Long-Term Performance of an AWAC Wave Gage, Chesapeake Bay, VA

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Abstract- **Evans-Hamilton, Inc. deployed a Nortek AWAC to collect long-term wave and current data in the Chesapeake Bay near Norfolk VA. The gage has been deployed since March of 2006 in approximately 7 meters of water and has been collecting currents profiles at 20 minute intervals and waves every hour. The system is equipped with an Acoustic Surface Tracking (AST) capability which uses a fourth acoustic beam to directly measure the water surface elevation at 4 Hz during the wave data collection burst and provide a water level time series for use in the wave analysis. Over the first 16 months of deployment the instrument has performed well and has not experienced any degradation to its physical components or in the system's electronics and signal strength. The error statistics for the data collected over the deployment period indicate the instrument has had very few data quality issues even during large wave events. The AST has been shown to be a reliable method of directly measuring critical wave statistics over a long-term deployment even during large wave events. For periods when the AST was not able to provide an accurate water level time series, an alternative method for estimating the maximum wave height based on spectral analysis was considered.**

I. INTRODUCTION

Evans-Hamilton, Inc. was contracted by an engineering firm to collect long-term data on waves and currents in the Chesapeake Bay to support engineering studies on nearby beaches and coastal structures. A Nortek AWAC wave gage with acoustic surface tracking (AST) was selected for the project. The gage has been deployed since March of 2006, in the Chesapeake Bay near Norfolk, VA.

The gage was intended to provide a long-term data set which could be used to calibrate and validate a numerical wave model for this area. Initially the deployment was planned for 12 months but was extended for a second year based on the success of the first year. The data set from this project provides an opportunity to assess the long-term performance of the AWAC under a variety of wave conditions in a typical coastal application.

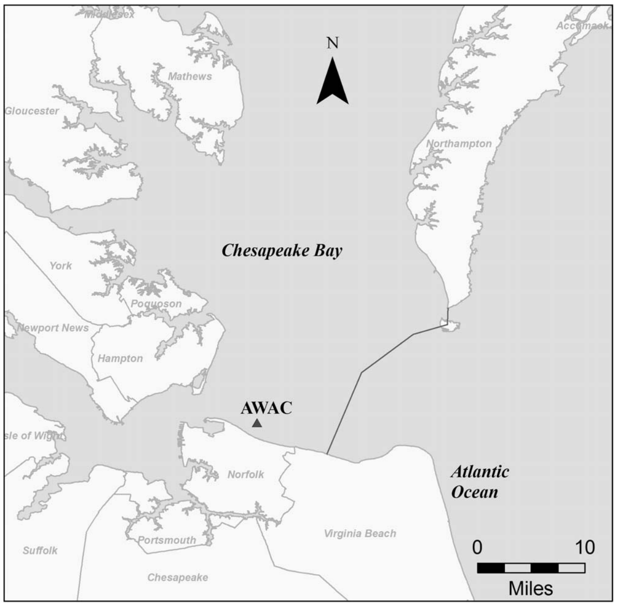

Figure 1. Site location map.

II. BACKGROUND

A. Site Conditions

The AWAC was deployed in 6.7 meters (m) of water, approximately 1.6 km off the beach near Norfolk, VA, and 9.6 km west of the Chesapeake Bay Bridge tunnel as shown in Fig. 1. The bathymetry in this area is relatively flat and featureless compared with the main body of the Chesapeake Bay to the north which is characterized by the presence of many channels and shoals [1]. To the east of the gage location, the bay mouth opens to the Atlantic Ocean, allowing ocean swell to be a dominant force in this environment. The continental shelf here is relatively wide and gently sloping.

One major concern for the gage at this site has been the crab dredging activities that take place during the winter months. While the instrument was deployed in a trawler-resistant pod, a direct hit by a crab dredge could damage the pod and the instrument. To minimize the potential of accidental damage to the system by a crab dredger, a lighted warning buoy was deployed at the site.

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B. *Instrumentation*

A Nortek 1-MHz AWAC-AST was used for project. The instrument uses three acoustic beams to measure water velocity in a series of bins in the water column from near the bottom to near the surface. In addition, the AWAC has a fourth vertical acoustic beam which measures the distance from the sensor to the surface. This allows the instrument to track the surface of the water with a high degree of accuracy. This capability is referred to Acoustic Surface Tracking (AST). The AWAC is also equipped with a pressure sensor which is used to calculate the water depth over the instrument. An integrated pitch-roll sensor and compass provide information on the orientation of the instrument. Power is provided by an external battery pack connected to the instrument via a 1-meter cable.

The AWAC provides wave measurements based on the various data being collected. The directional spectra and related wave statistics are calculated using near-surface water velocity measurements and the data provided by the AST. In addition, the AST data are used to make direct measurements of extreme wave parameters such as the maximum wave height which would typically be estimated from the spectral data.

C. *Deployment Approach*

For each deployment, the AWAC was placed in a trawler-resistant pod to reduce the possibility of damage to the system by fishing/trawling activities. The pod is aluminum to avoid interfering with the AWAC's internal compass and weighted with lead to provide stability. The pod is equipped with a diverless recovery system consisting of a buoy and an acoustic release. To recover the instrument for servicing, the acoustic release is activated using a surface deck box and the buoy is released and allowed to float to the surface. Using the recovery line attached to the buoy, the entire pod is recovered for servicing. EHI has used this approach extensively with great success at a wide variety of locations.

The AWAC housing is approximately half the height of the instruments normally used in the pods, so it was necessary to install a base in the mount that would raise the AWAC transducer faces high enough to clear the sides of the pod. To minimize growth on the instrument housing, the transducers were sprayed with an anti-fouling transducer paint and covered with a zinc-oxide cream before each deployment.

D. *Sampling Protocol*

The AWAC was programmed to measure water velocity in 50-cm bins starting approximately 1.2 meters above the instrument. The water velocity was measured in each bin over a 2-minute period at 2 Hz every 20 minutes and the average of those measurements for each bin was recorded. Each profile of recorded water velocity is referred to as an ensemble.

For wave measurements, the AWAC collected 2048 ensembles of currents and pressure at 2 Hz, over a 17-minute period, once every hour. Concurrent with the water velocity and pressure measurements for wave data analysis, the AST feature measured the water surface elevation at a rate of 4 Hz, providing improved resolution of small, high-frequency waves.

E. *Deployment History*

The AWAC was originally deployed in March of 2006. During the first year, the instrument was recovered every 3 months at which time the instrument was cleaned, the data were downloaded, and new batteries were installed. At each servicing the AWAC had some level of biofouling on it. In no instance, though, was the level of biofouling found to be excessive even during the summer deployments. At the end of the first year, the entire system underwent an annual servicing inspection which included cleaning and repainting the pod, replacing the desiccant in the AWAC, installing new batteries in the acoustic release, replacing zincs, and replacing the recovery line. During the second year of deployment, the time between servicing was extended to four months.

F. *Data Analysis*

The data recorded by the AWAC was processed with Nortek's QuickWave software which utilizes a Maximum Likelihood Method adapted for Surface Tracking (MLMST). This method uses the water surface record measured using the AWAC's AST capability to estimate the non-directional spectrum (wave height and period) and uses the three near-surface velocity cells and the AST data to calculate the wave directional spectrum. In addition, the software calculates the peak wave period, the mean wave period and the directional spread. Current data were converted to ASCII format using Nortek's AWAC-AST software and processed in MATLAB.

G. *Results*

The data indicate that tides in the area are semi-diurnal, with the duration of the flood and ebb being approximately equal. There was some vertical variation in current magnitude; with the surface currents being higher than the near-bottom currents during some phases of the tide. The currents also showed some vertical variation in direction. The flood currents were generally slightly higher than the ebb at this location, and during storm events, peak ebb currents approached 60 cm/s. Typical daily maximum, depth-averaged currents over the deployments ranged from 30 to 40 cm/s. The directional data indicate that during the flood tide, the currents started out running west-by-north and as the phase of the tide progresses, the direction became more northwesterly.

During periods with low significant wave height, the peak period typically increased as the ocean swell coming in from the Atlantic became the dominant wave energy. The higher wave events typically had peak directions out of the north or northeast. The period data indicate that the higher waves were associated with locally generated wind waves with peak periods of approximately 4 seconds.

There were 12 wave events during the first 16 months of the deployment in which the significant wave height reached or exceeded 1.22 m. The significant wave heights for the highest two wave events were 2.35 m on September 1, 2006 (during the passage of Tropical Storm Ernesto) and 2.65 m

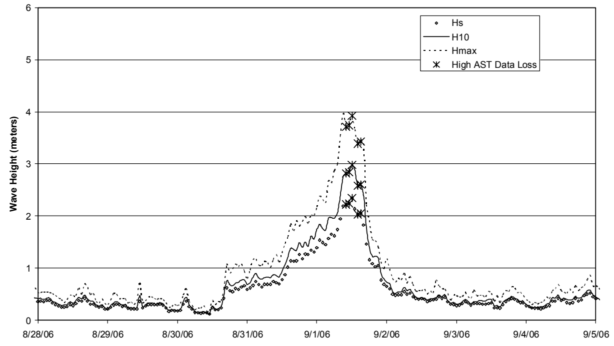

Figure 2. Wave measurements during passage of Tropical Storm Ernesto September 1, 2006.

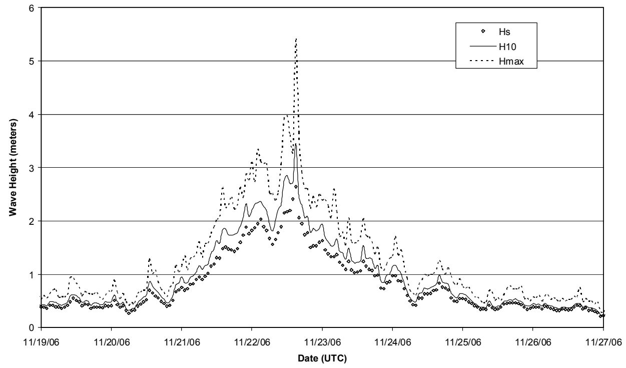

Figure 3. Wave measurements during storm on November 22, 2006.

on November 22, 2006. Plots of the wave statistics for these two events are shown in Figs. 2 and 3, respectively. The maximum wave height reported during these events was 3.97 m and 5.43 m, respectively. An interesting point to note is that the measured maximum wave height observed during the November 22, 2006 storm is approaching the estimated maximum wave height for this water depth.

III. COMPONENT PERFORMANCE

An important consideration for long-term deployments is how well the instrument physically holds up over time and whether any degradation in the electronics and transducer signal strength is observed.

A. Physical Components

Throughout the first 16 months of deployment, the overall physical condition of the system was good. Other than small scratches and scrapes resulting from biofouling and its removal, the housing and endcaps were in good shape and exhibited no cracking or warping. During the deployments covering the summer months, the transducer experienced significant fouling from barnacles and other "soft' marine growth. It was possible to remove almost all of this growth during each servicing and no pitting or damage to the transducers was observed. The only notable issue encountered with the system components was associated with the power connection on the bottom of the AWAC. During one of the deployments, an oyster began growing in the small space between the instrument endcap and the connector. As the oyster grew, it began to push against the connector and cable plug, slightly dislodging the cable plug from the connector. Even though the cable plug was dislodged slightly, water did not enter the connector and no damage or corrosion of the connector occurred. During the servicing, it was necessary to remove the connector to extricate the oyster. The area was covered with a zinc-oxide cream on subsequent deployments to limit oyster growth. While this did not affect the system performance, it is very likely that over time the oyster could have dislodged the connector to the point where it would have flooded and shorted the battery.

B. Electronics and Signal Strength

At the completion of the 5 deployments the AWAC passed all system tests indicating that all electronic circuitry was in order. To determine if the signal from the AWAC was degraded with time, the recorded signal strength from bin 1 (1.41 m from the transducer head) was reviewed for the March to June time frame for both 2006 and 2007 to see if there were any notable changes or trends. Comparable time periods were used to reduce any differences introduced by water temperature variations or environmental noise related to biology since it was assumed that these conditions would be similar for the same months from year to year. The difference between the average signal strength for the March to June time period for 2006 and 2007 was minimal indicating that the transducers and associated electronics had not degraded over the deployment period. The signal strength over each individual deployment was also examined to assess the possible impact of biofouling on the instrument performance. No discernable relationship between the signal strength and the amount of biofouling was observed.

IV. MEASUREMENT PERFORMANCE

A. Data Quality Parameters

The ability of the system to accurately track the water surface using the AST is critical to the performance of the system. Various factors such as high turbidity and aeration due to breaking waves can impact the ability of the AST to resolve the surface. Each measurement from the AST is evaluated by the system and if it does not meet certain data quality criteria, that measurement is rejected. The system keeps track of the number of bad surface detects by the AST in each wave burst and if the number exceeds 10% of the total number of measurements (410 in this case), the AST method is considered unreliable, in which case the time series of pressure and near-surface velocity data may be used for non-directional wave estimates. A frequency distribution of the number of bad detects per burst was calculated, and the results are presented in Table I. As can be seen in the Table, for over 99% of the wave bursts there were less than 50 bad surface detects. There were only 7 (0.03%) bursts for which the number of bad surface detects exceeded the 10% criteria.

TABLE I

SUMMARY OF BAD SURFACE DETECTS

Number of Bad Detects	Frequency	Cumulative %	% of Total
0	5262	45.65	45.65
1	2029	63.26	17.60
2 - 5	2967	89.00	25.74
6 - 10	651	94.65	5.65
11 - 15	238	96.71	2.06
16 - 20	105	97.62	0.91
21 - 50	176	99.15	1.53
51 - 100	52	99.60	0.45
101 - 200	24	99.81	0.21
201 - 300	9	99.89	0.08
301 - 410	6	99.94	0.05
411 - 500	3	99.97	0.03
>500	4	100.00	0.03
Total	**11526**		

TABLE II

SUMMARY OF ERRORS IN PROCESSED DATA

Error Code	Number of Occurrences	% of total errors	Low Pressure	Low Amplitude	Unreasonable Estimate	AST Out of Bounds	Dir. for Peak Period Out of Bounds	High AST Data Loss
4	15	1.5		**X**				
16	12	1.2			**X**			
66	4	0.4	**X**			**X**		
82	2	0.2	**X**		**X**	**X**		
128	951	95.9					**X**	
132	1	0.1		**X**			**X**	
1024	6	0.6						**X**
1030	1	0.1	**X**	**X**				**X**
Total:	**992**							
Total # of Samples: 11526 **Percentage of bursts with error codes: 8.6**								

In addition to looking at the number of bad surface detects, the analysis software performs a variety of quality control assessments for each wave burst and reports an error code if any of the data quality parameters are not met. Some error codes are used to indicate that two or more of the data quality parameters have not been met. Table II provides a summary of the error codes from the first 16 months of deployment.

Descriptions of the data quality errors are provided below (from the QuickWave Help index):

<u>Low Pressure</u> **-** This error suggests that there was no dynamic pressure detected in the time series, and suggests that the waves were not measurable (i.e. a constant pressure). This would occur if the instrument was deployed at a depth that is too deep to measure the waves or simply that there were no measurable waves.

<u>Low Amplitude</u> **-** This indicates that the amplitude of the Doppler signal was too low to measure the orbital velocity.

<u>Unreasonable Estimate</u> - If it appears that there is an unreasonable wave parameter estimate then the burst is flagged as bad. Such estimates that would be considered unreasonable are:

$H_s > 20$ meters

$T_{m02} > 35$ seconds or $T_{m02} < 0.5$ seconds

$T_p > 50$ seconds or $T_p < 0.5$ seconds

<u>AST Out of Bounds</u> **-** Since many of the AST estimates are based on the zero-crossing, there is a check to make certain none of these estimates are unreasonable. Estimates are limited as follows:

$H_3 < 20.0$ m

$H_{10} < 25.0$ m

$H_{max} < 35.0$ m

$0.5 \text{ sec} < T_{mean} < 35.0 \text{ sec}$

$T_{peak} < 30$ sec

<u>Direction for Peak Period Out of Bounds</u> **-** This limit is applicable for directional estimation using the Maximum Likelihood Method. As we move up in frequency the wavelength decreases and at some wavelength there is a limit associated with the array separation distance that can unambiguously resolve wave directions. A check is performed to see if the wavelength associated with the peak period is too small to resolve the wave direction at this frequency.

<u>High AST Data Loss</u> **-** This indicates that too many points were lost during the data clean-up or despiking steps. The level at which the data loss in the AST time series is considered excessive is 10% of the data.

B. Data Quality During Storm Events

One item of particular interest with the AWAC has been its performance during large wave events. The two largest wave events over the 16-month period were reviewed to assess the AWAC's performance under such conditions. During the passage of Ernesto, there was also an increase in the number of bad detects for the surface tracking, and the 10% threshold was exceeded for five bursts during the peak of the storm. These bursts are flagged with an asterisk in Fig. 2. In these five cases, the extreme wave statistics were calculated based on the spectral analysis results rather than directly from the water level time series. As can be seen in the time series, the H_{max} calculated based on the spectral data shows a drop from the previous measurement even as the H_s was increasing. This suggests that the H_{max} estimate based on the spectral methods (1.67*H_s) may be under-predicting the H_{max} relative to a direct observation from the water level time series.

During the November 22, 2006 storm, there was an increase in the number of bad surface detects, but at no time during the storm did the number exceed the 10% threshold above which the AST is considered unreliable. During this event there is a dramatic jump in the H_{max} for one burst of over seven feet from the previous burst indicating that wave conditions can evolve rapidly.

V. ADDITIONAL ANALYSIS

Given the potential discrepancy observed between the H_{max} based on the AST and the H_{max} estimated from the wave spectra statistics observed during the passage of Ernesto, a discussion was initiated with Nortek as to the possible source. Nortek noted that the AWAC's ability to collect an accurate surface elevation time-series presented a unique opportunity to perform a comparison between H_{max} calculated with the surface time series and that estimated from spectral analysis. Nortek further noted that Mr. Justin Vandever has performed similar comparisons of H_{max} on other shallow water data sets and his results indicated that wave statistics based on results of the spectral analysis may not be accurate under certain conditions that do not satisfy the assumption of a narrow banded spectra [2].

To assess if the AST approach for calculating wave statistics at this site provided significantly different results from those that would be obtained using a spectral approach, data from the first five deployments were provided to Mr. Vandever for analysis. Details of the analysis approach used are discussed in Ref [2] which looks at similar data from 12 other sites.

Significant wave height (H_s) is a standard measurement used to characterize wave conditions and is generally recognized to be equivalent to the average of the 1/3 highest wave heights in a water level time series ($H_{1/3}$). $H_{1/3}$ can be directly determined from a water level time series such as that provided by the AST. When spectral analysis techniques are used to estimate wave parameters, H_s is in practice considered to be equivalent to H_{m0} which is defined as 4*sqrt m0, where m0 is the zero moment of the wave spectrum. If this approximation is valid, the ratio of $H_{1/3}$ to H_{m0} should be 4. Generally, the ratio of 4 is found to be accurate only for data sets with a narrow frequency bandwidth. As the frequency bandwidth increased the ratio was generally found to decrease. As part of the analysis, a method was proposed for characterizing the bandwidth of a data set and a function for relating the bandwidth to H_s was developed.

The analysis indicates that the ratio of $H_{1/3}$ to H_{m0} for this data set is slightly less than 4, which is typical of other sites investigated by Mr. Vandever and approaches 4 only when the bandwidth becomes narrow. This result indicates that the significant wave height calculated from the spectral analysis technique would tend to over-estimate the significant wave height relative to that calculated from a zero-crossing analysis of the AST data.

The other wave statistic that was investigated is H_{max}, which is defined as the largest wave in the water level time series. Since the water level time series is often not available to make a direct measurement of H_{max}, it is estimated based on Hs using various techniques. For the Norfolk site, the ratio of H_{max} to H1/3 based on the analysis of the AST water surface elevation was determined to have a mean of 1.74 and a median of 1.71. This is similar to, but slightly higher than, the value of 1.67 often used as the ratio of H_{max} to H_s.

In the referenced document [2], Vandever demonstrated that H_{max} was a function not only of H_s but also of the number of waves in the data record. These findings were used to develop a new method for estimating H_{max} from the spectral data. This method is based on a bandwidth-corrected estimate of H_s and a relationship between H_{max} and $H_{1/3}$ which is dependent on the number waves in the record. For the remainder of this paper, this approach will be referred to as the Vandever method.

In analyzing the data for the Norfolk site, Vandever applied the following three methods for estimating the H_{max} in the absence of surface tracking:

- Vandever method: incorporates a bandwidth corrected Hs and variable $H_{max}/H_{1/3}$ ratio dependent on number of waves in the record.
- Constant transfer coefficient of 1.67 and a non-bandwidth corrected H_s
- Constant transfer coefficient of 1.67 and a bandwidth corrected H_s

From the analysis, two error statistics were reported: the mean signed error and the mean absolute error. The mean signed error can be interpreted to indicate whether a particular method has either an overall positive or negative bias, while the absolute error can be interpreted to indicate how far off the prediction is (either over- or under-predicted).

Based on these statistics, the Vandever method performed very well with less than a 1% signed error and approximately a 6% absolute error.

Method 2 showed the largest signed error (+7% bias). This is possibly because it doesn't compensate for the bandwidth effect so H_{m0} is slightly larger to begin with (i.e. evidence that bandwidth correction is necessary to correct H_{m0} to $H_{1/3}$).

Method 3 showed a slight negative signed error (-2%), which is consistent with the fact that the transfer coefficient of 1.67 is slightly less than the typical value for the data which was found to be 1.74 based on the AST results.

The results of this analysis highlight that standard methods for calculating certain wave statistics using a spectral analysis may not accurately reflect the true conditions at the sites, especially coastal sites that often do not meet the assumption of a narrow banded spectra. Furthermore, it demonstrates the value in having an accurate record of the water surface elevation for direct measurement of these parameters. In cases where a water level time series is not available, Vandever's method appears to provide a more accurate technique for estimating certain wave statistics than more traditional approaches.

VI. CONCLUSIONS

The Nortek AWAC has performed well over a 16-month deployment in the Chesapeake Bay near Norfolk VA. The instrument has not experienced any significant physical degradation despite deployment in a high biofouling environment. The electronics and transducers have also remained stable over the deployments with no discernable decrease in performance. The error statistics for the data collected over the deployment period indicate the instrument had very few data quality issues even during large wave events. The AST has been shown to be a reliable method for directly measuring critical wave statistics over a long-term deployment even during large wave events. Overall, the number of bad surface detects was found to be small.

The AWAC's ability to provide an accurate time series of the water level affords a unique opportunity to assess certain assumptions used frequently to estimate wave statistics based on spectral analysis. Analysis of the data set performed by Vandever indicates that the spectral bandwidth plays a role in developing accurate estimates of H_{max} as does the number of waves in the times series. For data sets where a water level time series is not available, the method proposed by Vandever provides a more accurate means of estimating H_{max}

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