Soil Moisture and Salinity using P-Band from Geostationary Orbit
Final Report

PI: Peter Hildebrand, GSFC Code 614
Co-Is: Bhaskar Chaudry, David Le Vine, Cary Johnson

1. Overview and Study Goals

A P-band radar/ radiometer, located in geostationary orbit has the potential to provide unequaled measurements of soil moisture and ocean salinity, two parameters that are intimately connected to the health or our planet. Soil moisture, which is strongly tied to habitability and the availability of food, is a key parameter of weather and seasonal climate processes. Likewise, Sea surface salinity is an important component in forcing the general circulation of the ocean, and is an important variable for understanding climate variability and change.

The system configuration proposed for this study is based on two concepts: 1) the use of the P-band wavelength, and 2) use of a geostationary vantage point. These are challenging technical concepts that require careful consideration.

P-band is proposed because a long wavelength is needed to make the specified measurements. This approach has been overlooked in the past in favor of the shorter L-band, primarily due to the difficulty of implementing large scanning antenna systems. Soil moisture measurements depend on the penetration depth of the microwave energy into/from the soil to measure moisture over the full root zone. The ~ 40 cm wavelength of P-band has twice the penetration of L-band, thus providing a soil penetration depth over the full root zone for most plants, plus improved penetration of the vegetative canopy—a particularly important parameter in forests. Salinity measurements are complicated, among other things, by the effects of Sea Surface Temperature (SST) on thermal emission. P-band significantly improves the sensitivity of T_b to salinity. In short, P-band provides the remote sensing characteristics we want for the measurement under consideration.

Use of a geostationary vantage point is ideal for two reasons. First, soil moisture measurements must be made over the diurnal cycle. A geostationary location that is longitudinally centered over the U.S. would optimally provide these observations with application to national needs. Second, at the geostationary range, Earth subtends only 18°. This narrow swath will facilitate design of the antenna's scanning and will simplify maintenance of the beam pattern over the full swath.

<u>Study Objective</u>

The goal of our study was to develop the scientific requirements for soil moisture and sea surface salinity uses of such a system, and to specify the microwave technical parameters for such a system in terms of the antenna element size and spacing, the use of thinned array approaches, possible active/passive use of the system, etc. A subsequent portion of the effort will evaluate options for various antenna configurations. The result of the full study will be to provide a technology development roadmap for deployment of a P-band based instrument in the ~ 2015 timeframe, and to provide the first rigorous evaluation of the feasibility of system concept, definition of key system requirements, and anticipated system capabilities and limitations relative to Earth science measurement needs.

Study Scope and Approach

Our study sought to develop a soil moisture /sea salinity instrument concept that met the soil moisture measurement needs of the nation, and of much of the western hemisphere. The study will not develop a detailed instrument or mission design, but will provide needed knowledge and foundation for future work delving further into development of such a system. As such, the intended outcome of the work was to develop the engineering requirements for such a system.

Our approach will be to:

1. Define the science measurement goals for the system. Science goals will be based on knowledge of soil moisture and sea salinity processes, and scientific measurement needs, such as the precision and the spatial/temporal sampling requirements over the field of view that are required for a useful observing system.
2. Define the microwave system requirements in terms of antenna beam pattern design requirements, the approach to beam swinging, the antenna element size and spacing, the use of thinned array approaches, possible active/passive components to the system, etc.
3. Provide a concept development that recommends an instrument configuration. This will include a specification of the antenna technical parameters for the baseline instrument configuration, and recommending candidate antenna design approaches to pursue with a follow-on antenna development study. A follow-on study would then concentrate on resolving antenna design challenges and identification of technology developments that would enable deployment of the baseline instrument in the 2015 timeframe.
4. Provide a technology development approach and document it in roadmap format.

2. Scientific Measurement Goals

Soil moisture is a key variable to measuring and understanding the environment that supports plant life on Earth. Full knowledge of the soil moisture budget involves, measuring not only the soil moisture, but also the soil moisture forcing factors such as precipitation, runoff, and soil hydraulic conductivity, which is a measure of the ease with which water moves through soil. Soil hydraulic conductivity is one of the most important soil characteristics because it determines infiltration of rain and redistribution of soil water with time, and with knowledge of hydrologic conductivity, the soil moisture could be estimated from precipitation measurements much more precisely than is presently possible. Through this, the relationships to the state of vegetative cover could be much more precisely know. Unfortunately, field measurements are time consuming, for extensive sampling is needed because observations have shown extreme spatial variability. Consequently, there are, at present, no spatially representative measurements for soil hydraulic conductivity for any place in the world.

Hydraulic conductivity is measured by observing the change of soil moisture with time after a significant wetting event. Extensive field observations have shown that passive microwave observations can provide soil moisture. Determination of the rate of change of soil moisture requires a geo-stationary orbit to get the frequent sampling needed to determine (time constant of hours). Long wavelengths are needed to mitigate the effects of the vegetation canopy and to get optimum penetration into the soil. L-band (l.4 GHz) has been used extensively in the past and has been proposed for use in space; however, an even lower frequency in the P-band would be more desirable because it is less affected by vegetation and samples a greater soil depth.

The possibility of providing salinity measurements with the instrument was a study goal. During the scourse of this study, this goal had to be eliminated from consideration. This was due to the required high precision in the microwave emission measurements needed for measurement of salinity—fractions of a degree K for salinity, versus ~2 K for soil moisture—and the system performance that we found we could expect from the instrument, as explained below in section 4.

2.1. Spatial Resolution Requirements

Since we need to determine the rate of change of soil moisture after soil has been wetted, it is pertinent to consider the dimension typical of a rain cell. The typical area receiving convective rain is considered to be about 10 km; The area is generally much larger for frontal storms. Thus, spatial resolution of 5 to 10 km would be ideal.

2.2. Temporal Resolution Requirements

The rate of change of soil moisture varies greatly with soil texture. Substantial changes have been observed on times of several minutes. On the other hand, success has been reported on modeling hydraulic conductivity using as few samples as one per day. The time constant for convective rain is on the order of hours. Hence, we take as a goal 4 samples per hour (i.e. 15 minutes).

2.3. Radiometric Resolution Requirements

Field measurements at L-band show changes in brightness temperature of about 25 K starting from saturation can occur in 15 minutes [1]. Assuming that change in brightness temperature would be 25 K, and that there would be 4 measurements to quantify this change, a ΔT of less than about 6 K [$\Delta T < (25 / 4)$] would be desirable. This ΔT is necessarily the sum total of all uncertainties (i.e., arising from uncertainties in quantifying effect of the vegetation canopy, effective soil temperature, incomplete soil saturation of a pixel area, atmospheric effects, and calibration). Hence, a reasonable target might be 2 K or better for the noise performance of the radiometer itself (all that will be considered here). Model studies should (could) be conducted to refine this requirement and might be a logical follow on step.

3. Microwave System Requirements

We consider two cases: a P-band and a L-band sensor. We added consideration of L-band because of the protected band for radiometry at L-band, and also because the shorter wavelength would provide a reduction of antenna size by a factor of two. Both of these considerations were considered potential impediments for the initially proposed choice of P-band.

The P-band sensor was considered as operating at a frequency of 750 MHz. This frequency was chosen after research of spectrum allocations. The available bandwidth at P-band is about 6 MHz. The L-band sensor was considered as operating in the window at 1.4 GHz that has been set aside for passive use only. This window has a long heritage for remote sensing of soil moisture. The bandwidth available at L-band is 25 MHz. We assume an equivalent receiver noise temperature of 400 K in each case.

Based on the scientific requirements, above, the microwave system requirements are:

1. An RMS radiometric noise (accuracy) of better than 2K
2. A spatial resolution of 10 km
3. Coverage of at least the continental US from geostationary orbit.
4. Complete coverage in 15 minutes (4 samples per hour)

4. Development Concept

We considered two development concepts: a conventional scanning radiometer and a synthetic aperture radiometer. The conventional scanning radiometer has the advantage that the antenna element design is less complex, but the disadvantages of needing the antenna to scan in some fashion, likely requiring moving components, plus the requirement that the time to scan the full field of view may become a driving design factor. The synthetic aperture radiometer has a considerably more electronic complexity that may result in potential implementation uncertainties for the very large aperture that will be required. However, the system will have no moving parts and the time to scan the full field of view will not be a design issue. The synthetic aperture is therefore, the conceptual design of choice.

4.1. Conventional Scanning radiometer.

The conventional scanning radiometer would need to have some sort of raster-style scan that would image the full field of view—the 18° Earth disk—in 15 minutes. In this case, the total number of pixels needed to image the field of view determines the integration time available per pixel. Using the conventional equations for radiometer performance ($\Delta T = T_{sys}/\sqrt{(\tau B)}$) where τ is the integration time and B is the available bandwidth [2], one obtains the following results. We see that the L-band system meets the ΔT requirements imposed by science sampling needs, and that P-band is a factor of two off these needs. This problem at P-band could potentially be resolved either by using some adaptive scanning that eliminated scanning portions of the Earth disk, e.g. ocean areas, and/or by relaxing the sampling interval requirement to a time grater than 15 minutes.

Coverage	ΔT at L-band (K)	ΔT at P-band (K)
Continental US	1	2
Visible disk	2.2	4.2

3.2. Synthetic Aperture Radiometer

Aperture synthesis is an interferometric technique in which the signals from pairs of small antennas are multiplied together. The concept is similar to earth-rotation synthesis employed in radio astronomy. The advantage of this technique is that sparse arrays of small antennas can be employed in place of large scanning antennas, as needed above for the conventional scanner, and no mechanical motion is needed. The disadvantage is an increase in signal processing and a potential loss in radiometric sensitivity if a thinned array is used. Using the same requirements as above and equations for radiometric sensitivity available in the literature [3], one obtains

Coverage	ΔT at L-band (K)	ΔT at P-band (K)
Visible disk	0.85	1.7

It therefore appears that both scanning approaches and both wavelengths have potential for this application. However, the large dimensions clearly favor a synthetic aperture radiometer (thinned array and no mechanical motion). In particular, to obtain 10 km spatial resolution from geostationary orbit will require a maximum dimension of 3600λ (760 m at L-band and 1.4 km at P-band). In the case of the conventional scanner this is the antenna diameter. In the case of the synthetic aperture radiometer, it is the length of each arm of the cross (and in this case only the cross is necessary).

Remote sensing at either P-band or L-band from geostationary orbit is potentially feasible to meet even the high revisit times required for applications such as mapping soil hydraulic conductivity. Given the large dimensions involved, a thinned array such as is possible with aperture synthesis is probably the concept to explore in more depth. This concept has additional flexibility as many configurations are possible. For example, sensors arranged around the circumference of circle (hoola-hoop) could achieve the same performance as above. Another possibility is formation flying in which pairs of small satellites replace the individual antennas.

5. Technology Development Approach

This technology approach to measurement of soil moisture and hydraulic conductivity appears theoretically robust and ready for an evaluation of the feasibility of constructing an antenna system. At this point, the scientific goals and needs are well described, and there remain a few minor questions to resolve. The following discussion identifies the remaining issues and the development approach to bringing the concept development to conclusion.

The remaining science question is whether the proposed 15 minute time scale could be relaxed. It is clear that 15 minutes is short enough to catch the highest frequency changes of value to the science; however, the ability to lengthen this sampling time requirement should be addressed with a study that trades sampling interval versus scientific impact of the results in a quantified manner.

The major remaining technical issue with respect to the microwave requirements relates to the system sensitivity requirements. While it is clear that a filled array has the needed sensitivity to observe all soil types and dryness/wetness conditions, it is also clear that thinning of the synthetic aperture array will affect the system sensitivity. The effect of this degradation in system sensitivity on the ability to observe all soil types and dryness/wetness conditions needs to be quantified.

The final step will be an analysis of design options for real aperture scanning and for synthetic aperture antenna systems. This study is outside the scope to the work proposed herein, but is the logical follow-on to this study, and we plan to assist this follow-on study if funded.

6. References

[1]. Jackson et al. (1998) *IEEE Trans. GE* **36**, 1376-1383

[2]. Ulaby, F. R.K. Moore and A.K. Fung, <u>Microwave Remote Sensing, Vol I (Chapter 6), Addison-Wesley, 1981</u>

[3]. Le Vine, D. M., "The Sensitivity of Synthetic Aperture Radiometers for Remote Sensing Applications from Space", Radio Science, Vol 25 (#4), pp 441-453.