NEXRAD-In-Space: A Geostationary Orbiting Doppler Radar for Hurricane Monitoring and Studies

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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). By operating in the Geostationary Earth Orbit (GEO), NIS would enable rapid-update sampling (≤1 hour cadence) of three-dimenional fields of 35 GHz (Ka-band) radar reflectivity factor (Z) and line-of-sight Doppler velocity (V_D) profiles, at mesoscale horizontal resolutions (~10km) over a circular Earth region of approximately 5300 km in diameter (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 2007-2016 NASA Science Mission Directorate (SMD) Science Plan (Table 4.3, p. 60) [1]. 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.

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 painfully reiterated in recent years with a number of powerful TCs landfalling in North America and elsewhere. In April 2007, the first NIS Science Workshop was convened at the University of Miami to galvanize the scientific community's interest in NIS's measurement capabilities for improved TC monitoring and prediction [2]. The general consensus of the workshop was that a GEO Doppler radar would provide a major breakthrough in regards to the observation of TCs, and, when combined with cloud-resolving numerical weather prediction (NWP) models.

This paper presents brief summaries of the instrument concept, the current technology status, the anticipated impacts on hurricane monitoring and model prediction, and the future science and technology roadmap.

HURRICANE PREDICTION CHALLENGES

The 2004 and 2005 hurricane seasons in the U.S. led to unprecedented death, damage, and suffering within the Gulf Coast and Florida region, particularly due to Hurricane Katrina which flooded over 80% of the City of New Orleans, destroyed entire sections of the city, and destroyed or incapacitated major infrastructure elements of the U.S. energy system. In addition to some 2,000 fatalities in Alabama, Mississippi, and Louisiana, and the wholesale destruction of over 350,000 homes and businesses, Hurricane Katrina (along with Hurricane Rita) destroyed many of the Gulf's stationary and mobile oil platforms, i.e., some 150 facilities responsible for approximately 15% of America's petroleum supply.

The frequency and ferocity of major storms making landfall during the 2004-05 hurricane seasons, and the possibility that such seasons are now an expected element of the global climate, have exposed a number of vulnerabilities within

federal, state, and local organizations charged with the responsibility for civil protection, hazard forecasting, and emergency management pertaining to hurricanes. Within the hurricane forecasting community, it is generally recognized that, whereas hurricane track forecasting has experienced steady improvement over the last three decades, over this same period, the forecast of hurricane intensity and structure has realized almost no meaningful improvement (see Fig. 1). In effect, using an analogy, computer models are only having verifiable success forecasting hurricanes as "corks floating in streams", while experiencing almost no success in forecasting how the sizes and shapes of the corks evolve.

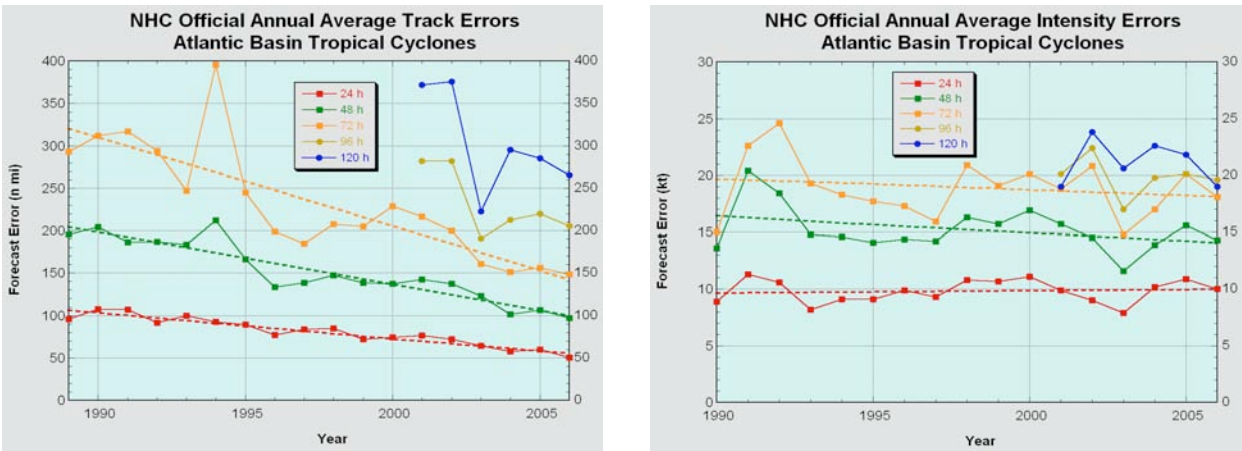

Fig. 1. U.S. National Hurricane Center predictions demonstrating gradual improvement in track forecasting over 1990-2004 period (left panel) while at same time demonstrating almost no meaningful improvement in intensity forecasting (right panel). (See "www.nhc.noaa.gov/verification/verify5.shtml".)

To understand why improvements in predicting the evolution of hurricane structure and intensity have lagged behind the ability to predict another classical storm event, the mid-latitude frontal cyclone, it must be recognized that there are fundamental differences in where and how these two types of storms derive their energy. Frontal cyclones, responsible for the rain and snow storms most common over North America, derive their energy from the contrasts of temperature between tropical and polar latitudes. These contrasts are readily observed and quantified by balloon-borne observations (radiosondes) taken twice daily at a spacing of several hundred kilometers around the developed world. The spacing and frequency of these observations are usually sufficient to define the energy processes involved in cold and warm air mixing that occur on scales of hundreds to thousands of kilometers and over periods of several days. Alternatively, energy released in cumulus clouds is the driving force for hurricanes, for which the relevant cloud systems occur on space scales of just tens of kilometers and time scales of just minutes. In effect, these features entirely fall between the conventional radiosonde observations that are sufficient to define and predict the frontal cyclones. Moreover, hurricanes evolve over the oceans, where even conventional observations are sparse. To define the state of these energy-generating processes, equivalent to the way energy-producing processes are observed for frontal cyclones, will require observations with the grid spacing of a few kilometers and the sampling frequency of a few minutes.

RATIONALE FOR THE GEOSTATIONARY ORBITING NIS SYSTEM

There are only a few instrument systems that can be used for measuring the behavior of tropical storms and hurricanes for the purpose of hurricane monitoring and prediction through data assimilation. In the U.S., only the U.S. Weather Service's network of NEXRAD coastal ground Doppler radars, National Oceanic and Atmospheric Administration's (NOAA) airborne Doppler radars, and the optical-infrared imaging radiometers on NOAA/National Environmental Satellite Data Information Service's (NESDIS) geostationary Earth-orbiting (GEO) operational GOES satellites are capable of continuously monitoring the position and appearance of hurricanes.

It is well recognized that optical-infrared instruments on the operational GEO satellites can only observe cloud tops – not the internal dynamics, vertical structure, and intensity of hurricanes. While the airborne Doppler radars fly out to collect data when the storms are out to sea, they are limited in temporal sampling to only one or two missions a day. Whereas the continuously-probing NEXRAD Doppler ground radars are very useful for monitoring storm behavior, since at radar frequencies the internal structure of a storm can be observed and thus 4-dimensional views of storm

dynamics and hydrology are achievable, there are limitations with ground radars associated with their range limitations, and the beam spreading – overshoot effects away from the radar beam source. There are also endemic problems with keeping the network of NEXRAD radars calibrated to a standard secondary calibration reference.

The National Aeronautics and Space Administration (NASA) first launched a satellite designed for the direct measurement of precipitation from space in November 1997 – i.e., the Tropical Rainfall Measuring Mission (TRMM) – a low Earth orbiting (LEO) satellite platform which is still making measurements from 400 km above the Earth out to the 35 degree latitude parallels. However, the rain-measuring instruments developed for this mission, which include a Ku-band (14 GHz), cross-nadir-scanning precipitation radar and a 9-channel, conical-scanning, passive microwave radiometer, only observe a given point within the tropical-subtropical latitudes some 25-28 times per month. The radar itself does not include Doppler measuring capability and thus does not measure the internal dynamics and intensities of tropical cyclones. Data collected by the TRMM satellite have led to some success in improving hurricane forecasts through data assimilation, but the success has been limited to minor improvements in hurricane track forecasting. The main reason for this is that the TRMM satellite was designed for monitoring hurricanes at the needed hourly-type sampling frequency, and with the required information on internal dynamics that only a Doppler radar can provide.

These are the main reasons why a continuously-profiling Doppler radar located on geostationary satellite platform would offer a more effective measuring capability. Indeed, it would bring about a paradigm shift in the prediction of hurricanes because such a system could provide the three most urgently needed measuring capabilities for making hurricane intensity predictions. First, a GEO measuring platform could produce the required sampling frequency over the required space-time domain. Second, a space-based Doppler radar system could provide the triad of foremost measurements of a hurricane's strength, i.e., its vertical profiles of vertical velocity, precipitation intensity, and rate of atmospheric heating through the release of latent heat of condensation. Third, a space-based data stream would enable continuous 4-dimensional data assimilation of these fundamental hurricane parameters into operational forecasts generated by very high-resolution cloud-resolving models (CRMs). All three of these capabilities are essential for greatly improved hurricane forecasts. These considerations led to the NEXRAD-In-Space (NIS) satellite design concept [3].

DESIGN FRAMEWORK FOR NIS'S GEO DOPPLER RADAR SYSTEM

In the following, a brief description of the 35-GHz NIS radar technology concept designed for greatly improved hurricane observing and forecasting is provided. It is necessary to understand that a GEO satellite platform used for flying the radar is the only type of platform that can ultimately provide the required time sampling (notionally a 1-hour sampling frequency), the required spatial integrity and cohesiveness, and the overall required Doppler capability – in a cost-effective package. It is also important to recognize that the radar antenna for the NIS GEO platform is very large (~35-meter diameter) using lightweight, deployable space-qualified material such as Shape Memory Polymer (SMP) that will require approximately a decade of lead time for development. A 35-meter diameter antenna is about 1/3 the size of a football field. This size requirement stems from the fact that the GEO satellite orbit must be about 35,270 km – approximately 100 times that of the LEO orbiting TRMM satellite – and thus the antenna must be large for the radar to achieve meaningful horizontal resolution for hurricane observations. Notably, Japan Aerospace Exploration Agency (JAXA) recently launched a geostationary communications satellite that uses two 17 x 19 meter size lightweight deployable antennas, each about the size of a tennis court. [See "www.jaxa.jp/ countdown/f11/outline/index_e.html".]

The NIS radar concept consists of a Ka-band (35 GHz) radar with Doppler acuity and optional polarimetric diversity. Because a GEO satellite is a quasi-stationary platform, some limited Doppler spectrum width information is also obtainable. The NIS antenna design consists of a deployable, inflatable spherical reflector (Fig. 2) with two radially opposed Doppler radar feed array pairs (one each for transmit and receive) situated in carriages which slide mechanically along a rotating arm below the antenna (Fig. 3), thus producing a spiral scan pattern over a 48-degree great circle arc once every hour. The antenna size provides for ~12 km spatial resolution at nadir (Fig. 4). The entire radar system can also be pointed (articulated) to the preferred domain of the Earth-atmosphere containing a target hurricane.

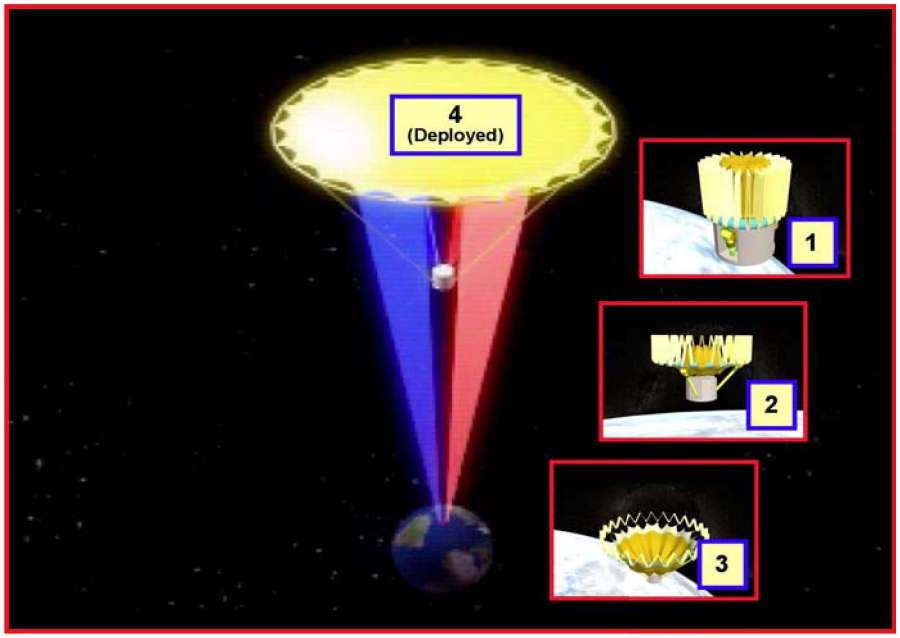

Fig. 2. Schematic of fully deployed GEO-NIS satellite viewing Earth with two spiraling Doppler radar feeds. Insets show 30-meter radar antenna in three different stages of deployment.

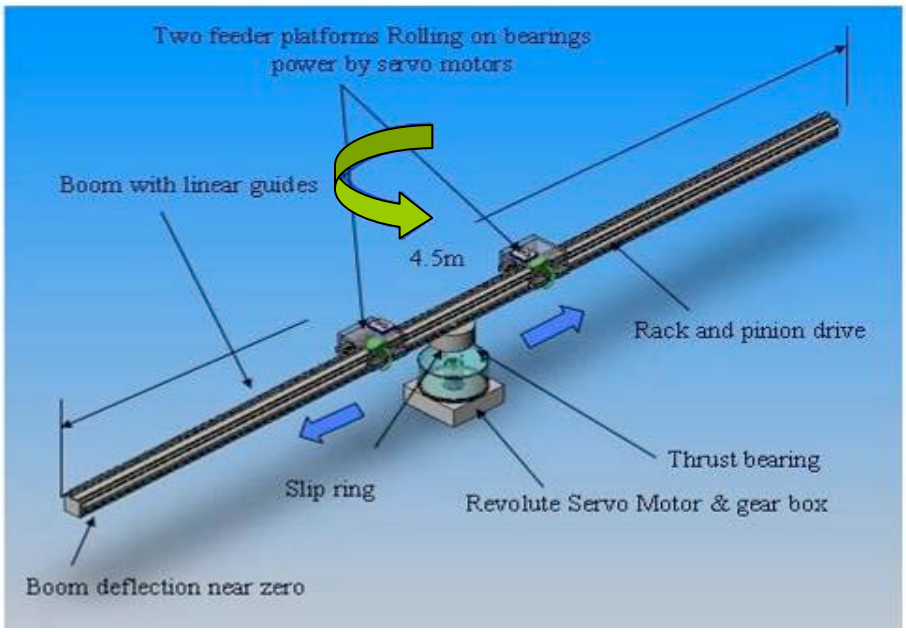

Fig. 3. Schematic of rotating arm for affixing to top of satellite below large spherical antenna in which arm includes two carriages each containing a transmit/receive feed array pair where combined sliding carriage motions generate two contiguous spiral trajectories.

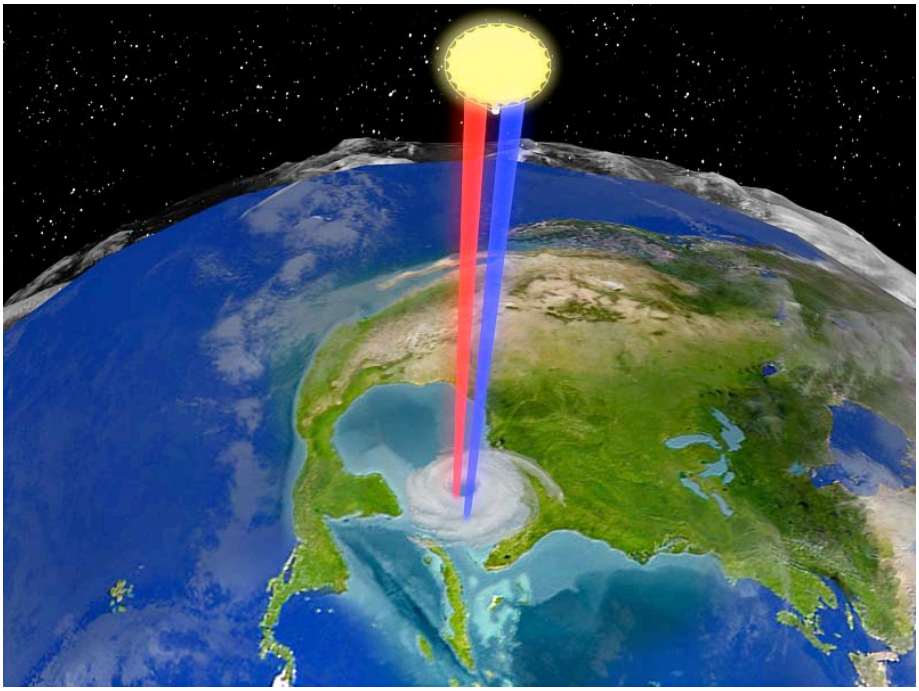

Fig. 4. Artistic rendition of GEO-NIS radar viewing Hurricane Katrina (28 August 2005).

The main technology development elements required to realize the GEO radar system are related to the large inflatable antenna, including lightweight flexible materials and the deployable structure, the ability to determine the shape of the antenna surface to the required accuracy (thus the current preference for SMP), and the ability to actively correct any antenna shape distortions while in flight with different types of actuator systems. Without correction, antenna shape distortions would arise because of stresses due to thermal gradients developing on the antenna due to variable solar heating across the antenna surface.

Looking beyond the current conceptual design, it is anticipated that NIS could be further refined by increasing the time sampling down to approximately 15 minutes and the spatial resolution down to approximately 5 km. Sampling improvement and some spatial resolution improvement could be achieved by modifying the design of the mechanically rotating arm and by including intelligent variable control of the feed motions drives, which could produce repeat sampling and thus spatial resolution enhancement through a deconvolution operator.

Additional spatial resolution could be obtained by making NIS a W-band (94 GHz) frequency radar. Another exciting path for improvement would be to develop NIS as a dual-frequency 35/94-GHz radar system, which through differential reflectivity algorithm schemes would enable measurements of hydrometeor drop-size distribution (DSD) and additional microphysical details within the hurricane environment. These are all technology improvement issues that go beyond the technologies that have been studied or tested for the current NIS design prototype, but nonetheless are improvements that lie well within reach of the NIS design concept.

CONCLUDING REMARKS

This paper describes satellite radar technology and hurricane modeling paths for improving hurricane observing and forecasting in the course of the next decade. The observing capability stems from the use of a Ka-band (35 GHz) Doppler weather radar system on-board a geostationary satellite platform (i.e., the NIS satellite), which would produce hourly observations of a hurricane's position, intensity, structure, and internal dynamics. The forecasting improvements would arise directly from this revolutionary observing capability by application of continuous data assimilation into very high resolution cloud resolving forecast models designed to exploit the three new major measuring capabilities that the GEO Doppler radar system would provide: (1) vertical/horizontal velocity, (2) precipitation intensity, and (3) rate of

atmospheric heating through release of latent heat of condensation. All of these physical processes would be captured in the profile measurements of reflectivity, line-of-sight Doppler velocity, Doppler spectrum width, and optionally co-/cross-polarization amplitudes.

This space technology, along with an upgraded numerical modeling approach involving CRM-based data assimilation, represents a complete paradigm shift insofar as observing and forecasting hurricanes in a 4-dimensionl framework. The outcome of proceeding with this strategy would be a greater understanding of hurricane behavior and greater accuracies in hurricane forecasts – especially the formidable properties of intensity, precipitation production, and flood potential. Ultimately, this strategy would lead to an improved disaster warning and civil defense system for the world population vulnerable to the destructiveness of intense, landfalling tropical cyclones.

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