Synthetic Thinned Aperture Radiometry (STAR) Technologies Enabling 10-km Soil Moisture Remote Sensing from Space

J.R. Piepmeier[1], F.A. Pellerano[1], P. O'Neill[2], D. LeVine[3], E. Kim[3], T. Doiron[1]
NASA's Goddard Space Flight Center
[1]Microwave Instrument Technology Branch/555
[2]Hydrological Sciences Branch/974
[3]Microwave Sensors Branch/975
Greenbelt, MD 20771

Abstract - **Remote sensing of soil moisture at 1.4 GHz at 10-km spatial resolution from space requires the use of very large radiometer apertures (>20 m). Synthetic thinned aperture radiometry (STAR) is a viable solution to the large aperture problem, and several technologies are being developed to enable a spaceflight STAR instrument. The primary motivation for the development is a reduction in power and size, which is achieved by using low power microelectronics, including silicon germanium (SiGe) and ultra low power (ULP) CMOS. STAR system architecture, SiGe microwave radiometer receivers, ULP digital correlators, and calibration are discussed.**

I. INTRODUCTION

NASA's Earth Science Enterprise and the hydrology community are focused on achieving a 10-km spatial resolution global soil moisture mission towards the end of the decade. This type of resolution represents a significant technological challenge. Observation of soil moisture is based on relatively low frequency thermal microwave emission at L-band (1.4 GHz). The long wavelengths at this frequency coupled with the high spatial and radiometric resolutions required necessitates the use of very large apertures (>20 m) [1, 2].

An engineering trade study was completed by NASA Goddard Space Flight Center (GSFC) 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 [1]. The conclusion of this study was that Synthetic Thinned Aperture Radiometry (STAR) is the most promising technology to enable these very large non-rotating apertures in space. 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 [3]. The reconstructed image includes all of the pixels in the entire field-of-view of the antennas.

The main advantage of the STAR architecture is that it requires no mechanical scanning of the antenna. Using a static antenna simplifies the spacecraft dynamics and improves the time-bandwidth product of the radiometer. Furthermore, aperture thinning reduces the overall volume and mass of the instrument. A disadvantage is the reduction of radiometric sensitivity (or increase in rms noise) of 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.

In essence, we are trading a nearly intractable mechanical problem for a tractable electrical one. Because a large STAR radiometer uses many receivers and correlators, the primary objective of our technology development has been to drive down electrical power dissipation, volume and mass. We accomplish this goal through the innovative use of low power microelectronics, including silicon germanium (SiGe) and ultra low power CMOS (ULP CMOS), for microwave receivers, analog-to-digital converters, and digital correlators. In addition, we are studying system architecture issues such as correlated calibration sources and signal distribution.

II. SYSTEM TECHNOLOGY

Technology development for the 10-km soil moisture remote sensing problem began with two investigations. First, a concept was developed for a space-based instrument through a science-driven architecture study [1]. From this study, engineering constraints were derived that motivated several component technology developments. Second, an aircraft instrument was developed to validate the two-dimensional STAR technique for soil moisture remote sensing [4]. The instrument is a research tool that will be used to address remote sensing and instrument systems engineering issues associated with development of a spaceflight STAR instrument.

A. Architecture Investigation

The GSFC study [1] looked at the feasibility of a 27-m 2-D STAR instrument. In particular, it addressed the packaging and deployment aspects of the design, as well as electrical design constraints. As a result, a point design was developed for a Y-shaped STAR with approximately 0.8-λ element spacing. This requires approximately 230 antenna elements, twice as many receivers for dual polarization operation, and ~52,000 complex correlators. A possible implementation would be for each

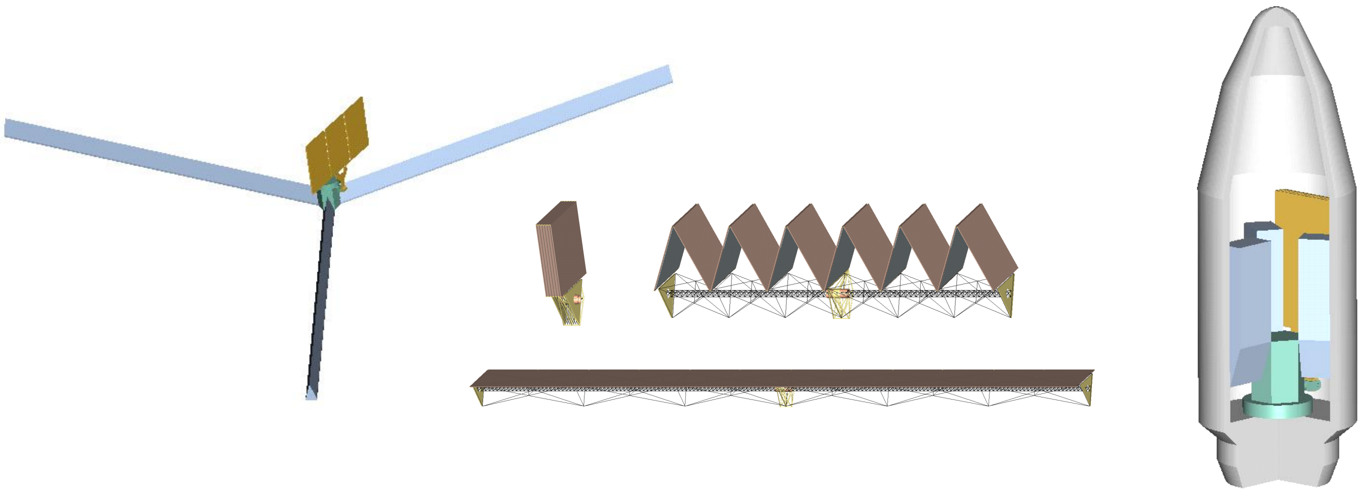
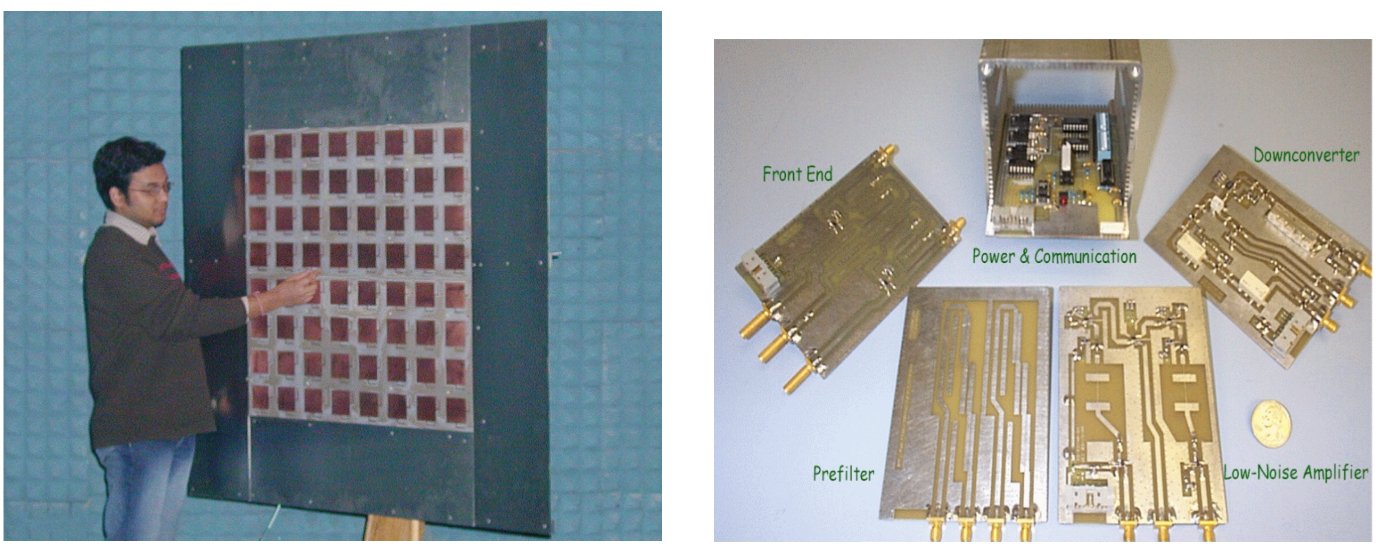


Figure 1: Mechanical concept for Y-shaped STAR with 13-m arms: (a) fully deployed, (b) arm details, and (c) stowed in the launch vehicle.



(a) (b)

Figure 2: 2D-STAR aircraft instrument components: (a) 8×8 element test array and (b) RF receiver module.

arm to be divided into panels, each with 9 antennas and approximately 1.5 m long. Using microstrip technology, each antenna would have a dual-polarized receiver right behind it. The panels have a central unit for science data collection, command and data handling, and power distribution. Figure 1 shows the mechanical concept. The system could be stowed in a Taurus-XL launch vehicle and the panels would be deployed using three masts each about 13 m long, similar to the one used in the Shuttle Radar Topography Mission (SRTM), which was 60 m long.

B. Validation by Aircraft Instrument

A 1.4 GHz airborne imaging radiometer, called 2D-STAR, is being developed under NASA's Instrument Incubator Program [4]. The 2D-STAR consists of three major subsystems: the antenna array, the RF receiver and the digital processor. The antenna array consists of a rectangular array of dual polarized, patch antennas tuned to L-band. Each patch is connected to its own microwave receiver that filters, amplifies and mixes to a common IF. The IF signal then goes to the digital processor where it is digitized, phase shifted to produce I and Q signals, and then multiplied by the signal from other antennas in the digital correlator. Figure 2 shows an 8x8 test antenna array and receiver electronics. A fully populated, rectangular array of patches is being built; however, only some of the patches will be connected to receivers. For example, the instrument could operate as a thinned array of a Y as proposed by the architecture study. Figure 2(a) shows an 8×8 element array in the anechoic chamber at the University of Massachusetts undergoing tests. Figure 2(b) shows one of the RF receivers. Each receiver consists of four printed microwave circuits: calibration switch network, prefilter, low noise amplifier (LNA), and intermediate frequency (IF) conversion section. Each receiver module also contains a microcontroller and power conditioning. The 2D-STAR will be field-tested for the first time during a soil moisture field experiment (SMEX02) in Iowa in June-July, 2002.

III. COMPONENT TECHNOLOGY

Using the above instrument concepts, engineering constraints were derived that motivated the development of several component technologies. Of particular importance is instrument power dissipation and size. These attributes are achieved through the use of low power microelectronics.

A. SiGe radiometers

A low-power and low-cost radiometer module has been developed for the L-band STAR envisioned above [5]. The low-power design is achieved by using SiGe, which is commercially available integrated circuit (IC) technology that recently has been widely utilized for wireless communications circuits. Leveraging this industry investment, the L-band microwave radiometer module uses commercial off-the-shelf (COTS) SiGe parts. The radiometer module is in a digital-IF receiver configuration and consists of a patch antenna, LNA, bandpass filter, mixer, IF amplifier, and analog-to-digital converter (ADC). The radiometer modules convert received L-band radiation into digital data streams that are transmitted to a digital cross-correlator. Figure 3 shows the RF components assembled together onto a microstrip circuit. The entire module measures only several centimeters across and dissipates $\sim$250 mW. Because of its small size and low-power dissipation, it will be possible to integrate these receivers onto panels for deployment similar to that shown in figure 1(b).

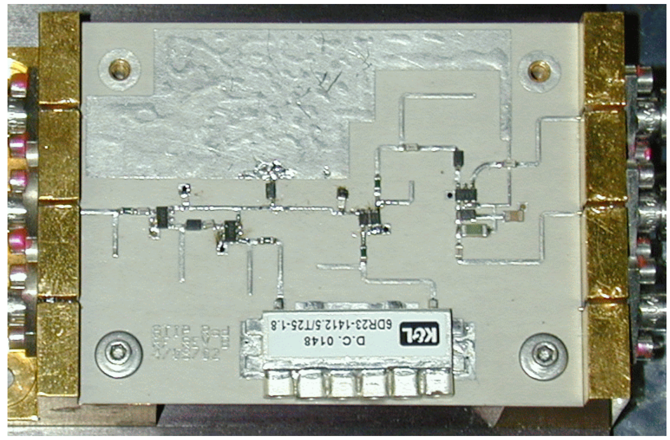


Figure 3: Photograph of prototype SiGe microwave radiometer front-end in test fixture.

B. ULP CMOS digital correlators

The coherent products of signals from antenna pairs are computed and accumulated in the digital correlator. Two digital correlators are being developed in ULP CMOS. ULP CMOS was chosen because of its low-power operation ($<$10% the power of conventional 5-V CMOS) and radiation tolerance. The first correlator to be developed in ULP CMOS was a 500 MS/s complex correlator targeted specifically to passive microwave polarimetry [6]. This correlator computes and accumulates the complex product of two 3-level inputs at a 500 MHz clock rate. A graphic of the IC layout is shown in figure 4. While not directly applicable to STAR, the high-speed logic and design techniques needed for STAR correlators were developed with this circuit. For example, the novel usage of different radiation-tolerant logic techniques allowed the correlator to be optimized for speed, power, and science data protection; this same technique can be applied to a STAR correlator.

The second correlator under development is a 2-bit 25-channel cross-correlator [7]. The correlator takes in 25 complex digital signals and computes the complex products of the $\sim$600 available baselines (or antenna pairs). A total of 1225 real multiplications and accumulations are performed at 112 MHz clock rate. The IC is estimated to dissipate only 1.5 W or about 1 mW per real correlation.

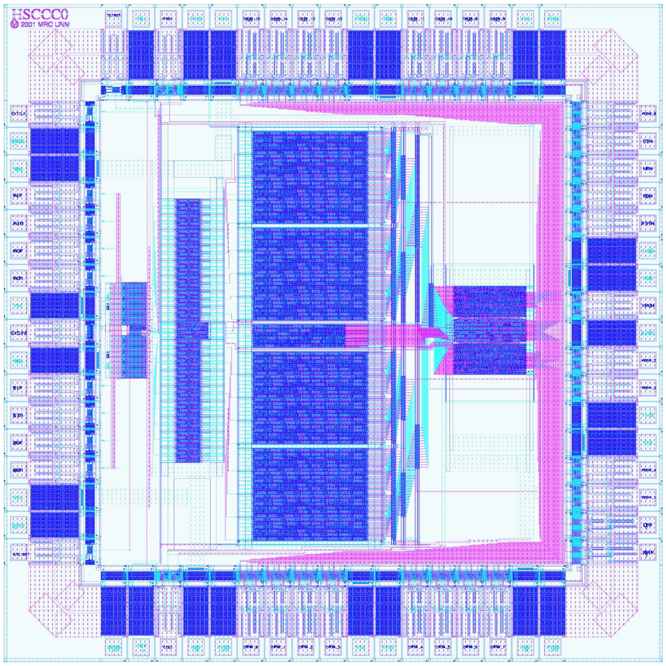


Figure 4: Metalization mask of ULP CMOS 500 MS/s cross-correlator.

C. Correlation radiometer calibration

The increased instrument complexity of a STAR radiometer imposes several technological requirements beyond those of a conventional total power radiometer, including tight balancing and stability of the radiometer receivers, as well as a more complex yet robust in-flight calibration subsystem. Calibration is a critical aspect of any instrument design and operation. However, it is often considered to be of secondary importance to the design of the instrument itself. As instrument complexity increases this approach becomes more risky, potentially increasing the chances of finding problems late in the development cycle and increasing cost. With this thought in mind, a compact low-power subsystem for in-flight STAR receiver calibration has been developed [8]. The controlled correlation calibration source can generate pairs of signals with precise correlation properties with several different states. Along with a laboratory correlation receiver testbed to provide realistic test conditions, to guide optimization, and to generate recommendations for the design of a flight-qualifiable on-board calibration subsystem, technology is being developed to ensure sufficient calibration of a spaceflight STAR instrument.

IV. FUTURE TECHNOLOGY AND SUMMARY

Several technologies motivated by science-driven system studies for 10-km soil moisture remote sensing from space have been presented. The primary developmental drivers are low power and size requirements, which are met using state-of-the-art microelectronics and sensible system design. The next steps needed to advance towards a flight instrument have been proposed and include an integrated panel of SiGe receivers and antennas, the study of a fully integrated SiGe RF-digital receiver-on-a-chip, and the appropriate demonstration of a deployable STAR arm either on the ground or in space. These developments are on-track for a soil moisture mission launch in ∼2008.

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