Development of the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP)

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Abstract - *The focus of this paper is on a technology development currently in progress under the NASA IIP called High Altitude Wind and Rain Profiling Radar (HIWRAP). This radar is a dual-frequency (Ka- and Ku-band), dual-beam (30^0 and 40^0 incidence angle), conical scan, solid-state transmitter-based system, designed for operation on the high-altitude (20 km) Global Hawk UAV. HIWRAP is a progression of technology from the current fixed-beam NASA high-altitude Doppler weather radars using tube technology, and the lower altitude solid-state IWRAP system. HIWRAP utilizes a solid state transmitter along with novel pulse compression scheme that will result in a system that is considerably more compact in size, requires less power, and ultimately costs significantly less than typical radars currently in use for precipitation and Doppler wind measurements. With the inclusion of Ka-band, HIWRAP will be able to image the winds through volume backscattering from clouds and precipitation, enabling it to measure the tropospheric winds above heavy rain at high levels. Further this effort and the HIWRAP prototype will potentially lead to a smaller, less expensive spaceborne instrument that provides wide swath coverage similar to the SeaWinds instrument and can image not only the surface winds but the 3D tropospheric winds and atmospheric boundary layer winds above and within precipitation systems and the precipitation itself.*

I. INTRODUCTION

Wind measurements are crucial for understanding and forecasting tropical storms since they are closely tied to the overall dynamics of the storm. The spatial and temporal resolution and availability of such measurements must be improved if hurricane intensity forecasting is to improve [1]. Aircraft instrumented with Doppler radars and other sensors have been the main tool for measuring horizontal and vertical winds within precipitation regions of tropical storms [2]. Operational aircraft have limited endurance and altitude capability which over the past decade has led to NASA's involvement with high-altitude remote sensing of tropical storms. NASA has unique high-altitude aircraft capabilities including the ER-2 and WB-57 aircraft that reach altitudes of 70,000 and 60,000 feet, respectively. The instrumented ER-2 has provided valuable science information on hurricanes and also has allowed for testing of remote sensing methods for spaceborne application. NASA's interests have more recently focused on UAVs, especially high altitude, long endurance platforms (HALE UAV) such as the Northrop Grumman Teledyne RG-4A Global Hawk. Tropical storms are often located in remote regions of the ocean making manned aircraft impractical because of their limited endurance.

HALE UAV instrumented with remote sensors have the potential to provide repeated passes over hurricanes and other weather events that can lead to improved data sets that provide critically needed observations for forecast models. At present, there is only one vertically profiling spaceborne precipitation radar called Tropical Rain Measuring Mission (TRMM), which has provided unique snapshots of hurricanes but it is non-Doppler. The main active winds measurements from space have been limited to surface winds from the QuikScat scatterometer. Ideally, satellite-based wind measurements are desired, but it is extremely difficult and costly to obtain these measurements. In addition, it has become increasingly clear that smaller scale processes with space and time scales of a few kilometers and 15 minutes are extremely important for the hurricane intensification problem. Aircraft and UAVs can be extremely helpful for obtaining high spatial resolution measurements of hurricanes with capabilities on sub-kilometer horizontal scales.

The need for high spatial resolution observations of tropical storms has been shown through NASA aircraft field experiments over the past decade with ER-2 remote sensing measurements. One example is the extremely strong convective entities in hurricane eyewalls called vortical hot towers that are hypothesized to be extremely important in hurricane intensification. These entities have been observed from satellites with low resolution sensors, and the vertical winds have been measured from the NASA ER-2 Doppler Radar [3] with much higher resolution. The spatial scales of these phenomena are a few kilometers. What has been lacking however is the horizontal winds attendant with these hot towers. Measurements are required through the entire atmospheric profile (15-18 km) of developing storms in order to understand these and other processes that control hurricane intensification.

Work over the past decade has provided rather convincing evidence that conical scanning radars on either an airborne or orbiting satellite can provide the full horizontal wind vector in precipitation and cloud regions. A theoretical study of a dual-beam (i.e., dual incidence angle) Ka-band conical scan spaceborne radar called Radar Wind Sounder (RAWS) [4] examined the use of this radar for determining horizontal wind measurements over the swath of the radar scan. They found from their simulations that reliable horizontal winds could be obtained over the radar swath for this orbiting satellite. More recently, a NOAA P3-based instrument called Imaging Wind and Rain Profiling Radar (IWRAP) [5] with a 4-beam C- and Ku-band conical scan radar has been used operationally in hurricanes. The radar scans rapidly providing forward and aft views of the same precipitation region at many different azimuth angles. Pixel based analysis of these measurements has provided promising results on low level wind fields in hurricanes. However, IWRAP is designed to fly on low altitude aircraft (below 5 km) and therefore views only a portion of the full vertical profile of the atmosphere. Nevertheless these above efforts indicate that horizontal winds can be retrieved over most of the conical scan region with acceptable accuracy.

The focus of this paper is on a technology development currently in progress under the NASA IIP called High Altitude Wind and Rain Profiling Radar (HIWRAP). This radar is a dual-frequency (Ka- and Ku-band), dual-beam (30^0 and 40^0 incidence angle), conical scan, solid-state transmitter-based system, designed for operation on the high-altitude (20 km) Global Hawk UAV. HIWRAP is a progression of technology from the current fixed-beam NASA high-altitude Doppler weather radars using tube technology, and the lower altitude solid-state IWRAP system. HIWRAP utilizes a solid state transmitter along with novel pulse compression scheme that will result in a system that is considerably more compact in size, requires less power, and ultimately costs significantly less than typical radars currently in use for precipitation and Doppler wind measurements. With the inclusion of Ka-band, HIWRAP will be able to image the winds through volume backscattering from clouds and precipitation, enabling it to measure the tropospheric winds above heavy rain at high levels. Further this effort and the HIWRAP prototype will potentially lead to a smaller, less expensive spaceborne instrument that provides wide swath coverage similar to the SeaWinds instrument and can image not only the surface winds but the 3D tropospheric winds and atmospheric boundary layer winds above and within precipitation systems and the precipitation itself.

The HIWRAP technology goals are as follows: 1.) develop a conical-scanning system utilizing a solid-state transceiver that provides comparable performance to high-power tube-based systems, 2.) develop a high-speed digital receiver and processor to handle high data rates resulting from the solid-state transceiver and conical scan, and 3) develop a compact system suitable for high-altitude operation that will fit into existing high altitude UAV's (Global Hawk) and manned aircraft

In this section, we provide an overview of the HIWRAP system and the progress in its development. Section 2 discusses the wind measurement concept and the measurement requirements, while section 3 provides a system level description. Section 4 describes the aircraft installation plans and test flights that will be conducted with the instrument.

HIWRAP is a joint effort between Goddard Spaceflight Center, the University of Massachusetts Center for Advanced Sensor and Communication Antennas (CASCA), Remote Sensing Solutions (RSS), University of Maryland Baltimore County, and Welch Mechanical Designs.

II. Wind Measurement Concept

The HIWRAP system will measure the tropospheric winds by collecting multi-look Doppler profiles from cloud volume backscattering measurements. By operating at Ku/Ka-band, HIWRAP is significantly more sensitive to cloud particles than lower frequency radars, enabling it to measure the mean cloud particle velocity and thus map the 3D tropospheric winds. Additionally, its dual-wavelength operation enables it to map the full atmospheric boundary layer winds from Doppler-precipitation volume backscatter measurements, derive information about the drop-size distribution of the precipitation and estimate the ocean surface wind field using ocean wind scatterometry techniques similar to that employed by the NASA SeaWinds. As shown in Figure 1, HIWRAP will produce two antenna beams at Ku-band and two at Ka-band, simultaneously. Based on numerical analysis of derived horizontal wind accuracies versus incidence angle and other parameters, incidence angles of 30^o and 40^o were chosen. Conically scanning, these beams will sweep through the volume beneath the aircraft, while simultaneously measuring the Doppler/reflectivity profiles from each beam. For any given volume cell within the inner swath, HIWRAP will view this cell at Ku and Ka-band from two different incidence angles and four different azimuth angles, from which the 3 components of the wind will be derived. The dual-wavelength measurements will extend the dynamic range of conditions that can be sampled, provide additional information about the precipitation drop-size distribution, and in many cases, provide additional independent samples. The unique sampling and phase correction strategy implemented by HIWRAP (RSS' frequency diversity Doppler processing technique) [6] will enable the Doppler measurements to be unfolded.

The measurement requirements for HIWRAP are given in Table I for wind retrievals in 1 km x 1 km x 60m pixels. The actual line-of-sight wind measurement accuracy is much smaller than the retrieved wind accuracy.

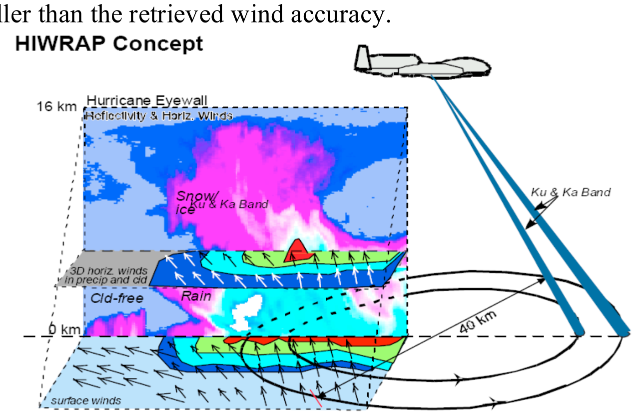


Fig. 1. HIWRAP Concept

TABLE I
HIWRAP MEASUREMENT REQUIREMENTS

	Parameters	Range	Accuracy
Retrieval Products (resolution cell: 1km x 1km x 60m)	Horiz. Wind Speed (ms^{-1})	0-100	2.0
	Horiz. Wind Direction (°)	0-360	15
	Surface Wind Speed (ms^{-1})	0-60	2.0
	Surface Wind Direction (°)	0-360	15
	Vertical Wind Speed (ms^{-1})	± 20	2.0

III. SYSTEM DESCRIPTION

Table II provides performance specifications for HIWRAP and Fig. 2 provides a drawing of HIWRAP configured in the Global Hawk. Most of the radar system will be mounted on a

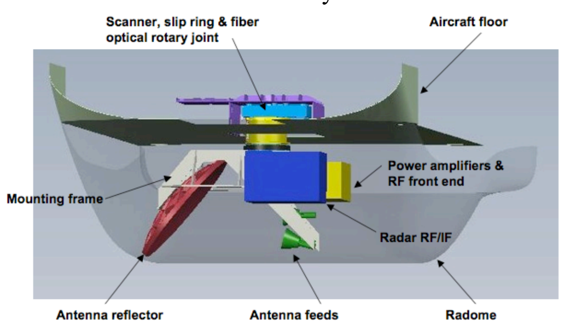


Fig. 2. HIWRAP mounted in Global Hawk radar chamber.

TABLE II
HIWRAP SYSTEM SPECIFICATIONS

Parameters	Specifications	
	Ku-band	Ka-band
RF Frequency (GHz)	Inner Beam: 13.910 Outer Beam: 13.350	Inner Beam: 35.560 Outer Beam: 33.720
Transmitter Peak Power (W)	30	10
3 dB Beam Width (°)	2.9	1.2
Polarization	Vertical (inner beam), Horizontal (outer beam)	
Minimum Detect. Reflectivity (dBZ_e, 60 m resolution, 10 km range and 3 km chirp pulse)	0.0	-5.0
Dynamic Range (dB)	> 65	
Doppler Velocity (ms^{-1})	0-150 (Accuracy < 1.5 ms^{-1} for SNR>10)	
Scanning	Conical Scan, 10-30 rpm	

rotating structure that will spin at about 10 rpm. This configuration minimizes waveguide and other losses that will affect sensitivity. HIWRAP has several subsystems and the following provides a brief description of each.

A. Antenna

An offset parabolic antenna with two feed horns was selected for HIWRAP by the University of Massachusetts, which is the responsible party for this subsystem. The offset reflector with feeds and the radar's RF front end can fit within the space available on the Global Hawk. The final antenna design was required to have a compact design that fits the space available, high gain, and low sidelobes. Prototype feeds have been developed (Fig.1) since this is the most challenging part of the design. Two more iterations will be performed on the feed for improved performance after which it will be light-weighted and integrated with the reflector.

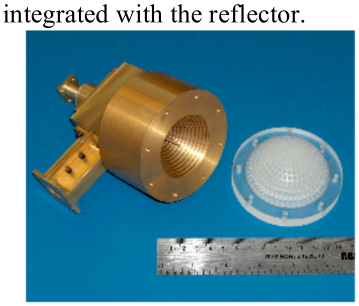


Fig. 1. Dual-frequency feed prototype.

B. Solid State Power Amplifiers

Solid-state amplifiers are used because they offer the most compact, light weight solution, and do not require high voltages that can be problematic for high altitude operations. Recent advances made in the communications industry have produced commercially available solid-state power modules capable of delivering average power levels greater than 10 W at Ku-band and 4 W at Ka-band. These power modules are often power combined to produce solid-state amplifiers with much higher output power. HIWRAP utilizes commercial power amplifiers that deliver 30 W at Ku-band and 10 W at Ka-band through power combining.

B. Transceiver

HIWRAP relies on a dual-wavelength transceiver that is modular in design. Due to the limited payload power, space and weight and the harsh environment of UAVs, a power efficient, compact dual-band transceiver compatible with high altitude operation has been designed for HIWRAP. This transceiver supports digital pulse compression through the use of inexpensive direct digital synthesizer (DDS) chips in order to obtain 50% of the average power of the Ku and Ka-band power amplifiers. The design supports simultaneous operation at two wavelengths and multiple incidence angles in order to maintain high temporal and spatial resolution. Innovative approaches are being taken to enhance independent sample rates and utilize the full average power that the power amplifiers can deliver. This design takes advantage of mixing products in the RF upconversion stage to produce the two RF channels at each band necessary to form the two beams. As such, this design only needs one LO for each band, and thus saves on space, power consumption and weight. If amplitude tapering is determined to be unnecessary for achieving the desired range sidelobe levels, a frequency multiplier may be used to generate the Ka-band signals from the Ku-band to further save space, power and weight. The DDS in the first stage will not only produce the linear FM chirp transmit waveform, but will also hop the center frequency to improve the independent sample rate. An internal calibration loop also provides an accurate measurement of the total transceiver gain to within 0.2 dB or better and samples of the transmit waveform so that pre-distortion techniques can be used to improve range sidelobe performance.

The transceiver design has been completed and components are presently in procurement.

C. Digital Receiver

The HIWRAP digital receiver and signal processor subsystem will be responsible for implementing digital I&Q detection, match filtering (i.e. pulse compression), spectral and/or Pulse-Pair processing and data reduction through coherent and/or non-coherent averaging. The subsystem is using field programmable gate arrays (FPGAs) and low power consumption processors. This will provide the most compact solution and not require pressurization. To reduce risk, the system is network based so that the data can be easily ingested by a PC-based system where further processing algorithms may be applied. As the algorithms are tested and validated, they can be transferred to the FPGA-based processors with minimum impact. To reduce risks, the critical FPGA-based algorithms are being tested within a development platform from which the final stand alone printed circuit boards will be designed and fabricated. The migration to radiation harden FPGA technology is also being studied.

Another novel feature of the FPGA-based digital receiver is that each IF channel will support up to eight independent sub channels. With more than 90 dB of rejection and a 1.5 filter shape factor, HIWRAP will be able to utilize frequency diversity to improve its independent sampling rate and implement an advance phase correction scheme for unfolding its Doppler measurements.

The primary digital receiver characteristics are:

- Two IF channels per board.
- Eight independent sub channels per IF channel.
- 80 MHz Max Intermediate Frequency.
- 500 kHz Min Frequency.
- 1 Hz resolution
- 500 KHz to 20 MHz bandwidth per subchannel.
- 40 MHz aggregated bandwidth per IF channel.
- Greater than 80 dB SNR.
- 14 bit A/D resolution.
- Matched Filter supports up to 30 dB pulse compression gain per subchannel
- Supports up to 1000 range gates.

D. Flight Testing

Our desire is to fly HIWRAP on the Global Hawk since it has an approximate flight duration of 32 hours. It is the only operational American UAV capable of the payload size, endurance and altitude requirements necessary for remote sensing payloads typical of NASA science missions. It has a maximum payload of about 2000 pounds and an altitude ceiling of about 60 kft depending on payload weight. Since it is unlikely that the Global Hawk will be available for testing within the next two years, initial flight tests for HIWRAP will be scheduled for Summer 2008 on the WB-57 aircraft based at NASA JSC. The WB-57 provides a good simulator for the Global Hawk since both planes are unpressurized in the radar/antenna compartments. Fig. 4 shows a concept drawing for HIWRAP mounted in a 6-foot pallet on the WB-57.

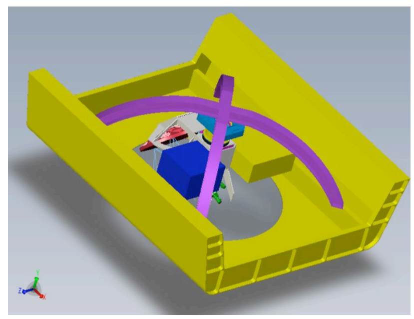
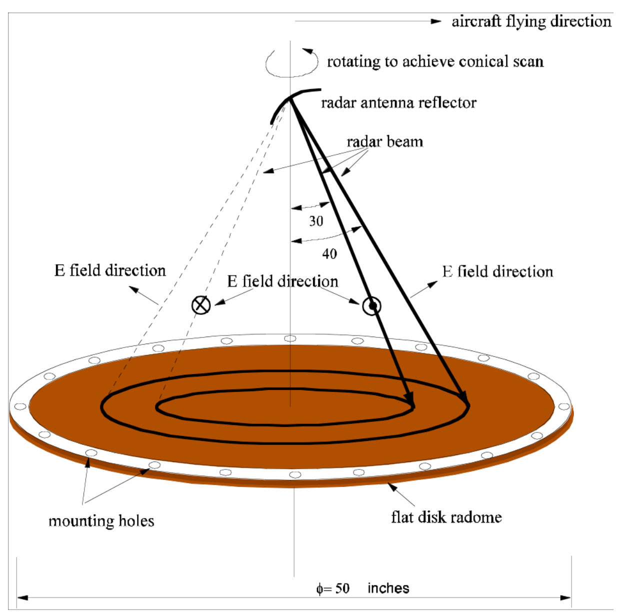


Fig. 4. HIWRAP mounted in WB-57 6-foot pallet.

One of the requirements for the WB-57 installation is a radome that is low-loss at Ku- and Ka-band. This radome is approximately 50 inches in diameter and is necessary since the

Fig. 5. WB-57 radome design.



bottom of the plane cannot be left open. A radome was designed commercially for HIWRAP (Fig. 5) and the delivered radome is shown in Fig. 6.

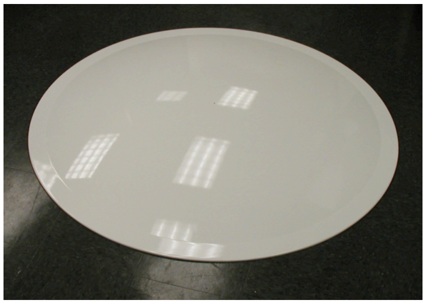


Fig. 6. WB-57 dual-frequency Ku- Ka-band radome

IV. Status and Future Plans

HIWRAP components are being procured and fabricated and system integration will be performed over the next year.

Acknowledgment

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