

8.2 USING MICROWAVE RADAR FOR LONG TERM REMOTE SENSING OF OCEAN SURFACE DYNAMICS

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1. INTRODUCTION

Over the past two hundred years, sea level observations in coastal areas have been used to help mariners navigate oceans and estuaries, cartographers develop nautical charts, government agencies regulate boundaries, and scientists gain a better understanding of various physical oceanographic processes. An important mission of the United States National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) is to support those who depend upon sea level information throughout U. S. coastal regions by providing the most up-to-date real-time products and services available along with easy access to quality controlled historical data archives. This involves continual development and maintenance of the National Water Level Observation Network (NWLON), a system of over 200 long-term observatories throughout the United States along with maintenance of web sites where real-time oceanographic and meteorological observations, forecasts, related analysis products and historical data can be accessed.

Although applications of NWLON products and services are most commonly related to enhancing safe navigation, generating tide predictions, and determining reference tidal datums (for example, Mean Lower Low Water), NWLON applications have recently broadened. For instance, the NWLON is now a key part of the NOAA Tsunami Warning System and the NOAA Storm Surge Warning System. Collecting continuous long-term observations of sea level along with simultaneous meteorological measurements at many NWLON station across all of the nation's coasts, including the Great Lakes, results in a unique data set that is expansive in space and time. Such observations have the potential to be extremely valuable to the oceanographic and meteorological research communities since continuous long term sea level records can capture various processes at the ocean surface over a range of time scales, including gravity waves, storm surge, astronomical tides, and long term sea level trends related to climate. An important ongoing mission of CO-OPS is to continue to encourage the use of NWLON's expansive oceanographic and meteorological data archives in basic research applications and to continue to provide information to various interested communities on the details of available data archives, characteristics of

the types of sensors employed, and developments in new measurement technology. The main purpose of this paper and corresponding presentation is related to this final item, sharing information with the oceanographic and meteorological research communities on the testing of a new type of sea level sensor.

When maintaining a network of coastal observatories it is important to keep abreast of evolving measurement technology in order to ensure that the most up to date and accurate instruments are being used. Methods for observing sea level began with the tide staff and human observer and then gradually evolved to tide gauges that required less human intervention. Today float/shaft angle encoders, as well as acoustic and pressure sensors are used to collect data at NWLON stations, with acoustic sensors being the most common primary sea level sensor throughout the network. Although these instruments have served NOAA well, they are not without disadvantages. For example, all of NWLON sea level sensors that are currently operational include components that are in contact with the water, making them susceptible to corrosion and bio-fouling.

Over the past several years CO-OPS has been monitoring developments in microwave radar technology including several studies that have recognized the many potential benefits of using such sensors to collect long-term sea level measurements (Barjenbruch et al 2002, Blasi 2009, Boon and Brubaker 2008, Bosley 2003, Fulford 2005, 2007, Gronlie 2006, Miguez et al 2005, Woodworth and Smith 2003). Microwave radar sensors offer the opportunity to overcome one of the largest disadvantages of currently-used water level sensors by avoiding contact with the harsh marine environment. Recently developed radar sensors can be deployed on structures in coastal areas, such as piers or pilings, in order to measure the ocean surface remotely, from above. As a result, many typical problems such as biological fouling, corrosion, and damage from vessel traffic can be avoided. Easy access resulting from an out-of-the-water setup can potentially simplify deployment and maintenance requirements. Also, microwave signals will not be impacted by temperature gradients occurring over their transmission path and signal wavelengths are large enough to prevent significant scattering from small water particles near the air-sea interface, for example sea spray, fog, or rain.

When introducing a new sensor technology into a pre-existing observatory such as NWLON, CO-OPS emphasizes the importance of conducting thorough testing and evaluation in order to fully understand how

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a new sensor will perform in the field over the wide range of environmental conditions experienced at various observatory locations. Over the past several months, CO-OPS has been conducting a series of laboratory and field tests of four different types of microwave radar sensors in order to gain a better understanding of their performance capabilities and to determine whether or not such sensors are suitable for integration into NWLON. Results to date have provided valuable information on optimizing sensor configurations, evidence of the sensor's ability to measure various physical processes, and the impact of various changes in environmental parameters on sensor performance (Heitsenrether, Bushnell, Krug, et al 2009, Boon 2008 & 2009).

This paper provides an overview of CO-OPS recent test activities involving four different selected microwave radar, including results obtained to date in the laboratory and field. Some sample microwave sensor sea level measurements, showing tidal signals and non-directional surface gravity wave statistics, will also be presented. The following section describes basic characteristics of both the acoustic sensors currently used at most NWLON stations and the new microwave radar sensors that are undergoing testing. Section three discusses the test and evaluation plan being followed and sections four and five summarize recent laboratory and field test activity. The final section summarizes results to date.

2. DESCRIPTION OF WATER LEVEL SENSORS

NWLON Acoustic Sea Level Sensors

Currently, the primary sea level sensor at most NWLON stations is the Aquatrak® 3000 series acoustic sensor manufactured by the Aquatrak Corporation. The sensor is deployed with a narrow calibration/sounding tube housed inside of a cylindrical protective well. The sounding tube and well extend down into the water column and a 5 cm orifice at the base of the well lets water in (Shih and Bear 1991). The well and orifice act as a partial filter eliminating a significant amount of high frequency surface wave motion from water level records before processing is applied. The acoustic sensor tracks sea level by transmitting an acoustic signal down the stilling well and then deriving distance from the time of flight of the echo returned off of the water surface. The diagram in Figure 1 shows a typical NWLON station setup including an Aquatrak in a protective well.

At NWLON stations, the Aquatrak collects 1-Hz water level values which are then used to calculate averaged values at 6 minute intervals. Six minute values are based on a sample of 181, 1 Hz data points centered on the hour and tenth-hour. Outliers of more than three sample standard deviations are rejected and then an arithmetic mean is calculated using the remaining points in the sample.

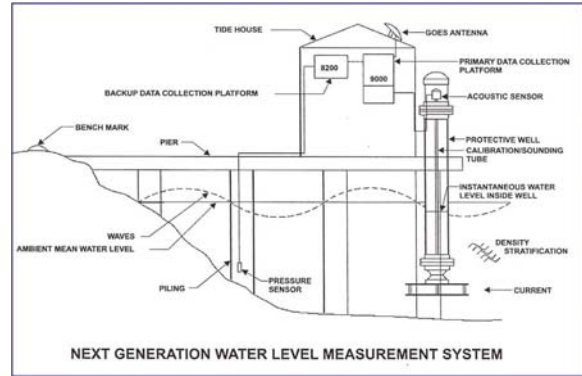


Figure 1. Diagram of a typical NWLON station with acoustic sensor deployed within a protective well.

Microwave Radar Sensors

There are two types of microwave radars most commonly used in current applications, the pulse and the frequency modulated continuous wave (FMCW). Pulse sensors transmit a series of single pulse signals that measure range based on the time of flight of the reflected signal from a given target surface. FMCW sensors continuously transmit a FM chirp signal and calculate range to target based on the phase shift between the transmitted and reflected signals.

After closely monitoring several tests of these devices for the purpose of measuring sea levels (Barjenbruch et al 2002, Blasi 2009, Boon and Brubaker 2008, Bosley 2003, Fulford 2005, 2007, Gronlie 2006, Miguez et al 2005, Woodworth and Smith 2003), based upon experience both within NOAA and outside organizations, CO-OPS has selected sensors from four manufacturers to test and evaluate: 1) Miros SM094, 2) Design Analysis H3611, 3) Ohmart/Vega Vega Puls 62, and 4) the Sutron RLR-0002 (The use of brand names in this paper is for the purpose of identifying sensors only and does not imply endorsement by NOAA). Table 1 summarizes the attributes of the four selected sensors.

Table 1. Characteristics of the four microwave sensors selected for testing.

Sensor Make/Model	Signal Type	Beam Angle (deg)	Max Range (m)
Miros SM094	FMCW	10	10
Design Analysis H3611	Pulse	10	22
Ohmart/Vega VEGAPULS 62	Pulse	8	10
Sutron RLR-0002	Wideband Pulse	32	18.5

Microwave sensor beams are dispersive, so the size of the sensor footprint on a given target, such as the ocean surface, increases linearly with range. This parameter is important when considering the impact of sensors' spatial resolution on measurement capability. Manufacturer specified beam spreading angles for the four sensors to be tested (listed in Table 1) were used to calculate surface footprints as a function of range from the detected surface. The relation between beam spreading angle, α , sensor range from a surface, R , and foot print size, X is depicted in Figure 2. Footprint width as a function of sensor range from the ocean surface was calculated using the following expression:

$$X = 2R \tan \frac{\alpha}{2}$$

Figure 3 shows a plot of calculated sensor footprint size as a function of sensor distance from the ocean surface, for the four sensors tested. Note, the Miros SM094 and Design Analysis H3611 sensors have the same beam angle, and hence the same footprint values.

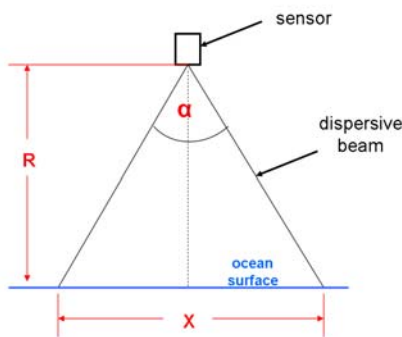


Figure 2. Relation between beam angle, α , sensor range from ocean surface, R , and sensor foot print size, X .

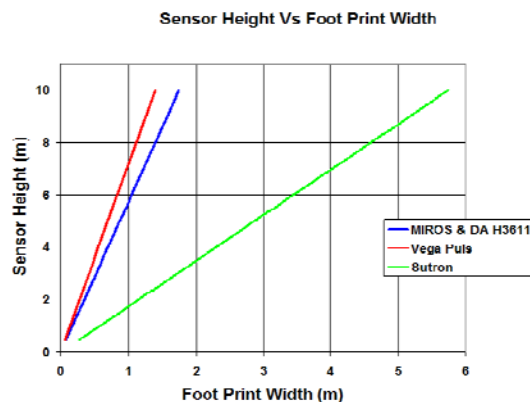


Figure 3. Sensor footprint versus range to water surface, based on specified beam spreading angles listed in Table 1.

3. OVERVIEW OF TEST PLAN

Starting in March 2008, CO-OPS has been conducting a series of laboratory and field tests of the four selected microwave radar sensors (Bushnell, 2008). The test plan is primarily based on the unique applications and stringent requirements of NWLON, however, information on other microwave sensor testing conducted to date throughout the sea level community has also been taken into account in an attempt to build off other's useful results. The main objectives are to better understand fundamentals of sensor functioning, demonstrate the operational capability of all sensors, quantify their accuracy, assess their suitability for integration into the NWLON, and pending successful test results, determine what is required to transition this type of sea level sensor to an operational status.

NWLON stations are located in many different coastal areas throughout the United States, covering a variety of different environments. Testing needs to address how different environmental parameters will impact the performance of these sensors. NWLON sea level data are used in multiple applications, all of which are very important to the public, including transmission of real-time 6 minute water level for safe navigation, development of tidal prediction models, the coastal element of tsunami detection systems, and long term monitoring of sea level change to assess impacts of climate change. Data collected during testing should be adequate for developing optimal methods for processing raw microwave range records to obtain sea level changes at all temporal scales of interest.

A series of laboratory tests were incorporated into the plan for the purpose of observing the impact of certain individual environmental parameters on sensor performance in a controlled environment. Two laboratory tests have been completed to date (discussed in Section 4), one to observe impacts of various types of surface gravity waves and another to observe the impact of extreme temperature variability on measurement stability. Additional laboratory testing currently underway at CO-OPS field office facility in Chesapeake, VA involves observing sensor performance in small enclosed areas to investigate possible waveguide effects and observing the impact of rain, mist, etc on return microwave signal strength.

Field test planning began with the selection of three locations to test the four microwave sensors. The test sites are NWLON station locations with significantly different coastal environments: Duck, NC, Port Townsend, WA, and Fort Gratiot, MI. These sites were selected to represent the most challenging, average, and least-challenging NWLON field locations for an open air sensor to accurately measure sea level, respectively. Since each test site is located near an NWLON station, at least one reference sea level sensor will be available along with basic meteorological measurements to assist in characterizing environmental variability. The goal is to collect at least one year of data from each of the

four sensors at each field site, longer if possible, in order to capture sea level measurements over a broad range of environmental conditions.

As an extra, a Universal Laser Sensor (ULS) range sensor, manufactured by Laser Technology, Inc. is also being included in all of the microwave sensor tests. CO-OPS currently uses the ULS as a redundant range sensor at a number of operational observatories as a QA check for measuring the air clearance below a bridge.

Since the series of tests will span more than a year, CO-OPS will compile results in a series of bi-annual interim reports that will be available for external distribution.

3.1 BASIC FEATURES OF TEST SENSOR SETUP

In all of CO-OPS laboratory and field test deployments, the four microwave sensors and laser are mounted in the same type of metal plate, which is shown in Figure 3. This allows sensors to be positioned to aim at a target in the same direction relative to a common reference plane. The mounting plate is designed such that accompanying triangular brackets on each side of the plate permit the entire mount and sensors to be conveniently attached to different types of structures extending over a water surface, for example poles or railings along the side of a pier as shown in Figure 5.

In all test setups, each microwave range sensor records 1 Hz range measurements (with the exception of the VegaPuls sensor which collects at 0.5 Hz due to sensor setting limitations) to their own individual data collection platform (DCP). DCPs are used to internally store range data which is downloaded manually. At each field site, DCPs that are kept inside a metal enclosure, along with a set of 12-V, sealed rechargeable batteries that provide power to sensors and DCPs, as shown in Figure 6.

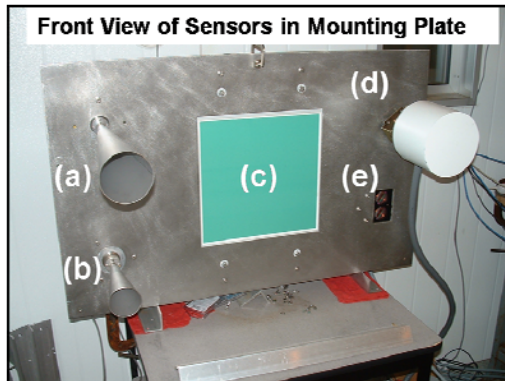


Figure 4. Sensors in mounting plate in lab, (a) Ohmart-VEGA, (b) Design Analysis, (c) Miros, (d) Sutron, (e) ULS.



Figure 5. Sensors in mounting plate attached to pier railing at the Duck, NC field test site.



Figure 6. Four DCPs and batteries in metal enclosure at field site.

4. LABORATORY OBSERVATIONS

4.1 Wave Tank Test

On March 5-6, 2008, an experiment was conducted at the U.S. Naval Surface Warfare Center (NSWC) Maneuvering and Sea Keeping Basin (MASK) facility to assess and quantify impact of surface gravity waves on water level measurements in a controlled setting. Data were used to gain a better fundamental understanding of the interaction of microwave signals and a rough water surface and to develop techniques for removing high frequency surface wave-induced noise from long-term microwave water level records, while retaining low frequency signals (such as tides, wind setup, etc).

The NSWC MASK facility consists of an indoor basin that is 110 meters long, 73 m wide, and 6.1 m deep. Two sides of the basin (one 110 m and one 73 m side) are equipped with a series of pneumatic wave-maker units that can be operated in unison or

individually. Constant wavelength waves from 1.25 m to 10 m long and up to 0.6 m high can be generated continuously or random surface realizations for a specified wave frequency spectrum can be generated over time. During the test, the four microwave sensors in the mounting plate were suspended from an overhead crane above the water surface, at tank's center, with sensors looking vertically downward (Figure 7). A series of runs were conducted with sensors located at four nominal heights (above the water surface) 3, 5, 7, and 9 m, in order to vary sensor footprint widths. At each measurement height, a series of varying wave conditions were repeated. First a series of 1-D regular waves were generated, over a range of different lengths (short to long relative to sensor footprint widths), and then a series of irregular-ocean like wave conditions were generated, including a 2-D wave field.

Figures 8(a)-(d) show examples of time series of water level measured by each microwave sensor for the series of wave conditions generated at the measurement height of 3m. Water level records were obtained by demeaning and inverting measured sensor-to-water range. Annotations at the top of each figure (red text with arrows) specify the wavelength and wave conditions that correspond to each period of water level fluctuation seen in the 1-Hz records.

Plots show that both the MiroS and Sutron sensors [(a) and (b)] have a relatively fast time response compared to the Design Analysis and Ohmart/VEGA and resolve more of the wave-induced water level fluctuations. Both the Design Analysis and Ohmart/VEGA show a significantly slower time response, which CO-OPS participants later learned was a result of built-in filtering and tracking algorithms

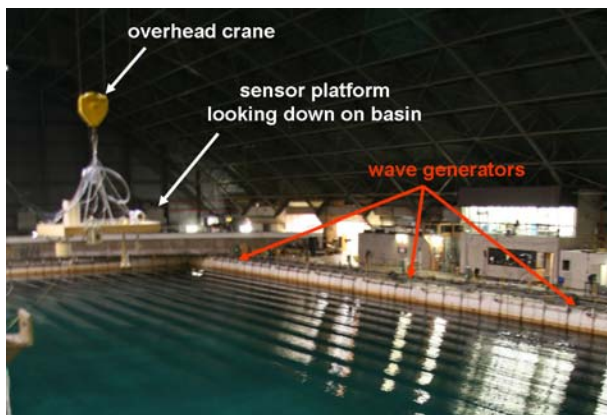


Figure 7. Sensor platform, suspended from overhead crane, with sensors looking down on the water surface.

employed by these sensors when they are set up “out of the box” with default configuration settings. During runs with regular 10-meter long waves, the Ohmart/VEGA seems to lock on to either the crests or troughs of the continuous wave train, flipping back and forth from one to the other, which seems to

indicate that the sensor's default processing settings that are not optimal for this application. Since this experiment, the CO-OPS team has learned more about sensors' settings via test results and has worked with vendors to ensure more optimal setups are used during field testing. In summary, it seems best to configure sensors to provide raw 1 Hz range measurements (disable temporal filtering beyond 1 second) and then perform filtering during post processing, based on the nature of the record at a particular site.

More details on this work can be found in a paper recently published in the IEEE Oceans'08 conference proceedings (Heitsenreth, Bushnell, Boon2008). Results showed that presence of continuous, regular short wavelength waves revealed some limitations of the microwave sensors and resulted in offsets in water level measurements. However, for most test runs involving waves generated over a broad range of frequencies (more representative of real conditions in the field), sensors performed well and measured water levels within 1 cm during the presence of surface roughness. Wave-induced offsets in water level measurements showed a dependency on surface wave wavelength/sensor footprint ratio and bandwidth of surface wave spectra.

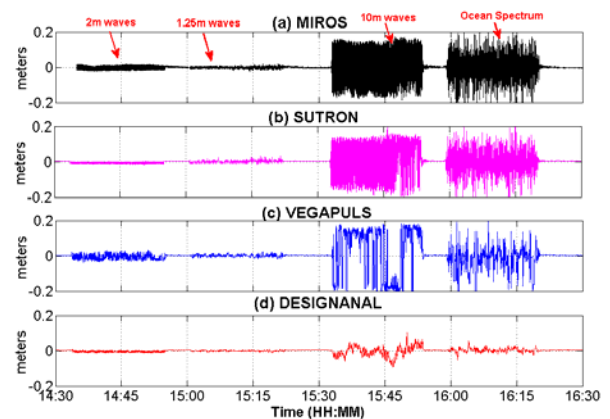


Figure 8. Time series of water level fluctuations from run with sensor platform at 3 m; (a) MiroS SM-094 (b) Sutron RLR-0002 (c) Ohmart/VEGA VEGAPULS 62, and (d) Design Analysis H3611.

4.2 TEMPERATURE CHAMBER TEST

On August 20-22, 2008 CO-OPS conducted a temperature dependency test of the four microwave radar and ULS laser at the U.S. Geological Survey (USGS) Hydrologic Instrumentation Facility (HIF) environmental chamber at the Stennis Space Center, MS. The main objective was to observe the impact of extreme temperature variability on microwave range measurements.

The 2.5-day test involved setting up the four microwave and sensors inside the HIF environmental chamber, with the sensors aimed to record range on a

flat, fixed target approximately 1.7 m from the sensor (picture in Fig. 4 was taken inside this chamber). Once sensors were set up and recording range to the fixed target, the chamber was closed and the temperature inside was changed in 10°C increments, ranging from -20° to 50°C. At each increment, the chamber temperature was maintained for approximately one hour.

Results indicate that the Design Analysis, Sutron, and Ohmart/VEGA sensors remained very stable throughout the entire test and showed no change in measured range resulting from temperature changes, while the ULS Laser showed a strong dependence on temperature with correlated range changes of ±10 cm. The particular Miros unit taken to the facility turned out to contain a software-firmware mismatch that was accidentally implemented during a routine upgrade, so no useful measurements were obtained with this sensor. More details on results of this laboratory test are provided in a March 2009 NOAA project report which can be made available upon request (Heitsenrether, Bushnell, Krug 2009)

5. FIELD OBSERVATIONS

As discussed above, the CO-OPS microwave sensor test plan (Bushnell 2008) involves installation of a set of the four selected microwave sensors at three different field locations: Duck, NC, Port Townsend, WA, and Fort Gratiot, MI, for long term data collection. Maps in Figure 9 show test locations.

The first test site is at the Duck, NC NWLON station at the U. S. Army Corps of Engineers Field Research Facility (USACE FRF). USACE FRF is an internationally-recognized coastal observatory, which includes a 560-meter pier that extends through the open ocean surf zone. The facility is equipped with a suite of environmental instruments that provide constant high resolution measurements of several oceanographic and meteorological parameters. The pier's open ocean location on North Carolina's Outer Banks often experiences high wave conditions and storm surges, representing one of the most challenging environments for an open air sensor to accurately measure water level. The site offers an ideal setting to observe the effect of surface gravity waves on MWWL measurements and the impact of the harsh physical environment on sensor hardware, such as corrosion. At this site, sensors are deployed at the end of the FRF pier, over sea level in the surf zone (shown in Fig 5).

The second test site is located at an NWLON station in the city of Port Townsend, WA on the city ferry terminal pier. Port Townsend is just northwest of Seattle and its coast is in an enclosed area in the northern region of the Puget Sound, just eastward of the Strait of Juan de Fuca. Due to the region's high latitude and complex bathymetry of the enclosed basin, the site experiences a stronger than average tidal signal. Since there is limited fetch due to the surrounding land, surface roughness development is limited during periods of high winds. As a result,

water level records collected at this site typically have a high signal-to-noise ratio (tidal signal to surface wave noise), which is why the site was selected to represent an average environment, less challenging than that of USACE FRF. Sample comparisons of microwave radar versus NWLON acoustic sensor 6 minute average sea level measurements shown in Figure 10 provide an example of the difference in tidal sea level changes experienced at the Duck, NC (a) and Port Townsend, WA (b) sites. The plots show sample 5 day demeaned sea level records from each site.

The third test site, the Fort Gratiot, MI NWLON station, is on the southern banks of Lake Huron. The NWLON station is on land near the shore's edge and consists of an in-ground cylindrical concrete well connected to an intake on the lake. With this setup, when water levels rise or fall in the lake, there is a corresponding change in water level in the well. The well is enclosed by a small building, or gauge house. This site is in one of the enclosed Great Lakes, a region that does not experience significant tidal water level changes and surface gravity waves will not be created by wind inside of the enclosed well. Most water level changes that occur at this site are low amplitude and result from physical processes that occur over longer time periods, for example, seiches or lake surface-atmosphere interactions, such as rain or evaporation, that occur over several days. The typical small magnitude of water level changes and lack of tides is why this site was initially selected to represent the least challenging environment for an open air sensor to accurately measure water level.

From March-November 2008, significant progress was made on the MWWL field test effort. Sensor installations were completed at all three test sites, and data collection is currently underway. Preliminary analysis of the first series of data recorded at all three sites indicates that all sensors are functioning properly and are recording reasonable water level measurements as compared to reference NWLON sensors at each site [as shown in Fig 10, 5 day sample microwave versus acoustic NWLON demeaned sea level measurements for Duck, NC (a) and Port Townsend, WA (b)]. Initial data analysis results have provided valuable insight into sensor functioning and configuration settings. In some cases initial results have been used to detect and trouble shoot initial problems and to optimize sensor setups, for example, observations were used to optimize some sensors' time averaging, range gating, false signal suppression, and total detection settings (Heitsenrether, Bushnell, Krug, 2009).

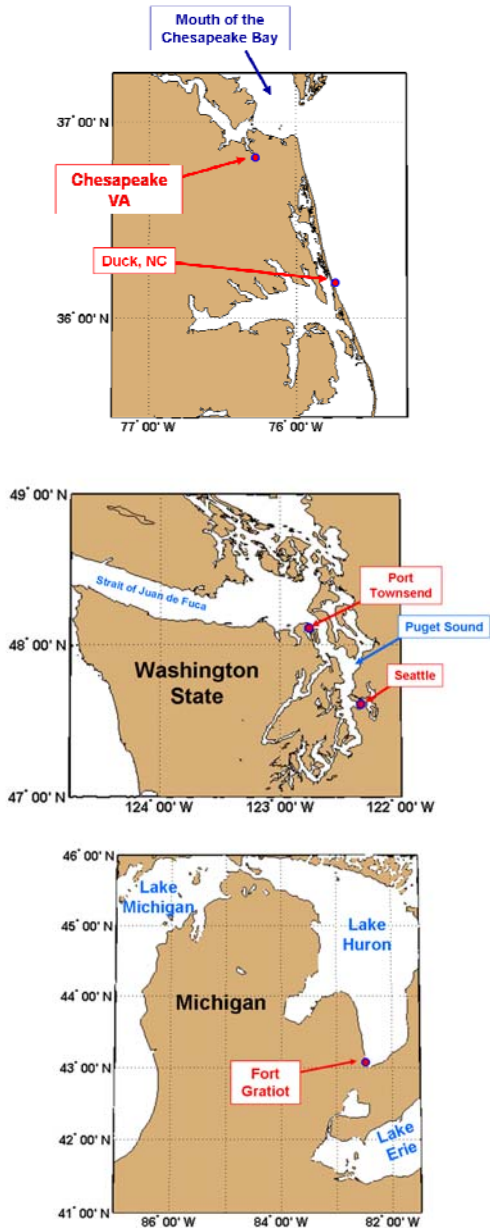


Figure 9 Maps of showing locations of the three different microwave sensor field test sites

Thorough analysis of incoming field data will be critical to prove with high confidence that sea level records measured by microwave range sensors meet NWLON accuracy requirements. First, microwave sensor 1 Hz range measurements will be used to determine the optimal processing methods for obtaining average sea levels at 6 minute intervals, which is based on the NWLON's real-time transmission requirements. Since microwave sensors transmit signals through the open air and sense a large patch of the open sea surface, as opposed to sensors that measure water surface within stilling wells, these processing techniques will require

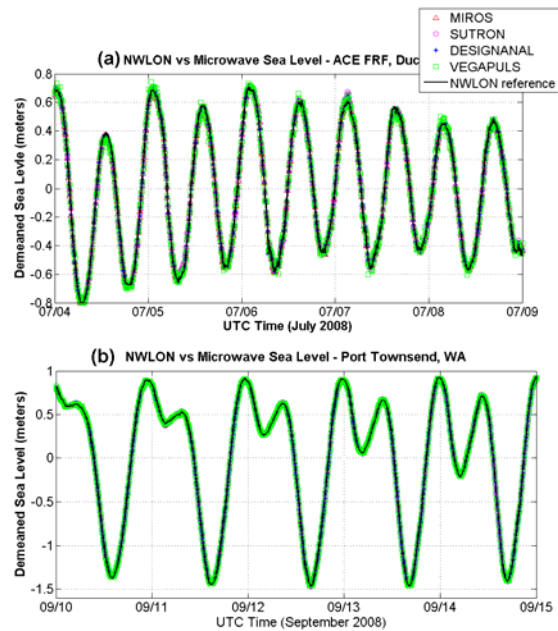


Figure 10. Sample 5 day period of 6 minute averaged sea level data from NWLON reference sensor (black line) and the 4 test microwave sensors (various symbols) at the (a) ACE FRF Duck, NC and (b) Port Townsend, WA.

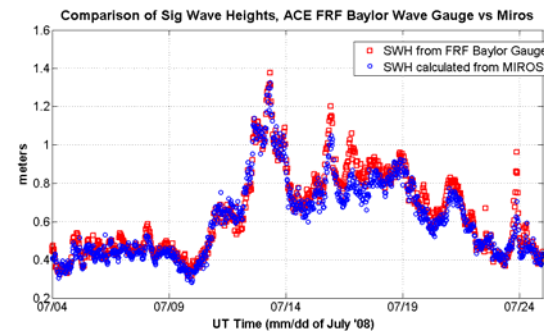


Figure 11. Comparison of hourly significant wave heights at ACE FRF site from Miros SM-094 sensor (blue circles and FRF's Baylor wave gauge (red squares).

application of mathematical filtering to remove high frequency noise induced by surface gravity waves while retaining, longer period signals of interest, such as surge and tides (Boon 2008). Once an optimal data processing method is in place, continuing analysis of incoming field data will involve comparing sea level data measured by the test microwave sensors and the reference NWLON sensor at each site. Correlation between the difference in sea level measurements from different sensors and various environmental parameters will provide information on the impact of environmental variability on sensor performance (Boon 2009).

Sea level records recorded at the field sites are also being used to examine microwave sensors' ability to measure non-directional surface gravity

waves. Figure 11 shows an example comparison of hourly significant wave heights (SWH) measured by a microwave sensor and a reference wave gauge over the month of July 2008 at the ACE FRF test site. Blue circles show SWH calculated from the Miroc SM-094 1 Hz sea level record and red squares show SWH measured by the FRF's Baylor staff system that is currently deployed beneath the pier at a location relatively close to the microwave sensor suite. Initial results compare well.

6. SUMMARY

Over the past several months, NOAA's Center for Operational Oceanographic Products and Services has made significant progress on a test effort focused on determining the suitability of using microwave range sensors for the purpose of measuring sea level and related oceanographic processes at the many coastal observatories that make up NWLON.

Two unique laboratory tests, one in a wave tank and another in a temperature chamber, were conducted, providing valuable insight into the impact of surface gravity waves, as well as extreme temperature variability, on microwave range measurements. Both resulted in valuable data sets and the subsequent post-test analysis has led to an enhanced understanding of sensor functioning.

Completion of field installations and the initiation of long-term data collection in three different coastal environments will result in an additional valuable data set from which the impact of a broad range of environmental conditions on sensor performance can be assessed. Continuing analysis of field observations will provide the information necessary to evaluate the performance of the four microwave sensors, demonstrate operational capability, quantify accuracy, assess suitability for integration into NWLON, and facilitate transition to an operational status.

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7. REFERENCES

Barjenbruch, et al, "Monitoring of Water Level, Waves and Ice with Radar Gauges," Proceedings of the Hydro 2002 Conference, Kiel 2002.

Balsi, C., "A New Technology for the Measurement of the Sea Level and the Sea State," Environmental Geology, v 57, No 2, March 2009.

Bosley, Kathryn T., "Preliminary Results from a Coastal Setting Evaluation of the Miroc Microwave Air Gap Sensor," NOAA CO-OPS Report, 2003.

Bushnell, M. H. "Microwave Water Level Sensor Operational Capability Test and Evaluation Plan," NOAA CO-OPS internal test plan, January 2009.

Boon, J. D., J.M. Brubaker. "Acoustic-Microwave Water Level Sensor Comparisons in an Estuarine Environment," proceedings from MTS/IEEE Oceans'08 International Conference, Quebec City, Canada, September 2008.

Boon, J. D., "Operational filter design for non-contact water level sensors deployed in an open ocean environment," NOAA/CO-OPS Consultant Report, January 2009.

Boon, J. D, "Microwave-Acoustic Water Level Comparisons: Comparison with Oceanographic and Meteorological Parameters in an Open Ocean Environment," NOAA/CO-OPS Consultant Report, March 2009.

Boon, J. D, Heitsenrether, R. M., Bushnell, M. H., "Microwave-Acoustic Water Level Sensor Comparisons: Sensor Response to Change in Oceanographic and Meteorological Parameters in an Open Ocean Environment," abstract submitted for presentation at upcoming IEEE/MTS Oceans09 International Conference to be held in Biloxi, MS, October 2009 – currently awaiting acceptance.

Fulford, Janice M., Davies, William J., "Radar Water-Level Measurement for Open Channels", Proceedings of Third International Conference on Irrigation and Drainage (USCID), San Diego, CA, 2005.

Fulford, Janice M., Ester, L., Heaton, John, W., "Accuracy of Radar Water Level Measurements," 2007 Hydraulic Measurements & Experimental Methods Conference, Lake Placid, NY, September 2007.

Gronlie, Oistein "Wave Radars - A Comparison of Concepts and Techniques," Hydro International, April 2006.

Heitsenrether, R.M., Mark Bushnell, and John Boon. "Understanding the Impact of Surface Waves on Microwave Water Level Measurements," proceedings from MTS/IEEE

Oceans'08 International Conference, Quebec City, Canada, September 2008.

Heitsenrether, R. M., Bushnell, M. A., Krug, W., "Microwave Water Level Sensor Semi-Annual Status Interim Report # 1," NOAA CO-OPS Report, March 2009.

Martin Miguez B, Perez Gomez B, Alvarez Fanjul E "The ESEAS-RI Sea Level Test Station: Reliability and Accuracy of Different Tide Gauges," International Hydrographic Review v 6(1), pp.44-53, April 2005.

Shih, H. H., and L. Baer, "Some Errors in Tide Measurement Caused by Dynamic Environment," Tidal Hydrodynamics, B. B. Parker, Ed., John Wiley and Sons, p 641-671, 1991.

Woodworth, P. L. and D. E. Smith "A One Year Comparison of Radar and Bubbler Tide Gauges at Liverpool," International Hydrographic Review, 4(3): 42-49, 2003.