An Autonomous GNSS Wave Sensor Module for Deployment on Existing Buoy Infrastructure

Comparison and Validation of Co-Located GNSS and Accelerometer Directional Wave Sensors

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Abstract

For this paper a standalone OEM (Original Equipment Manufactuer) GNSS wave sensor module is co-located on an existing accelerometer-based three-meter diameter disc wave buoy for statistical comparison. Additionally, a GNSS wave sensor is placed on an existing, already deployed, nearby navigational buoy 700 meters away to assess suitability as a platform for a GNSS directional wave height sensor. Both sensors were deployed in 30 meters depth of water in Herring Cove, Nova Scotia, Canada.

Keywords—GNSS, wave height, accelerometer, buoy

I. INTRODUCTION

This paper investigates the deployment of a GNSS (Global Navigation Satellite System) based wave height sensor on a navigation buoy and environmental buoy equipped with an existing accelerometer-based wave height sensor.

A new GNSS wave height sensor, the Brizo, was developed by Xeos Technologies to address the need in the market for an OEM (Original Equipment Manufacturer) GNSS wave height and direction sensor. Two Brizos were deployed on oceanographic buoys over the summer and fall of 2017. The first deployment was a co-location of a Xeos Brizo with a TRIAXYS Directional Wave Sensor on a dedicated 3-meter oceanographic buoy platform. The second deployment was on a nearby navigational aid, bell-equipped buoy. The Brizos were configured to output wave statistics three times an hour after a 20 minute measuring period, with one of the periods aligning with the TRIAXYS sensor every hour.

This paper compares the performance of the Brizos with an existing accelerometer-based wave height sensor across five major wave height spectrum parameters.

II. BACKGROUND

Spot measurements of wave parameters and spectra have developed over the last half-century. Technologies include acoustic Doppler profilers, pressure-based sensors, accelerometer and GPS/GNSS-based solutions (Herbers et al. 2012). Accelerometer and force-feedback based systems have been the traditional choice for sensors since Datawell released their first Waverider buoy in 1968. Accelerometers have the advantage over acoustic and pressure-based systems of being suitable for deployment in any environment including deep water. GNSS sensors have similar advantages but are also more robust than accelerometers due to the lack of moving parts, lower cost, less maintenance, and ease of deployment on existing offshore infrastructure.

Traditional accelerometer-based sensors need to be deployed at the center of gravity of the buoy to correctly measure wave parameters. GNSS-based sensors are not limited by this restriction. The 3D accelerometers experience errors in data readings when placed on buoys away from the center of rotation due to the introduction of rotational acceleration. These errors are naturally reduced in GNSS-based sensors because the GNSS receiver is measuring velocity and not acceleration. This frees the antenna to be placed along the central Z-axis with minimal effects on outputted wave statistics. Travelling away from the central Z-axis is possible but can add bias to the directional statistics.

Xeos Technologies has been developing the Brizo, a GNSS-based bidirectional wave height sensor with a goal of designing a highly accurate OEM unit that can be easily deployed on existing buoys. By integrating cellular and Iridium telemetry, the Brizo is a standalone sensor, datalogger and telemetry unit. The Brizo utilizes standard NDBC spectral analysis techniques and formulas to calculate wave parameters for waves of periods from 1.6 s to 33 s (Earle, 1996).

III. TEST PLATFORMS AND EQUIPMENT

Two Brizos were deployed in a local harbor port alongside a third directional wave sensor for comparison. The first Brizo referred to as Brizo1 was mounted on an AXYS 3-meter met-buoy equipped with a NextWave II directional wave sensor which provides the comparison data for this paper.

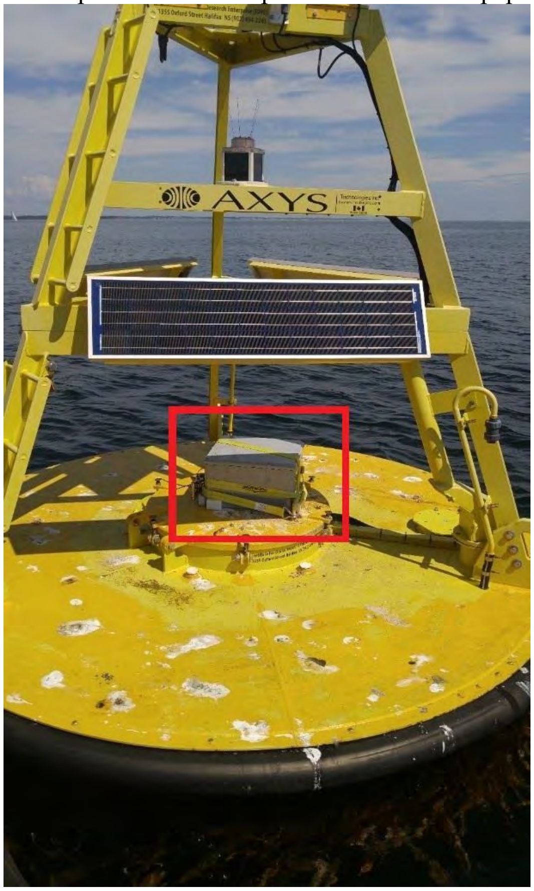

Fig.1 – *Co-located Brizo1 deployed (grey box) on AXYS Directional Wave 3 Meter Disk buoy in Herring Cove, NS, Canada*

Brizo1 was deployed on top of the access hatch, with the NextWave II installed inside of the buoy. Co-locating the sensors on the same platform removes potential sources of error based on buoy suitability and spatial difference in wave patterns providing an accurate comparison of sensors. The GNSS antenna, Brizo sensor and batteries were all inside of the grey box pictured above and temporarily attached with ratchet straps. Data retrieval was achieved by the Brizo's embedded cell modem. It should be noted that the GNSS antenna placement in this configuration is sub-optimal for GNSS performance. The superstructure above the antenna in addition to the proximity to the metal deck of the buoy creates conditions for loss of lock and multipath.

Brizo2 was deployed in a similar fashion on an existing navigational aid 'bell buoy', numbered HM1 in the Halifax Harbor, as seen in Fig. 2. The Brizo was once again placed in a gray waterproof enclosure with batteries equipped with an embedded cell modem to transfer the data. Due to the density of the superstructure surrounding the lower portion of the central axis of the buoy, this was not thought to be an advisable antenna location. To overcome this an external antenna was placed on a pole to allow the antenna to clear the superstructure (antenna can be seen above the green superstructure to the right side). The pole was then clamped to the superstructure using U-bolts at a height reachable from the deck. This placement is a compromise due to the horizontal offset from the central axis. Increasing the vertical antenna offset beyond the top of the buoy is not recommended due to the possibility of measurement errors and loss of lock during heavy sea states with severe buoy tilting. Horizontal offsets will result in a bias in the direction measurement. This bias is reduced as the vertical offset increases. The results of this test are compared with parameters output by the TRIAXYS sensor located on the environmental buoy 700m away.

Fig. 2 - *Brizo2 Deployment (Grey Box) on Navigation Bell Buoy in Herring Cove, NS. Antenna Above Buoy.*

Fig. 3 shows the location of the two buoys relative to the shore and each other. The distance between the buoys is approximately 700m, while the depth of water beneath is 30m. Both of the buoys are located in the mouth of Halifax harbour along an important shipping channel. The wave statistics are representative observed were utilized for operational decisions by the pilotage authority. Both locations were determined by existing buoy infrastructure and endorsed by the Atlantic Pilotage Authority and Canadian Coast Guard who own the rights to both buoys.

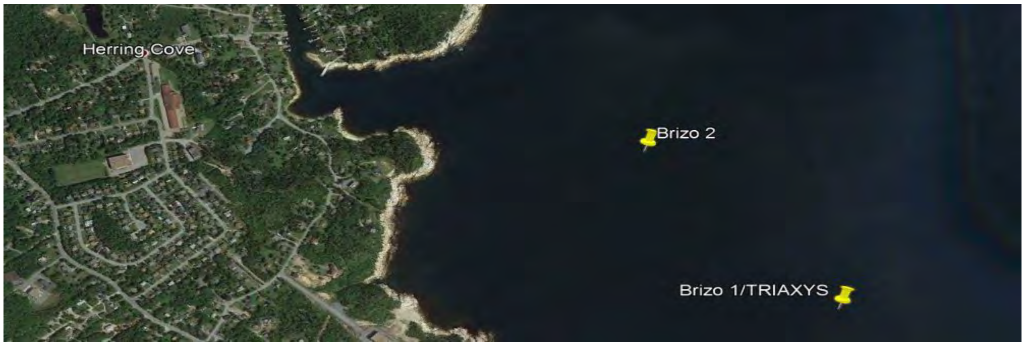

Fig. 3 – *North oriented satellite map of test bed with buoy locations marked*

IV. TESTED PARAMETERS

For the purpose of comparison, the parameters of interest for this test were those outputted by TRIAXYS sensor: Significant Wave Height (m), Maximum Wave Height (m), Peak Wave Period (sec), Average Wave Direction (deg) and Average Wave Spread (deg). Other parameters have been calculated but cannot be validated through this test such as swell height, wind wave height/period, wave steepness ratio and others.

Throughout the test the significant wave height varied between 0.10 m and 2.43 m. Table 1 below indicates the minimum and maximum readings of the sensor throughout the test for the remainder of the statistics being validated.

V. FIELD DATA

The field test was operating for the majority of the month of September 2017. The Brizos were installed on already developed buoys without removing the buoys from the water. Data from sensors was output at the rate of two measurements per hour from both sensors. To allow direct statistical comparisons of similar wave conditions, only measurements that were temporally aligned from all three sensors were included in statistics.

As denoted in Table 2 on page 4, there were 1052 data points and 1201 data points for Brizo1 and Brizo2, respectively. The reduced number for Brizo1 is due to a trial of an RTK (Real-Time Kinematic) system that would be used in a future tide gauge application for the Brizo. Since the GNSS data was used in RTK and not as standalone readings, it was not considered for this validation study.

Table 1: Statistical Ranges of Data

Statistic	Minimum	Maximum
Significant Wave Height (m)	0.10	2.43
Maximum Wave Height (m)	0.37	4.96
Peak Wave Period (sec)	2.66	12.80
Peak Wave Direction* (deg)	46	158
Peak Wave Spread (deg)	33	49

* Peak wave direction is measured from True North

VI. OCEANOGRAPHIC WAVE HEIGHT BUOY: BRIZO1

The deployment of Brizo1 was designed to mimic as closely as possible the deployment of a traditional GNSS or accelerometer sensor. Analyzing the statistical data over time, the Brizo closely follows the TRIAXYS sensor. Only some of the comparison graphs are presented here for briefness, with the remainder presented in Appendix A. The purpose of deploying one of the Brizos on the same structure as an accelerometer-based sensor was to not only show relation in data but also to compare robustness in design and ease of deployment. The direct comparison shows a large degree of agreement between the two sensors. This test confirms the validity of using GNSS-based wave height sensors agreeing with previous findings (Herbers et al. 2012).

As seen below in Fig. 4, the significant wave height statistics measured by Brizo1 trend closely with the TRIAXYS sensor for values with reasonable wave signal (significant wave height above 0.25 m). This is further supported by a scatter plot of the results of the two sensors contained in Appendix A as Fig. 6.

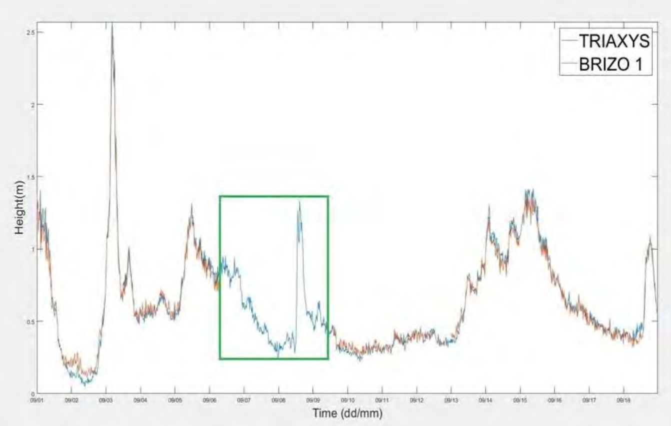

Fig. 4 – *Comparison graph of significant wave height Brizo1 vs TRIAXYS*

Table 2: Brizo Location Details

Unit	Location	Water Depth	Number of Records	Dates Operational
Brizo1	44°33’31.20”N 63°32’44.38”W	30m	1052	Sept 1st, 2017 – Sept 29th, 2017
Brizo2	44°33’52.29”N 63°32’55.61”W	30m	1201	Sept 1st, 2017 – Sept 29th, 2017

The close trends in data between Brizo1 and the TRIAXYS sensor are also observed in other wave parameters. As seen in Fig. 7 in Appendix A, peak wave period also shows agreement in results between the two sensors. There is however one period in the data that shows some varying results. Between September 2nd and 3rd there is a divergence of results of the sensors on the graph. This period is outlined by a green box on the graph as well. This difference in data aligns in time with a period of non-significant wave signal (significant wave height less than 0.25m). The graph comparing peak wave periods indicates the Brizo is measuring more signal from a longer period wave than the TRIAXYS sensor during this timeframe.

The peak wave direction plot shown in Fig. 8 in Appendix A displays shows a consistent 5 degree bias between the sensors for this wave parameter. It is unknown what is causing this difference, but it is possible that it is due to compass magnetic calibration error or magnetic interference. GNSS-based wave height sensors rely on the WGS 84 (World Geodetic System 1984) datum North for direction calculations that does not require calibration.

Seen in Table 3 there is a statistical analysis of the data between Brizo1 and the TRIAXYS sensor. All parameters are considered, and comparatively displayed to give a numerical representation of the agreement between the sensors. Included in the table are statistical values of Bias, MAE (Mean Absolute Error), RMSE (Root-Mean-Square Error) and MPE (Mean Percentage Error). All equations are shown below, respectively.

$$E(\bar{X}) - \mu = E\left(\frac{1}{m}\sum_{k=1}^{m} X^{[k]}\right) - \mu \tag{1}$$

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n} = \frac{\sum_{i=1}^{n} |e_i|}{n}. \tag{2}$$

$$\mathrm{MPE} = \frac{100\%}{n} \sum_{t=1}^{n} \frac{a_t - f_t}{a_t} \tag{3}$$

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{T} (\hat{y}_t - y_t)^2}{T}}. \tag{4}$$

VII. NAVIGATION (BELL) BUOY: BRIZO2

Brizo2 was deployed 700 m from the TRIAXYS buoy, on a navigational buoy. As shown the distance between the two sensors and difference in buoy shape and weight has a minimal effect on the difference between the datasets. No additional processing was done to account for the buoy profile and response. Comparison data is from the TRIAXYS sensor mounted on the buoy 700 m away. Evaluation of results for this study was done between Brizo2 and the TRIAXYS sensor.

As shown in Fig. 9 in Appendix A the significant wave height closely trends with the TRIAXYS. This is further supported by Fig.10 in Appendix A, a scatter plot of the results of the two sensors. The peak wave period of the Brizo2 also tracks well with the TRIAXYS sensor, though the quality is slightly noisier relative to the Brizo1 and TRIAXYS sensors. This slight variation in data can be attributed to the change in position, as individual data points may be slightly different, but the overall trends and are agreeable.

Fig. 11 in Appendix A shows a peak wave direction plot with a similar small bias between the sensors comparable to that observed in the same graph for the Brizo1. The measurements from Brizo2 again show some extra noise compared to Brizo1 and TRIAXYS sensor. This is likely from the offset from centre of the antenna on the navigation buoy, though the data still tracks with that if the TRIAXYS sensor well. A statistical analysis of the parameters from both sensors can be viewed in Table 4 using the same equations as those in Table 3.

The mean percentage error of all statistics is increased except for peak wave direction. This increased difference can be accounted for by differences in buoy dynamics, wave fields, water depth, proximity to shore and antenna offset errors. Despite these errors, the agreement between the two data sets is at a substantial level.

Table 3: Statistical Analysis of Parameters, Brizo1 vs TRIAXYS

	Significant Wave Height (m)	Maximum Wave Height (m)	Peak Wave Period (sec)	Peak Wave Direction (deg)	Peak Wave Spread (deg)
Bias	-0.01	0.01	0.03	+7.4	-1.2
MAE	0.03	0.08	0.623	9.34	2.4
RMSE	0.035	0.11	1.21	11.43	3.14
MPE	1.01%	0.67%	0.37%	5.28%*	3.48%

*Included for completeness, percentage error is a poor indicator of directional accuracy as statistical error is not correlated to the magnitude of the value measured

Table 4 Statistical Analysis of Parameters, Brizo2 vs TRIAXYS

	Significant Wave Height (m)	Maximum Wave Height (m)	Peak Wave Period (sec)	Peak Wave Direction (deg)	Peak Wave Spread (deg)
Bias	-0.01	0.00	-0.075	7.0	-0.197
MAE	0.04	0.11	0.98	13.2	2.84
RMSE	0.06	0.15	1.55	16.92	3.6
MPE	2.07%	1.35%	2.82%	4.16%	4.36%

VIII. CURRENT AND FUTURE DEVELOPMENT

As of writing the Brizo sensor has finished its initial development cycle and is available on the market to output "First Five" wave parameters. Further development and testing of the platform Brizo continues. Further validation of other wave parameters and complete directional wave spectra are under way in multiple locations around the globe comparing the Brizo to other available sensors.

The Brizo can export all of the GNSS observable data via its embedded cellular and Iridium modems to a land-based server for wave spectra processing. Future development will allow the Brizo to process complete directional spectra onboard the sensor and transmit via Iridium, cellular or 900 MHz radio.

Further research and testing will look at the use of additional sensors to augment performance when the antenna is offset from the center of gravity of the buoy in addition to allowing the Brizo to be compatible with external sensors as a data source. Additional work is currently underway to use the Brizo as a tide gauge sensor, through an RTK connection using the built-in telemetry.

In July 2018 the wave measuring met buoy in Halifax Harbor was removed for maintenance. The Brizo was chosen to be deployed to provide critical real time wave data to the local port authority while the met buoy was under going maintenance. The Brizo was deployed on the same navigation buoy as Brizo2 during the the initial experiment. The user interface of XeosOnline was used in this case to display real-time wave data on graphs as the Brizo processed and transmitted data over Iridium. XeosOnline also displays all SOH (Status of Health) messages received reporting temperature, battery voltage and time of message.

As seen in Fig. 5 the results of this test were consistent with those of the previous deployments, reporting wave significant height results between 0.18 m and 1.07 m. Wave height and direction data was reported to the Atlantic Pilotage Authority for operational use.

IX. CONCLUSION

A comparison of a new GNSS wave height and direction sensor (Brizo) against an accelerometer-based wave height buoy, showed a high level of agreement for parameters evaluated. This was true even when data was compared at another site 700 m away on a different, non-purpose buoy style. This development specifically leverages the advantages of GNSS sensors over accelerometer-based systems in modifying buoys for the addition of OEM wave height sensors.

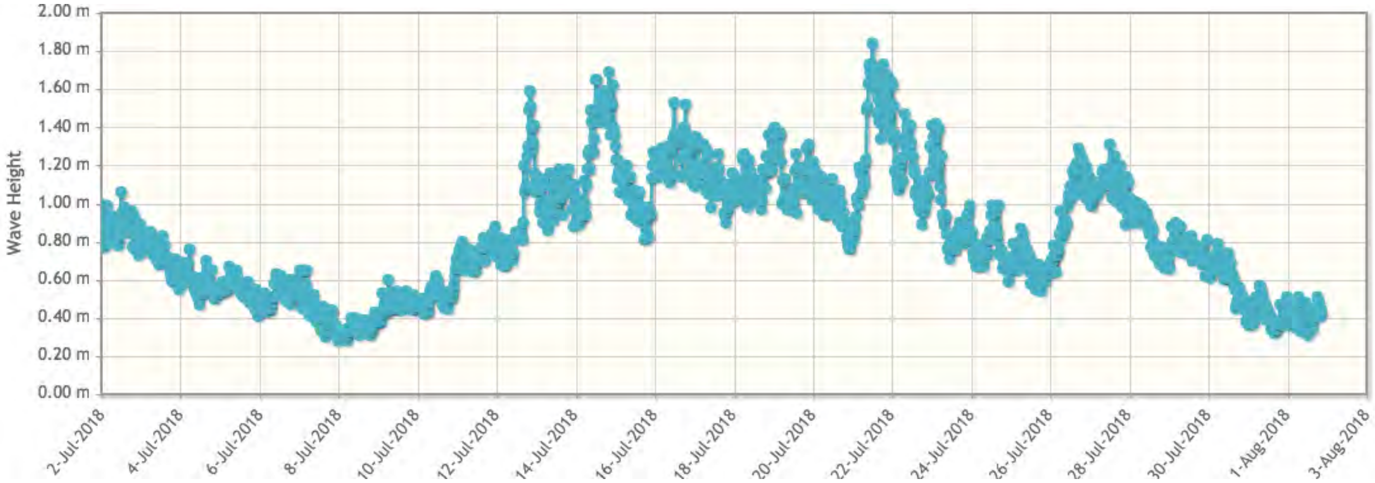

Fig. 5 – *Significant Wave Height graph at re-deployed Brizo2 location in July of 2018*

APPENDIX

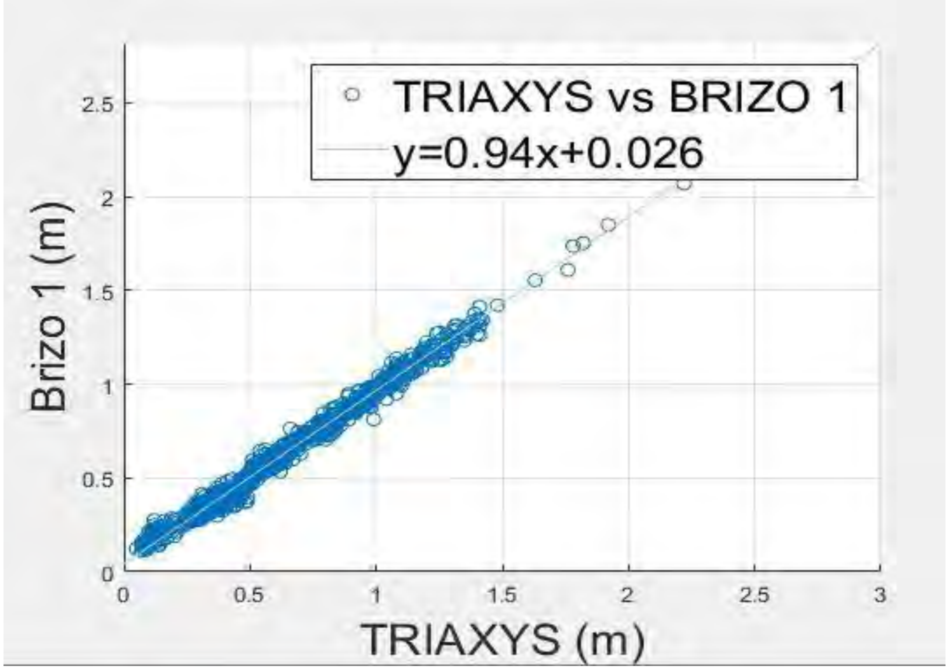

Fig. 6 – *Scatter plot of Brizo1 vs TRIAXYS significant wave heights*

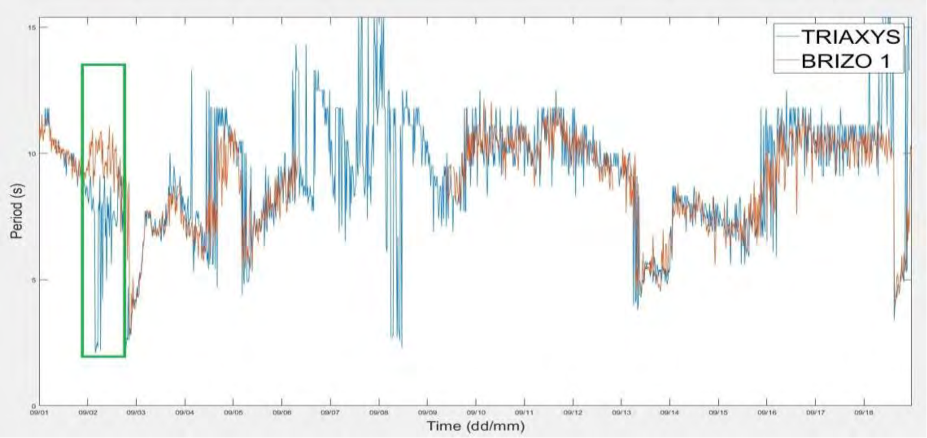

Fig. 7 – *Comparison graph of peak wave period, Brizo1 vs TRIAXYS*

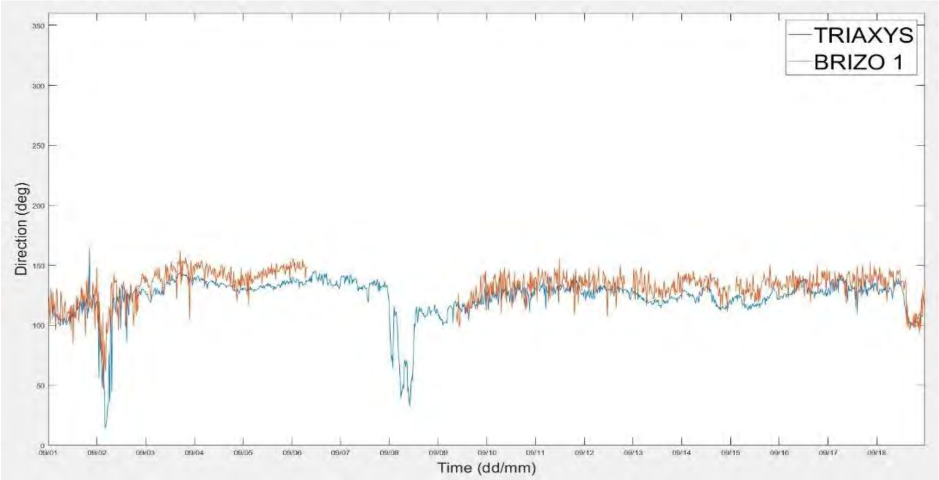

Fig. 8 – *Comparison of peak wave direction, Brizo1 vs TRIAXYS*

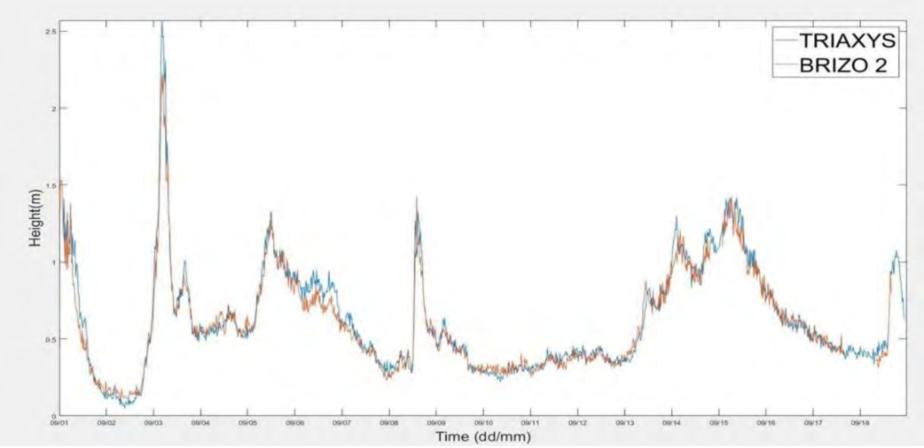

Fig. 9 – *Comparison graph of significant wave height, Brizo2 vs TRIAXYS*

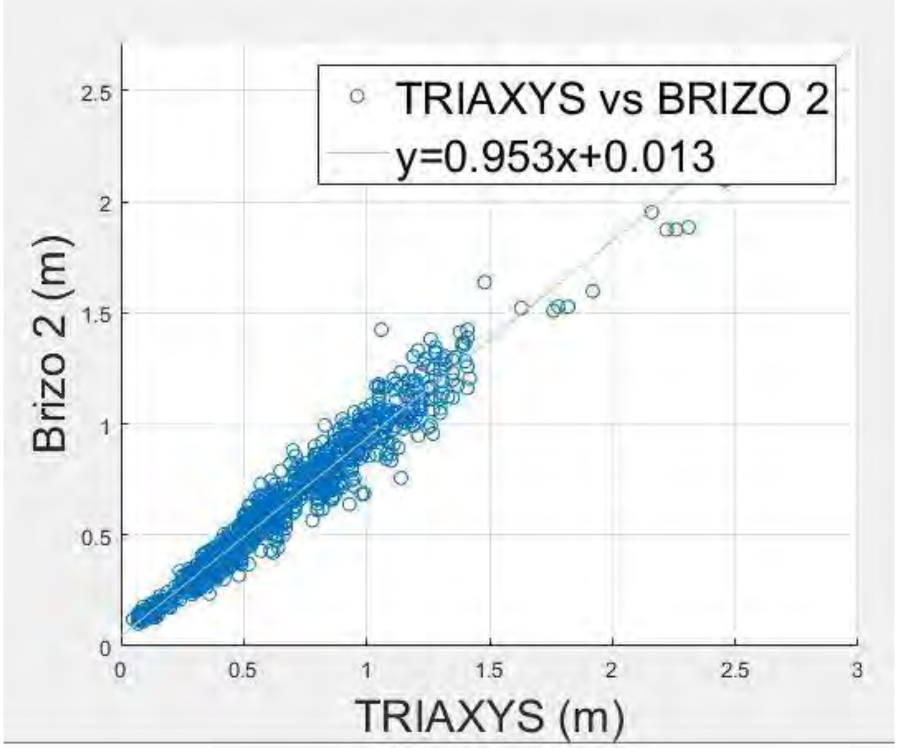

Fig. 10 – *Scatter plot of Brizo2 vs TRIAXYS significant wave heights*

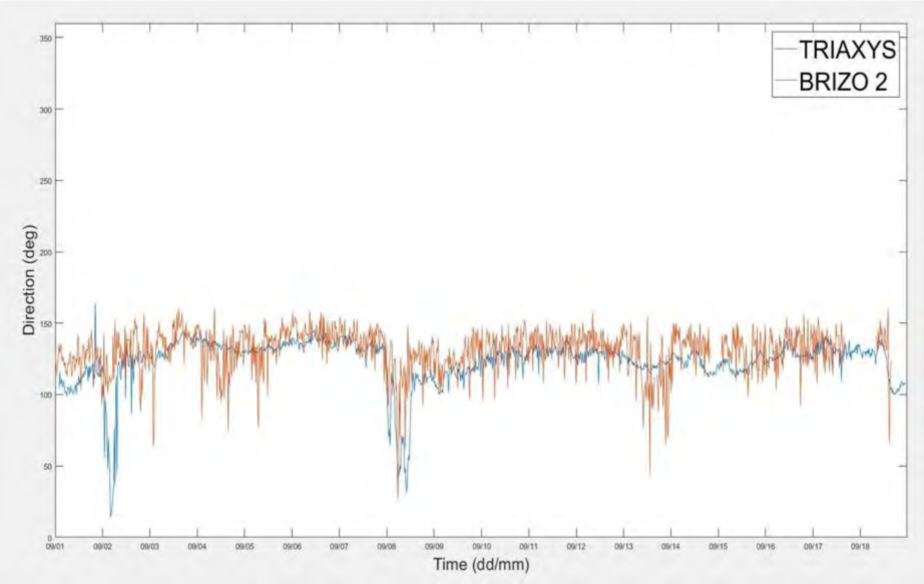

Fig. 11 – *Comparison of peak wave direction, Brizo2 vs TRIAXYS*

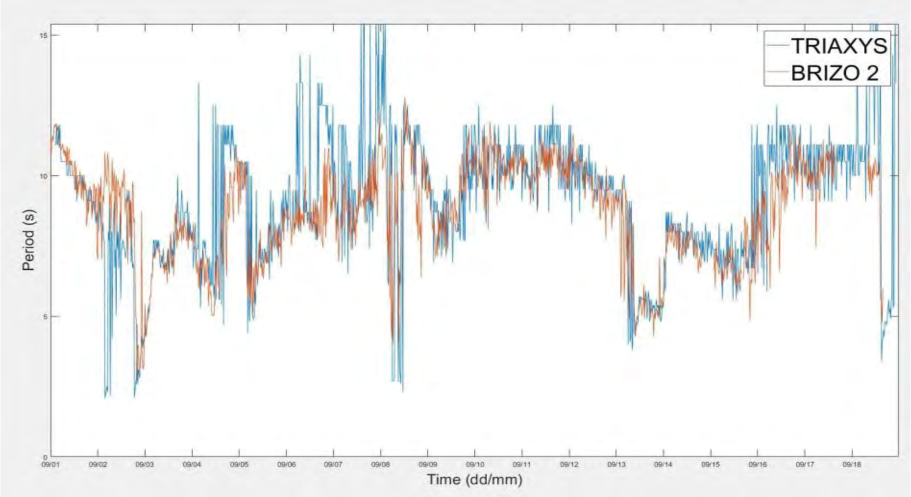

Fig. 12 – *Comparison graph of peak wave period, Brizo2 vs TRIAXYS*

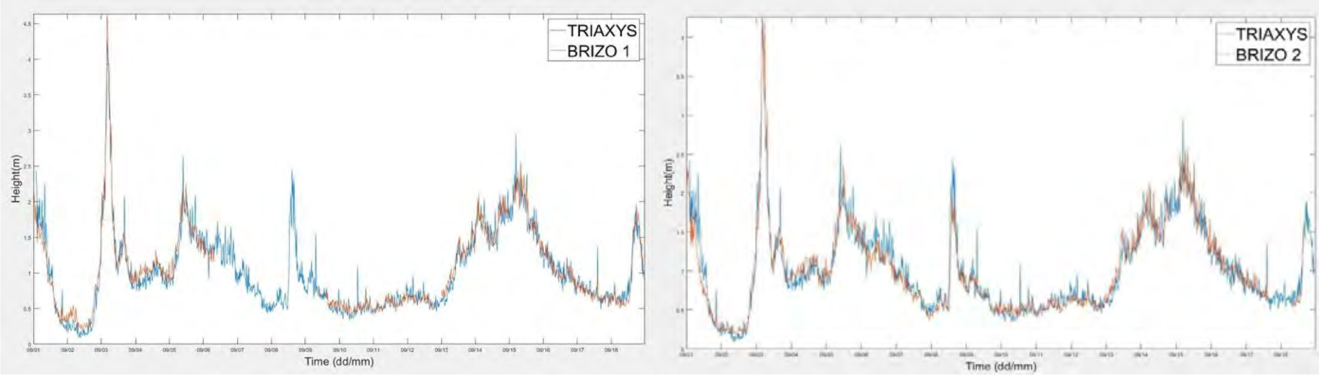

Fig. 13 – *Comparison graphs of maximum wave height, Brizo1 and Brizo2, respectively, vs TRIAXYS*

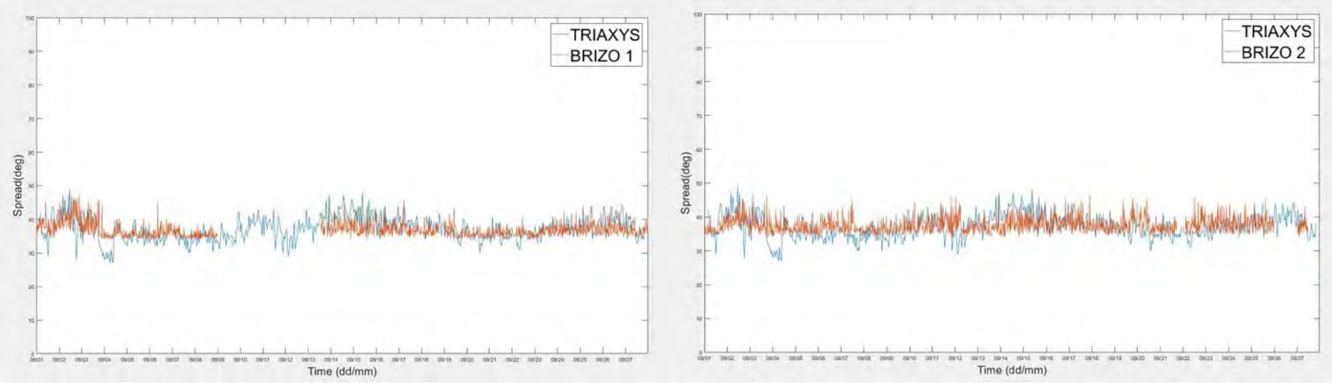

Fig 14 – *Comparison graphs of peak average wave spread, Brizo1 and Brizo2, respectively, vs TRIAXYS*

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