Improved Hurricane Boundary Layer Observations with the Imaging Wind and Rain Airborne Profiler

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***Abstract*— During the NOAA/NESDIS 2005 Hurricane Season (HS2005) and the 2006 Winter Experiment, the University of Massachusetts (UMass) installed two instruments on the NOAA N42RF WP-3D research aircraft: the Imaging Wind and Rain Airborne Profiler (IWRAP) and the Simultaneous Frequency Microwave Radiometer (SFMR). IWRAP is a dual-band (C- and Ku), dual-polarized pencil-beam airborne radar that profiles the volume backscatter and Doppler velocity from rain and that also measures the ocean backscatter response. It simultaneously profiles along four separate incidence angles while conically scanning at 60 RPM. SFMR is a C-band nadir viewing radiometer that measures the emission from the ocean surface and intervening atmosphere simultaneously at six frequencies. It is designed to obtain the surface wind speed and the column average rain rate. Both instruments have previously been flown during the 2002, 2003 and 2004 hurricane seasons.**

For the HS2005, the IWRAP system was modified to implement a raw data acquisition system. The importance of the raw data system arises when trying to profile the atmosphere all the way down to the surface with a non-nadir looking radar system. With this particular geometry, problems arise mainly from the fact that both rain and ocean provide a return echo coincident in time through the antenna's main lobe. This paper shows how this limitation has been removed and presents initial results demonstrating its new capabilities to derive the atmospheric boundary layer (ABL) wind field within the inner core of hurricanes to much lower altitudes than the ones the original system was capable of, and to analyze the spectral response of the ocean backscatter and the rain under different wind and rain conditions.

I. Introduction

IWRAP, the Imaging Wind and Rain Airborne Profiler, is the first high-resolution dual-band airborne Doppler radar designed to study the inner core of Tropical Cyclones (TCs). IWRAP is currently operated from a National Oceanic and Atmospheric Administration (NOAA) WP-3D aircraft during missions through TCs and severe ocean storms. The system is designed to provide high-resolution, dual-polarized, multi-beam C- and Ku-band reflectivity and Doppler velocity profiles of the atmospheric boundary layer within the inner core precipitation bands of TCs and to study the effects precipitation has on ocean wind scatterometry as it applies to TCs. This dual-wavelength system also provides for the use of differential attenuation techniques to derive the rainfall rate and to characterize the drop size distribution (DSD) within TCs. IWRAP implements a very unique measurement strategy; it profiles simultaneously at four separate incidence angles (approximately 30, 35, 40 and 50 degrees) while conically scanning at 60 RPM. This instrument has already demonstrated its capability to measure the wind field and the rainfall rate over the range of winds and rain rates usually present in tropical cyclones during the NOAA/NESDIS Ocean and Rain experiments. For a full description of the IWRAP system, the reader is referred to [1].

One of the lessons learned during these experiments was the limitation in retrieving the wind field at the lowest part of the boundary layer, since the off-nadir looking geometry makes the ocean surface return impact the precipitation measurements from which the wind field is derived. To overcome this problem, the IWRAP instrument was recently equipped with a new data acquisition system that allows us to acquire raw data and, therefore, to separate both ocean and rain contributions through spectral processing. This paper shows the approach followed and presents initial results derived from the dataset acquired during the 2005 hurricane season. This will also illustrate how this instrument enables us to obtain ABL wind fields within the inner core of TCs closer to the ocean surface, and to analyze the spectral behavior of the ocean backscatter response and the rain under different wind and rain conditions.

II. Limitations of the pulse-pair profiling

To clearly illustrate the situation under consideration, Fig. 1 shows a typical power profile obtained by IWRAP in the presence of heavy rain. The peak at the end of the profile corresponds to the ocean surface echo.

For every range gate, the original data acquisition system, based upon a hardware-based pulse-pair processor, would deliver the power and mean Doppler velocity estimates. When only one signal is present (rain or ocean backscatter), such system can deliver accurate estimates of the Doppler moments (mean and variance). When both components are present simultenously, however, the resulting Doppler velocity estimate will be a power weighted average of both contributions, therefore resulting in incorrect Doppler velocity estimates. At 30 deg incidence, and for nominal flying altitude conditions, the ocean surface backscatter would start to be noticeable at altitudes of around 250 m over the ocean surface. This clearly imposes serious limitations when retrieving the lower part of the atmospheric boundary layer winds.

Moreover, the nadir echo can also leak through the antenna sidelobes, effectively appearing as a third contribution for a small and definite number of range gates. The strength of this echo would normally cause the corruption of the profile for the ranges gates situated at a range distance equivalent to the flying altitude. This effect, however, is less apparent at Ku-band than at C-band at high to very high high winds. This is due to the fact that the specular return from a rough ocean surface is greatly reduced compared to the one obtained with a flat ocean.

III. Spectral Techniques for Profiling

To address the limitations of the pulse-pair processing, a new digital acquisition system, capable of storing the full raw data, was designed and implemented. Compared to the old pulse-pair processor, the new raw data system literally delivers a whole new dimension: the Doppler velocity dimension, or frequency dimension. Whereas a single estimate of the mean and the variance of the Doppler velocity was before provided at each range gate,

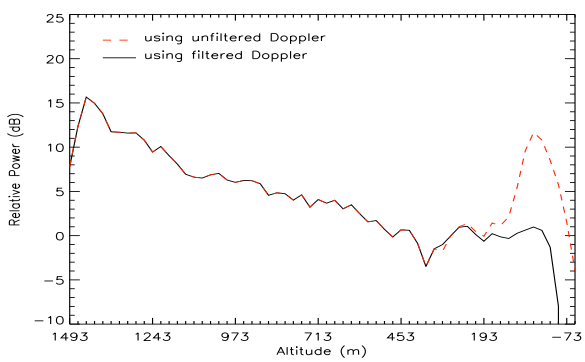

Fig. 1. Example of a typical power profile in the presence of heavy rain, all the way from the flying altitude down to the ocean surface (dashed red line). The peak at the right is the backscatter from the ocean surface. Using spectral techniques, the ocean contribution can be removed and the rain profile can be retrieved down to the surface (solid black line).

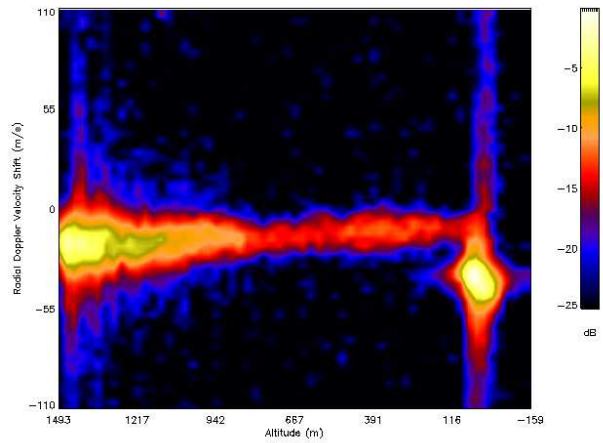

Fig. 2. Example of a FFT vs. range gate contour plot. This plot should be understood as a contour plot of a collection of spectra obtained at every single range gate. The x axis is the altitude from the ocean surface, and the y axis is the radial Doppler velocity, or frequency domain.

now a full spectrum can be easily derived from the raw data measurements. Fig. 2 presents an example of a typical two-dimensional, range-gated FFT. Basically the image is a contour plot of a series of FFTs obtained at every single range gate, all the way from the aircraft down to the ocean.

Fig. 2 clearly shows two separate contributions, namely: 1) the rain, roughly centered at around -25 m/s, is present all along the way and down to the surface, and 2) the ocean surface, a bright spherical-shaped region, roughly situtated below the rain, located at the right far end of the figure. From this simple display, several observations can be noted. First, both contributions can be visually seen: volume precipitation backscatter response and ocean surface backscatter response. They are clearly separated in frequency. As for the rain, both its power and its spectral width change significantly along the path, and not exactly in a monotonically decreasing way. Also, a simple visual inspection reveals that the ocean response starts roughly at 150 m altitude. A small peak is seen growing and expanding as the altitude decreases to the surface. The large bright region represents the surface.

Another feature present in Fig. 2 is the fact that the position of the ocean surface response shifts as the altitude decreases. This is a purely geometrical effect and it is not due to large variations in the ocean surface velocity. It is rather the result of the fact that the instanteous incidence angle changes from range gate to range gate. Given that the Doppler velocity is a function of the incidence angle, its variation will result in this apparent ocean velocity variation. The rain contribution, however, is always seen at constant (nominal) incidence angle.

In general, once both components are individuated, two main techniques can be used to extract one of them: filtering and substraction. Filtering requires both components to be visually separated, and it is the approach followed here. For the following examples, the data corresponding to a full conical scan was used, where all the profiles were separated in to 32 azimuth bins. With the profiles for each azimuth bin, 128-point FFTs were calculated, and all the resulting FFTs for a bin averaged together into one. The procedure followed was to remove the ocean when possible, remove the nadir returns if any, and obtain an estimate of the mean Doppler velocity of the rain spectra for all the range gates and azimuth bins. Then, Velocity-Azimuth Display (VAD) techniques were applied to retrieve a vertical wind profile. Finally, the obtained profile is corrected for the aircraft velocity and relative azimuth.

For some of the azimuth bins of any given scan, where the separation between both spectral components reaches its peak, it is fairly simple to filter out the ocean backscatter virtually down to the ocean surface. In some other cases, filtering the ocean response is not possible without totally removing the rain component. This constitutes the worst case scenario, and for that azimiuth bin, the profile can be derived only down to the point where the ocean response appears. Most of the cases, however, fall in an intermediate situation, where it is possible to preserve the rain response to lower altitudes than when the first appearance of the ocean surface backscatter takes place, but not all the way down to the surface. Therefore, in order to derive a wind profile down to the lowest possible altitude, it is necessary to consider that not all the azimuthal looks will be available for the retrieval. This is not of major concern for VAD techniques since for any given range gate, an LMS algorithm can be used to fit a sinusoid to the available azimuthal mean Doppler velocity points. This approach was successfully applied for the scan corresponding to the measurements presented in the previous figures.

Figure 3 presents the retrieved wind profile, both when the ocean surface response has been filtered out and when it has not. It is clear from this figure that when using the unfiltered measurements, the retrieval breaks off at an altitude of around 300 m. When the ocean surface response is filtered, the profile is valid down to around 100 m, after which the ocean backscatter response affects most of the azimuthal points and it is not possible to do the retreival any further. The resulting gain is however a net 200 m more of wind profile closer to the ocean surface. Note that for this analysis, the range gates were not mapped into altitude levels. Therefore, the ABL retrieval was performed in range gate space. Due to non-zero pitch and roll, this has the effect of increasing the minimum level. It is thus expected that

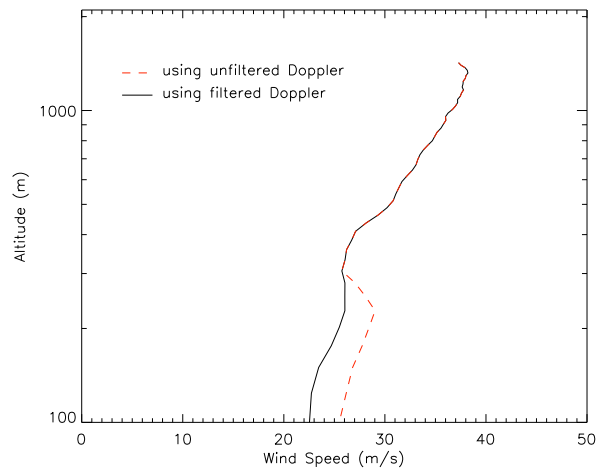

Fig. 3. Derived wind profile, both filtering and not filtering out the ocean surface response. The altitude, along the y axis, is in log scale.

this initial minimum level of 100 m will be slightly lower (approximately 70 to 80 m). Using more sophisticated techniques, it is expected to retrieve the ABL winds to within approximately 2 to 3 range gates of the surface, which corresponds to 30 to 60 m altitude. Given that scatterometry techniques can be used with the ocean backscatter measurements to derive the 10 m ocean surface wind vector, only a very small portion of the ABL wind profile will not be retrieved (i.e. 30 m range level).

IV. Conclusions

It has been shown how the recently modified IWRAP system can be exploited together with the use of spectral techniques to derive the ABL wind field within the inner core of hurricanes to much lower altitudes than the ones the original system was capable of. Initial results have been shown were the initial limitation of a minimum altitude of 300 m has been reduced to just 100 m, and it is expected to be further decreased to within 30 to 60 m from the ocean surface. This constitutes a truly unique effort towards the obtention of radar datasets and the development of advanced spectral techniques capable of revealing the lowest part of the ABL wind field within tropical cyclones. These measurements can also be used to analyze the spectral behavior of the ocean backscatter response and the rain under different wind and rain conditions.

V. Acknowledgements

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[1] Esteban Fernandez, D., E. Kerr, A. Castells, S. Frasier, J. Carswell, P. Chang, P. Black, and F. Marks, "IWRAP: the Integrated Wind and Rain Airborne Profiler for remote sensing of the ocean and the atmospheric boundary layer within tropical c ylones", to appear in *IEEE Trans. Geosci. Remote Sensing*, 2005.