

# Prospects for Geostationary Doppler Weather Radar

Simone Tanelli<sup>1</sup>, Houfei Fang<sup>1</sup>, Stephen L. Durden<sup>1</sup>, Eastwood Im<sup>1</sup>, Yahya Rhamat-Samii<sup>2</sup>

1 - Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California, USA

2 - University of California,  
Los Angeles, CA 90095, USA

E-mail: [Eastwood.Im@jpl.nasa.gov](mailto:Eastwood.Im@jpl.nasa.gov)

**Abstract** — A novel mission concept, namely NEXRAD in Space (NIS), was developed for detailed monitoring of hurricanes, cyclones, and severe storms from a geostationary orbit. This mission concept requires a space deployable 35-m diameter reflector that operates at 35-GHz with a surface figure accuracy requirement of 0.21 mm RMS. This reflector is well beyond the current state-of-the-art. To implement this mission concept, several potential technologies associated with large, lightweight, spaceborne reflectors have been investigated by this study. These spaceborne reflector technologies include mesh reflector technology, inflatable membrane reflector technology and Shape Memory Polymer reflector technology.

**Keywords** - cloud radar ; CloudSat; EarthCARE ; ACE

## I. INTRODUCTION

Under NASA's Earth Science Technology Program, a novel mission concept has been developed for detailed monitoring of hurricanes, cyclones, and severe storms from a geostationary orbit: "NEXRAD in Space" (NIS). NIS would enable GEO-style rapid-update sampling ( $\leq 1$  hour cadence) of 3-D fields of 35 GHz radar reflectivity factor ( $Z$ ) and line-of-sight Doppler velocity ( $V_D$ ) profiles, at mesoscale horizontal resolutions ( $\sim 10$ km) over a 5300 km diameter area (equivalent to much of an oceanic basin, such as the Atlantic). NIS GEO-radar concept was chosen as one of only four potential post-2020 missions for the Weather Focus area in the 2007-16 NASA Science Mission Directorate (NSMD) Science Plan (Table 4.3, p. 60). The results of the first project aiming at developing the NIS concept highlighted the enormous potential of such mission, and the technological challenges presented by it [1].

In essence, it is because of its rapid-cadence capability that NIS science planning is focusing on hurricane monitoring and prediction. Hurricanes, or generically tropical cyclones (TCs), have always been among the most devastating natural phenomena. This has been forcefully reiterated in recent years with a number of powerful TCs landfalling in North America and elsewhere. In April 2007, the 1st NIS Science Workshop was convened at the Univ. of Miami to galvanize the scientific community's interest in NIS's measurement capabilities for improved TC monitoring and prediction [2]. It was agreed that a GEO Doppler radar would provide a breakthrough in regards to the observation of TCs, and, when combined with cloud-resolving NWP models.

Among the technological challenges that are to be resolved before NIS can progress to final design and implementation,

This work was supported by NASA Earth Science Pathfinder Program (ESSP), and the ACE Mission Program.

the ones presented by the main reflector are by far the most conspicuous. The NIS radar achieves its sampling capabilities by use of a 35-m diameter in-space deployable spherical reflector, and a set of mechanically moving feeds that complete spiral scans to  $4^\circ$  off-nadir to cover the 5200-km diameter circular area on the Earth's surface. This space deployable 35-m diameter reflector operates at 35-GHz with a surface figure error of 0.21 mm RMS. This reflector technology, however, is well beyond the current state-of-the-art. In order to implement NIS, several potential technologies associated with large, lightweight, spaceborne reflectors are being investigated. These spaceborne reflector technologies, which include mesh reflector technology (MR), inflatable membrane reflector (IMR) technology and Shape Memory Polymer (SMP) reflector technology, will be discussed in the following sections. Notably, the National Academy's National Research Council Decadal Survey [3] included a specific recommendation to further the technologies necessary for the deployment of a geostationary weather radar.

## II. ANTENNA ELECTRICAL DESIGN

The NIS antenna requirements include an antenna gain of 77 dB, a beamwidth of  $0.02^\circ$ , a sidelobe level of better than -30 dB, and a scan of up to  $4^\circ$  off its axis. This angular scan translates into a scan of  $\pm 200$  beamwidths. The first potential antenna candidate is an electronically scanned array antenna. However, such a large array at 35 GHz would require over 6 million array elements. This is indeed a formidable and very expensive task. A second candidate is a parabolic reflector antenna. However, such antenna suffers from severe limitation at large beam scans. A focal plane array can potentially compensate for this performance degradation. Such implementation, however, necessitates the use of an active array with adaptively varying excitation coefficients for different look angles. Such an implementation could also become an expensive proposition. The third candidate is a mechanically rotating antenna. For such a large antenna, the torque created by rotating the entire reflector will be very large. The fourth candidate is a spirally-rotating spacecraft with a fixed-mounted antenna. This option, can be very complicated and requires extensive interface between the radar and the spacecraft. For NIS, we focus on a novel spherical reflector antenna design [4] which is capable of scanning its beams to any desired direction without compromise on the radiation performance. Any spherical aberration-induced degradation will be overcome by using a small planar array in the focal plane. Such a focal array can achieve any desired

beam direction; more importantly, there is no need to reconfigure the array excitation coefficients for new beam direction. Spherical reflector antennas produce almost identical beams when their feeds are rotated with respect to the focal point. The major drawback is the excessive gain loss due to the presence of an extended focal region. Since the objective is to cover a  $\pm 4^\circ$  angular range, an oversized reflector antenna at 35m diameter is necessary to cover the desired angular range. A 271-element, rotating, fixed feed array  $\sim 20$  cm in diameter with complex excitation coefficients substantially improves the performance of the spherical reflector antenna. The corresponding antenna radiation patterns at  $4^\circ$  scan are shown in Fig. 1: an antenna gain of  $\sim 80$  dB with sidelobe levels below 30 dB are obtained. The feed arrays are mechanically moved to achieve scanning.

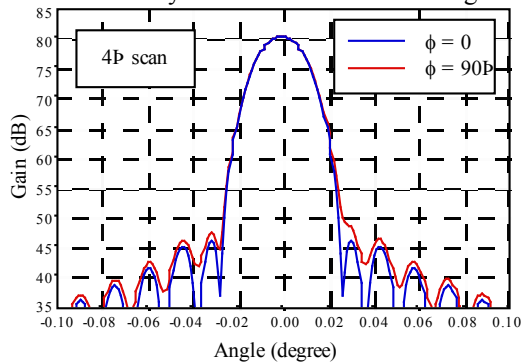


Fig. 3. NIS antenna patterns

### III. DEPLOYABLE ANTENNA TECHNOLOGIES

#### A. Mesh Reflectors (MR)

MRs are the only types of deployable antenna reflectors that have successfully flown in space as parts of an instrument or other satellite system. More than twenty two MRs have or will be flown by 2009 for USA commercial and/or science missions. The largest current MR aperture is 17 meters and will be increased to 22 meters with the launch of the MSV telecommunications satellite by 2009.

Of all the current MR technologies the current state-of-the-art for demonstrated on-orbit stability and surface accuracy is Northrop Grumman Space Technology's AstroMesh reflector. The primary components of an AstroMesh reflector are a flat deployable perimeter truss, front and rear nets, tension ties, and mesh. The front and rear nets are composed of high stiffness, near-zero CTE composite web elements that form two back-to-back geodesic domes. One of the domes is shaped to approximate the required parabolic surface metric with triangular facets. The webs are tensioned to high stress levels by even application of normal loads from the tension ties. These high stress levels allow the front net to maintain very high stability and precision despite parasitic mesh loads. The flat truss is relatively deep and is composed of near-zero-CTE carbon fiber composite. This deep truss is very stiff and highly thermally stable. Seven AstroMesh reflectors have been deployed on commercial spacecraft since 2000.

The antenna mesh that comprises the reflective surface of all current deployable MRs is evenly stretched across the

aperture. Mesh is typically made of extremely fine gold-plated molybdenum wire that is Tricot knitted thus making it highly elastic, which allows it to yield to the structural definition provided by the reflector structures. Noteworthy advantages of using mesh include its ability to be arbitrarily packaged in an extremely small volume without introducing any permanent plastic deformations, its extremely low areal mass, high stability and longevity in a space environment. With minor development effort mesh will be capable of excellent RF reflectivity and cross-pol performance to the 35 GHz band required by the NEXRAD instrument.

The deployable reflector structures that support mesh, however, will require significant development to be able to support the required surface accuracy of 0.21 mm. The best MR surface accuracy that has been demonstrated thus far, in terms of the ratio of aperture diameter ( $D$ ) to surface accuracy ( $\delta_{\text{RMS}}$ ) is in the vicinity of  $D/\delta_{\text{RMS}} = 20,000$  to  $30,000$ . Extrapolation from a theoretical study [5] leads us to conjecture that the maximum possible value of  $D/\delta_{\text{RMS}}$  for a passively maintained reflector structure is well below  $100,000$ .

Because the NIS Goal for  $D/\delta_{\text{RMS}} = 170,000$  its MR must offer in-flight adjustment of the surface figure. Whether this control is fully active with short update periods or more quasi-static in nature has yet to be determined. Nonetheless, an appropriate reflector surface metrology system with feedback and control of the mesh surface shaping structure is required.

To achieve surface figure control to 0.21 mm RMS during orbit, the contour of mesh can be controlled by changing the lengths of the tie elements, whether it is the drop ties of a radial rib reflector or the tension ties of the perimeter truss. With advancements in miniature actuator technologies potentially appropriate linear actuators for this application are readily available. This and other similar approaches are being considered by the NIS project for application to MRs.

#### B. Inflatable Membrane Reflector (IMR)

During the last two decades, on- and off-axis parabolic IMRs with apertures up to 10-m have been fabricated and tested. Lightweight inflatable structures were also developed to support these antennas [6].

A typical inflatable antenna consists of two thin films, a reflector and a canopy, joined around the edges. The relatively thin ( $<1$ -mil) polymer films are cast on a precisely shaped mandrel and then thermally cured and released. The reflector film is typically metalized with a vapor deposited silver or aluminum coating, nominally very thin. The membranes are then joined using a leak tight bonding technique. Following fabrication, the antenna is integrated with an inflatable torus via compliant features that minimize loading changes associated with thermal excursions. The antenna and torus structures are precisely inflated to approximately achieve the desired membrane stress and structural stiffness. Then, the boundary tension is adjusted to achieve the best shape. While the reflector film and canopy film are cast as one piece polymer thin films with a parabolic shape, achieving high surface accuracy after inflation deployment and in the space thermal environment is more

challenging. Inflation pressure and film stress introduce shape errors, especially slope error near the edges (W-Error). Thermal loads cause less systematic shape errors. The thermal induced shape errors can be significant and may drive the need for active control of the inflatable antenna. However, recent improvements in low coefficient of thermal expansion space ratable polymers can potential reduce the magnitude of thermal distortions.

To date, on-axis, off-set, and Cassegrain antennas, from 0.3-m to 4-m in aperture, have been designed, fabricated, and radio frequency (RF) characterized via range testing. Thus far, frequencies through Ku-band have indicated excellent antenna performance. Ka-band test results indicate that improved antenna surface shape accuracy (sub-millimeter values) is required for efficient operation. Thus, shape optimization, tooling technology, fabrication processes, and active shape control techniques are being considered to enable Ka-band operations.

### C. Shape Memory Polymer (SMP) Reflector

Rigidizable materials in general are materials that are initially flexible to enable system packing and deployment, and become rigid when exposed to an external stimulus. Although many types of rigidization mechanisms exist, this section only deals with thermally activated SMP composite materials and structures for antenna reflector applications [7]. The effect of shape memory can be triggered by a stimulus other than temperature such as light or chemicals and these are classified as photo responsive and chemical responsive shape memory respectively. By definition, thermally activated SMP are polymers that can be predetermined to regain their original cured shape after being packed or deformed above their glass transition temperature by applying an external thermal influence. The SMP polymers differ from the traditional thermoplastic polymers in their ability to restore to their original shape by mere application of heat. To date, SMP have been demonstrated to recover more than 99% of their original shape in most applications if they are not under the influence of an external mechanical load.

The thermo-mechanical response of a thermally activated SMP can be characterized by four critical temperatures. The glass transition temperature,  $T_g$ , is the transition point for thermo mechanical deformation and recovery. Polymers possessing a glass transition temperature exhibit rubbery characteristics above  $T_g$  and exhibit a glassy state below  $T_g$ . The deformation temperature,  $T_d$ , is the temperature at which the polymer can be deformed into a temporary shape.  $T_d$  can be above or below  $T_g$ , but for folding or packing purpose it is not recommended to tightly fold SMP below  $T_g$ . The folding temperature for this class of SMP is typically 20°C above  $T_g$ . The storage temperature,  $T_s$ , is lower than  $T_g$  and denotes the temperature at which the polymer is stable in the packed or deployed state over long period of time. Finally, the recovery temperature,  $T_r$ , is the temperature at which the original shape is recovered.

The manufacturing methods for SMP composite structures are similar to the traditional thermoset composites. The desired final shape of the SMP composite structure is set

during its initial cure cycle at an elevated temperature. Once the SMP material is completely cured, it can be reheated to a minimum of 20°C above the  $T_g$  where it becomes flexible and can be tightly folded. The flexibility of the SMP composite at the folding temperature depends on the properties of both the resin and the fiber. After the material is folded, it can be constrained in that position and then cooled to approximately 15°C below  $T_g$  or  $T_s$  at which point the SMP composite can be unconstrained and will remain frozen in the folded position until it is heated again. When the SMP is heated to the recovery temperature after being folded, the SMP material will naturally begin to return to its initial cured shape based on the shape memory recovery force of the composite. In actual applications, although the composite has a higher shape memory recovery force than the SMP resin alone, inflation gas is often required to augment the structure's return to its originally cured shape. Recently test has been conducted on this SMP composite material and results can be found in several published papers.

SMP have been widely used in the commercial and medical fields with well known performance heritages. Some examples of biomedical applications are artificial muscles, catheters, wire mesh stents and other human interface devices. However, to date, SMP have only seen limited applications in space systems, but a number of applications are under development. These applications include structural components such as composite tube structures, reflector dish structures, and hinges. Several systems under developed are for very large truss or boom structures. In structural applications where large system payload mass is part of the deploying structure the limited recovery force available from the SMP is not sufficient to deploy the system. Therefore, some form of force augmentation is required to deploy the system. One option is to use inflation pressure inside the SMP structure to assist with the deployment. For precision structures where the fibers must be properly strained to remove all packing deformities, the use of inflation deployment offers the benefit of accuracy.

SMP composite materials have recently been utilized for investigation on a number of development programs for space applications. Such programs that can directly benefit the development of large deployable antenna reflector include SMP booms, truss structures and SMP antenna reflectors.

SMP cylindrical booms of various sizes (from 10 mm to 100 mm in diameter and 1-meter to 5-meter in length) have been extensively tested under NASA, DARPA and IRAD programs in the past few years at ILC Dover. The technical readiness levels of these booms are at 5 to 6 and they have also been assembled into truss structures for packing, deployment, structural, mechanical and thermal properties evaluations. Truss structures designed using SMP composites demonstrated deployed-to-packed length ratios of 100:1. Truss structures like this can be used to construct the back support structure (struts and perimeter trusses of various shape) for large lightweight space based antenna reflectors.

SMP composite materials have also been used to manufacture deployable parabolic reflector dishes. The use of

this technology is currently planned for JHU/APL's Hybrid Inflatable Antenna and JPL's Advanced Precipitation Radar Antenna Singly Curved Parabolic Antenna Reflector. For the Hybrid Inflatable Antenna, a 2-m diameter SMP composite reflector was recently fabricated and assembled into a support structure to demonstrate the feasibility of the technology. For this application, both the reflector dish and the support torus are envisioned to be fabricated from the SMP composite. To date, packing and deployment trials have not been demonstrated on the 2-m reflector, but two 0.5-m reflectors were fabricated from a carbon/SMP composite to demonstrate a potential folding scheme.

The same carbon/SMP composite has also been used to fabricate the singly curved parabolic antenna models for feasibility study. These antenna models are 1/10<sup>th</sup> scale of the actual application with a length and width of approximately 0.5-m. After cure, a vapor deposited aluminum (VDA) polyimide film was bonded to the inner surface of the antenna to increase its reflectivity. For packing and deployment demonstration, the reflector was heated in an oven to above glass transition temperature for packing. After the antenna was packed it was taken out of the oven and allowed to cool in the rolled up shape. Then it was placed back in the oven for deployment by the material's shape memory return function only. This shape memory return feasibility test was qualitatively successful and further work is continuing in this area to work on the details of scaling this technology up to larger size antennas and quantitatively measure the shape memory recovery response of the composite.

#### ACKNOWLEDGMENT

The authors would like to acknowledge James C. Pearson and James Moore of ManTech SRS Technologies as well as

John K. Lin of ILC Dover for their contributions to the development of reflector technologies.

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).

#### REFERENCES

- [1] Smith, E.A., V. Chandrasekar, S.S. Chen, S. Durden, H. Fang, Z. Haddad, G.J. Holland, J. Huang, E. Im, R.K. Kakar, K.-S. Kuo, W.E. Lewis, F.D. Marks, A. Mugnai, U. Quijano, Y. Rahmat-Samii, S. Tanelli, G.J. Tripoli, and C. Velden, 2007b: NIS White Paper. [Available at <http://nis.ssec.wisc.edu/>.]
- [2] Im, E. E.A. Smith, V.C. Chandrasekar, S.S. Chen, G.J. Holland, R.K. Kakar, S. Tanelli, F.D. Marks, and G.J. Tripoli, 2007: Workshop Report on NEXRAD-In-Space - A Geostationary Satellite Doppler Weather Radar for Hurricane Studies. Proc. of AMS 33<sup>rd</sup> Radar Meteorology Conference, Cairns, Australia, Aug 6-10, 2007.
- [3] National Research Council, "Earth Science and applications from space: national imperatives for the next decade and beyond," *The National Academic Press*, 2007.
- [4] Bahadori, K., and Y. Rahmat-Samii, 2005: An array-compensated spherical reflector antenna for a very large number of scanned beams. *IEEE Trans. Antennas Propagation*, 53, 3547-3555.
- [5] Hedgepeth, J. M., "Accuracy Potentials for Large Space Antenna Reflectors with Passive Structure," *Journal of Spacecraft and Rockets*, Vol. 19, No. 3, May-June 1982, pp. 211-217.
- [6] E. Im, M. Thomson, H. Fang, J.C. Pearson, J. Moore, J.K. Lin, "Prospects of Large Deployable Reflector Antennas for a New Generation of Geostationary Doppler Weather Radar Satellites," AIAA-2007-9917, AIAA SPACE 2007 Conference & Exposition, Long Beach, California, September 18-20, 2007
- [7] H. Fang, E. Im, "Mechanical Technology Development on A 35-m Deployable Radar Antenna for Monitoring Hurricanes", NASA ESTO B6P2, Earth Science Technology Conference 2006, Adelphi, Maryland, June 27-29, 2006