GeoSTAR – A Breakthrough in Remote Sensing Technology

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Abstract—**The Geostationary Synthetic Thinned Radiometer (GeoSTAR) is a new concept for a microwave sounder intended for geostationary satellite applications. A small ground based proof-of-concept prototype has been developed at the Jet Propulsion Laboratory under the Instrument Incubator Program. The prototype, which is a fully functional 50-GHz temperature sounder, is now complete and has been undergoing testing at JPL and at the Goddard Space Flight Center, and the results have exceeded all expectations. The system is both accurate and extremely stable, and realistic and accurate radiometric images of natural scenes have been obtained for the first time with such an aperture synthesis system. This is a breakthrough achievement, which is expected to lead to a space based version within a decade, and GeoSTAR is likely to become one of the payloads on NOAA's next-generation geostationary satellites, the GOES-R series. We present some of the latest test results.**

I. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) has for many years operated two weather satellite systems, the Polar-orbiting Operational Environmental Satellite system (POES), using low-earth orbiting (LEO) satellites, and the Geostationary Operational Environmental Satellite system (GOES), using geostationary earth orbiting (GEO) satellites. Similar systems are also operated by other nations. The POES satellites have been equipped with both infrared (IR) and microwave (MW) atmospheric sounders, which together make it possible to determine the vertical distribution of temperature and humidity in the troposphere even under cloudy conditions. Such satellite observations have had a significant impact on weather forecasting accuracy, especially in regions where in situ observations are sparse, such as in the southern oceans. In contrast, the GOES satellites have only been equipped with IR sounders, since it has not been feasible to build the large aperture system required to achieve sufficient spatial resolution for a MW sounder in GEO. As a result, and since clouds are almost completely opaque at infrared wavelengths, GOES soundings can only be obtained in cloud free areas and in the less important upper atmosphere, above the cloud tops (i.e. less important in a weather context). This has hindered the effective use of GOES data in numerical weather prediction. Full sounding capabilities with the GOES system is highly desirable because of the advantageous spatial and temporal coverage that is possible from GEO. While POES 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. Such observations are also important for climate and atmospheric process studies.

Based on a concept first developed at the Jet Propulsion Laboratory in 1998 and intended for the NASA New Millennium EO-3 mission [1], GeoSTAR synthesizes a large aperture to measure the atmospheric parameters at microwave frequencies with high spatial resolution from GEO without requiring the very large and massive dish antenna of a real-aperture system. Sponsored by the NASA Instrument Incubator Program (IIP), an effort has been under way at the Jet Propulsion Laboratory since 2003 to develop the required technology and demonstrate the feasibility of the synthetic aperture approach with a small ground based proof-of-concept prototype [2]. This is being done jointly with collaborators at the NASA Goddard Space Flight Center and the University of Michigan and in consultation with personnel from the NOAA/NESDIS Office of System Development. The objectives 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. When this risk reduction effort is completed, a space based GeoSTAR program can be initiated, which will for the first time provide MW temperature and water vapor soundings as well as rain mapping from GEO, with the same measurement accuracy and spatial resolution as is now available from LEO – i.e. 50 km or better for temperature and 25 km or better for water vapor and rain. Furthermore, the GeoSTAR concept makes it feasible to expand those capabilities without limit, to meet future measurement needs.

The GeoSTAR prototype has now been completed, and tests are under way to assess its performance. Results so far are excellent, and this development can now be characterized as proof of the aperture synthesis concept. This constitutes a major breakthrough in remote sensing capabilities. Further technology development is under way, both as risk reduction and to enhance the measurement capabilities of the GeoSTAR system. At the same time, efforts are also under way to identify sponsorship and secure funding for a space demonstration mission in the 2012-2015 time frame. It is likely that a GeoSTAR mission will be a joint NASA-NOAA undertaking, which increases the programmatic complexity, and many programmatic issues remain to be resolved.

II. Performance requirements

In developing the GeoSTAR technology and prototype a notional space system performing at the same level as the Advanced Microwave Sounding Unit (AMSU) system now operating on NASA and NOAA polar-orbiting LEO satellites was used for design and sizing purposes. The notional operational GeoSTAR will provide temperature soundings in the 50-60 GHz band with a horizontal spatial resolution of 50 km and water vapor soundings and rain mapping in the 183-GHz band with a spatial resolution of 25 km. A possible third band would operate in the 90-GHz window region (and would possibly also cover the 118-GHz oxygen line for additional information about clouds). Radiometric sensitivity will be better than 1 K in all channels. These are considered to be the minimum performance requirements, but the first space implementation could be built to exceed this minimum performance. We stress that it is necessary to operate in these bands in order to provide soundings to the surface. In particular, moist and cloudy tropical conditions, such as encountered in the tropical cyclones that are of paramount interest, can only be fully sounded in the 50- and 183-GHz bands.

With the notional GeoSTAR system, it will be possible to produce temperature soundings within the troposphere for most of the visible Earth disc (out to an incidence angle of 60° or more) with a 2-4 km vertical resolution every 30 minutes and humidity soundings with a vertical resolution of 2-4 km every 5-10 minutes. GeoSTAR is a non-scanning 2D imaging system. These soundings are obtained everywhere at the same time – i.e. there is no time lag between different portions of the scene as there is in a mechanically scanned system. That also makes this system ideal for derivation of wind profiles through tracking of water vapor features – although the vertical resolution is limited. GeoSTAR produces several 2D "snapshots" every second. These images are combined over longer time periods to produce low-noise radiometric images that are then used for geophysical "retrievals" or directly assimilated into forecast models. It is also possible to recover temporal information at a much higher resolution than the "averaging window" of 30 minutes (in the case of temperature soundings), and this can be exploited when rapidly evolving processes need to be resolved more precisely. The retrieval of vertical profiles of temperature, water vapor density and liquid density from spectrally sampled brightness temperatures is well established (see, e.g., [3]), and such profiles are routinely derived from AMSU observations. These methods will also be used with GeoSTAR.

In addition to atmospheric profiles GeoSTAR will also be used to measure precipitation. There are two approaches for this, both depending on scattering. The first method is one developed by Ferraro and Grody [4], which uses window channels at 89 and 150 GHz to measure the scattering caused by ice particles formed in and above rain cells. This method may be adapted to use a 50-GHz window channel in lieu of 89 GHz. A second approach has been developed by Chen and Staelin [5] and uses a number of channels in the 50-GHz band and the 183-GHz band to derive precipitation estimates – this is also based on the ice scattering signature. Although there are limitations with these methods (some stratiform and warm rain conditions are problematic), GeoSTAR offers the advantage of continuous full-disc coverage and can therefore be used to fill in the gaps between the narrow swaths of LEO-based systems. In addition, frozen precipitation (snow), which is difficult to detect by conventional means, can also be observed with these methods. These capabilities will be used to complement the observations obtained from the planned Global Precipitation Mission and its successors.

An extensive error budget analysis has been undertaken, which shows that a full-sized GeoSTAR space system will have performance that matches the measurement requirements.

III. Instrument concept

As illustrated schematically in Fig. 1, GeoSTAR consists of a Y-array of microwave receivers, where three densely packed linear arrays are offset 120° from each other. Each receiver is operated in I/Q heterodyne mode (i.e. each receiver generates both a real and an imaginary IF signal). All of the antennas are pointed in the same direction. A digital subsystem computes cross-correlations between the IF signals of all receivers simultaneously, and complex cross-correlations are formed between all possible pairs of antennas in the array. In the small-scale example of Fig. 1 there are 24 antennas and 276 complex correlations (=24*23/2). Accounting for conjugate symmetry and redundant spacings, there are 384 unique so-called uv-samples in this case. Each correlator and antenna 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 antennas and the wavelength of the radiation being measured. The complex cross-correlation measured by an interferometer, called the visibility function, is essentially the 2-dimensional Fourier transform of the brightness temperature. By sampling it over a range of spacings and azimuth directions one can reconstruct, or "synthesize," an image by discrete Fourier transform. In Fig.

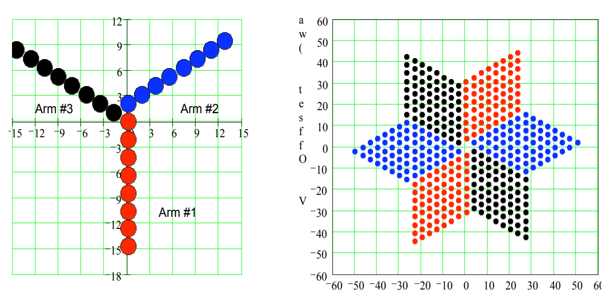

Fig. 1. Antenna array (left) and uv sampling pattern (right), as

1, the left panel shows the distribution of receivers in the instrument's aperture plane, and the right panel shows the resulting sampling points in spatial Fourier space i.e. in terms of spatial harmonics.

The smallest spacing of the sample grid in Fig. 1 determines the unambiguous field of view, which for GeoSTAR must be larger than the earth disk diameter of 17.5° when viewed from GEO. This sets both the antenna spacing and 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, which for the array in Fig. 1 is about 0.9° (i.e. 17.5°/√384). 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 sampling points (given conjugate symmetry), and therefore 60,000 independent pixels in the reconstructed brightness temperature image, each with an effective diameter of about 0.07° - about 45 km from GEO.

IV. PROTOTYPE

A small-scale prototype, consisting of an array of 24 elements operating with 4 AMSU channels between 50 and 54 GHz, has been built to address the major technical challenges facing GeoSTAR. Fig. 2 shows a photo of the prototype and Fig. 3 shows a simplified system block diagram. The challenges are centered around the issues of system design and calibration. (Power consumption has also been a major concern, but recent and continuing miniaturization of integrated circuit technology has demonstrated that this should no longer be seen as a major issue.) 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. To these ends the prototype was built with the same receiver technology, antenna design, calibration circuitry, and signal processing schemes as are envisioned for the spaceborne system. Only the number of antenna elements differ.

From left to right in Fig. 3 - or from front to back in Fig. 2 - the signal starts at the horn aperture with a vertical polarization, and then passes through a waveguide twist which aligns the waveguide to the orientation of the 8-element array arm. Each of the three arms require different twists: the top two arms of Fig. 2 twist 60° in opposite directions, and the bottom arm doesn't twist at all. This results in all receivers detecting the same linear polarization, as is commonly required for sounders with channels sensitive to surface radiation (which is polarized). GeoSTAR is very sensitive to antenna pattern differences among antennas, and a waveguide twist proved to be the easiest solution to guarantee a precise polarization match. The signal in Fig. 3 then passes through an 8-way calibration feed which periodically injects a noise signal into all receivers from a common noise diode source. This signal will be used as a reference to stabilize the system against gain, phase, and system noise drifts. The injected noise signal needs to be in the range of 1 to 10 K of equivalent noise temperature at the receiver input.

The noise diode signal is distributed to the three arms via phase shifters. Each of these phase shifters consists of a PIN diode and hybrid MMIC assembly which can switch between 0° and 120°. Correlations that occur between receivers of different arms can be excited by the noise diode with three possible phases using any two of these switches. This capability is key to ensuring 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 cannot be shifted among the 8 antennas of a given arm, but that such a capability is not needed for the staggered-Y arrangement of the antennas. With the staggered-Y all correlations within an arm represent visibility samples that are redundant to samples that 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.

Continuing the discussion of Fig. 3, the antenna signal passes into the MMIC receiver module, where it is amplified using InP FET low noise amplifiers and then double-sideband downconverted in phase quadrature by

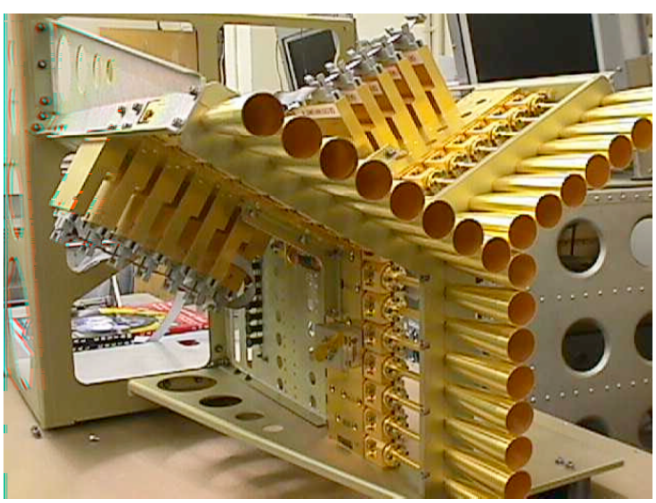

Fig. 2. GeoSTAR prototype

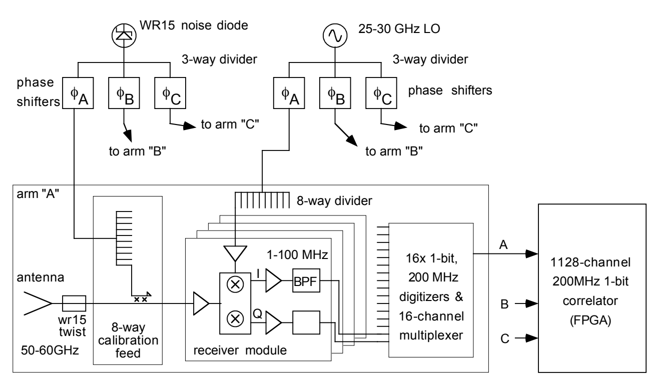

Fig 3. Receiver system block diagram – one of three arms shown

subharmonic mixers to two IF signals of 100 MHz bandwidth. The bandwidth is defined by lumped element filters. The local oscillator operates from 25 to 30 GHz, and is distributed via three phase shifters. These MMIC phase shifters periodically shift the phase of each arm by 90° (180° at RF) to provide a means of switching the correlator phase and chopping out correlator biases. Again, the staggered-Y arrangement of the array proves crucial to this function since one would otherwise need phase shifters within each arm. (This was the original plan, but it proved impractical due to the timing complexity when switching phase among all 24 receivers.)

The in-phase (I) and quadrature (Q) IF signals from each receiver are then digitized at a clock rate of 110 MHz. For reasons of product availability, the analog to digital converter is presently an 8-bit device, but this could be replaced with a two-bit or possibly just a one-bit converter to save power. The correlations only require 1-bit resolution (i.e. the sign bit), and the extra bits are only used to monitor changes in system noise temperature. There is a single multiplexer for each arm of the array - the term "multiplexer" here refers to the fact that eight receivers are combined on a single digital bus for transmission to the central correlator. An FPGA performing most of the functions of the multiplexer also includes "totalizers", which are used to count the occurrences of each ADC output state so that the threshold levels can be compared with the known Gaussian statistics of the IF voltage.

Perhaps the most important subsystem is the correlator, which must perform multiplications of all 100-MHz signal pairs in real time. For a spaceborne operational system with 100 elements per arm discussed earlier, that requires on the order of 20 trillion multiplications per second. To achieve such a high processing rate with a reasonable power consumption, the correlators are implemented as 1-bit digital multiply-and-add circuits using a design developed by the University of Michigan. 1-bit correlators are commonly used in radio astronomy. The correlator for the GeoSTAR prototype, where low cost was more important than low power consumption, is implemented in FPGAs. An operational system will use low-power application specific integrated circuits (ASICs). Current state of the art would then result in a power consumption of less than 20 W for the 300-element system discussed above, and per Moore's Law this will decline rapidly in future years.

IV. DATA AND IMAGE PROCESSING

The 1-bit correlations are first mapped to linear correlations using the Van Vleck formula [6]. This removes the nonlinearity of a 1-bit correlator when the input signals are known to be Gaussian. This step is applied to all four correlators associated with each antenna pair. Each antenna is associated with an "I" and a "Q" IF signal, so each antenna pair is associated with four correlators: "II", "QQ" "QI" and "IQ". This represents a two-fold redundancy in our data which we use to reduce measurement noise. If there were no biases, and if the subharmonic mixers of Fig. 3 were perfectly balanced in quadrature, then these four correlations could be immediately combined into a single complex correlation. Yet the quadrature balance is know to be poor-- on the order of 10 degrees of phase-- and the raw correlations are known to contain large biases due to digitizer null offsets and leakage of correlated noise from the LO. To fix this, the LO phases are shifted in a sequence that rotates all correlations to all four phase quadrants. The exact phase shifts are determined from network analyzer measurements made prior to system integration. These are applied in a linear regression to resolve the amplitude, offset, and phase of each correlator. This yields four complex correlations which are redundant in their expected values, but independent in noise. These are averaged to form the final complex correlation. This process ensures very precise quadrature balance, and virtually eliminates biases caused by anything other than direct leakage of the RF signals among the antennas. At present, we have observed total biases ranging from about 3 mK in the larger baselines to 40 mK in the short baselines, due almost entirely to leakage between antennas. This nearly meets our 2 mK goal in all but a small fraction of UV samples. The remaining biases are stable, and should be easily corrected.

The above correlations are next scaled to visibility using an estimate of the system noise temperature, and then aligned in phase to the aperture plane. We have thus far used LN2 and ambient targets to estimate receiver noise temperature, and point sources on an antenna range to align the phase. These references are transferred to operations by at least two methods: the first uses the internal noise diode to deflect the correlation and system noise by a reliable amplitude and phase. This provides a convenient and steady reference, but there are noise penalties due to the time required to measure the noise diode. The second method relies on the intrinsic stability of the receivers. The receiver noise temperatures of GeoSTAR are quite stable at the ~2K level, which represents about 0.3% of the ~700 K system noise. The observed phase stability is better than ~1 degree. These stabilities readily satisfy the phase and amplitude needs of most correlators. To meet the stricter phase requirements for correlations near the center of the UV plane, we will likely need the noise injection. This is an ongoing study, but we now envision a hybrid scheme which uses long running averages of low duty cycle noise diode injection-- possibly applied only to those correlators near the center of the UV plane.

The visibilities are next transformed into an image. Ideally, this step is a Fourier Transform followed by a scaling within the earth disk by the elemental antenna pattern. This requires, among other things, that the pattern of every antenna element be identical and precisely characterized by a single model. Our goal is to come as close as possible to this ideal-- to within 0.5% in the short baselines and 5% in the longer baselines. We have recently performed end-to-end system tests on the antenna range which validate our model at the 2% level, and show consistency among antenna elements at the 1% level. We have also used solar observations to validate the antenna range results at the 0.5% level. Details are beyond the scope of this paper, but these are very encouraging results which clears a path to a workable calibration. We envision a G-matrix solution [7] for short baselines, based on precise antenna measurements, and a Fast Fourier Transform for the larger baselines where requirements are relaxed.

V. Test Results

Fig. 4 presents the first images from GeoSTAR, as measured November 2, 2005 looking towards the hills north of JPL. These were produced with a straight Fourier Transform, without any corrections for elemental patterns or for biases from mutual coupling. In spite of these errors, the quality is quite good. The large dish antenna and the horizon boundaries are clearly visible and geometrically accurate. The hexagonal image boundary represents our unambiguous FOV, which represents a single period of the Fourier integral given the hexagonally gridded UV samples of Fig. 1. Beyond this region, the Fourier Series replicates the same hexagonal image (with the same orientation). We refer to these as the aliased regions. These regions are largely suppressed by the elemental pattern, but the residual sensitivity does affect the main image. In space, these regions will be off of the earth disk, and do not pose a problem. In the present images, the aliased regions result in some artifacts: note that in the image of the hillside that there is an anomalously cold region in the sky to the upper right; this can be traced to aliasing from the small dish antennas which is just outside of the image to the lower left (visible in the photograph). These effects are well understood, and do not pose a problem for the GEO application.

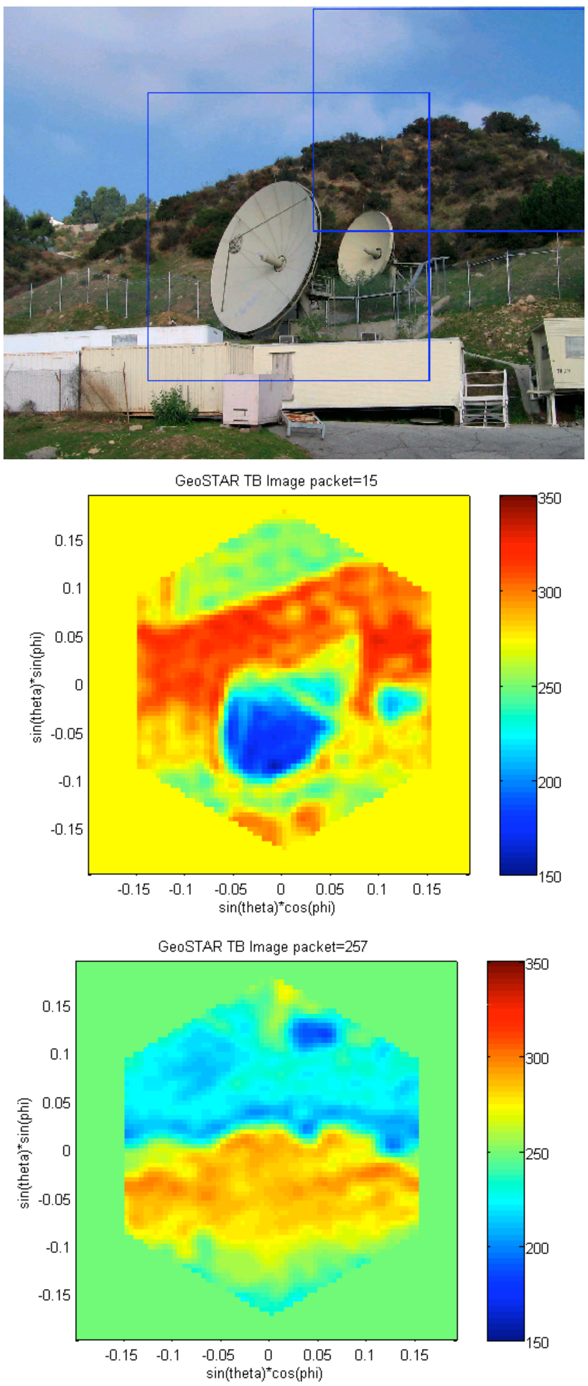

Fig 4. GeoSTAR images of hillside at 50.3 GHz with reference photograph and approximate frame positions.

The prototype system is now functioning so well that it can be operated in “portraiture mode”. Fig. 5 shows an example. The integration time here was about 5 minutes,

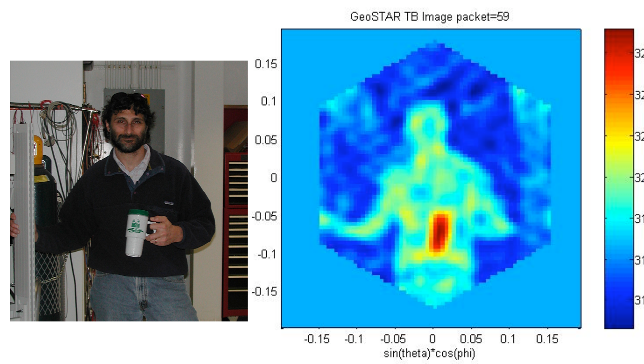

Fig. 5. Brightness temperature image produced with the GeoSTAR prototype (right panel) and a photo of the subject scene (left panel)

and the apparent speckle noise in the image represents a combination of the limited radiometric sensitivity (i.e. NEDT on the order of 1 K) and biases as discussed above. These biases are largely stationary and are easily measured and compensated for, which will yield clean and low noise images when applied.

The excellent performance of the prototype system and the excellent match between predicted and actual performance indicates that the GeoSTAR development represents a major breakthrough in remote sensing technology and capability.

VI. Future Space Missions

The GeoSTAR team has worked closely with representatives from the NOAA National Environmental Satellite Data and Information Service (NESDIS) Office of System Development (OSD) since the inception of the IIP prototyping project. NASA Headquarters has also provided programmatic and scientific oversight. This has resulted in the GeoSTAR design being closely aligned with “customer” needs. The measurements that GeoSTAR will provide are needed by NOAA for operational use and are needed as well by NASA for research use. NOAA now considers a GEO MW sounder to be their highest-priority unmet need and carries it on top of their list of Pre-Planned Product Improvements (P^3I) for GOES-R. Normally, as soon as funding for such a payload has been identified and the technological maturity deemed sufficient for an operational mission, the payload is elevated to baseline status. The GeoSTAR prototype is intended to retire some of the more challenging technology risk, and results obtained to date show that this has largely been accomplished. However, it is difficult for NOAA to fund the first space mission of a new instrument, and it generally looks to NASA to do that. On the NASA side, science research missions tend to have higher priority than pre-operational missions (as a GeoSTAR space demonstration might be), and it has therefore been difficult also for NASA to identify funding for GeoSTAR. A promising mechanism is through the "Research-to-operations" path, which has been identified by both organizations as worthwhile. Here, NASA first develops the necessary technology, followed by a space "research" mission that demonstrates the capabilities and elevates the maturity to operational status – at which point the mission is handed over to NOAA for operational use. NOAA would subsequently procure additional copies of the payload to populate future platforms. A GeoSTAR space demonstration mission is being discussed between NASA and NOAA, and it is likely that such a mission will be recommended. Another possible path is as a NASA research mission, such as through the Earth System Science Pathfinder (ESSP) series. Those missions generally require fairly high technologic maturity, but ongoing GeoSTAR related technology development efforts may make such a mission plausible. A science driven GeoSTAR mission has been discussed in some detail in a white paper [8] provided in response to the RFI issued for the NRC Decadal Survey of the NASA Earth science program that is currently under way. The first launch in the GOES-R series (i.e. of GOES-R) is now scheduled for 2014. If startup funding becomes available in the next 1-2 years, it will be possible to have GeoSTAR ready for integration in 2012, as required for the 2014 launch. Another possibility, and a more relaxed schedule, is to fly GeoSTAR on GOES-S, 2 years later. In any case, it is now likely that GeoSTAR will become part of the GOES payload – subject to the availability of funds.

VI. Conclusions

The GeoSTAR prototype construction is nearly complete, but very promising measurements have already been made that indicate excellent performance. In the coming months we will exercise the various calibration subsystems and complete the proof of concept that has been our main objective. Our efforts are focused on building a practical low power system which will form the basis of a future spaceborne system. We are very carefully examining error budgets, and we are well on the way to demonstrating a comprehensive and well justified system calibration based on real hardware.

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