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A Low-Cost, Open-Source, Wave Monitoring Device For Use On Data Buoys

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Submitted for the Bachelor of Engineering in Electronic Engineering

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Submitted to the Institute of Technology, Sligo, January 2019

ABSTRACT

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by

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Ocean wave measurement has a wide range of applications including forecast model validation, early warning systems for extreme weather events, and design specifications for marine structures to name just a few. The cost of adding a wave sensor to a data buoy is currently prohibitively expensive for many academic and industry ventures, especially for small to medium sized projects. By developing a wave sensor that utilises low-cost components and making it open-source, it is hoped that the proliferation of wave sensors worldwide will increase which in turn will increase the understanding we have of how our oceans behave. This literature review looks at the currently available wave sensing technologies and evaluates them based on how accurately they can measure waves and how viable they are for developing a new wave sensor with. Based on the evidence found, it is apparent that by avoiding the use of proprietary algorithms, it is entirely possible to make a wave sensor with low-cost components.

Declaration

I declare that I am the sole author of this thesis and that all the work presented in it, unless otherwise referenced, is my own. I also declare that this work has not been submitted, in whole or in part, to any other university or college for any degree or qualification.

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January 2019

Abbreviations

9DOF	9 Degrees of Freedom
IMU	Inertial Measurement Unit
MEMS	Micro-Electrical Mechanical Sysems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
AWAC	Acoustic Wave and Current
GNU	GNU’s Not Unix!
PCB	Printed Circuit Board
WIMU	Wireless Inertial Measurement Unit

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1 Introduction

Measuring the size of ocean waves has far-reaching applications in the marine industry and academia [4], [9], [10], [11], [12]. Shipping ports around the world use wave sensors to ensure safe navigation during ship arrival, departure, and cargo transfers [10] . Wave data is also used to validate forecast models which allow localised predictions to be made of what the conditions will be like several days in advance. These forecasts are again used by seafaring vessels to plan operations whilst ensuring conditions are safe enough [13]. Commercial wave sensors while accurate and reliable are prohibitively expensive for many academic and industry ventures [14]. This literature review investigates currently available wave sensing technology and its suitability for use in an open-source and low-cost wave sensor. The aim with developing an open and low cost sensor is to encourage wider use of wave sensors on data buoys worldwide.

2 Literature Review

This section will examine the two main technologies which can be used for measuring wave parameters on data buoys, Inertial Measurement Unit (IMU) and Global Navigation Satellite System (GNSS) based wave sensing [6] . Research into both IMU and GNSS wave sensing will be examined to compare the viability of using each technology for wave sensing.

2.1 General Overview

In general terms, a wave sensor works by detecting the motion of a data buoy moored out at sea. This motion data is then fed into algorithms specifically designed to deliver the required wave parameters in real time. A wave sensor measures parameters such as the significant wave height, maximum wave height, wave direction, wave period, as well as the full wave spectrum [3].

2.2 GNSS Motion Sensing

Most modern GNSS receivers output location and elevation data. A number of these receivers can also output velocity data. The idea of using Global Positioning System (GPS) velocity signals for real-time wave measurement was first proposed by B.J Doong, B.C Lee and C.C Kao in their paper titled “Wave Measurements Using GPS Velocity Signals” published in 2010. As all data buoys usually have an on-board GPS for monitoring of position, using this GPS data to also measure wave parameters would present a potentially low-cost alternative to accelerometer based buoys [6].
A field test was conducted by logging GPS data on one of 15 data buoys that are deployed along the Taiwanese coastline in areas prone to coastal flooding. The set-up of this buoy is shown in Figure 1 below.

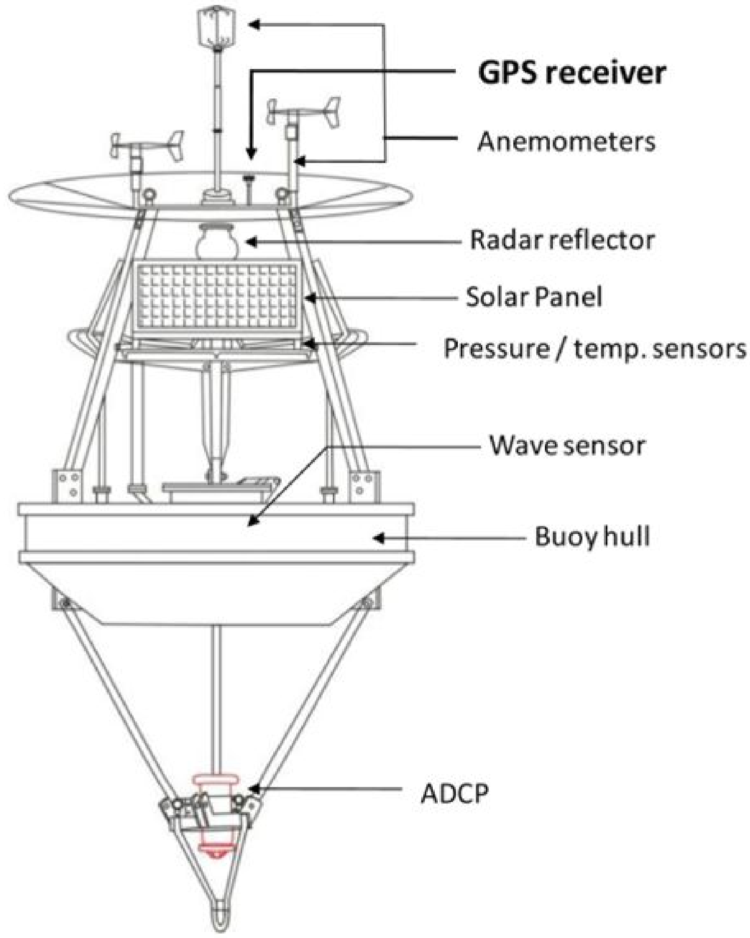

Figure 1. Diagram of buoy configuration used for GPS wave data field test [6]

The steps for measuring wave parameters from GPS velocity data are outlined as follows [6]
:

1. Acquisition of GPS output velocity.
2. Detecting and culling of data with signal loss or drifting.
3. Derivation of vertical spectrum.
4. Transformation from vertical spectrum to vertical displacement spectrum.
5. Derivation of wave parameters and one-dimensional spectrum.
6. Estimation of directional wave spectrum.

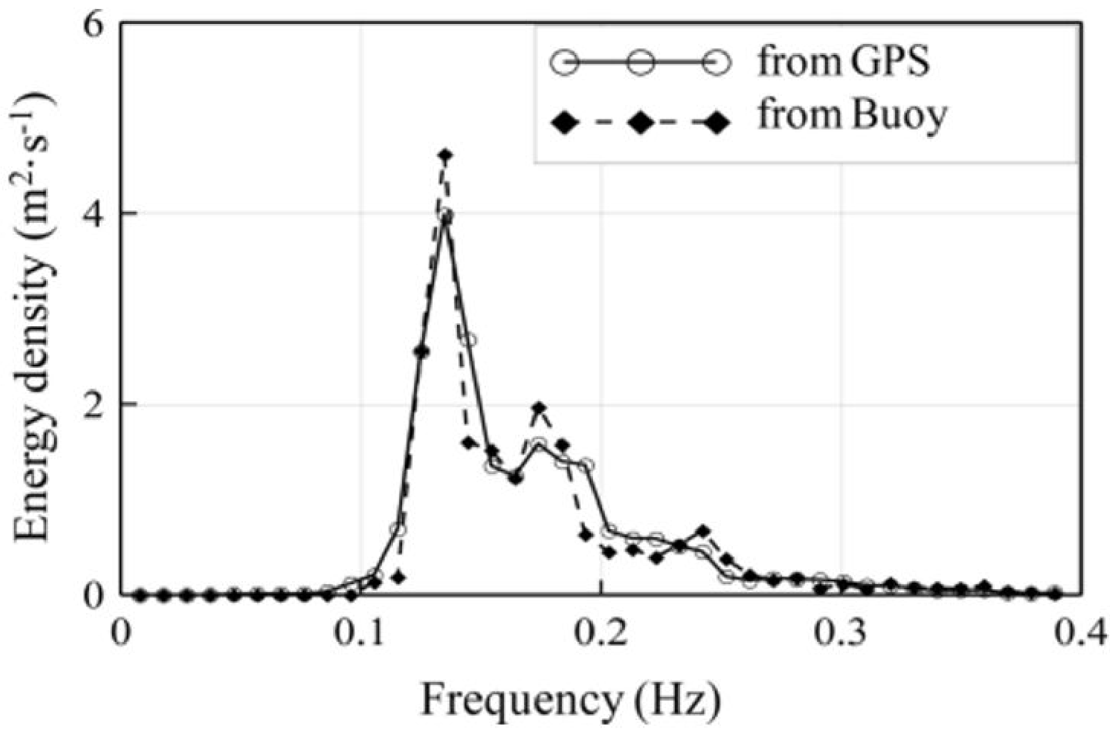

Figure 2. Comparison of GPS-derived and accelerometer measured frequency spectrum

Figure 2 shows a high correlation of the wave energy density spectrum between GPS and accelerometer measured values. The study concludes that despite some issues encountered such as signal loss and drifting as well as energy spikes at low frequencies, a correlation coefficient of 0.95 or higher with an accelerometer based wave buoy was found. The use of moving averages and frequency cut-off to filter the data allowed for this high cross-correlation value. The frequency cutoff at low frequencies could potentially restrict the usefulness of this system for measuring waves with long periods, but apart from this one downside, GPS based wave measurement has been proven to be a viable option [6].

2.3 IMU Motion Sensing

In 2011, one of the earliest examples of a compact and low power IMU based wave sensor was produced by Brown and Meadows working out of the University of Michigan's Ocean Engineering Laboratory [15]. They found that some of the inaccuracy concerns regarding sensor drift could be eliminated by looking at statistics of waves rather than individual wave height data. Another early limitation was the need for the sensor to be placed exactly at the roll center of the buoy or else the acceleration data would contain spurious results. The integration of gyroscopes together with accelerometers and magnetometers has allowed for this spurious acceleration to be accounted for making sensor placement within a buoy less of an issue. As IMU technology has grown over the past several years, IMU sensor chips now have lower power consumption, increased processing power and increased built in algorithmic capability [1].

Despite still having issues with integral drifting and bias instability, Micro Electrical Mechanical Systems (MEMS) based IMU technology is rapidly approaching the performance levels attributed to traditional macro-scale technologies [16]. MEMS based IMU wave sensors have been proven capable as wave measurement devices. For example the SVS-603 wave sensor developed by Seaview Inc. which built on the earlier work of Brown and Meadows, showed a very high correlation for significant wave height when compared with an Acoustic Wave and Current (AWAC) sensor [1]. These results are shown in Figure 3 below. An AWAC sensor is normally placed on the seafloor in a specialised frame where it is pointed towards the ocean surface. From here it can measure ocean currents and waves using acoustic pings [17].

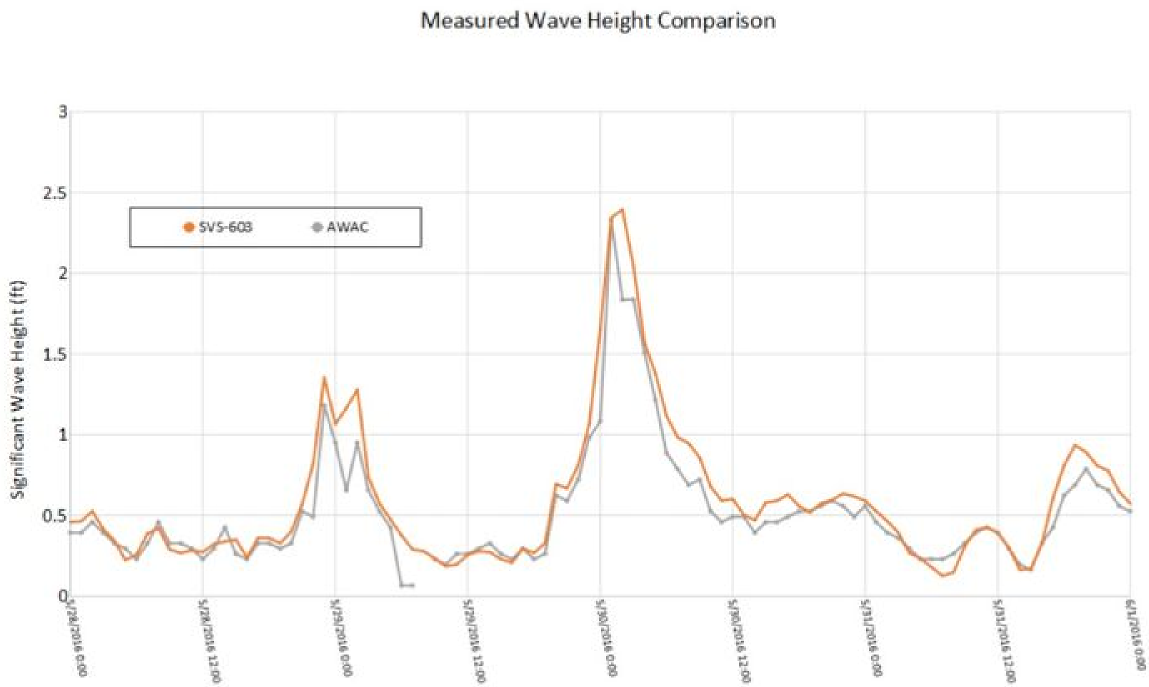

Figure 3. Comparison of Significant Wave Height Between SVS-603 and AWAC

2.4 Conclusion

By examining the experimental results shown in section 2.2 and 2.3, it is apparent that both IMU and GNSS based wave sensing are a viable option when it comes to measuring wave parameters.

3 Comparison of Wave Sensing Technologies

Following on from section 2, which shows that both IMU and GNSS can be successfully used to measure wave parameters, this section will examine the suitability of IMU and GNSS technology for the development of an open-source and low-cost wave sensor.

3.1 Suitability of IMU

The use of an IMU to develop a wave sensor would have the advantage of being able to draw from the extensive research already carried out related to IMU position sensing [18], [19], [20]. As IMU sensors are used in a wide variety of different movement based applications such as manufacturing, navigation, robotics, gaming and medical, there has been a huge amount of effort invested in improving the technology [1], [18].

There are also a variety of open source IMU sensor fusion algorithms available. Sensor fusion refers to the combining of sensory data to produce enhanced data in the form of an internal representation of the process environment. Sensor fusion allows for increased confidence, extended spatial and temporal coverage and improved resolution [21]. One of the most widely used open source sensor fusion algorithms was developed by Sebastian Madgwick as part of his Ph.d research at the University of Bristol in 2009. His unique approach to sensor fusion avoids the use of kalman filters which can be difficult to implement and demand high sampling rates. Through the use of a gradient descent algorithm the difficulty of implementation is lessened and computational load is also reduced [20]. An implementation of this algorithm in the C programming language is open source and available on GitHub under the GNU's Not Linux! (GNU) General Public License [22].

There has also been research carried out in the area of low-cost inertial wave measurement devices. The best example of this is a paper titled "Low-Cost Inertial Measurement of Ocean Waves" written by Donal Kennedy, Michael Walsh and Brendan O'Flynn working out of the Tyndall National Institute. In this paper they explore the use of a Nine Degrees of Freedom (9DOF) MEMS IMU sensor to measure waves. The experimental results are very promising and the study concludes that these sensors are well suited to sea state measurement applications. The details of this experiment will be discussed in detail in section 4.

The National Data Buoy Center, which is a subsidiary of the American scientific agency the National Ocean and Atmospheric Administration, provides a 43 page technical document which goes into great detail about wave measurement techniques for accelerometer based sensors. The topics it covers includes the types of data measured and the assumptions made, data segmentation, mean and trend removal, covariance calculations, Fourier transforms, directional and nondirectional wave spectra, How to calculate wave parameters and buoy hull considerations [2].

3.2 Suitability of GNSS

GNSS based wave sensing has the advantage of a dual purpose on data buoys. It could be used for wave sensing [6] as well as buoy position tracking which would allow the buoy to be tracked and recovered should it break its moorings. Several academic articles and journals written on the subject of GNSS based wave sensing make the claim that it is a low cost alternative to expensive commercially available IMU based wave sensors [6], [23], [24]. However, they do not specify the reason why IMU based wave sensors are so expensive. When examining the hardware of GNSS sensors versus IMU sensors in section 3.3, it is not clear that there is a huge disparity in cost. In fact, a study carried out by the Tyndall National Institute identified IMU sensors as a low-cost option and even developed a custom Printed Circuit Board (PCB) and carried out tests in a wave tank with very encouraging results [14]. This finding would raise the point that perhaps it is the proprietary algorithms used in these commercially available inertial wave sensors that explains their high cost.

Working on the assertion that it is not the hardware that causes the high cost of IMU sensors, but the use proprietary algorithms, we are left once again with two technologies that can be used to measure waves, either GNSS or IMU. A case against using a GNSS based sensor to develop a low-cost and open source wave sensor is the fact that it is a relatively new technology compared to IMU based sensors [23]. As such, there is less information available out there which would be useful in developing a wave sensor using this technology. To illustrate this point, there are several commercially available IMU based wave sensors available [3], [25], [26], [27] however at the time of writing this review there is only one commercially available GNSS based wave sensor. This sensor is made by Xeos and is named “Brizo”, it first went on sale in April of 2018 [5].
While there are several studies demonstrating that measurement of ocean waves using GPS velocity signals is a viable option [6], [23], [24], there is just not the same amount of prior research available compared to IMU based sensing techniques. This prior research mentioned in section 3.1 includes technical documents which contain the accumulated knowledge of years of experience working with accelerometer based wave buoys assembled by an American state body, the National Data Buoy Centre [2], as well as open source algorithms [22] and several studies which prove that IMU technology is suitable as a low-cost solution to ocean wave sensing [14], [28].

3.3 Commercial Sensor Comparison

This section will compare two commercial wave sensors. The SVS-603 sensor was chosen for this comparison because it has similar specifications to other commercially available wave sensors [25], [26], [27]. The Brizo GNSS wave sensor was chosen as it is the only commercial example of a GNSS wave sensor that could be found.

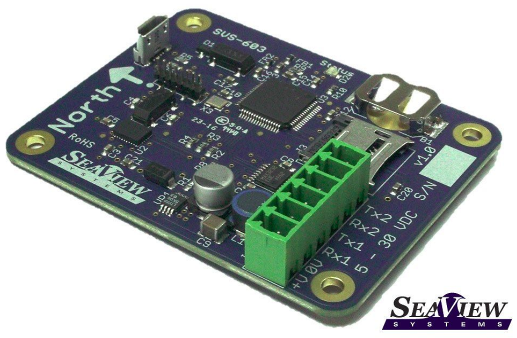

Figure 4. SVS-603 Wave Sensor

Figure 5. Brizo GNSS Wave Sensor

3.3.1 Power Consumption

The hardware of most commercially available IMU-based wave sensors normally consists of a 9DOF MEMS sensor with a processor which will analyse the IMU data and transmit the wave data via a serial data link for integration into a larger buoy data collection system or as a standalone system [1], [25], [26], [27]. The advantage of this type of hardware is it requires a relatively low amount of power to run compared to a GNSS based system. For example, the SVS-603 wave sensor made by Seaview Inc. shown in Figure 4 above, consumes only 150mW when powered from a 12V supply [3]. The Brizo GNSS-based sensor made by Xeos shown in Figure 5 by comparison consumes between 0.75-1.3W when powered from a 12V supply depending on the settings used. Use of the Brizo requires a separate GNSS antenna to be purchased and installed on the data buoy for the system to function [5].

3.3.2 Accuracy Comparison

The SVS-603 wave sensor claims an accuracy of ± 0.5% for significant wave height, period measurement has an error of less than 1% and heading angle is accurate to within ± 4 degrees [3].

The Brizo wave sensor claims an accuracy of greater than 1% for significant wave height, better than 1% accuracy for period measurement and heading angle is accurate to within ± 3 degrees [5].

Based on these results, it would seem that both GNSS and IMU based technologies have the ability to provide roughly equal accuracy in the measurement of significant wave height, period and direction.

It should be noted that neither manufacturer provides exact details or background information on how these accuracy numbers were calculated [3] [5].

3.4 Conclusion

Based on the arguments outlined in section 3.1 and 3.2 , IMU technology is the best option currently available for the goal of developing an open-source and low-cost wave sensor. While GNSS was worth mentioning and exploring, the wealth of information available related to IMU motion sensing and wave measurement gives it a distinct advantage over GNSS.

4 Existing Research Related to Low-Cost Inertial Wave Measurement

This section will examine previous research which has been carried out in the area of low-cost inertial wave measurement to determine if low-cost 9DOF IMU sensors can be used to accurately measure wave parameters.

4.1 Tyndall Wireless Inertial Measurement Unit (WIMU) Wave Sensor

Research into the development of a low cost inertial wave measurement sensor has been carried by Donal Kennedy, Michael Walsh and Brendan O'Flynn working out of the Tyndall National Institute. Their research came about after they identified the prohibitively high cost of commercially available wave sensors and the potential for a low-cost 9DOF IMU based solution [14]. The system used was the Tyndall WIMU seen in Figure 6 below.

Figure 6. Tyndall 9 DOF WIMU

The Tyndall WIMU consisted of custom made stackable PCBs with an onboard accelerometer, gyroscope, magnetometer and an XBEE wireless transceiver. It is interesting to note that this device was not made with the specific intention of wave measurement. The original intention was gathering motion data of people for use in rehabilitative, sports and at-home healthcare [31]. The Tyndall WIMU was tested both on a ferris wheel apparatus as shown in Figure 7 and then using a wave tank such as the one shown in Figure 8 [14].

Figure 7. Ferris Wheel Apparatus

Figure 8: Wave Tank

As particles in a wave at sea exhibit motion in a circular orbit, a Ferris wheel type apparatus can be used to mimic the motion of a data buoy at sea [33]. The use of a Ferris wheel is the standard testing and calibration method used to characterize Waverider buoys [32].

Using the Ferris wheel apparatus, an average wave height was calculated over the course of several minutes with the error found to be -0.6% ±3.1%. The Tyndall sensor was then fitted to a scaled version of a floating buoy and deployed in a wave tank. An error of average wave height measurement was found to be -0.9% ±6.7% , while the period was consistently measured within 1% of the true value. The study concludes that MEMS based IMU sensors are well suited to sea state measurement applications, although they do note that their algorithms have not been tested in a real life deployment with realistic ocean conditions [14].

4.2 Bares Wave Sensor

The Bares wave sensor was developed by two researchers working out of the University of Vigo in Spain. The hardware they used was an Arduino Mega development board with a 9DOF IMU sensor. In a paper presented at the International Workshop On Marine Technology, they outlined the testing process and a rough overview of the results. This study is particularly interesting because it went as far as deploying a wave buoy at sea with the Bares wave sensor and a commercially available wave sensor on board. While this particular paper neglects to include hard numbers such as correlation coefficients and error margins, it does provide several graphs which indicate a high correlation with the TRIAXSYS commercial wave sensor. An example of one of the graphs provided is shown in Figure 9 below.

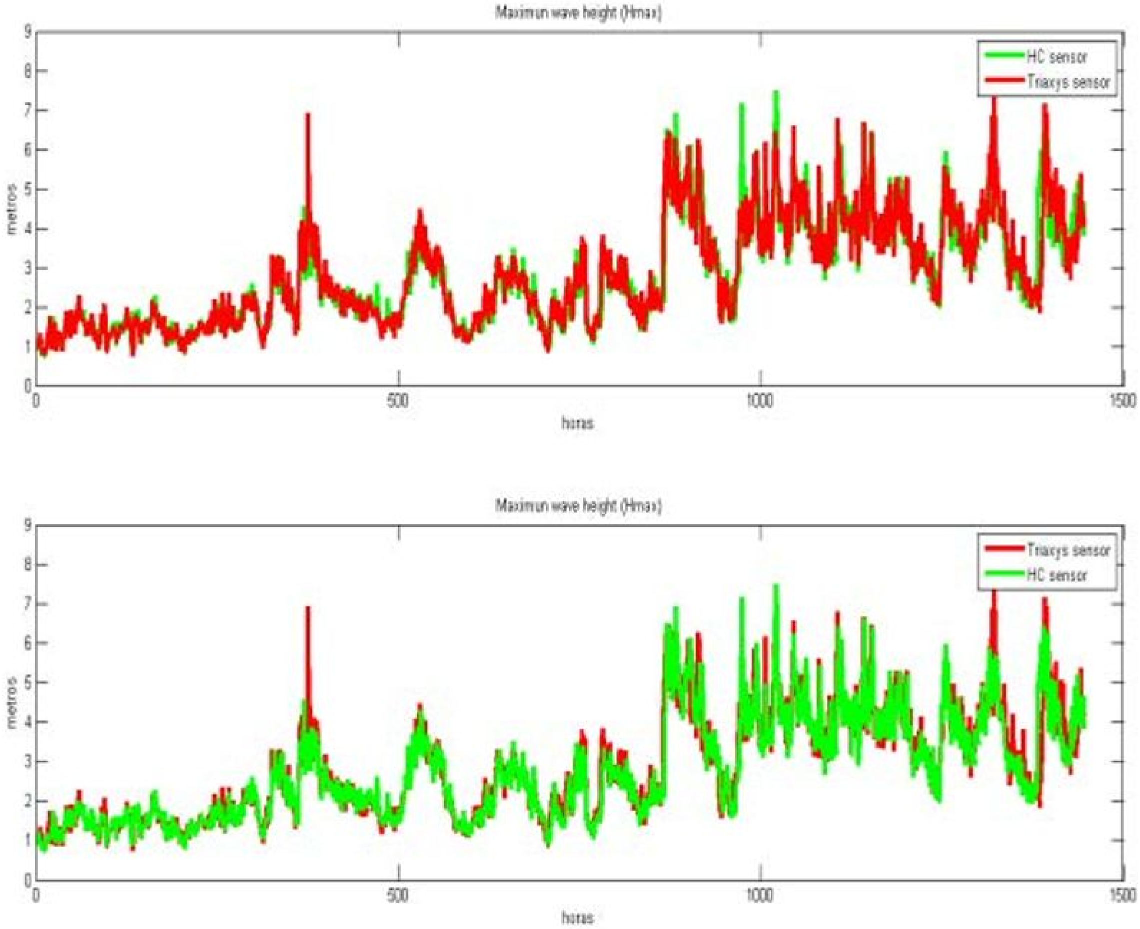

Figure 9. Maximum wave height reported by Bares and Triaxys wave sensors

There are also graphs provided for significant wave height, peak period and mean direction which show similar levels of correlation with the Triaxys wave sensor. The paper concludes that comparative results are very good and that it is possible to access wave sensing technology with lower cost and retain accurate measurement [28].

4.3 Conclusion

The studies mentioned in section 4.1 and 4.2 provide very encouraging results which prove that it is possible to accurately measure wave parameters using low-cost IMU sensors. Both studies conclude that these sensors are well suited to the measurement of wave parameters. The Bares wave sensor which was actually compared in a real life scenario against a commercial wave sensor provides the strongest proof so far that low-cost inertial wave measurement is a viable option.

5 Summary

This literature review started with an overview of some of the uses of wave sensors and a statement that wave sensors are prohibitively expensive for many industry and academic ventures. By decreasing the cost of wave sensors, this barrier to entry can hopefully be reduced which will encourage the wider use of wave sensors on data buoys worldwide.
Section 2 began by providing an overview of what a wave sensor is and the types of parameters it measures. Sections 2.1 and 2.2 then go on to outline the two main wave sensing technologies used on data buoys, IMU based and GNSS based sensors. Both of these sections explore the existing research on each technology and the data showing its viability for use in wave sensing applications.
Following on from section 2, which showed that both IMU and GNSS based sensors were viable options for measuring wave parameters, section 3 compares each of the technologies for suitability in creating an open-source and low-cost wave sensor. Section 3.1 outlines the case for IMU technology, including an abundance of IMU related research to draw from, open source IMU algorithms, technical documents related to measurement of wave parameters and research into the area of low-cost IMU wave sensors which show promising results. Section 3.2 outlines the case for GNSS technology which does have the advantage of being able to track the position of the buoy as well as measuring wave parameters. That seems to be where the advantages end, despite the claim that GNSS is a low-cost alternative to IMU based wave sensors, this claim is examined and found to have no evidence behind it. This section also mentions that there are studies available which specifically examine low-cost IMU sensors and show that they are suitable for wave measurement, whereas the same cannot be said for GNSS based sensors.
Section 4 examines two separate studies which examine the viability of inertial wave measurement using low-cost components. The first study, carried out by the Tyndall National Institute, tested a custom made wave sensor on a Ferris wheel apparatus and in a wave tank. Both of these experiments showed promising results with the caveat that these tests were carried out in a controlled environment. The second study, which came from the University of Vigo, developed a custom made IMU wave sensor and performed a real-world test. This test was also successful and showed very good correlation with a commercially available wave sensor known as TRIAXSYS.

6 Conclusion

The initial premise of this review was that commercial wave sensors are prohibitively expensive for many academic and industry uses. Previous studies into low-cost inertial wave measurement have shown that accurate results can be obtained, even when compared against commercially available sensors. The Bares wave sensor, mentioned in section 4.2 actually uses some open hardware, namely the Arduino Mega [28]. The issue with both of the studies outlined in section 4 is that whilst they do prove that it is possible to measure wave parameters using off the shelf IMU devices, they have done little to change the situation of prohibitively expensive wave sensors. This is partly because neither study has disclosed any details regarding the specifics of the algorithms used to extract wave parameters from IMU motion data. By developing a wave sensor and making all of the hardware and software open-source, it would at least provide a starting point for others to use and build upon. Instead of having separate studies on completely different hardware and different algorithms, making everything open-source provides the potential for sustained collaboration across academic and industry groups.

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