

Synthetic Thinned Aperture Radiometer Technology Developments Enabling a GPM Lightweight Rainfall Radiometer

Christopher Ruf¹, Caleb Principe², Tom Dod², Bryan Monosmith², Steve Musko¹,
Steve Rogacki¹, David Steinfeld², Eric Smith², Alphonso Stewart², Zhaonan Zhang²

¹University of Michigan, Ann Arbor, MI 48109 USA
734-764-6561 (V), 734-764-5137 (F), cruf@umich.edu (E)

2. NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA
301-286-8726 (V), 301-286-1750 (F), caleb.principe@gsfc.nasa.gov (E)

Abstract – The US/Japan Tropical Rainfall Measuring Mission has led to the initiation of a new international satellite precipitation mission, the Global Precipitation Measurement (GPM) mission, to be led primarily by NASA and NASDA. One of the main objectives of GPM is high frequency global sampling of rainfall. Our work develops passive microwave radiometer technology that is suitable for high quality rain measurement but is also lightweight and low power, and follows a technology path that leads to significantly reduced per unit recurring costs. Taken together, these improvements will permit multiple sensors to be flown in a constellation of small satellites, thereby increasing the sampling frequency of global precipitation.

1. INTRODUCTION

Our research and engineering developments will produce an aircraft prototype of a synthetic thinned aperture radiometer (STAR) at 10.7 GHz that is being considered as the primary instrument for a dedicated GPM constellation satellite. STAR technology provides wide swath push broom imaging with no moving parts, which significantly reduces spacecraft accommodation requirements. Additional technology developments associated with this project will lower the cost and power and increase the reliability of the spaceborne STAR sensors using: (1) a Monolithic Microwave Integrated Circuit (MMIC) for the analog receiver components; (2) an Application Specific Integrated Circuit (ASIC) low-power analog-to-digital converter for the MMIC receivers that has been optimized for use by a STAR sensor; and (3) an ultra low power, high speed ASIC for the digital signal processing correlator stage of the sensor. Notably, each of these technologies will also benefit other future spaceborne microwave radiometers.

2. SPACEBORNE MMIC RECEIVER DEVELOPMENT

A first generation hybrid MMIC-based receiver was developed together with TRW under a previous (1998) Instrument Incubator Program project. The initial design derived from flight heritage receivers flown on the Jason-1 Microwave Radiometer, with modifications made to accommodate the specific needs of a STAR correlating

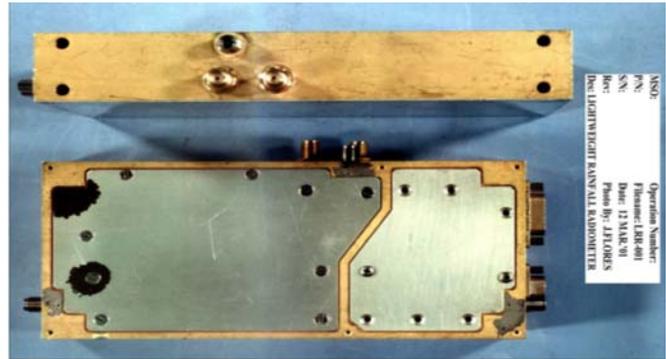


Fig. 1. First generation MMIC-based STAR correlating radiometer receiver module at 10.7 GHz., developed together with TRW. A second generation version is currently under development.

radiometer. A pair of receiver modules were fabricated. A photo of the completed module is shown in Fig. 1. These receivers operate at 10.7 GHz with a 30 MHz bandwidth, include a back end digitizer sampling at 125 MHz, and require 1.56 watts of power. Because of the hybrid nature of the receiver construction, there is some custom tuning required of the high-Q band definition stage of the RF front end. This is needed to ensure proper phase and amplitude matching between units as required for STAR applications.

A follow-on development effort is presently underway with TRW to produce a second generation receiver module that: a) has imbedded band definition stages to eliminate the need for custom tuning, improve the repeatability and phase and amplitude matching between units, and reduce the recurring costs of multiple units; b) has custom RF and IF MMIC modules that reduce the DC power requirement to 1/2 watt/each; and c) incorporates a custom low power STAR-optimized analog-to-digital converter that is also being developed (see below). The wafer run for the 2nd generation receivers also includes 1st generation versions of key RF modules that will be needed by STAR receivers at 19 and 37 GHz. This is in anticipation of the possible utilization of the STAR sensor approach by GPM at these higher frequencies on either its core or constellation spacecraft.

3. SPACEBORNE ASIC A/D AND CORRELATOR DEVELOPMENTS

The Microelectronics Research Center (MRC) at the University of New Mexico is designing and fabricating custom ASICs that will significantly enhance the performance of, while simultaneously reducing the power required by, a spaceborne STAR sensor. An analog-to-digital converter (ADC) is being built which has capabilities specific to a correlating radiometer. It has four quantization levels (2 bits) that have adjustable boundaries (input voltage thresholds). The boundaries are individually set by high precision digital-to-analog converters that are imbedded in the ADC itself but are controlled externally by the user. The ADC is expected to require 30 milliwatts of power when clocked at the 84 MHz rate required of the spaceborne 10.7 GHz STAR sensor. Its power requirement increases to ~100 milliwatts as the clock rate is increased to the 224 MHz rate that is required of a 37 GHz spaceborne STAR sensor. Note that the bandwidth accommodated by the analog input stage of the ADC is significantly higher than the allowable clock rate. This permits the ADC to operate in a sub-sampling mode, as required by the current STAR sensor design.

A digital correlator ASIC is also being developed at the MRC. This device performs complex cross-correlations of all pairs of digitized input signals, as well as computing total power self-correlations of each individual signal. A functional clock diagram of its architecture is shown in Fig. 2. The chip is capable of handling up to 25 input channels at clock rates of up to 224 MHz (as required by the spaceborne STAR design at 37 GHz). The chip also includes individual “totalizer” counters for each quantization bin of every input channel which generate real time histograms of the distribution of signal strength across the ADC input voltage ranges. This information is needed to produce STAR brightness temperature images with maximum signal-to-noise ratio without resorting to very high precision ADC and correlator subsystems. The ability to perform all necessary digital signal processing using only 2 bit precision is needed in order to keep the power requirements of the system low

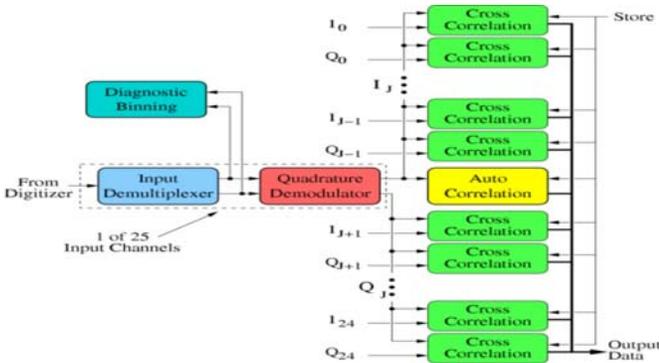


Fig. 2. Functional block diagram of ASIC digital correlator under development by the University of New Mexico Microelectronics Research Center.

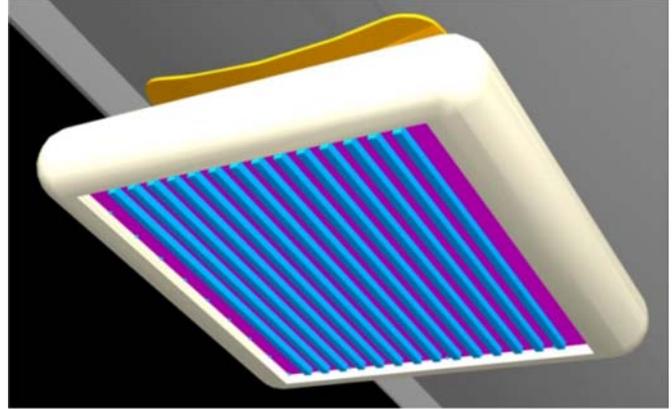


Fig. 3. A preliminary design for the mechanical housing of the aircraft LRR-X sensor is shown. The long thin antennas provide a wide (fan beam) field of view perpendicular to the direction of aircraft motion. (Actual antenna positions are non-uniformly spaced, see [3].)

The correlator is expected to require ~1.5 watts of DC power when clocked at its maximum rate of 224 MHz.

4. AIRCRAFT SENSOR DESIGN OVERVIEW

The LRR-X prototype aircraft sensor is functionally equivalent to a candidate space flight sensor design [2]. The prototype will provide high fidelity estimates of the image resolution and field of view, absolute calibration, ΔT sensitivity and data rate requirements for the space flight version. LRR-X can be divided into a number of major subsystems: (a) The antenna consists of 14 slotted waveguide antenna array elements that are mounted below a solid ground plane that extends out 3λ beyond the outermost waveguide edges in order to ensure repeatable antenna backlobe behavior whether undergoing characterization testing in an anechoic chamber or mounted on the aircraft in operation. (b) The receivers are discrete component versions of the flight MMIC design with functional equivalence. They amplify an RF signal centered at 10.7 GHz and with a 30 MHz bandwidth, demodulate it to an intermediate frequency range centered at 41 MHz, and digitize it at 125 MHz with 2 bits of resolution. (c) The correlator performs real and complex self and cross correlations on the signal pairs. (d) The Control & Data Handling (C&DH) subsystem interfaces between the sensor and a user computer and it archives data. (e) The calibration subsystem includes uncorrelated reference loads and correlated injected noise diodes to monitor system gain and offset parameters. Calibration also includes the image reconstruction algorithm used to convert raw measurements into a brightness temperature image. (f) The power supply convert aircraft power to regulated and conditioned DC voltages. (g) The thermal/mechanical housing controls sensor temperature, packages and protects the sensor, and provides the mechanical interfaces to the aircraft. Fig. 3. shows a preliminary design for the housing. The LRR-X system block diagram is shown in Fig. 4.

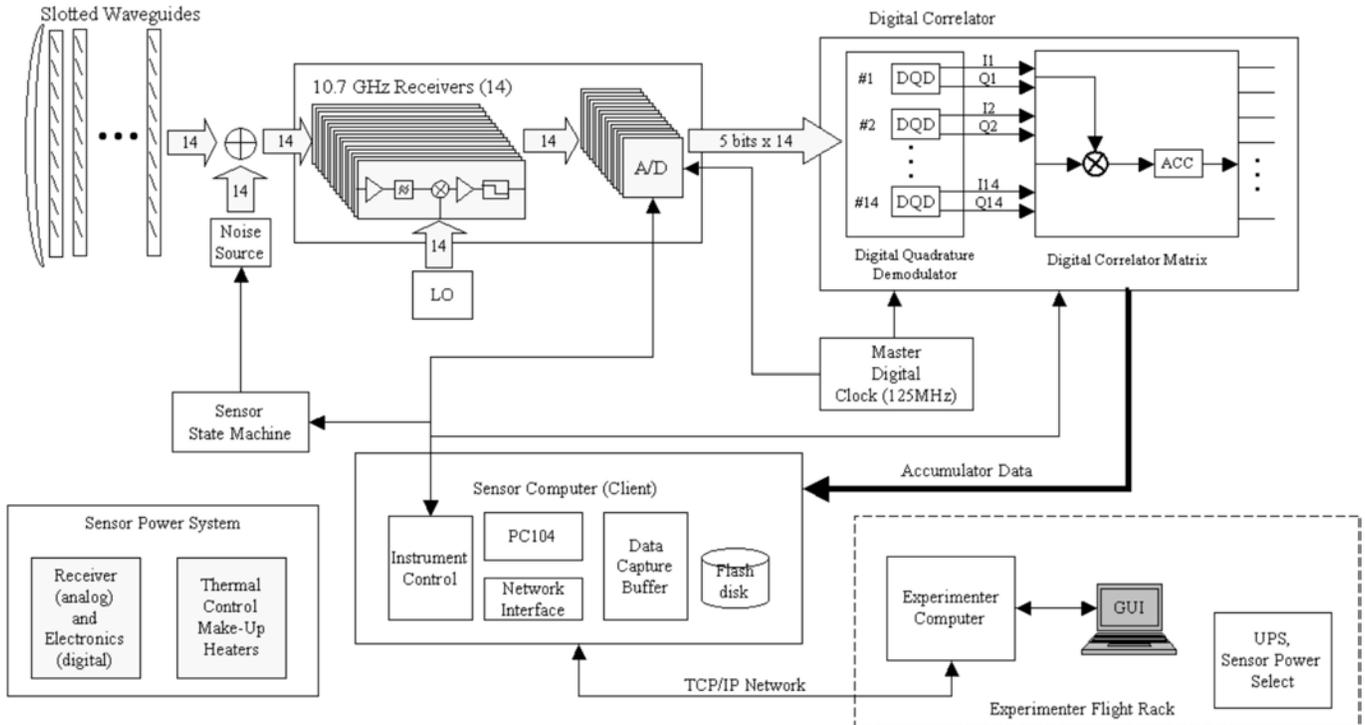


Fig. 4. LRR-X aircraft sensor system block diagram.

5. AIRCRAFT SUBSYSTEM DESIGN DETAILS

A. Antenna

The antenna consists of 14 fan beam antenna elements in an optimally thinned configuration distributed over a $\sim 110 \times 110$ cm plane [3]. Each antenna element is a 36 slot slotted waveguide antenna. Fig. 5 shows a single 36 element slotted waveguide antenna installed in the ground plane assembly that will eventually be populated by all 14 fan beam antennas.

B. Receivers

The output from each of the 14 antenna array elements passes first through a directional coupler that can inject a correlated noise signal from a common calibration noise diode. Next is a SPDT PIN switch that can switch the receiver between either of the antenna signal or a blackbody coaxial termination. Following that is the receiver's low noise amplifier, band definition filtering and additional gain, a down conversion mixer, an IF gain stage and additional filtering, and finally a 125 MHz 2 bit digitizer (30 MHz RF bandwidth with x2 oversampling to permit digital quadrature demodulation).

C. Correlator

The digital correlator will be implemented using Programmable Logic Devices that are capable of supporting

14 parallel input lines from the individual digitizing receivers at their full 125 MHz clock rate. In the first stage of the digital correlator board, each input is quadrature demodulated into separate In Phase (I) and Quadrature (Q) channels. An array of self- and cross-correlators next perform the necessary multiplications between channels, followed by accumulations of 100 ms prior to data archiving. Fourteen self-correlations of each I channel will be performed, together with 91 each of $I_i I_j$, $Q_i Q_j$, $I_i Q_j$, and $Q_i I_j$



Fig. 5. A single 36 element slotted waveguide antenna is shown installed in the ground plane that will eventually be populated by 14 similar antennas. cross-correlations between receiver channels i and j .

D. Control & Data Handling

The C&DH subsystem will perform several tasks. It will archive correlator data products. It will manage thermal control of the a/c sensor using a real time P.I.D. controller. It will configure the digital correlator and calibration switching controllers as a state machine to raster through the sequence of modes of operation in the proper order and with the proper individual dwell times. The nominal sequence of modes is: 1) clear Earth view; 2) clear Earth view plus injected calibration noise diode; and 3) reference calibration load view. Finally, the C&DH subsystem will provide a real time data and system configuration interface between the sensor and a separate user interface computer (nominally a portable laptop computer). C&DH CPU and Experimenter Laptop – PC104 stack inside sensor and user control laptop inside the aircraft cabin. The CPU module is built using a PC104: P266 CPU running QNX realtime Unix OS, Solid State hard drive, GPS, and Ethernet card. The prototype assembled, OS installed, and the ethernet interface to user control laptop are working. •Thermal monitoring & control interface board will be designed for 64 input channels (temps, voltages). This board will also have Independent PID zone heater controls for each receiver. Design requirements and interfaces have been established.

E. Calibration

There are three major components of the calibration subsystem. A controllable, highly repeatable source of partially correlated thermal noise is needed as a calibration standard for ground testing and characterization. The Correlated Noise Calibration Standard (CNCS) uses two synchronously clocked digital arbitrary waveform generators capable of producing two highly reproducible noise sources with arbitrary quadrature components of partial correlation [4]. It has been developed specifically to evaluate the performance of the receiver modules but is also intended for use as a more general piece of test equipment. Specifically, the CNCS will be used to: 1) evaluate benchtop performance of all receivers and correlators; and 2) determine the calibration information contained in on-board calibration noise diodes and reference loads (used in both aircraft and spacecraft designs).

The second component of the calibration subsystem is the on-board calibration that is a part of the instrument hardware. This includes individual uncorrelated black body warm loads assessable by each receiver via a calibration switch and a single noise diode that provides correlated noise to each receiver via a directional coupler inserted between each antenna and its receiver. These devices are intended to monitor and allow for correction of instrument gain and offset drifts, including those due to changes in the relative phase and amplitude matching between receivers.

The third component of calibration of a synthetic aperture radiometer is the image reconstruction algorithm. Image reconstruction takes the measured correlations as inputs and produces brightness temperature images as outputs. These images are, to first order, simple Fourier transforms of the measured correlations. However, this first order relationship only holds given ideal antenna characteristics. In practice, the overall accuracy of a synthetic aperture radiometer's images is dominated by the accuracy with which actual antenna element and interference patterns can be accounted for. It is for this reason that the proposed antenna design has been optimized with respect to stabilizing as much as possible the behavior of the element and interference patterns.

Absolute accuracy of the image reconstruction algorithm will be tested and demonstrated by a series of system-level tests. Ground Integrated System Testing will include a Sky cal on a rooftop instrument pedestal to exercise instrument internal cal with a cold, zero reflection antenna scene. This will measure antenna losses, ΔT , injected cal brightness, test ground plane effectiveness, and establish spacecraft accommodation requirements for antenna clearance. A Compact range anechoic chamber will be used to measure antenna-pair interference patterns. This will produce the G-matrix needed for image reconstruction. Aircraft Integrated System Testing will overfly an open ocean test site instrumented with a ground based upward directed noise beacon and full surface met data. This will provide a model TB scene from surface instrumentation to verify LRR absolute calibration.

F. Mechanical/Thermal Housing

Thermal analysis is on-going for an instrument operating specification of -50° to $+50^{\circ}$ C. A liquid-based chiller/heater system will be used as part of the thermal control system. Controller specifications will be further refined once a more precise definition of physical model, power dissipation, environmental parameters, and instrument calibration requirements are reached.

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