A deployable 4 Meter 180 to 680 GHz antenna for the Scanning Microwave Limb Sounder

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Abstract—**The Scanning Microwave Limb Sounder (SMLS) is a space-borne heterodyne radiometer which will measure pressure, temperature and atmospheric constituents from thermal emission between 180 and 680 GHz. SMLS, planned for the Global Atmospheric Composition Mission of the NRC Decadal Survey, uses a novel toric Cassegrain antenna to perform both elevation and azimuth scanning. These provide better horizontal and temporal resolution and coverage than were possible with elevation-only scanning at typical Low-Earth orbit spacing in the two previous MLS satellite instruments.**

Development of the SMLS antenna was the focus of a 2006 Small Business Innovative Research (SBIR) program whose phase II culminated in the fabrication and thermal stability testing of a composite demonstration model of the SMLS primary reflector. This reflector has the full 4m height and 1/3 the width planned for flight. An Instrument Incubator Program (IIP) titled "A deployable 4 Meter 180 to 680 GHz antenna for the Scanning Microwave Limb Sounder" continues development of the SMLS antenna with the study of 5 topics: 1) detailed mathematical modeling of the antenna patterns from which we simulate geophysical parameter retrievals in order to establish FOV performance requirements; 2) thorough correlation of finite-element model predictions with measurements made on the SBIR reflector. We will again measure deformations of this reflector, under more flight-like thermal gradients, using higher precision metrology techniques available in a new large-aperture facility at JPL; 3) fabrication of a full-width primary reflector whose as-built surface figure will better meet the figure requirements of SMLS than did the SBIR reflector; 4) integration of the primary with other reflectors, and with residual front ends built in a 2007 IIP, in a breadboard antenna; and finally 5) RF testing of the breadboard on a Near Field Range at JPL.

We report on significant progress in 3 areas of the current IIP: development of the mathematical model to predict SMLS antenna patterns and their application in a preliminary set of geophysical retrievals; the correlation between surface deformation predicted by finite element models and measurement in the 2009 isothermal stability tests of the SBIR, with implications for the thermal gradient testing to be performed at JPL; and aspects of the conceptual design of the full-width primary reflector to be fabricated and tested in the 2nd and 3rd years of the IIP.

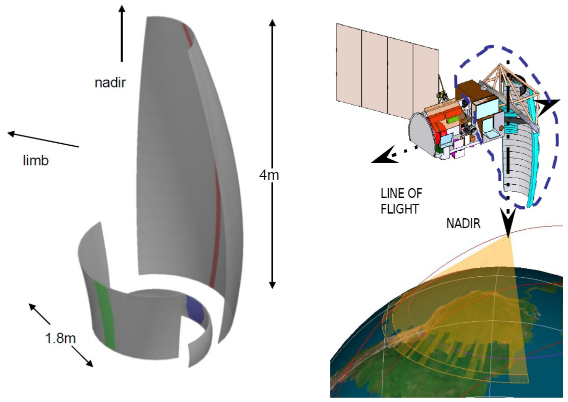
I. INTRODUCTION

The Scanning Microwave Limb Sounder (SMLS) instrument, planned for launch aboard the Decadal Survey's Global Atmospheric Composition Mission (GACM), studies fast tropospheric processes using the microwave limb sounding technique, whose vertical resolution and cloud and aerosol penetration have already been demonstrated with current instruments (UARS and Aura MLS). While daily vertical profile observations from these satellite instruments have provided needed first-order information on the upper troposphere, they lack the spatial and temporal resolution required to quantify important smaller-scale processes that dominate this region's behavior on larger scales from regional to global.

The toric Cassegrain antenna developed for SMLS [1] provides azimuth-independent scanning over a $\pm 65^\circ$ swath of a conical scan (about the nadir axis) from the 830 km GACM orbit. Primary, secondary and tertiary surfaces are generated by rotating conic sections about a common toric axis in the nadir direction. Proper choice of the conic foci and the toric axis transforms a feed pattern with circular symmetry into a very narrow vertical illumination of the primary. The resulting footprint is diffraction limited in the limb vertical direction and $\sim 20\times$ broader, independent of azimuth, in the horizontal. A small (~ 10 cm diameter) mirror scans the beam over the antenna, while a slower $\sim 2^\circ$ nod of the entire antenna provides the vertical scan. Benefits to Earth science are dramatic improvements in temporal and spatial (lateral) resolution and coverage, which will propagate to the body of atmospheric science and become available for policy decisions pertaining to climate change and pollutant transport.

Fig. 1 shows the accommodation of SMLS on a conceptual GACM spacecraft and its illumination for a single azimuth pixel. This paper presents plans to demonstrate fabrication of a 4 meter composite primary reflector for SMLS, in a recently awarded Instrument Incubator Program (IIP). We will also measure the reflector's thermal deformations under flight-like thermal gradients and quantify their effect on geophysical parameter retrievals expected in the GACM orbit. Finally we will combine the primary reflector with other optics in a breadboard antenna (including front-end components from a 2007 IIP which developed receivers and a cooler for SMLS), and measure beam patterns on a Near Field Range (NFR).

In previous development of the SMLS primary reflector under a NASA Small Business Innovative Research (SBIR) program [2], Vanguard Composites/DR Technologies, Inc. built a 4×0.8 meter graphite fiber reinforced composite reflector. This provides full diffraction-limited performance of the center pixels covering 1/3 the azimuth range of GACM SMLS. A thermal stability test, based on similar tests on communications antennas at lower frequencies, verified figure performance under flight-like isothermal environments using photogrammetric measurements. Having shown that thermal stability would meet expected GACM requirements [3], we



(a) (b)

Fig. 1. SMLS antenna: (a) reflector illumination for a single azimuth pixel and (b) accommodation on GACM spacecraft.

deferred correlation of test results with finite element models developed by Vanguard and JPL, and prediction of in-orbit optical performance, to this research.

Section II describes the fabrication of a full-width Primary with improved accuracy capable of meeting GACM requirements at 680 GHz, based on the experience and test results of the 1/3-width SBIR demonstration model. This fabrication will follow model refinement and thermal gradient testing of the SBIR reflector at JPL. Section III describes mathematical models used by JPL for design and analysis of the SMLS antenna. Previously we used these models to predict optical performance in both the candidate GACM orbits (for the full-size SMLS) and the thermal soak test of the demonstration reflector. In this research we revisit those test results to correlate model predictions and extend them to thermal gradient tests of both the 1/3 and full-width primary reflectors in a JPL test facility. We shall also use modeled antenna patterns in geophysical parameter retrieval simulations, in order to specify performance requirements based on GACM science requirements. Section IV covers the thermal gradient tests planned for the primary reflectors. Section V describes our plans to integrate the primary with other reflectors and feed optics, and with receivers from the 2007 SMLS IIP, into a breadboard antenna whose beam patterns we will measure using a NFR at JPL.

II. REFLECTOR FABRICATION

Following the success of JPL's Aura MLS (operating from 118 to 660 GHz) [4], we designed, fabricated and tested a demonstration primary using SBIR and ESTO funding. This reflector has an all-composite architecture with egg-crate core and front and rear face skins, to meet a total surface error budget of 12 μm rms. We identified key material properties, notably near-zero in-plane face skin and core laminate CTE, and thermally conductive core laminate technology, achieved through pre-preg selection, tuning of materials, and standard lay-up and curing processes. Both the segmented core ribs and faceted back skin are planar elements to simplify design, analysis and assembly while maintaining low parasitic mass and high fundamental resonant frequency. For the core laminate, mesh was embedded in composite to reduce thermal strain. Both front and rear skins were tiled to improve isotropy of material properties, especially CTE.

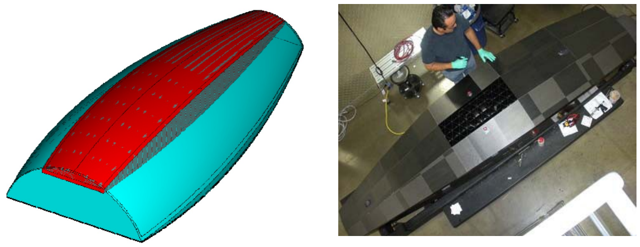


Fig. 2. SMLS antenna: (left) reflector mold, comparing center third used in the SBIR (red) to full width for this IIP (blue), and (right) installation of back skin facets over core in the SBIR reflector inverted on its mold.

To fit within the resources of an SBIR program, we determined that the critical parts of the toric primary design could all be met with a demonstration reflector of the full 4 m height but only 1/3 the width. Fig. 2 shows the 1/3xfull-height mold concept and a photograph of the latter stages of the demonstration reflector assembly with the core structure still visible before installation of the last back skin facet.

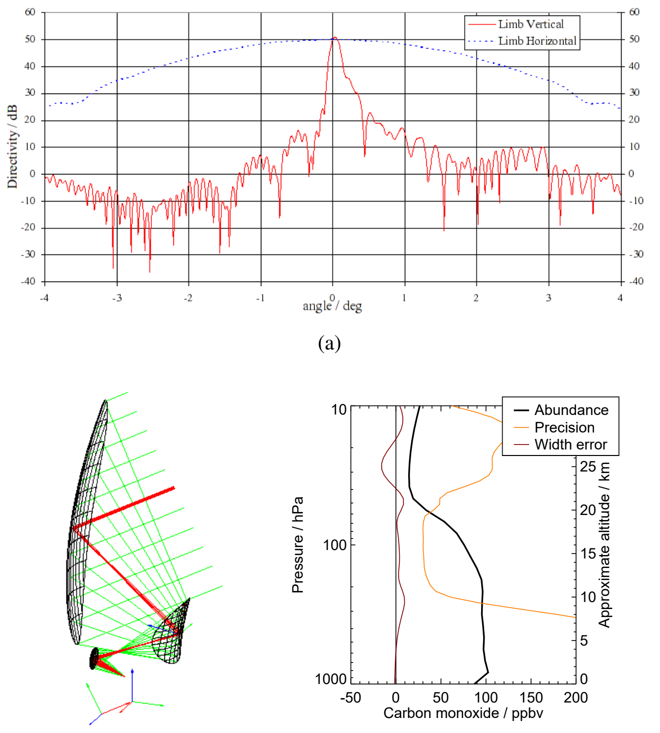
We also relaxed the GACM SMLS surface accuracy requirement ten-fold, to 120 μm rms, and separated the thermal stability requirement from the total accuracy budget (*i.e.*, even with as-built figure errors much larger than a flight SMLS could tolerate, the thermal deformations we could measure would accurately indicate the thermal stability of the flight article). Surface accuracy of the mold delivered to Vanguard was 24 μm rms, i.e. 1/5 the specification but still 7 times more than GACM SMLS will allow for the mold.

For the current program, Vanguard has identified improvements in mold fabrication, mold machining to the tolerances SMLS will require, and metrology of both the improved mold and the replicated reflector. With the IIP resources and the 2 year development time we plan, these will allow replication of full width face skins meeting SMLS requirements, from a monolithic mold.

III. MATHEMATICAL MODELS

A suite of thermal, structural and optical models has been maintained and refined since a 2006 study showed feasibility of the composite architecture of the 4 m SMLS antenna. The model includes primary, secondary and tertiary reflectors, support structure and a notional spacecraft bus. Optical performance in the presence of surface deformations is calculated using a ray-based algorithm which calculates the Optical Path Difference (OPD) at each node for which deformations are known. This method has been used for many previous reflector antenna systems [5] and is compatible with more refined models based on Physical Optics (PO).

In [3] we described use of the OPD model and plotted metrics of FOV performance for a range of solar β angles studied, as 1-orbit time series for selected pixels spanning



(a)

(b)

(c)

Fig. 3. SMLS FOV models: (a) far-field patterns scaled from a previous SMLS design [1], (b) GRASP physical optics model showing principal ray fans, and (c) example of effect on atmospheric constituent retrieval.

the ±65° azimuth width. We also modified JPL's structural model to match the SBIR primary in its thermal soak test configuration, and compared deformations visually with those of the Vanguard model. This IIP begins with completing model correlation, as a prerequisite for defining thermal tests and to guide in the design of the full-width primary.

We have also begun development of a PO model of the antenna, using the commercially available program GRASP. Figure 3 shows how SMLS transforms axisymmetric ray fans emitted by a feed system to a 20:1 beam aspect ratio, as seen in the far-field pattern. Like the OPD model, the PO model accepts surface deformations produced by our thermal and structural models. The 3rd panel of the figure shows the effect of a putative 10% beamwidth error on an atmospheric constituent, illustrating how we will apply geophysical retrieval models to the beam patterns perturbed by thermal deformations. This enables us to flow antenna performance specifications down from science requirements. After developing these models in the 1st year, we will apply them to both predicted patterns, from our engineering models, and measured deformations obtained from the thermal tests.

IV. THERMAL GRADIENT TESTS

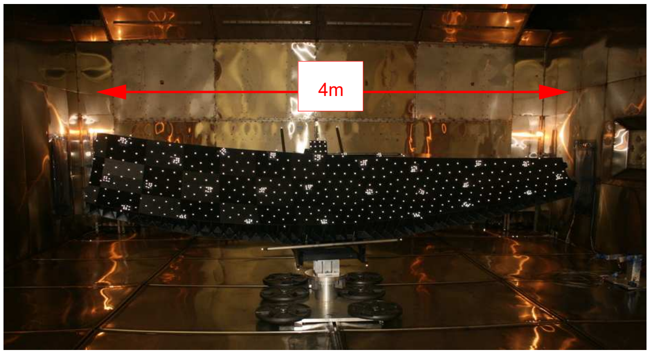
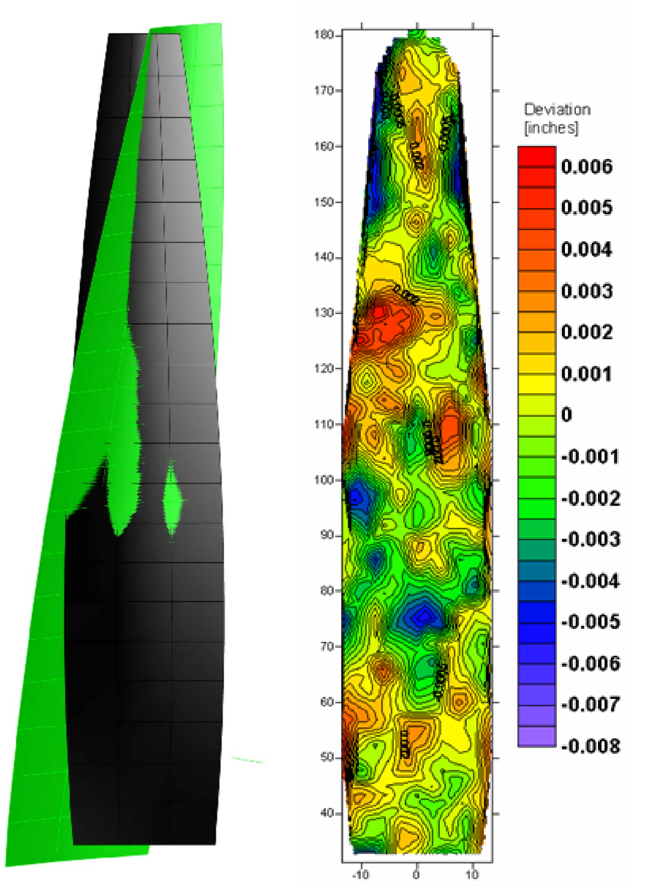


Fig. 4. SBIR demonstration reflector with photogrammetry targets in thermal stability (soak) test chamber.



(a)

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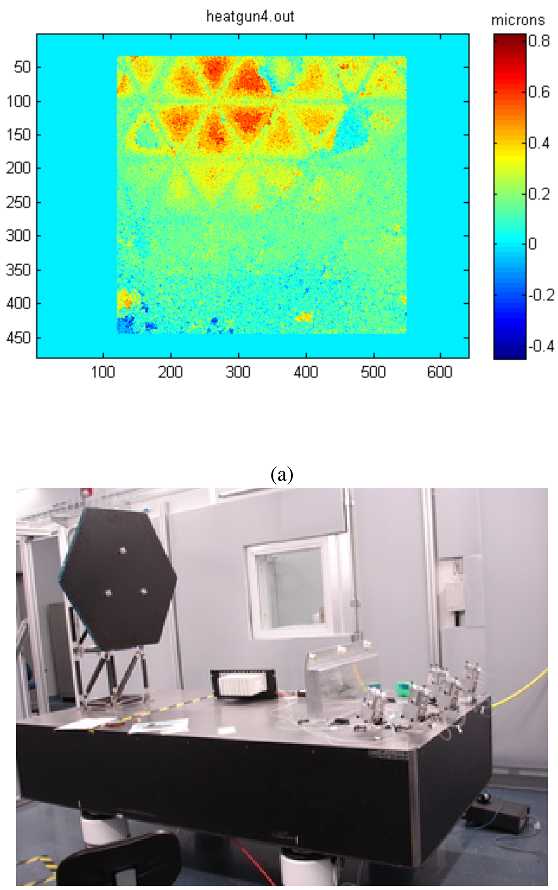
Fig. 5. Surface distortions: (a) NASTRAN model predictions (green) exaggerated 5000×; (b) photogrammetry of reflector at -100°C, expressed as half-Optical Path Difference (OPD/2) from a best-fit surface. We will correlate model and measurements in this IIP.

We shall measure deformations of the SMLS reflectors in JPL's Advanced Large Precision Structures (ALPS) facility. Given the significant OPDs predicted from thermal deformations, thermal gradient testing is an obvious successor to the isothermal soak testing performed on the SBIR reflector as shown in Figures 4–5. ALPS features a thermally stable and isolated $3 \times 5 \times 10$ m test enclosure within a class 100K clean room. Localized heaters will be applied to simulate orbital heat loads on the SMLS antenna, according to the math models and results of the SBIR thermal soak tests. ALPS also provides gravity compensation fixtures if needed.



(a)

(b)

Fig. 6. Metrology capability in ALPS: (a) Electronic Speckle Interferometry of a 16 inch panel from the SBIR, and (b) Laser Ranging Interferometry.

In the SBIR we subjected the reflector to a much larger range of soak temperatures than would be encountered in orbit, in order to infer the micron-level deformations a flight SMLS would undergo. This let us use metrology techniques already proven for lower frequency large antennas. In contrast, ALPS provides two metrology techniques with greatly improved precision, letting us measure sub-micron-level distortions directly. An electronic speckle interferometer measures relative displacement over an entire surface; upgrading the current instrument will illuminate the 4m primary reflector. For absolute position measurements, we will deploy laser ranging interferometry sensors (available from other JPL projects operating at visible light wavelengths) at selected positions on the periphery of the SMLS reflectors. Figure 6 shows previous uses of these techniques in ALPS.

For the IIP, we are developing a test plan for the SBIR reflector recently delivered to ALPS, using the JPL deformations model described above, plus the correlated results of the SBIR soak test. We will incorporate results into both the geophysical and engineering models, and repeat the tests on the full-width primary when it is delivered to ALPS in year 3.

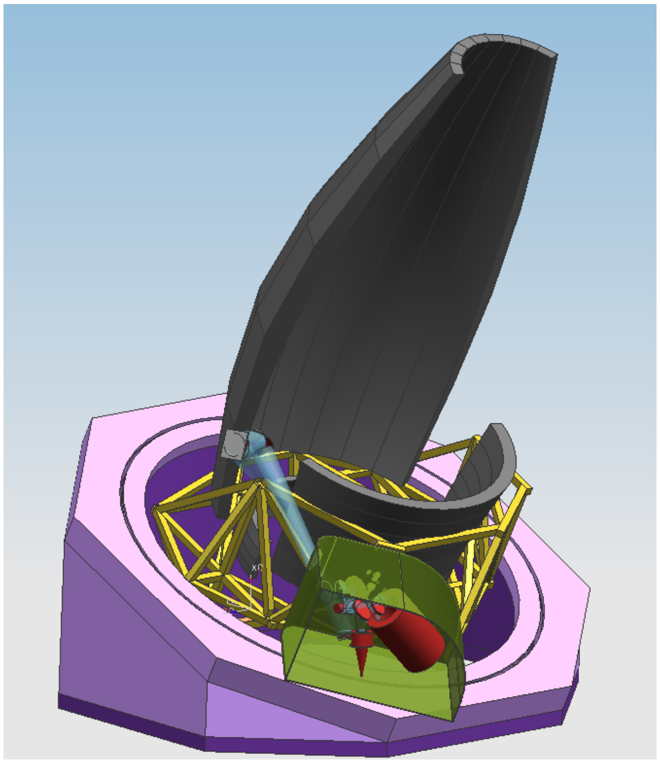


Fig. 7. Concept of SMLS breadboard on a fixture for beam pattern measurements on a NFR. Receivers and calibration optics in the green enclosure are being developed in a 2007 SMLS IIP.

V. BREADBOARD ANTENNA BEAM PATTERNS

After its thermal tests we shall integrate the composite primary reflector into a breadboard antenna for beam pattern measurements. The OPD analysis of [3] showed that at least 80% of the total expected optical performance degradation in orbit comes from the primary. Therefore it is reasonable to use simple and inexpensive materials, such as aluminum, for the secondary and tertiary reflectors and support truss, in a 1st-order demonstration of system optical performance. We expect the small reflectors which perform azimuth scanning and couple the beam into the front ends to be relatively inexpensive, based on preliminary designs for the 2007 IIP. To uncouple antenna development from the IIP primary fabrication, the breadboard structure will accommodate either the SBIR or IIP Primary reflector (With 37 μm rms, even the SBIR reflector could be tested at as low as 60 GHz, giving a meaningful test of the toric antenna concept without unduly large Ruze tolerance losses). By the 3rd year of this research, receivers developed in the 2007 IIP will have been tested in aircraft and balloon flights and be available for integration into our breadboard. Performing this integration in ALPS will let us take advantage of gravity off-loading features in ALPS, and permits thermal tests of the primary in the presence of the antenna truss, as appropriate and permitted by schedule.

Two near field ranges at JPL were identified as candidates for beam patterns measurements of the breadboard antenna: a 30 x 15 foot range, upgraded for capability at the CloudSat frequencies of 90 GHz, and the planar scanner used for FOV calibration of Aura MLS at 660 GHz. The manufacturer of these ranges has quoted upgrades to extend their capability to 280 GHz and the 3.2 m aperture of SMLS; we shall select an option in year 2. Designs and components for transmitters and phase lock electronics ranging from 60 to 660 GHz are available from our previous MLS work and other JPL projects. Figure 7 shows our concept of the breadboard SMLS antenna, oriented for NFR measurements.

VI. CONCLUSION

This IIP will advance flight readiness of the SMLS antenna significantly beyond levels achieved in the preceding SBIR.

ACKNOWLEDGMENTS

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REFERENCES

[1] R. E. Cofield, T. A. Cwik, and N. A. Raouf, “Toric offset three-reflector antenna for an advanced microwave limb sounder,” in *Highly Innovative Space Telescope Concepts, Proceedings of SPIE, 4849*, August 2002.

[2] E. P. Kasl, “Lightweight Thermally Stable Multi-Meter Aperture Submillimeter Reflectors,” DR Technologies, Inc., Tech. Rep., 2010, phase II SBIR Final Report.

[3] R. E. Cofield and E. Kasl, “Thermal stability of a 4 meter primary reflector for the scanning microwave limb sounder,” in *Earth Science Technology Forum 2010*, June 2010.

[4] R. E. Cofield and P. C. Stek, “Design and Field-of-View Calibration of 114–660 GHz Optics of the Earth Observing System Microwave Limb Sounder,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, no. 5, pp. 1166–1181, May 2006.

[5] W. A. Imbriale *et al.*, “Instrument packages,” in *Spaceborne Antennas*. JPL DESCANSO Monograph Series, 2006, ch. 7, ISBN: 0470051507.