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Millimeter-wave Array Receivers for Remote Sensing

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ABSTRACT

Recent developments in millimeter-wave receiver have enabled new remote sensing capabilities. MMIC circuits operating at frequencies as high as 200 GHz have enabled low-cost mass producible integrated receivers suitable for array applications. We will describe several ground-based demonstrations of this technology including development of integrated spectral line receivers for atmospheric remote sensing, a synthetic thinned aperture radiometer for atmospheric sounding and imaging and polarimetric array radiometers for astrophysics applications.

Keywords: microwave radiometry, monolithic microwave integrated circuits.

1. INTRODUCTION

Passive microwave radiometry has been used for several decades to provide atmospheric temperature and humidity retrievals in a variety of cloud cover conditions. The varying atmospheric opacity as a function of frequency difference from molecular emission lines, provides the ability to vertically profile the atmosphere for the physical property sampled by the constituent line [1]. The relatively long wavelength of microwaves allows for the penetration of radiation through small scatterers, such as rain and ice, and outside the absorptive frequency bands of water, through water vapor clouds. For this reason, microwave radiometers have been employed for several decades in weather forecasting and atmospheric science.

In the 1970's the Microwave Sounding Units (MSUs) [2] were fabricated and flown aboard the TIROS-N spacecraft. These radiometers are simple four-channel instruments operating from 50.7-58 GHz, sampling the 59 GHz O₂ line. The MSUs scan a single pixel across a field of view, sounding a 2-dimensional field by the ground motion of the spacecraft. These data retrieve the atmospheric temperature, particularly the deep layer temperatures. Improving technology enabled frequencies up to 180 GHz to be added in subsequent instruments. The Atmospheric Microwave Sounding Units (AMSU), A and B provide coverage from 22 GHz to 180 GHz, sampling O₂ and H₂O lines as well as several window channels probing the surface. The shorter wavelengths are selectively susceptible to scattering and are capable of monitoring ice and precipitation. The generation of sounder currently in development, the Advanced Technology Microwave Sounder (ATMS) [3] utilizes improving technology to reduce mass and power while improving sensitivity and thus retrievals, while retaining the model of a single scanning pixel.

Monolithic microwave integrated circuit (MMIC) technology offers the possibility of integrating radiometer functions into a single chip or several chips in compact low-cost modules. This in turn allows multiple receivers to be used to image a field, improving the sampling and the sensitivity. MMIC technology has advanced to the point where circuits are now being realized at frequencies up to 350 GHz. In addition, automated packaging technologies developed for commercial applications, now demonstrate the tolerances necessary to mass-produce radiometers up to 180 GHz. It is now possible to consider *arrays* of radiometers which can be realized for modest cost. Such systems can in principle improve spatial and temporal coverage as well as synthesize large apertures, enabling observations from high altitudes with improved resolution. Exploration of architectures and technologies reveals entirely new capabilities in atmospheric remote sensing.

2. ARRAY ARCHITECTURES

Arrays of receivers can be generally classified into two categories, focal plane arrays and synthetic aperture arrays. In a focal plane array, the receiving elements are placed at the focus of a real imaging aperture. The instantaneous field of view and the resolution are determined by optical elements and the number of receivers. Since it is difficult to design optics with high magnification and a large field of view, these systems typically require mechanical steering of the optical elements.

Synthetic apertures take advantage of amplification of the incoming signal to form coherent combinations of sampled wavefronts to form a desired beam. These systems can have large instantaneous fields of view at high resolution, but require large numbers of receivers and complicated beamforming networks to do so.

2.1 Focal Plane Arrays

When considering any radiometer design, one must realize that radiometers and indeed, most instruments exhibit long-term instability, often referred to as “1/f noise”. In the case of radiometers, this noise is due mostly to gain instability of the amplifiers. To stabilize radiometers, signals are typically modulated at a high frequency and then synchronously detected. The sensitivity of such a receiver is given by the radiometer equation:

$$\Delta T = \frac{kT_{sys}}{\sqrt{\beta\tau}} \quad (1)$$

Where ΔT is the minimum detectable temperature deviation, T_{sys} is the receiver noise temperature, k is a constant of order unity depending upon the modulation scheme, β is the predetection bandwidth and τ is the integration time. An array of n receivers mapping a field (larger than the subtended solid angle of the array) has a sensitivity [4] :

$$\Delta T = \frac{kT_{sys}}{\sqrt{\beta\tau} \frac{n}{N}} \quad (2)$$

Focal plane arrays require real apertures in order to form a beam. The n receivers operate independently implying n data acquisition and processing paths. Mapping is performed by scanning the aperture. In radioastronomy focal plane arrays have been realized with as many as 32 elements, while others which are larger are in development. Small focal plane arrays have been used for remote sensing applications including SSMI and the AMSR series of radiometric imagers.

2.2 Synthetic Aperture Radiometer Arrays

Alternatively, a synthetic aperture can be used to image a field. In this scenario, n receivers all view the whole field. Phase differences between the signals received at each element can be used to reconstruct the observed radiation field. In order to reproduce the image, all possible combinations of antenna spacings and angles must be sampled. This is referred to as sampling in the u - v plane. It is possible to sample this plane with minimal redundancy in order to reproduce the observed radiation field using a thinned array. The sensitivity of the minimally redundant thinned array is given by [5]:

$$\Delta T(r, s) \cong \left(\frac{\Omega \sqrt{1-r^2-s^2}}{A_u |f(r, s)|^2} \right) \frac{\pi T_s}{2 \sqrt{2\beta\tau}} 2n \quad (3)$$

Where the term in parentheses is due to beam effects and is close to unity. For a close packed non-redundant array, the number of pixels synthesized is roughly $N=n^2$. The number of correlations is also proportional to n^2 . This can be a limiting factor in realizing a large array. For atmospheric sounding applications, where the predetection bandwidth is narrow, digital correlators make it possible to realize large n systems. The primary advantage of the synthetic aperture system is the instantaneous observation of a large field of view without scanning parts. In addition, signal modulation to overcome instrument instability can be performed with phase switching of the individual elements, a process which requires no moving parts.

In both cases, receivers arrays enabled by MMIC technology are a fundamental enabling technology.

3. MMIC RECEIVER TECHNOLOGY

We will now describe several different compact receiver systems suitable for array applications. These technologies have been demonstrated at frequencies as high as 180 GHz. The receivers all utilize monolithic microwave integrated circuit (MMIC) amplifier based technologies. These devices combine multiple functions necessary to realize a functional circuit on a single chip. The chips are generally produced using GaAs or InP transistor technologies.

3.1 Compact Correlation Receivers

For continuum applications, a large bandwidth is required. As the bandwidth increases, the $1/f$ noise corner frequency grows linearly. One solution to the modulation required to stabilize the radiometer is correlation receivers. A signal and a reference input are fed into a power combiner with in-phase and out-of-phase outputs. These two outputs are amplified and multiplied. The product signal has amplifier gain fluctuations removed. Residual fluctuations in the receiver can be modulated out by including a phase switch in the design. A schematic of a correlation receiver is shown in Figure 1.

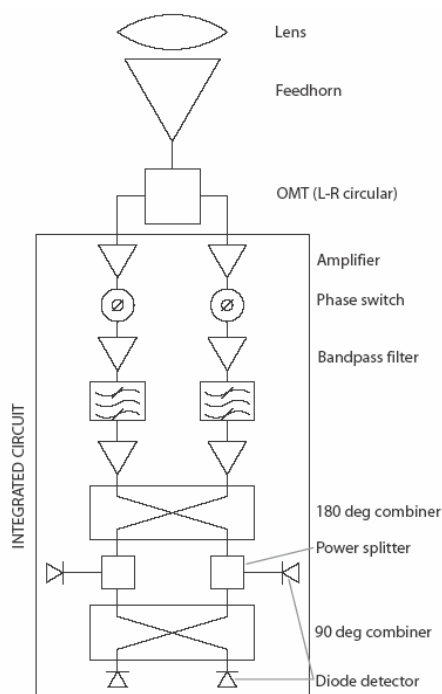


Figure 1. Schematic of a correlation receiver. The polarizer in front can be replaced by a magic-tee coupler to make the receiver a Dicke-switched intensity receiver. The 180° combiner at the back, along with the diode detectors, multiplies input signals.

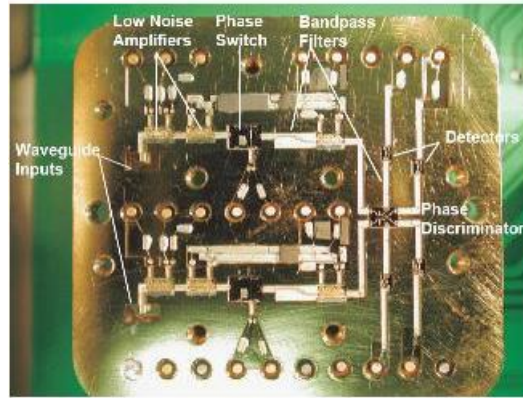


Figure 2. 90 GHz integrated correlation receiver.

We have designed built and tested correlation receivers at 40 and 90 GHz. These receivers are intended for an cosmic microwave background polarization experiment, but function as Dicke-switched intensity receivers. The 90 GHz module is shown in Figure 2. The continuum noise of the receivers is roughly 600K. The size of the module is 3cm on a side and with a compact magic-tee coupler integrated, the entire module fits within a 3 cm cube. The receivers are designed specifically for focal plane array integration with the modules mounted densely on a printed circuit board (Figure 3). With a left-right circular polarizer installed on the input, the receiver is a Q & U Stokes polarimeter.

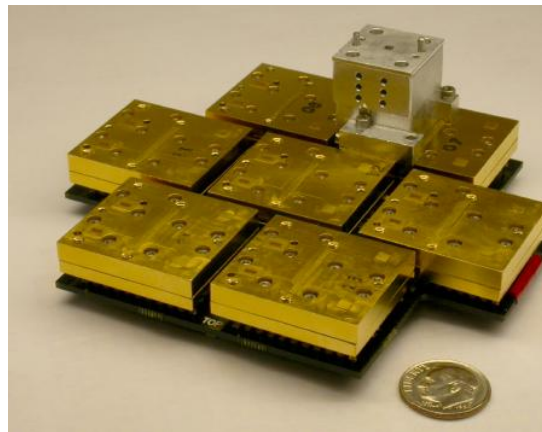


Figure 3. 7 polarimeter modules integrated on a circuit board. One of the modules has the required OMT to make the detector a polarimeter (Photo Courtesy B. Winstein, University of Chicago).

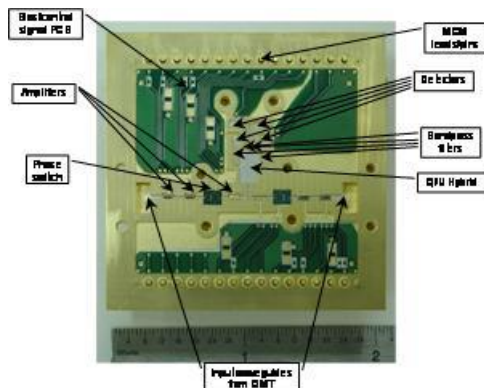


Figure 4. 40 GHz correlation receiver module. The design is similar to the 90 GHz module. The bandpass of this receiver is 38-45 GHz and the room temperature noise is 250 K.

The 40 GHz receiver (Figure 4) performs much the same way as the 90 GHz receiver. The chip sizes are approximately the same as the higher frequency version, but the waveguide interfaces are larger in proportion to the wavelength. The module is therefore 5 cm on a side. The noise of the receiver is roughly 250 K[6].

Mass production of both of these receivers is made possible by use of robotic assembly techniques. Such techniques have become widely used in commercial applications. Recent adaptation of these techniques to MMIC die along with improved placement accuracy has enabled automated assembly at frequencies well into the millimeter bands. The module in Figure 2 is fabricated robotically in a matter of minutes.

3.2 50 GHz Downconverter modules for GeoSTAR

GeoSTAR is a prototype synthetic thinned aperture radiometer designed to test the feasibility of sounding/imaging the earth disk from geostationary orbit. The STAR approach allows for a large effective aperture to obtain the required 25 km resolution, without the need for moving parts. The prototype for the GeoSTAR (Geostationary Synthetic Thinned Aperture Radiometer) required the fabrication of 24 receivers at 50 GHz. Since the signals need to cross correlated between receivers, a heterodyne architecture was required.

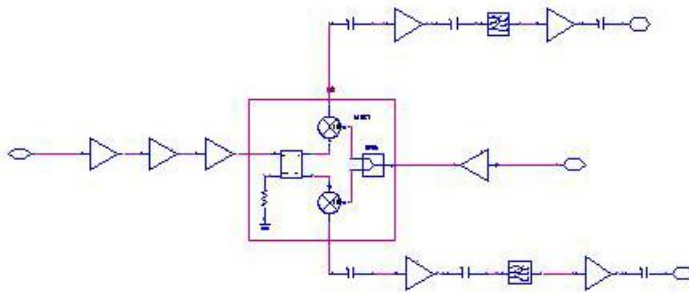


Figure 5. Schematic of a GeoSTAR downconverter module. Included in the module are RF amplifiers, and I/Q mixer, LO buffer amplifier and IF amplifiers. The bias supply is integral to the module and controllable via serial line.

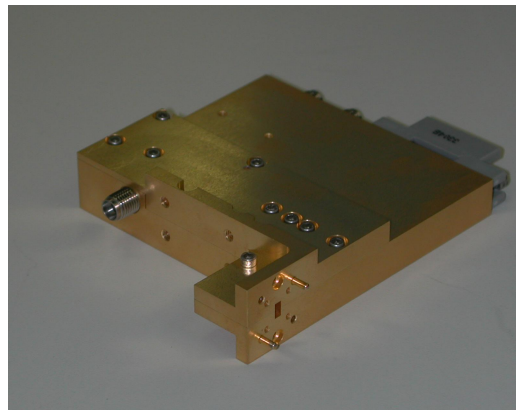


Figure 6. GeoSTAR prototype downconverter module.

Each receiver comprises an amplifier, mixer, LO buffer amplifier and IF amplifier (Figure 5). In order to directly convert to a 10-200 MHz baseband, image separation is performed with I/Q mixing with both IFs being independently digitized. For the prototype receiver, it was decided to include bias remotely programmable bias electronics in the receiver block. For a future flight system, these electronics would be removed from the modules and placed on a nearby circuit board. The receivers shown in Figure 6, cover 50-60 GHz with 4 dB noise figure[7].

4. INTEGRATED RECEIVERS

4.1 GeoSTAR Prototype

The modules described in Section 3.2 were installed in a prototype receiver designed to test the performance of a synthetic thinned aperture radiometer. The GeoSTAR instrument is shown in Figure 7. A block diagram of the instrument is shown in Figure 8. The system signal path comprises a feed horn array, calibration manifold, RF downconverter modules, IF digitizers, multiplexers, digital correlator and a data storage and processing computer. For field observations, the entire instrument was held at nearly constant temperature ($\sim 1\text{K}$) using a TE cooler and controller.

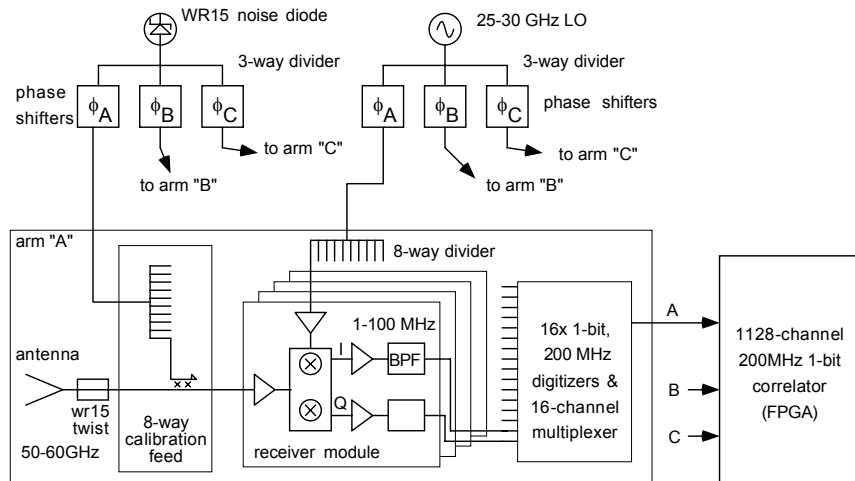


Figure 7. Schematic block diagram for the integrated GeoSTAR prototype.

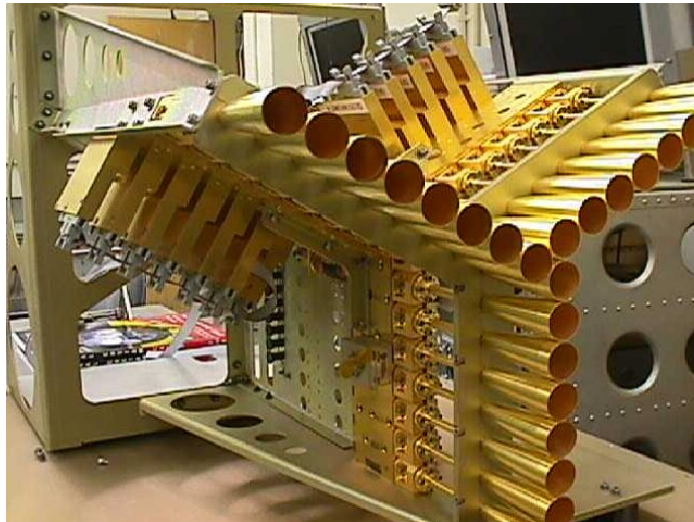


Figure 8. Photograph of the integrated GeoSTAR instrument.

With instantaneous sensitivity of $1\text{ K}\cdot\text{s}^{1/2}$ on ~ 500 pixels, the receiver was used to observe a variety of targets including the sun, the horizon, zenith, nearfield laboratory targets and a calibrator designed to simulate the Earth's field of view from geostationary orbit. The target is made of microwave absorbing material and is 4m in diameter. Two temperature controlled panels at the center of the target allow for a temperature controlled stimulus to be applied to the target. Temperature sensors are located throughout the target and accurately track temperature changes through the observations. While the far-field distance for the instrument is more than 100m, which would require an exceptionally

large calibration target, the instrument was “refocused” to a distance of ~20m using a noise source located on the target which provided a phase reference[8].

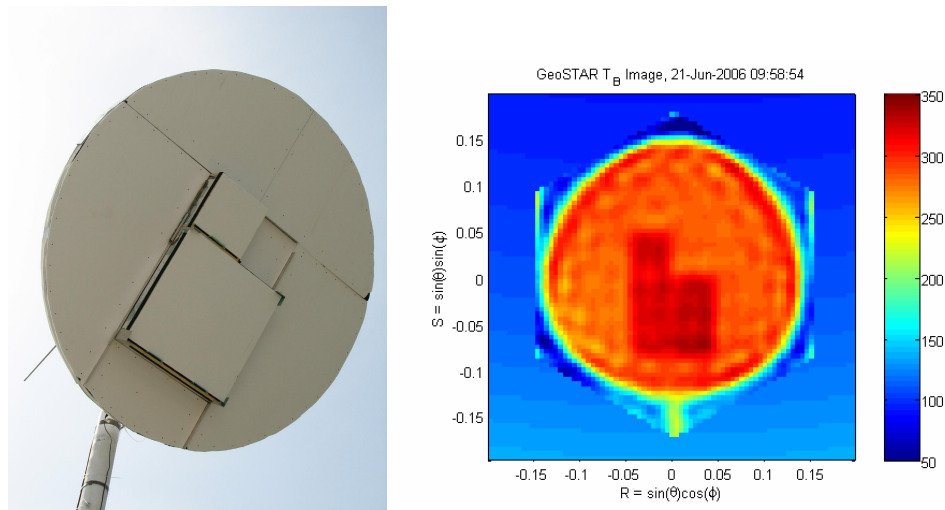


Figure 9a (left) The test calibrator is designed to subtend the same field of view as the Earth from geostationary orbit. Temperature sensors are embedded throughout the microwave absorbing structure and the two square panels near the center are temperature controlled to provide a calibrated known temperature difference. 9b(right) A 50.1 GHz image of the calibrator, produced by GeoSTAR.

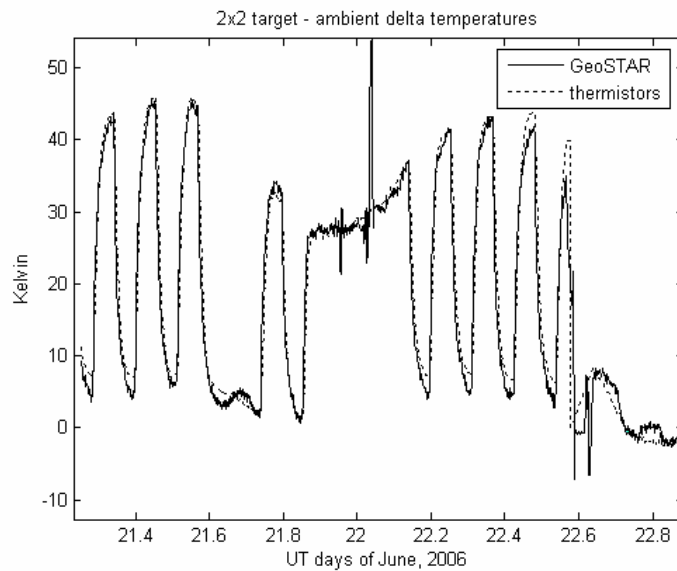


Figure 10 GeoSTAR instrument response and embedded thermistor response on the smaller of the two temperature controlled sections of the calibrator. This demonstrates the ability of GeoSTAR to produce calibrated thermal images.

The calibrator was mounted on a fiberglass boom, allowing the target to be held against a cold sky (Figure 9a). Several days of observations were carried out in June 2006. During these observations, the solar angle on the target was varied allowing the target to warm and cool with the diurnal cycle. The temperature controlled panels were heated and cooled to verify the instrument calibration. Finally the target was positioned so that the sun would be eclipsed by the target to simulate the daily eclipse seen from geostationary orbit. This is important because the spacings chosen for the array create a region around the primary disk which can be aliased into the field of view. This final test allows evaluation of the aliased sun image within one hour of sunset/sunrise on the image, testing our ability to remove this signal based

upon knowledge of the system. A thermal image of the calibration target is shown in Figure 9b. The ability to track thermal changes in the target is clearly demonstrated in Figure 10[9].

5. CONCLUSION

We have demonstrated the feasibility of using MMIC multichip modules to develop arrays of radiometers. These modules have been developed as correlation receivers for focal plane arrays, primarily for astronomy applications, but applicable as well to Earth remote sensing. We also developed components for synthetic aperture arrays for Earth atmospheric observations. The receiver modules were successfully integrated into a fully functional prototype STAR instrument. The instrument was used to observe a calibration target, successfully demonstrating the feasibility of thermal calibrations with this system.

6. ACKNOWLEDGEMENTS

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