Wave Heights from a 3m Discus Buoy During Hurricane Katrina

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Abstract—In August 2005 the eye of Hurricane Katrina passed 49 nm to the west of a 3-m discus buoy (USM3m01), in 20 m water depth, operated by the Central Gulf of Mexico Ocean Observing System (CenGOOS). Buoy wave heights were measured with an onboard 6-axis accelerometer and from the displacement of a GPS antenna as measured by Real-Time-Kinematic (RTK) GPS. The computed wave heights are compared to the nearby NDBC 42007 buoy and show reasonable agreement for wave heights less than 2-3 m. At higher wave heights there is a potential bias in the wave heights if the buoy’s heel is not accounted for. This is believed to be the result of swell in shallow water, a heel in the buoy caused by wind and currents, and the failure to tilt-correct the accelerometer data.

I. INTRODUCTION

On December 14, 2004 the University of Southern Mississippi (USM) deployed a 3-m discus buoy in the Mississippi Bight at 30° 2’ 32.7” N, 88° 38’ 50.2” W (see Fig. 1) near the 20-m isobath. The buoy was funded in part to evaluate the feasibility of extending the range that Real-Time-Kinematic (RTK) Global Positioning System (GPS) could be used in the marine environment [1]. The buoy was outfitted with three instruments for measuring buoy motion, a survey-grade GPS receiver, a solid state six degrees of freedom strapped down accelerometer, and a high quality aviation grade 3-axis magnetometer, as well as a suite of instruments for monitoring local meteorological and oceanographic conditions. The design, fabrication and integration of the buoy were done independently by the Geochemical and Environmental Research Group (GERG) at Texas A&M University. The mooring itself however was designed and built by NOAA’s National Data Buoy Center (NDBC). GERG has operated the Texas Automated Buoy System since 1995 [2] and has designed and operated four types of TABS buoys, two spar and two discus buoys.

On August 29, 2005 at approximately 1400 GMT the eye of hurricane Katrina passed approximately 49 nautical miles (nm) to the west of the USM buoy’s location (Fig. 1). The buoy experienced sustained tilts of 20 – 30 degrees during Katrina that were directly recorded by the magnetometer and indirectly measured by the pitch, roll and yaw rate sensors of the accelerometer. The buoy dragged its 8500 lb. (in air) concrete anchor slightly to the northeast during the final approach of Katrina, but following the hurricane’s landfall, and as a direct result of the storm surge relaxation, the buoy was dragged at speeds up to 2 knots to the southeast from 1500 to 2300 GMT. A maximum current of 5 knots was recorded by an Aanderaa DCS current sensor at 2-m depth. The GPS receiver on the buoy operated continuously through the storm, but the base station at nearby Horn Island was partially destroyed by the storm at 0700 GMT. The buoy’s onboard accelerometer and magnetometer also operated continuously throughout the storm. All of the motion sensor’s raw data were saved onboard and later retrieved when the buoy was recovered on September 20, 2005.
The GPS and accelerometer motion sensors provided two independent data sources that were used to determine significant wave heights and periods. These results were then compared to NOAA’s National Data Buoy Center 3-m discus buoy 42007 that was deployed approximately 7 nm to the west-northwest at 30° 2’ 32.7” N, 88° 38’ 50.2” W near the 14-m isobath (Fig. 1). Buoy 42007 provided directional spectra, wave heights and wave periods until the buoy broke free from its mooring on August 29th at 0500 GMT.

The basic premise of this paper is wave heights calculated from a strapped down accelerometer should be corrected for buoy tilt during storm events when accurate measurements are critical. This paper describes the instrument setup of the buoy, the data obtained, and the methods used to process the GPS and accelerometer data into significant wave heights.

II. DATA

The buoy was equipped with three instruments to measure three-dimensional motion, a Crossbow IMU400CC accelerometer, a Honeywell HMR 3300 compass, and a Novatel OEM4-g2 GPS. A PC104 UNIX based central computer directed the sampling strategy and saved all of the raw data to an onboard hard drive, which were retrieved after the buoy was recovered. This allowed us to develop and investigate numerous different processing strategies.

The Crossbow IMU 400CC series accelerometer is a solid state measurement system 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 (see Fig.’s 2 & 3). The sensor was installed along the centerline of the buoy at approximately the waterline and aligned so that its positive z axis was oriented down and normal to the deck of the buoy (the standard orientation for this unit so that it measures a +1 g when at rest), while the positive x-axis pointed to the “south” of the buoy and the positive y-axis to the “west.” The instrument has an update rate of greater than 100 Hz, but was sub-sampled to 4 Hz. The sub-sampled data were time stamped by the buoy’s central computer as the data was saved to the data base. The accelerometer was cycled on for the first twenty minutes of each hour and then cycled off for the remaining 40 minutes. The data used in this study covered the first twenty minutes of every hour from August 5 to September 20, 2005.

The Honeywell HMR3300 digital compass (Fig. 3) is a solid state 3-axis, magnetometer-based compass that uses a two-axis accelerometer for enhanced operation up to a ±60” tilt range. This electronically gimbaled compass gives accurate headings even when the compass is tilted at 60°; though this never occurred even during the height of Katrina. The compass is capable of data rates up to 8 Hz, but was sub-sampled to 4 Hz. The sub-sampled heading, pitch and roll data were time stamped by the central computer after the data was acquired. The compass operated continuously and collected 4 Hz data. The data used in this study covered the period from April 18 to September 20, 2005.

![Fig. 1 Location of NDBC and USM buoys and the path of Hurricane Katrina.](image1)

![Fig. 2 The USM 3-m discus buoy during final testing showing the location of the GPS antenna and the instrument well in the center of the hull.](image2)
The Novatel OEM4-g2 survey grade GPS (Fig. 2) is a 24-channel 20 Hz, differential GPS unit that is capable of yielding highly accurate horizontal and vertical positions. The vertical displacement record provided an independent means of determining wave heights. The GPS receiver operated continuously and collected 1 Hz data. The data used in this study covered the period from 23 August 2006 through 0700 GMT on 29 August 2006 when the baseline station on nearby Horn Island went offline.

NOAA’s National Data Buoy Center (NDBC) buoy 42007 is a 3-m discus buoy with the Data Acquisition and Control Telemetry (DACT) payload. The DACT payload contains a 3-axis magnetometer for measuring buoy slope and heading and a fixed, one-axis accelerometer for measuring buoy heave. The Magnetometer Only Directional Wave Analyzer (DWA-MO) wave measurement system is used to calculate directional wave estimates from these measurements. The sample length is 20 minutes long, begins at the top of each hour, the sampling rate is 2 Hz, and the data is processed through an analog filter and sub-sampled to 1 Hz, [3]. We retrieved hourly one-dimensional spectral estimates, the significant wave height, the peak period, and the mean period from the NDBC website for this buoy for all of 2005.

III. PROCESSING

One-dimensional displacement spectra were calculated using either the accelerometer data or the GPS displacement data. The development of several different methods, specific to the instrument, is discussed in this section.

Accelerometer

The 3-axis linear accelerometer data allowed us to investigate the influence of buoy tilts on the deck relative z acceleration or heave. The z acceleration measures the component of gravity perpendicular to the deck of the buoy. It is the method used in the NDBC DACT payload [3]. If the buoy is level and heaving, the measured component of gravity contains the vertical accelerations of the waves. If the buoy is pitching and rolling, but not heaving, then the component of gravity perpendicular to the deck is changing and is interpreted as waves. If the rolling and pitching is small (< 15 degrees) then the effect is small and is typically ignored [4]. If the mean pitch and roll of the buoy is not zero, i.e. has a heel, then the combination of the heel, pitch, roll and heave can have unexpected effects on the calculated significant wave heights.

A straightforward means of correcting for the buoy’s tilt is to simply use the magnitude of the three axes accelerations. This eliminates the difficulty of synchronizing the pitch and roll data recorded by the Honeywell HMR3300 digital compass to that of the z axis accelerometer data. Alternatively, the heave acceleration from the z axis of the Crossbow IMU400CC sensor can be used directly, without tilt correcting to remove the pitch and roll of the buoy. This is what we do in order to mirror the method used by NDBC 42007.

The Crossbow acceleration sensor is sub-sampled by the buoy’s internal computer at a nominal 4 Hz, but the timestamp can show some minor (< 50 ms) drift over time. This drift is a consequence of the varying workload of the central computer and the fact that it time stamps the data packet when it is appended to the working data file. However, the Crossbow data have a built-in time lag that can be used to correct the time stamp. The Crossbow sensor associates a time tag with each data packet where the time tag is simply the value of a free running counter at the time the sensor’s A/D channels are sampled. The clock counts down from 65,535 to 0 and a single tick corresponds to 0.79 microseconds and the timer rolls over approximately every 50 milliseconds. This information was used to adjust the time stamp.

The time lag corrected acceleration data were then processed to remove outliers. The outliers were removed by first linearly de-trending the data and then removing any value that exceeded three times the standard deviation. This typically accounted for less than 0.5% of the data. The data were then cubic spline interpolated to a 4 Hz time base, which replaced any removed outliers.
Next, the data were processed through a Kalman filter to remove instrument and process noise. The estimate of the measurement and process noise variance needed for the Kalman filter was defined a priori, but chosen to minimize the difference in the wave heights between the USM buoy and the NDBC buoy during the high wave height regime of 2 – 5 m.

The acceleration wave spectra were determined by taking the Fast Fourier Transform (FFT) of the noise filtered, 4 Hz acceleration data. Using 19.2 minutes of data, the data was segmented into 17 50% overlapping segments with 512 data points in each segment. A Kaiser-Bessel window based on the modified zero-order Bessel function of the first kind was applied to each segment to reduce spectral leakage. The Kaiser-Bessel window was used because it has very good dynamic range, is superior to most other windows with respect to selectivity, and uses an adjustable parameter beta ($\beta = 0.5$ in our case) to trade off side lobe energy for the main lobe. The FFT of the windowed segment was computed, corrected for the energy reduction due to the windowing, and the one-sided power spectra calculated. Each of the seventeen power spectra were then averaged to obtain the final acceleration wave spectra.

The next processing step applied a frequency domain filter to the acceleration spectra, ostensibly to remove spurious low-frequency noise. According to [5] a noise filter is used to remove low frequency energy induced by a hull-fixed accelerometer and nonlinear hull motions. We utilized a modification of the empirical noise correction of [6] which establishes a noise estimate and then removes that noise in a linearly decreasing manner between a lower (0.05 Hz) and upper (0.15 Hz) frequency. We determined the noise estimate to be the product of the mean spectral density between 0.01 and 0.05 Hz and the slope of the noise correction factor, $S_{nc}$, where $S_{nc} \equiv 18$ in our case.

Finally the noise corrected acceleration spectra was converted to the displacement spectra by dividing by the frequency to the fourth power. The heave response amplitude operator used by NDBC for its 3-m discus buoys was applied. The significant wave height, peak period and mean wave period were determined from the displacement spectra using the standard NDBC definitions [3].

Global Positioning System

The GPS derived displacement time series is a measure of the displacement of the buoy’s GPS antenna, not the geometric center of the buoy where the accelerometer sensor is located. 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 30º relative to buoy north. As a result of this lever arm the displacement data reflects a combination of the heave of the buoy and its pitch and roll. It would make sense to tilt correct the measurements, but because of still to be resolved synchronization issues between the GPS data and the Honeywell HMR pitch and roll data, the GPS data used in this study were not tilt corrected.

The significant wave height can be calculated from the GPS displacement data using the classical definition,

$$H_{sig} = 4 \cdot \sqrt{d}.$$  

Alternatively the 1 Hz displacement time series can be processed as a displacement spectra, yielding the significant wave height, mean period and peak period. Most of the processing steps for doing this are the same as the accelerometer methods described previously, though with specific differences described as follows.

The displacement data were first processed to remove outliers. The outliers were removed by linearly de-trending the data and then removing any value that exceeded three times the standard deviation. The data were then cubic spline interpolated to a 4 Hz time base, which filled in any removed outliers. Next, the data were processed through a Kalman filter to remove instrument and process noise. The estimate of the measurement and process noise variance needed for the Kalman filter was identical to that of the previous section.

The displacement wave spectra were determined by taking the Fast Fourier Transform (FFT) of the noise filtered, 4-Hz displacement data. Using 19.2 minutes of data, the data was segmented into 17 50% overlapping segments with 512 data points in each segment. A Kaiser-Bessel window based on the modified zero-order Bessel function of the first kind was applied to each segment to reduce spectral leakage. The FFT of the windowed segment was computed, corrected for the energy reduction due to the windowing, and the one-sided power spectra calculated. Each of the seventeen power spectra were then averaged to obtain a displacement wave spectra.

Unlike acceleration wave spectra, the displacement spectra did not need to be corrected for spurious low frequency noise. The heave response amplitude operator used by NDBC for its 3-m discus buoys was applied. The significant wave height, peak
period and mean wave period were determined from the displacement spectra using the standard NDBC definitions [3], except that the significant wave heights were computed over the frequency band from 0.03 to 0.485 Hz.

IV. RESULTS

The major premise of this study is that the pitch and roll of a discus buoy should be considered when determining one-dimensional spectra from a fixed, one-axis accelerometer, particularly when the sea state is high, the water depth is shallow, and the buoy is subject to heeling. We sought to establish that the USM buoy measured similar wave heights to that of NOAA’s NDBC 42007. We would not expect the wave heights to be exactly the same - 42007 is 7 km shoreward of the USM buoy and in shallower water – but for wave heights on the average of 1 - 2 m, they should be statistically similar. Consequently the first part of this section deals with the z only acceleration, and like 42007, it is not tilt corrected. The second part of this section compares the GPS displacement against the z only acceleration and finds excellent agreement. Finally, the third part compares the tilt corrected acceleration to the non tilt corrected, z only acceleration.

Accelerometer – z only

Using the non tilt corrected z acceleration data, we computed a time series of significant wave heights, peak periods, and mean periods. The a priori estimate of variance for the Kalman filtering was adjusted so that the wave heights differences with 42007 were minimized for wave heights greater than 1.25 m. The time series of significant wave heights is shown in Fig. 4. There is a difference in wave heights less than 1.5 m, the USM buoy being lower, but for wave heights greater than 1.5 m there is good agreement. The maximum wave height of 9.85 m occurred at 1300 GMT on August 29, 2005. We postulate that this could have been the maximum wave height recorded by 42007 had it not slipped its mooring.

GPS vs. z only Accelerometer

Using the non tilt corrected z acceleration data and the GPS displacement data, we computed two time series of significant wave heights, peak periods, and mean periods. The non tilt corrected z acceleration was used instead of the tilt corrected because it is more nearly what is measured by the GPS antenna. The time series of resulting significant wave heights is shown in Fig. 5. Up until the time the GPS base station went offline, the two wave heights show exceptional agreement.

Accelerometer – Tilt Corrected

Using the tilt corrected z acceleration data, we computed a time series of significant wave heights, peak periods, and mean periods. The time series of significant wave heights is shown in Fig. 6. There is no visual difference in wave heights less than 2.5 m, but there is a marked difference in larger wave heights. For the non tilt corrected acceleration data, the maximum wave height of 9.85 m occurred at 1300 GMT on August 29, 2005. For the tilt corrected acceleration data, the maximum wave height is only 7.01 m and occurs four hours later at 1700 GMT. This represents a 29% reduction in the peak wave height.
Buoy Heel

The pitch and roll data were combined with the azimuth data to obtain a geographically referenced East-West (EW) tilt, corresponding to roll, and a North-South (NS) tilt, corresponding to pitch. Hence for the purposes of this discussion a reference to the east axis of the buoy doesn’t refer to the x-axis of the buoy, but to the axis of the buoy that is aligned along the compass direction of west to east. The east-west tilt is positive for upward motion of the east axis of the buoy. The north/south tilt is positive for upward motion of the north axis of the buoy. A wind from the east, defined as positive, would act on the superstructure of the buoy and rotate the buoy about its center of momentum, causing the eastward orientation of the buoy to tilt upwards, i.e., become positive. On the other hand, if the buoy mooring is scoped out to the west of the buoy because the buoy is drifting to the east, this would cause the east axis of the buoy to tilt down. A wind from the south, defined as negative, would result in the north axis of the buoy tilting downwards, i.e., become negative. If the buoy mooring is scoped out to the north of the buoy, this would cause the north axis of the buoy to tilt upwards.

In Fig. 7 we show the earth oriented pitch and roll of the buoy, averaged over twenty minutes and defined as the buoy heel, the associated wind speed, averaged over the first ten minutes of the pitch and roll sampling period, and the difference in significant wave heights, defined as the non tilt corrected minus tilt corrected. As seen from Fig. 7, the buoy heel and wind speed follow very closely, as one might expect. The easterly wind causes a sustained positive EW heel and the southerly wind causes a negative NS heel. But when the buoy is moving to the south southeast, the mooring is scoped out to the west of the buoy and causes the east axis of the buoy to tilt down more than expected for the velocity of the easterly wind. The largest over estimation in significant wave heights occur at the point the NS heel is most negative. The southerly winds causing this heel correspond to the period when the swell is from the south as well. Once the buoy began to move to the south southeast, the north–south heel becomes more negative. This corresponds to the rapid reversal in the bias of the significant wave heights, where the non tilt corrected heights are now less than the tilt corrected. During this period, the swell is still out of the south. We postulate that the bias in significant wave heights is due to the same underlying mechanism, a non-linear transfer between the three axes of the accelerometer caused by swell steepening in shallow water combined with a buoy heel. A simple model of a wave following buoy (not presented here) indicates that this behavior can be modeled. It also suggests that is the interaction of the long period swell with the bottom combined with a buoy heel that appears to be responsible for the difference in tilt corrected and non tilt corrected wave heights.

V. CONCLUSION

The major premise of this study is that the pitch and roll of a discus buoy deployed in shallow water should be considered when using a fixed, one-axis accelerometer. This is particularly important when the buoy is heeled over during the wave sampling period, a condition that can be expected to occur when the wind speeds are high and obtaining accurate wave heights is most critical. What we attempted to demonstrate in this
paper is that the larger the heel, the greater the deviation in wave heights one can expect if the tilt is not corrected for. Whether this phenomenon is equally important in deep water, where the swell does not interact with the bottom and rapidly steepen, is unknown. But up on a continental shelf, the working environment for a 3-m discus buoy, it should certainly be considered.

It is reasonable to expect that the all-chain catenary mooring was probably scoped out during the nine hours it was dragged to the southeast. How this affected the ability of a large reserve buoyancy discus buoy to respond to the wave field is a complex question that can’t be answered here. One could argue that the wave heights, corrected or not corrected for tilt, may have been biased low during the period the buoy was moving. However, the deviation in non tilt corrected and tilt corrected wave heights is seen even before the USM buoy was dragged from its deployment location by the force of the relaxing storm surge. At the point at which the buoy begin to move to the southeast, 1400 GMT on August 29th, the z only significant wave height had decreased from its peak of 9.85 m to 9.01 m. This compares to a tilt corrected wave height of 5.70 m. This is a difference of 3.31 m, or a wave height that is 58% higher if tilt correction is not accounted for.

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REFERENCES