7.4 GPS-Based Measurements of Ocean Surface Roughness

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1. **INTRODUCTION:** Recent results have shown that the GPS reflection technique can be used to provide surface wind speed retrievals whose maximum value is consistent with techniques such as scatterometers, flight level winds, microwave radiometers, and dropsondes (Katzberg, *et al*. 2006) The importance of this investigation rests on the nature of the GPS systems: Inexpensive and small in size, they are eminently compatible with flight platforms such as UAV's. Use of such combinations can materially enhance the frequency of storm sorties while simultaneously virtually eliminating human risk. While the success of the GPS technique enhances the toolbox for remote sensing of the ocean, certain questions remain: The GPS retrieved winds are not necessarily a perfect spatial match with the spatial dependence of the other techniques. For example, flight level winds or SFMR might show a strong wind then low wind in the storm eye and then a strong eye wall wind in a transect of the storm. The GPS technique might show a strong exit wind and weak entrance wind, or vice versa. While the overall patterns are highly correlated, the wind intensity of the storm might show important disagreement in structure.

This paper will show some results of using the bistatic measurement of ocean surface roughness to infer wind speed. It will be shown that even at wind speeds approaching 60 meters per second, the surface slopes are continuing to increase. The relationship of the bistatic technique to altimetry-based wind speeds will be discussed and as will congruency with microwave radiometer techniques. It will be shown that the GPS technique inherently provides measurements of multiple geophysical parameters related to air-sea interaction.

2. **GPS BACKGROUND:** The GPS technique operates by measuring the radio frequency signal reflected from wind-driven ocean surface facets. The ocean's high reflectivity to L-band radiation is made use of by recording the power from the surface. The range coding of the GPS signal can be used to record signals originating from elliptical areas (circular areas, at normal incidence.) These elliptical areas, shown in Figure 1, can be shown to originate from increasing time delay and can be presented as a reflected "power-versus-delay" using a properly modified GPS receiver and nadir-looking antenna. From electromagnetic scattering theory (Beckmann, 1987), it can also be shown that the signal appears to originate from facets on the surface in a particular elliptical area which have the proper orientation to reflect the incoming electromagnetic field back to the nadir-viewing antenna. The filling of the range bins is governed by the slope probability function for ocean surface waves.

Recording the "power-versus-delay" is equivalent to measuring the slope probability function averaged over the elliptical areas on the surface. Comparing the recorded signals with model waveforms, properly calibrated, allows for retrieval of surface wind speeds (Garrison, *et al.*, 2002).

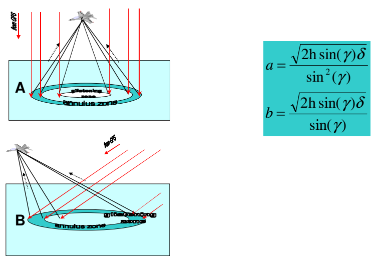


Figure 1 Locii of points corresponding to the same time delay projected onto the surface. The size of the semi-major axis (a) and semi-minor axis (b) is given in the box.

An example of the model waveform for 5 and 10 m/s is shown in Figure 2. Each range delay projects onto the surface as an annulus within which signals will be recorded. These annular rings also subtend a range of required surface slope angles, increasing monotonically with delay. Thus, the "power versus delay" data is a measured form of the slope probability function in terms of time delay and surface coordinates. Under the assumption, and it is an important assumption, that the surface reflectivity remains constant with wind speed, the sum of all the power versus delay is a constant with wind speed.

3. **OTHER TECHNIQUES:** Currently employed techniques for tropical cyclone wind speed determination are *in situ* (buoys, ship observations, etc.), GPS dropsondes, aircraft-derived flight level winds, scatterometers, and microwave radiometers.

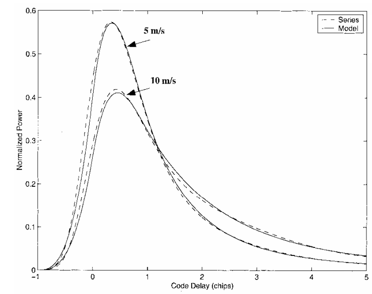


Figure 2 Example of model waveforms used in wind speed retrievals for reflected GPS. Each Code Delay Chip represents a 300 meter range bin. On the surface each chip or part of a chip defines an annulus from which signals can originate and be detected.

3.1. **Dropsondes-** Dropsondes are small packages which are typically deployed from an aircraft and contain a GPS receiver. The receiver transmits Doppler shifts in the detected satellite frequencies back to the aircraft, which in turn give both components of the sonde's velocity. Accuracies of the sondes wind speed measurements are quoted by the manufacturer as ± 0.5 m/s but some results have suggested no better than ±2.0 (Yueh, *et al.*.) Nevertheless dropsondes are considered the gold standard for wind speed determination from research aircraft. Only buoy wind measurements are more trusted.

3.2. **Flight Level Winds-** Flight level winds are determined by measurements of true airspeed and ground track which are solved to yield wind speed at the aircraft altitude.

3.3. **Scatterometers-** Derive their wind speed measurements in a fashion relatable to the GPS technique. While the GPS approach is described as "bistatic" with a separate transmitter and receiver locations, scatterometers use collocated transmitter and receiver and are described as "monostatic". (Altimeters can also yield wind speed by carefully measuring the return signal compared to the transmitted one.)

A bistatic configuration would find its strongest signals near the specular point, almost always the location for strong signals, while the scatterometers cannot view the specular point and must receive their signals from surface roughness facets in the tail (and least well known part) of the slope probability function.

Scatterometers use a short pulse of radiation to define a surface range cell in one dimension and antenna size to define resolution in another.

3.4. **Microwave Radiometers-** Currently the most used method for obtaining with surface wind speeds from aircraft, radiometers make use of emitted microwave radiation from the ocean. Water has a low emissivity at L-band frequencies and appears very cold to the radiometer. With increasing wind speed, the surface emissivity increases and the ocean emits more radiation. Wind speed is determined by calibration of the change in apparent ocean temperature ("brightness temperature") with wind speed.

Simple changes in ocean roughness do not appreciably affect emissivity, and the supposed mechanism is believed to be the increase in wind-driven surface foam which increases emissivity (Uhlhorn, *et al.*, 2003). The Hurricane Research Division of NOAA has supported the development and calibration of one particular implementation of the microwave radiometer, called the Step Frequency Microwave Radiometer, SFMR, (Uhlhorn, *et al.* 2003) multiple frequencies are required to separate rain effects from surface emitted wind effects. Ocean surface temperature is also required for retrieval.

Surface resolution is set by antenna gain pattern and can be expressed as:

Equation 1 $$d = 2.44 \cdot \frac{\lambda}{D}$$

Where d is the diameter antenna gain pattern (Airy disk) on the surface for an antenna of aperture D and wavelength λ. For the SFMR, the surface resolution is on the order of 24 degrees, which yields a spot size of approximately 1.25 km when flying at a typical 3 km altitude.

Resolution degrades linearly with altitude, so microwave radiometers with high surface resolution are best suited to aircraft platforms. Scatterometers with the transmitted pulse width setting one dimension of resolution are less sensitive to altitude as far as resolution is concerned and easier to accommodate at spacecraft altitudes.

For the GPS bistatic approach, the "resolution" is not by antenna size, which can be quite small, but by the area on the surface from which the "power-versus-delay" arises. The area on the surface with appreciable signal level for a 20 meter per second wind would be approximately 1.7 km at 3 km altitude.

4. RECENT RESULTS FOR GPS AND COMPARISON WITH SFMR AND FLIGHT LEVEL WINDS

4.1. **Calibration of the GPS technique for high wind speeds**

The GPS technique has only recently appeared as a remote sensing technique for tropical storm monitoring and was flown into a hurricane in year 2000 for the first time. The conditions for GPS data acquisition are highly restricted, without an in-flight operator. Software problems are identifiable only at the expense of loss of the already limited number of missions and the lack of an onsite collaborator. Nevertheless, better understanding of the performance parameters have led to improving data sets taken in 2003 and then in 2005.

Data sets acquired during this recent period have been the subject of intense analysis and comparisons with other wind speed data such as flight level winds and dropsondes have been done. In 2005 an SFMR was added to the aircraft on which the GPS has flown (N42RF) providing another wind speed retrieval source for comparison.

Retrieval techniques described earlier in which idealized waveforms were compared with data taken from the GPS instrument had been shown to match buoy and other measurements (Garrison, *et al.,* 2002). Nevertheless, virtually all of the data used for verification purposes has been taken at wind speeds below 15-20 m/s. When data sets from year 2000 and later were compared to flight level winds and other information sources at tropical storm and hurricane force levels, the retrievals were invariably too low.

Close investigation of the measured data and the model waveforms confirmed that end-to-end processing was being done properly. One underlying assumption was being relied upon without confirmation of validity: The slope probability function. The slope probability function was assumed to be that developed by Cox and Munk (Cox and Munk, 1954). This function is a modified bivariate Gaussian with a standard deviation (mean square slope or variance) dependent on wind speed. Corrections to account for the L-band radiation instead of the optical measurements of Cox and Munk were made as well as simplifying the modified bivariate Gaussian. Wind speed retrievals based upon this model were shown to give excellent agreement with surface truth.

The slope variance's dependence on wind speed was determined by Cox and Munk to be linear (possibly a non zero constant and linear slope.) The wind speeds over which this linear dependence was developed were below 20 meters per second. There is reason to believe from other research that the mean square slope is not linear and has an upper limit.

The assumption of linear mean-square-slope on wind speed was reexamined in 2005 by using a novel approach to calibration (Katzberg, *et al.*, 2006). The results of this study showed that not only was the linear relationship invalid, but that using the updated empirical function yielded competitive wind speed retrievals.

One major condition that was set for the data sets was that the elevation angle of satellites be very high, as close to Zenith as possible. This was done to eliminate the effects of anisotropy in the slope probability density with respect to wind direction. Anisotropy can be used to determine wind direction, but introduces a second parameter in the calibration which is as yet not very well known.

5. Examples from Hurricanes Isabel and Dennis

The data sets prior to 2005 were generally at low elevation angles and with artifacts in them that limited their usefulness. For example, the GPS receivers, run without operator intervention, would be turned on while waiting for takeoff which could last for an hour or more. The satellite being recorded would drop to a low elevation angle and not be automatically replaced by a high angle one. Occasional loss of lock on the reference satellites tracked from the top-looking antenna would cause restart of the satellite tracking, and a drop-out data. Experimental software of one or another type, required to establish best operation, was tried and rejected, necessarily sacrificing more data opportunities.

In the past the most extensive "surface truth" was actually extrapolated "flight level data." Dropsondes also provide data but are extremely limited in numbers deployed. In 2005 an SFMR was added to N42RF on which the GPS was mounted and a much better remote sensor for comparison became available.

For these reasons, only a few data sets prior to 2005 gave very good results and in any case had anything to compare against. One of these is presented to illustrate the success of the re-calibration process.

Isabel 2003- An example of retrievals from hurricanes that compare well with other data sources even at fairly low elevation angles is Hurricane Isabel from September 16, 2003.

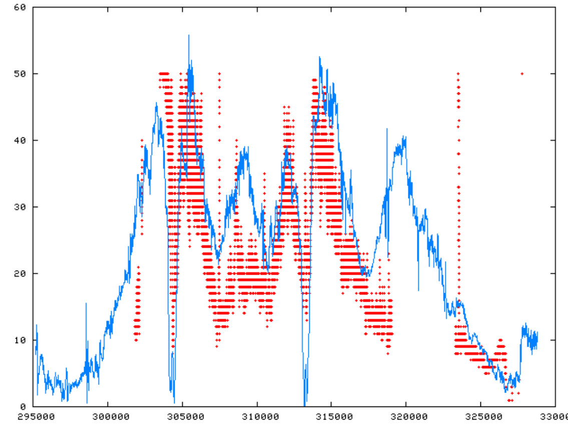
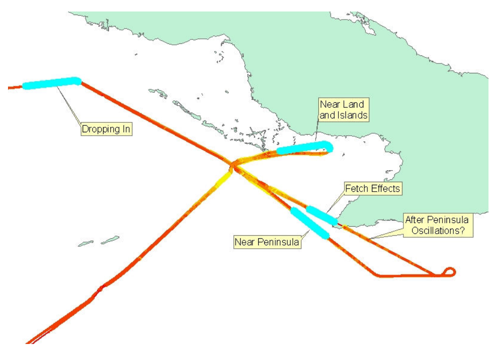


Figure 3

Dennis 2005- Hurricane Dennis has provided perhaps the first data sets that illustrate the true potential of the GPS technique and allow a detailed look at what surface parameters actually control the bistatic technique. The storm was south of Cuba in the Golfo de Guacanayaboa shown in Figure 4

Dennis July 8, 2005



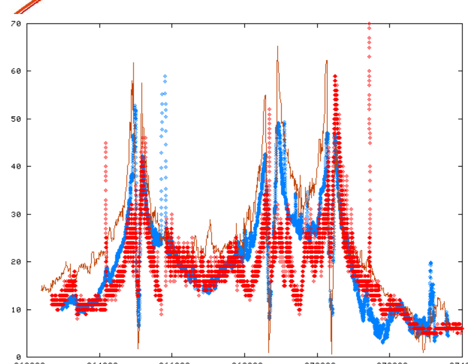
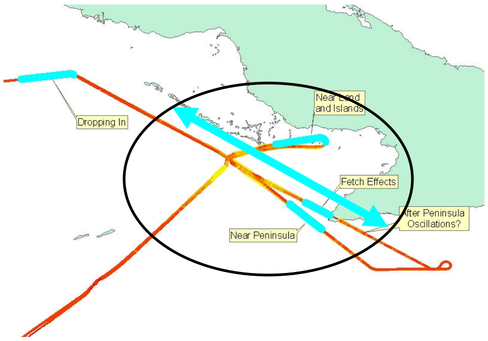


Figure 4 Hurricane Dennis July 8, 2005 south of Cuba. The highlighted tracks represent areas of interest for this paper.



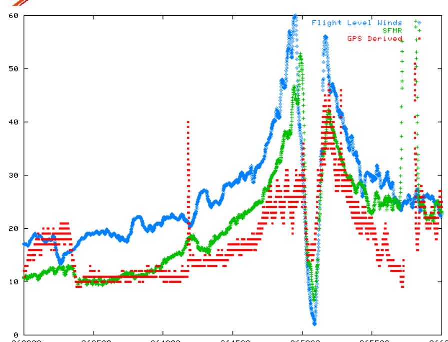
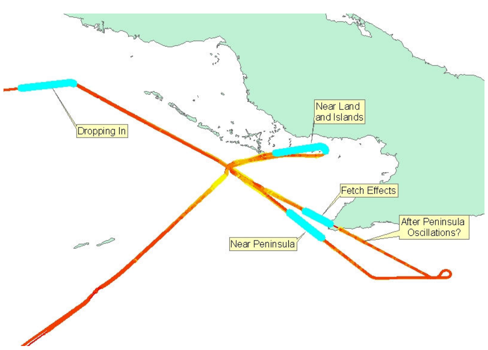


Figure 5 Flying into the storm. Large spike at right is effect of land (peninsula) on GPS and SFMR where no retrieval is possible.



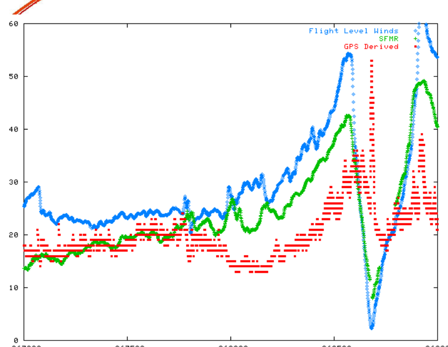
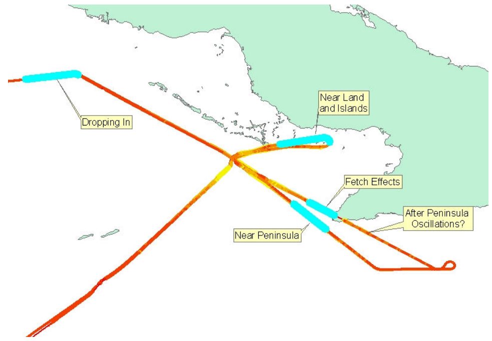


Figure 6 Second pass into storm (Near Peninsula) GPS retrieval is significantly lower than Flight Level or SFMR wind speeds.



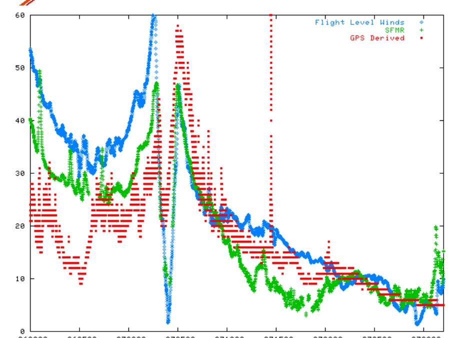


Figure 7 Near Cuban coast, behind islands, through the storm again and out to the southwest to open sea.

Dennis July 9, 2005

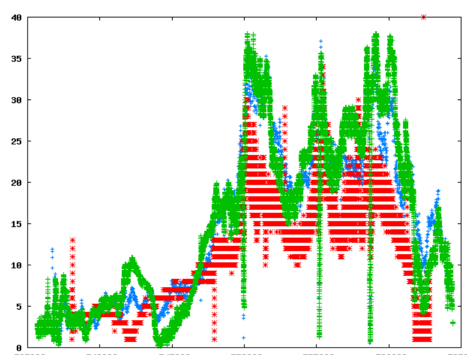


Figure 8

Dropping in

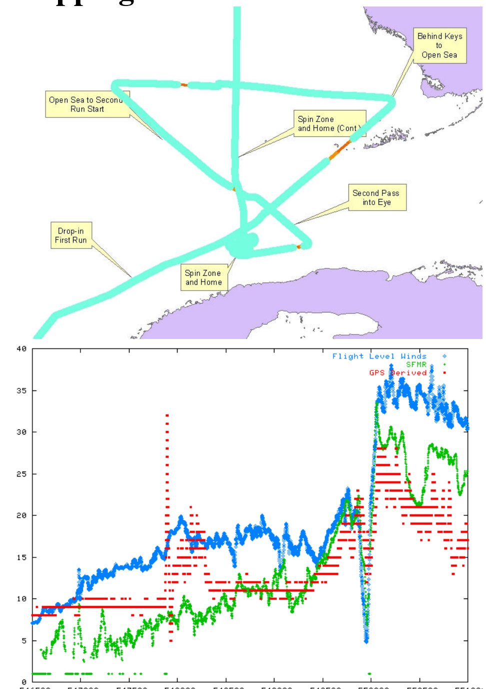


Figure 9 Aircraft Dropping In from cruise altitude to near 3 km and First Pass through storm.

Behind Florida Keys to Open Sea

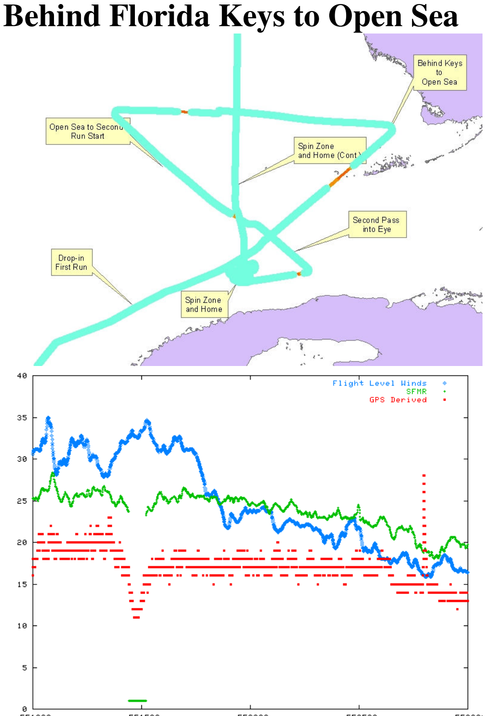


Figure 10 Behind Florida Keys showing differences between GPS, SFMR and Flight Level Winds. Major effect might be fetch from the Keys, but this is yet to be determined.

Open Sea to Start of Second Run

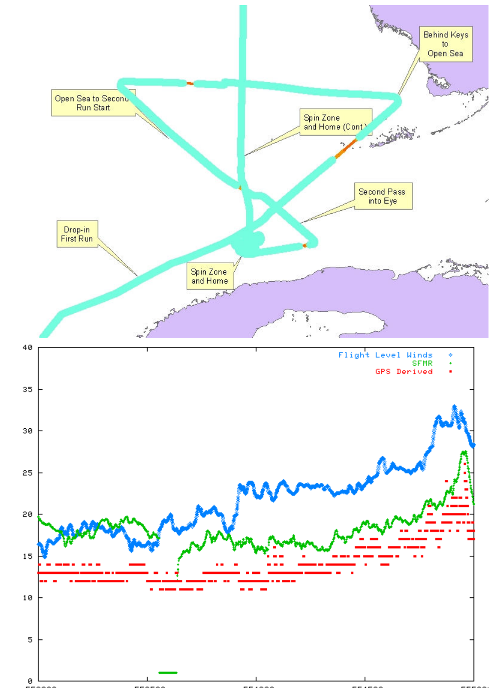


Figure 11 Out to sea from behind the Keys to start of second run.

Second Pass into Eye

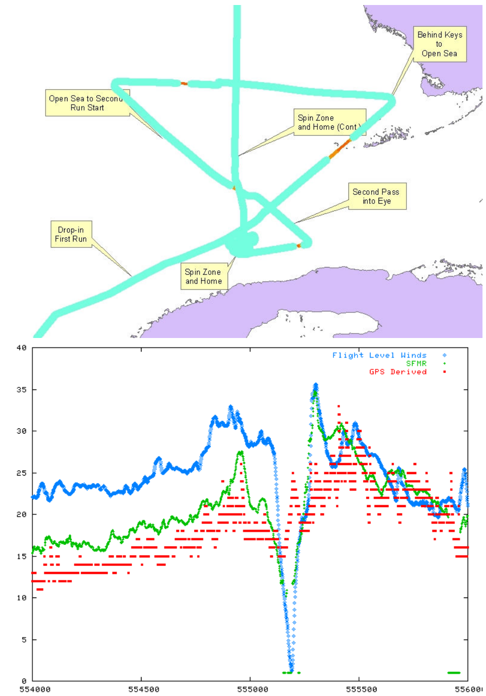


Figure 12 Second pass into Dennis, July 9, 2005

It can be seen that the GPS wind speed retrievals generally track the light level winds and SFMR; however there are areas of sometimes large differences. Not that the flight level winds and SFMR always agree, they generally do not in detail. In fact it has been a subject of considerable Hurricane Research Division study to relate flight level winds to surface (generally 10 meter) values and it is well understood that flight level winds can be misleading. Flight level winds are typically taken at 3 km altitude and extrapolated to the surface with some scale factor. Scale factors of 80%-90% are currently the suggested range of reduction factor depending on pressure altitude (Ref **7**.)

The SFMR has undergone considerable calibration and is being installed on the Air Force C-130 Hurricane Hunters as well as the NOAA P-3's. As noted earlier, the SFMR operates on the basis of increased emissivity of the ocean surface under the influence of increased wind speed. It is not surprising that the SFMR retrieval does not necessarily match the (scaled) flight level winds inasmuch as the flight level winds do not necessarily match surface winds.

In summary, the SFMR and Flight Level Winds show a strong correlation in wind speed strength and spatial structure, but do not and should not agree in detail. Each results from different geophysical processes. The GPS retrievals result from still a third process and the nature of that process and its relation to wind speed retrievals is the subject of this study.

7. RELATION TO AIR SEA INTERACTION. With respect to studies of air-sea interaction, the GPS offers not only a direct measurement of apparent ocean surface roughness, but also two other modes relatable to other techniques. Two important characteristics of having a "power-versus-delay" measurement are discussed in the Appendix. These bear directly on both altimeter measurements of wind speed and those of radiometers.

Altimeters- While the GPS technique does not appear to share any obvious relationship with altimeters, the condition where the GPS satellites are at very high elevation angle represents a similar configuration. Altimeters are useful for ocean surface studies in addition to ocean topography. The scattering cross-section which is commonly produced from altimeters can be related to the ocean surface mean-square-slope by (Barrick, 1968)

Equation 2 $$\sigma_0 = \frac{|R(0)|^2}{s_f^{\;2}}$$

This relationship is the foundation for wind speed retrievals from altimeters such as TOPEX, Jason and others.

On the other hand, it is shown in the Appendix that for a sufficiently wide slope probability density, the "power-versus-delay" after two code chips of delay yields the same measurement. In fact, since any elevation angle for the GPS receives its maximum signal for near normal slopes on the surface, under proper experimental conditions, measuring the reflected power can give a measurement of reflectivity and mean-square-slope. (See equation A.5).

Microwave Radiometers- The controlling physical parameters of radiometers are temperature and emissivity. Reflectivity is 1-ε, where ε is emissivity. The GPS technique provides both incoming signal power and reflected power. As shown in the Appendix, again under proper experimental conditions, summing all the power in the "power-versus-delay" is equivalent to integrating the slope probability density. With other things being held constant, reflectivity is produced.

Using the GPS technique, therefore, another view of the ocean surface is possible to study the surface layer that produces the stimulus to which microwave radiometers such as the SFMR respond. For example, there is reason to believe that the ocean surface becomes an emulsion at very high wind speeds (Emanuel, 2003).

It is known that an emulsion (air and water) will result in a transition between the unity dielectric constant of air and the very high dielectric constant of water (~80). Such a transition would manifest itself as a lowered reflectivity (and enhanced emissivity.) Shown in Figure 13 is an example of adding the range bins together. It can be seen that this estimate proportional to reflectivity is strongly anti-correlated with wind speed. While by no means conclusive, one explanation for the results is reduced reflectivity (increased emissivity) at the higher wind speeds. Current GPS reflection hardware is very limited, so to fully investigate the previous conclusion must await enhancement of the technology.

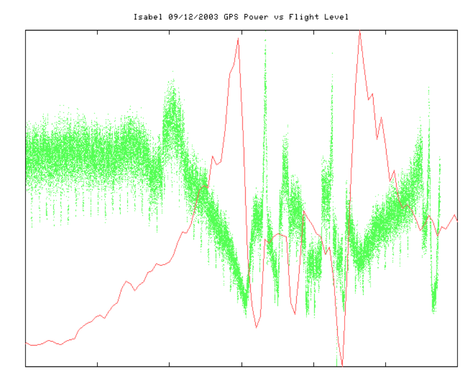


Figure 13 Summation of all range bins for GPS power-versus-delay in Hurricane Isabel, 2003, to show anti-correlation with Flight Level Wind determination.

8. CONCLUSIONS. This paper has presented some recent results in use of bistatic remote sensing for ocean surface winds. The technique utilizes signals from GPS satellites reflected from the ocean. The successful generation of wind speed retrievals from the ocean surface confirms the theoretical considerations identify ocean surface slopes as the parameter being measured. It has also been shown how the GPS technique relates to other sensors used to study ocean surface properties. Measurements of surface reflectivity, slope probability density and means-square-slope can be gotten by properly setting experiment parameters. The GPS technique is simple, very light and easily accommodated on even the smallest of aircraft platforms, including UAV's. The technique opens new opportunities for study of interaction of air and ocean.

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Appendix

For the case of isotropic Gaussian

$$\left\langle \left| E_2 \cdot E_2 * \right| \right\rangle = \left| \mathcal{R} \right|^2 \frac{\pi k^2 E_0^2}{(\pi)^2 R_0^2} \frac{[1+\cos(\theta_1)\cos(\theta_2)-\sin(\theta_1)\sin(\theta_2)\cos(\theta_3)]^2}{k^2(\cos(\theta_1)+\cos(\theta_2))^4} \frac{T^2}{(2\sigma)^2} \exp\left(-\frac{v_{xy}^2 T^2}{4 v_z^2 \sigma^2}\right) \cdot \delta A$$

distributed surface slopes, the scattered power density is given by (Beckmann 1987):

A. 1

Or, eliminating the redundant terms gives:

A. 2

$$\left\langle \left| E_2 \cdot E_2 * \right| \right\rangle = \left| \mathcal{R} \right|^2 \frac{E_0^2}{R_0^2} \frac{[1+\cos(\theta_1)\cos(\theta_2)-\sin(\theta_1)\sin(\theta_2)\cos(\theta_3)]^2}{(\cos(\theta_1)+\cos(\theta_2))^4} \frac{T^2}{\pi(2\sigma)^2} \exp\left(-\frac{v_{xy}^2 T^2}{4 v_z^2 \sigma^2}\right) \cdot \delta A$$

The term $\frac{v_{xy}^2}{v_z^2} = \frac{v_x^2 + v_y^2}{v_z^2}$ represents the two dimensional slope random variables in x and y and gives the factor $\frac{T^2}{\pi(2\sigma)^2}$ multiplying the exponent. This factor is the normal scaling factor for a two dimensional Gaussian distributed random variable.

The total power density from the surface at the receiving antenna is then found by integrating over an area on the surface defined by the receiver range-code aperture function and any antenna response pattern:

A. 3

$$\left\langle \left| E_2 \cdot E_2 * \right| \right\rangle = \mathcal{K} \cdot \left| \mathcal{R} \right|^2 \cdot \iint \frac{T^2}{\pi(2\sigma)^2} \exp\left(-\frac{v_{xy}^2 T^2}{4 v_z^2 \sigma^2}\right) \cdot \Lambda^2\left(\delta + \delta_0 - \frac{r(x,y)}{c}\right) \cdot \mathcal{A}((x,y)\, dxdy$$

Where now $\mathcal{K}$ represents the group of constants from A.2, the Λ function is defined as

A. 4

$$\Lambda(x) = \left(1 + \frac{x}{T_c}\right) \qquad x \geq -T_c$$

$$\Lambda(x) = \left(1 - \frac{x}{T_c}\right) \qquad x \leq T_c$$

and $\mathcal{A}$ is the antenna far-field pattern.

The Λ function is the result of the GPS range-coding and constrains the range of delays to which the receiver is sensitive. Projected onto the surface, the Λ function creates the elliptical surface areas capable of being recorded at any particular delay setting.

The delay, δ, represents the excess delay between the signals directly arriving at the upward looking antenna compared to that from the (collocated) downward looking antenna. The other delay, δ_0, accounts for the fact that the signal from the surface actually begins giving a non-zero correlation response one code chip before perfect overlap with the incoming direct signal.

As can be seen from equation A.3, should the slope probability function become significantly wider than the Λ-function, the scattered power for delay bins greater than two code chips (600 meters) would be proportional to:

A. 5 $$\frac{|\mathcal{R}|^2}{\sigma^2(U)}$$

Where U is wind speed.

On the other hand, the summing of power from the range bins, if the bins are sufficiently narrow with respect to the slope probability density, is tantamount to integrating a probability density. The result would be a constant times the reflectivity of the surface.