GEO/SAMS — The Geostationary Synthetic Aperture Microwave Sounder

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INTRODUCTION

Background

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 makes 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. In contrast, the GOES satellites have only been equipped with IR sounders, since it has not been feasible to build a large enough antenna to achieve sufficient spatial resolution for a MW sounder in GEO. As a result, 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. 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 coverage, making it possible to monitor highly dynamic phenomena such as hurricanes.

In response to a NASA Research Announcement calling for innovative measurement concepts suitable for non-LEO deployment, GEO/SAMS was proposed as a solution to the GOES microwave sounder problem. Using an approach similar to that proposed by European investigators for the Soil Moisture and Ocean Salinity (SMOS) mission [1], which will operate at low MW frequencies with high spatial resolution from LEO, GEO/SAMS synthesizes a large aperture to measure atmospheric parameters at high MW frequencies with high spatial resolution from GEO. In 1999 NASA s Office of Earth Science selected GEO/SAMS for a Phase A study, sponsored through the New Millennium Program.

Instrument Concept

GEO/SAMS represents a radical departure from the traditional approach to microwave sounding. It will employ a two-dimensional sparse array of receiving elements to synthesize a large aperture. This stationary array will be nadir pointed and will have a continuous full view of the Earth disk, providing high spatial resolution and wide coverage without the need for a very large scanning antenna dish. GEO/SAMS is based on interferometric principles and in effect observes the Earth radiometric field through a complete set of spatial Fourier filters by measuring the cross-correlations between pairs of receiving elements distributed throughout the aperture to be synthesized. The measurements are transferred to the ground, where the spectral radiometric temperature fields are reconstructed. This can be done continuously to achieve uninterrupted temporal coverage. The temporal resolution will be sufficient to allow important dynamic features such as hurricanes to be resolved.

Observables

The functionality of an operational version of GEO/SAMS will be equivalent to that of the latest operational microwave sounders now used on the NOAA POES system, the Advanced Microwave Sounding Units (AMSU-A and AMSU-B). Observables include vertical profiles of tropospheric temperature, water vapor and liquid water, as well as precipitation rates. The GEO/SAMS microwave soundings will cover the crucial mid-to-lower troposphere, all the way down to the surface. Stratospheric coverage can also be added, to match the full AMSU capabilities. GEO/SAMS should be considered complementary to and operated in tandem with an IR sounder. It is in the mid-to-lower troposphere, where clouds dominate, that microwave observations become a crucial complement to the infrared observations. This is the focus of GEO/SAMS. The future GEO/SAMS operational measurement requirements will be based on those of the AMSU system. It will have similar spatial resolution (50 km for temperature and 15—30 km for water vapor), spectral channels (5—6 near 50 GHz, 3—4 near 183 GHz and 2—3 in spectral window regions), and radiometric accuracy (0.3—1.0 K). Full Earth disk soundings will be available every 20—30 minutes out to an incidence angle of 70¡.

Proposed Demonstration Mission

To demonstrate the GEO/SAMS measurement concept, a small 64-element planar Y array, operating at 50 to 55 GHz, has been proposed. This array will provide full Earth disk temperature sounding images every 30 to 60 minutes, with a radiometric accuracy <1 K and a spatial resolution <300 km. A system suitable for such a demonstration mission is described below. The proposed implementation is discussed in greater detail by Boncyk [2].

Technology: Feasibility and Maturity

For the GEO/SAMS demonstration mission, 64 receivers and 8000 correlators are required. The receivers will generate a digital signal rate into the correlators totaling 15 Gb/s, and the correlators will perform an astounding 10^{12} multiplications per second. This requires two key enabling technologies: miniature receivers with low mass, power and per-unit cost; and ultra low-power, high-speed correlators. When the GEO/SAMS study effort began, 1/2-kg 3-W receiver modules could be obtained from industry for several hundred thousand dollars each, and high-speed correlators could be obtained which consume 100 mW each. As a result of preliminary engineering work during the GEO/SAMS Phase A study, there is now strong reason to believe that 100-g 700-mW receivers costing about $10k each in quantity and chip-based correlators consuming no more than 1 mW each can be developed in 2-3 years. This remarkable advance in receiver technology is possible because of prior related NASA-led development efforts (JASON project and IMAS study) and the parallel development of industrial capabilities. The even more astounding advance in correlator technology is possible because of the continuing rapid development of commercial integrated circuit technology. These developments can, with confidence, be extrapolated to 50-g 1/2-W receivers, also operating in the 183-GHz water vapor band, and correlators consuming 1/10 mW each, in time for an operational GEO/SAMS mission in the 05— 10 time frame. The spatial resolution required for such a mission will necessitate a much larger number of receivers and correlators, but the GEO/SAMS system architecture has the enormous advantage of being fully scalable.

SYSTEM ARCHITECTURE

System Description

Fig. 1 shows a block diagram of the GEO/SAMS instrument. It contains the following elements:

- a millimeter-wave antenna array structure, where each array element consists of a feedhorn and a receiver
- an analog processor
- a correlator module
- a local oscillator (LO) signal generator

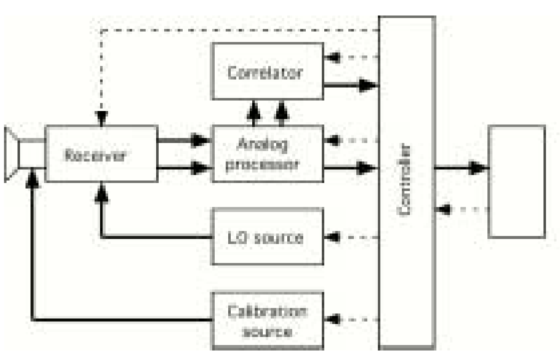

Figure 1. System architecture

- a calibration signal generator

The receiving elements are arranged in three linear arrays of closely packed receiver modules, and the three arrays (arms) are arranged so that they form a planar Y pattern. This plane faces the Earth, i.e. the antenna array is nadir pointed. The array is stationary and anchored to the spacecraft. The other system elements are collocated in electronics modules, which can be positioned behind the receiver array plane or in any other nearby location. The space between the antenna arms may be occupied by other equipment. Consequently, GEO/SAMS will be easy to accommodate.

Signal Flow

Signals flow through the GEO/SAMS system in the following manner:

- Upwelling thermal radiation from the Earth in the microwave part of the spectrum is captured by the feedhorns and fed to the receivers. All feedhorns are aligned to receive the same linear polarization.
- All receivers get a common LO signal, which is used to downconvert a narrow band of the received radiation, centered on the LO frequency, to a narrow-band baseband signal. The central LO frequency is selectable and is distributed to the receivers via a waveguide that is embedded in the antenna structure.
- Each receiver produces an in-phase (I) and a quadrature (Q) component baseband signal.
- The baseband signal pairs from each receiver are brought to the analog processor, where each is passed through a low pass filter and split into a path which leads to a power detector/digitizer and a path which leads to a high-speed 1-bit digitizer.
- The digitized power readings are periodically sent to the system controller for downlink, while the digitized I/Q bit streams are sent to the digital correlator unit, where all possible pair cross-products are formed and accumulated.
- The accumulated cross-correlations are periodically transferred to the system controller for downlink.

Calibration Signals

There are two separate internal calibration signal sources incorporated into the GEO/SAMS system.

The first source is a central random (i.e., thermal) noise source, distributed via a corporate feed waveguide manifold so that it arrives at all receivers with the same phase. This waveguide manifold is embedded in the antenna structure. It is possible to insert fixed phase offsets between the calibration signals fed to each antenna arm. The signal is inserted into each receiver at the same point where the feedhorn signal is inserted and therefore adds to the external RF signal. This correlated calibration signal is used to determine relative phase offsets in the system.

The second source is a noise source which is local and embedded inside each receiver. An electronic switch allows the receiver to process either the signal from the feedhorn or the internal noise signal. These uncorrelated calibration signals make it possible to completely de-correlate the receivers and are used to determine systematic bias in the measurements.

In addition, a ground-based transmitter provides an external correlated calibration signal, which is used for absolute phase calibration. This is possible because the location of the transmitter relative to the spacecraft is known with high accuracy, and is always visible to the GEO/SAMS instrument. Finally, the sun will act as an additional known noise source when it is in the field of view, and space beyond the Earth s limb will be used as an absolute radiometric reference.

Key System Parameters

Key parameters that determine system performance and measurement capabilities are:

- The spacing between the receiver modules determines the overall alias free field of view of the instrument. For GEO/SAMS the required FOV is 20¡, which covers the 17.4¡ Earth disk as seen from GEO. This requires a receiver spacing of about 3.5 wavelengths, or about 2 cm in the 50—55 GHz sounding band.
- The length of the linear receiver array arms defines the radius of the synthesized aperture, and the overall diameter of this aperture determines the smallest spatial scale which can be resolved. For the demonstration system, which has 21 elements per arm, the aperture diameter is about 80 cm. This diameter results in a nominal spatial resolution element of about 0.45¡, or about 300 km on the ground at nadir.
- The sounding frequencies are determined by the LO frequency, which can be switched to a number of values in the 50 to 55 GHz band. Thus, the system can be tuned to any of the AMSU-A tropospheric channels. The demonstration mission plan calls for operation at four sounding channels, but the system is very flexible and will be able to support other observation strategies. The four baseline channels are 50.3, 52.8, 53.48 and 54.4 GHz.
- The radiometric NEDT of GEO/SAMS is determined by a number of system parameters, both fixed and varying. In particular, it depends on the overall observation time. Available observation time depends on the rate of change of the radiometric field and therefore on atmospheric processes. With a spatial resolution of 300 km the atmospheric time constant may be very conservatively estimated to be of the order of 60 minutes. Dividing this between four spectral channels, results in an available integration time of 15 minutes, which is estimated to yield a radiometric noise less than 0.6 K.

Scalability of the Architecture

A unique and valuable feature of the GEO/SAMS architecture is that it is fully scalable. This means that all aperture sizes can be based on the same architecture. The demonstration instrument of 64 receivers has a synthesized aperture of 80 cm. The aperture can easily be doubled in size to 128 elements and 160 cm, respectively, by adding the required number of receivers and correlator elements. Most system components scale linearly with the aperture: the size and mass of the structure, the number of receivers, and the analog-processor components. The correlator scales quadratically with the aperture, so that doubling the size will quadruple the number of correlator elements. As the size is increased, it will also be necessary to add additional correlator channels to achieve the required NEDT. This is easily accomplished by using the future ultra-low power correlators. The calibration distribution manifold is a binary tree structure, and doubling the array size requires adding one level to this structure. There is no theoretical limit to the size of the array; it is only a matter of adding receivers and correlator chips, along with the structure to hold the array together. The primary considerations are mass and power, as well as the structural stability of a very large array. The extension from a small concept validation instrument to a large operational instrument is direct and requires little system development.

THE MEASUREMENTS AND THEIR INTERPRETATION

Physical Measurements

GEO/SAMS is a spatial interferometric system, which measures the complex cross-correlations between all pairs of receivers that can be formed from a Y receiver configuration. The symmetric Y configuration results in a symmetric hexagonal sampling grid in uv-space (i.e. in the receiver plane, measured in wavelength units), as illustrated in Fig. 2 for a small array with an element spacing of 3 wavelengths.

The measurements are divided into relatively brief measurement cycles of a few seconds duration. During each cycle the cross-correlations are accumulated at each grid point. Interleaved with these are special calibration observations, as well as receiver power measurements. (The latter yield the 0,0 sample at the origin of the uv-plane.) At the end of each measurement cycle, all observations from that cycle are prepared for downlink, along with pertinent engineering data. In the meantime, the next measurement cycle gets under way. The measurement cycles alternate between the selected sounding frequencies.

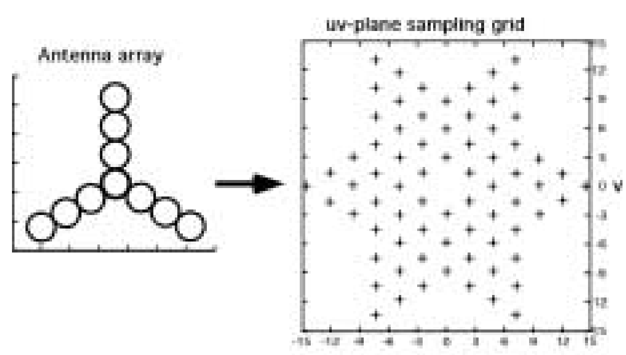

Figure 2. Example array and resulting uv sampling grid

Determining the Visibility Function

The measurement cycle is relatively short to make it possible to compensate for possible phase changes, which could be caused by thermal strains in the receiver array, spacecraft pointing changes, and other effects. The first major processing task on the ground is to apply phase calibration measurements and other equivalent information (such as observation of the sun when it is in the field of view) to the visibilities formed in the measurement cycle. The objective is to produce a set of adjusted visibility images which are aligned in phase. They can then be added to form a single visibility image for each sounding frequency, which represents the much longer time span needed to achieve the required radiometric accuracy (typically, of the order of 10 minutes for each spectral channel). These combined visibility images have much better noise characteristics than the individual measurement cycle images.

Determining the Radiometric Fields

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 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 field (i.e. $\sin\theta\cos\varphi$ and $\sin\theta\sin\varphi$, where θ is the nadir angle and φ is the azimuth angle to a point on the Earth disk), and

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

is the so-called fringe wash function. $H_i(f)$ is the normalized frequency response of receiver i. We will use an iterative method called the CLEAN technique, which is also used in interferometric radio astronomy. Although it was developed for the point sources encountered in astronomy, it has recently been modified for continuous source fields, as encountered in Earth remote sensing, by Camps et al [3]. A major element of this technique is a Fourier transform, and we will use an FFT procedure adapted for hexagonal grids, also by Camps et al [4]. Since the measurements are made on a hexagonal grid, this FFT makes it possible to avoid having to resample the data to a rectangular grid. To reduce grid-cell beam sidelobes, it is also necessary to incorporate a spatial sampling window (often called a taper) into the inversion process. It may be noted that this processing step also makes use of calibration measurements, notably the power measurements (which yield the 0,0 uv sample). The inversion process will also be tuned by using ground truth data, such as coincident independent radiometric observations from sounders flying on LEO satellites and on aircraft. Also important is the view of cold space around the Earth disk with a known radiometric temperature of 2.7 K. This cold band will always be present and will serve as a radiometric reference in every image. In a non-GEO orbit it would be difficult to obtain this permanent reference, and the result would be a handicapped calibration system.

Determining the Geophysical Fields

Before the geophysical variables can be derived it is necessary to ensure that the spectral radiometric fields are spatially aligned. That would normally require a spatial interpolation. For GEO/SAMS, however, a pointing offset is equivalent to a rotation in phase space. The spectral visibility images that are first aligned by counter-rotating them as necessary to compensate for pointing offsets. The resulting radiometric images will then be properly aligned. When the fields are aligned, a set of spectral values is extracted at each Earth grid cell and put through the geophysical inversion process, which is an inversion of the atmospheric radiative transfer equation. Our initial approach will be to use a standard iterative physical method, such as has been developed for AMSU-A by NOAA as well as by NASA.

CONCLUSION

GEO/SAMS will for the first time make it feasible to put a microwave sounder in geostationary orbit. It combines the best elements of a POES system (high spatial resolution and accuracy) and a GOES system (frequent sampling of the entire disk). Combined with a GOES IR sounder, the full potential of the microwave-infrared synergism will finally be realized in GEO, as it already has in LEO.

ACKNOWLEDGMENTS

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