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Wave Heights during Hurricane Katrina: An Evaluation of PPP and PPK Measurements of the Vertical Displacement of the GPS Antenna

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NOTES AND CORRESPONDENCE

Wave Heights during Hurricane Katrina: An Evaluation of PPP and PPK Measurements of the Vertical Displacement of the GPS Antenna

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ABSTRACT

In August 2005 the eye of Hurricane Katrina passed 49 n mi to the west of a 3-m discus buoy operated by the Central Gulf of Mexico Ocean Observing System (CenGOOS). Buoy motions were measured with a strapped-down 6 degrees of freedom accelerometer, a three-axis magnetometer, and a survey-grade GPS receiver. The significant wave heights were computed from the buoy's accelerometer record and from the dual-frequency GPS measurements that were processed in two different ways. The first method was postprocessed kinematic (PPK) GPS, which requires another GPS receiver at a fixed known location, and the other was precise point positioning (PPP) GPS, which is another postprocessed positioning technique that yields absolute rather than differential positions. Unlike inertial measurement units, either GPS technique can be used to obtain both waves and water levels. The purpose of this note is to demonstrate the excellent reliability and accuracy of both methods for determining wave heights and periods from a GPS record. When the motion of the GPS antenna is properly understood as the motion of the buoy deck and not the true vertical motion of the sea surface, the GPS wave heights are as reliable as a strapped-down 1D accelerometer.

1. Introduction

The University of Southern Mississippi (USM) deployed a 3-m discus buoy in the Mississippi Bight (see Fig. 1) on 14 December 2004 near the 20-m isobath. The buoy was one element of a research project that evaluated the feasibility of extending the range for which the postprocessed kinematic (PPK) global positioning service (GPS), and by extension the real-time kinematic (RTK) positioning, could be used in the marine environment for subdecimeter horizontal and vertical positioning (Bender et al. 2010, hereafter BEN). The buoy had three instruments for measuring motion: a survey-grade GPS receiver, a solid-state 6 degrees of freedom strapped-down inertial measurement unit, and a high-quality aviation-grade three-axis magnetometer. This presented the opportunity for directly comparing wave heights computed from a 3D accelerometer against wave heights computed from GPS measurements. From a moored buoy the GPS vertical positions either can be used for water-level monitoring, from which tides and other long-period signals, such as surges, can be obtained (S. D. Howden et al. 2010, unpublished manuscript), or the higher-frequency signal can be used for wave measurements.

On 29 August 2005 at approximately 1400 UTC the eye of Hurricane Katrina passed 49 n mi to the west of the USM buoy's location (Fig. 1). The GPS receiver on the buoy operated continuously through the storm, but the base station at nearby Horn Island was disabled

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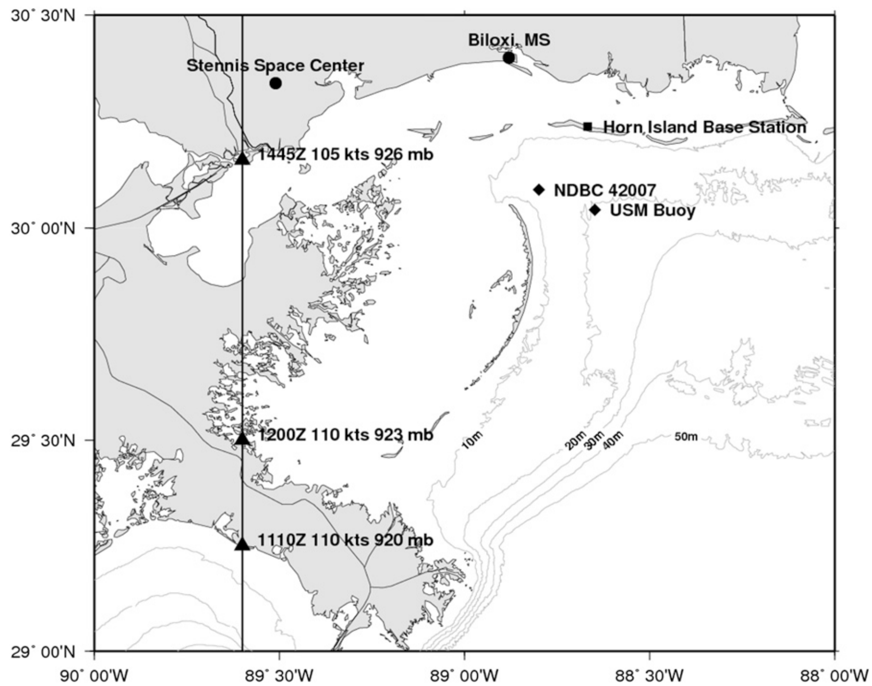

FIG. 1. Location of the USM buoy in the Mississippi Sound and the path of Hurricane Katrina on 29 Aug 2005.

by the storm at 0727 UTC 29 August. The ability to obtain precise vertical positions of the buoy using PPK positioning was lost at this point. However, a newer absolute postprocessing GPS positioning technique, termed precise point positioning (PPP), does not require a base station receiver and can yield kinematic vertical positions at the subdecimeter level (e.g., Kouba and Heroux 2001). Harigae et al. (2005) investigated the use of a low-cost 3D GPS receiver in floating buoys in order to replace higher-cost accelerometers used by the Japanese Meteorological Agency. Using a moored slope-following discus buoy as a test platform, they found that the PPP-derived wave heights coincided very well with that of the accelerometer, but there were little specific details on whether the data were corrected for buoy tilt. The issue of whether a GPS wave buoy is cheaper than an accelerometer buoy remains to be seen, especially when the cost of system integration is considered. The advantage of a GPS system is that it is more widely used, and understood, than accelerometers. This means there will be more opportunities to measure waves with GPS buoys.

Past concerns about selective availability (SA) being activated in time of war and rendering a GPS-based wave system inoperable are no longer an issue following the President's proclamation on 18 September 2007 that SA will not be part of the newer-generation GPS satellites. This means that there is a strong commitment by the U.S. government to the civil users of GPS data who can count on the present GPS accuracy being available at all times.

The buoy's system design, electronics, and sensor integration were done independently by the Geochemical and Environmental Research Group (GERG) at Texas A&M University and are fully described in BEN. Meteorological data during Hurricane Katrina are described by Howden et al. (2008). BEN describes the instrument setup of the buoy, the motion sensor data obtained, and the methods used to process the PPK GPS measurements and the accelerometer data into significant wave heights and periods. All of the motion sensors operated through the storm and the raw data were saved on board the buoy's computer to be retrieved when the buoy was recovered on 20 September 2005.

In this paper we use the dual-frequency PPP GPS positions to extend the GPS wave record through the entire storm, something that was not possible in BEN, and we demonstrate that the atmospheric moisture retrieval algorithms are accurate through a hurricane. We also show that the motion of the GPS antenna is not necessarily the motion of the sea surface, unless the antenna is at the center of motion of the buoy. Understanding this difference is critical to understanding what the wave heights really mean. To accomplish these goals, the significant wave heights, peak periods, and mean periods are compared amongst the three different methods: accelerometer, PPK, and PPP.

2. Data

The buoy was equipped with three instruments to measure three-dimensional motion, a Crossbow IMU 400CC inertial measurement unit, a Honeywell HMR compass, and a Novatel OEM4-g2 GPS. A PC104 UNIX-based central computer directed the sampling strategy and saved the raw data to an onboard hard drive, which were retrieved after the buoy was recovered. The data available for this study covered the first 20 min of every hour from 26 August through 1 September 2005.

The Crossbow IMU 400CC is a solid-state inertial measurement unit designed to measure the linear acceleration along three orthogonal axes and the rotation rates around the same three orthogonal axes. The unit was not gimbaled, but was mounted (strapped down) inside the system controller housing within the instrument well of the buoy. The instrument has an update rate of greater than 100 Hz, but it was subsampled to 4 Hz. The subsampled data were time stamped by the buoy's central computer as the data were saved to the database.

The Honeywell HMR 3300 digital compass is a solid-state three-axis, magnetometer-based compass that uses an internal two-axis accelerometer for enhanced operation. This electronically gimbaled compass gives accurate headings even when the compass is tilted at 60°. The compass is capable of data rates up to 8 Hz, but was subsampled to 4 Hz. The subsampled heading, pitch, and roll data were time stamped by the central computer after the data were acquired. This orientation data were used to correct the acceleration data for pitch and roll, but it could not be used to correct the GPS data because of unresolved synchronization issued between the two instruments. Additional details of the Crossbow accelerometer and the Honeywell compass are found in BEN.

The survey-grade GPS receiver was a parallel 24-channel, dual-frequency Novatel OEM4-G2 GPS. Dodd et al. (2006) show how a time series of the three-dimensional positions of the GPS antenna on the buoy was determined using PPK techniques on the 1-Hz dual-frequency data logged on both the buoy and a GPS receiver that was located on Horn Island, about 20 km to the north of the buoy. Although the GPS receiver on the buoy logged data throughout the storm, the PPK positions could only be processed through 0700 UTC 29 August 2005, after which time the battery bank for the Horn Island base station was washed into the Mississippi Sound. Positions computed using PPP, on the other hand, do not rely on information from a dedicated reference receiver. It is a technique where the absolute vertical uncertainty from a single Global Navigation Satellite System (GNSS) receiver is several decimeters or less (e.g., Ovstedal et al. 2006), but the epoch-to-epoch relative uncertainty (precision) is likely to be much better.

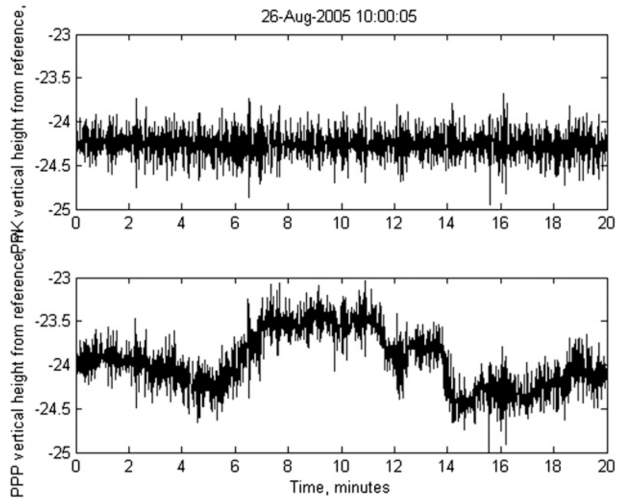

FIG. 2. The (top) PPK and (bottom) PPP record at 1000 UTC 26 Aug 2005 showing the low-frequency error signal and jumps in the PPP signal.

3. Processing

One-dimensional displacement spectra, which contain information about the significant wave height, peak period, and mean period, were calculated from the accelerometer data and from both the PPK and PPP GPS vertical displacement data.

a. Accelerometer

The specific details of how the accelerometer data were processed are discussed in BEN. In brief, the first step was to determine which of five different methods would be used to remove the effects of gravity from the data and orient the strapped-down accelerometer data from the buoy frame, which is moving, to a vertical reference frame. The acceleration data were then processed to remove outliers, followed by a Kalman filter to remove instrument and process noise. The acceleration spectra of the filtered data were calculated as the fast Fourier transform (FFT) of the vertical displacement data. The details of the segmenting and windowing are described in BEN. A frequency domain filter was applied to the acceleration spectra in order to remove spurious low-frequency noise. The acceleration spectra were then converted to the acceleration spectra. The significant wave height, peak period, and mean wave period were determined from the displacement spectra using the definitions provided on the National Data Buoy Center (NDBC) Web site (see National Data Buoy Center 2008).

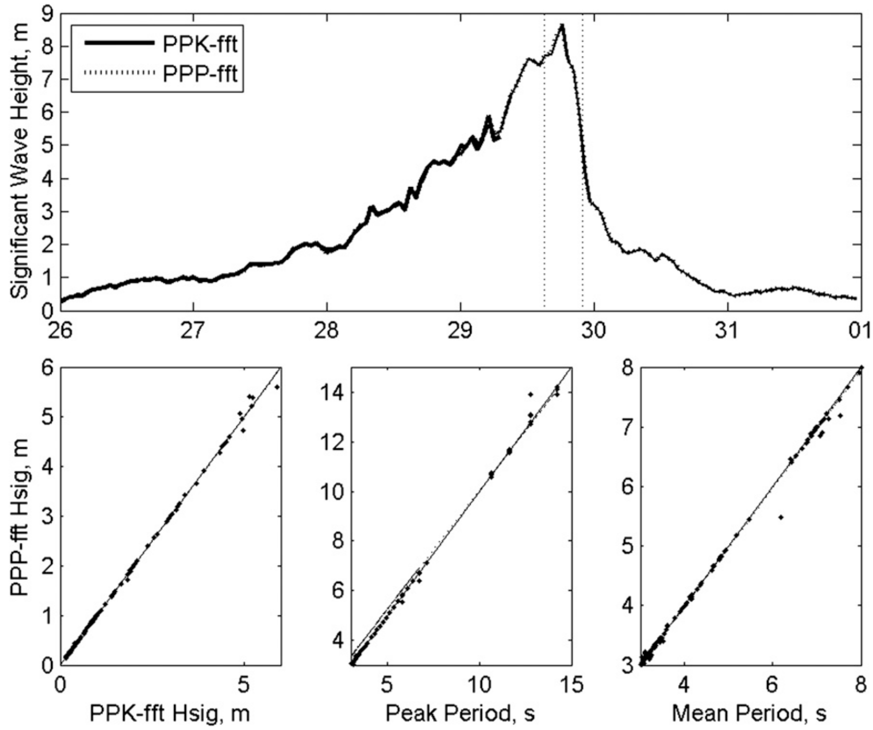

FIG. 3. (top) The time series of the FFT spectra determined significant wave heights for the PPP and PPK measurements for the period from 26 Aug through 1 Sep. As noted in the text the PPK measurements cease at 0727 UTC 27 Aug, but the PPP measurements continue through the storm. The vertical dotted lines denote the time period the buoy was moving, as described in BEN. (bottom) The scatterplot of the significant wave height, peak period, and mean period for the PPK (horizontal axes) and the PPP (vertical axes).

Of the five possible correction methods for acceleration data outlined in BEN, we used the deck-relative acceleration (method II) and the earth-referenced vertical acceleration (method V) to correct for gravity and buoy tilt. The true deck-relative acceleration in method II gives the vertical motion of the buoy deck, which is most similar to the motion of the GPS antenna. The antenna is located approximately 380 cm above mean water level, offset by approximately 60 cm from the center of the buoy, and at a clockwise angle of 30° relative to buoy north. As a result of this lever arm the GPS displacement data reflect a combination of the heave of the buoy and its pitch and roll, which is what either a strapped-down 1D accelerometer measures along its main axis or a 3D accelerometer measures along its z axis.

The earth-referenced vertical acceleration method V uses the accelerations from all three axes of the Crossbow accelerometer, as well as the pitch-and-roll information from the Honeywell compass, to correct for the motion of the buoy and obtain the earth-referenced accelerations of the buoy. Direct comparison of this acceleration data to the GPS data was complicated by the fact that it simply was not possible to precisely synchronize the pitch-and-roll data with the GPS data. The HMR and the GPS are two separate instruments, each with its own time stamp. The HMR utilizes the buoy's computer, which was not synched to the GPS; the GPS uses the satellite signal, which has a multisecond difference. Attempts to understand what the time offset there was between the two were unsuccessful. Unfortunately, a time lag of just 0.25 s makes a significant difference in the pitch and roll of the buoy during storms.

TABLE 1. Statistical parameters for significant wave height scatterplots.

Comparison	Slope	Scatter index (%)	Bias (cm)	Rmse (s)	r^2 correlation
PPP-fft vs PPK-fft	1.001	3.57	0.03	4.45	0.999
PPP-hmo vs PPP-fft	0.999	1.79	2.69	3.97	0.999
PPP-fft vs Xbow-method II	0.997	7.34	1.29	10.39	0.996
PPP-fft vs Xbow-method V	1.052	10.56	4.93	15.26	0.995
Xbow-method II vs method V	1.052	8.81	2.72	9.84	0.998

TABLE 2. Statistical parameters for peak period scatterplots.

Comparison	Slope	Scatter index (%)	Bias (s)	Rmse (s)	r^2 correlation
PPK-fft vs PPP-fft	1.001	3.60	0.020	0.223	0.996
Xbow-method II vs PPP-fft	1.012	9.09	−0.023	0.618	0.969
Xbow-method V vs PPP-fft	1.015	9.20	−0.019	0.624	0.968
Xbow-method II vs method V	1.002	1.49	0.003	0.093	0.999

TABLE 3. Statistical parameters for mean period scatterplots.

Comparison	Slope	Scatter index (%)	Bias (s)	Rmse (s)	r^2 correlation
PPK-fft vs PPP-fft	0.993	1.89	−0.016	0.085	0.998
Xbow-method II vs PPP-fft	1.103	6.74	−0.368	0.501	0.971
Xbow-method V vs PPP-fft	1.117	7.11	−0.361	0.508	0.969
Xbow-method II vs method V	1.012	0.69	0.005	0.033	0.999

b. GPS

GPS PPK and PPP data were processed in a manner similar to that of BEN, but with several modifications described here. The 1-Hz GPS vertical displacement data contain information about the high-frequency wind waves, lower-frequency tides, currents, and surge heights, and GPS system errors (Harigae et al. 2005), such as atmospheric or ephemeris errors. The PPK record, because it is referenced to a base station, shows little, if any, low-frequency GPS system errors over the 20-min wave-sampling period. The PPP record, on the other hand, exhibits a low-frequency component that slowly changes, and occasionally jumps in a nonlinear manner, over the 20-min sampling period. This is best seen when the wave heights are low, less than 2–3 m (see Fig. 2, e.g.). Simply removing the mean from the PPP sample does not remove all of the power from the low-frequency signal, but in fact biases the PPP-determined wave heights high when compared to both the PPK and accelerometer results. The low-frequency signal was removed, not by using a frequency domain high-pass filter, but by first filtering the PPP and PPK data through a running average filter with a window size of 40 s. This filtering identified the low-frequency error signal, as well as any discontinuous jumps (resulting from loss of the carrier phase lock or changes in satellite constellation, etc.) that a high-pass filter could not remove. The wave displacement data used in subsequent processing steps are the difference between the data and the filtered signal.

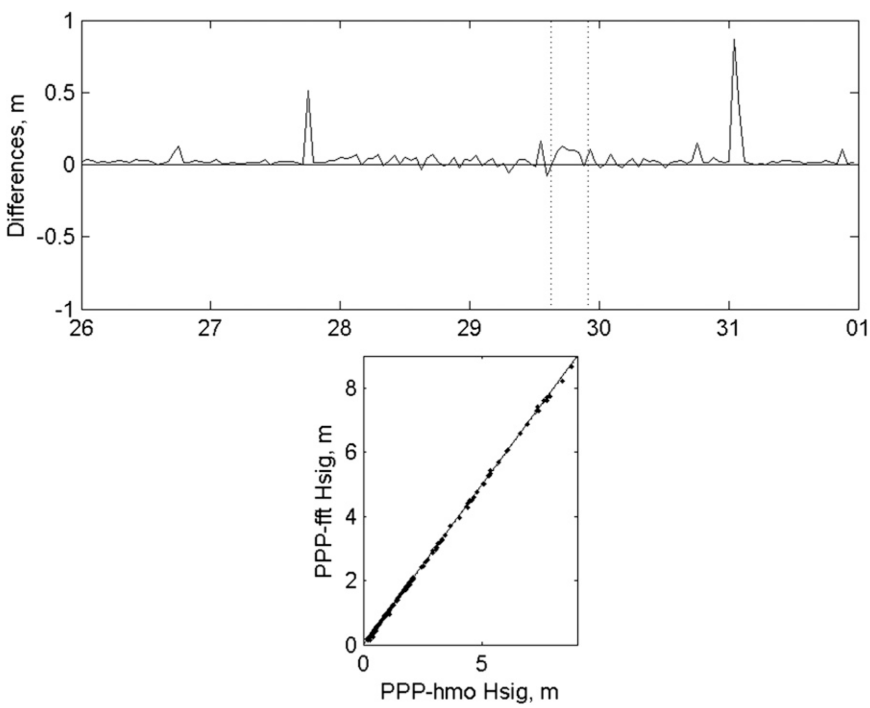

FIG. 4. (top) The differences between the classical method (-hmo) and the FFT spectral method (-fft) of determining significant wave heights from the PPP measurements. (bottom) The scatterplot of the significant wave height for the classical method (horizontal axes) and the spectral method (vertical axes). See Fig. 3 and text for additional details.

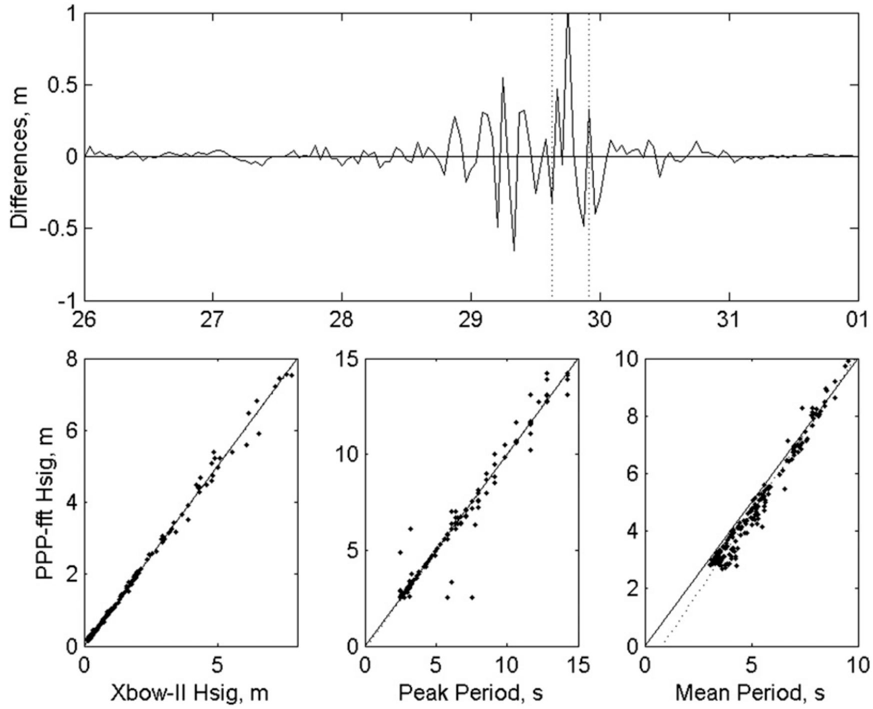

FIG. 5. (top) The differences of the FFT spectra-determined significant wave heights between the PPP and the accelerometer (method II) measurements. (bottom) The scatterplot of the significant wave height, peak period, and mean period for the accelerometer (horizontal axes) and the PPP (vertical axes). The scatterplots do not include any data during the period the buoy was moving. See Fig. 3 for additional details.

In BEN a Kalman filter was applied to the GPS wave-displacement data, but here no Kalman filtering was performed. The data were examined for outliers, which were usually less than 1% of the total, and those were removed. The displacement spectrum was calculated using the FFT of the vertical displacement data. The FFT displacement spectra, on the other hand, had enough low-frequency energy that a modified Lang (1987) frequency domain filter (Snc = 5, fu = 0.15 Hz, fl = 0.03 Hz) was applied.

The significant wave heights were calculated from the GPS wave-displacement data in one of two ways—either the classical method, based on the variance of the displacement data, or from the displacement spectra using the definitions provided on the NDBC Web site (National Data Buoy Center 2008). The spectral method also provided the mean and peak period.

4. Results

There were four questions we sought to answer.

1) How well do the PPP and PPK wave measurements match? Unlike the PPK technique, PPP positioning does not require a base station. For obvious reasons it would be desirable to establish that a base station may not be necessary for the measurement of waves.
2) Are there significant differences between the classical method of determining the significant wave height and that of the displacement spectra? We would expect the spectral height to be somewhat less than the classical definition because of some energy loss in computing the spectra. A significant difference might indicate the spectral algorithms were attenuating too much energy.
3) How well do the PPP measurements, which continue through the entire storm, match that of method II, the deck-relative acceleration? A good match would strongly suggest that the PPP measurements are reliable in the midst of a strong hurricane with large amounts of atmospheric moisture.
4) How much bias is introduced by using the PPP measurements rather than that of method V, the best estimate of the earth-referenced vertical acceleration? Higher PPP wave heights were expected because of the buoy heel effects previously described in BEN.

The significant wave heights for the PPP and PPK measurements are compared in Fig. 3 for the fast Fourier transform method. The wave heights are visually identical

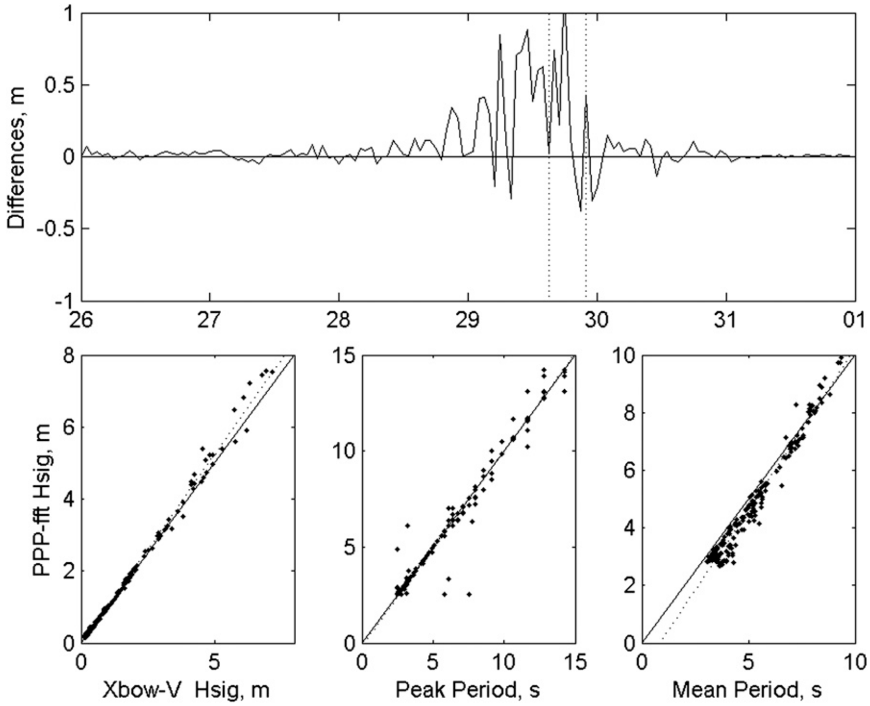

FIG. 6. (top) The time series of the FFT spectra-determined significant wave heights for the PPP vs the accelerometer (method V) measurements. (bottom) The scatterplot of the significant wave height, peak period, and mean period for the accelerometer (horizontal axes) and the PPP (vertical axes). The scatterplots do not include any data during the period the buoy was moving. See Fig. 3 for additional details.

up to the point the PPK data ceases at 0727 UTC 29 August 2005. At times the PPP data are noisier than the PPK, but not significantly so. The scatterplot between the PPP and PPK significant wave heights has a symmetric regression (Taagepera 2008) slope of 0.9995 and an r^2 correlation of 0.998. Table 1 shows the matrix of statistical parameters for the wave height comparison, Table 2 for the peak period, and Table 3 for the mean period. The comparison between the PPP and the PPK data is excellent, not only for wave heights but also for the mean and peak periods. For all practical purposes there is no statistical difference in the two types of measurements.

Figure 4 shows the differences between the classical method (-hmo) and the FFT spectral method (-fft) of determining significant wave heights from the PPP measurements. The time series shows only two instances where the classical definition is significantly greater than the spectral definition, probably because of residual low-frequency energy in the vertical displacement data that the FFT filters out. Discarding those two points, the scatterplot and the statistical matrix of significant wave height show exceptional agreement. The positive bias confirms that the classical method is slightly larger than that of the FFT, but only by a very small amount. The spectral processing algorithm is not attenuating excessive energy.

The GPS displacement data are not the vertical motion of the sea surface, but is better interpreted as a combination of the heave of the buoy and its pitch and roll. This is what a strapped-down 1D accelerometer measures along its main axis. This conveniently provides us with the opportunity to verify the GPS-determined wave heights against a completely independent sensor suite on board the buoy. Figure 5 shows the differences between the PPP measurements using the FFT spectral method (-fft) for determining significant wave heights and the accelerometer measurements using method II of BEN. This is the vertical motion of the deck and is closely related to the motion of the GPS antenna. As Hurricane Katrina begins to approach, the differences between the two measurements, which were small, begin to grow in size and exhibit a noticeable pattern of oscillation. There is no overall trend, but relative to the more reliable accelerometer measurements, the PPP wave heights are overestimated and then underestimated. This pattern, which only occurs during the peak of the storm, may reflect changes in the atmospheric moisture or other conditions affecting the GPS signal, but even then the

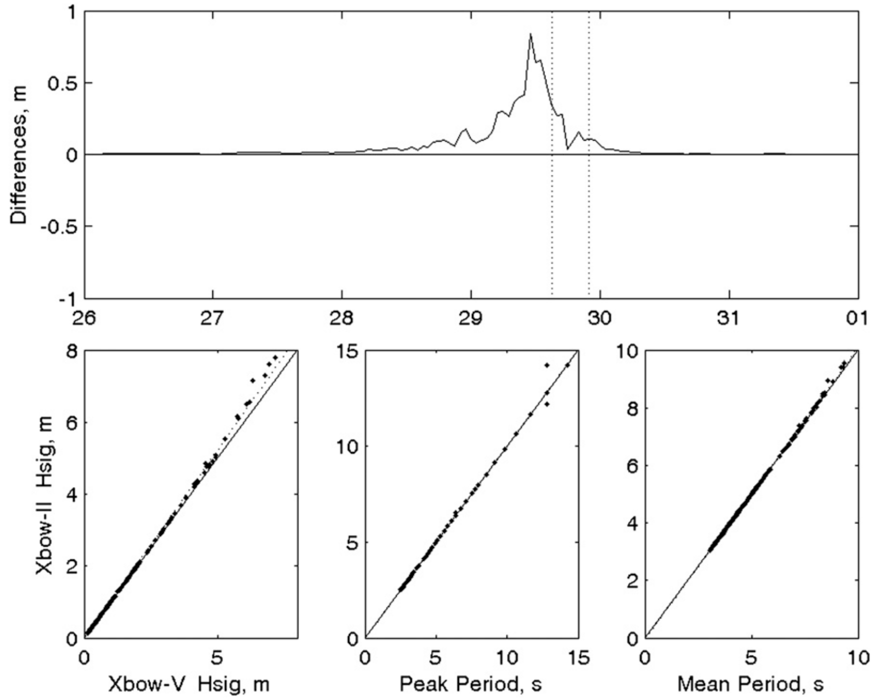

FIG. 7. (top) The time series of the FFT spectra-determined significant wave heights for the method II vs method V accelerometer measurements. (bottom) The scatterplot of the significant wave height, peak period, and mean period for method V (horizontal axes) and method II (vertical axes). The scatterplots do not include any data during the period the buoy was moving. See Fig. 3 for additional details.

individual differences are never more than 0.5 m. On a statistical basis (see Table 1) the scatter index of wave heights is only 7.34% and the rms error is 10.39 cm. The PPP wave measurements can be considered very reliable, but not without some acceptable level of uncertainty during strong hurricanes when large amounts of atmospheric moisture are present.

The mean period for the accelerometer is greater than that of the PPP for periods less than about 8 s, but the peak period is nearly the same. This simply indicates that the GPS data capture more high-frequency energy than the accelerometer does, even though the accelerometer data are recorded at 4 Hz. This suggests that the buoy's heave response amplitude operator, which is an integral part of the spectral processing algorithm (BEN), may attenuate too much high-frequency energy. The positive bias in wave heights, in which the PPP measurements give slightly higher wave heights than the accelerometer, supports this contention. However, any changes in the heave-response amplitude operator would result in small wave height changes and would certainly not eliminate the difference oscillations.

The final question asks how well the PPP measurements compare to the best estimate of the vertical motion of the sea surface. As we have already noted, the motion of the buoy deck, which is what the GPS antenna actually measures, is constantly tilting with the wave motion and is not the vertical motion of the sea surface. The earth-referenced vertical motion of the buoy is determined by knowing its orientation in space and transforming the buoy motions to an earth-referenced coordinate frame. This is given as method V in BEN. Unfortunately, this could not be done with the PPP measurements. The pitch-and-roll data from the HMR were time stamped by the buoy clock and the GPS data were time stamped by the satellite. It was not possible to synchronize the two data streams at the level of accuracy needed to transform the PPP measurements to an earth-referenced frame.

Figure 6 compares the PPP measurements using the fast Fourier transform method for determining significant wave heights to that of the method V accelerometer measurements. We would expect differences because of the GPS antenna motion, and this is clearly seen. The PPP wave heights show a consistent trend to be too high and the scatter index, bias, and rms error are at their highest (Table 1). The biggest differences between the two estimates are seen when the wave heights exceed 5 m, which corresponds to a buoy heel greater than 10° (BEN). This is similar to the overprediction of GPS wave heights previously identified by Rossouw et al. (2000). They were unable to identify a specific reason for the difference, but suggested that the discrepancy could be linked to the dynamic response of the buoy. We postulate that a possible explanation begins by recognizing the GPS antenna tracks the motion of the buoy deck and not the vertical displacement of the sea surface.

Finally, Fig. 7 shows the comparison between method II and method V acceleration data, where method V yields the most reliable estimate of the wave heights. The differences between the two are relatively smooth compared to the differences between the GPS and accelerometer. This suggests that the oscillation in PPP-to-accelerometer differences seen in Figs. 5 and 6 are primarily due to GPS errors.

5. Conclusions

There is very good agreement between the PPP, PPK, and accelerometer measurements of the wave height, peak period, and mean period. When properly understood as the motion of the buoy deck, which is constantly tilting and is not the vertical motion of the sea surface, the GPS measurements are as reliable as a strapped-down 1D accelerometer. The strapped-down 1D accelerometer, and hence the GPS measurements, are a reliable estimate of the vertical motion of the sea surface when the heel of the buoy is not excessive. In the case of this buoy in this storm, that corresponded to a heel of no more than 10° and a wave height of less than 5 m (BEN). The GPS measurements from a buoy could be an accurate estimate of the vertical motion of the sea surface in all of the sea states at any buoy heel if the pitch and roll of the slope-following buoy were independently determined from a 3D differential GPS antenna and receiver. This would readily resolve any synchronization issues as well as explore the possibility that an accelerometer-equipped directional wave buoy may not be necessary.

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