Prototype development of a Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR)

Pekka Kangaslahti, Alan Tanner, William Wilson, Steve Dinardo and Bjorn Lambrigsten

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Abstract — **Weather prediction and hurricane tracking would greatly benefit of a continuous imaging capability of a hemisphere at millimeter wave frequencies. We are developing a synthetic thinned aperture radiometer (STAR) prototype operating from 50 to 56 GHz as a ground-based testbed to demonstrate the technologies needed to do full earth disk atmospheric temperature soundings from Geostationary orbit with very high spatial resolution. The prototype consists of a Y-array of 24 MMIC receivers that are compact units implemented with low noise InP MMIC LNAs, second harmonic I-Q mixers, low power IF amplifiers and include internal digital bias control with serial line communication to enable low cost testing and system integration. Furthermore, this prototype STAR includes independent LO and noise calibration signal phase switching circuitry for each arm of the Y-array to verify the operation and calibration of the system.**

Index Terms — **Millimeter wave low noise amplifiers, Millimeter wave antenna arrays, MMIC phase shifters, MMIC receivers, Synthetic aperture imaging**

I. INTRODUCTION

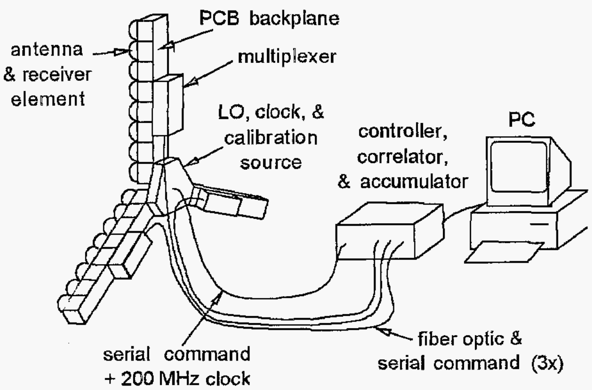
The National Oceanic and Atmospheric Administration (NOAA) has for many years operated environmental satellite systems in polar orbiting low earth orbits, and Geostationary Operational Environmental Satellite systems (GOES) in geostationary earth orbit (GEO). The low earth orbit satellites have been equipped with both infrared and millimeter wave atmospheric sounders, which together enable characterization of the vertical distribution of temperature and humidity in the troposphere even under cloudy conditions. In contrast, the GOES satellites have only been equipped with infrared sounders due to the large apertures required to achieve sufficient spatial resolution from GEO at millimeter wave frequencies. This lack of cloud penetrating millimeter wave instrumentation has limited the GOES soundings to cloud free areas and to the upper atmosphere, above the cloud tops, hindering the effective use of GOES data in numerical weather prediction. However, full sounding capabilities with the GOES system would be highly desirable because of the advantageous spatial and temporal coverage that is possible from GEO. While low earth orbit satellites provide coverage in relatively narrow swaths, and with a revisit time of 12-24 hours or more, GOES satellites can provide continuous hemispheric or regional coverage, making it possible to monitor highly dynamic phenomena such as hurricanes.

As a solution to this observational need, we have designed a prototype instrument to demonstrate enabling technology for a new operational millimeter wave sounder on GEO, the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR). GeoSTAR synthesizes a large aperture to measure the atmospheric parameters with high spatial resolution from GEO. The main benefit of the STAR approach is the stationary and light weight receiver array structure, which, in comparison to the very large and massive dish antenna and mechanical scanning system of a real-aperture instrument, makes it possible to integrate it with other instruments on the GOES platform. These receiver arrays are one of the enabling technologies of the GeoSTAR and to implement them we have developed MMIC receiver modules that have low noise and low power consumption. These modules included internal digital bias control to allow switching between operating modes and to simplify the testing and tuning. For the purpose of verifying the performance of the receiver arrays we have designed to the local oscillator and noise signal sources several phase switching components that enable various calibration schemes. The overall objectives of our GeoSTAR prototype development are to reduce technology risk for future space implementations as well as to demonstrate the measurement concept, test performance, evaluate the calibration approach, and assess measurement accuracy.

II. INSTRUMENT CONCEPT

As illustrated in Fig. 1, GeoSTAR consists of a Y-array of horn antennas and receivers, and a digital system which computes cross-correlations between the IF signals of the receivers. The receivers are pointed in the same direction and remain fixed throughout the measurement which is conducted by forming complex cross-correlations between all possible pairs of receivers of the array. In the small scale example of Fig. 1 there are 24 receivers and 276 correlations (=24*23/2). Each correlator and receiver pair forms an interferometer which measures a particular spatial harmonic of the brightness temperature image across the field of view (FOV). The spatial harmonic depends on the spacing between the receivers, which increases as we correlate the outputs of receivers further down the arms. As a function of this receiver spacing, the complex cross-correlation measured by an interferometer is called the visibility function. The visibility function is the Fourier transform of the brightness temperature versus incidence angle. By sampling the visibility over a range of spacings one can reconstruct, or "synthesize," an image in a computer by Fourier transform. These techniques are well known in radio astronomy, but are relatively new to earth imaging problems.

The "Y" configuration of the GeoSTAR array is motivated by the need to measure a complete set of visibility samples with a minimum number of receivers and, thus, Geostar uses a thinned (or "sparse") array to simultaneously measure all the required spacings from a fixed geometry. There are many kinds of sparse arrays, and the "Y" array of Fig. 2 is one of the best in terms of efficient use of receivers and in terms of the simplicity of the structure - which lends itself well to a spaceborne deployment. As illustrated in Fig. 2, when each receiver output gets correlated with the outputs of the receivers in the other arms, it yields a uniform hexagonal grid of visibility samples. From radio astronomy conventions, the spacings are called the "baselines" with the dimensions "u" and "v." The area covered by this sampling grid is the synthetic aperture of the system, which is comparable to a real aperture of the same outer dimensions (e.g. a dish antenna, or a filled aperture phased array). The primary advantage to the sparse array is that it uses far less physical antenna aperture than the comparable real aperture.



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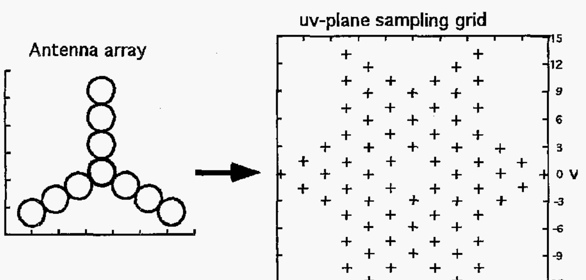

Fig. 2. Antenna array and UV samples

The smallest spacing of the sample grid in Figure 2 determines the unambiguous field of view, which for GeoSTAR must be larger than the earth disk diameter of 17.5 degrees when viewed from GEO. This sets both the receiver spacing and the horn antenna diameter at about 3.5 wavelengths, or 2.1 cm at 50 GHz, for example. The longest baseline determines the smallest spatial scale that can be resolved. To achieve a 50 km spatial resolution at 50 GHz, a baseline of about 4 meters is required. This corresponds to approximately 100 receiving elements per array arm, or a total of about 300 elements. This in turn results in about 30,000 unique baselines, 60,000 uv sample points (with conjugate symmetry), and 60,000 independent pixels in the reconstructed brightness temperature image. These individual image pixels will have a delta T of 1K.

III. Prototype Instrument

A small scale prototype is being built to address the major technical challenges facing GeoSTAR. The challenges are centered around the issues of calibration and power consumption. Synthesis arrays are new and untested in atmospheric remote sensing applications, and the calibration poses many new problems, including those of stabilizing and/or characterizing the phase and amplitude response of the antenna patterns and of the receivers and correlators. These system requirements need to be better understood and furthermore, power consumption per receiver and correlator must be low given the very large number of receivers and correlators in the spaceborne system. To these ends the prototype is being built with InP MMIC receiver technology, parabolic potter horn antennas, phase switchable noise calibration circuitry, efficient and phase switchable LO distribution system and advanced signal processing. The in-phase and quadrature IF signals from each MMIC receiver are digitized and correlated in a FPGA correlator following the design of a similar system which was built for an airborne radiometer [1]. An operational spaceborne system will use low-power application specific integrated circuits (ASICs).

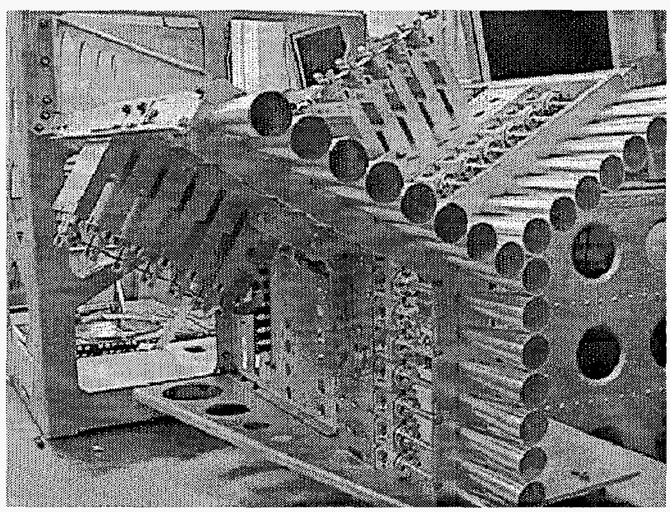

Fig. 3. Prototype instrument with 24 receivers.

The center horn in Fig. 2 poses a number of complications to the physical package and to the electrical design. The solution seen in Fig. 3 is to remove the one odd horn from the center of the array, stagger the three arms counter clockwise, and then bring them together so that the three inner most horns form an equilateral triangle. This 'staggered-Y' configuration eliminates the need for an odd receiver at the center. The only penalty is a slight and negligible loss of visibility coverage. The new configuration also has an advantage in that all visibility samples in the UV plane may be derived from receivers located on different arms of the array; this eliminates a number of phase shifters and other components in the calibration and local oscillator sub-systems.

A. Millimeter Wave I-Q Receivers

The received signal from the parabolic potter horn antennas is amplified and downconverted in MMIC receiver modules. These receiver modules include highly efficient and low noise InP MMIC LNAs. The measured noise performance of the 24 receivers is shown in Fig. 4 with the internal three LNAs providing 60dB of gain and consuming about 50mW of power. The gate and drain voltages of the MMIC LNAs are controlled with digital bias circuitry that is placed inside the receiver module. Thus, the interface to the receiver module is an addressed serial line to set and store the LNA bias voltages to the internal controllers. This implementation enables automated testing and tuning of the receiver modules and simplified system control.

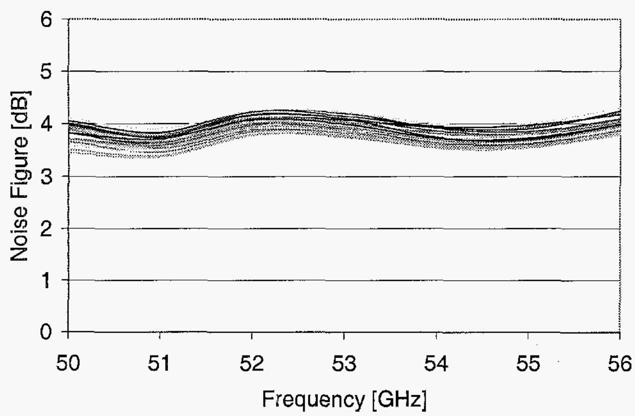

Fig. 4. Noise figures of the 24 receivers.

For calibration purposes we will switch receiver modules between the nominal receiving mode and isolated noise mode, where the first LNA will be turned off to provide more than 40dB of isolation and the subsequent LNAs will be switched to a higher gain bias point to provide digitizable level of noise power that is uncorrelated to the signal in the other receivers. The receivers perform a double-sideband second harmonic downconversion in phase quadrature to two IF signals at 10 to 100 MHz frequency band. The LO buffer amplifier at 25 to 27.5 GHz frequency range and the second harmonic I-Q mixer are commercially available GaAs MMICs. The 100 MHz IF is amplified with commercially available SMD SiGe MMICs and defined by lumped element filters. The LO buffer amplifier has a power consumption of 200mW and the IF amplifiers use 110mW of power to amplify the two IF channels by 40dB. Total power consumption of the amplifiers in the unit is 360mW, however, the bias regulation circuitry is supplied with Vs = +5V and, thus, the total power consumption of a single receiver module is twice as high. A photograph of the receiver module is provided in Fig. 5.

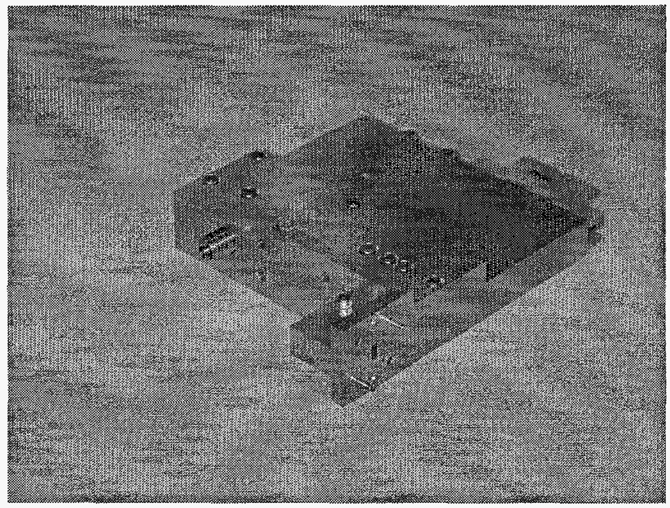

Fig. 5. Millimeter wave receiver module.

B. LO system

A simplified block diagram of the GeoSTAR prototype is given in Figure 6. The local oscillator signal is from 25 to 30 GHz, and it is split to the three phase switch and buffer amplifier modules, one for each arm of the array. These MMIC phase switches periodically switch the phase between the four positions of 0, 45, 90, and 135 degree, which results in phases of 0, 90, 180, and 270 degrees, respectively, at the second harmonic RF. This mechanism provides two functions: (1) it is used to eliminate correlator biases (i.e. by synchronous demodulation of the 0/180 states and the 90/270 states) and (2) it provides a redundant means of ensuring quadrature balance between the in-phase and quadrature correlators of a given receiver pair. The staggered-Y arrangement of the array is crucial to this function since one would otherwise need individual phase shifters for each receiver module.

C. Noise Calibration System

Figure 6 shows the 8-way calibration feed which periodically injects a noise diode signal into all receivers from a common noise diode source. This signal will be used as a reference to stabilize the system against phase and system noise drifts. The critical assumption here is that the calibration distribution network - consisting of power dividers and couplers - is more stable that the receiver RF, IF, and correlator electronics. This assumption will be carefully re-examined when the system is operational. The injected noise diode signal needs to be in the range of 1 to 10 Kelvin of equivalent noise temperature at the receiver input. In Figure 6 the noise diode is distributed to the three arms via phase shifters. Each of these phase shifters consists of a PIN MMIC assembly which can switch between 0 degrees and 120 degrees. Correlations which occur between receivers of different arms can be exited by the noise diode with three possible phases using any two of these switches. This capability is critical to ensure that every correlator can be stabilized with respect to both phase and amplitude. Without this capability one must otherwise depend on perfect quadrature balance of the complex correlations- which is predictably not perfect. It is also worth noting that the phase of the noise diode can not be shifted among the 8 antennas of a given arm, but that such a capability is not needed given the staggered-Y arrangement of the antennas. With the staggered-Y all correlations within an arm represent visibility samples which are redundant to samples which can otherwise be obtained between elements of different arms. These redundant correlations are not needed for image reconstruction, so they do not need to be calibrated.

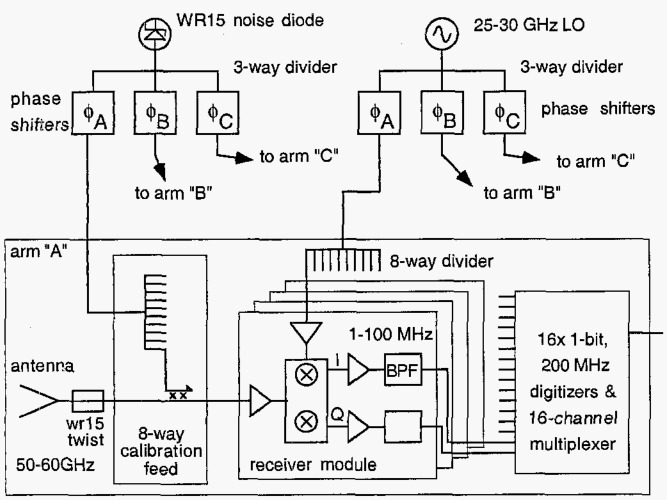

Fig. 6. Block diagram of the prototype instrument. The multiplexers in each arm provide the signals to the correlator that is not shown here.

VII. Conclusion

The real time imaging of earth's atmosphere with global coverage requires a synthetic aperture temperature sounder at geostationary orbit. We have developed a prototype 2-D system to demonstrate the feasibility of the system. The 24 millimeter receivers in the system have low power consumption and low noise figure due to the advanced InP MMIC technology used. They are also digitally controlled to ease the testing and system integration. Phase switching and distribution networks were developed both for the LO and noise signal to enable calibration and testing of the prototype instrument. With the integration of the digitizer and correlator modules the system is ready for testing and imaging.

Acknowledgement

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References

[1] Ruf, C.S., et al, "Synthetic Thinned Aperture Radiometer Technology Developments Enabling a GPM Lightweight Rainfall Radiometer," NASA Earth Science & Technology Conference, Pasadena, CA, Jun 11, 2002. http://esto.nasa.gov/conferences/estc-2002/Papers/B2P1(Ruf).pdf

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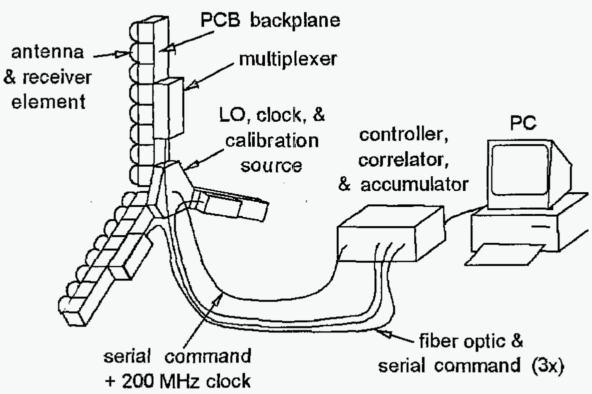
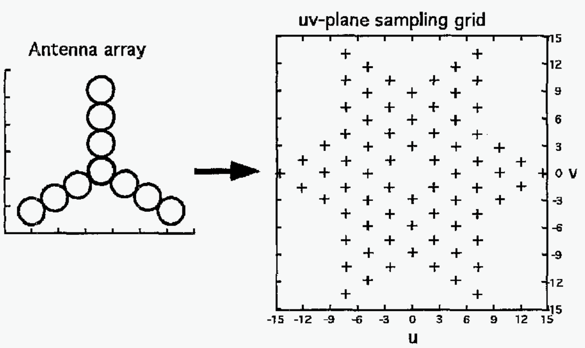


Fig. 1. Conceptual prototype configuration



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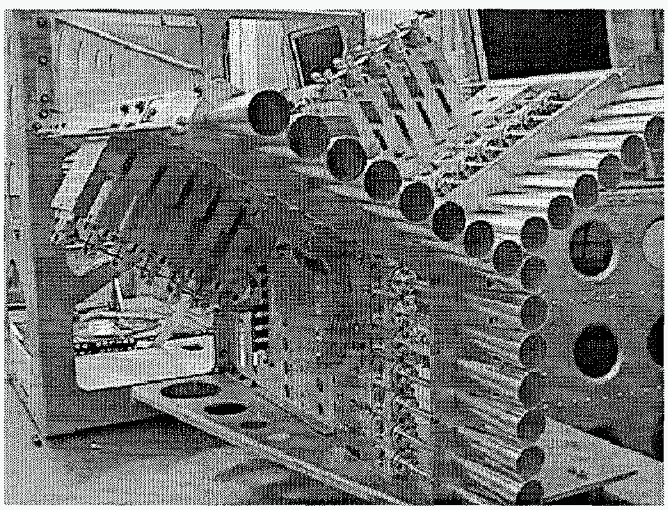

Fig. 3. Prototype instrument with 24 receivers.

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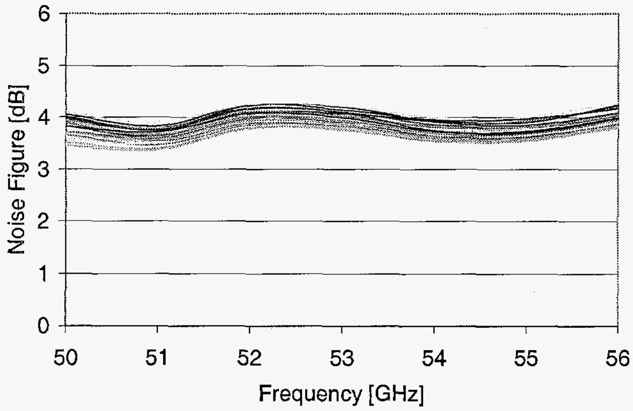

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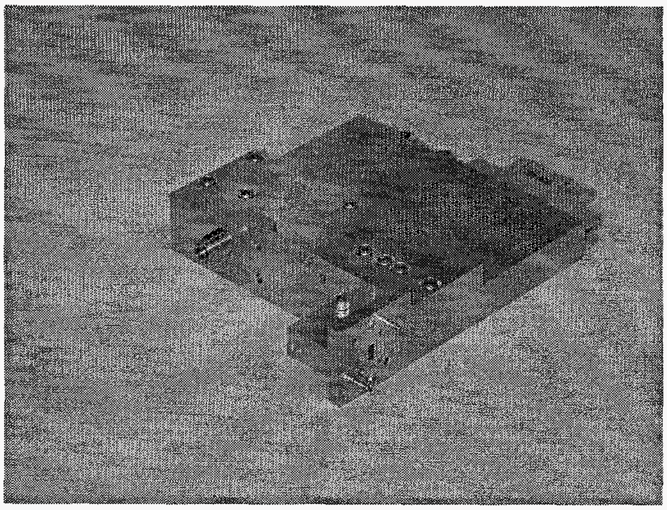

Fig. 5. Millimeter wave receiver module.

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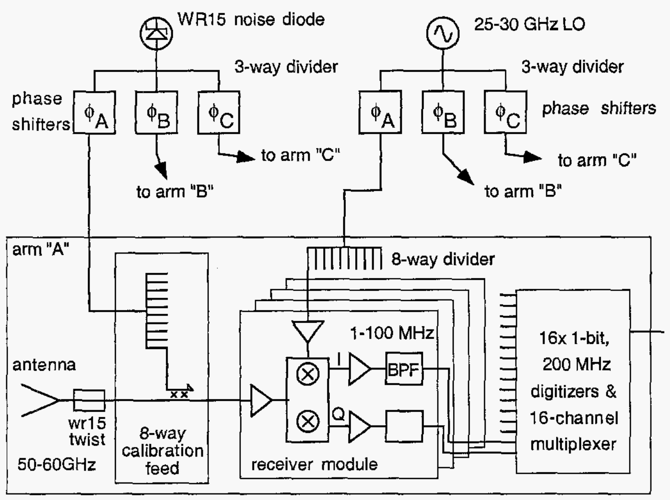

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