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Calibration of reflected GPS for tropical storm wind speed retrievals

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[1] Since 1996 when GPS reflected signals were purposefully acquired, an effort to assess the utility of these signals has been under way. It was early determined that the reflected GPS signal can be related to ocean surface wind dependent slope probability densities. Quantifying that relationship has resulted in considerable data taken at wind speeds below those associated with tropical storms. During the 2005 hurricane season, data were taken in high wind speed conditions that have been used to compare with the U.S. Navy's COAMPS model. The gridded data were used to develop a calibration for high wind speeds which also represents a measurement of apparent ocean surface slopes at L-Band. This paper presents the results of this GPS surface reflection calibration for winds up to 35 meters per second. In addition a simple function is developed that models the mean square slope variation with surface wind speed and includes winds above 35 meters per second. This model is applied to data from Hurricanes Dennis and Isabel to demonstrate the ability of surface reflected GPS signals to yield good retrieval performance for winds at and above tropical storm strength. **Citation:** Katzberg, S. J., O. Torres, and G. Ganoe (2006), Calibration of reflected GPS for tropical storm wind speed retrievals, *Geophys. Res. Lett.*, *33*, L18602, doi:10.1029/2006GL026825.

1. Introduction

[2] Since the first demonstration that ocean surface reflected GPS signals can be directly related to wind speed [*Garrison et al.*, 1998; *Lin et al.*, 1999] on-going efforts have been directed to understanding the phenomenology of the GPS technique. While the use of backscattered microwave signals is one of the established methods for determining surface wind fields, the bistatic configuration represented by the GPS technique has only recently had extensive modeling done and seen a body of experimental data collected.

[3] Several aircraft flight campaigns have been done to develop the phenomenology of the GPS technique applied to remote sensing of ocean surface winds. A review of these results can be found in work by *Garrison et al.* [2002] along with a discussion of the instrumentation used and examples of waveforms created in the modified GPS receivers. Comparisons with buoys, TOPEX-Poseidon under-flights and other data sets are also shown which summarize the performance of the technique.

[4] Since the year 2000, NASA's Langley Research Center has had opportunities to fly its GPS reflection receivers on the NOAA Aircraft Operations Center (AOC) Hurricane Hunter P-3's. This has been part of a continuing effort to understand the results found in performing wind speed retrievals on data taken in high wind speed regimes and to determine the utility of the GPS technique for monitoring tropical cyclones.

[5] GPS Surface reflection data have been acquired in the period 2000 to 2005 from several hurricanes and tropical storms: Keith, Michael, Hanna, Isidore, Lili, Isabel, Fabian, and recently Hurricanes Dennis, Ophelia, and Rita. The first retrievals from inside a tropical storm of hurricane force (>75 knots) were done on data from Hurricane Michael, October 10, 2000 [*Katzberg et al.*, 2001]. While a wind speed profile was generated which could be compared with Flight Level or Step Frequency Microwave Radiometer (SFMR) data, the profiles had to be done from composites of retrievals from reflected signals from different satellites. Retrievals generated from a particular satellite might show a high wind speed peak when entering the eye wall and then not show the eye wall upon leaving the eye. Conversely one might show the eye wall upon exiting but not entering the eye. The reason for these inconsistent results has been the subject of considerable effort and follow-on investigation.

[6] In general, retrievals from high wind speed regimes have been characterized by the underreporting of wind speeds. GPS-based wind speed retrievals depend on a monotonically increasing surface mean square slope versus wind speed. The possibility that the mean square slope does not follow a linear relationship on wind speed is well recognized [e.g., *Apel*, 1994; *Elfouhaily et al.*, 1997] and is supported by theoretical considerations referred to as the Plant Limit [*Plant*, 1982]. More importantly, it is possible that the mean square slopes saturate and fail to continue to increase with increasing wind speed, leading to a high-speed limit for the GPS technique and lack of usefulness for studying tropical cyclones or other high wind speed regime ocean winds.

[7] It is the purpose of this paper to present the results of a calibration effort to quantify the relationship between apparent L-Band-wavelength-ocean- surface-slopes as a function of wind speed. It will be shown that there is a monotonically increasing, non-linear relationship between wind speed and apparent mean square slopes that varies from near a modified Cox and Munk value at low wind speeds to a value somewhat lower at high wind speeds. It will also be shown that if a function is properly fitted to the data and used in GPS wind speed retrievals, results consistent with other methods of remote wind speed monitoring result.

2. Background

[8] As shown in work by *Katzberg and Garrison* [1996] and *Lin et al.* [1999] the GPS technique is dependent upon the surface slope probability density integrated over range bins impressed upon the reflecting surface that result from the GPS range coding. The effect in the receiver is to

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produce a (reflected) power versus range delay which can be generally well represented by a convolution between the internal receiver correlation function and the surface slope probability density integrated over the surface.

[9] The slope probability density used by *Lin et al.* [1999] is the Gramm-Charlier probability density developed by Cox and Munk [*Cox and Munk*, 1954]. This probability density of slopes has upwind-downwind and crosswind anisotropies dependent on wind speed. Fundamentally, the Gramm-Charlier density is a bi-variate Gaussian with correction terms. The mean-square-slopes (m.s.s.) for both directions are linear functions of wind speed with a range of validity for this relationship of 1–14 meters per second.

[10] The GPS wind speed retrievals are created by generating model waveforms that come from convolving the receiver correlation function and the slope probability function evaluated in terms of surface x-y coordinates at altitude z. The slope probability function widens as the wind speed increases producing a model waveform set which also follows this pattern.

[11] The model waveforms are then processed through a matched filter algorithm to select the appropriate waveform and its related wind speed [*Katzberg and Garrison*, 2000].

[12] It was apparent from initial results utilizing the *Lin et al.* [1999] model that the relationship between the mean square slopes and wind speed greatly overestimated the dependency of effective slopes on wind speed at the GPS wavelength (19.05 cm.) Following the suggestion of *Wilheit* [1979] the mean square slopes for the GPS technique were reduced by a factor of 0.33 to account for the L-band wavelength versus optical wavelengths. Upon later comparisons with an increasing data set a preliminary value of 0.45 was found to give better agreement between data and surface truth (buoys) at low wind speeds (<10 meters per second).

[13] Models such as Cox and Munk or *Shaw and Churnside* [1997] incorporate a bi-variate Gaussian function as the dominant component of the slope probability density. It is easily seen that the GPS iso-range surface ellipses define surface slope angles which are symmetric in only one dimension. Thus, at satellite elevation angles less than 90 degrees, there is more or less overlap with the surface slope probability density depending on the angle the wind direction makes with respect to the direction to the satellite. For a purely bi-variate slope probability density there is a twice per cycle variation of the reflected power versus azimuth satellite-to-wind direction angle. For a surface probability density (SPD) with upwind-downwind as well as crosswind anisotropies, there is a once per cycle variation of the reflected power versus azimuth satellite-to-wind direction.

[14] As the data sets have continued to be collected and the software improved to more effectively capture the data at higher signal-to-noise-ratio, the anisotropy predicted has been observed. At lower satellite elevation angles, there is evidence of increasing anisotropy in the wind speed retrievals. This is manifested by different wind speed retrievals for satellites at similar elevation angles but different azimuth orientations with respect to wind direction.

[15] It should be noted that power versus range integration over the surface can be significantly affected by platform motion. Doppler shifts can lead to generation of frequency components in the reflected data that are attenuated in the receiver correlation and time integration process and must be taken into account. For the results reported here, it can be shown that the aircraft platform speed causes negligible effect except in the outer range-Doppler bins which do not produce significant effect on the retrieval process used to determine wind speed.

[16] At the same time the data sets have revealed another characteristic of the phenomenology. For satellites at high elevation angles, high values of wind speed (>20–25 m/s) were almost never found in the retrieval process when operating on data taken from known high wind speed areas (35+ meters per second).

[17] At low wind speeds the anisotropy is difficult to resolve with the current simple technological state of reflection receivers. Until recently few data sets were available with sufficient cases of similar elevation angle and widely distributed azimuth angles to allow the necessary curve fitting to separate wind speed from wind direction effects. To add to the complexity, the anisotropy is expected to be dependent on absolute wind speed and elevation angle.

[18] In order to separate the effects on the detected signal of high wind speeds and wind direction, a very large experimental data base of various azimuth angles and wind speeds would have to be acquired. Conversely, another case is more easily evaluated: utilizing reflections at or near vertical elevation angles only.

[19] From symmetry, a satellite at ninety degree elevation angle must cause no wind-direction-to-satellite-direction azimuthal anisotropy. At elevation angles below, but still near vertical, satellites would cause only weak azimuth variation if the surface is characterized by a bivariate Gaussian slope probability density.

[20] Recent upgrades to the receiver software include a satellite selection algorithm that ensures that an increasing elevation angle satellite is selected for the channel from which reflected surface power is recorded. After a satellite drops to a selectable minimum elevation angle, a satellite that is known to have an increasing elevation angle is selected to replace it. This change has resulted in a much larger data set derived from high elevation angle satellites than before.

[21] The recent improvements in receiver software and accumulating data sets have made possible an investigation into the effects of high wind speed on retrievals. The result of finding consistency in the relationship of high wind speed on retrieval value would lead to a calibration function for the high elevation angle regime.

3. Method

[22] Since the NOAA aircraft typically fly over the open ocean as they approach the tropical storm, a wind field of increasing strength passes beneath the aircraft. Such flight paths would seem to provide ideal opportunities to develop a GPS-based wind speed versus surface truth calibration function. In essence, the flight path (time or space) would provide a parametric variable over which the various values of wind speed could be “mapped.” The question arises as to what to use for surface truth wind speeds versus the same flight path time or space parameter?

[23] While the NOAA AOC aircraft deploy dropsondes, these are typically used only in and near the tropical storm

leaving the path to and from the storm without wind speed measurements. For this reason they do not provide the necessary information required to generate the calibration curve. The most obvious alternative is model-based wind fields from weather prediction systems. The one used for this study is the U.S. Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS.) COAMPS "represents state-of-the-art analysis (including the Nowcast capability) and short-term (up to 72 hours) forecast tools applicable for any given region of the Earth in both the atmosphere and ocean" [*Chen et al.*, 2003]. With its 0.2 × 0.2 degree grid, COAMPS has sufficient density to compare with the detail inherent in the high spatial resolution GPS data. Analysis of COAMPS wind speed data compared to buoys, etc. in the Gulf of Mexico have shown root-mean-square accuracies of 2 meters per second [*Hsu et al.*, 2002].

[24] Certain considerations had to be taken into account when using COAMPS. First, the COAMPS is not expected to reproduce the wind field detail quite near the core of a tropical storm where multiple eye walls, strong asymmetries, fetch, and other effects can be found. On the other hand, close to land other inaccuracies might be found resulting from the land-water transition.

[25] COAMPS data sets are available for the Gulf of Mexico and Atlantic areas (subset of the "Central American" model run) and Atlantic ("Western Atlantic" model run). One or another of the set was selected as appropriate for each particular storm. The COAMPS models were available for 00 and 1200 hours with 3 hour increments of prediction for up to 48 hours. At the start of the model runs, available ground truth (sondes, buoys, etc.) are used to set initial conditions for the model runs. For this effort, the COAMPS winds at 10 meter height were selected.

[26] The P-3 flights for which data sets were acquired generally cover approximately eight hours and include an outbound leg a storm pattern and a return or homebound leg. The time in the storm core might last several hours spanning multiple prediction steps for the COAMPS code. Therefore each flight was broken into three parts: outbound, storm core and homebound. Only the outbound and homebound legs were used.

[27] Once the model run closest in time to each flight leg was selected, the GPS derived wind speed retrieval files for the appropriate leg were used to select the matching point in the COAMPS grid in longitude and latitude to give the reference wind speed. The GPS data are generated at a rate of approximately 1 second per point for the data sets used and the accumulated data values were then averaged to produce a single value at each grid point. Since the P-3's travel at approximately 100 meters per second and the grid intervals are 0.2 degrees (~10 km) there are about 100 points that are averaged together per grid point.

[28] The data from the highest elevation satellites were selected from the GPS wind speed retrievals to fit functional forms to the data. A good fit was found in the case of a logarithm function:

$$U_{gps} = 6 \cdot \ln(U_{COAMPS}) - 4.0 \quad (1)$$

where U_{COAMPS} is the COAMPS surface "truth" wind speed and *Ugps* is the wind speed from the GPS retrieval.

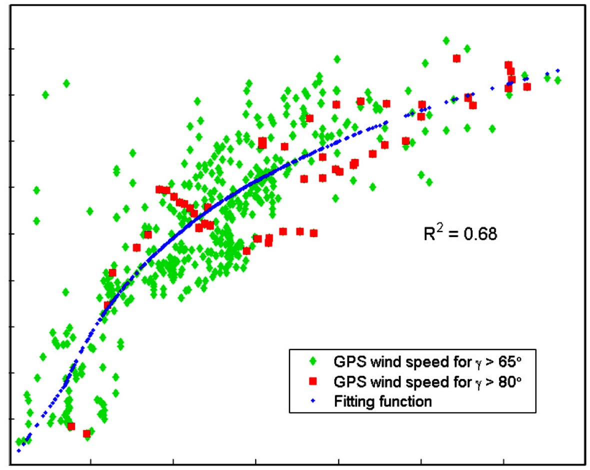

Figure 1. Summary of wind speed comparison between the GPS technique and the COAMPS model using data sets from Hurricanes Ophelia and Rita.

[29] Since comparisons with buoys have shown a 1:1 relationship for GPS-derived and true wind speeds, below the point of equality for the fitted equation, 3.49 meters/second, a 1:1 relationship was used instead of the ln relationship.

[30] Illustrated in Figure 1 are the data and this hybrid linear log function found to give a good fit.

[31] In Figure 1, the squares are retrievals done on data taken for satellite elevation angles eighty degrees and higher. The diamonds represent retrievals that correspond to satellite elevation angles of sixty degrees or more. It is interesting to note that the data from satellites down to at least sixty-five degrees elevation angle appears to be well represented by the fitted logarithmic function. For the high elevation satellites (>65 degrees) an R^2 value of 0.68 was found.

[32] In order to test the model function in representing the actual dependence of the surface mean-square-slopes, retrievals for some of the storms from the 2005 hurricane season were rerun. Instead of the linear Cox and Munk mean-square-slope dependence on wind-speed relationship previously used, the wind speed used to generate the model wave forms for matching, was "mapped" to of true wind speed using a relationship based upon the fitting function of equation (1).

[33] Examination of the data used for Figure 1 shows that for GPS wind speed retrievals above 19–20 meters per second (corresponding to 46 meters per second, true wind speed), the relationship between GPS derived winds and surface winds appears to reach a value of approximately 0.41 times the true wind speed. While the data sets to defend that value are sparse and not at high elevations angles, it is clear that the log function cannot match the data over too large a range. For this reason, a completely heuristic relationship of GPS wind speed versus true wind speed above 46 meters per second was set to be:

$$U_{gps} = 0.41 \cdot U_{COAMPS} \quad 46 < U_{COAMPS}. \quad (2)$$

[34] The modified mean-square-slope relationships (parallel to the wind and perpendicular to the wind direction) used for the reruns was then:

$$M.S.S._{\parallel}(U) = 0.45 \cdot (0.00 + 0.00316 \cdot f(U))$$
$$M.S.S._{\perp}(U) = 0.45 \cdot (0.003 + 0.00192 \cdot (U)) \quad (3)$$

where the U is related to the actual wind speed U_{true} through:

$$f(U) = U \qquad 0.00 < U \leq 3.49$$
$$f(U) = 6 \cdot \ln(U) - 4.0 \qquad 3.49 < U \leq 46 \quad (4)$$
$$f(U) = 0.411 \cdot U \qquad 46.00 < U$$

where now the COAMPS subscript has been replaced by true surface wind for the retrievals.

[35] It is important to note that this paper is not proposing the "trial" m.s.s. relationship above as in any way defining a new L-Band model of effective mean square slope dependence on wind speed. The functional relationship is presented here to make clear how the SPD was changed to allow a new set of wind speed retrievals to compare with other data.

[36] The version of the software for the GPS receiver capable of generating a high signal to noise ratio data stream and tracking only very high elevation angle satellites was running during P-3 aircraft number N42RF flights into Hurricane Dennis in July of 2005. Flight level winds as well as data from one of the SFMR were taken during this flight.

[37] Shown in Figure 2 is a three-way comparison of flight level winds (FLW,) SFMR retrievals and GPS reflection-based wind retrievals using the function described in equation (4). Figure 2 represents three passes through the eye of Hurricane Dennis while it was south of Cuba. The y-axis is in meters per second, while the x-axis is GPS time of the week in seconds.

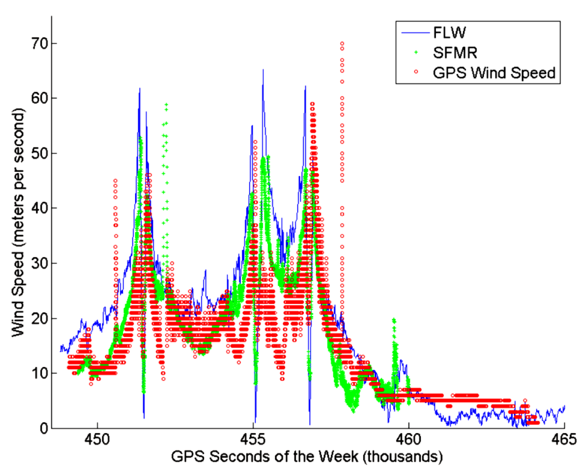

Figure 2. Comparison of flight level winds, Step Frequency Microwave Radiometer, and GPS wind speed retrievals for Hurricane Dennis July 8, 2005.

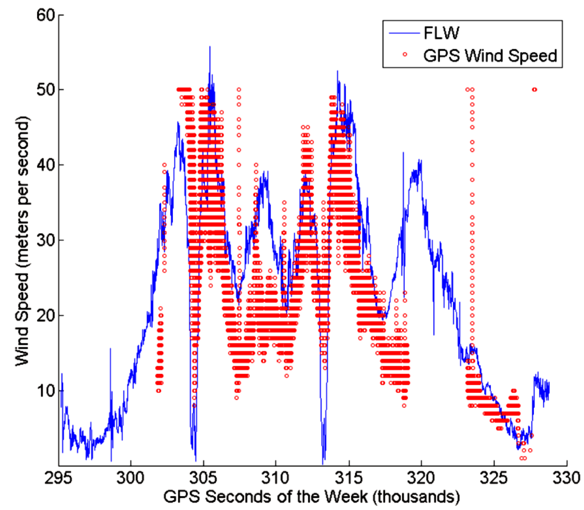

Figure 3. Comparison of flight level winds and GPS retrievals for Hurricane Isabel, September 16, 2003.

[38] The spikes in the GPS data are generally associated with extreme changes in altitude of the P-3. The spike in the SFMR and dip in the GPS retrieval comes from the aircraft passing over a peninsula along the south Cuba coast, making the retrieval meaningless.

[39] It is clear in this example that use of equation (4) for the mean square slope creates retrieved winds similar in pattern as well as maximum strength to that from flight level or SFMR. The difference in detail is yet to be understood, but it should be noted that while high elevation satellites were selected, the data that they receive are not directly under the aircraft, and in fact can come from a kilometer or so off from the aircraft nadir point, depending on the specific satellite and aircraft altitude. One should note that in the examples presented here the model function used was generated from Hurricanes Ophelia and Rita data sets and has been applied to a completely different storm (Dennis).

[40] Older data have also been rerun with the model mss relationship. Shown in Figure 3 are data from Hurricane Isabel in 2003 compared to flight level winds. No SFMR data were available for this flight. The data for this flight came from earlier versions of code that did not ensure that the data from the highest elevation satellite were recorded so Figure 3 includes data from satellites down to 30 degrees elevation.

4. Conclusions

[41] Previous retrievals of wind speeds from tropical storms and other high wind speed regimes have shown underreporting of wind speeds. This paper has demonstrated that the likely cause is a reduction in the slope of the dependence of surface mean square slopes on wind speed and that the surface slope remains unsaturated up to hurricane force winds. It has been shown that a functional form for the apparent (L-band) ocean surface mean square slopes can be found that describes high wind speed conditions for GPS surface reflection wind speed retrievals. While this relationship must be considered provisional, it

demonstrates that GPS reflected signals can be used to produce wind speed retrievals that capture the form and intensity of winds in tropical storms with winds in excess of 60 meters per second (120 knots).

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