

A Geostationary Microwave Sounder for NASA and NOAA

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Abstract

The Precipitation and All-weather Temperature and Humidity (PATH) mission is one of 15 Earth space missions that the U.S. National Research Council recently recommended that NASA undertake in the next decade. The PATH mission will place a microwave atmospheric sounder, operating in the same temperature and water vapor bands used by the low-earth-orbiting Advanced Microwave Sounding Units (AMSU), into geostationary orbit. The objective is to enable time-continuous observations of severe storms, tropical cyclones and atmospheric processes associated with the hydrologic cycle under all weather conditions. The ultimate goal is to improve models in these areas, provide initial conditions and assimilation data for improved forecasts, and develop long time series to support climate studies. Both NOAA and NASA have long sought to develop such a sensor, but it is only recently that new techniques have emerged that enable such a mission. The Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) is a microwave sounder concept based on aperture synthesis that has been developed at the Jet Propulsion Laboratory. A small proof-of-concept prototype was completed in 2006 under the NASA Instrument Incubator Program, and this demonstrator proves that the aperture synthesis method is a feasible approach for attaining the very large aperture required for adequate spatial resolution. The performance of the prototype and projections to a full-scale space version indicate that GeoSTAR, unlike alternative approaches, can meet all measurement requirements. It is therefore now considered the baseline PATH payload and is expected to be implemented by NASA in the next decade. A near-term option is to fly GeoSTAR as a “Mission of opportunity” on one of the first two satellites in NOAA’s GOES-R series currently under development. Such a joint NASA-NOAA mission would satisfy important NASA research needs and serve as a fast-track “Research-to-operations” pathfinder mission for NOAA as well.

Overview

The National Research Council, an arm of the U.S. National Academies of Science, recently released a “decadal survey” of NASA and NOAA Earth space missions [1]. Among the 15 missions recommended for NASA to undertake was one called the “Precipitation and All-weather Temperature and Humidity” mission (PATH). A “MW array spectrometer” was identified as the recommended instrument payload for PATH. Such an instrument, called the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR), is being developed at NASA’s Jet Propulsion Laboratory (JPL). Sponsored by the NASA Instrument Incubator Program a proof-of-concept prototype has been developed and tested at JPL, in partnership with the NASA Goddard Space Flight Center and the University of Michigan. This development has been closely coordinated with the NOAA NESDIS Office of System Development to ensure that the GeoSTAR design will meet the needs and measurement requirements of NOAA as well. The prototype, a ground-based fully functional temperature sounder with capabilities similar to the Advanced Microwave Sounding Unit – currently the most advanced microwave sounder operating on polar-orbiting low-earth-orbiting (LEO) satellites, shows excellent performance and has provided the intended proof of concept. This represents a major breakthrough in remote sensing capabilities, since it makes it possible to deploy a microwave sounder as part of the Geostationary Operational Environmental Satellite (GOES) system – a long sought goal, since the GEO vantage point offers key advantages over LEO, such as a continuous view of the entire life cycle of storms and hurricanes. Due to the very large antenna aperture needed for a microwave sounder to provide the required spatial resolution, it has not been possible to develop such instruments for GEO. Only infrared sounders have been feasible, but they are severely hampered by clouds – which is not a problem for microwave sounders. GeoSTAR overcomes those difficulties by synthesizing a large aperture. This new concept was clearly viewed by the NRC as a very important break-

through. Plans for a PATH/GeoSTAR mission are now under development, and a mission study was recently completed by JPL for NASA. A similar study has been done for NOAA as well, and both conclude that GeoSTAR can meet all relevant measurement requirements. The emergence of a viable approach to implement a GEO microwave sounder is of particular interest to NOAA, which is currently developing the next generation of GOES satellites (named GOES-R after the first in the new series). This new system was intended to carry an advanced hyperspectral infrared sounder (the Hyperspectral Environmental Suite – HES), but HES was recently cancelled for the first two satellites (GOES-R and GOES-S). There remains a strong need for an atmospheric sounder, and the possibility of flying GeoSTAR on one of the first GOES-R satellites as a “Mission Of Opportunity” is now under investigation. A joint effort by NASA and NOAA, where NASA would provide the instrument and NOAA would provide the platform and launch, would be a compelling demonstration of a new “Research to operations” paradigm.

PATH will provide a number of measurements that are crucial for the monitoring and prediction of hurricanes and severe storms – including hemispheric 3-D temperature, humidity and cloud liquid water fields, rain rates and totals, tropospheric wind vectors, sea surface temperature, and parameters associated with deep convection and atmospheric instability – everywhere and all the time, even in the presence of clouds. These parameters will be derived from a continuous stream of 2-D radiometric “synoptic snapshots” covering the entire visible disc. With these capabilities, GeoSTAR will become a prime hurricane sensor, in addition to providing the basic sounding functions required by operational agencies for regional weather prediction and will in addition provide key observations needed for studies related to the hydrologic cycle. In particular, with GeoSTAR the diurnal cycle can be fully resolved, and atmospheric processes related to cloud dynamics and convection can be studied without the diurnal temporal sampling biases that are prevalent with polar-orbiting sun-synchronous satellite sensors. As has been demonstrated in LEO, microwave sounders are excellent tools for climate applications, with their superior stability and lack of sampling bias. Much of the technology risk of this new measurement concept has been retired with the prototype and related developments, but additional technology development as well as application studies are under way, funded by NASA and NOAA.

PATH

The primary objective of PATH is to provide continuous soundings and precipitation measurements under both clear and cloudy conditions, with very rapid refresh rates. Those 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.

The NRC in its report states that current numerical weather prediction models are widely recognized as having an inadequate representation of the processes of cloud formation, evolution and precipitation. They rely on simplistic parameterization schemes and an incomplete understanding of the underlying cloud microphysics to represent the most rapidly changing weather phenomena. The PATH measurements will impose powerful new constraints on, and are expected to lead to greatly improved models for boundary layer, cloud, and precipitation processes. The availability of continuous observations will also significantly mitigate the requirements on those models because they will be able to be frequently re-initialized by observations. The observations will also enable major scientific advances in the understanding of El Niño, monsoons, and the flow of tropical moisture to the U.S. The NRC report suggests that “accommodation of an all-weather sensor suite on future GOES GEO platforms is the most promising option in the next ten years”.

The PATH measurements require penetration well into clouds, and that requires temperature sounding in the 50-70 and 118 GHz oxygen absorption bands and water vapor sounding at the 183 GHz water vapor line. These bands are also suitable for precipitation observations. Although the report does not specify a particular payload design, numerous references make it clear that the study panel envisioned that this would be a mission based on the GeoSTAR concept and recognized that known alternative concepts would not be able to satisfy the measurement requirements. This is reflected by the report identifying a “MW array spectrometer” as the presumed payload.

GEOSTAR

GeoSTAR is a “MW array spectrometer” that will meet all the requirements of the PATH mission. The measurement concept was initially developed for the NASA New Millennium Program “EO-3” mission in 1999 [2]. Subsequently, a small proof-of-concept prototype was developed at JPL in 2003-2006 [3]. The performance of the prototype shows that the STAR approach is feasible and that a full-scale space version will perform as required. The design and test results are discussed by Tanner et al. [4].

GeoSTAR is a spatial interferometer that essentially measures the upwelling radiation emitted by the atmosphere in the spatial Fourier domain. This is accomplished by deploying a large number of individual microwave receivers arranged in a sparsely filled 2-D array. In the baseline configuration there are three linear arrays arranged in a “Y” shape, and the effective aperture is then essentially defined by the circle that circumscribes the “Y”. In this way it is possible to form the large effective aperture required for geostationary satellites, where the orbit altitude is nearly 50 times greater than for low-earth orbiting satellites and therefore requires an aperture that is also 50 times as large. This array configuration is illustrated in Fig. 1. All of the antennas are pointed in the same direction. A digital subsystem computes the complex cross-correlations between all receiver pairs in the array simultaneously. In the small-scale example of Fig. 1 there are 24 receivers, 276 complex correlations and 384 unique so-called uv-samples, which means that the spatial imaging field can be resolved into 384 “pixels”. Each receiver pair forms an interferometer, which measures a particular spatial harmonic of the brightness temperature image across the field of view. 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 (a term coined by radio astronomers, who have used the STAR approach for many years, such as in the Very Large Array operated by the National Radio Astronomy Observatory in New Mexico), 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. 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.

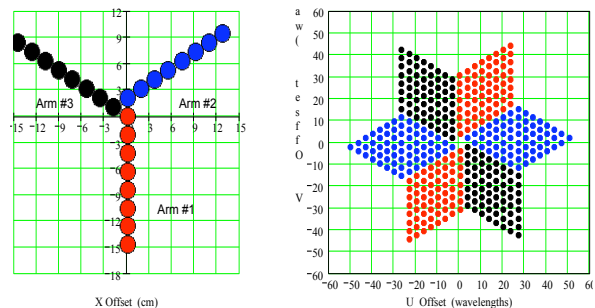


Figure 1. Antenna array (left) and uv sampling pattern (right)

Fig. 2 shows the hexagonal imaging region (left panel) resulting from this star-shaped uv-sampling pattern imposed on the Fourier transform of the Earth brightness temperature field (right panel). As in all interferometric systems, there are “ghost” imaging hexagons adjacent to the primary one, and radiation originating from those areas is aliased into the primary area. However, in the GeoSTAR case this is not a problem since the space beyond the Earth disc is featureless and at a uniform 2.7 K temperature. (The sun and the moon will periodically be aliased into the imaging area, but those occurrences will be used to help calibrate the system.) As we discuss below, the primary imaging area can even be reduced somewhat to reduce the number of receiving elements needed to attain the required spatial resolution, and portions of the observations near the limb would then be contaminated by aliasing. That can be

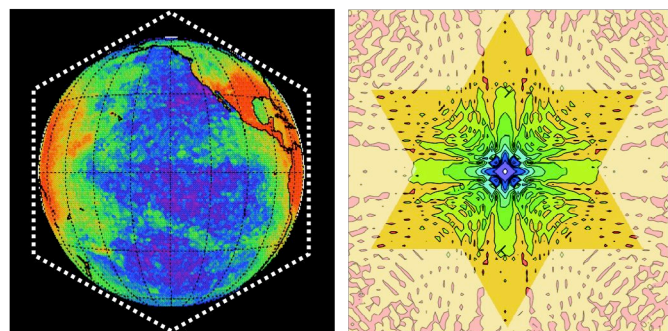


Figure 2. Brightness temperature image of Earth (left) and its Fourier transform (right)

tolerated, however, since accurate sounding is limited to relatively high elevation angles.

Baseline PATH mission

A preliminary PATH mission study was conducted for NASA in 2007, which concluded that all requirements discussed in the NRC Decadal Survey can be met with the GeoSTAR design, and mission cost is projected to be within 15% of NRC's estimate. The study also showed that a PATH-GeoSTAR mission is feasible in terms of mass and power as well. Power consumption has been a matter of concern, since a full-size instrument will have nearly 1000 receivers and close to 1 million correlators – digital multipliers operating at 100 MHz or more. The state of technology is now such that this can be done with comfortable margins, and the mass and power requirements are currently estimated at less than 250 kg and 350 W, respectively. These numbers are expected to decline as the technology matures further.

The baseline GeoSTAR design consists of a dual collinear array, one with ~300 receivers in the 50-GHz band and one with ~600 receivers in the 183-GHz band. Each “arm” of the 50-GHz array is approximately 2 meters long. That results in a spatial resolution of 50 km for temperature sounding and 25 km for water vapor sounding – this compares with 50 and 15 km, respectively for the LEO AMSU system. Future versions are envisioned to have significantly higher spatial resolution, which can be achieved by adding receivers and thus extending the lengths of the array arms. Fig. 3 shows the array layout, which features provisions for redundancy near the center of the array, i.e. for the critical larger spatial scales (which represent most of the radiative energy). In general, an aperture synthesis system like this is quite fault tolerant: the loss of a receiver or correlator will create a gap in the uv sampling pattern shown in Fig. 1, but the consequence of that is usually merely a degradation of image quality. The redundant receivers (and redundant correlators) reduce the chance of such degradation. The visibility spectrum of the Earth is such that most of the energy is in the shorter baselines (i.e. larger spatial scales), and the loss of a receiver near the center of the array is therefore the most serious. This design therefore protects against the most serious type of loss.

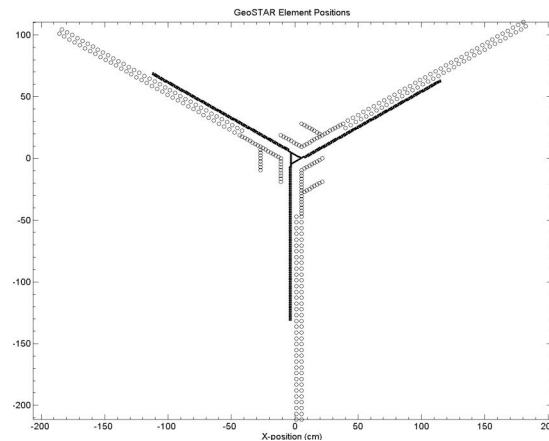


Figure 3. Dual-array layout

Fig. 3 also illustrates the use of two receiver spacings; the spacing in the outer portion of the array is twice that in the inner portion, and the receiver horns are scaled correspondingly. This “dual-gain” design results in a more focused imaging and increases the effective antenna efficiency. This approach makes it possible to increase the radiometric sensitivity in the central region of interest. The basic element spacing is 4 wavelengths in this design, which results in an alias-free field of view that is slightly smaller than the Earth disc and also results in regions near the Earth limb that are affected by aliasing, as shown in Fig. 4. This is of minor consequence, however, since atmospheric profiles cannot be reliably “retrieved” at such small elevation angles.

The array shown in Fig. 3 has a total of 312 50-GHz receivers and 576 183-GHz receivers. Each receiver consumes 100-150 mW. The 50-GHz array requires about 150,000 correlator cells, each of which is a multiplier-accumulator operating at about 100 MHz. The 183-GHz array requires about 460,000 such cells. (These estimates are based on computing 4 visibility components per baseline, each of which produces two pairs of real and imaginary readings – this also results in a significant measure of redundancy.) Implemented as a 1-bit multiplier with accumulator on a 90-nm application-specific integrated circuit (ASIC), each cell will consume less than

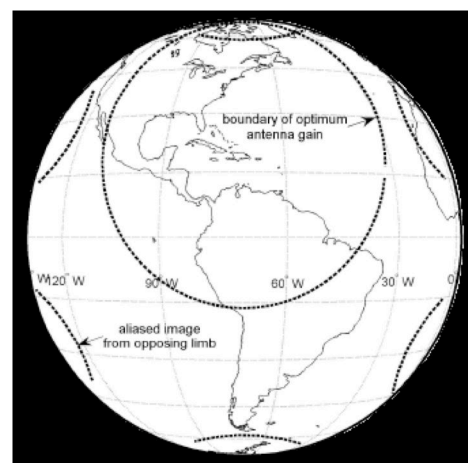


Figure 4. Nominal field of view

10 μ W. Power consumption of the entire 183-GHz correlator will then be less than 5 W. This is expected to decrease as newer IC technologies become available, which will continue to drive down overall GeoSTAR power consumption and make it possible to increase radiometric performance by operating several correlator systems in parallel and thus extending the per-channel integration time.

With the design described above, but using broad-band 1.5-bit correlators implemented with 65-nm ASICs and using recently developed technology that yields receiver temperatures below 300 K, we estimate a radiometric sensitivity in the 183-GHz band of about 1/3 K, similar to AMSU performance, for all channels every 15 minutes, which is adequate to meet or exceed all relevant measurement requirements.

Mission of opportunity

An intriguing possibility for implementing the PATH mission in the near term is to fly it as a Mission of Opportunity on one of the first satellites in the GOES-R series now being developed by NOAA. An infrared hyperspectral sounder, HES, had been planned as one of the primary payloads on GOES-R, but it was temporarily removed from the manifest due to programmatic risk. As a result, there will be unallocated space and resources (mass and power) on the first 2-3 GOES-R satellites – sufficient to accommodate GeoSTAR with only relatively minor redesign. There is therefore the possibility of implementing the PATH decadal-survey mission for NASA and provide an advanced geostationary sounder for NOAA, at greatly reduced overall mission cost. This is now being vigorously pursued and remains a realistic possibility. The launch of the first GOES-R satellite is planned for the end of 2014, and the second satellite is planned for two years later.

Measurements and applications

Table I lists the data products that PATH/GeoSTAR will provide. Most of these products are routinely generated from LEO systems with mature algorithms but with only the limited spatio-temporal sampling available from LEO orbit. The lower portion of the table (in italics) lists emerging new products, where algorithm development is currently under way.

Table 1: PATH data products

Parameter	Horiz.	Vertical	Temporal	Accuracy
Tb (50 GHz)	50 km	(6 ch's)	3 min per ch	1/3 K
Tb (183 GHz)	25 km	(4 ch's)	5 min per ch	1/3 K
Temperature profile (T)	50 km	2-3 km	20 min	2 K
Water vapor profile (q)	25 km	2-3 km	20 min	25%
Liquid water profile (L)	25 km	3-4 km	20 min	40%
Total precipitable water	25 km	N/A	20 min	10%
Column liquid water content	25 km	N/A	20 min	20%
TC-core MSLP anomaly	50 km	N/A	20 min	~ 5 mb
SST	100 km	N/A	1 hour	0.5 K
Stability index	50 km	N/A	20 min	N/A
<i>Radar reflectivity</i>	<i>25 km</i>	<i>2 km</i>	<i>20 min</i>	<i>3-4 dBZ</i>
<i>Rain rate</i>	<i>25 km</i>	<i>TBD</i>	<i>20 min</i>	<i>TBD</i>
<i>Convective intensity</i>	<i>25 km</i>	<i>TBD</i>	<i>20 min</i>	<i>TBD</i>
<i>Ice water content</i>	<i>25 km</i>	<i>N/A</i>	<i>20 min</i>	<i>TBD</i>
<i>Wind vector</i>	<i>25 km</i>	<i>2-3 km</i>	<i>30 min</i>	<i>TBD</i>

These observations and derived products will enable a wide range of analyses and applications:

Weather forecasting

- All-weather soundings, in cloudy and stormy scenes
- Full hemispheric 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 H₂O 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
- Major forecast impact expected, esp. for hurricanes
- 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 \approx AMSU

Summary

The GeoSTAR concept and the related technology have been maturing rapidly. Test results from the prototype amount in effect to proof of concept, and this represents a major breakthrough in remote sensing capabilities. Continuing efforts to develop the technology further will enhance the system’s performance as well as retire technology risk, and it is anticipated that the concept will be mature enough that a space mission can be implemented in the 2014-2016 time frame – making a GOES-R/S “ride-share” mission feasible. The recent mission studies have shown that GeoSTAR is of only moderate size in terms of mass and power, and the cost is reasonable as well. The only major obstacle remaining will then be of a programmatic nature. It is likely that this will be overcome, and a GEO/MW mission is therefore likely within the next 10 years. This will add significantly to the nation’s remote sensing capabilities. The GeoSTAR observations are expected to have a significant forecast impact and will greatly benefit research related to the hydrologic cycle as well. In particular, the GeoSTAR observations will add much to our ability to observe, understand and predict severe storms and hurricanes, just as the need for such observations is becoming critical.

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