Getting the GeoSTAR Instrument Concept Ready for a Space Mission

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Abstract— **The Geostationary Synthetic Thinned Array Radiometer – GeoSTAR – is a microwave sounder intended for geostationary satellites. First proposed for the EO-3 New Millennium mission in 1999, the technology has since been developed under the Instrument Incubator Program. Under IIP-03 a proof-of-concept demonstrator operating in the temperature sounding 50 GHz band was developed to show that the aperture synthesis concept results in a realizable, stable and accurate imaging-sounding radiometer. Some of the most challenging technology, such as miniature low-power 183-GHz receivers used for water vapor sounding, was developed under IIP-07. The first such receiver has recently been adapted for use in the High Altitude MMIC Sounding Radiometer (HAMSR), which was previously developed under IIP-98. This receiver represents a new state of the art and outperforms the previous benchmark by an order of magnitude in radiometric sensitivity. It was first used in the GRIP hurricane field campaign in 2010, where HAMSR became the first microwave sounder to fly on the Global Hawk UAV. Now, under IIP-10, we will develop flight-like subsystems and a brassboard testing system, which will facilitate rapid implementation of a space mission. GeoSTAR is the baseline payload for the Precipitation and All-weather Temperature and Humidity (PATH) mission – one of NASA's 15 "decadal-survey" missions. Although PATH is currently in the third tier of those missions, the IIP efforts have advanced the required technology to a point where a space mission can be initiated in a time frame commensurate with second-tier missions. An even earlier Venture mission is also being considered.**

Index Terms — millimeter-wave, microwave interferometry, microwave remote sensing, atmospheric sounding.

I. Introduction

The aperture synthesis concept that GeoSTAR is based on was developed in the US [1] and Europe [2]. GeoSTAR is similar to the Microwave Imaging Radiometer by Aperture Synthesis (MIRAS) developed by ESA for the Soil Moisture and Ocean Salinity (SMOS) mission, but with the important distinction that MIRAS operates at 1.4 GHz while GeoSTAR operates at 50 GHz and up. The frequency ratio is close to the ratio between the LEO/GEO orbit altitudes, and it was the realization that there is a scaling similarity that made it clear that the MIRAS concept can be used for GeoSTAR. Fig. 1 illustrates the concept. The upper-left figure is a depiction of the sparse array of receivers, the upper-right figure shows the resulting sampling points in Fourier space (the so-called uv-plane), the lower-right figure shows the Fourier transform of the Earth brightness temperature image in the lower-left, with the sampling pattern overlaid. The system is a spatial interferometer. The direct measurements consist of "visibilities", which are essentially the coefficients of a 2-dimensional Fourier series (lower-right). These are sent to the ground, where an inverse Fourier transform is used to reconstruct the brightness temperature image. This is done for each spectral channel, and the plan is to implement the AMSU tropospheric channels. The system will be built large enough to yield a spatial resolution of 50 km at 50 GHz – the same as for AMSU. Thus, GeoSTAR will have the same functionality and performance as AMSU but with the crucial difference of giving time-continuous observations, with a refresh period of 15 minutes. The technology required to achieve this performance has been under development at the Jet Propulsion Laboratory since 2003, and it is now sufficiently mature that a space mission can be initiated by 2012.

In 2007 the National Research Council (NRC), an arm of the US National Academy of Sciences, recommended that NASA develop 15 space missions in the coming decade, to

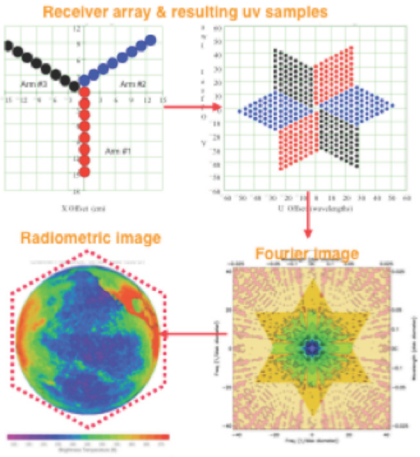

Fig. 1. The STAR concept

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replace and enhance the current rapidly aging fleet of earth satellites [3]. Among those was the Precipitation and All-weather Temperature and Humidity (PATH) mission, which will place a microwave sounder in geostationary orbit. The report identified a "MW array spectrometer" as the recommended payload. GeoSTAR is one such concept – the only one being developed in the US – and will therefore likely be the PATH payload. The primary objective of PATH, according to the NRC, is to provide continuous soundings and precipitation measurements under both clear and cloudy conditions, with very rapid refresh times (15-30 minutes). These observations will be used to improve and constrain atmospheric models, which is expected to lead to significant improvements in storm forecasts as well as improved understanding of atmospheric processes related to the hydrologic cycle. Table I lists the most important PATH applications. The PATH mission can be viewed as a mission to monitor the hydrologic cycle [4].

The NRC placed PATH in the third tier of recommended missions, due to a perception that some time would be required to develop the necessary technology. The GeoSTAR technology is now at least as mature as for second-tier missions. NASA is in the process of systematically implementing the first-tier missions, followed by second-tier missions, and finally third-tier missions. Due to budget limitations, it is unlikely that PATH, as a third-tier mission, will be implemented in the foreseeable future. Nevertheless, there is still a good chance that a US geostationary sounder will be implemented in the near future, for example under the new Ventures program. Thus, a low-cost mission is now under consideration. It will be based on the GeoSTAR concept and have a limited science objective of observing hurricanes and severe storms. With a newly developed method of deriving vertical profiles of reflectivity from microwave sounders, i.e. equivalent to radar observations but at a lower spatial resolution, such a mission will enable powerful new research and applications related to convective processes and severe storms.

The PATH sounder needs to operate in the 50-GHz band for temperature sounding and in the 183-GHz band for water vapor sounding, just as the current AMSU system does, but as noted by the NRC, limited temperature soundings can also be obtained at 118 GHz. PATH will provide near continuous coverage of temperature and humidity profiles over a large portion of the globe. Operating at microwave and millimeter-wave frequencies, PATH can penetrate clouds and provide soundings into the lower troposphere. Continuous coverage is only possible from geostationary orbit, which creates the requirement of a very large effective aperture to obtain a spatial resolution of 25-50 km, to match AMSU capabilities.

The preferred approach towards this goal is a Synthetic Thinned Aperture Radiometer (STAR), in which the thermal image is formed interferometrically. This provides for a large effective aperture without a large antenna, while imaging the entire field of view with no moving parts. The feasibility of the aperture synthesis concept was first demonstrated on the ground with the GeoSTAR prototype discussed below, and it has now been demonstrated in space with SMOS.

TABLE I
PATH applications

Weather forecasting	All-weather soundings, in cloudy and stormy scenes Soundings @<50/25 km every 15-30 minutes (continuous) Synoptic rapid-update soundings Forecast error detection; 4DVAR applications
Hurricane & severe-storm diagnostics	Location, intensity & vertical structure of deep convection NRT atmospheric instability; tornado precursor detection Intensification/weakening in NRT, frequently sampled Measure all H_2O phases: vapor, liquid, ice, rain/snow Operational analysis, forecast verification Improved model microphysics
Rain	Full hemisphere @ ≤ 25 km every 15 minutes Directly measure storm and diurnal total rainfall: predict flooding events Snowfall, light rain, intense convective precipitation
Tropospheric wind profiling	1000-300 mb; very high temp.res.; in & below clouds Air quality applications (pollution transport)
Climate research	Stable & continuous MW observations Long term trends in T & q and storm statistics Fully resolved diurnal cycle ENSO; monsoon; tropical moisture flow into the US "Science continuity": GeoSTAR ≈ AMSU

II. IIP-03: Prototyping the Concept

The primary objective of the IIP-03 GeoSTAR effort was to demonstrate that the aperture synthesis concept is a viable approach for microwave sounding. Although the development of the ESA SMOS mission, which would use aperture synthesis to measure soil moisture and ocean salinity, was then well under way, the concept had not yet been demonstrated. Also, since GeoSTAR will operate at frequencies 35-130 times higher than that of SMOS, different issues and technology needs needed to be addressed. The result of IIP-03 was a complete, fully functional ground-based 50-GHz temperature sounder implemented with 24 compact receivers forming a Y-array made up of three single rows of receivers, similar to the concept illustrated in Fig. 1. Each receiver is fed by a feedhorn about 1" in diameter, so that each of the three arms is about 8" long, and the effective aperture diameter is therefore about 16". This results in an image with 384 unique pieces of information equivalent to "pixels" in conventional imaging and a spatial resolution of about 0.9°. Fig. 2 shows a photo of the instrument at an early stage of the development.

The key technology items that had to be developed to implement this system were compact low-power high-

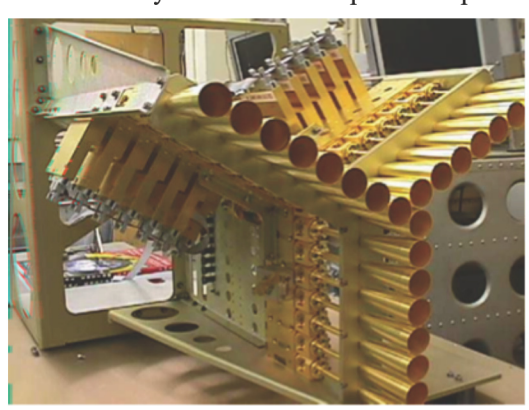

Fig. 2. The GeoSTAR proof-of-concept prototype - 2005

performance quadrature (I/Q) receiver modules operating in the 50-GHz band, feedhorns with low mutual coupling, and a phase shifting local oscillator subsystem. Fig. 3 shows one of the 25 receivers that were developed and three of the parabolic Potter horns being measured for mutual coupling.

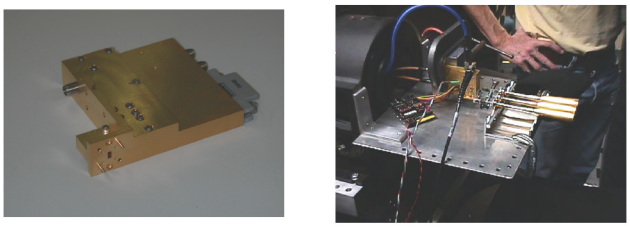

Fig. 3. 50-GHz receiver (left), feedhorns (right)

The system was put through a number of tests [5], which included antenna pattern measurements in a test chamber at the Goddard Space Flight Center in Greenbelt, MD and observations of the sun as a proxy for a point source. Fig. 4 shows an example of images at 50.3 GHz of a natural scene – the first time that had been done with a fully functional 2-D aperture synthesis radiometer operating at sounding frequencies, a major achievement.

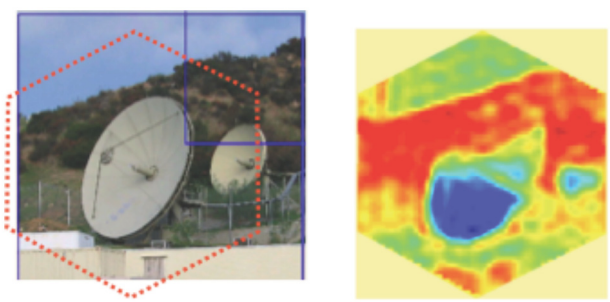

Fig. 4. 50-GHz image (right) of a natural scene (left) - 2005

In 2005 the NRC was soliciting white papers from the science community for the "decadal survey" then getting under way, and one based on the GeoSTAR concept was also submitted. With the success of the IIP-03 development, the panel was able to recommend a mission based on this new sounding concept, in the form of the PATH mission.

III. IIP-07: ADVANCING THE TECHNOLOGY

NOAA had at this time developed a strong interest in GeoSTAR, with a view toward complementing a planned hyperspectral infrared sounder for its new geostationary satellite system, "GOES-R", with a microwave sounder. That would match the capabilities of its polar-orbiting satellite system. Discussions were already under way about the possibility of flying GeoSTAR as an "instrument of opportunity" on one of the first satellites in the GOES-R series. The JPL team therefore undertook mission studies to examine requirements and performance of such an instrument. One of the outcomes of that was a new antenna array concept [6], where 2-4 parallel rows of feedhorns would replace the single row in the initial design. That would make it possible to shape the effective antenna pattern closer to an ideal "top hat" function rather than the conventional Gaussian shape. That would in turn maximize the antenna efficiency and enable improved radiometric sensitivity within an overall field of view less than the entire Earth disk while at the same time minimizing aliasing from regions outside the field of view. Fig. 5 shows two examples. This design looked so promising that it was deemed worth prototyping in the proposed next IIP effort.

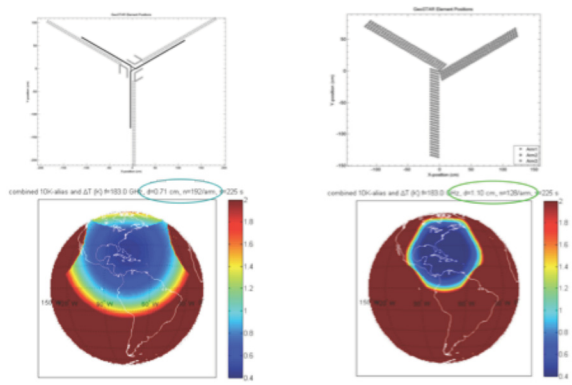

Fig. 5. 2-row and 4-row antenna designs and resulting FOVs

In addition to prototyping this new antenna design, the focus of IIP-07 was to develop the remaining most challenging technology, namely low-noise low-power 183-GHz receivers and an ASIC-based correlator. Since the aperture synthesis concept had already been demonstrated in IIP-03, it was not felt to be necessary to construct a new fully functional sounder. Instead, the focus was on developing components and subsystems.

By leveraging MMIC development effort under related programs (ESTO's Advanced Component Technology – ACT – and the Industrial Partnership Program – IPP) the development of a new 183-GHz receiver was a tremendous success, deemed enabling of the PATH mission. This receiver technology has now been transferred to the High Altitude MMIC Sounding Radiometer (HAMSR), a 25-channel aircraft based microwave sounder originally developed at JPL under the IIP-98 program. The radiometric sensitivity in the 183-GHz band improved by an order of magnitude as a result, as shown in Fig. 6, where the right panel shows the thermal noise level of the new receiver (green line) vs. the original receiver (blue curve). HAMSR is now the most sensitive and accurate microwave sounder in existence. This receiver was flown for the first time in the NASA "GRIP" hurricane experiment in late summer of 2010 and is now field tested.

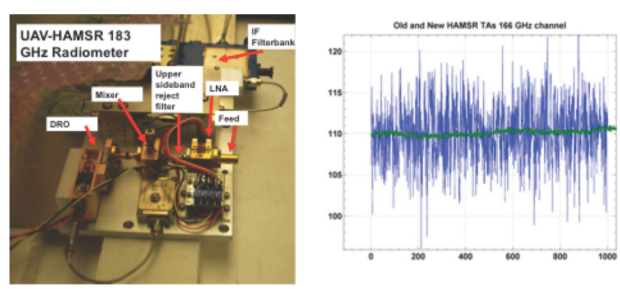

Fig. 6. HAMSR/GeoSTAR 183-GHz receiver (left); noise level (right)

The new antenna design has been prototyped by manufacturing a small number of "tiles", each of which consist of a 4x4 array of feedhorns and receivers. A complete array is formed by mounting tiles end to end. This is illustrated in Fig. 7 and Fig. 8. A notable achievement is the substantial miniaturization of the receivers, which are now assembled on small chip carriers and are substantially smaller than the receivers developed in IIP-03 (Fig. 2).

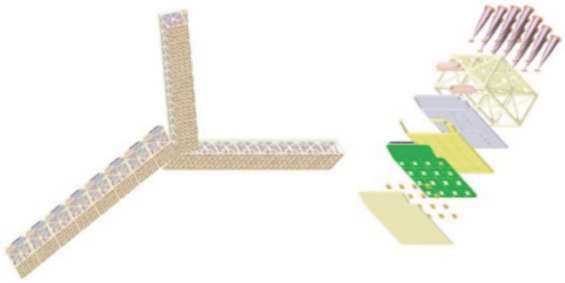

Fig. 7. 4x4 receiver tile (right) and array of tiles (left)

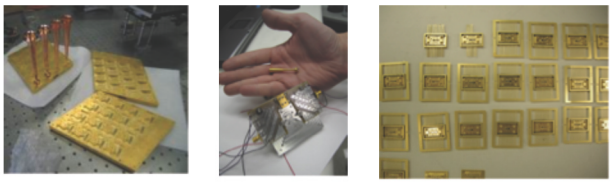

Fig. 8. Receiver "tile" components (left); feedhorns (center); receiver boards (right)

The correlator ASIC development was not successful, due to an unexpectedly low yield of functioning correlator cells. This problem will be solved under IIP-10 with a different design architecture. On the other hand, a successful (and unplanned) digitizer chip was developed, which will become a key element in the effort to reduce power consumption of a space system. Fig. 9 shows the ADC chip.

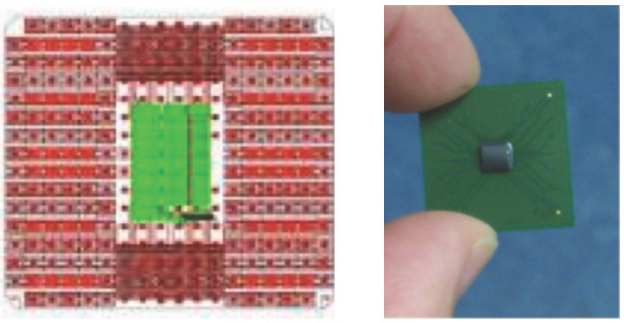

Fig. 9. Digitizer chip

The IIP-07 effort will end in August 2011. In lieu of testing the failed correlator ASIC, a final effort will consist of designing and prototyping a small correlator with 5x5 elements. That effort will be completed under IIP-10.

IV. IIP-10: Getting Ready for a Space Mission

IIP-10 started in April 2011 and is just now getting under way. The objective here is to build up a near full scale version of the 183-GHz sounder, i.e. by fabricating a number of the 4x4 tiles developed under IIP-07 and integrating them into a complete sounder. A full-scale 128x128 flight-like ASIC correlator will also be developed. The design of that chip may be based on the 5x5 prototype now under development under IIP-07, if that design proves successful. Another objective is to develop this system as a testable brassboard that can be used to support and possibly accelerate a space mission development - see Fig. 10.

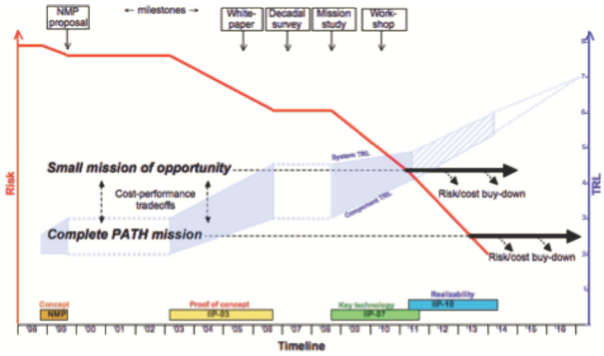

Fig. 10. Technologic maturity vs. mission readiness

V. Conclusion

The GeoSTAR development sponsored by the IIP program has largely been extremely successful and has already resulted in technology that has seen application in real science missions. The maturity of the key technology and the instrument design is now approaching a level where a space mission can be initiated. Indeed, there are now plans to pursue a mission under the Ventures program, with launch possible in the 2016-2018 time frame. The IIP-10 effort, although ultimately dedicated to fully enabling the PATH mission, will be carried out in such a way as to facilitate an early Ventures mission.

Acknowledgements

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References

[1] C. Ruf et al., "Interferometric synthetic aperture microwave radiometry for the remote sensing of the Earth," *IEEE Trans. Geosci. Remote Sens.*, vol. 26, pp. 597-611, 1988

[2] M. Martin-Neira and J. Goutoule, "A two-dimensional aperture-synthesis radiometer for soil moisture and ocean salinity observations," *ESA Bull.* No. 92, pp. 95-104, 1997

[3] R. Anthes and B. Moore (eds.), *"Earth science and applications from space—National imperatives for the next decade and beyond,"* National Academies, Washington, DC, 2007

[4] B. Lambrigtsen et al., "Monitoring the hydrologic cycle with the PATH mission," *Proc. IEEE*, vol. 98, pp. 862-877, 2010

[5] A. Tanner et al., "Initial results of the Geostationary Synthetic Thinned Array Radiometer (GeoSTAR) demonstrator instrument," *IEEE Trans. Geosci. Remote Sensing*, vol. 45, pp. 1947-1957, 2007

[6] A. Tanner, B. Lambrigsten, T. Gaier, "A dual-gain antenna option for GeoSTAR," *Proc. IGARSS'07*, 227-230, 2007