Prototyping GeoSTAR for the PATH Mission

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Abstract—**The NRC recommends in the report on its decadal survey of NASA Earth science a mission called Precipitation and All-weather Temperature and Humidity (PATH). The PATH sensor is a microwave sounder deployed in geostationary orbit, with a primary mission of observing hurricanes and severe storms. The Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) concept developed under the Instrument Incubator Program is the only sensor that can meet the PATH mission objectives. Under the IIP a proof-of-concept prototype was developed at JPL to demonstrate the feasibility of the aperture synthesis approach. The prototype was essentially completed in 2005, and testing and characterization has continued since then – both as part of the IIP effort, which came to end in mid-2006, and as part of internal JPL R&D efforts. The results are outstanding and show that a GeoSTAR-centered PATH mission is both feasible and affordable before the coming decade is over. The GeoSTAR effort has retired much of the technology risk associated with this concept, and ongoing cost and design studies indicate that engineering and implementation risks are only moderate. The GeoSTAR development is an example of how the IIP can be a fast track to space.**

I. 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 over 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 (i.e. less important in a weather context). This has hindered the effective use of GOES data in numerical weather prediction. Full sounding capability 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 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.

Based on a concept first developed at the Jet Propulsion Laboratory (JPL) in 1998, intended for the NASA New Millennium EO-3 mission [1] and similar to the Microwave Imaging Radiometer by Aperture Synthesis (MIRAS) [2] then being studied in Europe[1], GeoSTAR synthesizes a large aperture to measure the atmospheric parameters at microwave frequencies with high spatial resolution from GEO without requiring the very large and massive dish antenna of a real-aperture system. Sponsored by the NASA Instrument Incubator Program (IIP), an effort has been under way at JPL since 2003 to develop the required technology and demonstrate the feasibility of the synthetic aperture approach with a small ground based proof-of-concept prototype. This was done jointly with collaborators at the NASA Goddard Space Flight Center and the University of Michigan and in consultation with personnel from the NOAA/NESDIS Office of System Development. The objectives were 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. With the completion of this risk reduction effort, a space based GeoSTAR program can be initiated. This will for the first time provide MW 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. The GeoSTAR concept makes it feasible to expand those capabilities without limit, to meet future measurement needs.

The GeoSTAR prototype – first reported on in [4] has now been completed, and tests have been under way for some time to assess its performance. Results so far are excellent, and this development can now be characterized as proof of the aperture synthesis concept. This constitutes a major breakthrough in remote sensing capabilities. Further technology development is under way, both as risk reduction and to enhance the measurement capabilities of the GeoSTAR system. At the same time, efforts are also under way to secure funding for a space demonstration mission in the 2014-2016 time frame. With the recent recommendation by the NRC, it is likely that a

[1] MIRAS is now being implemented by the European Space Agency as the Soil Moisture and Ocean Salinity (SMOS) mission [3]

GeoSTAR mission will proceed, whether it is as a NASA mission or a joint NASA-NOAA mission.

II. Decadal Survey

The National Research Council (NRC), an arm of the US National Academies of Science, was commissioned to conduct a Decadal Survey of Earth science missions planned by NASA, NOAA and the USGS. In its report, which was released in January 2007 [5], it recommends that NASA undertake 14 new space missions in the coming decade. Among those is one called the "Precipitation and All-weather Temperature and Humidity" (PATH) mission, which consists of a microwave sounder placed in geostationary orbit. Although the report does not specify a particular payload design, references throughout it makes 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. The primary objective of PATH is to provide continuous soundings and precipitation measurements under cloudy conditions, and those observations will be used to improve and constrain models of boundary layer, cloud and precipitation processes. This is expected to lead to significant improvements in storm forecasts. The forecast models can also be re-initialized very frequently – a refresh cycle of 15-30 minutes is envisioned. This rapid-update capability, which is possible from GEO, significantly mitigates the requirements on those models.

III. Instrument Concept

As illustrated schematically in Fig. 1, GeoSTAR consists of a Y-array of microwave receivers, where three densely packed linear arrays are offset 120° from each other. Each receiver is operated in I/Q heterodyne mode (i.e. each receiver generates both a real and an imaginary IF signal). All of the antennas are pointed in the same direction. A digital subsystem computes cross-correlations between the IF signals of all receivers simultaneously, and complex cross-correlations are formed between all possible pairs of antennas in the array. In the small-scale example of Fig. 1 there are 24 antennas and 276 complex correlations (=24*23/2). Accounting for conjugate symmetry and redundant spacings, there are 384 unique so-called uv-samples in this case. Each correlator and antenna pair forms an interferometer, which measures a particular spatial harmonic of the brightness temperature image across the field of view (FOV). 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, 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.

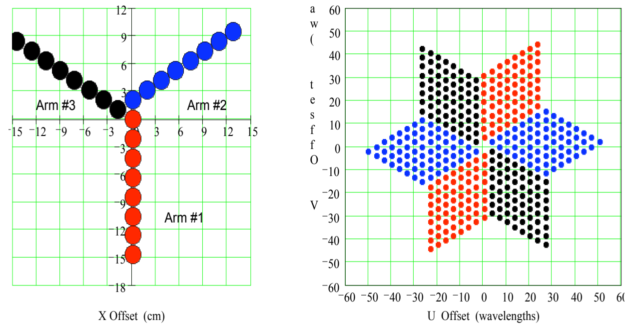

Figure 1. Antenna array (left) and uv sampling pattern (right), as implemented in the GeoSTAR prototype

The smallest spacing of the sample grid in Fig. 1 determines the unambiguous field of view, which for GeoSTAR must be larger than the earth disk diameter of 17.5° when viewed from GEO. This sets both the antenna spacing and diameter at about 3.5 wavelengths, or 2.1 cm at 50 GHz, for example. The longest baseline determines the smallest spatial scale that can be resolved, which for the array in Fig. 1 is about 0.9° (i.e. 17.5°/√384). To achieve a 50 km spatial resolution at 50 GHz, a baseline of about 4 meters is required. This corresponds to approximately 100 receiving elements per array arm, or a total of about 300 elements. This in turn results in about 30,000 unique baselines, 60,000 uv sampling points (given conjugate symmetry), and therefore 60,000 independent pixels in the reconstructed brightness temperature image, each with an effective diameter of about 0.07° - about 45 km from GEO.

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

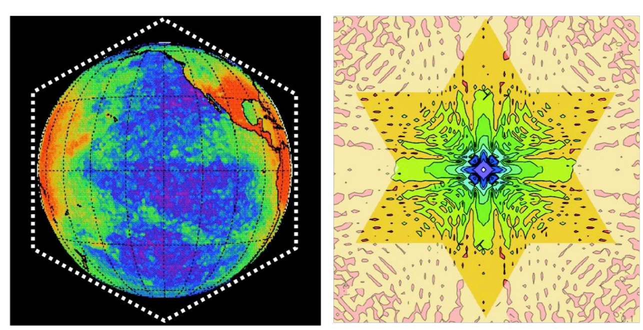

Figure 2. Example brightness temperature image of Earth (left) and its Fourier transform (right). The uv sampling area from Fig. 1 is highlighted (right), and the resulting primary imaging region is outlined (left)

aliasing. That can be tolerated, however, since accurate sounding is limited to relatively high elevation angles. (Current LEO sounders and the algorithms developed for them typically cover elevation angles to about 30°; it is likely that this can be extended to at least 20°.)

IV. PROTOTYPE

The GeoSTAR prototype, developed under sponsorship of the NASA Instrument Incubator Program, consists of an array of 24 elements, such as that illustrated in Fig. 1 and operates with 4 spectral channels between 50 and 54 GHz. It was built to address the major technical challenges facing the aperture synthesis concept. Fig. 3 shows a photo of the prototype.

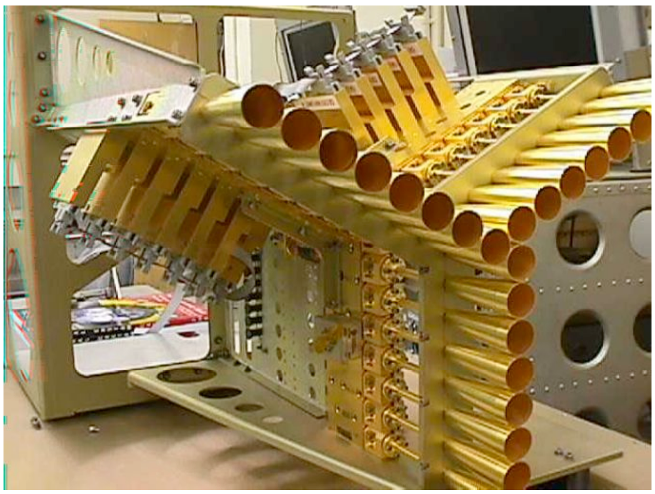

Figure 3. GeoSTAR prototype

In developing the GeoSTAR technology and prototype, a notional space system performing at the same level as the Advanced Microwave Sounding Unit (AMSU) system now operating on NASA and NOAA polar-orbiting LEO satellites was used for design and sizing purposes. This is a crucial aspect that makes it possible to assess the performance in a meaningful way and transfer results directly to a space version. The notional operational GeoSTAR will provide temperature soundings in the 50-60 GHz band with a horizontal spatial resolution of 50 km and water vapor soundings and rain mapping in the 183-GHz band with a spatial resolution of 25 km – this is discussed further below. Radiometric sensitivity will be better than 1 K in all channels. These are considered to be the minimum performance requirements, but the first space implementation could be built to exceed this minimum performance. Table I summarizes the spectroscopic measurement specifications of the POES AMSU for tropospheric sounding. GeoSTAR is intended to operate with those same spectral channels, to allow use of the same geophysical "retrieval" algorithms and to provide "science continuity" between the two systems, as well as to enable cross-calibration. The intention is further to focus on the portions of the atmosphere where clouds are prevalent and IR sounders are not performing well – i.e. in the troposphere, particularly in the lower and mid-troposphere. The two highest-frequency 50-GHz channels listed in Table 1 provide sensing in the upper troposphere and are therefore of secondary importance in this context. The temperature fields there also have less spatial and temporal variability than in the lower atmosphere, which will be exploited in the design and operation of a space version of GeoSTAR.

TABLE I
AMSU/GEOSTAR SPECTROSCOPIC REQUIREMENTS

Band	Func	Channels					
50 GHz	T(z)	50.3	52.8	53.6	54.4	54.9	55.5
183 GHz	q(z)	167	183 ±7	183 ±3	183 ±1		

A number of tests have already been done, both in the laboratory and in the field, and the results are very encouraging – the system is working exactly as expected, which is a remarkable achievement. Fig. 4 shows the first imaging at 50.3 GHz of an environmental scene. In this case there are

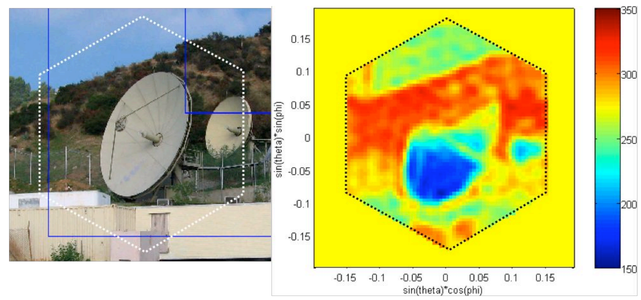

Figure 4. First image of a natural scene

significant sources of thermal radiation outside the primary imaging area that generate aliasing; this makes it difficult to perform quantitative analysis. For that reason a calibration facility was constructed, which emulates the GEO environment by suspending a "warm" disc against the cold sky, as illustrated in Fig. 5. This has allowed a quantitative assess-

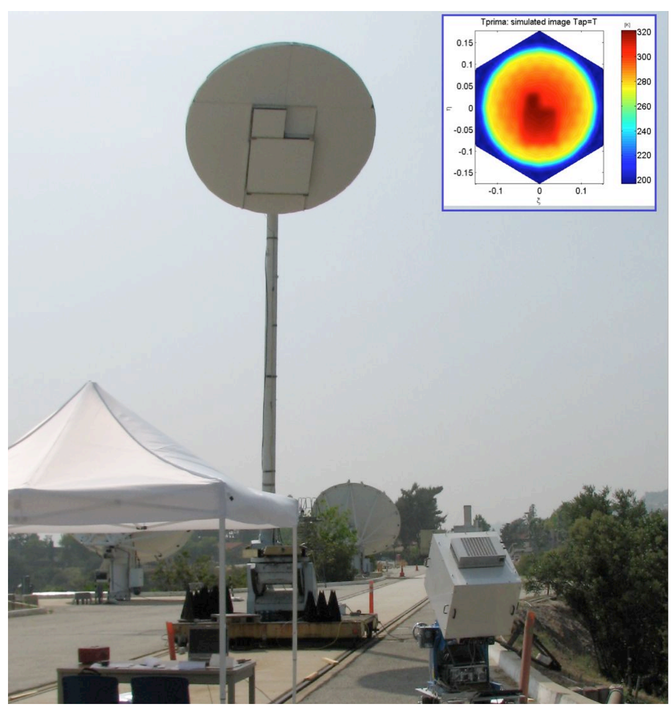

Figure 5. Calibration facility; GeoSTAR is at the lower right

ment of the system, which has confirmed that it performs as designed and as expected. The system is extremely stable – on time scales from minutes to months – and under adverse conditions. The absolute radiometric accuracy is on the order of 1 K, and a 1 K radiometric sensitivity requires an integration time of about 10 seconds per channel.

Testing and analysis are continuing, and preliminary results are reported in [6]. In addition, a field demonstration program is now under way to measure the vertical temperature structure in the lower atmosphere.

V. Science Mission

Following the successful prototype development and consequent proof of concept and the NRC Decadal Survey recommendation of a PATH mission, various mission studies and related development efforts are now under way. Two focus areas have been identified: a) weather applications, with emphasis on tropical cyclones and severe storms; and b) climate research, with emphasis on atmospheric processes and climate variability on intra-seasonal to inter-annual time scales and mesoscale to continental/ocean-basin spatial scales. For climate variability researchers it will be of particular interest to have the diurnal cycle of water vapor, clouds and convection fully resolved.

A notional mission scenario consists of one focused primarily on the North Atlantic hurricanes, and secondarily on Continental US (CONUS) severe storms as well as East Pacific hurricanes. The platform would be stationed at 75° W, as illustrated in Figure 6, where the smaller circle indicates the area of maximum sensitivity for GeoSTAR. The spacing between receiving elements has been increased to reduce the number of elements required. The primary imaging area is therefore smaller than that illustrated in Fig. 2 and portions of the Earth's limb are aliased. The small regions affected by that, indicated in the figure, do not affect the performance in the primary region of interest.

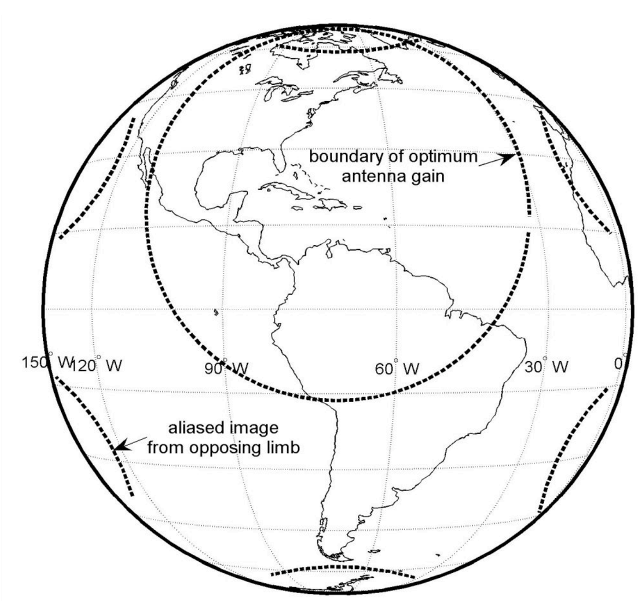

Figure 6. Notional PATH/GeoSTAR mission scenario

The sensor would operate in two spectral bands: near 50 GHz, with 4-6 channels, for temperature sounding and near 183 GHz, with 4-5 channels, for water vapor sounding. That would give the same functionality and capabilities as provided by current and future LEO sounders. Table II summarizes the data products that can be generated with such a sensor system – this list corresponds to baseline capabilities equivalent to products generated with existing LEO systems (except for temporal and spatial characteristics). In addition, a number of experimental products are under development that will have particular applicability to hurricanes and severe storms. A selected list is shown in Table III. These observations and derived products will be generated continuously, day and night, with a temporal resolution of 10-20 minutes in the central focus area. The "experimental" products include parameters that can currently only be produced from precipitation radar systems: rain rates, atmospheric ice content, convective intensity, but analysis of microwave sounder data from recent hurricane field campaigns indicate that the radiative effects of scattering from ice in deep convective systems is similar to the backscatter observed by radar – although with a lower vertical resolution. An example is illustrated in Fig. 7, which shows a parameter derived from the

TABLE II
BASELINE GEOSTAR DATA PRODUCTS

Parameter	Horiz. (km)	Vertical (km)	Temporal (min)	Accuracy
Tb (50 GHz)	50	N/A	3 per ch	< 1 K
Tb (183 GHz)	25	N/A	5 per ch	< 1 K
Temperature	50	2	~ 10	2 K
Water vapor	25	3	~ 20	25%
Liquid water	25	4	~ 20	40%
TPW	25	N/A	~ 20	10%
LWC	25	N/A	~ 20	20%
SST	50	N/A	~ 10	2 K
Stability index	50	N/A	~ 20	N/A

TABLE III
EXPERIMENTAL GEOSTAR DATA PRODUCTS

Parameter	Hor.res (km)	Vertical (km)	Temporal (min)	Accuracy
Rain rate	25	N/A (2)	20	TBD
Convective intensity	25	N/A (2)	20	TBD
IWC	25	N/A (2)	20	TBD
Wind vector	25	2	30	TBD

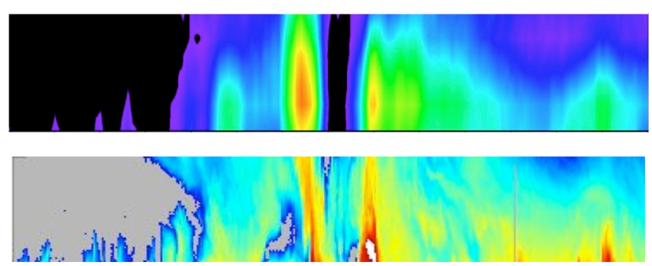

Figure 7. Hurricane observations with a microwave sounder vs. radar Hurricane Emily, July 17, 2005 (from NASA TCSP field campaign)

Lower panel shows radar reflectivity (EDOP, G. Heymsfield PI)
Upper panel shows sounder scattering index (HAMSR, B. Lambrigtsen PI)

sounder (upper panel) and the corresponding radar reflectivity for the nadir view of a pass over the eye of a hurricane (Emily in 2005). The similarities are striking. This analysis continues and is expected to lead to algorithms that can be used to derive the experimental products listed in Table II. Along with the vertical profiles of wind vectors that can be derived by tracking height resolved water vapor features, these products will be crucial in the effort to improve hurricane intensity forecasts as well as for now-casting.

VI. SUMMARY

The GeoSTAR concept and the related technology have been maturing rapidly. The recent test results amount in effect to proof of concept, and this represents a major breakthrough in remote sensing capabilities. The 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. The only major obstacles remaining will then be of a programmatic and budgetary nature. It is likely that those will be overcome, and so a GeoSTAR mission is likely within the next 10 years. This will add significantly to the nation's remote sensing capabilities, and 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, such as hurricanes.

The advantages of an synthetic aperture system over a real aperture system are significant. For example, 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. Another advantage is that the GeoSTAR system does not require platform-disturbing mechanical scanning, and there is no time lag between different portions of the images, as there is in mechanically scanned real-aperture systems – where there can be a time lag of as much as an hour between the start of scan at the northern limit of the Earth disk and the end of scan at the southern limit. GeoSTAR thus produces true synoptic soundings; no other sounder has that capability. An additional advantage is fault tolerance. It is easy to add redundancy in the correlator system. Also, if one receiver should fail, the result is simply a slight degradation in image detail – there are no gaps in the image. (The reader can easily verify that by considering the effect of removing one receiver in Fig. 2.) This "graceful degradation" is in sharp contrast with the catastrophic failure modes of a conventional system, where the loss of one receiver will cause the loss of an entire sounding band.

REFERENCES

[1] B. Lambrigtsen et al., "GEO/SAMS – The Geostationary Synthetic Aperture Microwave Sounder", Proc. IGARSS'00, Vol. 7, 2984-2987, 2000

[2] M. Martín-Neira et al., "A two-dimensional aperture-synthesis radiometer for soil moisture and ocean salinity observations," ESA Bull., no. 92, pp. 95–104, 1997

[3] P. Silvestrin et al., "ESA's second Earth Explorer Opportunity mission: The Soil Moisture and Ocean Salinity mission—SMOS," IEEE Geosci. Remote Sensing Newslett., no. 118, 11–14, 2001

[4] B. Lambrigtsen et al., "GeoSTAR – A Microwave Sounder for Geostationary Satellites", Proc. IGARSS'04, Vol. 2, 777-780, 2004

[5] R. Anthes et al. (eds.), "Earth Science and Applications from Space: National Imperative for the Next Decade and Beyond", Washington, D.C., National Academies Press, 2007

[6] A. Tanner et al., "Performance Evaluation of the Geostationary Synthetic Thinned Array Radiometer (GeoSTAR) Demonstrator Instrument", IEEE Trans. Geosci. Remote Sensing, in press

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