Instrument Concept of NEXRAD In Space (NIS) – A Geostationary Radar for Hurricane Studies

Eastwood Im[1], Eric A. Smith[2], Stephen L. Durden[1], Simone Tanelli[1], John Huang[1], Yahya Rahmat-Samii[3], Michael Lou[1]

[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[2] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[3] University of California, Los Angeles, CA 90095, USA

Abstract — **The current Geostationary Operational Environmental Satellites (GOES) are equipped to make cloud top measurements only. In contrast, a millimeter-wave radar allows 3-D measurements of precipitation associated with hurricanes and other convective systems. It also provide important inputs for numerical weather prediction models for improving the accuracy of weather nowcasting and forecasting. Recently, a novel instrument concept and the associated critical technologies are being developed for a 35-GHz Doppler radar for detailed monitoring of hurricanes and severe storms from a geostationary orbit. This instrument is designed to be capable of producing rainfall rate at 13-km horizontal resolution and 300-m vertical resolution, and the line-of-sight Doppler velocity at 0.3 m/s precision, of the 3-D hurricane structure once per hour throughout its life cycle.**

I. Introduction

The existing Geostationary Operational Environmental Satellites (GOES) have proven to be valuable for cloud meteorology, water vapor and surface temperature retrieval, and weather synopsis. However, the lack of cloud penetrating ability does not permit current GOES instruments to directly measure rainfall associated with hurricanes and severe storms.

Ground-based Doppler radars have long been used for monitoring severe precipitating storms. Unfortunately, they cannot observe hurricanes at their genesis or developing stage (i.e., the "out-of-sea" phase). Recently, the Precipitation Radar (PR) [1] abroad the Tropical Rainfall Measuring Mission [2] satellite has demonstrated an unprecedented capacity to cat-scan precipitating storms, and to enable improved understanding of hurricane structure. Nonetheless, due to the relatively long return cycle (less than once per day) the value of PR data has only been limited to understanding of hurricane's climatological properties.

Radar remote sensing of the atmosphere and severe storms from geostationary orbit is highly desirable owing to its unique ability to simultaneously provide vertical rainfall profiles, large spatial coverage, and frequent observations. With the rapid advances in radar technology, the feasibility of developing such an instrument has greatly improved. In fact, under NASA's Earth Science Technology Program, a novel instrument concept and the associated antenna technologies are being developed for a 35-GHz Doppler radar for detailed monitoring of hurricanes, cyclones, and severe storms from a geostationary orbit. Since this radar approach is analogous to putting a NEXRAD system in orbit, it is being referred to as "NEXRAD in Space (NIS)".

II. Novel Radar Observational Concept

NIS is designed to operate in the geostationary orbit at an altitude of 36,000 km. From the trade study between spatial resolution and rain penetration/profiling, we have selected 35 GHz as the radar frequency. A deployable, 30-m, spherical antenna reflector will be used together with two antenna feeds, one for signal transmission and the other for echo reception, to form the overall antenna subsystem. Both the reflector and the spacecraft will remain stationary as the antenna feeds perform spiral scan maneuvers up to 4° to cover a 5300-km circular disk on the Earth surface. This surface coverage is equivalent to ~48° (±24°) in both longitude and latitude. If necessary, small spacecraft articulation can be used to extend the latitudinal coverage. This scan approach allows continuous and smooth transition between adjacent radar footprint coverage. One complete disk scan will require 200 spirals. The NIS surface coverage is graphically illustrated in Fig. 1, and the average time required for each spiral is given in Fig. 2. The corresponding horizontal resolution ranges from 12 km at nadir to 14 km at 4° scan.

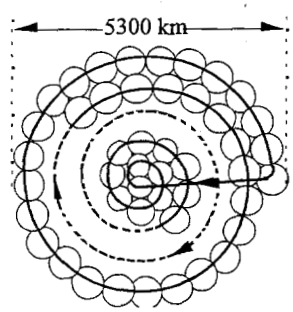

Fig. 1: Illustration of surface coverage by the spiral scan pattern.

The two feed approach is used to compensate for the long range distance. The angular spacing between the transmit and receive feeds is designed to be 0.45° such that the rain return echoes can be captured 0.25 seconds after pulse transmission. Furthermore, this approach enables a two-fold increase in the number of radar echo samples obtained, which translates into a factor of 1.4 reduction in measurement noise. As the feeds scan through the spiral, the radar will continuously transmit radar pulses at a rate of 3.5 KHz. This selected rate will allow a vertical observation window of 25 km and will accommodate the changes in range distance throughout the spiral scans. The spiral scan

rate as shown in Fig. 2 is designed to obtain one full disk coverage within 60 minutes and to allow a constant dwell time on each radar resolution cell.

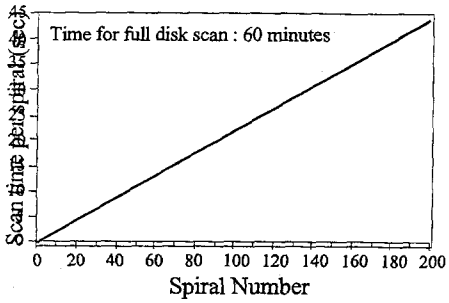

Fig. 2: Time for each spiral (from inner-most piral to outer-most spiral).

III. Revolutionary Antenna Concept

The NIS antenna requirements include an antenna gain of 77 dB, a beamwidth of 0.02°, a sidelobe level of better than −30 dB, and a scan of up to 4° off its axis. This angular scan translates into a scan of ±200 beamwidths. The first potential antenna candidate is an electronically scanned array antenna. However, the implementation of such a large array at 35 GHz would require over 6 million array elements. This is a formidable and very expensive task. A second candidate is the parabolic reflector antennas. However, such antennas suffer from severe limitation at large beam scans. Potentially, one might use a focal plane array to compensate for off-axis performance degradation. Such implementation, however, necessitates the use of an active array with adaptively varying excitation coefficients for different beam look angles. Such an implementation could also likely become an expensive proposition. The third candidate is the 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-rotated spacecraft with the fixed-mounted antenna. This option, however, can be very complicated and requires extensive interface between the radar and the spacecraft. For the NIS instrument, we focus on a novel spherical reflector antenna design which is inherently 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.

Appropriate sub-illumination of the 30-m diameter reflector antenna will achieve the ±4° angular coverage. This antenna configuration is graphical illustrated in Fig. 3. Our initial study showed that a 271-element, rotating, fixed feed array with complex excitation coefficients would substantially improve the performance of the spherical reflector antenna. The size of the feed array is ~20 cm in diameter.

The two feed arrays will be mechanically moved on a spiral track. The mechanism which achieves the desired motion is a rotating arm which carries a trolley containing the two feeds. The trolley travels at 60 cm/sec along the axis of the arm on precision wheels preloaded against precision rails. Arm rotation speed varies from just over 6 rad/sec to under 0.5 rad/sec as the trolley moves out from center of rotation of the arm to a maximum distance of 130 cm. This is achieved by driving a lead screw geared to the rotation motor. The arm has a ball nut which rides on the lead screw.

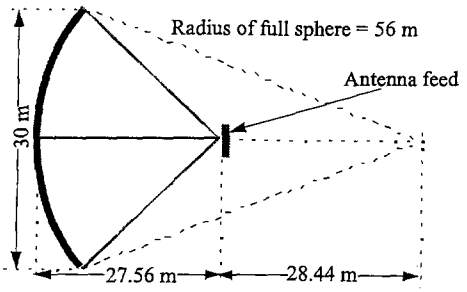

Fig. 3: Geometry of the NIS spherical reflector antenna.

The corresponding antenna radiation patterns at 4° scan are shown in Fig. 4. Note that an antenna gain of ~80 dB with sidelobe levels below 30 dB are obtained.

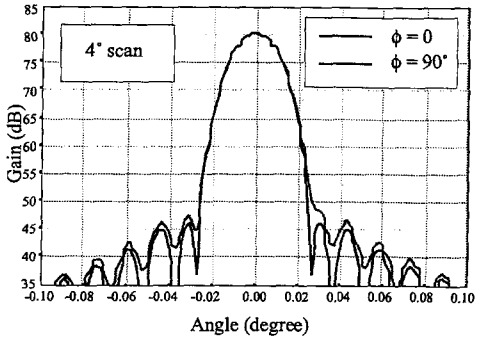

Fig. 4: NIS antenna patterns at 4° off-axis.

IV. Deployable Antenna Mechanical Design

From mass and size considerations, two mechanical reflector concepts can potentially be adaptable for the NIS antenna application. The first concept, shown in Fig. 5(a), employs the emerging space inflatable technology. When deployed, the reflector assumes a lenticular shape formed by two spherical thin-film membrane halves. One of the membrane halves is coated and functions as the reflective surface. The other membrane half is a transparent canopy, with the sole function of holding the extremely low (about 10-4 psi) inflation pressure. A circular torus and three struts, all are made of membrane materials and are inflation deployable and space rigidizeable, provide structural support for the reflector. To improve the surface accuracy, adaptive shape control can be used for on-orbit configuration adjustments.

The second design concept, shown in Fig. 5(b), uses the AstroMesh reflector developed by TRW/Astro. Structurally, this reflector consists of a cable-actuated synchronized

parallelogram mechanism (that deploys the reflector) and a pair of ring-stiffened, tension-tied geodesic domes. The reflective mesh is stretched over the back of one of the domes. Based on the measured surface error of less than 0.36 mm RMS on Astro's 6-m flight model and several proposed design improvements, a 30-m AstroMesh reflector should meet the 0.75-mm RMS performance goal.

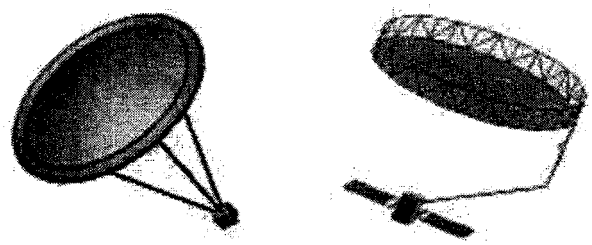

Fig. 5: (a) Inflatable reflector approach; (b) AstroMesh approach.

V. NIS Radar Parameters and Estimated Performance

The key NIS instrument and performance parameters are summarized in Table 1. Note that by an averaging of 120 pulses, the NIS detection sensitivity is improved to ~5 dBZ. The rain signal-to-noise ratios (SNRs) in Fig. 6 show that NIS can indeed achieve significant rain penetration. For example, NIS can measure ~35 mm/hr rain down to 2.5 km from the cloud top. At higher rain rates, the attenuation become significant and NIS's penetration ability reduces.

Radar System Parameters			
Frequency	35 GHz	Bandwidth	0.58 MHz
Antenna diameter	30 m	Pulsewidth	100 μsec
Ant. effective aperture	28 m	PRF	3.5 KHz
Ant. 3-dB beamwidth	0.019°	Power duty cycle	35%
Antenna gain	77.2 dBi	Transmit path losses	2 dB
Antenna sidelobe	-30 dB	Receive path losses	2 dB
Max. spiral scan angle	4°	Sys. noise temp.	910 K
Time for a full scan	60 mins.	Dynamic range	70 dB
Peak power	100 W	Downlink data rate	155 kbps
Performance Parameters			
Disk coverage diameter	5300 km	Doppler Precision	0.3 m/s
Vertical resolution	300 m	Pulse samples	120
Horiz. Resolution (nadir)	12 km	Min. Zeq (1 pulse)	15.4 dBZ
Horiz. Resoution (4°)	14 km	Min. Zeq (after ave.)	5.0 dBZ

Table 1: NIS radar parameters.

Like all downward pointing atmospheric radars, the NIS return signals from light rain can be contaminated by the simultaneous surface returns when the antenna is scanned away from nadir. However, since the rain rates associated with hurricanes and the 35-GHz rain attenuation are high, the surface clutter contamination is much less an issue than one might expect. To articulate this point, we computed the ratios of the rain signal to the combined noise and clutter (SNCR) at different rain rates. An example at 5 mm/hr rain over the ocean is shown in Fig. 7. At or near nadir the SNCR is dominated by thermal noise. Between ~5° and 15° incidence angles and at lower altitudes, the surface clutter becomes dominant. At larger incidence angles the clutter effect is reduced due to increased attenuation and weaker surface backscattering. The results thus show that at 5 mm/hr rain NIS can indeed penetrate down to lower than 2 km altitude at most incidence angles of interest. At larger rain rates the detectability is primarily determined by attenuation and thermal noise, not clutter.

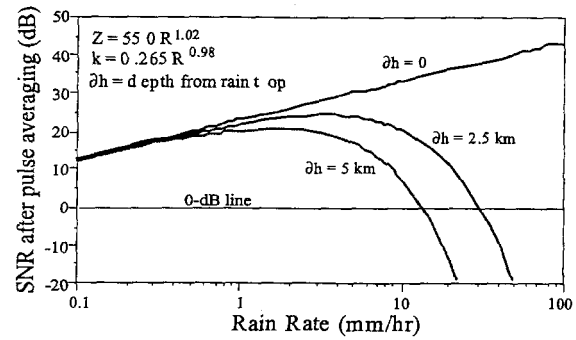

Fig. 6: SNRs for the NIS rain measurements.

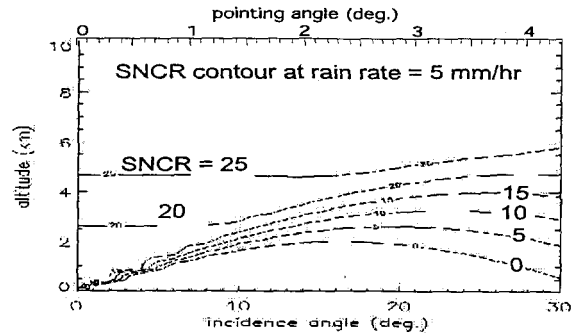

Fig. 7: SNCRs for the NIS at 5 mm/hr rain.

VI. Summary

NASA's Earth Science Program is currently developing the technology for the NEXRAD In Space (NIS) instrument concept - a 35-GHz, spiral scanning Doppler radar for detailed monitoring of hurricanes, cyclones, and severe storms from a geostationary orbit. This instrument is designed to be capable of producing rainfall rate at 13-km horizontal resolution and 300-m vertical resolution, and the line-of-sight Doppler velocity at 0.3 m/s precision, of the 3-D hurricane structure once per hour throughout its life cycle.

ACKNOWLEDGMENTS

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

REFERENCES

[1] T. Kozu et al., "Development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite" *IEEE Trans. Geosci. Remote. Sensing,* vol. GE-39, pp. 102-116, 2001.

[2] C. Kummerow et al., "The status of the Tropical Rainfall Measuring Mission (TRMM) after 2 years in orbit" *J. Appl. Meteor.,* vol. 39, pp. 1965-1982, 2000.