Wave Sensing in the Upper-Great Lakes Observing System

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***Abstract*—This paper reports the design and implementation of a low-cost inertial wave sensor (IWS) for installation on coastal environmental monitoring buoys. The University of Michigan's Ocean Engineering Laboratory design integrates a Digi International Rabbit RCM3600 embedded controller with a Honeywell HMR3300 MEMS accelerometer to measure buoy accelerations and estimate directional and non-directional wave spectral information. This information is then output via standard RS-232 communications to the buoy data-logger for storage or real-time dissemination to data centers at the University of Michigan, the National Data Buoy Center, and others. Details of the electrical design and on-board processing, in addition to related research enabled by this device, are discussed. A comparison of observations with the Great Lakes Coastal Forecasting System predictions and future upgrades is also presented.**

I. INTRODUCTION

The Upper-Great Lakes Observing System (UGLOS) began deploying buoys on the Great Lakes in 2003 as part of the Integrated Ocean Observing System (IOOS) regional partner Great Lakes Observing System (GLOS). Oceanographic and meteorological data gathered by the buoys (Figure 1) is transmitted every ten minutes back to receiving stations on land for further processing and visualization [1]. As the system gained popularity, new partners such as DTE Energy, the Great Lakes environmental Research Laboratory (GLERL) of NOAA, the National Data Buoy Center (NDBC), and Alliance for Coastal Technologies (ACT) began requesting new data products in addition to more in situ platforms. Coastal researchers and data modelers noticed a distinct lack of wind and wave data from the near-shore region, especially in the Great Lakes [2], [3]. One highly requested data product was the observation and estimation of near-shore surface wave information.

In 2008, GLOS funding allowed the Ocean Engineering Laboratory (OEL) to pursue buoy refurbishments and the design of a new buoy-mounted wave sensor. Many technologies exist to measure waves such as submerged pressure gauge fields, acoustic surface tracking, marine radars, laser altimetry, and inertial measurements. The OEL investigated each technology to assess the applicability for inclusion on the UGLOS monitoring buoys.

Submerged pressure gauge fields, such as the U.S. Army Corps of Engineers (USACE) Field Research Facility at Duck, North Carolina (and many others), measure the water pressure at several locations and calculate the height of the water column above the (bottom-mounted) sensor. Over time, a record of wave heights is built. Results from pressure fields are typically very accurate but installation requires a large spatial area for good coverage or the concurrent measurement of horizontal velocity components along with pressure. These are not feasible for a single-point moored buoy such as the UGLOS buoys.

Fig. 1. UGLOS Environmental Monitoring Buoy.

Acoustic devices measure water column height by timing an acoustic signal as it reflects off the sea-surface. As [4] notes, the speed of sound in water is directly impacted by temperature and salinity induced pycnoclines and therefore dictates well-mixed conditions for good surface estimates. These sensors are bottom-mounted and do not apply to water surface applications such as buoys.

Radar detection of waves [5], is gaining popularity but typically requires a large initial investment in equipment and a land-based operating station. One advantage of buoy systems, however, is the relative ease of relocation. Due to the cost and stationary requirements of most radar installations, this technology is precluded from use as a UGLOS buoy-mounted sensor.

Laser altimetry measures the distance between the sensor and the sea surface by timing optical reflections of the laser. Typically, the sensor is mounted on an aircraft or large structure such as an oil rig, and was therefore rejected as a potential buoy-mounted technology.

Inertial sensors are low cost and can be implemented in very small electrical packages. Inertial measurements also have a relatively long developmental lead over newer technologies. In 1963, Longuet-Higgins published the foundational work on calculating wave specta from acceleration measurements [6]. Since that time, measurement sensors have been vastly improved, algorithm technology has advanced, and processing power has become faster, cheaper, and smaller. Three-axis accelerations are measured directly using gravity as a reference. The data is transformed into the frequency domain and wave information is extracted through spectral analysis.

In 2011, the UGLOS deployed eight environmental monitoring buoys with seven inertial wave sensors (IWSs). Each IWS reports roughly 175,000 observations (wave height, period, direction, and Fourier coefficients) per deployment season for a system total of around 1.2 million wave data fields per season plus a suite of additional environmental parameters. This data is made publicly available through the UGLOS website at http://uglos.engin.umich.edu.

II. INERTIAL WAVE SENSOR DETAILS

The OEL IWS (Figure 2) is a $+12V$ $(+9$ to $+38Vdc)$ powered inertial wave sensor that reports heading, significant wave height, dominant wave period, and mean wave direction via RS-232 communications. The IWS contains an integrated three-axis accelerometer (Analog Devices ADXL330) and a digital compass (Honeywell HMR3300) which also reports roll and pitch. These components provide 12bit measurements at a sample rate of 2Hz. Due to the amount of data that is measured, it is impractical to store the entire wave record over the duration of deployment. Instead, each sample of approximately 8.5 minutes of data is temporarily recorded and post-processed to extract wave statistics from the record. Wave analysis is computed by a Digi International Rabbit RCM3600 core module using a custom discrete Fast Fourier Transform algorithm. At a sampling rate of 2Hz, Nyquist theory states that the fastest wave measurable is 1Hz, well within the design criteria.

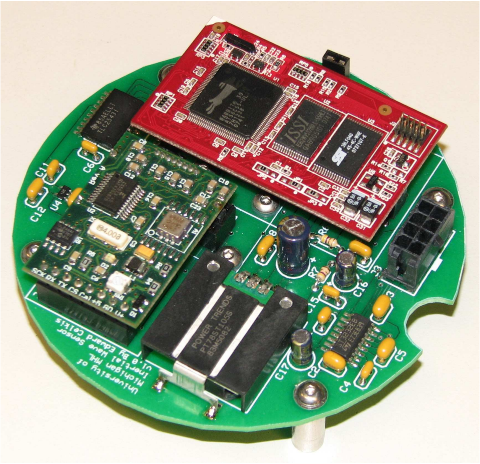

Fig. 2. Ocean Engineering Laboratory (OEL) inertial wave sensor (IWS).

The Analog Devices ADXL330 is a three-axis accelerometer with signal conditioned outputs and low power consumption ($180\mu A$ at 1.8V). The $\pm 3g$ minimum range of the ADXL330 well contains the naturally occurring environment to be measured, and the sample rate of up to 550Hz affords a wide range of operational modes. The output of the ADXL330 is sent through an analog low-pass filter with a bandwidth, F_{3db}, determined by a capacitor network defined by the equation,

$$F_{-3db} = \frac{1}{2\pi(R_{filt})C_{(x,y,z)}} \tag{1}$$

Where $C_{(x,y,z)}$ is the capacitor value on the output lines x, y, and z, and R_{filt} is the internal resistor value (nominally 32kΩ). The tolerance of the internal resistor typically varies as much as $\pm 15\%$ of its nominal value, and the bandwidth varies accordingly. Also to note, the external capacitors have up to a $\pm 10\%$ error in their actual value. Individual testing ensures matched components for optimal efficiency.

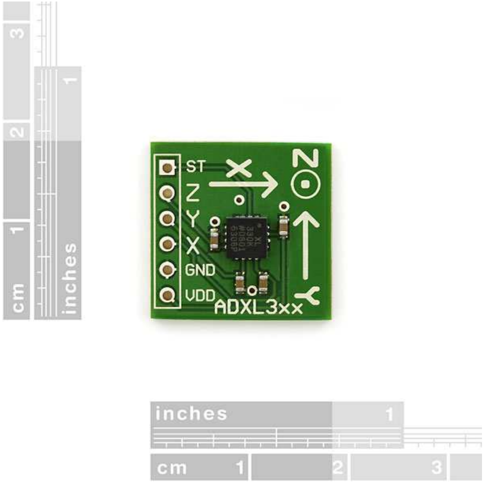

Fig. 3. Analog Devices ADXL330.

The ADXL330 (Figure 3) has a typical measurement range of $\pm 3.6g$ (minimum is $\pm 3g$). According to Longuet-Higgins in [7], real (Lagrangian) accelerations for steady ocean waves very rarely exceed $+0.3g$ in the trough, and $-0.39g$ at the crest. For unsteady waves, or progressive waves, however, the negative (downwards) Lagrangian acceleration can approach $-g$ [8]. All these values fall within the operating range of the ADXL330.

Fig. 4. Honeywell HMR3300.

The Honeywell HMR330 (Figure 4) is a compact magneto-resistive based digital compass which provides precise heading information, as well as roll and pitch angles using a micro-electromechanical system (MEMS) accelerometer. Heading, roll, and pitch are all accurate to within $\pm 1^\circ$ ($\pm 1^\circ$ resolution). Roll and pitch measurements are limited to a range of $\pm 60^\circ$. As roll and pitch become more extreme, heading errors degrade to an accuracy of $\pm 4^\circ$ at 60° tilt. Outside this range, heading information is unreliable. Due to the mechanical design of the buoy platform, a particle follower, roll and pitch are minimized and kept well within the normal operating range of the HMR3300. The maximum output frequency of the Honeywell HMR3300 is 8Hz. Typical NDBC buoys sample at frequencies ranging from 1Hz to 2Hz [9]. This limits the frequency of the fastest waves reliably sensed to a Nyquist frequency of 0.5 to 1Hz. The UMich IWS samples at a rate of 2Hz so that waves up to 1Hz in frequency can be measured accurately.

Fig. 5. Digi International Rabbit LP3500.

The Rabbit RCM3600 (Figure 5) is a low-power embedded controller with on-board A/D (Analog-to-Digital) inputs, 4 serial ports, and power consumption under 40mA when fully operational. In this case, one serial port is connected to the HMR3300 compass, while three analog inputs are connected to the ADXL330 three-axis accelerometer. Dynamic-C has a built-in discrete Fast Fourier transform (FFT) algorithm, but it is limited to 1024 samples. A new discrete FFT algorithm was implemented in Dynamic-C which can handle an arbitrary number of samples up to the limitations of the Rabbits memory (following Cooley and Tukey [10] and Cormen et al. [11]).

According to [12], [13], the lowest frequency limit for significant wave energy is approximately 0.035 Hz. Tucker explains that occasionally 0.04 Hz is used as a lower limit, but severe storms on the open ocean produce waves that are below this frequency (perhaps one to two storms per year in the North Atlantic [14]). The upper frequency limit has been chosen to be the Nyquist frequency (half of the sampling frequency) of the measurement system. As mentioned, in this case the sampling frequency of 2Hz drives the Nyquist frequency to 1Hz.

The introduction of low-frequency noise during the integration step (performed in the frequency domain) is addressed through the introduction of an empirically determined low-frequency filter. In accordance with Lang's 1984 paper [15], the IWS digital filter is defined as,

$$NC(f) = (13*0.5)*[C_{11}^m(0.01)+C_{11}^m(0.02)]*(0.15-f) \quad (2)$$

where C_{11}^m are the acceleration spectra at 0.01Hz and 0.02Hz and f is a fixed frequency. Equation 2 (#3 from [15]) was tested on NDBC buoy 45007 in Lake Michigan and buoy 45008 in Lake Huron and most closely approximates the UGLOS buoy geometry and environment. If $NC(f)$ is, in magnitude, less than the signal at a particular frequency, $NC(f)$ is then subtracted from the signal. If the noise function is greater than the signal at a particular frequency, the signal is canceled for that frequency.

Spectral leakage, where a measured signal contains component wavelengths that do not have the exact frequency of a harmonic of the measured record length, is ignored as in the NDBC Wave Processing Module (WPM). The NDBC, in [9], argues that leakage effects are small for wave parameters even though spectra may differ from the results calculated with leakage reduction. Also, the effects of spectral leakage are "generally far less than spectral confidence interval sizes." Following these suggestions, the OEL IWS performs no spectral leakage compensation. This also means that there is no need to perform later variance corrections.

After the acceleration data has been transformed to the frequency domain (via FFT), and Lang's low-frequency filter has been applied, directional analysis as described by [6] is performed. The first five Fourier coefficients, as described by Longuet-Higgins, a_0, a_1, b_1, a_2, b_2 are determined from the co- and quadrature spectra [16], and reported in the sensor output. The mean wave direction is calculated with the arctangent of $a1$ and $b1$.

III. RESEARCH

Coastal waves have a tremendous impact on society by impacting shipping lanes, beach erosion through sediment transport, coastal flooding, rip-currents, and more. Much is unknown, however, about the littoral region since it is notoriously difficult to study. Wave action, sediment transport, corrosion, and other highly dynamic environmental forces all contribute to the hurdles involved in near-shore research. Remote sensing, such as satellite products, have offered modern researches unprecedented access to the this region, but only the deployment of in situ devices, such as near-shore monitoring buoys, can fill much of this data gap by measuring both meteorological and oceanographic data throughout the water column and local atmosphere.

The University of Michigan's Ocean Engineering Laboratory is currently engaged in three research efforts motivated by the near-shore wave and meteorological data provided by the UGLOS buoys. These studies further demonstrate the need for high temporal resolution of nearshore observations.

The natural phenomenon known as lake breeze has been known for centuries to sailors, fishermen, and even coastal farmers, but there are few models available for lake-breeze prediction. Through the UGLOS buoy data products, the OEL is developing tools to accurately predict lake breeze events in the Great Lakes area. For recreational boaters and surfers, this means better forecasts of near-shore waves. For pest control agencies, this means better prediction of peak spray times for maximum effectiveness. For scientists, this means a better understanding of the natural processes involved in upwelling, downwelling, and mixing in the near-shore regions.

In addition to lake-breeze identification and prediction, the OEL is investigating automatic forecasting of harmful algal blooms (HABs). The OEL has partnered with Michigan Tech Research Institute (MTRI), known for their remote sensing expertise, to develop combined satellite-based products with in situ measurements for more accurate HAB models. These models will use real-time in situ water quality data from the UGLOS buoys and optical imagery from satellites to identify and eventually predict the conditions associated with HABs.

Another research thrust, coupled with forecasting of HAB events, involves nutrient and pollutant transport throughout the Great Lakes. Strong benthic and pelagic currents have been observed in the near-shore region by the UGLOS buoys, which has considerable implications for the distribution of both helpful and harmful nutrients and elements. Agricultural runoff, such as phosphorous, is particularly concerning in bays and harbors where current circulations may prevent thorough mixing and cause adverse environmental reactions (such as HABs). The UGLOS buoys use acoustic current sensors, combined with submersible chemical sensors, to provide near real-time observations of subsurface flow conditions, which is essential to the development of chemical and nutrient transport models in the Great Lakes. These models will assist with remediation efforts and preventative efforts in the future.

IV. COMPARISON TO GLCFS

The National Oceanic and Atmospheric Administration (NOAA) Great Lakes Coastal Forecasting System (GLCFS) provides nowcast and forecast information for a variety of physical properties involving the Great Lakes. Products include winds, waves, surface temperatures, air temperatures, water levels, ice cover, cloud cover, and more. These products are used by scientists, engineers, municipalities, and the general public in making informed decisions about activities in and around the Great Lakes such as fishing, surfing, beach activities, coastal projects, and research missions.

While the UGLOS data is available on a 10 minute sample interval, GLCFS data is offered on an hourly basis (standard for NOAA). Accordingly, the six UGLOS data samples per hour are averaged to create a single value which is then compared to the NOAA data.

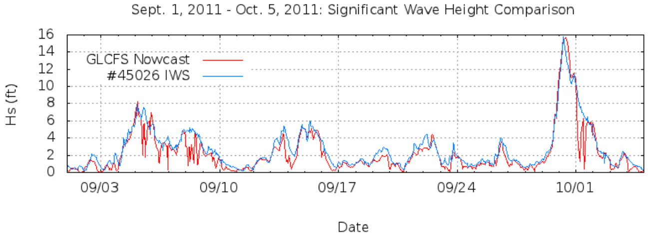

Fig. 6. Significant Wave Height comparison between GLCFS and OEL IWS.

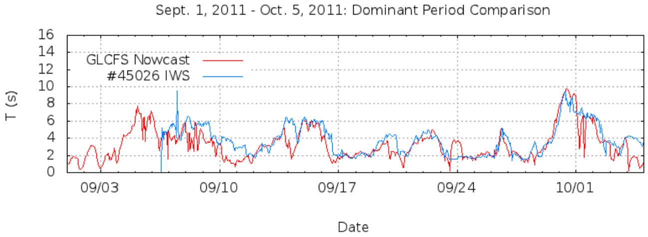

Fig. 7. Dominant Period comparison between GLCFS and OEL IWS.

Graphs (Figures 6, 7, and 8) depict comparisons between the GLCFS Nowcast2D and the IWS output as installed on UGLOS buoy #45026 in lower Lake Michigan. Of particular interest are the storm systems on September 5 and September 30. Significant wave height estimates for the GLCFS and the IWS are in agreement much of the time. Comparisons between buoy observations and numerical predictions are equally close for both moderate and for very large wave Great lakes wave events (H_s approaching 16 feet on 9/30/11). Small separations are expected due to the statistical nature of wave observation. Dominant period estimates also follow similar trend lines, and are in close agreement for much of the comparison time-span. A new post-processing filter was added to the IWS in early September to remove spurious spikes in the data (evident in the first day of readings from the IWS).

Directional comparisons showed encouraging results, similar to the wave height and period comparisons. Many of the spikes visible in the directional comparison are artifacts of the numerical discontinuity occurring at $0° = 360°$.

V. GPS WAVE SENSING

There are well known computational limitations involved in integration of acceleration data to retrieve positional information. Low-frequency noise, introduced during the two

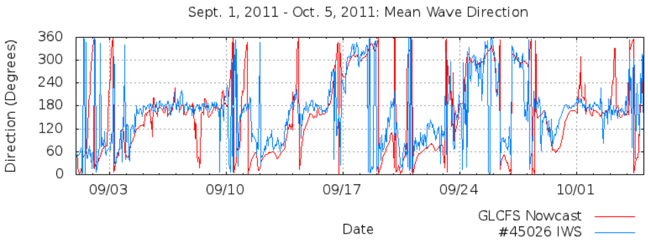

Fig. 8. Mean Wave Direction comparison between GLCFS and OEL IWS.

integration steps, highly influences positional estimations. In an effort to eliminate some of this low-frequency noise (as in [17], [18]), the OEL is currently designing a new wave sensor based on global positioning system (GPS) velocity signals.

A ublox NEO-6 GPS receiver has been successfully tested, using the proprietary NAV-VELNED (Navigation, Velocity North-East-Down) binary sentence, in laboratory conditions at 2Hz and 4Hz sample rates. Circular tests, however, such as the standard stationary-double-pendulum (Ferris wheel) test are invalid for directional waves since an equal portion of time is spent traveling in opposing directions. Field testing of the new GPS-based sensor is scheduled for the 2012 deployment season.

VI. CONCLUSION

This paper described a low-cost inertial wave sensor (IWS) designed by the OEL. The research goal of including the new low-cost IWS device on near-shore buoys is to enhance near-shore wave process observations for use in updating Great Lakes and coastal forecasting and prediction models. These models assist environmental managers and emergency responders in making beach closure decisions and public safety announcements about potential safety concerns such as rip-current conditions or dangerous wave conditions. To this end, we have reported the design and integration of the IWS into a near-shore buoy, and an operational comparison of data to the GLCFS.

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