Update on NOAA's development and test of measuring waves with a radar tide gauge

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***Abstract*—The NOAA Center for Operational Oceanographic Products and Services (CO-OPS) maintains the National Water Level Observation Network (NWLON), consisting of over 200 stations providing real-time water level observations along U.S. coasts. The transition to microwave radars as the primary water level sensors at most stations has allowed for the exploration of the sensor's wave measurement capability and plans to incorporate nearshore wave observations into the network. CO-OPS currently does not operate and maintain any wave measurement systems, but the new radar water level sensors offer a cost-effective way to enhance nearshore wave coverage for navigational safety and ocean research.**

Previously reported work evaluated the wave measurement capabilities of microwave radars in the CO-OPS inventory [1], [2]. Initial field tests showed that the Xylem WaterLOG H3611 radar, currently deployed at NWLON stations, had an output limited temporal resolution for accurately measuring high-frequency wind waves. However, the Endress+Hauser Micropilot M FMR240 (E+H) radar, which serves as the base sensor component for the WaterLOG, demonstrated better performance in resolving higher-frequency energies without low-frequency aliasing issues.

Recent efforts that have followed previous reports involve demonstrating radar water level sensor wave measurement performance at a broader range of coastal environment types and implementing real-time, automated wave processing capability on the field systems data logger. We will provide a detailed description of the latest wave processing and transmission capabilities, along with latest data results from new field stations.

***Index Terms*—waves, microwave radar**

I. Introduction

The NOAA Center for Operational Oceanographic Products and Services (CO-OPS) maintains and develops the National Water Level Observation Network (NWLON), which consists of over 200 long-term stations that provide real-time water level observations across U.S. coasts. CO-OPS is in the process of transitioning the primary water level sensor at most stations, from an acoustic ranging system to microwave radars. During this transition, we have explored the potential of using the radar water level sensors to directly measure non-directional hourly waves in order to expand the range of NWLON products. The possibility of incorporating real-time wave measurements into the CO-OPS observatory network has been a topic of discussion for several years and is in alignment with the NOAA IOOS National Operational Wave Observation Plan [3]. At present, CO-OPS does not operate any wave measurement systems of its own, and all the wave data it shares is sourced externally. Using the new radar water level sensors may offer a low cost and convenient way to increase nearshore wave observational coverage throughout the U.S. to support navigational safety and ocean research applications.

Previously reported work focused on evaluating the wave measurement capability and efficacy of microwave radars in the CO-OPS' inventory [1], [2]. Several radar sensors advertise wave measuring capabilities, but few studies have presented wave heights measured directly from radar water level sensors. Our initial field test results found that the microwave radar, Xylem WaterLOG H3611, currently deployed at NWLON stations did not have adequate temporal resolution for accurately measuring high frequency wind wave energy. However, we were able to use the Endress+Hauser Micropilot M FMR240 (E+H)(seen at each station in Fig.1), which is the base sensor component, on which the WaterLOG is based. The E+H radar demonstrated a greater capability to resolve higher frequency energies while avoiding the low frequency aliasing issue observed in the WaterLOG.

After confirming the wave measurement capabilities of the E+H radar at one test station, our next goals were to test its performance in a range of different wave environments and to develop a method for real-time processing and transmission of the wave parameters on the field system's data logger, alongside the standard water level products. The initial field test was conducted alongside an existing NWLON station on the US Army Corps of Engineers (USACE) Field Research Facility pier in Duck, NC.

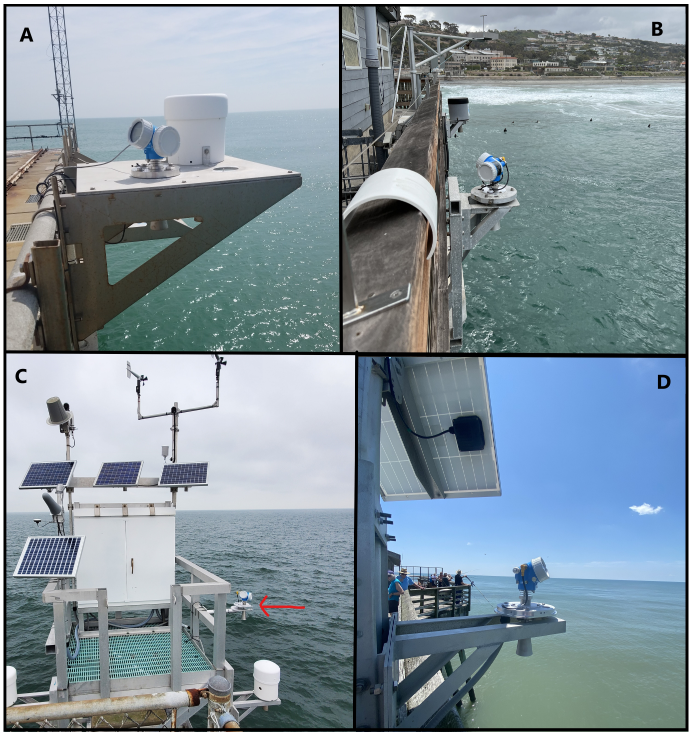

Fig. 1. Microwave radar test stations: A) Duck, B) La Jolla, C) CBBT, D) Myrtle Beach

Fig. 2. Sutron Satlink 3

Duck, NC is representative of an Atlantic coast, open ocean NWLON site that experiences a broad range of wave conditions. We have extended the test to include 3 more sites. A sensor is installed in La Jolla, CA on the Scripps pier. This is another open ocean NWLON site, with a different wave energy regime due to its Pacific coast location. A Nearby Datawell Waverider buoy and a Digital Paros pressure sensor, both operated by the Scripps Institution of Oceanography Coastal Data Information Program (CDIP) are used as references. Another E+H sensor is installed alongside the NWLON station on the Chesapeake Bay Bridge-Tunnel (CBBT), which crosses the mouth of the Chesapeake Bay. This location represents an intermediate wave environment inside a bay and near a major shipping channel. It is also located within the region of the Chesapeake Bay South NOAA Physical Oceanographic Real-Time System (PORTS®). As a reference, we have installed a bottom mounted 600 kHz Nortek acoustic wave and current profiler (AWAC). We have also deployed a Sofar Spotter buoy nearby, as part of another field test and evaluation effort. Most recently, a fourth test station has been installed on the Myrtle Beach State Park pier in South Carolina. Similar to Duck, this site is also off the Atlantic coast, however differences in coastal boundaries and shelf extent result in a lower average wave energy than Duck, NC.

For previously reported results summarized in references [1] and [2], wave parameters were computed manually, post data collection, using raw 1 Hz water level measurements from the radar tide gauge, downloaded remotely from the system's data logger. We computed hourly spectral densities from the 1 Hz water level time series using a Welch FFT approximation with Mathworks MATLAB software. More recently we have developed and implemented real-time wave processing on the tide gauges data logger, following the previously reported, Matlab implemented, algorithms. The logger is an OTT\Hydromet Sutron Satlink3 (Fig. 2), with availability to create customized Python scripts. Currently, field systems at the Duck, NC, CBBT, and Myrtle Beach test sites are equipped with the real-time wave measurements capability, along with standard NWLON water level products.

We will present a detailed description of the latest radar water level and waves system updates including details of the onboard wave processing and transmission that were recently implemented on the Satlink3 data logger. We will also present the results from all sites with comparisons between the microwave water level sensors and their respective reference sensors.

II. Real-Time Wave Processing

During previous field testing, wave parameters were computed using MATLAB software. It was necessary to download the 1 Hz range to surface measurements that were stored on a Sutron XLite 9210B data logger. Outliers were removed and the samples were detrended. Hourly power spectral densities were computed from the first 2,048 one Hz samples using the Welch FFT approximation (pwelch function in MATLAB) with an NFFT length of 64 and a Hamming window with a 50% overlap. Significant wave height ($H_{m0} = 4.0\sqrt{m_0}$, where m_0 is the zeroeth spectral moment) and other wave parameters were estimated from the spectra. In addition, the maximum wave height (H_{max}) and top one-third of wave heights ($H_{\frac{1}{3}}$) were computed by identifying the zero crossings.

The latest version system employs the Satlink 3 (SL3) data logger and satellite transmitter (Fig. 2), which allows for the custom implementation of algorithms to process 1 Hz measurements to wave parameters directly on a data logger. The SL3 provides on-board python scripting capabilities. Python code was developed to process 1Hz range to surface measurements directly on the SL3 to provide real-time hourly wave measurements using the same algorithm as the one described above. Additionally, it incorporates CO-OPS' traditional real-time 6 minute water level observations. This advancement makes it possible to obtain the wave measurements in real time, as it is no longer necessary to transmit very large amounts of data (1 Hz) or do any computations post-transmission.

Two tests were conducted to ensure consistency in results generated by the two waves processing tools - the previous Matlab analysis tools and newly developed SL3 codes. For the first test, a simple time series consisting of superimposed sine waves and a linear trend was generated using Matlab. For the second test, a 30 day range of E+H radar 1 Hz range measurements from previous field testing at Duck, NC were used. For both tests, the data were processed with both the Matlab and SL3 codes to generate spectral energy density and wave parameters and then results compared. For the sample field data from Duck, NC, E+H radar results from the two processing codes were also compared to available measurements from an AWAC that has served as a wave measurement reference at the site. The results from the SL3 compared well to those from Matlab.

The SL3 logger also offers both a built in GOES satellite transmitter and a cellular modem. A real-time wave data telemetry scheme was developed and implemented along with the new wave processing capability. The system has the capability to encode and transmit the spectra and bulk parameters listed above, at an hourly rate, via GOES. As an alternative, the system's cellular modem can be polled to return a listing of the latest hourly wave measurements.

III. Field Testing

In addition to updating real-time wave processing capabilities, CO-OPS has expanded field test installations to four different field test sites, three of which employ an SL3 with real-time wave processing and telemetry capabilities. Initial testing was conducted at existing NWLON stations that were nearby other wave sensors that could be used as reference. Please note, any gaps in radar measurements are a result of the mishandling of data ingestion and will be retrieved directly from the sensor to back fill each time series for future analysis.

A. USACE Pier, Duck, NC

We upgraded our original test site, located on the United States Army Corps of Engineers (USACE) pier at their Field Research Facility in Duck, NC (Fig. 1A), to the new real-time system in April 2022, and it has operated successfully since then. The top two panels of Fig. 3 show automatically processed and transmitted significant wave height (top) and spectra (middle) for over one year. We have compared the results with the colocated AWAC, run by the USACE, to ensure that the switch did not affect the expected performance. Significant wave height and average period (T_{m1}) compare well between the reference and microwave radar. (Fig. 3, bottom). The average significant wave height during this time period (from AWAC) was 0.89 m and the peak significant wave height was 4.23 m. The maximum, maximum wave height (obtained from the radar) was 5.19 m. The average period was 6.31 s. The bias (average difference) in significant wave height was 5.34 cm and the bias in average period was -0.25 s.

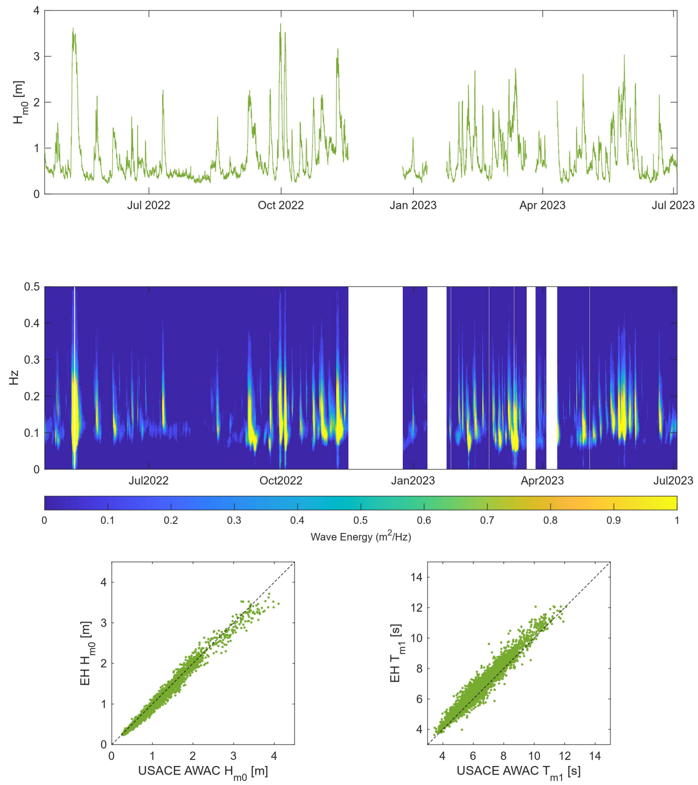

Fig. 3. Field test results from Duck, NC test site. Top: significant wave height, middle: spectral density, bottom left: significant wave height comparison with AWAC, bottom right: first moment period comparison with AWAC.

B. Scripps Pier, La Jolla, CA

The second field test site is another open ocean location, situated on the University of California Scripps Pier in La Jolla, CA (Fig. 1B). A preliminary measurement system employing the original internally logging 1 Hz setup was established at the site during May 2022. The system is planned to be transitioned to the latest real-time station version in the near future. Resulting data still provides a valuable demonstration of the radar waves and water level system's measurement capability in a new, Pacific Coast environment type. It is located near both a CDIP Datawell Waverider Buoy and a CDIP pressure gauge and has performed well for over two years. Results from

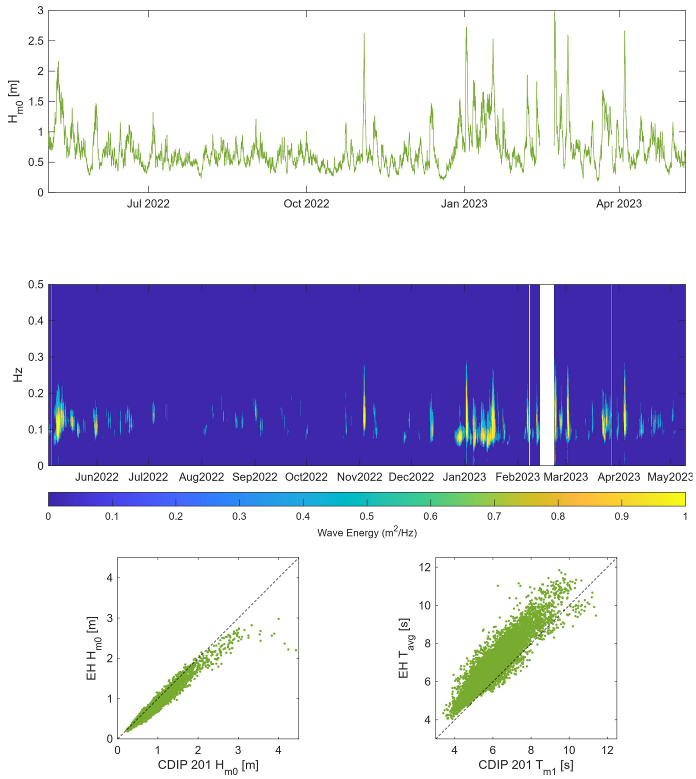

Fig. 4. Field test results from La Jolla, CA test site. Top: significant wave height, middle: spectral density, bottom left: significant wave height comparison with Waverider buoy, bottom right: average period comparison with Waverider buoy.

the past year (May 2022-May 2023), including comparisons with the nearby CDIP buoy, are presented in Figure 4. The average significant wave height during this time period (from the Waverider) was 0.82 m and the peak significant wave height was 4.52 m. The average period was 6.11 s. The bias (average difference) in significant wave height was 11.67 cm and the bias in average period was -0.72 s.

C. *Chesapeake Bay Bridge and Tunnel, Virginia*

In order to demonstrate the systems wave measurement capability at an intermediate wave environment, the next field test site selected was an NWLON Station at the mouth of the Chesapeake Bay, along the Chesapeake Bay Bridge and Tunnel in Virginia. It is located near a major shipping channel and may be valuable as a long term addition to the Chesapeake Bay South PORTS®. The system was established during March 2023, alongside the water level station (CBBT, Chesapeake Channel, VA), on the northern part of the middle bridge (Fig. 5, Fig. 1C). The radar is mounted approximately eight to ten meters above the water surface. Although there are wave measurements from several buoys in the vicinity, their availability is inconsistent and not sufficiently close. Shortly following the radar sensors installation a bottom mounted AWAC was deployed approximately 100 m north of the NWLON station. We also used the opportunity to test a newly acquired Sofar Spotter Buoy and compare its performance to that of the

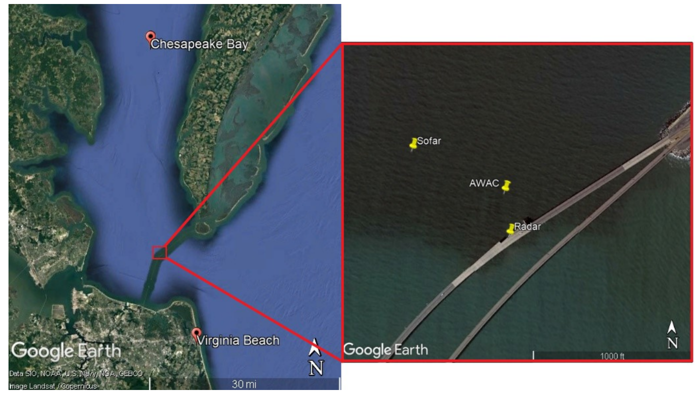

Fig. 5. Map of Chesapeake Bay and CBBT test site location, including AWAC, microwave radar, and Sofar buoy.

AWAC and radar. It was deployed approximately 180 m north of the radar. The water in this area is generally about 16 m deep. The instruments were installed throughout the spring of 2023 and concurrent data collection began on 23 March 2023. The Sofar Spotter system is relatively new to CO-OPS and a more detailed evaluation of system performance and summary of field experiences will be reported in subsequent work.

Overall, all three instruments performed well and consistently throughout the test period. The bottom mounted AWAC was recovered on 29 June 2023, and the microwave radar and Sofar buoy are still operating. The significant wave height, alongside wind speed captured at the collocated NWLON station are shown in Figure 6. The E+H radar generally reported wave heights slightly below that of the AWAC, an average difference of 5.74 cm (Fig. 7). This can likely be attributed to the location of the radar, which is somewhat sheltered by the bridge and a small island. Significant wave height from the Sofar buoy also compared well to the AWAC and to the E+H radar. Average differences between each sensor are presented in Table I.

Differences between the instruments become clear when we analyze the spectral density. Figure 8 shows a time series of the energy density for each sensor and Figure 9 shows the average spectral density of each sensor over the entire test period. We can see that energy peaks generally match well, but the AWAC usually has stronger peaks. An initial look at Sofar power spectral density shows peaks at the low end of the frequency range that do not appear in the other two sensors' measurements. Further analysis is required to assess whether or not this is actual low frequency wave energy or perhaps aliased noise.

D. *Myrtle Beach State Park Pier, Myrtle Beach, SC*

The most recent radar water level and waves field site was established at the Myrtle Beach State Park Pier in Myrtle Beach, SC, during May 2023(Fig. 1D) . The new system makes use of a temporary water level station that was installed following the destruction of nearby Springmaid Pier (which has since been replaced). We used the opportunity to install a Gill Maximet all-in-one weather station on site to

	AWAC-EH		AWAC-Sofar		EH-Sofar	
	Avg. Diff. (cm)	RMSE (cm)	Avg. Diff. (cm)	RMSE (cm)	Avg. Diff. (cm)	RMSE (cm)
H_{m0}	5.72	8.61	2.53	9.27	-3.15	12.05
H_{max}	13.70	18.60				
$H_{1/3}$	8.95	10.82				

TABLE I
WAVE MEASUREMENT COMPARISONS FOR CBBT FIELD TEST.

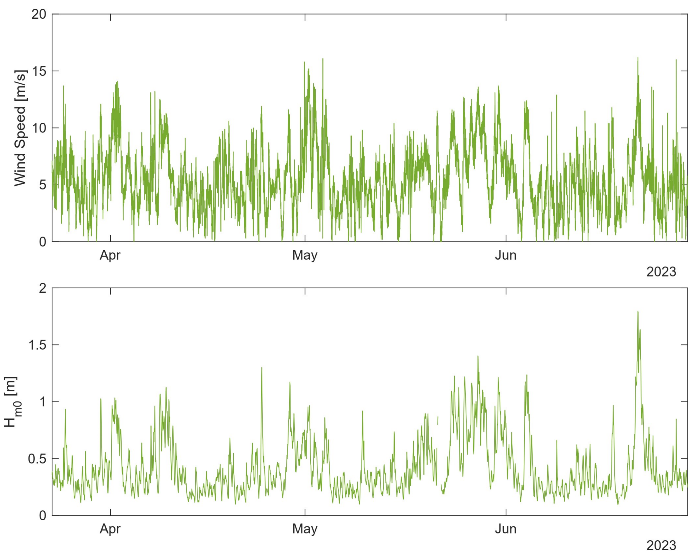

Fig. 6. CBBT test site results. Top: wind speed from collocated NWLON station, bottom: significant wave height.

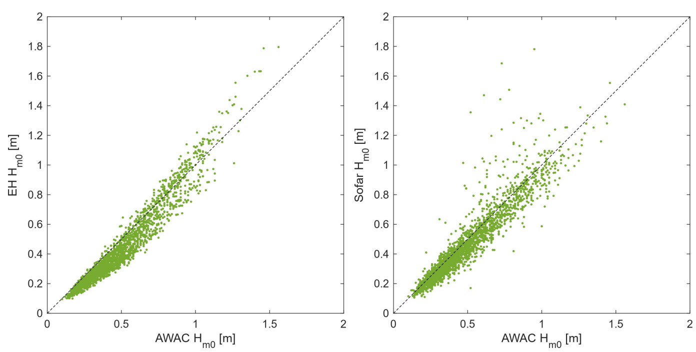

Fig. 7. Significant wave height comparisons from CBBT test. Left: AWAC and E+H radar, right: AWAC and Sofar buoy

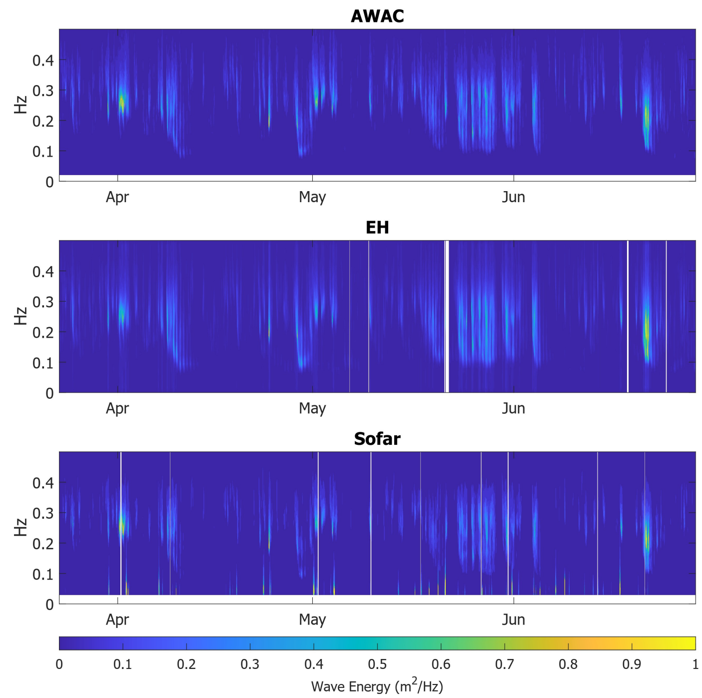

Fig. 8. Spectral density from each sensor at CBBT test station. Top: AWAC, middle: E+H microwave radar, bottom: Sofar buoy.

compare with meteorological measurements the Springmaid Pier NWLON station. This final system is performing well thus far, and some of the most recent results are shown in Fig. 10. The average significant wave height was 0.55 m and the maximum wave height measured was 2.10 m. The average wave period was 5.00 s.

IV. DISCUSSION

The transition of radar water level sensor technology across NWLON offers the opportunity to leverage existing NOAA observatory infrastructure to collect simultaneous water level and wave observations, expanding CO-OPS' suite of observations and analysis products. Extensive testing over the course of several years has demonstrated the microwave radar's capability to measure both hourly non-directional wave spectra and derived bulk parameters, along with traditional 6 minute average water level time series.

Since initial field test and evaluation results were collected at the Duck, NC station and reported in references [1] and [2], CO-OPS has expanded its field demonstration efforts to include three additional sites, each with different coastal environment types. Results for all three new locations further demonstrate the radar sensors performance capabilities and potential to serve as an operational system.

Successful field results of the radar water level sensor's wave measurement capability motivated the design, development and implementation of a real-time, automated wave processing capability on the field system's data logger. The transition to the SL3 combined logger and transmitter allowed for the implementation of wave processing algorithms using Python. Additionally, wave data real-time telemetry capabilities were implemented, via GOES Satellite transmission and cellular modem. Field testing of the real-time, fully automated

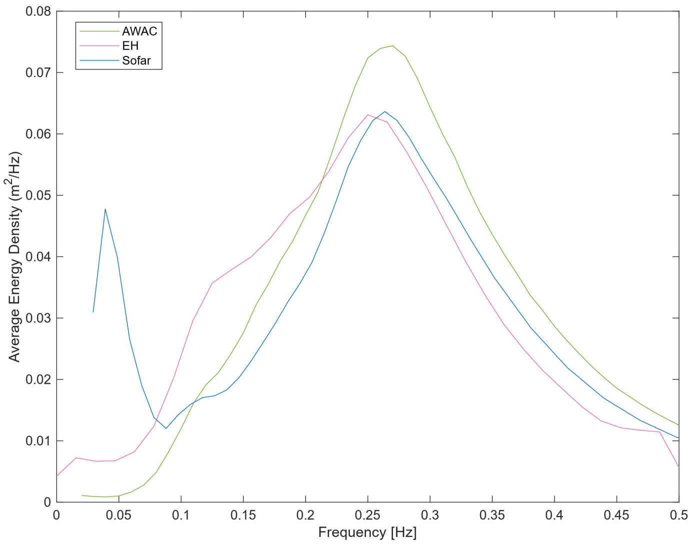

Fig. 9. Average energy density for full time period from each sensor at CBBT test station. Green: AWAC, pink: E+H microwave radar, blue: Sofar buoy.

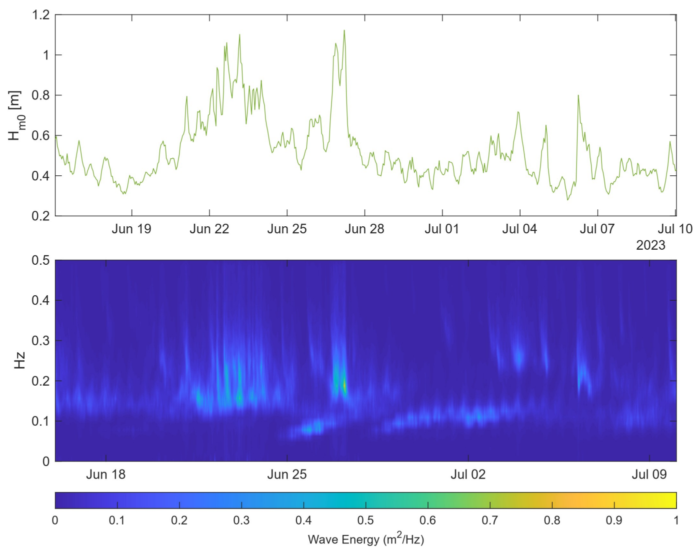

Fig. 10. Myrtle Beach site results. Top: significant wave height, bottom: spectral density.

radar waves and water level system to date has yielded successful results, taking the system another step toward the technology readiness level required for operational use across NWLON. The purpose of this paper is to demonstrate the design and performance of the real-time radar wave measurement system. Further data analysis on specific results at each field test site will be presented in future work.

CO-OPS is currently planning the next steps required to establish an operational wave measurement capability that can be implemented across a range of select NWLON station locations. Critical challenges to be addressed include IT infrastructure, measurement system design and configuration modifications, field operations procedures, and prioritizing NWLON sites of interest for the addition of waves.

V. Acknowledgements

Disclaimer: The mention of trade names or commercial products in this paper does not constitute endorsement or recommendation for use by the National Oceanic and Atmospheric Administration or any of its components.

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