

# **GeoSTAR - A New Approach for a Geostationary Microwave Sounder**

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## **Abstract**

The Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) is a microwave atmospheric sounder, with capabilities similar to those of the AMSU-A/B system, and is intended for deployment in geostationary orbit – where it will complement future infrared sounders to enable all-weather temperature and humidity soundings. It also has the capability of mapping rain rates, and it can be deployed in medium earth orbits as well. GeoSTAR is based on spatial-interferometric principles and uses a stationary array of a large number of individual receivers to synthesize a large aperture and achieve the required spatial resolution, an approach that has significant advantages over conventional real-aperture systems – such as full-disk scanning with no moving parts. GeoSTAR will implement the same tropospheric sounding channels as AMSU-A (temperature) and AMSU-B (humidity) and will achieve an initial spatial resolution of 25-50 km. Future versions will have significantly higher spatial resolution. The required technology is currently being developed at the Jet Propulsion Laboratory and other collaborating organizations, under NASA's Instrument Incubator Program, and a ground based demo system will be ready in 2005.

## **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. Full sounding capabilities with the GOES system are 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.

In response to a 2002 NASA Research Announcement calling for proposals to develop technology to enable new observational capabilities from geostationary orbits, the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) was proposed as a solution to the GOES microwave sounder problem. 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 approach. 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.

### Physical Basis for Measurements

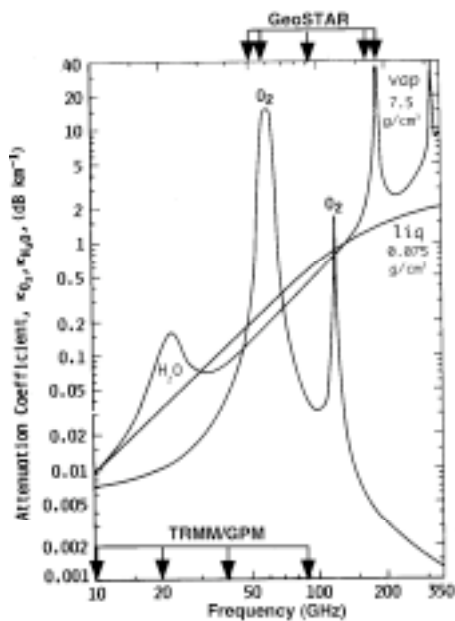


Fig. 1. Microwave atmospheric absorption spectra everywhere, not just in clear areas.

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 near 50 GHz. For water vapor sounding it will use a set of 183-GHz channels, which are also used for rain mapping, as well as an intermediate “window” channel near 90 GHz. The atmospheric absorption spectra and the GeoSTAR channels are illustrated in Fig. 1, where the spectral channels of GeoSTAR are marked at the top of the figure. 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 provide information to ‘cloud clear’ the observations from the GEO IR sounders, just as is currently being done in the LEO sounding systems. The cloud-cleared radiances are either directly assimilated into a weather forecasting system or are used to retrieve atmospheric profiles. This is done

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 highly desirable advantage of permitting a much smaller aperture for a given spatial resolution, but as Fig. 2 (Grody 1993) shows, the atmosphere is often so opaque, due to water vapor and clouds, as to make such a sounder useless 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.

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

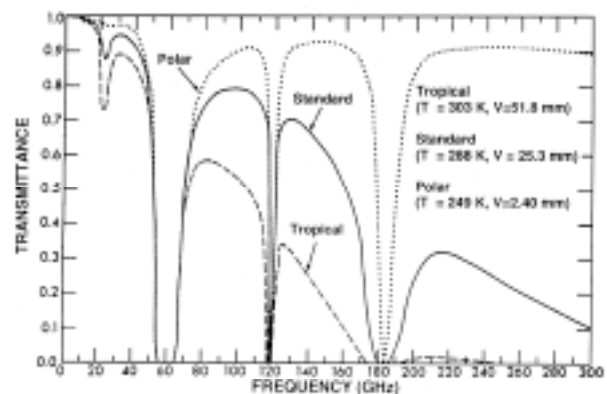


Fig. 2. Atmospheric transmittance

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.

The GeoSTAR scattering approach derives from observations made in recent years with 183-GHz radiometers operated on high altitude aircraft. When passing over rain cells, a pronounced apparent cooling due to scattering is observed. This cooling can exceed 100 K over intense convective cells, a very large signal that can be used to detect and track hurricanes and other severe storms without the need for high radiometric sensitivity (i.e. dwell time). Since these radiometers are sounders, they have channels with a varying degree of opacity (so that they can sound different depths of the atmosphere). Some are so opaque that the surface is normally invisible. When rain is observed through an opaque channel, the scattering, which dominates over absorption at these frequencies, causes a severe apparent cooling over a background that represents the underlying atmospheric state (i.e. its temperature, water vapor, and cloud liquid water). This background is easily measured with a sounder. A new method has recently been developed by Staelin and Chen (2000) to retrieve rain rates from such high frequency observations and is now used with the NASA Aqua satellite launched in 2002. It is expected that the retrieval accuracy will be substantially improved during the Aqua mission.

### 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<sup>1</sup>, 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 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.

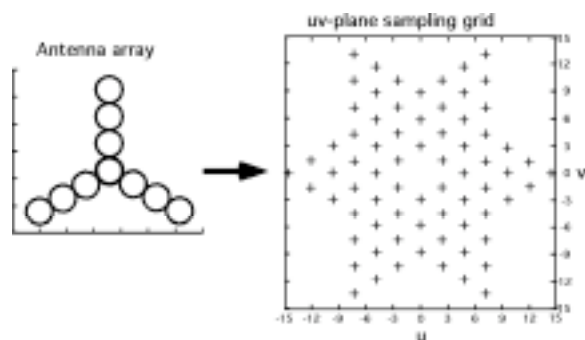


Fig. 3. Antenna array and UV samples

An innovative calibration system is used to

<sup>1</sup> Other configurations are also possible, such as a square, a U-shape, a T-shape or a circle

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.

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 uv-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 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.

Once the visibility image has been determined, the interferometric equation

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

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,  $F_i(\alpha, \delta)$  is the normalized antenna pattern for receiver  $i$ ,  $\alpha$  and  $\delta$  are the direction cosines to the radiometric source field, and

$$\tilde{r}_{ij}(t) = e^{i 2\pi f_0 t} \int_0^\infty H_i(f) H_j^*(f) e^{i 2\pi f t} df$$

is the so-called fringe wash function.  $H_i(f)$  is the normalized frequency response of receiver  $i$ . For the GeoSTAR prototype, various methods to invert the visibility equation will be explored, including the so-called G-matrix method and an iterative method called the CLEAN technique. The latter is used in interferometric radio astronomy, but the technique has been modified for extended source fields. A major element of this technique is a Fourier transform, and an FFT procedure adapted for hexagonal grids by Camps et al. (1997) will be used. To reduce grid-cell sidelobes, it may also be necessary to incorporate a spatial sampling window - a so-called taper - into the inversion process. A number of different taper functions will be examined as part of the prototyping effort. During routine operation, the inversion process will also be tuned by using “ground truth” data.

## Calibration Approach

Unlike for conventional radiometers, where radiometric calibration is the most important, for interferometric radiometers it is phase calibration that is most important. The image synthesis process requires accurate knowledge of the interferometric fringes associated with each visibility measurement. Such calibration data will be established and validated through pre-flight measure-

ments, multiple on-board (internal) calibration circuits, and external references available from GEO.

The pre-flight measurements will include

- receiver frequency response
- elemental antenna patterns
- antenna element mutual coupling
- antenna range measurements of the interferometer as a system

These measurements are used to validate models of the system's spatial response, which form the basis for image synthesis.

The on-board calibration subsystem will be used to stabilize the system response so that pre-flight measurements and models can be transferred to orbit. These circuits include a correlated noise source, which is distributed from a central source and injected behind each antenna in an array "arm" with equal phase to provide an accurate amplitude and phase reference. The phase between each arm can be controlled separately, which makes it possible to rotate the calibration measurements in phase space. Independent noise sources in each receiver front-end will be used to measure null-offsets in the correlators.

It will also be possible to use external calibration sources to validate the calibration on-orbit. These fall into four categories:

- ground beacon
- the Earth's limb
- radiometric references
- the Sun

The ground beacon is a noise source that periodically transmits a brief noise signal in a narrow beam. Since the location of the transmitter is known, this allows absolute phase calibration. The Earth limb also acts as an absolute reference, since the space background temperature of 2.7 K is known. Other radiometric references will be available from time to time from other simultaneous radiometric remote sensing observations from LEO orbiters and aircraft. These can be used to provide absolute radiometric calibration of GeoSTAR. Finally, when the Sun transits near the Earth, it will be aliased into the field of view in a fully predictable manner. That will be used to provide an additional phase calibration.

Two self-consistency techniques will also be applied to the calibration. The first, closure, traces errors in the visibility plane to the amplitude and phase response of each receiver through a network analysis approach. This method makes it possible to extend a partial calibration to the entire uv-plane. The second method, self-calibration, developed by the radio astronomy community – where no absolute calibration references are available, consists of starting with a trial image and then solving for all unknown system parameters until the reconstructed image converges.

The uv-plane sampling grid illustrated in Fig. 3 lacks a sampling point at the origin, the so-called zero-baseline. This point corresponds to the constant in a Fourier expansion and represents the spatial mean value of the brightness temperature field that is being observed. A single, separate receiver is dedicated to provide that measurement, since it cannot be provided by a correlation system. This receiver is operated as a conventional Dicke switched radiometer and is otherwise identical to the array receivers. All receivers, including the zero-baseline one, have the same field of view to encompass the entire Earth disk – about  $17.5^\circ$  from GEO. The zero-baseline receiver therefore measures the average brightness temperature of the Earth disk, as required.

Coincident AMSU observations from underpassing POES satellites will give additional absolute radiometric reference points, since the GeoSTAR channel frequencies will be identical to those used for AMSU.

### 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 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 will be 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 will incorporate 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 and a block diagram is shown in Fig. 5.

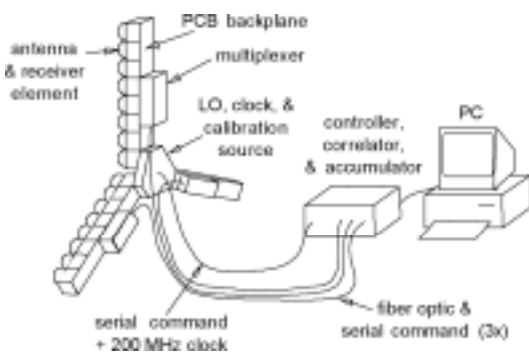


Fig. 4. Prototype GeoSTAR configuration

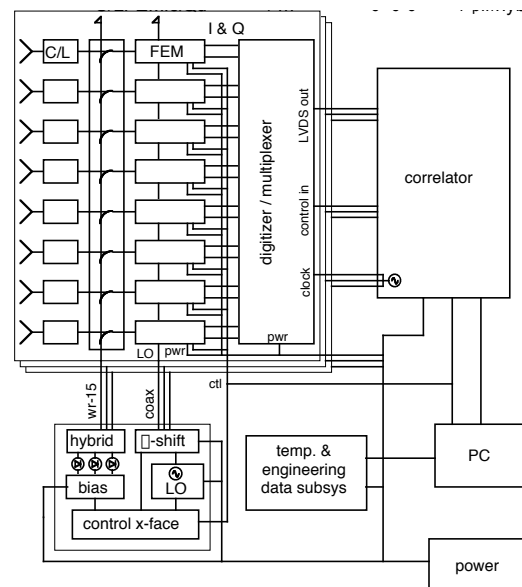


Fig. 5. Receiver system block diagram

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. Fig. 6 shows the antenna array and illustrates an innovative staggered arrangement that makes it possible to transfer phase measurements between the arms.

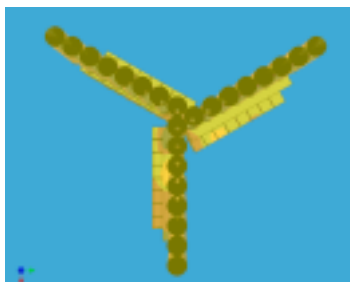


Fig. 6. Antenna array

Each element receives RF energy through a feedhorn, and Fig. 7 illustrates a Potter horn design that is being considered. Other designs are also being evaluated. The receivers are miniature I/Q



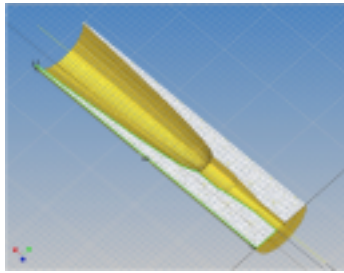


Fig 7. Drawing of Potter horn

mixer designs using low noise amplifiers as a first stage and utilizing MMIC technology. The physical layout of a prototype 50-GHz receiver is illustrated in the photos in Fig. 8.

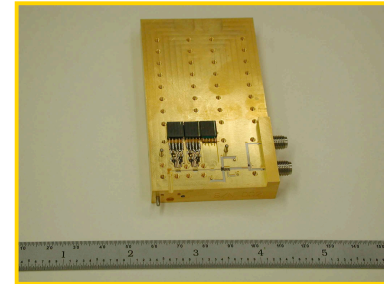
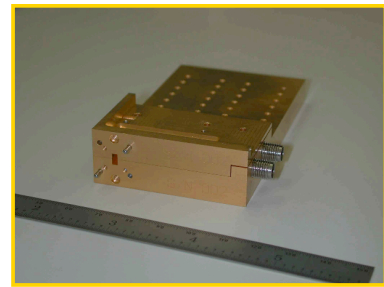


Fig. 8. Prototype 50-GHz receiver

Perhaps the most important subsystem is the correlator, which must perform multiplications of all 100-MHz signal pairs in real time. For an operational system with 100 elements per arm, as discussed above, that requires on the order of 20 trillion multiplications per second. (The prototype system requires substantial lower bandwidth, however.) 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 for the University of Michigan. For the GeoSTAR prototype, where low cost is more important than low power consumption, this design will be implemented in FPGAs, while an operational system will use low-power application specific integrated circuits (ASICs).

## 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. 1-bit multipliers operating at 100 MHz have been demonstrated that consume about 0.5 mW each, and that is expected to decline to less than 0.1 mW within 3-5 years. At that level, the correlator 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, summarized in Table 2, 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	'03: high; '08: low	Moderate
Platform disturbance	None	High

Table 2. Error budget

Array size	$\Delta T = \frac{T_{\text{sys}}}{\sqrt{B\Delta f}}$ additive noise	$\Delta G$ =gain error in each correlator	$\Delta P$ =phase error at each correlator	phase error scaled by spacing (at max spacing)	antenna pattern error
50x50	0.0076 K	0.32 %	0.19°	1.7°	0.17 %
200x200	0.0019 K	0.32 %	0.19°	3.5°	0.17 %

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