E., D. Moller, and M. Moghaddam, "Synthetic aperture processor prototype for a tower-based UHF and VHF soil moisture radar," *IGARSS'03*, Toulouse, France, July 2003.

[6] Moghaddam, M., E. Rodriguez, and J. Hoffman, "Estimating Soil Moisture from Surface to Depth using a Multiple Low-Frequency Tower Radar," *PIERS'03*, October 2003.

[7] Thomson, M., "The Astromesh deployable reflector," *IMSC'99*, June 16-19, 1999, Ottawa, Canada.