GeoSTAR – A Microwave Sounder for Geostationary Satellites

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Abstract—GeoSTAR represents a new approach to microwave atmospheric sounding that is now under development. It has capabilities similar to sensors currently operating on low earth orbiting weather satellites but is intended for deployment in geostationary orbit – where it will complement future infrared sounders and enable all-weather temperature and humidity soundings and rain mapping. The required spatial resolution of 50 km or better dictates an aperture of 4 meters or more at a sounding frequency of 50 GHz, which is difficult to achieve with a real aperture system – this is the reason why it has until now not been possible to put a microwave sounder on a geostationary platform. GeoSTAR is instead based on a synthetic aperture imaging approach. Among the advantages of such a system are that there are no moving parts, and the size of the aperture is easily expandable to meet future needs. A ground based prototype of GeoSTAR is currently under development in an effort led by the Jet Propulsion Laboratory.

1. 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. This has hindered the effective use of GOES data in numerical weather prediction. A full sounding capability from GEO is highly desirable because of the advantageous spatial and temporal coverage that is then possible. 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 dynamic phenomena such as hurricanes. Such observations are also important for climate and atmospheric process studies.

The Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) was proposed as a solution to the GOES microwave sounder problem and is now being considered for inclusion on the next series of GOES satellites (GOES-R) planned for the next decade and beyond. GeoSTAR synthesizes a large aperture to measure the atmospheric parameters at MW frequencies with high spatial resolution from GEO without requiring the very large and massive dish antenna of a real-aperture system – a major advantage of this technology. There are a number of other advantages as well. Sponsored by the NASA Instrument Incubator Program, an effort is currently under way at the Jet Propulsion Laboratory to develop the required technology and demonstrate the feasibility of the synthetic aperture approach – in the form of a small ground based prototype. When this risk reduction effort is completed in 2005, a space based GeoSTAR program can be initiated, which will for the first time provide microwave 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.

2. Physical Basis for Measurements

Atmospheric soundings

GeoSTAR is an atmospheric sounder with rain mapping capabilities. It operates primarily in two millimeter-wave bands. For tropospheric temperature sounding it will have a small number of channels positioned near 50 GHz. For water vapor sounding it will use a set of channels positioned near 183 GHz, which are also used for rain mapping. There may also be an intermediate "window" channel near 90 GHz. GeoSTAR will utilize the same approach as is used with the Advanced Microwave Sounding Unit (AMSU-A/B) system currently operated by NOAA as part of its POES weather satellites as well as by NASA for its Aqua research satellite, an approach that is now well established. These measurements will be used to provide all-weather soundings, with atmospheric profiles derived directly from the microwave observations, but they will also make it possible to 'cloud clear' the observations from companion IR sounders (such as the Hyperspectral Environmental Suite – HES, planned for GOES-R), just as is currently being done in the LEO sounding systems. Such observations are used in numerical weather prediction, where either calibrated microwave and infrared radiances, cloud-cleared infrared radiances or derived atmospheric profiles are assimilated into atmospheric computer models.

To enable full IR-based soundings under cloudy conditions, the ability to provide microwave soundings all the way to the surface, at incidence angles up to 60°, is critical. For temperature sounding, which uses oxygen absorption features, this necessitates using the 50-60 GHz oxygen band and precludes the use of the oxygen line at 118 GHz. The latter would have the advantage of permitting a much smaller aperture for a given spatial resolution, but as Fig. 2 [1] shows, the atmosphere is often so opaque, due to water vapor and clouds, as to make such a sounder insensitive under many common weather conditions. For example, the 118-GHz transmittance in a tropical cloudy atmosphere and at high incidence angles is so low that the crucial planetary boundary layer (i.e. the lowest 2 km) will be invisible.

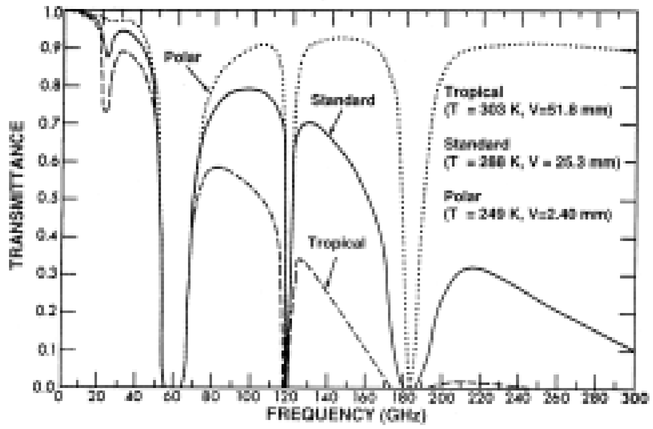

Fig. 2. Atmospheric transmittance

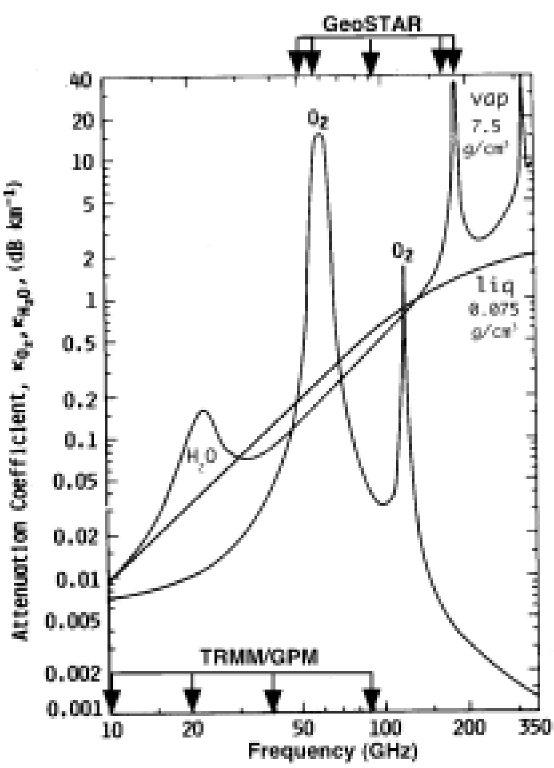

Fig. 1. Microwave atmospheric absorption spectra and GeoSTAR vs. GPM channels

Rain measurements

GeoSTAR will also use the 183-GHz water vapor sounding channels for precipitation measurements. While the approach used with LEO rain radiometers, such as the currently operating Tropical Rain Mapping Mission (TRMM) and the planned Global Precipitation Mission (GPM), is primarily based on measuring the absorption effects of rain at lower frequencies, between 10 and 37 GHz (marked on Fig. 1), the GeoSTAR approach is primarily based on measuring the scattering effects associated with precipitation. The greatest advantage of the high frequency GeoSTAR approach is that high spatial resolution is easily achieved. This is because the antenna size required to achieve a certain spatial resolution is inversely proportional to the frequency. For a given spatial resolution, the aperture of a 200-GHz radiometer is 20 times smaller than that of a 10-GHz radiometer. That is what makes it feasible to deploy GeoSTAR as a rain mapper in GEO, where the great advantage of continuous spatio-temporal coverage is also realized. Because of size and weight and torque effects, it is very difficult and high-risk to implement the conventional scanning antenna approach in GEO. GeoSTAR for the first time makes it feasible to directly measure rain from GEO.

3. INSTRUMENT CONCEPT

GeoSTAR uses a two-dimensional sparse array of receiving elements to synthesize a large aperture. The array is rigid and stationary, and is rigidly attached to the spacecraft. The array is pointed toward the Earth and has a constant full view of the visible Earth disk. This yields continuous high spatial resolution and wide coverage. GeoSTAR is a 2-D spatial interferometric system, which measures the complex cross-correlations between the output signals of all pairs that can be formed from a large number of millimeter wave radiometers arrayed in a "Y" shaped configuration[1], as shown in Fig. 3. The symmetric Y configuration results in a symmetric hexagonal sampling grid in UV-space (i.e. in the receiver plane, measured in wavelength units), also

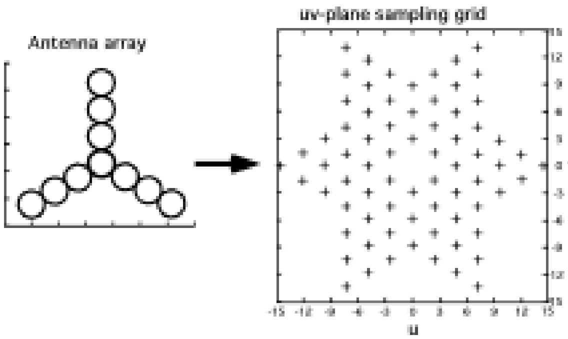

Fig. 3. Antenna array and UV samples

shown in Fig. 3. The smallest pair spacing (called a baseline), i.e. the spacing between neighboring receiving elements, determines the overall field of regard. For GEO, where the required field of regard is about 17.5° - the size of the Earth disk as seen from GEO, the receiver spacing is therefore approximately 3.5 wavelengths (about 2 cm at 50 GHz and about 6 mm at 183 GHz). The longest baseline determines the smallest spatial scale that can be resolved. To achieve a 50 km spatial resolution at 50 GHz, an aperture diameter in excess of 4 meters is required. That corresponds to approximately 100 receiving elements per array arm, or a total of about 300 elements. This in turn results in 45,000 unique baselines and 90,000 uv sampling points.

The measurement system consists of the array of receivers, a digital signal processing system and a calibration system. Each receiver is an I/Q mixer design that produces an in-phase (I) and a quadrature (Q) signal mixed down to baseband and tuned to a particular channel with a tunable local oscillator frequency. These IF signals are digitized and passed on to a correlator module, which is implemented as a large number of 1-bit multipliers operating in parallel on all receiver signals simultaneously.

An innovative calibration system is used to constantly monitor the phase relationships between the array elements. That eliminates the need for precise control of the alignment between the antenna elements. This is what makes the aperture synthesis approach superior to the real aperture approach – no ultra precise surface accuracy, alignment or mechanical scanning are required. Phase knowledge takes the place of mechanical control, and the field of view is inherently matched to the Earth. Absolute radiometric calibration is achieved by operating a separate radiometer as a conventional Dicke switched receiver, which will then measure the average brightness temperature of the Earth disk – corresponding to the "zero baseline" missing from the center of the uv sampling grid shown in Fig. 3.

The measurements are divided into relatively brief measurement cycles of a few tens of seconds in duration. During each cycle the cross-correlations are accumulated simultaneously at each grid point. Interleaved with these are calibration measurements of phase and offset. At the end of each measurement cycle, all observations from that cycle are summed and saved for later transmission to the ground, along with engineering data. In the meantime, the next measurement cycle gets under way. The radiometers are sequentially tuned to different frequencies to measure the separate channels across the frequency band. The measurements are called visibilities and represent samples at the UV-grid points of the so-called visibility function.

The visibility function

The measurement cycle described above is relatively brief (~20 seconds) to make it possible to compensate for possible instrument phase changes, which could be caused by thermal strains in the receiver array as well as system pointing changes and other effects. The first processing task on the ground is therefore to apply phase calibration measurements and other equivalent information to the visibilities formed in the measurement cycle. The objective is to produce a set of adjusted visibility images that are aligned in terms of phase. They can then be co-added to form a single visibility image for each channel, which represents the much longer time span needed to achieve the required radiometric accuracy – typically, on the order of 5-15 minutes for each spectral channel. These visibility images have much lower noise than the individual measurement-cycle images.

The radiometric field

Once the visibility image has been determined, the interferometric equation

$$V_{ij} = \iint \frac{T_B(\xi,\eta)}{\sqrt{1-\xi^2-\eta^2}} F_i(\xi,\eta) F_j^*(\xi,\eta) \tilde{r}_{ij}\left(-\frac{u_{ij}\xi+v_{ij}\eta}{f_0}\right) e^{-i2\pi(u_{ij}\xi+v_{ij}\eta)} d\xi d\eta$$

is inverted to form the radiometric field T_B. Here V_{ij} is the visibility (i.e. the complex cross-correlation) measured between receivers i and j (i.e. at uv location u_{ij}, v_{ij}), f_0 is the center frequency, $F_i(\xi,\eta)$ is the normalized antenna pattern for receiver i, ξ and η are the direction cosines to the radiometric source field, and

$$\tilde{r}_{ij}(t) = e^{-i2\pi f_0 t}\int_0^\infty H_i(f)H_j^*(f)e^{i2\pi ft}df$$

is the so-called fringe wash function. Hi(f) is the normalized frequency response of receiver i. For the GeoSTAR prototype, various methods to invert the visibility equation will be explored.

4. PROTOTYPING EFFORT

An effort, funded by NASA, is currently under way at the Jet Propulsion Laboratory to develop a small ground based prototype unit. This is being done jointly with collaborators at the NASA Goddard Space Flight Center and the University of Michigan. 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. The prototype will be used for laboratory and

[1] Other configurations are also possible, such as a square, a U-shape, a T-shape or a circle

antenna range measurements. A limited set of field observations will also be made to demonstrate the ability to derive geophysical parameters with commonly used retrieval algorithms.

To minimize cost and time to completion, the prototype consists of a small array of 24 elements operating with 4 channels between 50 and 54 GHz. This makes it feasible to address the most important and difficult system issues relevant to an operational 2-D system and to use mature MMIC receiver technology and components. The physical configuration is a Y shape, with 8 elements in an arm with about 3.5-wavelength element spacing (2.0 cm) as required for a GEO system. The system incorporates similar calibration and LO subsystems and distribution schemes as the operational instrument. The prototype correlator is being developed at the University of Michigan based on current related work with other synthetic aperture systems. A standard personal computer (PC) will be used for the data collection and instrument control. A sketch of the system is shown in Fig. 4.

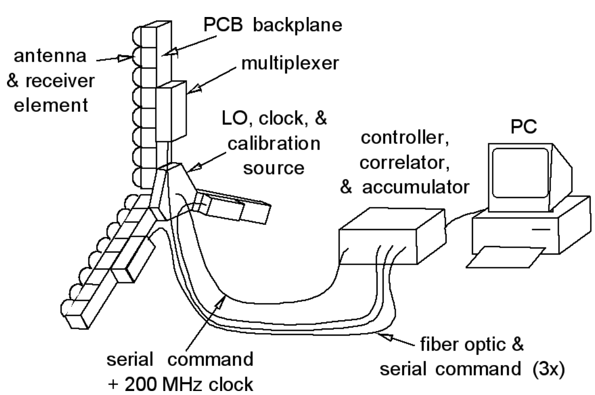

Fig 4. Prototype GeoSTAR configuration

The 24 receiving elements are arranged in the Y-formation described above. Each arm is a single physical module containing a linear array of 8 receiving elements combined with a signal multiplexer. It is envisioned that larger arrays will be formed by combining a number of such modules end to end. The design of the prototype is described in detail by Tanner [2].

5. CONCLUSIONS

The technology elements required for an operational GeoSTAR are relatively mature. For example, MMIC chips required for 50-GHz miniature low-power receivers are available commercially off the shelf. Low noise amplifiers up to 200 GHz are also maturing rapidly. The same is the case for correlator integrated circuits, where technology developed for miniature low-power consumer and communications electronics can be leveraged. 2-bit multipliers operating at 100 MHz have been demonstrated that consume about 0.5 mW each – equivalent to 0.1 mW for 1-bit multipliers, and that is expected to decline to less than 0.01 mW within 3-5 years. Even with the current state of the art, the corelator subsystem for the 100 elements per arm example discussed above would consume only about 20 W – an almost trivial amount for today's satellite systems. The current challenge, where the GeoSTAR prototype is intended as a risk reduction effort, is in terms of system development and integration. Although several efforts have been under way for some time to develop 2-dimensional aperture synthesis systems, none has been demonstrated to date.

The advantages of an aperture synthesis system over a real aperture system are significant. The most important ones are summarized in Table 1. In particular, error budget calculations based on simulations indicate that a synthetic aperture system can be expanded in size without unduly stressing the phase stability requirements. It is therefore well suited to meet future needs as the spatial resolution of numerical weather prediction models increase.

Table 1. GeoSTAR vs. real-aperture systems

Feature	GeoSTAR	Real-Aperture
Aperture size	**Any size**	**Limited**
Scanning	**No scanning**	**Mech. scanning**
Spatial coverage	**Full disk**	**Limited**
Spectral coverage	**One array: one band**	**One antenna: all bands**
Accommodation	**Easy**	**Difficult**
Power consumption	**Moderate**	**Moderate**
Platform disturbance	**None**	**High**

REFERENCES

[1] From N. Grody, in "Atmospheric Remote Sensing by Microwave Radiometry" (M. Janssen ed.), Wiley, 1993

[2] Alan Tanner, IGARSS'04

ACKNOWLEDGMENTS

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