Report to the National Hurricane Center Regarding the Performance of the Stepped-Frequency Microwave Radiometer (SFMR) During the Landfalls of Hurricanes Ivan and Jeanne

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Overall comparison of SFMR surface winds with GPS winds

A set of SFMR surface wind estimates co-located with GPS dropsonde wind measurements during the 2004 flights have been obtained. All samples are transmitted data from NOAA-43, and have not been adjusted based on averaging considerations in any way. The GPS wind measurement used for the comparison is the reported WL150 wind speed. During all flights in Hurricanes Frances, Ivan, and Jeanne, 194 SFMR/sonde paired samples were identified. The SFMR measurement reported for the same minute as the sonde drop time is utililized. Based on these measurements, a linear best-fit (forced to zero offset) with 95% confidence limits on the fit parameters yields:

$$SFMR = (0.88 \pm 0.05) \bullet WL150 \pm 3.6 \text{ (kts)}.$$

A plot of these data is shown in Fig. 1.

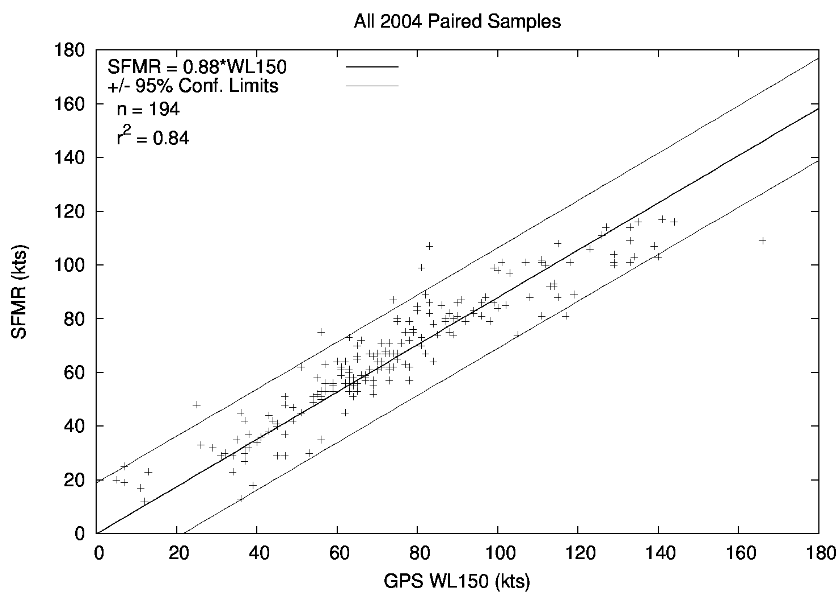

Figure 1. SFMR-GPS (WL150) wind speed comparisons for all samples identified for NOAA-43 hurricane flights in 2004. The linear best-fit along with 95% confidence limits are indicated.

Based on these results, over the range of SFMR surface (assumed to be 10 m) wind speeds of 0-120 kts, the surface wind is on average around 88% of the GPS WL150 wind speed, and 95% of the time, lies from 83-93%. The scatter in the sample data, characterized by a correlation coefficient of $r^2 = 0.84$, compares well with results from previous work which compared SFMR winds with GPS surface estimates ($r^2 = 0.86$, Uhlhorn and Black 2003).

A tendency for a "roll-off" in the SFMR wind estimate at around 100-120 kts is noted, but based on the overall uncertainty of the estimates in this limited sample, this trend does not appear to be statistically significant. While we believe the SFMR is physically capable of accurately estimating winds well in excess of 100 kts, further direct comparisons are required to assess whether the instrument (or theory) has limitations in these extreme cases. The over-estimate in the SFMR surface winds below 20 kts is typical of measurements taken inside the eye of hurricanes, and is not of particular concern here.

It has been speculated that SFMR winds measured in shallow water may be biased. This is due to influence of wave shoaling on breaking activity and subsequent foam generation, upon which the SFMR measurements are physically based. To this point, no analysis has been performed to help quantify if this effect may exist. Surface wind measurements made during landfalling situations would be candidates for these issues. For purposes of this preliminary work, a sub-sample is drawn of SFMR/GPS winds measured during the NOAA-43 landfall flights of Hurricanes Ivan and Jeanne, to statistically assess whether these measurements are significantly different from the overall sample. A least-squares best-fit for the landfall dataset gives:

$$SFMR = (0.92 \pm 0.04) \bullet WL150 \pm 4.2 \text{ (kts)}.$$

A plot of these measurements is shown in Fig. 2.

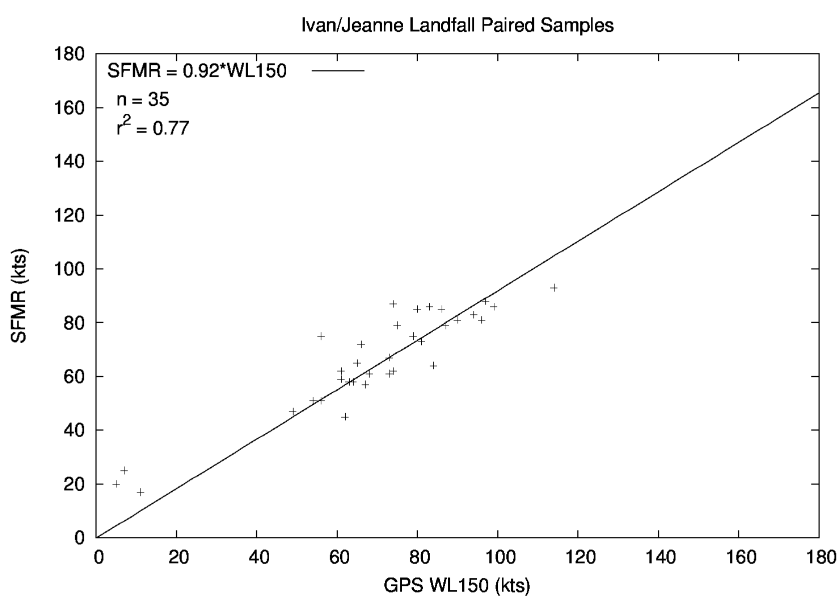

Figure 2. SFMR-GPS (WL150) wind speed comparisons for samples identified for NOAA-43 hurricane landfall flights in Hurricanes Ivan and Jeanne.

Comparison of the slopes of the fits between the two storm landfall sub-sample and the overall 2004 sample data suggests that there is little statistical significance in the differences. Previous work has indicated an overall ~4 kt high bias of the SFMR wind relative to the GPS surface (10 m) wind measurement (Uhlhorn and Black 2003). This bias has been traced to an offset in the emissivity/wind speed relationship employed in the retrieval algorithm, and will be addressed in any future re-development. Additionally, another source of uncertainty in the SFMR surface wind measurement may arise due to surface current effects on breaking waves, especially when the surface wind opposes the current direction. A number of measurements were obtained over the Gulf Stream in Hurricanes Frances and Jeanne. **Analysis of these effects, if any, will be the subject of future efforts, but we do not believe the specific conclusions here will be greatly affected.**

Analysis of SFMR surface winds prior to Ivan's landfall

Surface winds in Hurricane Ivan during its landfall have been recently called into question. NOAA-43 flew a pattern that sampled all storm quadrants from 00 to approximately 06 UTC on 16 September 2004. Additionally, a final Air Force Reserve Command flight measured winds from 06 to 09 UTC. Transmitted surface and flight-level wind measurements along flight legs in the right (NE and SE) quadrants (where the highest winds were found) have been identified along with peak estimated winds. These data from NOAA-43 are plotted in Fig. 3, and Fig. 4 shows the wind data measured by AF-977.

The highest GPS wind measured just prior to landfall was deployed by NOAA-43 at 0134 UTC. This particular sonde indicated a WL150 wind speed of 114 kts and an 11 m wind of 96 kts, which compares quite well with the SFMR estimate of 93 kts at the same time (Fig. 3, lower-left panel).

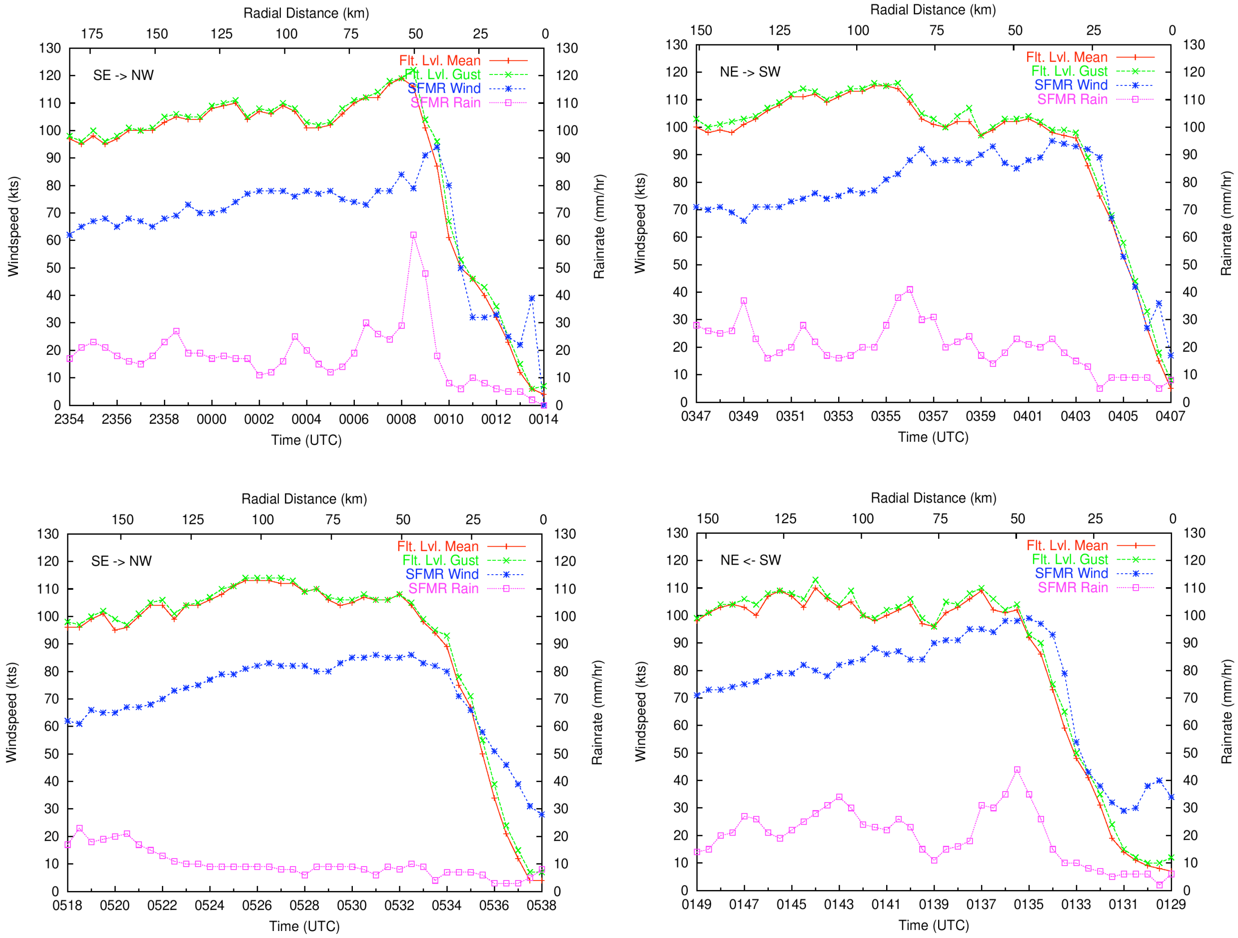

Figure 3. Flight-level wind, SFMR wind, and SFMR rain measurements from NOAA-43 along the four legs that sampled the right quadrants of Ivan. Flight-level mean winds are red, flight-level gusts are green, SFMR surface winds are blue, and SFMR rain rates are magenta. The center of the storm is on the right side of all plots, such that outbound flight legs are plotted in reverse chronological order.

Table 1 lists the peak flight level and SFMR surface winds measured along each of the four NOAA-43 and the one AF977 flight leg to the east of Ivan. Considering the ratio of peak surface to peak flight level winds, a relationship between SFMR and flight-level mean wind along individual flight legs of 0.82 ± 0.09 is found, and for the flight-level gust, 0.80 ± 0.09. Applying these relationships to the AFRC flight-level peak winds found at landfall, this would correspond to an SFMR estimate of 96 ± 11 kts based on the flight-level mean, and 98 ± 10 kts based upon the flight level gust. Based on these results, it may be safely concluded that there was little significant change in Ivan's intensity over the period from 00 to 07 UTC just prior to landfall.

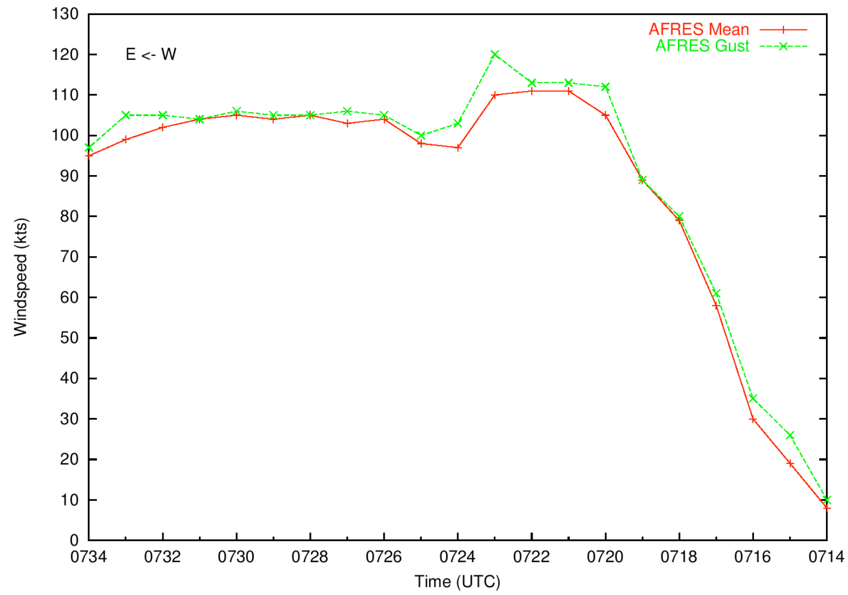

Figure 4. Flight-level wind measurements from AF-977 to the east of Ivan where the highest winds were measured at landfall. Flight-level mean winds are red and flight-level gusts are green.

A/C	***Peak SFMR (Time/Dist.)***	***Peak Flt.Mean (Time/Dist.)***	***Peak Flt. Gust (Time/Dist.)***	***Quad.***
NOAA-43	94 (000930/45)	119 (000800/55)	122 (000830/50)	RR (SE)
NOAA-43	99 (013500/45	110 (014400/115)	113 (014400/115)	RF (NE)
NOAA-43	95 (040200/40)	115 (035430/95)	116 (035430/95)	RF (NE)
NOAA-43	86 (053300/45)	113 (052700/100)	114 (052700/100)	RR (SE)
AF-977	--	111 (072200/50)	120 (072300/60)	R (E)

Table 1. Peak SFMR surface and flight-level winds (kts) measured along flight legs just prior to Ivan's landfall. Data are listed in chronological order. Also indicated is the time (HHMMSS UTC) and estimated radial distance (km) of the measurement from the storm's center.

In light of all wind measurements obtained during the NOAA and AFRES flights just prior to landfall, **it is our opinion that the maximum SFMR estimates of 99 kts (0135 UTC), and later 95 kts (0402 UTC) observed in the RF (NE) quadrant of Hurricane Ivan at 0135 UTC represent the highest surface winds**.

Analysis of SFMR surface winds prior to Jeanne's landfall

Surface wind estimates by the SFMR have been called into question during the landfall of Hurricane Jeanne, particularly those measurements made by NOAA-43 during a final outbound leg paralleling the Florida east coast to the north of the storm. Transmitted SFMR data indicated a significant period of time when surface winds equaled, or even slightly exceeded, flight-level wind measurements. A peak SFMR surface wind was reported as 112 kts at 022830 UTC around 85 km to the north of Jeanne's center. Data from the final two flight legs of the landfall flight have been obtained to help assess the quality of the surface wind reports. Fig. 5 shows time series of these data.

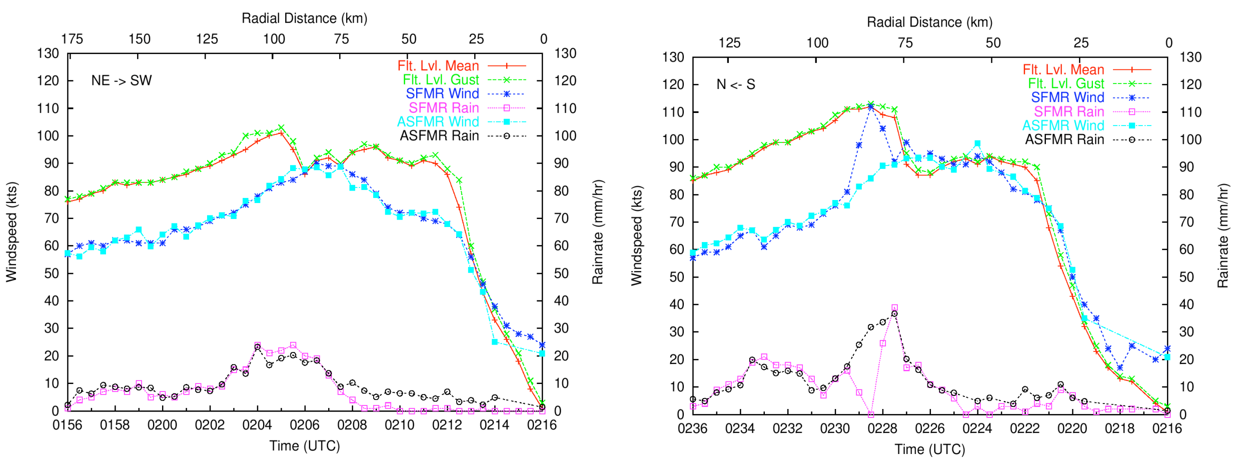

Figure 5. Flight-level wind, SFMR wind, and SFMR rain measurements from NOAA-43 along the final two legs that sampled the NE (left panel) and N (right panel) quadrants of Jeanne. Flight-level mean winds are red, flight-level gusts are green, SFMR surface winds are blue, and SFMR rain rates are magenta. In addition, winds and rain from the AOC SFMR (ASFMR) are plotted in cyan and black, respectively.

The right panel of Fig. 5 shows the outbound leg to the north of the storm. To assist in the analysis, surface winds and rain rate measurements from the new AOC SFMR have been utilized. After slight bias corrections to the AOC SFMR data, it is clear that overall there is good agreement between the transmitted SFMR data and the measurements from the new instrument. Also clear is the lack of agreement in the winds and rain from 0228 to 0229 UTC, which corresponds to the time of the maximum reported surface wind (Fig. 5, right panel). Based on this observation, these measurements are questioned. Radar reflectivity data indicate that significant convection was present in the north eyewall of Jeanne, which runs contrary to the 0 mm/hr rain rate estimate by the SFMR at 022930 UTC. This period of low rain rate measurement corresponds to anomalously high surface wind measurements. The estimates from the new AOC SFMR help to show that the SFMR measurements at 022800, 022830, and 022900 UTC (104, 112, 98 kts) are inaccurate. A surface wind measurement of 99 kts at 022700 does, however, appear to be reasonable, as does the winds measured over the period of time from 0223 to 0227 UTC in which surface and flight-level winds were roughly equal. The AOC SFMR indicated a peak surface wind of 98 kts three minutes earlier. No GPS sondes were deployed along this flight leg, so no independent confirmation of these results is possible, but the highest WL150 wind measured in the NE eyewall along the leg shown in the left panel was 94 kts at 0205 UTC, which corresponds to an SFMR estimate of around 83 kts. The SFMR wind reported at this same time was also 83 kts, and the maximum wind along this leg was estimated as 90 kts at 020630 UTC. *In summary, we believe the maximum surface wind measurement by the SFMR just prior to Jeanne's landfall was 98-99 kts in the north eyewall, just offshore of Sebastian, FL.*

There are a number of possible reasons why the SFMR gave erroneous surface winds during this particular flight. One candidate is radio frequency interference (RFI) of one or more SFMR channels from an external source. Essentially these results are indicative of a failure of the wind/rain retrieval algorithm to identify contamination of the measurements and to converge to the proper solution. In this particular situation, the algorithm attributed all radiative emission measured by the SFMR to surface winds, when clearly there was significant rain present. The result being an overestimate of the surface wind when the rain rate was underestimated. Careful analysis of the raw instrument measurements will be required to assess the true cause of the problem. These results should lead to algorithm improvements to prevent situations like this from re-occurring. In any case, the conclusions presented are expected to remain consistent.

Summary

Nearly 200 SFMR/GPS sonde sample intercomparisons were identified from the 15 NOAA-43 flights in Hurricanes Frances, Jeanne, and Ivan. These data were used to make a preliminary assessment of overall SFMR surface wind quality during 2004. It was found that, in general, the data compared well with results from an intercomparison study from data obtained in previous years (Uhlhorn and Black 2003), and that the SFMR surface wind was typically 88% of the reported GPS WL150 wind speed. Using sonde data and flight-level winds measured by NOAA-43 and Air Force Reserve aircraft, as well as measurements from the new AOC SFMR, we conclude that maximum surface winds measured by the SFMR just prior to landfall were 95-99 kts in Hurricane Ivan, and 98-99 kts in Hurricane Jeanne. A direct comparison of these estimates with other surface wind measurements should consider the ~4 kt apparent high bias of the SFMR previously identified.

In the coming months, additional validation studies will be undertaken. Coastal anemometer towers placed by the Florida Coastal Monitoring Program, Texas Tech University, together with NOAA's moored buoys and C-MAN stations were well positioned to sample portions of the eyewall previously traversed by the NOAA and Air Force aircraft in Hurricanes Ivan and Jeanne. These observations (corrected for exposure, anemometer height, and averaging period) will provide supplemental coastal comparisons for validating the SFMR observations. When monitored in a storm-relative coordinate system (e.g. as in H*Wind), on several occasions the SFMR aircraft passed over GPS sonde splash locations of sondes that were launched by Air Force or other NOAA aircraft. These comparisons have relatively small spatial and temporal separations and will add to the set already identified and discussed above. Furthermore, stratification of the SFMR comparisons by water depth will allow continued investigation of possible shoaling wave effects. Finally, these efforts will lead to an assessment of the quality of surface winds measured by the AOC SFMR, which is the prototype for future instruments to be installed on Air Force reconnaissance aircraft.

Reference

Uhlhorn, E. W. and P. G. Black, 2003: Verification of remotely sensed sea surface winds in hurricanes. *J. Atmos. Oceanic Tech.*, **20**, 99-116.