Workshop Report on Nexrad-In-Space – A Geostationary Satellite Doppler Weather Radar for Hurricane Studies

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Abstract – **NEXRAD-In-Space (NIS) is a mission concept to provide a geostationary satellite Doppler radar. It was developed over the last 4 years under the auspices of NASA's Earth Science Instrument Incubator Program (IIP). The NIS would provide Ka-band (35 GHz) reflectivity and line-of-sight Doppler velocity profiles over a circular Earth region of approximately 5200 km in diameter with a 12-km horizontal resolution, and a minimum detectable signal of 5 dBZ. The NIS radar achieves its superb sampling capabilities by use of a 35-m diameter, deployable antenna made from lightweight membrane material. The antenna has two transmit-receive array pairs that create a dual-beam, spiral-feed combined profile image of both reflectivity and Doppler velocity approximately every 60 minutes. This sampling time can be shortened even further by increasing the number of transmit-receive array pairs.**

I. Introduction

The NEXRAD-In-Space (NIS) Science and Technology Road Map Workshop was held on 10-11 April 2007. NIS is a mission concept to provide a geostationary satellite Doppler radar. It was developed over the last 4 years under the auspices of NASA's Earth Science Instrument Incubator Program (IIP). The NIS would provide Ka-band (35 GHz) reflectivity and line-of-sight Doppler velocity profiles over a circular Earth region of approximately 5200 km in diameter with a 12-km horizontal resolution, and a minimum detectable signal of 5 dBZ. The NIS radar achieves its superb sampling capabilities by use of a 35-m diameter, deployable antenna made from lightweight membrane material. The antenna has two transmit-receive array pairs that create a dual-beam, spiral-feed combined profile image of both reflectivity and Doppler velocity approximately every 60 minutes. This sampling time can be shortened even further by increasing the number of transmit-receive array pairs.

It is generally recognized that the processes important in governing hurricane intensity and structure span a wide range of spatial and temporal scales. The environmental forcing considerations require a large domain. The vortex response to the environmental forcing ultimately involves convection on small horizontal scales in the eyewall and rainband regions. Resolving this environment-vortex-convection feedback in a numerical model requires observations on the space and time scales necessary to unambiguously define these structures within and surrounding the tropical cyclone. Because the time and space scales of these processes are small, continuous 3-dimensional independent observations of the 3-dimensional wind and precipitation structures will be needed to initialize numerical models critical for this purpose. The proposed NIS Doppler radar would be the first instrument capable of accomplishing this feat at time scales less than hours, and would create the opportunity for hurricane science to enter a new era of understanding and improved prediction. Thus, the scientific thrust of the Workshop was to develop the scientific framework for exploiting the NIS radar data through continuous 3-dimensional data assimilation of the Doppler and reflectivity signals in non-hydrostatic cloud resolving models.

This paper presents the key findings and recommendations from the NIS Workshop, including 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.

II. Disastrous 2004 and 2005 Hurricane Seasons

The 2004 and 2005 hurricane seasons led to unprecedented death, damage, and suffering within the Gulf Coast and Florida region, particularly due to Hurricane Katrina (Figure 1) 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.

These two recent hurricane seasons have spurred hyper research activity into the scientific cause(s) of such destructive sequences of storms and the possibility that the Earth has evolved a climate in which this type of hurricane season represents the norm rather than the exception. This debate is complicated by the fact that there are decadal and longer oscillations in climatic processes that can affect hurricane frequency, track preference, and intensity, variations that are

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superimposed over an almost certain global warming trend, all of which is strongly influenced by uncertain changes in ocean temperatures. Accordingly, the debate has intensified in the same fashion as the recent hurricanes.

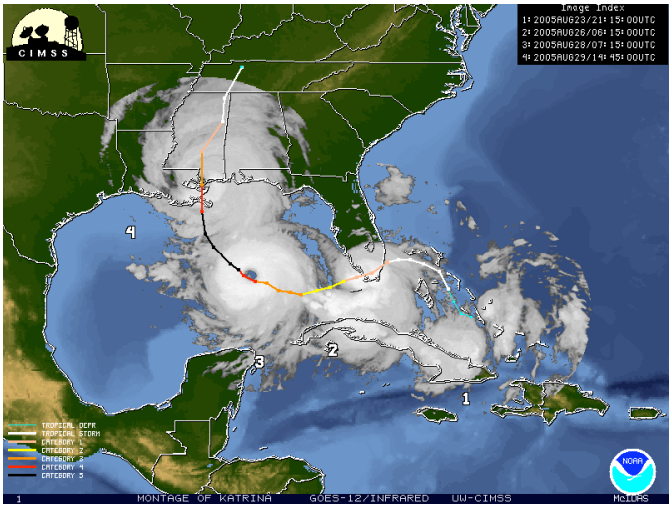

Figure 1: Montage created from sequence of Hurricane Katrina infrared satellite images obtained from NOAA's Geostationary Operational Environmental Satellite (GOES) showing advance of storm into vicinity of New Orleans over 23-29 August 2005. [Courtesy of Christopher Velden at NOAA/Cooperative Institute for Meteorological Satellite Studies (CIMSS) at Univ. of Wisconsin.]

III. Importance of Improving Hurricane Forecasting – Especially Intensity

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. As a result, the National Oceanic and Atmospheric Administration (NOAA) Science Advisory Board established a Hurricane Intensity Working Group (HIRWG), to review NOAA's efforts to improve hurricane intensity prediction [1]. At the same time, the National Science Foundation's National Science Board (NSF-NSB) established a working group to examine the national needs for research into hurricanes covering all aspects of the problem, from forecasts to mitigation [2]. These reports supplement the series of planning documents developed by the federal and academic communities under the auspices of the Office of the Federal Coordinator for Meteorology (OFCM) and the U.S. Weather Research Program (USWRP), e.g., "www.ofcm.gov/tcr/tcr-index.htm". In addition, OFCM just issued the latest federal plan for hurricane research ("www.ofcm.gov/p36-isrtc/fcm-p36.htm") [3], while the American Geophysical Union (AGU - Hurricanes and the U.S. Gulf Coast: Science and Sustainable Rebuilding, June 2006 [4]), the American Meteorology Society (AMS – AMS Statement on Hurricane Research and Forecasting, September 2006 [5]), and the National Science and Technology Council (NIST – Windstorm Impact Reduction Implementation Plan, April 2006 [6]) released white papers on the research needed to address hurricanes and their impact. Such government reassessments identify what types of civic and forecasting strategies are needed to cope with tropical storms and hurricanes that impact not only Florida and the Gulf Coast region, but also the entire eastern seaboard – which, as Hurricane Isabel demonstrated during 2003 (see Figure 2), can experience severe damage and widespread fatalities well north of the southeastern high impact region.

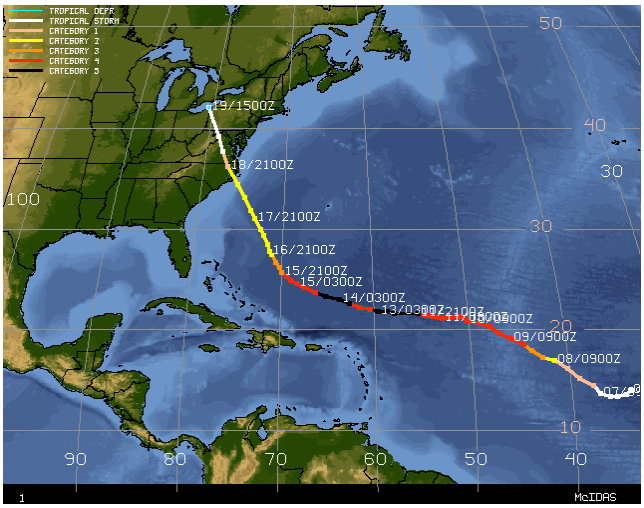

Figure 2: Track of Hurricane Isabel (category 5 hurricane) into northeastern U.S. during September 2003. [Courtesy of NOAA/CIMSS at Univ. of Wisconsin.]

A major element of these reassessments has involved seeking means to improve hurricane intensity and structure forecasting. It is well recognized that in order to improve responsiveness to hurricane related hazards, it is essential to reduce the uncertainties in the hurricane model forecasts, and to improve the ability to forecast the expected impact of hurricanes using sophisticated models that base their outlooks directly on the hurricane forecasts themselves. Outside of the forecasting community, it is generally not appreciated 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 Figure 3). 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.

In fact, it is now recognized that operational hurricane forecast models have only improved in their ability to trace the path that hurricanes will follow as they move downwind, while their ability to predict the speeds at which they move along their trajectories have not improved substantially. This helps understand why NOAA, NSF, AGU, and NIST have

gone on record with planning strategies needed to revise how hurricane predictions are carried out and which factors involving hurricane forecasting deserve the most attention. It also explains why various new hurricane prediction program initiatives focusing on accuracy improvement and forecast timeliness, such as the Hurricane Intensity Forecast Improvements (HiFi) project ("www.nova.edu/ocean/hifi/index.html"), are now underway.

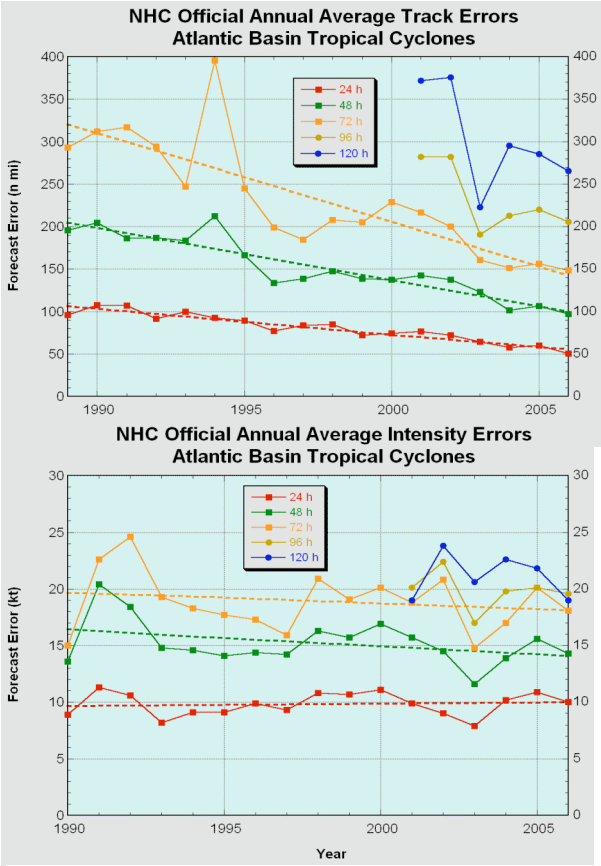

Figure 3: National Hurricane Center predictions demonstrating gradual improvement in track forecasting over 1990-2004 period (upper panel) while at same time demonstrating almost no meaningful improvement in intensity forecasting (lower panel). (See "www.nhc.noaa.gov/verification/verify5.shtml".)

IV. Upgrading Numerical Prediction of Hurricanes to CRM-based Models

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.

The problem is further complicated by the fact that operational computer prediction models have traditionally been limited to predicting storm scale circulations while representing the smaller scale flows as somehow being driven in a prescribed fashion by the ambient storm scales themselves. However, when the energy originates on the small scales and then wells up to drive the storm scales, as with tropical cyclones, traditional models utterly fail in a fundamental way. We call convectively-driven storms such as hurricanes " bottom up" systems since the energy comes from the small scales to drive the large scales, whereas frontal cyclones are "top down" systems since they derive their energy from thermal contrasts on scales at least as large as the storms themselves. It is thus clear that if verifiable hurricane intensity forecasting is to become a reality, the 20th century observation and weather model prediction paradigm must change. The change is made possible by converting the computer models to what are called cloud-resolving models (CRMs) which are able to represent the very small scale cloud processes, and by converting the observational technologies to continuously-monitoring, very high spatiotemporal resolution space-based radar remote sensing technologies. Most notably, the computer model and space technologies needed for such a transformation are now available.

V. Potential for Doppler Radar Monitoring of Hurricanes from Space

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. Of these, only the U.S. Weather Service's network of NEXRAD coastal ground Doppler radars, NOAA's airborne Doppler radars on the NOAA WP-3D and G-IV aircraft, 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 (refer to Fig. 1 above) – 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.

These are the main reasons why continuously-profiling Doppler radars located on geostationary satellite platforms would offer a more effective measuring capability. In fact, Doppler radar profiling from above a storm is superior to side-view profiling since, because hurricanes are shorter than they are wide, they reveal more of their internal structure when viewed from above. Moreover, GEO satellites can follow hurricanes throughout their entire lifetime – unlike NEXRAD radars for which the range limits, fixed viewing domains, and the inability to see hurricanes out to sea fracture the observing process over key portions of hurricane life cycles. Nonetheless, despite the great success of ground Doppler weather radars in monitoring local weather and tracking landfalling hurricanes, and although the technology required to make Doppler weather radar measurements from space was developed over a decade ago by the National Aeronautics and Space Administration (NASA), this technology has yet to be exploited by NASA or NOAA on an Earth-observing spacecraft.

VI. Disadvantages of TRMM Satellite for Hurricane Observing and Forecasting

Notably, 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. In fact, to date, the National Centers for Environmental Prediction (NCEP), the U.S. National Weather Service's primary numerical weather prediction unit, has been unable to achieve any meaningful improvement in hurricane forecast accuracy through assimilation of TRMM data into their operational forecast models. The main reason for this is that the TRMM satellite was designed for the collection of a multi-year climatology of rainfall in the tropics, not 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.

VII. Advantages of NIS-type Satellite for Hurricane Observing and Forecasting

A space-based Doppler radar system on a GEO satellite platform 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 [7].

VIII. 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, inflated spherical reflector (Figure 4) 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 (Figure 5), 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 (Figure 6). The entire radar system can also be pointed (articulated) to the preferred domain of the Earth-atmosphere containing a target hurricane.

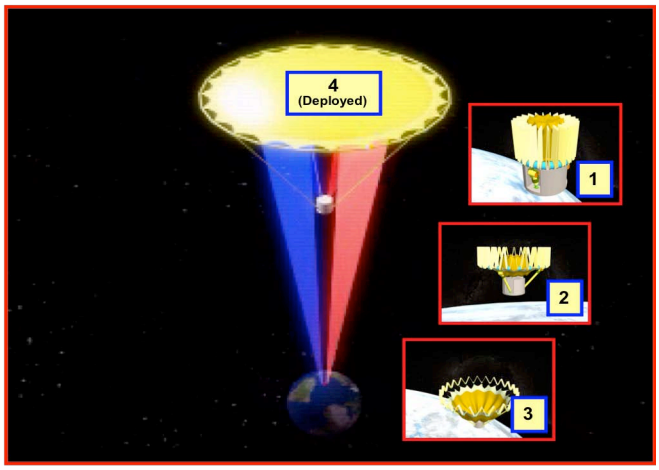

Figure 4: Schematic of fully deployed GEO-NIS satellite viewing Earth with two spiraling Doppler radar feeds. Insets show 30-meter radar antenna in three different stages of deployment.

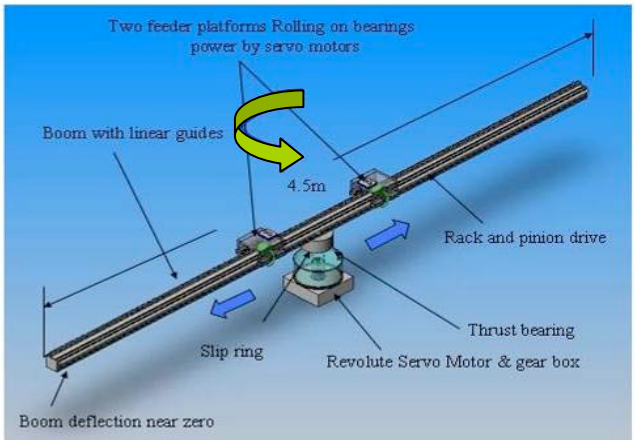

Figure 5: Schematic of rotating arm for affixing to top of satellite below large spherical antenna in which arm includes two carriages each containing a transmit/receive feed array pair where combined sliding carriage motions generate two contiguous spiral trajectories.

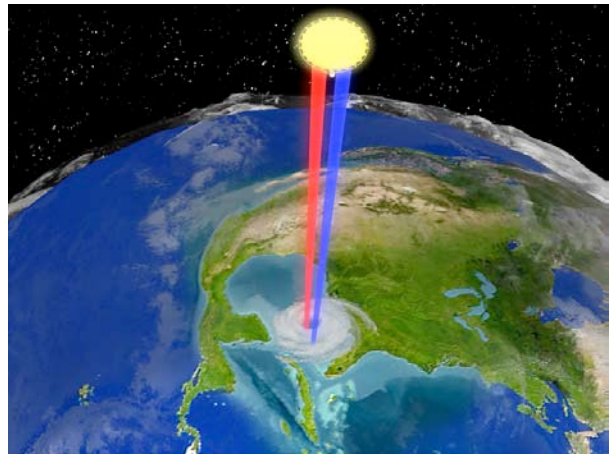

Figure 6: Artistic rendition of GEO-NIS radar viewing Hurricane Katrina (28 August 2005).

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.

IX. Concluding Remarks

This report 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 level 1 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 U.S. population vulnerable to the destructiveness of intense, landfalling hurricanes such as highlighted in Figure 7, illustrating the American southeast during August and September 2004 being pounded unmercifully by one destructive storm after another.

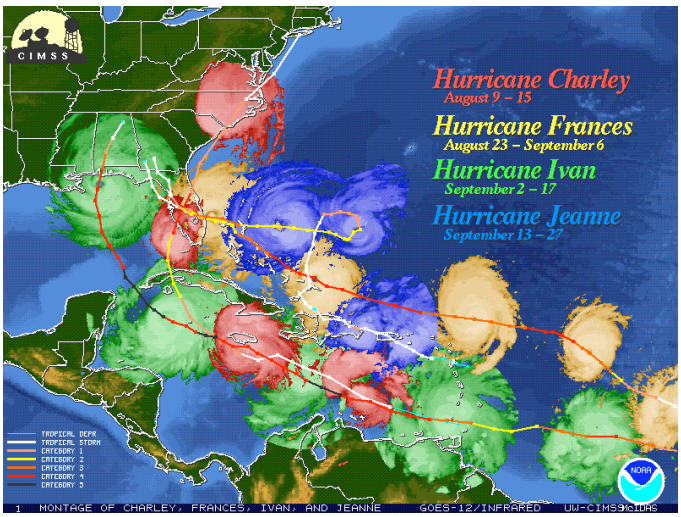

Figure 7: During 2004 Hurricane Season, the state of Florida experienced barrage of intense and destructive hurricanes from which it has yet to recover in terms of destroyed property and displaced people. [Courtesy of Mr. Christopher Velden at NOAA/CIMSS at Univ. of Wisconsin.]

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