An Architecture Trade Study for Passive 10-km Soil Moisture Measurements from Low-Earth Orbit

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Abstract- **In 1999 NASA HQ, as a result of an internal NASA study on potential Earth Science Enterprise Post-2002 Missions, directed the hydrology community to focus on achieving a 10-km spatial resolution global soil moisture mission. This type of resolution represents a significant technological challenge for an L-band radiometer in sun-synchronous low-earth orbit. An engineering trade study has been completed to determine alternative system configurations that could achieve the science requirements and to identify the most appropriate technology investments and development path for NASA to pursue in order to bring about such a mission. The results of the study are presented here together with a short discussion of future efforts.**

I. INTRODUCTION

As a result of NASA's Post-2002 Baseline Mission Profile Scenario exercise in 1999, NASA HQ directed the hydrology community to focus on achieving a 10-km spatial resolution global soil moisture mission [1]. To attain this type of resolution with an L-band radiometer in sun-synchronous low-earth orbit represents a significant technological challenge in antenna and instrument design. As a first step in addressing this challenge, an engineering trade study has been completed to determine alternative system configurations that could achieve the science requirements. The primary objective was to identify the most appropriate technology investments and development paths for NASA to pursue in order to bring about such a mission around the end of the decade.

II. POTENTIAL CONFIGURATIONS

The study was strictly driven by the soil moisture science requirements, as outlined in [1] and [2], rather than particular technologies or implementation strategies. Here, we will review the implications of these requirements as well as that of soil moisture retrieval algorithms currently in use. We will then present the instrument configurations considered, along with their pros and cons, and technology maturity estimates and satellite size constraints used for the tradeoff.

The science requirements can be summarized as follows:

- Revisit interval of ~2-3 days.
- Complete global mapping within the revisit interval with no data gaps.
- Spatial resolution of 10 km or better.
- Soil moisture retrieval accuracy of 4% volumetric or better over ≥65% of land surface.
- Mission life of 2 years or longer.

The first three will determine the orbit as well as the required field-of-view, and the retrieval accuracy determines the instrument and algorithm performance. In our study we associated each mission concept to an algorithm, and considered how it affected the technical implementation (*e.g.*, the required incidence angle). The study, however, did not seek out to evaluate the algorithm performance. Instead we considered their maturity, as described in [2], as part of the overall evaluation of a concept. These retrieval algorithms include a single-channel nadir-pointing radiometer algorithm [3], a multi-channel 45°-pointing radiometer algorithm [4], and synthetic aperture radar (SAR) algorithms.

Because of the potentially large number of configurations, we determined a set of down-selection criteria that we used to pick the best candidates for further study. A critical part of these criteria is the assumption that the mission target launch date is ~2008-2010. This requires a proposal submission by ~2004-2006. The criteria are described below:

- Science: Technology aside, can a mission be designed to meet the science requirements? *E.g.*, can we find an orbit and FOV combination that meets the revisit and coverage requirements?
- Algorithm: Has the algorithm been proven, or does it stands a reasonable chance by ~2004?
- Technology: What are the chances that the required technologies will be available for a ~2008 flight, provided an adequate R&D program is in place? This was defined as "flight qualified" by ~2006.

The study team researched the refereed literature and engaged in communications with soil moisture and remote sensing scientists to come up with a broad list of alternative concepts [5-12]. We then developed high-level designs for each concept, which basically consisted of orbit parameters and antenna size. The advantages and disadvantages of each were determined and compared against the down-selection criteria. Synthetic thinned aperture radiometers (STAR), scanning reflectors (both mesh and inflatable), push-broom inflatable torus reflector, and SAR were among the most promising configurations of the sixteen considered.

With antenna sizes on the order of 27 meters, it was deemed unlikely that a 1-dimensional STAR would be feasible. This technique requires real aperture antennas in one dimension, which would be extremely lossy for the required linear aperture size, and very difficult to package inside the launch vehicle. Two-dimensional STAR, on the other hand, has significantly less surface area making it easier to package and less RF loss because each element is connected to a receiver. Also deployable structures of that size have already been developed. A scanning reflector using mesh technology also seems possible with the biggest issue being the control dynamics of such a large structure and the RF properties of the mesh. Inflatable technology was considered as too immature and unlikely to be flight qualified by 2006. Lastly, while SAR shows great potential for very high-resolution soil moisture, algorithms to invert an unambiguous estimate of soil moisture are less accurate than desired [2]. Based on this high-level evaluation, the most likely candidates are the scanning mesh reflector and 2-D STAR. Since GSFC has been working in STAR for over a decade and JPL has on-going research into large mesh reflectors, we elected 2-D STAR for further study.

III. SYNTHETIC THINNED APERTURE RADIOMETER SYSTEMS

In this technique, the coherent product (correlation) of the signal from pairs of antennas is measured at different antenna-pair spacings (baselines). These products yield sample points in the Fourier transform of the brightness temperature map of the scene, and the scene itself is reconstructed by inverting the sampled transform [6]. The reconstructed image includes all of the pixels in the entire field-of-view of the antennas. The advantage is that it requires no mechanical scanning of the antenna, which also improves the time-bandwidth product. A disadvantage is the potential worsening of radiometric sensitivity (rms noise) in the image due to a decrease in signal-to-noise for each measurement compared to a filled aperture. Pixel averaging is required for good radiometric sensitivity.

Table 2 shows likely orbits and the required instrument field-of-view (FOV) in order to have global coverage every 3 days. The table shows the STAR apertures needed to achieve a ≤ 10-km spatial resolution. Two concepts are shown, a single instrument, and two instruments flying in formation each covering half the swath. This provides an interesting

TABLE 1: STAR ANTENNA DIAMETER AS A FUNCTION OF ORBIT HEIGHT

Orbit Height (km)	1 S/C		2 S/C	
	FOV (deg)	Ant. Dia. (m)	FOV (deg)	Ant. Dia. (m)
775	60.4	27.7	33.0	19.3
665	66.9	26.7	37.2	17.2
560	84.6	27.2	50.2	13.7
460	96.7	30.2	60.1	12.5

trade between the increased complexity of larger antennas and the cost of two simpler ones. It's also interesting to note that, for a planar antenna, a lower orbit requires a smaller aperture to obtain a given spatial resolution; however, the required FOV to meet coverage increases which in turn increases the aperture size.

Another problem that arises for very large STAR is that of signal decorrelation [6]. We assumed that the system bandwidth would be the available L-band radiometry allocation of about 20 MHz. Therefore, configurations with FOV > 70° are not feasible due to signal decorrelation at wide angles from nadir. The next consideration was that of system performance. An instrument error budget was developed based on [13] and requires a $\Delta T \leq 2$ K, and stability of ≤ 2 K. Based on the above discussion, we concentrated our efforts on the configurations for a 665-km orbit.

Significant effort was devoted to the packaging and deployment aspect of the design. To do this accurately, we developed a strawman electrical design. We looked at the "T" and "Y" antenna shapes and selected the "Y" because it minimizes the number of redundant baselines [8], and therefore receiver hardware. Assuming an element spacing of approximately 0.8λ [9], the 27.7-m system requires approximately 230 antenna elements and 52,000 correlators. Similarly, the 19.7-m needs about 170 elements and 28,900 correlators. For this concept, each arm of the STAR antenna was divided into panels of 9 antennas each. The antennas and the circuitry are assumed to be microstrip-based with each antenna having a dual-polarized receiver behind it. The panels would have a central unit for collecting science data from each, as well as for command and data handling. Similarly, a single power distribution unit would take power from the spacecraft and provide the required power for all the electronics. This panel would be about 1.5m x 0.5m x 5cm. Figure 2 shows the mechanical concept for the 27.7-m STAR. It uses three masts about 13-m each, similar to the one used in the Shuttle Radar Topography Mission (SRTM) which was 60-m. The study also showed that this system can be stowed in a Taurus-XL launch vehicle. Two spacecraft each with a 19.7-m STAR would fit together into a Delta L/V launch vehicle.

Another important issue is instrument power consumption. Based on typical mid-sized spacecraft, the goal of the

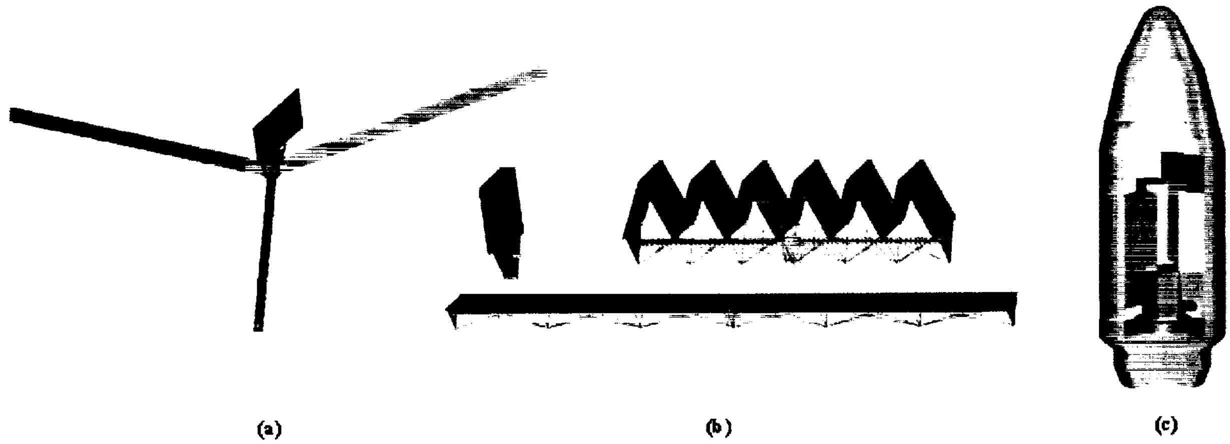

Figure 2: Architecture concept for a 27.7-m diameter STAR instrument: (a) deployed Y-configuration, (b) antenna panel deployment concept, and (c) stowed inside a Taurus-XL fairing.

instrument should be to consume ≤400 W. In our panel based approach, this would require the radiometers to be ≤0.25 W each, and correlators of ≤1.0 mW per correlation. When the other electronics in a panel are considered, power per panel is about 12.5 W.

IV. SUMMARY AND CONCLUSIONS

The results of an architecture study to achieve the goal of 10-km soil moisture have been presented. Likely candidate design approaches are scanning mesh reflectors and 2-D STAR. A more detailed look at 2-D STAR shows that up to 27.7-m instruments are technically feasible provided certain key technologies are addressed in the near future. Ongoing projects at GSFC and elsewhere show that meeting the goals of power consumption for the radiometers and correlators can be achieved. Likewise, mechanisms to deploy antennas of this size either exist or are being developed. However, work must continue in areas like on-orbit calibration and mechanical distortion and pixel averaging effects. Finally, cost estimates based on these studies must be completed.

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REFERENCES

[1] "Earth Science Enterprise Mission Scenario For The Post-2002 Period", *Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions, Easton, MD, October 10, 1998,* http://www.earth.nasa.gov/visions/Easton/

[2] T. Jackson (Ed), "Soil Moisture research mission (EX-4)," *Report of the NASA Post-2002 Land Surface Hydrology Planning Workshop, Irvine, CA, April 12-14, 1999*, http://www.earth.nasa.gov/science/water.html

[3] T. Jackson, "Measuring surface soil moisture using passive microwave remote sensing," Hydrological Processes, 7:139-152, 1993

[4] E. Njoku, L. Li, "Retrieval of land surface parameters using passive microwave measurements at 6 to 18 GHz", IEEE Trans. on Geoscience and Remote Sensing, Vol. 37, p.79, 1999

[5] E. Njoku, *et al.*, "Evaluation of an inflatable antenna concept for microwave sensing of soil-moisture and ocean salinity", IEEE Trans. on Geoscience and Remote Sensing, Vol. 37 (1), p.63, 1999.

[6] D. LeVine, *et al.*, "ESTAR: A synthetic aperture microwave radiometer for remote sensing applications", Proc. IEEE, Vol. 82 (12), p.1787-1801, 1994.

[7] A. England, *et al.*, "HYDROSTAR: An L-band radiometer for hydrology and soil moisture", Proposal in response to NASA AO-98-OES-01, 1998.

[8] D. LeVine, "Synthetic aperture radiometer systems", IEEE Trans. on MTT, Vol. 47 (12), p.2228-2236, 1999.

[9] Y. Kerr, *et al.* "Soil Moisture-Ocean Salinity (SMOS): Proposal in Answer to the Call for Earth Explorer Opportunity Missions", 1998.

[10] E. Njoku, *et al.*, "Large deployable-mesh antenna system for ocean salinity and soil moisture sensing", IEEE Aerospace Conference Proceedings, Vol.5, p.141-150, 2000.

[11] K. Carver, "Design Concepts for a Dual-Frequency Dual-Polarization Aperture Synthesis Antenna", Final Report to Swales Aerospace Corp., 1999.

[12] "Large, Lightweight Deployable Antennas", *Report of the ESE Technology Planning Workshop, Arlington, VA, January 23, 2001 http://nmp.jpl.nasa.gov/workshop-eo4/proceedings/ESE_Wkshp_antennas.pdf*

[13] P. O'Neill, "Sensitivity analysis of error in retrieved soil moisture using Wichita '92 corn data", GSFC Internal Memorandum, 1996.