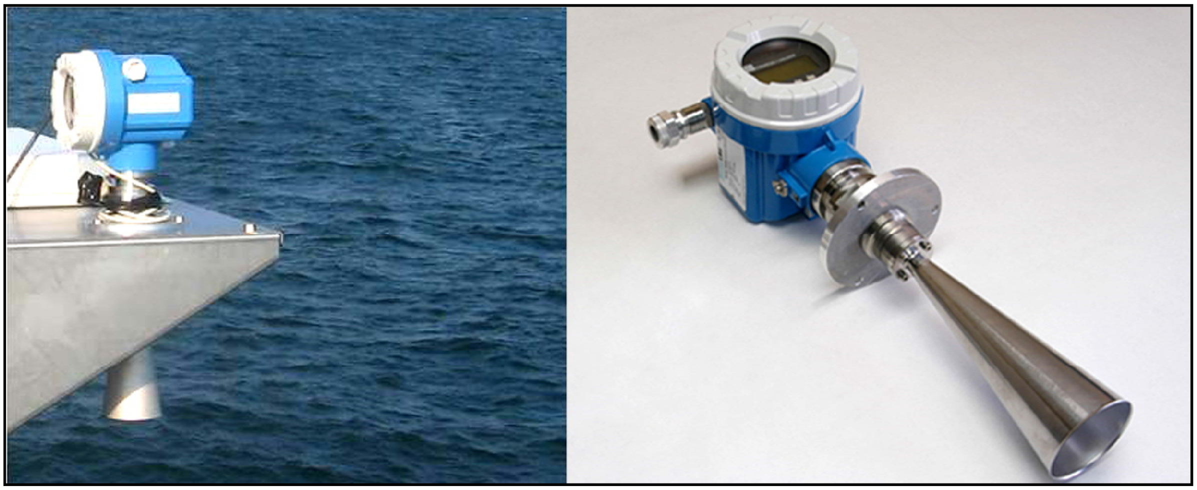
NOAA Technical Report NOS CO-OPS 061

Ocean Systems Test and Evaluation Program

Test and Evaluation Report

Limited Acceptance of the Design Analysis WaterLog® H-3611i Microwave Radar Water Level Sensor



Silver Spring, Maryland
March 2011

noaa **National Oceanic and Atmospheric Administration**

U.S.DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

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The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) provides the National infrastructure, science, and technical expertise to collect and distribute observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and tidal current products required to support NOS' Strategic Plan mission requirements and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), a national network of Physical Oceanographic Real-Time Systems (PORTS®) in major U.S. harbors, and the National Current Observation Program, consisting of current surveys in near shore and coastal areas utilizing bottom mounted platforms, subsurface buoys, horizontal sensors and quick response real-time buoys. The Center: establishes standards for the collection and processing of water level and current data; collects and documents user requirements which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

Ocean Systems Test & Evaluation Program

The CO-OPS Ocean Systems Test and Evaluation Program (OSTEP) facilitates the transition of new technology to an operational status, selecting newly developed sensors or systems from the research and development community and bringing them to a monitoring setting. OSTEP provides quantifiable and defensible justifications for the use of existing sensors and methods for selecting new systems. The program establishes and maintains field reference facilities where, in cooperation with other agencies facing similar challenges, devices are examined in a non-operational field setting. Through OSTEP testing and data analysis results, sensors' performance is evaluated, data sampling and processing methodology are developed, along with quality control procedures, and maintenance routines generated. The quality of the measurement systems used in the field is assured by both rigorous traceable calibrations and redundant sensors.

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Limited Acceptance of the Design Analysis WaterLog® H-3611i Microwave Radar Water Level Sensor

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March 2011

U.S.DEPARTMENT OF COMMERCE
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NOTICE

Ocean Systems Test and Evaluation Program

Design Analysis WaterLog® H-3611i Microwave Radar Water Level Sensor Limited Acceptance Report

CO-OPS STATEMENT OF ACCEPTANCE

CO-OPS management personnel have reviewed this document and concur that the evaluated sensor/system, when deployed and implemented as described herein, will meet the defined requirements and is suitable for operational use. While additional testing may lead to superior performance or more economical operation, the existing sensor/system configuration is sufficient as described.

3/25/11
OSTEP Program Manager — Date

3/25/11
System Support and Evaluation Branch — Date

3/31/11
Chief, Engineering Division — Date

4/11/11
Chief, Field Operations Division — Date

4/6/11
Chief, Oceanography Division — Date

4/4/11
Chief, Information Systems Division — Date

3/25/11
CO-OPS Technical Review Board Leader — Date

4/12/11
Director, CO-OPS — Date

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Acknowledgments

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Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) is responsible for developing and maintaining the National Water Level Observation Network (NWLON). CO-OPS, like most operational, technical programs, analyzes state-of-the-art and emerging technologies to identify potential improvements in data quality and operating efficiency and to maintain core expertise for authorized missions. A critical challenge facing CO-OPS is to ensure that water level measuring technologies are capable of delivering data that meet prescribed accuracies, are reliable and resilient in harsh environments, offer improvements in deployment, operation and maintenance efficiencies, and are expected to have a reasonable life-of-industry support for parts manufacturing and service. The ocean observing community has recognized that microwave radar technology, which was previously developed for various range measurement applications, also offers many potential benefits for long-term water level monitoring. In response, the CO-OPS Ocean Systems Test and Evaluation Program (OSTEP) conducted a series of extensive laboratory and field tests on a set of four types of microwave radar sensors from four different manufacturers to determine their suitability for use at NWLON stations and other locations where CO-OPS requires long- and short-term water level measurements observing systems.

Analysis of data collected by the selected four sensors over the last 2.5 years of testing points to the Design Analysis WaterLog® H-3611i radar sensor as the best suited for CO-OPS measurement applications at this time. Analysis included an assessment of the four sensors' water level measurement performance over a broad range of environmental variability. Sensor selection was based on quantitative criteria and a related scoring method specifically designed with CO-OPS' unique operations and applications in mind. All four sensors demonstrated similar measurement accuracy capabilities, and their scores were very close. However, specific aspects of each sensor influenced the choice of the WaterLog® sensor for this application. Testing of newer versions of the other three sensors, as well those from other manufacturers including Design Analysis, may continue, and they may still be considered for use in CO-OPS operational water level stations. Results presented in this report, however, focus only on measurements collected from WaterLog® radar sensors.

Since NWLON sites span more than 200 different coastal locations that are affected by varying combinations of meteorological and oceanographic conditions, field tests of the new microwave radar water level sensor were designed to assess the impact of various environmental parameters on sensor performance. From June to November 2008, test microwave radar sensors were installed at three different NWLON stations with varying coastal environments: Duck, NC; Port Townsend, WA; and Fort Gratiot, MI. Based on analysis of the first year of data from these sites, test microwave radar sensors were installed in 2010 at two additional field test locations: the Bay Waveland, MS and Money Point, VA NWLON stations.

Analyses of field results include comparisons between 6-minute (min) average water level measurements collected by the test microwave radar sensor and accepted operating reference NWLON sensors at each site (Aquatrak acoustic at Duck, Port Townsend, Money Point, and Bay Waveland, and BEI float/shaft angle encoder system at Fort Gratiot). In most cases water level measurements from test and operational sensors are in good agreement; however, in some cases measurements show deviation closely correlated to changes in environmental conditions. Most notable is the impact of large surface gravity waves (with amplitudes of 1 meter and larger and periods of 10 seconds and longer) and strong long shore and cross shore currents that are most likely set up by wave radiation stress [1,2]. Results from the Duck, NC site, which is an open ocean environment in the most energetic wave regime of the entire East Coast, demonstrate the impacts of the most extreme wave events (significant wave height of approximately 3.5 meters) where monthly WaterLog® versus Aquatrak root mean squared differences (RMSDs) were as large as 7 centimeters (cm), and differences between individual 6-min water level sensors sometimes exceeded 10 cm.

Understanding deviations between water levels measured by operational NWLON acoustic sensors and test microwave radar sensors in the presence of a dynamic, open ocean environment such as Duck remains a work in progress; however, observations from the Port Townsend, Money Point, and Fort Gratiot test sites indicate that microwave radar sensors meet accuracy requirements and produce results that generally agree with NWLON sensors. At all three sites, the monthly RMSDs between the Aquatrak and WaterLog® 6-min water level series are generally less than 1 cm, and differences in monthly means are within plus or minus 5 mm. Also, a set of CO-OPS standard water level analysis products generated from an 18-month WaterLog® data record from Port Townsend using the CO-OPS Excel-based Data Management System further confirms that the test sensor can generate accurate measurement results that compare well to those generated by existing NWLON sensors operating in environmental conditions similar to those at the test stations. All test microwave radar data that yielded excellent comparisons with reference NWLON sensors were collected in semi-enclosed, fetch limited, low surface wave coastal environments. Based on these results, OSTEP recommends limited acceptance of the WaterLog® radar as a water level sensor in similar coastal environments.

Efforts to facilitate the transition of WaterLog® microwave radar sensors from test to operational status include development of water level quality control (QC) guidelines and a recommended pre-deployment laboratory test procedure specifically designed for this new measurement technology. Extensive analysis of several laboratory tests and 1.5 years of raw 1-Hz data from the Port Townsend field test site were used to optimally tailor previously implemented CO-OPS water level data QC guidelines to accommodate the performance characteristics of the new sensor type. Test results, including problems encountered and lessons learned, have been used to develop and document a standard, four-step microwave radar sensor pre-deployment laboratory test procedure and required data analysis procedures. These laboratory tests are specifically designed to significantly decrease the likelihood of problems during deployment.

Although further testing and analysis are needed before a final microwave radar test and evaluation report is issued, most periods of field test data collected by OSTEP to date indicate that microwave radar sensors meet accuracy requirements. Consequently, this report supports operational use of the WaterLog® microwave radar sensor in semi-enclosed, fetch limited coastal regions with a small wave environment.

1.0 Introduction

Through its operation of the National Water Level Observation Network (NWLON), the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) supports those who depend upon water level measurements. NWLON consists of over 200 observatories throughout the U.S. coastal regions, including the Great Lakes and Pacific and Caribbean island territories. To ensure that NWLON provides the most up-to-date water level products and services available, CO-OPS keeps abreast of evolving measurement technology and employs the most accurate, state-of-the-art instruments within the network. The CO-OPS Ocean Systems Test and Evaluation Program (OSTEP) assists with this effort through its team of scientists and technicians who conduct rigorous testing of newly selected oceanographic and meteorological sensors and related systems in both laboratory and field settings.

The most recent OSTEP tests involve the long-term water level monitoring capability of several different microwave radar sensors. Many potential benefits of using such sensors have already been identified by several other organizations throughout the ocean observing community [3-11]. The most notable advantage of microwave radar technology is the ability to measure water level from above the sea surface. With no parts directly in contact with the water column, many problems typical of long-term subsurface ocean sensors, such as biological fouling and corrosion, can be avoided. Use of a microwave radar sensor for water level measurements also results in significant equipment cost savings and simpler deployments because a remote sensing setup requires significantly fewer hardware components for successful installation (for example, sounding tubes, protective wells, parallel plates, or related hardware are not required).

In accordance with the OSTEP *Microwave Water Level Sensor Operability Test and Evaluation Plan* [12], a series of laboratory and field tests are currently being conducted on four different microwave sensors. Sensors from four different manufacturers were selected for testing based on recent sensor developments and results of multiple related studies conducted over the last several years [3-11]. The make and model of the four sensors initially selected for testing include: 1) Miros SM-094; 2) Design Analysis WaterLog® H-3611i; 3) Ohmart/VEGA VEGAPULS 62; and 4) the Sutron RLR-0002. OSTEP's test planning was completed in January 2008 and test execution began in February 2008.

Based on results from several individual laboratory tests and field data collected over 2.5 years at the three different sites, OSTEP has identified the Design Analysis WaterLog® H-3611i (subsequently referred to as WaterLog®) as the best suited of the four selected sensors for CO-OPS measurement applications at this time. All four sensors demonstrated good performance and yielded similar accuracy. Several documented studies indicate that other institutions/organizations have been successful in collecting accurate, high quality water level observations using microwave radar sensors other than the WaterLog® unit. NOAA in no way endorses one tested sensor over another for general applications or one manufacturer over another. Selection of the WaterLog® as the sensor best suited for NOAA at this point is based on quantitative criteria specifically designed with CO-OPS' unique operations and applications in mind, as well as specific aspects of each sensor operating within this application. Table 1 provides an overview of the characteristics of the WaterLog® that give it an advantage in this setting. Testing of newer versions of the other three sensors, as well those from other manufacturers including Design Analysis, may continue, and they may still be considered for use in CO-OPS operational water level stations based on analysis of system performance and mission requirements. The OSTEP *Microwave Water Level Sensor Interim Status Report #1* [13] and *Microwave Water Level Sensor Interim Status Report* #2 [14] provide further details on comparisons between performance of different brands of sensors and the selection criteria applied. Results of microwave radar sensor measurements presented in this report focus only on the WaterLog® sensor.

Table 1. Aspects of WaterLog® sensor that influenced selection for use at Port Townsend and similar environments.

Sensor Characteristic	Resulting Advantages
Smaller signal spreading angle (10 degrees)	Narrow footprint, high spatial measurement resolution, and decreased likelihood of false echoes when transmitting in enclosed well/sump (required in Great Lakes applications).
Required input voltage of 10-16 Volts DC	Low enough power requirement to operate in system consisting of DCP with just one 12-volt battery and one solar panel.
SDI 12 interface	Three-wire interface easily connects to Xpert DCP used by NOAA; sensor can be powered directly from DCP, eliminating need for additional power source.
Time of Flight (TOF) Tool Windows-based software - configuring sensor parameters	Sensor configuration parameters can be set very easily via laptop and RS232 connection. Software setup with graphics makes most parameters easy to understand.
TOF – automated plotting of return signals	A plot of sensor return signal, intensity versus range, is easily generated.
TOF – preventing detection of return signals from obstructions	TOF software can be used to easily eliminate return signals from obstructions in sensor field of view (in scenario where sensor still has a clear view of water surface).
TOF – enabling fast time response	Sensor time response can be easily adjusted to be very short (5 seconds) via TOF software.
1-Hz sampling	Sensor comes from the factory capable of logging range data to DCP at 1-Hz rate.
26 -GHz pulse signal	Addresses NTIA concerns about the possibility of sensor transmissions causing harmful interference.
Consistent, reliable, long-term performance	No signs of system reboots, sensor failures, or power downs. Minimal dropouts/gaps in 1-Hz record.

Since CO-OPS maintains real-time water level observations at more than 200 different coastal locations affected by varying combinations of meteorological and oceanographic conditions, field testing a new NWLON water level sensor must assess the impact of various environmental parameters on sensor performance. For this reason, microwave radar sensors were initially installed for field testing at three different NWLON station locations with varying coastal environments [12, 13]. The three initial microwave radar sensor test sites located at Duck, NC, Port Townsend, WA, and Fort Gratiot, MI were selected to represent the most challenging, average, and least-challenging NWLON field location, respectively, for an open air sensor to accurately measure water level. Each test site is located near an NWLON station, so at least one reference water level sensor is available, along with basic meteorological measurements, to assist in characterizing environmental variability [12]. Analysis of the first year's worth of field data collected at the three sites provides further insight into the environmental variability experienced at each test location, and results suggested that testing in additional environments would help to achieve project objectives [13,14,15]. As a result, a microwave radar water level sensor was deployed for testing at a fourth field site, Bay Waveland, MS, in January 2010. Selection of this site was based on analyses of available historical oceanographic and meteorological data from the region, which indicate that the region typically experiences a combination of wind, surface wave, and tidal conditions that are on average significantly different than those experienced at the other three field test sites [14].

In addition to considering the environmental variability that CO-OPS water level sensors encounter, OSTEP also accounted for different potential measurement applications involving the new sensor technology when planning test activities. In response to interest from several other NOS program offices in the potential use of microwave radar technology in a CO-OPS "hydro" station, a prototype microwave hydro station was established at Money Point, VA [16].

Analyses of field results to date include comparisons of 6-minute (6-min) average water level measurements collected by both the test WaterLog® and reference NWLON sensors[1] at each site. The difference time series of the two 6-min water level records were plotted and observed, and monthly root-mean-squared differences (RSMD) and differences between monthly mean sea levels were calculated. The initial acceptance requirement of the microwave radar sensor is that its monthly RMSD must be close to or less than 1 centimeter (cm) from the NWLON reference sensor, and the difference between monthly means obtained from the microwave radar sensor and the NWLON water level records must be 5 mm or less. Although a significant period of all field observations collected to date indicates the WaterLog® microwave sensor meets this requirement, it is also clear that differences between the WaterLog® and the reference sensors' water level records are significantly affected by changes in environmental conditions, sometimes resulting in monthly RMSD values that exceed 1 cm. At the Duck, NC test site, where the NWLON reference is an Aquatrak acoustic sensor, most notable is the impact of surface waves and strong long shore and cross shore currents on deviations between acoustic and microwave sensor water level measurements [13,14,15,17]. Results from Duck, which is an open ocean environment in the most energetic wave regime of the entire East Coast, show a strong correlation between deviations in WaterLog® versus Aquatrak measurements and these two parameters. Monthly RMSDs as large as 7 cm between the two sensors' water level records were recorded, and differences between individual 6-min water level measurements exceeded 10 cm during the most extreme wave events (significant wave height of approximately 3.5 m). At other test sites, where a significant difference in air and water temperature occurs, near surface atmospheric conditions sometimes create a vertical temperature gradient in the Aquatrak sensor's sounding tube, which can significantly affect this sensor's measurement accuracy [18,19]. Certain periods of OSTEP field test data show strong correlations between differences in acoustic and microwave radar sensor water levels and differences between temperature readings from two vertically-separated temperature sensors installed in an Aquatrak sounding

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[1] Aquatrak 3000 series acoustic sensors at Duck, NC, Port Townsend, WA and Money Point, VA test sites, and a BEI shaft encoder at Fort Gratiot, MI.

tube. For this particular environmental impact, an approximate correction factor can be applied to the Aquatrak record, possibly resulting in a more accurate comparison between the WaterLog® and Aquatrak sensor records.

Evaluating microwave radar sensor performance based on observations of differences between Aquatrak and WaterLog® measurements is challenging because of the potential advantages of microwave over acoustic sensors, which is why microwave radar sensors are being considered for use at NWLON stations. In some cases, deviations between WaterLog® and Aquatrak sensor measurements may indicate that the WaterLog® is measuring water level more accurately than Aquatrak sensors, and in other cases the inverse may be true. The microwave radar sensor is likely to be at a disadvantage during significant surface roughness due to its open air transmission and lack of a protective well; however, OSTEP is also uncertain of the hydrodynamic effect of the acoustic sensor's protective well in open ocean environments, including time response to high frequency wave-induced fluctuations and draw down resulting from pressure drop caused by horizontal flow near the Aquatrak well intake. Although the impact of Aquatrak protective wells on various hydrodynamic processes was studied extensively during the development of the Aquatrak system [20-24] and several design enhancements were made to mitigate these impacts, the well's effect on water level measurements is not precisely quantifiable in some ocean regions with highly energetic surface wave environments (such as the surf zone on the shores of Duck, NC).

Although evaluation of the WaterLog® versus Aquatrak water level measurement comparison in the presence of a dynamic, open ocean environment such as Duck remains a work in progress, most observations from the Port Townsend, WA, Money Point, VA, and Fort Gratiot, MI test sites indicate that monthly RMSDs of NWLON sensor water level records versus those of the WaterLog® are generally less than 1 cm, and monthly mean sea level differences are less than 5 mm. These three field test sites are located in semi-enclosed, fetch limited coastal regions with small surface wave environments. Surface roughness can be present at these sites during periods of increased winds; however, roughness mainly consists of short, high frequency, locally-generated wind sea, and there are no high amplitude, longer period waves, which are commonly present at the U.S. Army Corps of Engineers Field Research Facility (USACE FRF) in Duck, NC (where waves are often greater than 1 m in amplitude and longer than 5 seconds [s]).

Because many periods of field test data have indicated that microwave radar sensors meet accuracy requirements and at some times may be more accurate than the Aquatrak acoustic sensors, this report recommends the limited acceptance of microwave radar water level sensors for use in coastal regions with characteristics similar to those of the field test sites described: semi-enclosed, fetch limited coastal regions with a small wave environment. The results summarized in this report help to support CO-OPS' decisions to use microwave radar sensors as the primary instrument for measuring water level at various prospective new sites and possibly some NWLON sites that are due for sensor replacement. Ultimately, a coastal classification system that evaluates average wind, wave, and tidal environments across U.S. coastal regions covered by NWLON stations should be developed to identify which NWLON stations are suitable for installation of microwave radar sensors. In the meantime, areas that have minimal impact from surface waves (beyond short, high frequency wind sea waves) may be considered suitable for microwave radar sensor use.

Section 2 of this report summarizes results of field observations made with the WaterLog® microwave radar sensors at the Port Townsend, WA, Money Point, VA, and Fort Gratiot, MI, field test sites and compares WaterLog® and Aquatrak data (or the BEI shaft encoder data at Fort Gratiot). Tidal water level products generated with 1.5 years of Port Townsend data using CO-OPS' standard processing tools provide further confirmation of adequate sensor performance. Section 3 describes the derivation of quality control thresholds and guidelines implemented in CO-OPS' main data processing system, and Section 4 describes a recommended pre-deployment laboratory test procedure that should be conducted on any WaterLog® sensor prior to field installation. Section 5 summarizes the report findings and provides recommendations for future WaterLog® microwave wave sensor installations.

2.0 Field Test Results

Field test results obtained with the Design Analysis WaterLog® H-3611i microwave radar sensor demonstrate its suitability for use as a water level sensor at NWLON sites that are semi-enclosed and protected from long period swell and have short fetch that limits the development of surface gravity waves during periods of strong wind forcing. Data analysis results presented involve a subset of field data collected in smaller wave environments throughout OSTEP's test and evaluation period [12,13]. As previously mentioned, studies of the performance of microwave radar sensors in open ocean regions with more energetic surface gravity wave environments and the investigation of proper application of data filtering and processing techniques for measurements collected in such regions are ongoing [17,25]. Interim Status Reports # 1 and #2 [13,14] provide microwave radar measurements collected in such environments, as well as results from the ongoing analysis.

Results from the Port Townsend, WA, Fort Gratiot, MI, and Money Point VA test sites show that the microwave radar sensor met accuracy requirements except for one month at Port Townsend, where the monthly WaterLog® versus Aquatrak RMSD was slightly greater than 1 cm. A set of standard CO-OPS water level products is presented, including monthly tidal datums generated by formatting 1.5 years of WaterLog® data from the Port Townsend, WA test site, entering that data into the CO-OPS staging database, and applying CO-OPS standard Data Management System (DMS) tools to the data. DMS products generated from Port Townsend data also provide a useful addition to the test and evaluation results and suggest a seamless transition of microwave radar measurement technology with respect to CO-OPS Oceanographic Division (OD) end data products, ensuring that there is no significant impact on the long term record of tidal datums maintained by CO-OPS.

2.1 Processing Technique Applied to a Specific Subset of Field Data

At all field test locations, WaterLog® sensors recorded 1-Hz water level measurements from which 6-min average values were derived using a 360-second (s) box car average, centered on 6-min time increments (corresponding to times in the NWLON record). Previous evaluation of 181-s and 360-s sample distributions from WaterLog® water level measurements collected at Duck, NC indicates that the 1-Hz WaterLog® data show a significant degree of asymmetry in their sample distributions during moderate to high wave events (significant wave height or H_s greater than 1 m). These asymmetrical distributions call into question the Gauss assumption of central tendency and undermine the choice of the arithmetic mean as the most efficient estimator of water level in higher wave environments. Results from measurements collected at the Port Townsend site show that data distributions also exhibit asymmetry but less frequently than Duck FRF, and mean-median differences are insignificant (1 cm or less) [17].

Results in this report, which focus on data collected in small wave environments, do not include 6-min microwave radar data values obtained using summary order statistics. Six-minute data for all results shown in the following sections were derived by conducting a 3-sigma outlier check on all 360 1-Hz data points in each 6-min increment, removing outliers, and then averaging the remaining 360 1-Hz data points in the 6-min block. This process is the same as the CO-OPS standard data quality assurance processing (DQAP), except that it uses a wider averaging window—360 data points instead of 181 points. Selection of the wider averaging window is based on previous work, which has shown improved results for microwave radar sensor data when using a 360-point average instead of the standard 181-s DQAP window [25]. Since the microwave radar sensor's raw 1-Hz record contains more high frequency variability in water level values, the wider averaging results in more smoothing of a 6-min record.

2.2. Analysis Results of the Raw Field Data from Three Field Sites

The following sections provide a summary of analysis results generated from raw 1-Hz WaterLog® measurements collected at three of the five field test locations: Port Townsend, WA, Fort Gratiot, MI, and Money Point, VA.

2.2.1 Port Townsend

The Port Townsend microwave radar sensor test site is located beside the CO-OPS NWLON station on the Port Townsend ferry terminal pier. This NWLON station is equipped with a meteorological station, as well as an Aquatrak primary water level acoustic sensor and a GE Druck bubbler pressure sensor as a backup. As shown in fig. 1, Port Townsend is northwest of Seattle, and its coast is in a semi-enclosed area in the northern region of the Puget Sound, just east of the Strait of Juan de Fuca. Due to the response of the estuary to the ocean tidal forcing and the complex local bathymetry of the surrounding basin, the site experiences a stronger-than-average tidal signal. Since there is a short fetch because of the surrounding land, surface roughness development is limited during periods of high wind. Also, the site is further inland from the ocean coast compared to Duck, so high wind events are experienced less frequently at Port Townsend. 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 [12].

Figure 2 shows 1-year time series of hourly averaged wind speed for both Duck, NC (top plot) and Port Townsend, WA (bottom plot), with red dashed lines marking the 30-knot threshold that is commonly used to classify a high wind storm event (corresponds to a wind stress of approximately 0.4 N/m^2)[26]. In this example, 22 storms occurred over 1 year at Duck, NC, but only 5 storms occurred at Port Townsend, WA. [2]

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[2] November 2008 was selected as a start month for the one-year period shown here, since the meteorological station at Port Townsend was first installed October 2008.

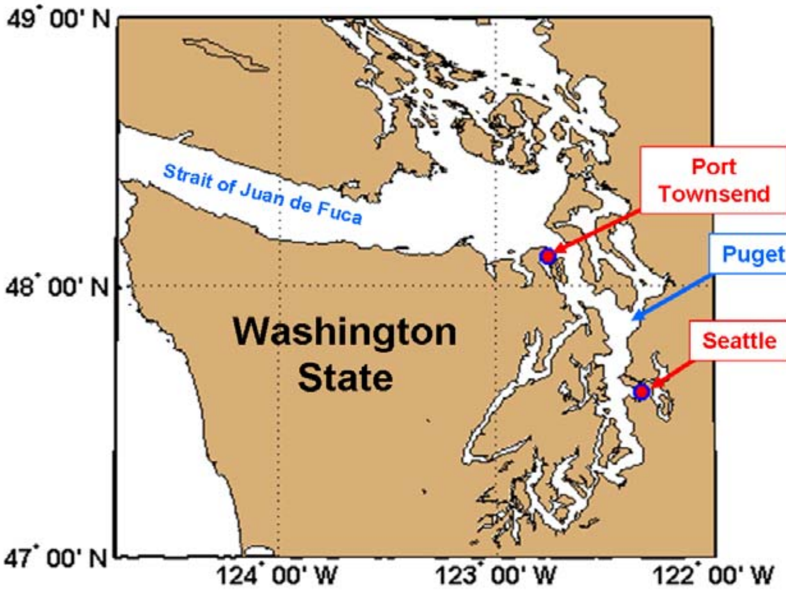

Figure 1. Location of Port Townsend WA field test site.

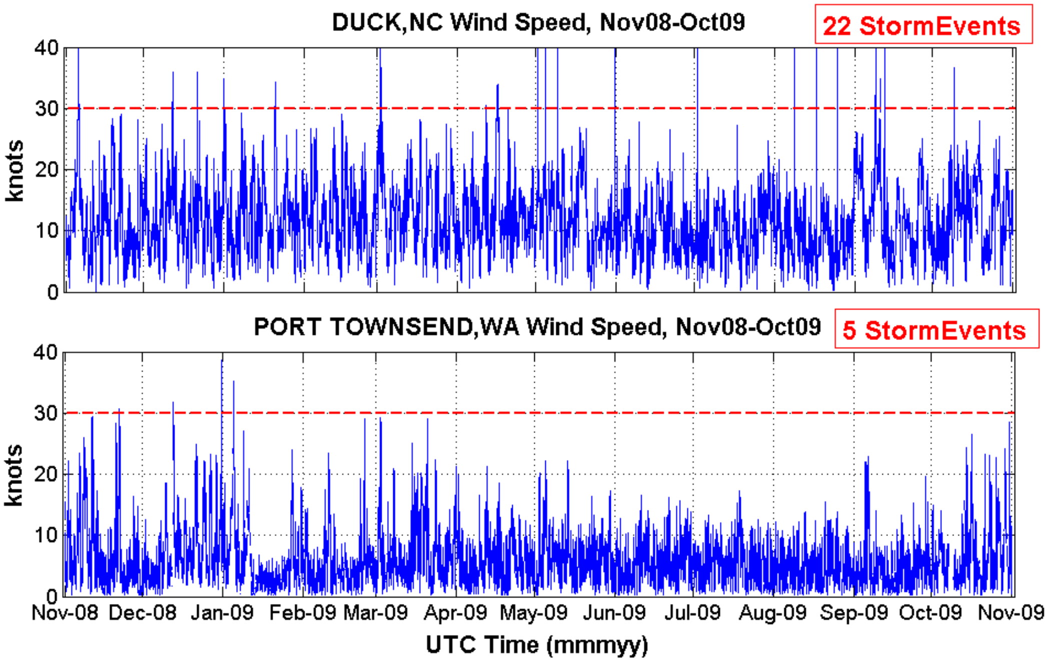

Figure 2. One-year record (November 2008 – October 2009) of hourly wind speed at Duck, NC (top) and Port Townsend, WA (bottom). Red dashed line in each plot marks the 30-knot threshold that is commonly used to classify a high wind storm event.

The test WaterLog® radar sensor was initially installed at Port Townsend in late July 2008, and follow-up work on the test system was conducted during August 2008 [13]. Shortly after the initial installation, the CO-OPS Field Operations Division (FOD) Pacific Region Operations (PRO) conducted geodetic leveling to provide a vertical separation between the station datum and a known fixed point on the WaterLog® sensor's mounting plate. A second geodetic leveling was conducted after station maintenance took place during April 2009. Reference height from the station datum obtained from the leveling and a derived sensor offset (distance from sensor's zero range point to the geodetic leveling point) were used to create a datum-referenced water level time series from the WaterLog® sensor's range time series. The test WaterLog® sensor at Port Townsend has successfully recorded continuous data at the site for its entire deployment time (as of this report date). Analysis results presented here cover test data recorded at Port Townsend from September 2008 through January 2010.

All of the WaterLog® raw 1-Hz data were converted to station datum-referenced water levels, processed to 6-min average values, and then, for each month, plotted against 6-min station datum-referenced water levels measured by the NWLON Aquatrak sensor at Port Townsend. The 6-min difference series between the WaterLog® and Aquatrak sensors was also calculated and plotted (WaterLog® water level minus NWLON Aquatrak water level, hereafter referred to as ΔWL). Corresponding wind speeds measured by the Port Townsend NWLON meteorological station were plotted, along with monthly water level records, as an indication of sea surface roughness. Periods of increased wind speeds clearly correspond to periods of increased high frequency variability in the raw 1-Hz WaterLog® water level series. Because surface roughness is limited at this site, increased wind-induced surface roughness did not result in an increase in deviations between 6-min average WaterLog® and Aquatrak measurement seen in the ΔWL series.

In fig. 3, the monthly Port Townsend WaterLog® versus Aquatrak water level plot from November 2008 shows that the site experienced significant wind speed variability. Hourly wind speeds (a) exceeded 20 knots several times during the month and twice reached the 30-knot storm classification threshold. An increase in high frequency variability in the WaterLog® raw 1-Hz water level series (blue line in [b]) occurs during periods of high wind speed; however, 6-min average water level values from the WaterLog® (black dots) and Aquatrak (red dots) compare quite well across the entire 1-month record shown. The ΔWL series shows that individual 6-min values from the two sensors are generally within ±2 cm with no increased deviations corresponding to high wind speed. The impact of high wind speeds (and resulting increased surface roughness) is better seen in fig. 4, which is the same type of plot as shown in fig. 3, but zooms in on one day, November 22, 2008. During this 24-hour period, wind starts in the 25-30 knot range and then subsides to 5 knots. This type of result, observed throughout most of the 1.5-year period of test data summarized here, indicates that applying a 3-sigma wild point edit and then a 360-s wide average to 1-Hz data adequately filters out high frequency variability from the 1-Hz record that occurs in the presence of wind-induced surface roughness at this site. A full set of monthly time series plots showing Port Townsend wind, water levels, and WaterLog® versus Aquatrak ΔWL from September 2008 through January 2010 are included in appendix A.

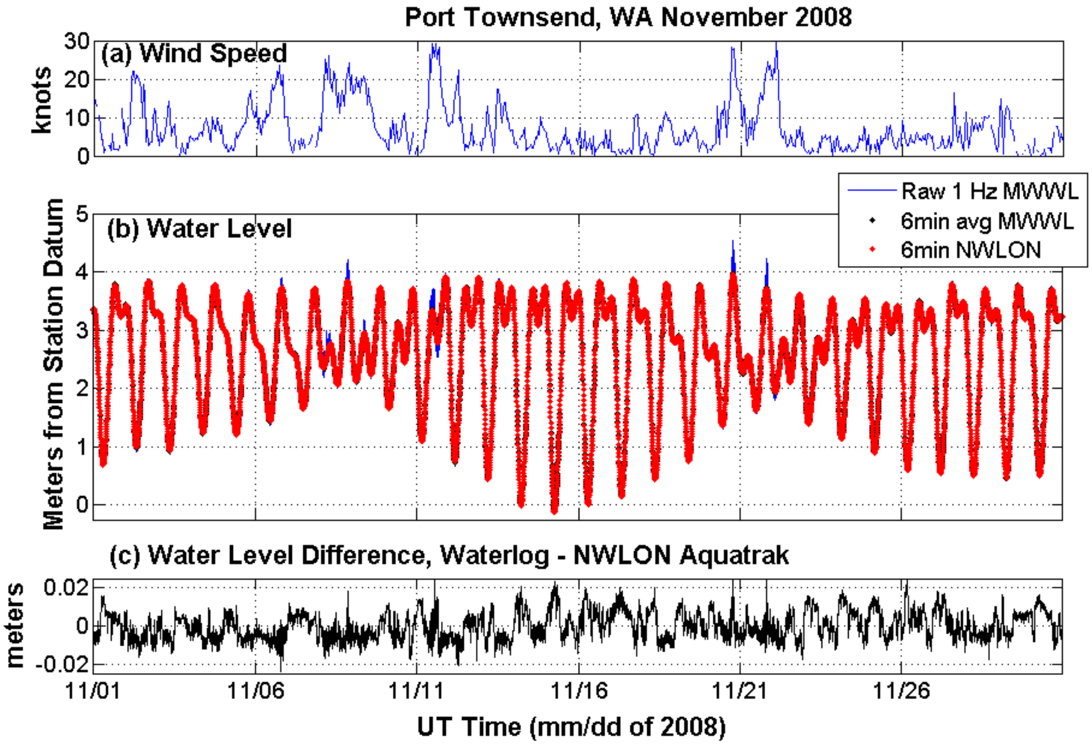

Figure 3. November 2008 time series of (a), hourly wind, (b) datum referenced water levels, 1-Hz WaterLog® (blue line), 6-min average WaterLog® (black dots), Aquatrak (red dots), and (c) WaterLog® versus Aquatrak ΔWL at the Port Townsend, WA NWLON site.

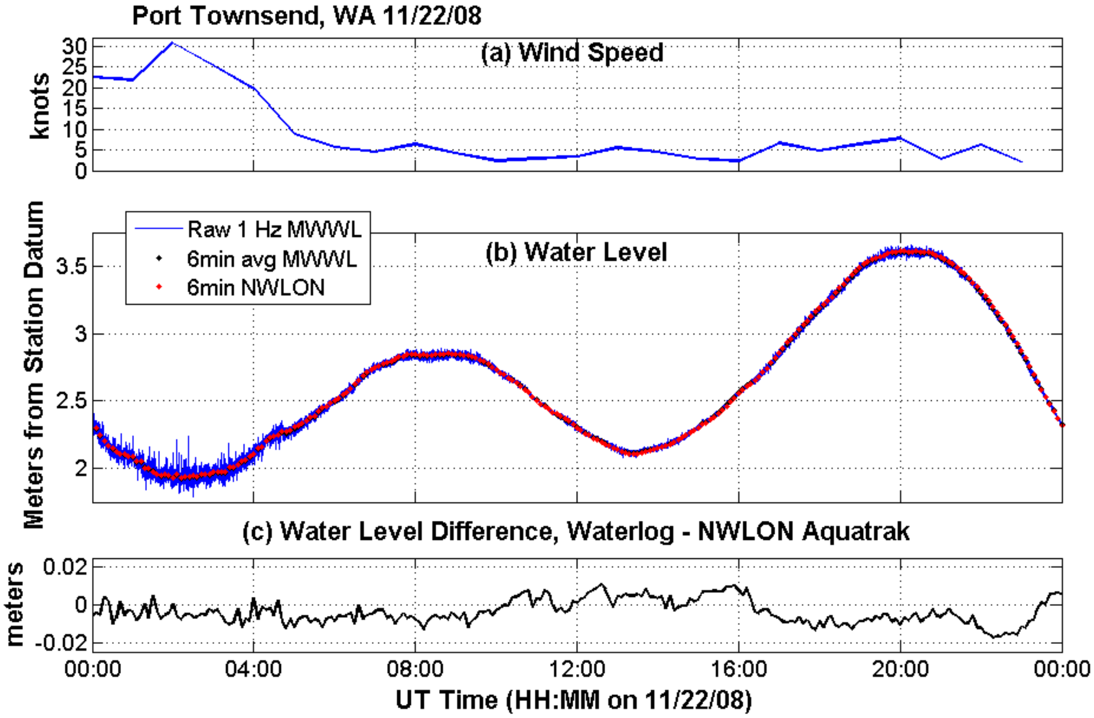

Figure 4. November 22, 2008 24-hour time series of (a), hourly wind, (b) datum referenced water levels, 1-Hz WaterLog® (blue line), 6-min average WaterLog® (black dots), Aquatrak (red dots), and (c) WaterLog® versus Aquatrak ΔWL at the Port Townsend, WA NWLON site.

The WaterLog® measurements derived from a 17-month period at Port Townsend are summarized in fig. 5, which shows monthly RMSDs calculated between the 6-min WaterLog® and Aquatrak water level series (red), as well as differences in monthly mean sea levels from the two sensors (blue). All monthly RMSD values are 1 cm or less, except for June 2009, which was 1.2 cm (still relatively small). Monthly mean sea levels calculated from the two sensors are within ±5 mm, which is insignificant. In addition, the series of monthly mean differences are randomly distributed and show no signs of a trend or constant offset. Monthly results from the 17-months of Port Townsend data show an acceptable WaterLog® versus Aquatrak comparison, providing a first indication that the WaterLog® sensor meets water level accuracy requirements.

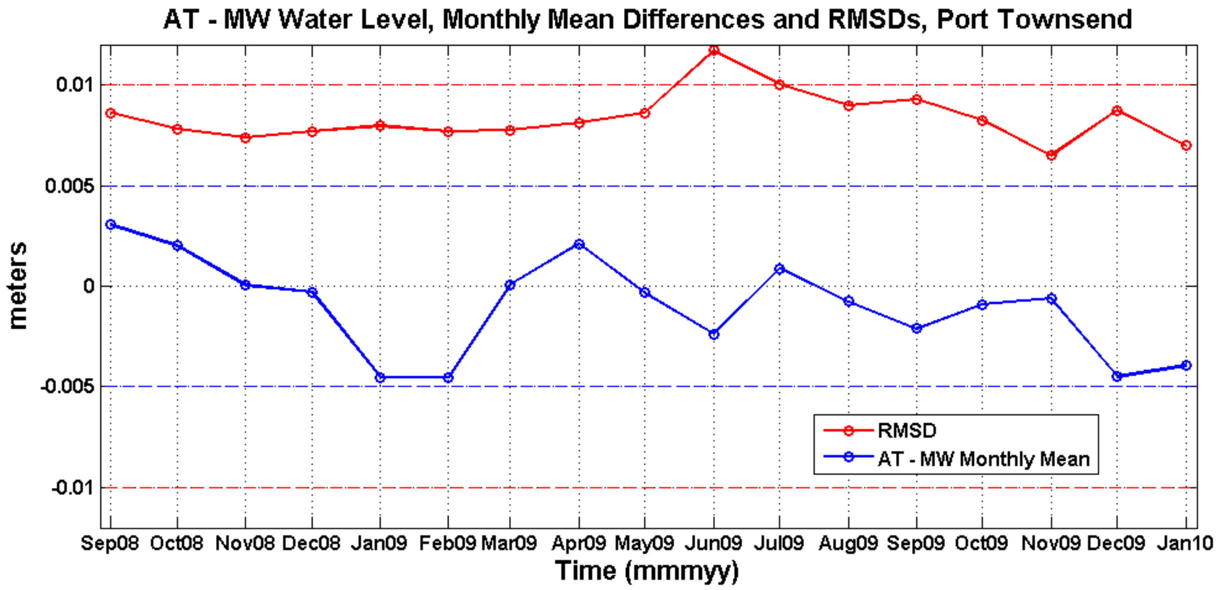

Figure 5. Monthly RMSDs between WaterLog® and Aquatrak 6-min water level series (red) and differences between WaterLog® and Aquatrak monthly mean sea levels (blue).

2.2.2 Fort Gratiot, MI

The Fort Gratiot, MI test site is located at a CO-OPS NWLON station on the southern banks of Lake Huron, as shown in fig. 6. The station is located 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 in a small building, or gauge house, which contains heat lamps that prevent freezing. The gauge house contains NWLON sensor electronics, DCPs, and power sources. The primary reference sensor at this site is a float/shaft angle encoder system with a float that rests on the water surface in the well. The site also includes a suite of standard meteorological sensors.

This site is located within one of the enclosed Great Lakes with no significant tidal water level changes and where surface roughness from wind forcing is limited due to a short fetch. Most water level changes that occur at this site are low amplitude and result from physical processes that occur on time scales that are different from tides, for example, seiches with periods that occur over several hours, or lake surface-atmosphere interactions, such as rain or evaporation, that take place over several days. This site was initially selected to represent the least challenging environment for an open air sensor to accurately measure water level because of the typical small magnitude of water level changes and lack of tides. Although the site may be a less common NWLON application of the least challenging environment for an open air microwave radar sensor with almost no wind induced roughness on the water level surface being measured, results from testing at the site provide valuable confirmation of the WaterLog® sensor's ability to track small amplitude water level changes that occur on longer time scales, and results provide a comparison with a water level measurement system other than the Aquatrak, i.e. the BEI float/shaft angle encoder system. WaterLog® test data from the Fort Gratiot site presented here were collected from June 2009 through February 2010.

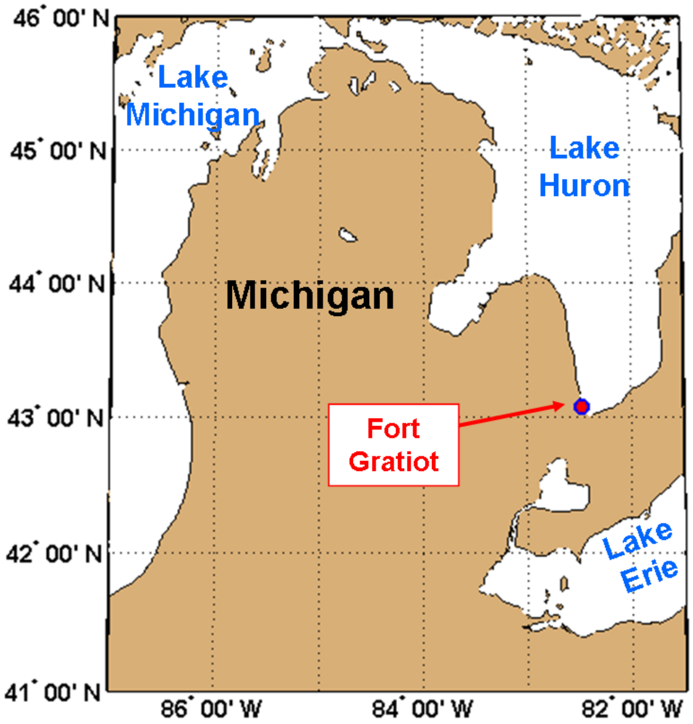

Figure 6. Location of Fort Gratiot, MI field test site.

The same results as those previously discussed for Port Townsend data were generated from measurements collected by the test system at Fort Gratiot. Figure 7 shows (a) hourly winds, (b) station datum-referenced water levels from the WaterLog® test sensor and the NWLON BEI float/shaft angle encoder system, and (c) the WaterLog® – NWLON ΔWL series from October 2009. As expected, no clear increases in high frequency variability appear in the WaterLog® 1-Hz record corresponding to increases in wind, since the water level surface that is being measured is enclosed in a sump inside a tide house. Six-minute average water level series from the WaterLog® and NWLON BEI compare quite well.

As with the Port Townsend data, 6-min RMSDs and differences in monthly mean water level between the WaterLog® and the BEI are small, indicating that the WaterLog® sensor can track small, gradual water level changes that occur in the concrete sump just as accurately as the shaft angle coder system (fig. 8). All RMSDs are 1 cm or less and monthly mean differences are all less than 4-5 mm.

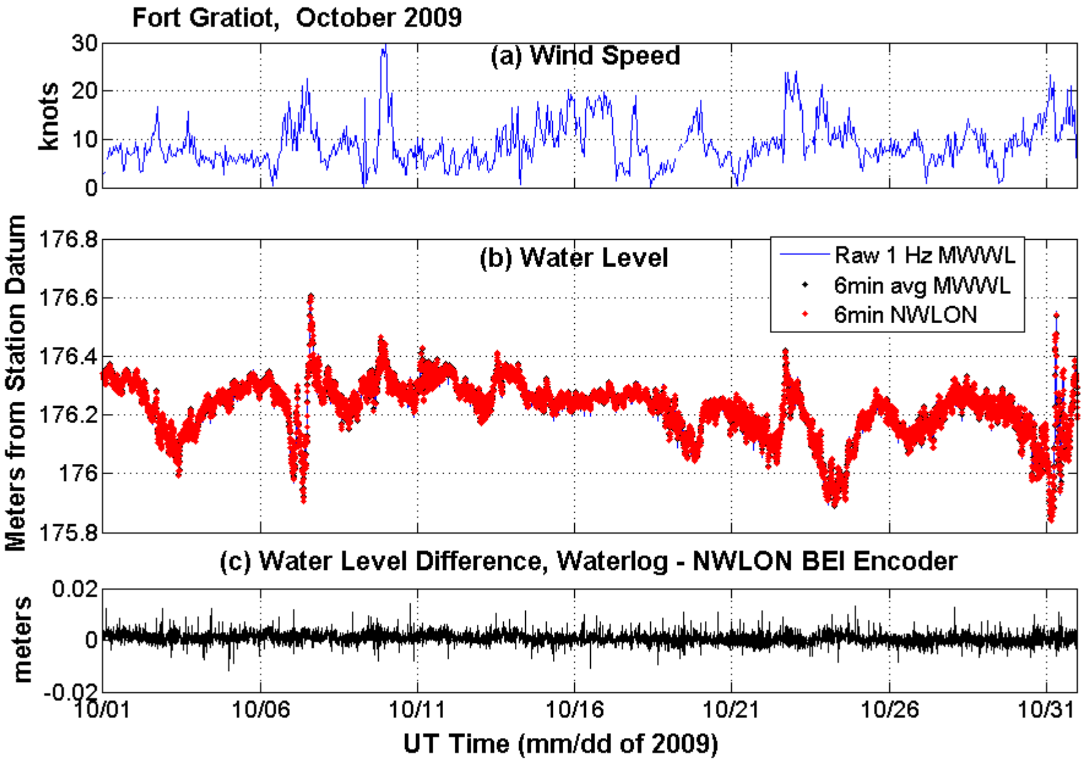

Figure 7. October 2009 time series of (a), hourly wind, (b) datum-referenced water levels, 1-Hz WaterLog® (blue line), 6-min average WaterLog® (black dots), BEI (red dots), and (c) WaterLog® versus BEI ΔWL at the Fort Gratiot, MI NWLON site.

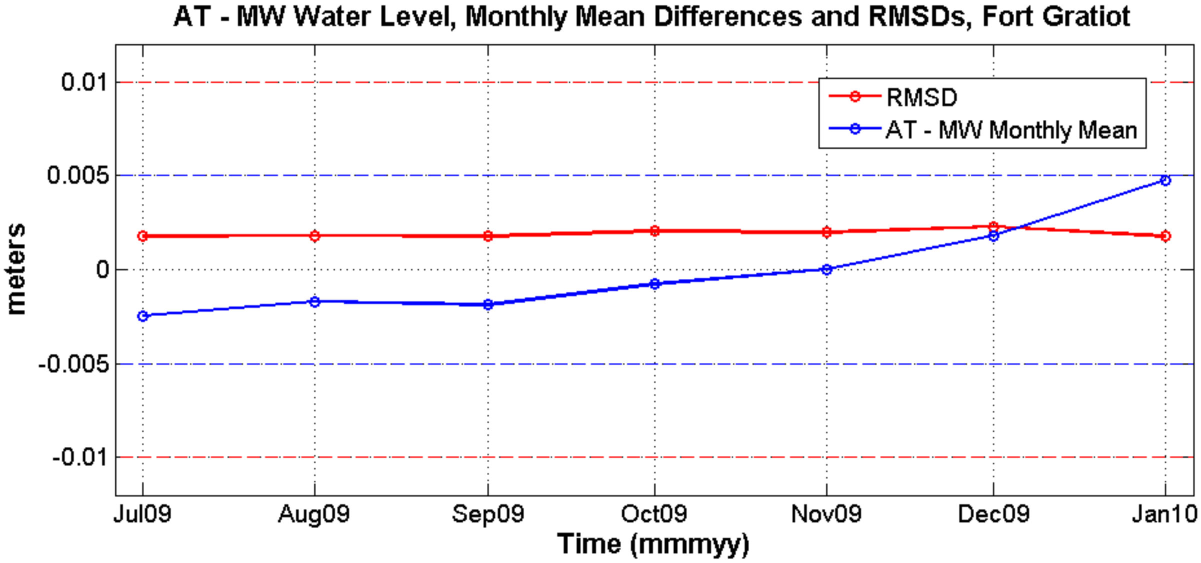

Figure 8. Monthly RMSDs between WaterLog® and BEI 6-min water level series (red) and differences between WaterLog® and BEI monthly mean water levels (blue).

2.2.3 Money Point

OSTEP deployed a WaterLog® microwave radar sensor at an additional field test location at Money Point, VA. The resulting data set provides another example of sensor performance in a fetch limited enclosed channel, in this case in a narrow section of a Chesapeake Bay tributary.

Throughout the microwave radar sensor project, CO-OPS and several other program offices within NOAA/NOS have expressed interest in the potential use of microwave radar technology for a typical CO-OPS station installed in support of NOAA hydrographic surveys (hydro station), which is a water level measurement station deployed temporarily for use in establishing Chart Datum and for use in reduction of soundings to datum. The ease of installation and low maintenance requirements of the microwave radar sensors offer significant value for the temporary and relatively short deployments required for hydro stations.

In response to NOAA/NOS interest, a prototype microwave sensor hydro station with a WaterLog® was developed and deployed for field testing to assess the suitability of this application based on an OSTEP *Test Plan for a Prototype Radar Hydro Station System* [16]. The test plan describes field testing for the prototype system at two sites that are representative of typical CO-OPS hydro station locations. Although system mounting hardware is different for each location, the sensor setup and configuration are the same for all microwave field test locations (records 1-Hz range to water data). Data were collected by the prototype microwave hydro station for 60 days, which is the typical deployment time of a hydro station.

In many cases, hydro stations that provide water level measurements in support of hydro surveys are installed in semi-enclosed waters that are significantly protected from high winds and larger surface gravity waves, such as sheltered and narrow rivers, locks, harbors, etc. Although this is not always the case, collecting measurements in this type of environment is very relevant to several NOS hydrographic surveying and shoreline mapping applications. Also, there are many benefits to conducting the first test of a new water level system in an enclosed, less dynamic coastal area. As a result, OSTEP selected the Money Point, VA NWLON station (fig. 9) as the first test location for a prototype microwave hydro station. The Money Point station is located in an enclosed, narrow branch of the Elizabeth River, which has a cross river distance of approximately 305 m (1,000 ft). Although water levels at the site experience tidal forcing, wind-induced surface roughness is minimal due to the narrow channel cross section as shown in fig. 9.

Figure 10 shows data for the month of April 2010 including (a) hourly winds, (b) station datum-referenced water levels from the WaterLog® test sensor and the NWLON Aquatrak system, and (c) the WaterLog® – NWLON ΔWL series. Since the first batch of data obtained from the Money Point microwave radar hydro station covers 60 days, NWLON versus WaterLog® RMSDs and monthly means are calculated over two subsequent 30-day periods. Results shown in fig. 11 further confirm that WaterLog® sensors meet accuracy requirements in small wave environments.

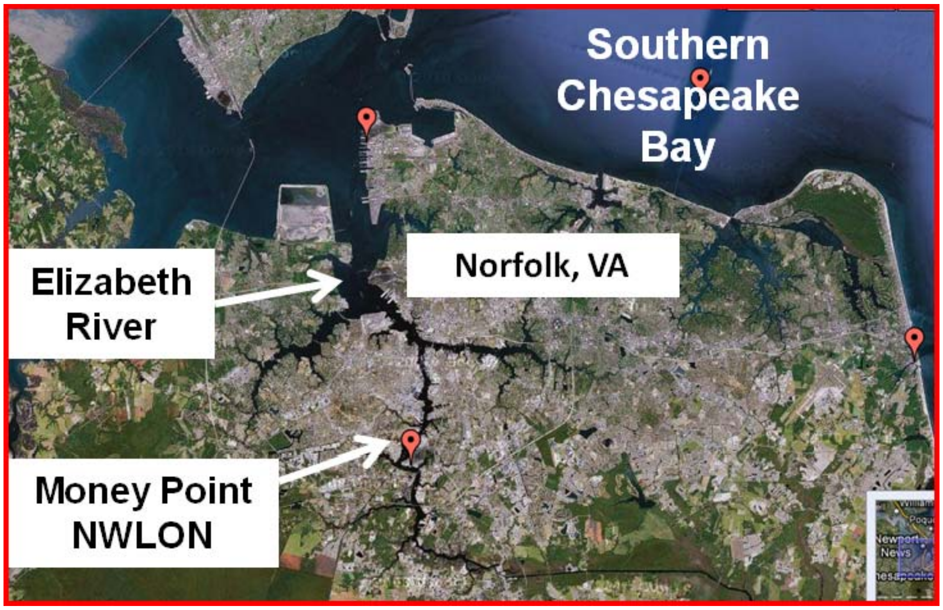

Figure 9. Location of Money Point, VA field test site.

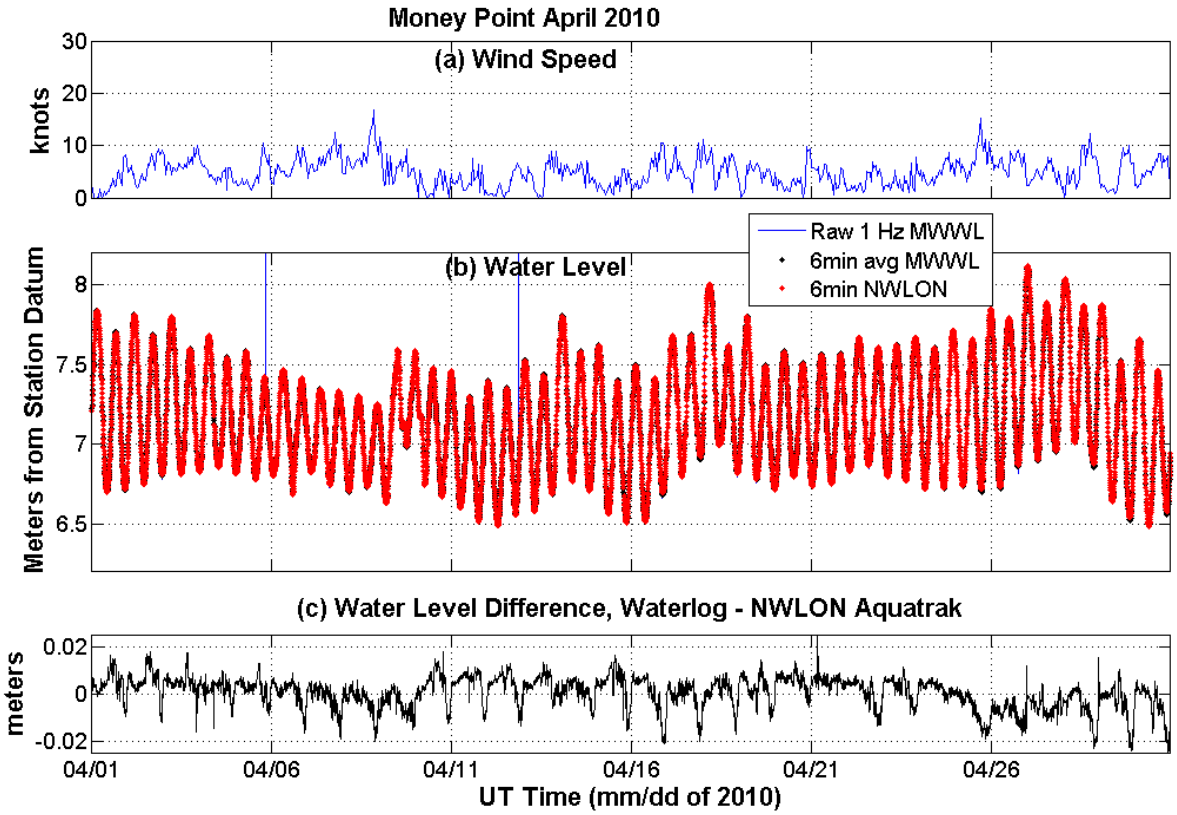

Figure 10. April 2010 time series of (a), hourly wind, (b) datum referenced water levels, 1-Hz WaterLog® (blue line), 6-min average WaterLog® (black dots), Aquatrak (red dots), and (c) WaterLog® versus Aquatrak ΔWL at the Money Point, VA NWLON site.

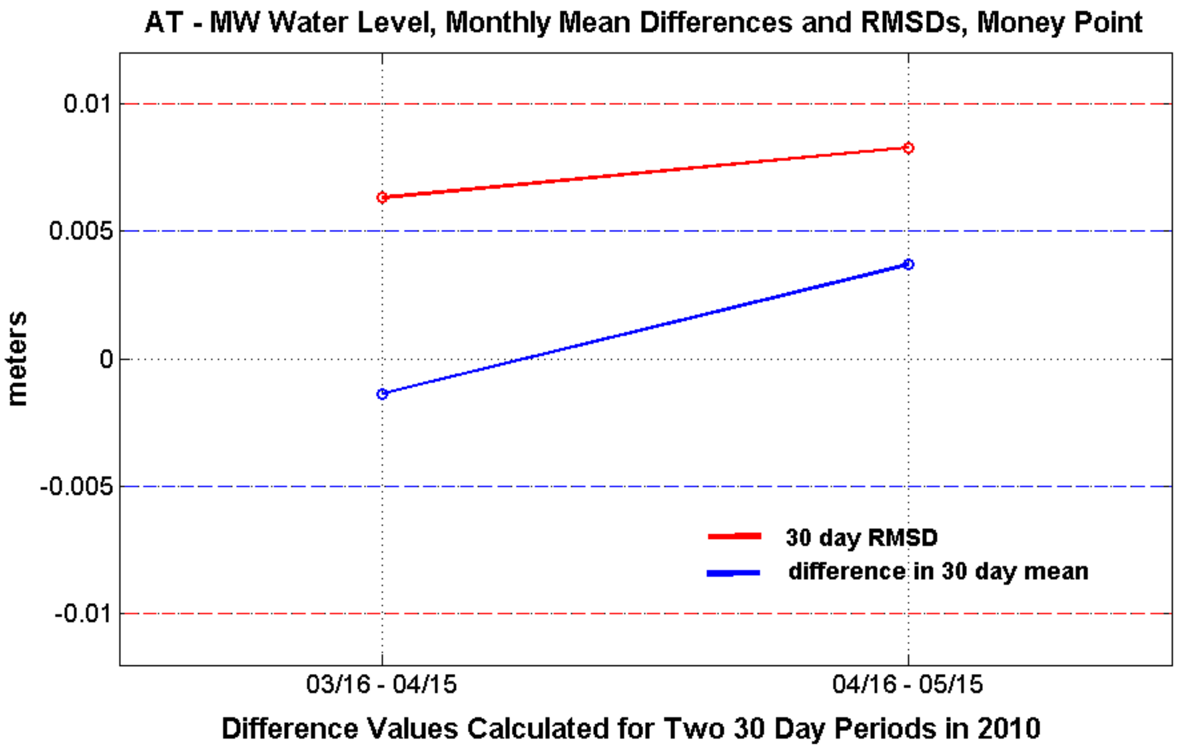

Figure 11. Monthly RMSDs between WaterLog® and Aquatrak 6-min water level series (red) and differences between WaterLog® and Aquatrak monthly mean sea levels (blue).

2.3 Generating Water Level Products Using CO-OPS Standard Processing Tools

Six-minute Port Townsend WaterLog® data sets for September 2008 through January 2010, including appropriate datum and estimated sensor offsets, were ingested into the CO-OPS staging database where calendar month water level products were generated in accordance with the Standard Operating Procedure (SOP) for tidal water level data processing [27]. The sensor offset is an estimated value of the physical separation between the sensor's zero point and geodetic leveling point as described in section 2.1. Verified Port Townsend (station ID 9444900) Aquatrak products serve as reference for comparison. The CO-OPS Data Management System (DMS), which is the Excel-based review, editing, and tabulation tool to develop water level products, was used to edit the microwave data—comparing the 6-min WaterLog® plots to Aquatrak plots for a visual overview and then running a DMS *Offline QC Check* to identify out-of-tolerance data and suspected problems. The microwave tidal signal was strong and good quality and had only one or two 6-min gaps that were filled using the DMS linear fit routine. After editing, the DMS tabulation feature calculated hourly heights, highs and lows, and monthly means. The strong tidal signal allowed the tabulation process to generally account for all tides with little manual intervention by the data processor.

Figure 12 shows the results of the DMS *Compare Monthly Means* routine that computed WaterLog® and Aquatrak monthly mean tidal parameter differences. In general, all differences are within ±1 cm except for four instances[3] of mean low water (MLW) where the values are near or outside ±2 cm. These differences are due to the DMS tide calculation curve fitting algorithm that tabulates the times and height of high and low waters. To be counted as a tide, the algorithm requires that adjacent high and low waters differ by at least 3 cm and be at least 2 hours apart. In September 2008, January 2009, and July 2009, the WaterLog® sensor measured a high and low tide that met or exceeded the requirement, whereas the same water levels measured by the Aquatrak did not. In March 2009, the Aquatrak measured a high and low tide that met the criteria, but the microwave values were below the ±1 cm threshold. In all four instances, the extra low water value was greater than the average of the other low waters, thereby skewing the mean by nearly 2 cm. If the extra tides measured were deleted in the mean calculation, the outlying MLW data points would fall within the ±1 cm range. This situation did not affect the mean high water (MHW) as much because the extra high water values were nearly the same as the means. Figure 13 provides ratios of mean range of tide (Mn), great diurnal range of tide (Gt), diurnal high water inequality (DHQ), and diurnal low water inequality (DLQ) of WaterLog® and Aquatrak monthly values. All the ratios are close to 1 (ranging from 0.961 to 1.038). The outlying values for DLQ in September 2008 and DHQ for March and July 2009 are again the result of the extra tides discussed for fig. 12.

Table 2 lists the WaterLog® and Aquatrak preliminary tidal datums (for the National Tidal Datum Epoch [NTDE] 1983-2001) and their differences using the standard datum calculation as described by the *Computational Techniques for Tidal Datums Handbook* [28] with Seattle (station ID 9447130) as the reference station. The datum differences vary from 0.003 m to −0.005 m, which are acceptable considering that the sensor offset was estimated.

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[3] September 2008, January 2009, March 2009, and July 2009.

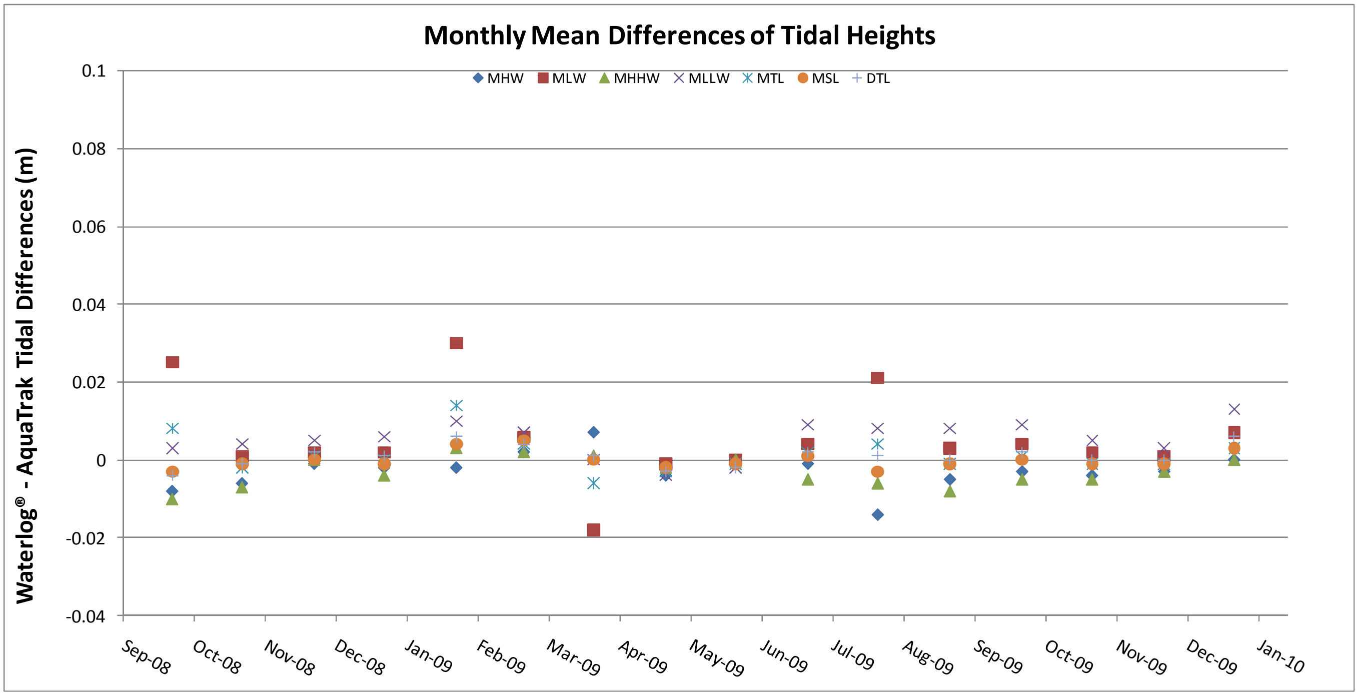

Figure 12. Monthly mean differences of tidal parameters processed from WaterLog® and verified Aquatrak data at Port Townsend.

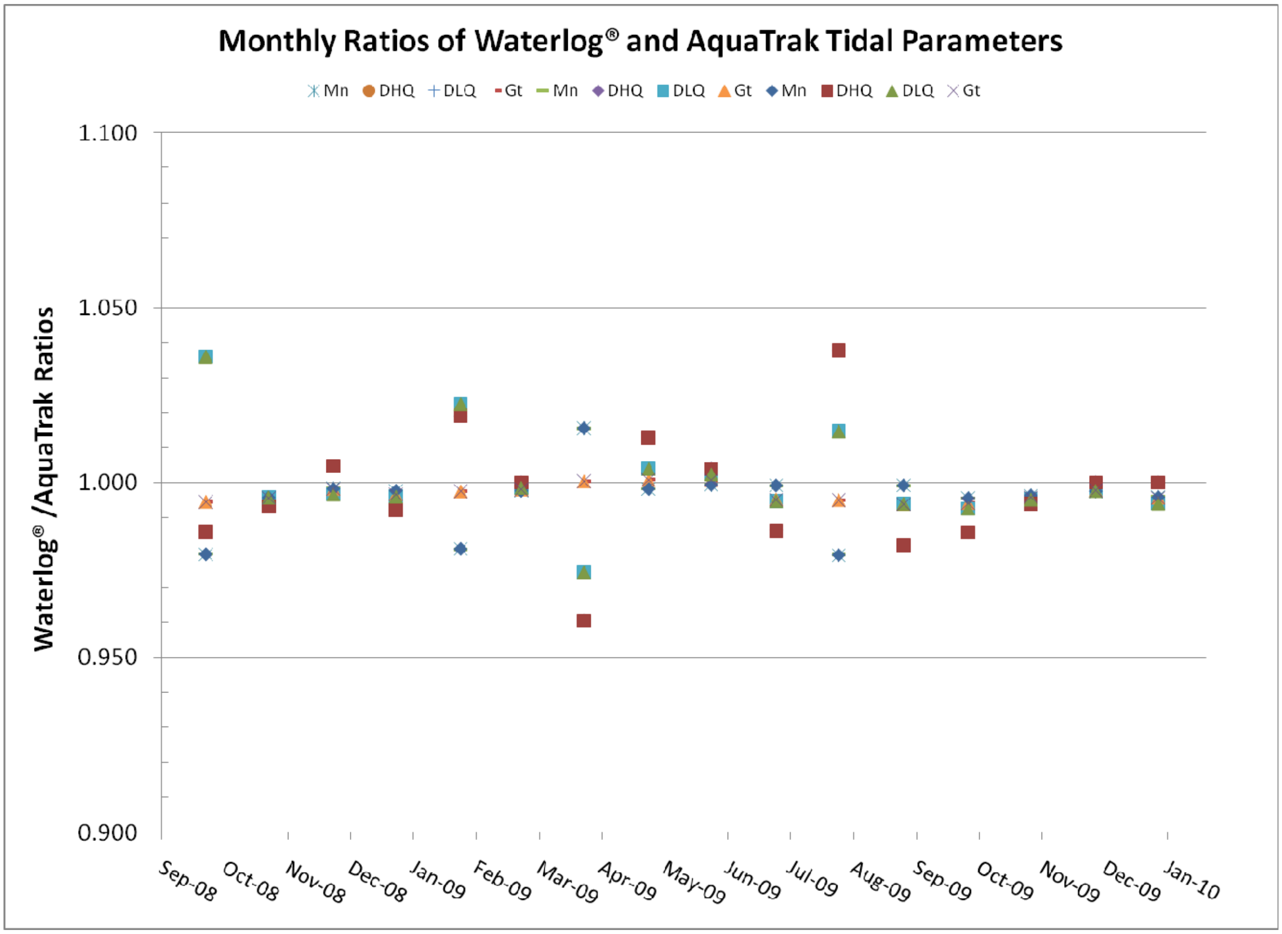

Figure 13. Monthly mean ratios of WaterLog® and Aquatrak tidal parameter products at Port Townsend.

Table 2. NTDE Datum comparisons using Seattle NWLON station 9447130 as a control.

NTDE (1983-2001) Datum	Aquatrak	WaterLog®	Difference
Mean Higher High Water	3.646	3.643	0.003
Mean High Water	3.444	3.442	0.002
Mean Tide Level	2.616	2.617	−0.001
Diurnal Tide Level	2.345	2.347	−0.002
Mean Sea Level	2.561	2.561	0
Mean Low Water	1.787	1.792	−0.005
Mean Lower Low Water	1.045	1.050	−0.005

3.0 Data Quality Control Guidelines

Introduction of a new type of water level sensor into the CO-OPS observation network requires that previously implemented data quality control (QC) guidelines be optimally tailored to accommodate the new measurement technology. CO-OPS applies specific QC processes to near real-time water level observations to achieve a high quality product. A standard procedure for applying QC processes to water level data has already been established and implemented within CO-OPS data ingestion software [29].

Established processes for specific QC parameters must be customized to accommodate the microwave radar measurement technology. As outlined in [29], the first step of the CO-OPS QC process involves applying simple logic to each 6-min water level observation during initial ingestion to determine whether a list of QC flags associated with each data point will be set. Setting a flag indicates that a particular 6-min water level value may be suspect or bad, and flag settings are taken into account during the next phase of data processing conducted by the Continuous Operational Real-time Monitoring System (CORMS) and the Oceanography Division's (OD) Data Processing Team. Determining whether a particular 6-min data value provided by a sensor is suspect/bad requires an assessment of the sensor's raw 1-Hz data time series, the characteristics of which are highly dependent on the signal technology employed by the sensor. The products that result from the processing and ingestion of microwave radar sensor data are the same 6-min data archive and displays that are generated by NWLON sensors (including the Aquatrak acoustic sensors and float/shaft angle encoder systems). However, to maintain identical water level observation products after introducing microwave radar sensors, a slight modification to the application of new QC flags to incoming water level is required.

This section summarizes the characteristics of previously-established CO-OPS software that performs initial quality control of NWLON data upon ingestion into the Data Ingestion System (DIS), including a list of related QC flags (section 3.1). Next, the newly-recommended criteria for setting QC flags associated with water level observations from a microwave radar sensor are described (section 3.2). Some of the currently implemented QC checks remain the same, so the focus here is on QC checks that require changes and modifications to criteria for setting certain flags. Analysis results obtained from several months of water level data collected during OSTEP's long-term microwave radar sensor field test data that support these recommended modified criteria are presented, along with the flag setting criteria.

Since this is a limited acceptance report, the QC guidelines discussed are only for measurements collected in fetch limited, semi-enclosed regions with a relatively small wave environment. Microwave radar sensor response to larger (>1 m) and longer (>10 s) surface gravity waves, as well as the impact on high frequency variability of water level measurements, remains an open area of study. Analysis results of measurements collected to date at the Duck, NC site indicate possible advantages to applying summary order statistics rather than Gaussian statistics (which use sigma criteria) for processing and applying QC to microwave radar sensor water level measurements collected in regions with more exposure to the open ocean [17].

3.1. NWLON Quality Control Software Functional Requirements

Functional requirements for the application of QC processes executed during the ingestion of data into the DIS and placement of data into the NWLON DMS are outlined in [29]. Related software includes set sensor "tables" associated with each sensor type. Each sensor table consists of a list of values calculated for each incoming 6-min water level data point before being stored in the DMS. These values include QC flags that can be set for a 6-min data point. Flags are assigned a value of zero as default; setting a flag involves changing its value to 1. A table for the microwave radar sensor already exists in the CO-OPS database. The table was previously implemented based on specifications in a request originally submitted on December 4, 2003 to ISD (CO-OPS Razor ticket #273) by Manoj Samant from CO-OPS Engineering Division (ED). ISD provided a list of single string descriptions for each column (table 3).

Table 3 List of values contained in the microwave radar sensor table established in DMS.

SENSOR_ID	single, constant numbers
STATION_ID	single, constant numbers
INFERRED	interpolations that fill in data gaps
MICROWAVE_WL	final, derived 6-min water level value
MW_SIGMA	standard deviation of raw 1-Hz data
MW_OUTLIERS	number of 1-Hz points that fall outside of ±3 standard deviations
SENSOR_TEMP	recommend removal from table
BOX_TEMP	recommend removal from table
MW_FLAG	set if water level exceeds minimum/maximum thresholds
MW_SIGMA_FLAG	set when MW_SIGMA indicates bad data
MW_OUTLIER_FLAG	set when MW_OUTLIERS indicates bad data
MW_FLAT_FLAG	set if flat lining
MW_ROFC_FLAG	set if difference between subsequent 6-min values indicate bad data
DATA_SOURCE	source of the data

Descriptions of every value in table 3 are included in appendix B, *Requirements for Ingestion and Processing of 6 Minute and Hourly GOES Transmitted Water Level Data Measured by a Microwave Radar Sensor*. Section 3.2 focuses on the description of the values associated with QC processing (**MW_FLAG**, **MW_SIGMA_FLAG**, **MW_FLAT_FLAG**, and **MW_ROCF**) and outlines the recommended guidelines specifically for microwave radar sensors.

3.2 Guidelines for Setting Quality Control (QC) Flags

Minimum/Maximum Check

The **MW_FLAG** value in table 3 is the water level minimum/maximum. This QC flag is applied to microwave radar sensor measurements the same way that it is applied to acoustic sensor measurements. Minimum and maximum water level value tolerances are specified for a particular station location, and then the flag is set for a given 6-min water level if it is above the maximum tolerance plus 3 m or is below the minimum tolerance minus 3 m.

Standard Deviation Magnitude

The **MW_SIGMA_FLAG** in table 3 involves a check of the standard deviation (sigma) calculated from the raw 1-Hz record, from which the 6-min water level was derived. If the value of sigma exceeds a certain threshold, the flag is set. In some cases when the value of sigma calculated for a 6-min period of 1-Hz water level data is relatively large, the data may be unusually noisy or contain a number of wild points that result in an average 6-min value that should be removed from the series because it is inaccurate and does not represent true water level. Defining a sigma threshold that can be used with high confidence to identify bad 6-min data points for a particular sensor depends on both detailed characteristics of the sensor and the water level variability that typically occurs at a specific measurement site.

At most NWLON stations, 6 min is the shortest period of water level variability that is required to be resolved in a measurement series, and, for a select subset of NWLON stations that are part of tsunami warning systems, 1 min is the shortest time period to be resolved. Currently, no attempt is made to measure water level variation on shorter time scales in any NWLON application. However, characteristics of a water level sensor's variability at higher frequencies should be taken into account when recommending a sigma threshold, since sigma is calculated from the sensor's raw 1-Hz record. A sensor's time response and corresponding cutoff frequency, along with the typical characteristics of the frequency spectrum calculated from a 1-Hz water level series, need to be considered to determine a sigma threshold that is appropriate for QC applications.

As previously discussed, significant differences between high frequency variability in water level measurements collected by an Aquatrak acoustic system and a WaterLog® microwave radar system occur mainly because the Aquatrak system's protective well mechanically dampens a portion of high frequency water level variability, while the WaterLog® system has no such well. The high frequency variability of WaterLog® radar's 1-Hz measurements may differ from those of other brands/models of microwave radar sensors, particularly the Miros sensor. This is noted specifically for CO-OPS personnel who are familiar with the characteristics of Miros microwave radar sensors, since they have been previously implemented into operational CO-OPS systems (e.g. air gap systems in PORTS®). Because there are subtle differences between the WaterLog® and Miros sensors' performance characteristics, along with significant differences between the air gap and NWLON applications, we cannot assume that the same set of QC parameters previously derived for an operational Miros microwave radar sensor system can be applied to a WaterLog® microwave radar sensor in an NWLON application. Instead, results of laboratory time response tests and several months of water level observations from multiple field test sites are used to derive a recommended sigma threshold.

The plot in fig. 14 shows range time series measured by both WaterLog® (red line) and Miros (blue line) sensors during a simple laboratory test. The plot demonstrates the difference in the time response of the two different sensors. When quickly moved toward and then away from a flat fixed target (for full details on the time response test procedure, see section 4), the Miros sensor's response time is close to 1 s, while the WaterLog® sensor's response time is slightly longer—approximately 3 s to 5 s (during this lab test, sensors' software parameters were configured optimally for measuring water level in the field based on previous OSTEP recommendations [13,14]). The WaterLog® sensor's time response results in a cut-off frequency in the 0.2-Hz to 0.3-Hz range, which is evident in the plots of sample frequency spectra shown in figs. 15 and 16.

Figures 15 and 16 show frequency spectra calculated from WaterLog® (red line) and Miros (blue line) sensors' 1-Hz water level series; fig. 14 from 1-Hz data collected over 5 days at Duck, NC and fig. 15 from 5 days at Port Townsend, WA. In both figures, the top plot shows spectral levels over a wide frequency range, 0.00001 Hz (approximately a 27.8-hour period) to 0.5 Hz, calculated using a 10^{17} point (36-hour) wide nfft window, and the bottom plot shows a zoomed-in view of spectra, from 0.05 Hz to 0.5 Hz, calculated from the same data but with a smaller, 10^{17} point (36-hour) wide nfft window. Although the focus of results in this report is on microwave data collected in small wave environments, the 5-day period of measurements selected from Duck provides a clear example of differences between frequency spectra calculated from the two different microwave sensors' water level records. During the July 12-17, 2008 period of data collected from Duck, NC, surface wave conditions were larger than those typical of Port Townsend, so the water level time series is a good example of a record with more high frequency variability than other test sites; however, wave conditions during this period were relatively small for the Duck site (significant wave heights remained within 1 m-1.5 m through the 5 days). In spectra plots for both Duck and Port Townsend records, the shorter time response of the WaterLog® is evident. The spectral levels calculated from the WaterLog® water level records are less than those calculated from the Miros record at frequencies of approximately 0.2 Hz and higher. These results provide further evidence that the value of sigma calculated from a WaterLog® 1-Hz series is smaller than the same value calculated from a Miros sensor in the presence of increased surface roughness. Since the WaterLog® sensor has a cutoff frequency range of 0.2 Hz-0.3 Hz, the peak in the WaterLog® spectrum appearing just above 0.4 Hz in the lower plot of fig. 15 is likely an artifact resulting from aliasing.

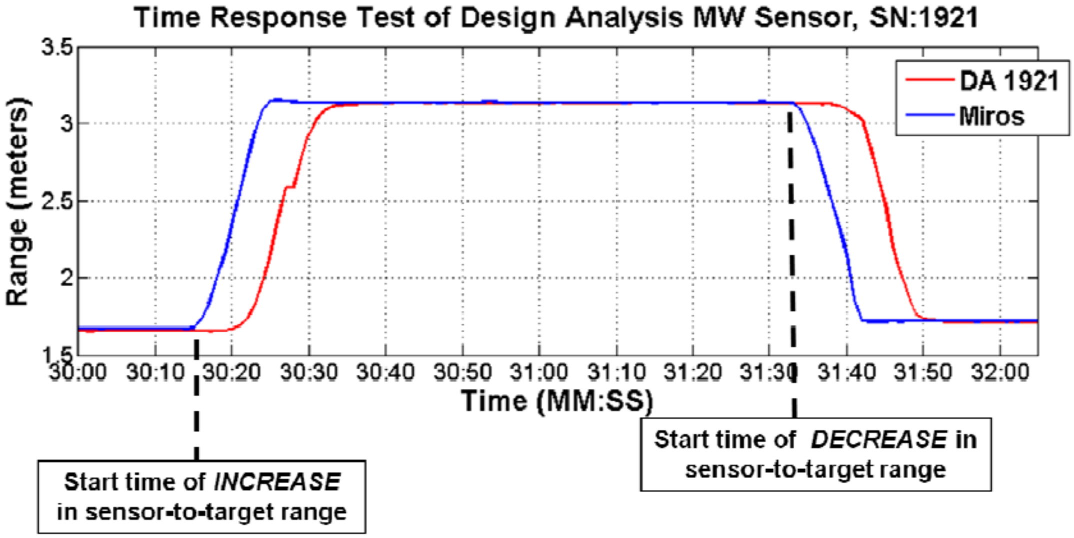

Figure 14. Range to target measured during a laboratory time response test by a Miros SM-094 (blue line) and a Design Analysis WaterLog® H3611i (red line).

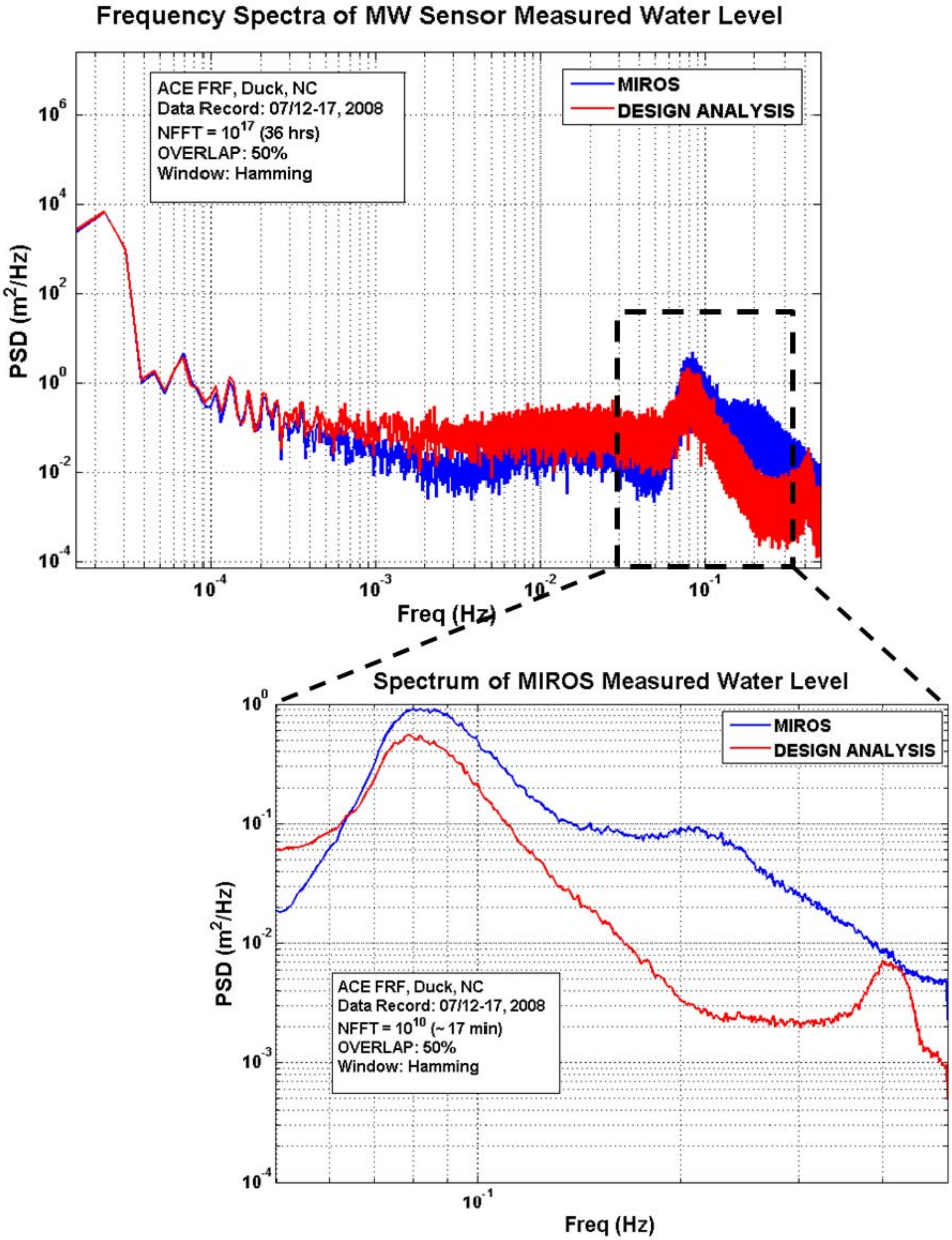

Figure 15. Frequency spectra calculated from a 1-Hz water level record measured by a Miros SM-094 (blue line) and a Design Analysis WaterLog® H3611i (red line) at the FRF in Duck, NC.

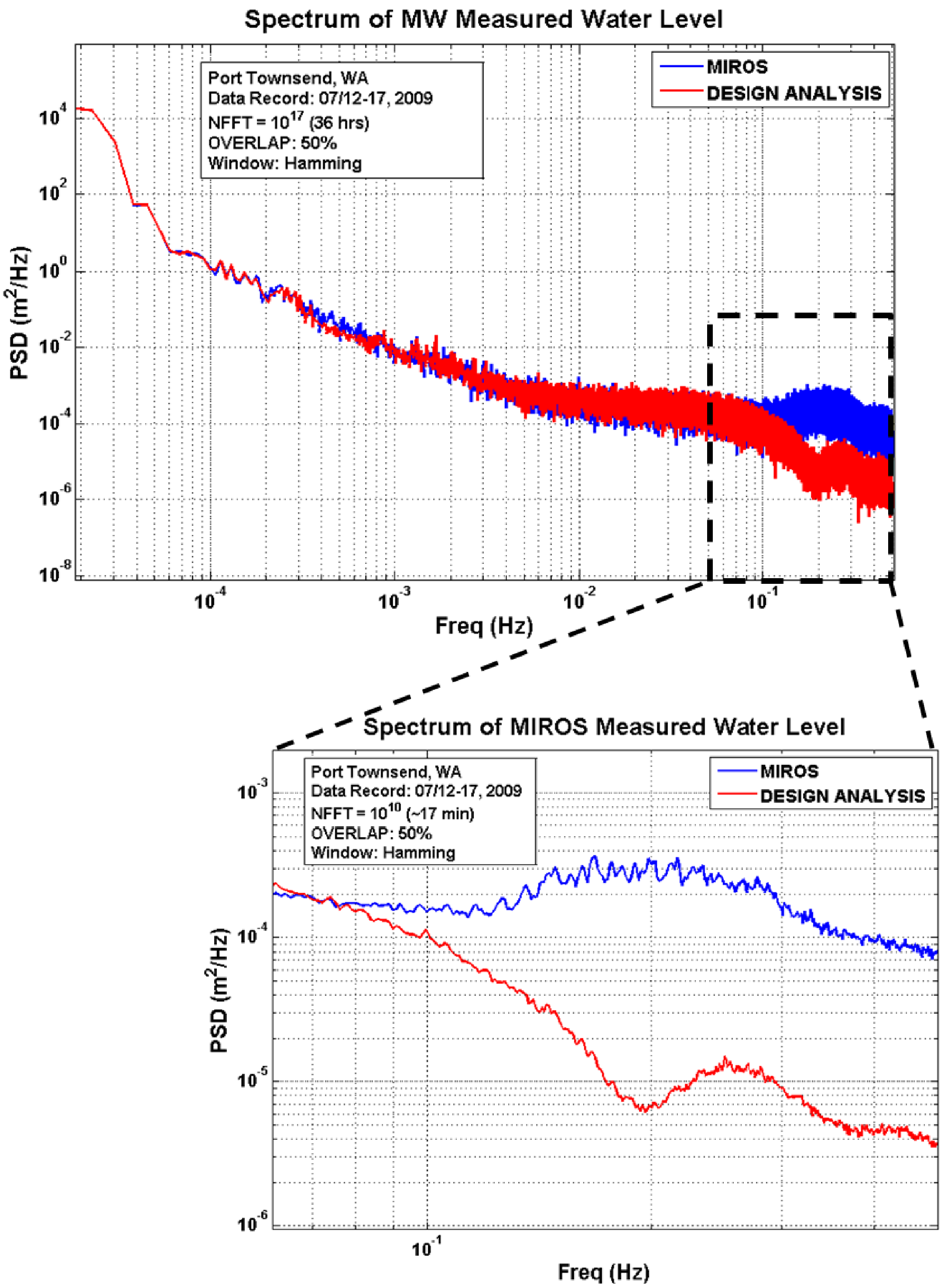

Figure 16. Frequency spectra calculated from 1-Hz water level record measured by a Miros SM-094 (blue line) and a Design Analysis Waterlog® H3611i (red line) at the Port Townsend, WA field test site.

When selecting a sigma threshold, OSTEP considered not only the characteristics of the WaterLog® sensor's time response and frequency spectra but also the time series of 6-min sigma values of WaterLog® 1-Hz water level data collected at Port Townsend, WA and calculated over

18 months. Because this site provides an excellent example of a semi-enclosed, fetch limited measurement region with a small wave environment, data collected here provide a good basis for deriving sigma and outlier thresholds for use at locations with similar coastal features. Figure 17 shows a sample one-month time series (November 2008) of 6-min sigma values (second plot down, black line), along with corresponding wind measurements (third plot down, blue line), which provide an indication of surface roughness at the Port Townsend site. The fourth plot (green line) shows raw 1-Hz range measurements from which sigma values are calculated. Also, the top plot displays the outlier number time series (red line), which is also calculated from 6-min blocks of data and is further discussed in the following subsection (*Number of Outliers*). A full series of plots like the one in fig. 17 were generated for the 18 months of 1-Hz WaterLog® test data collected at the Port Townsend site and are included in appendix A.

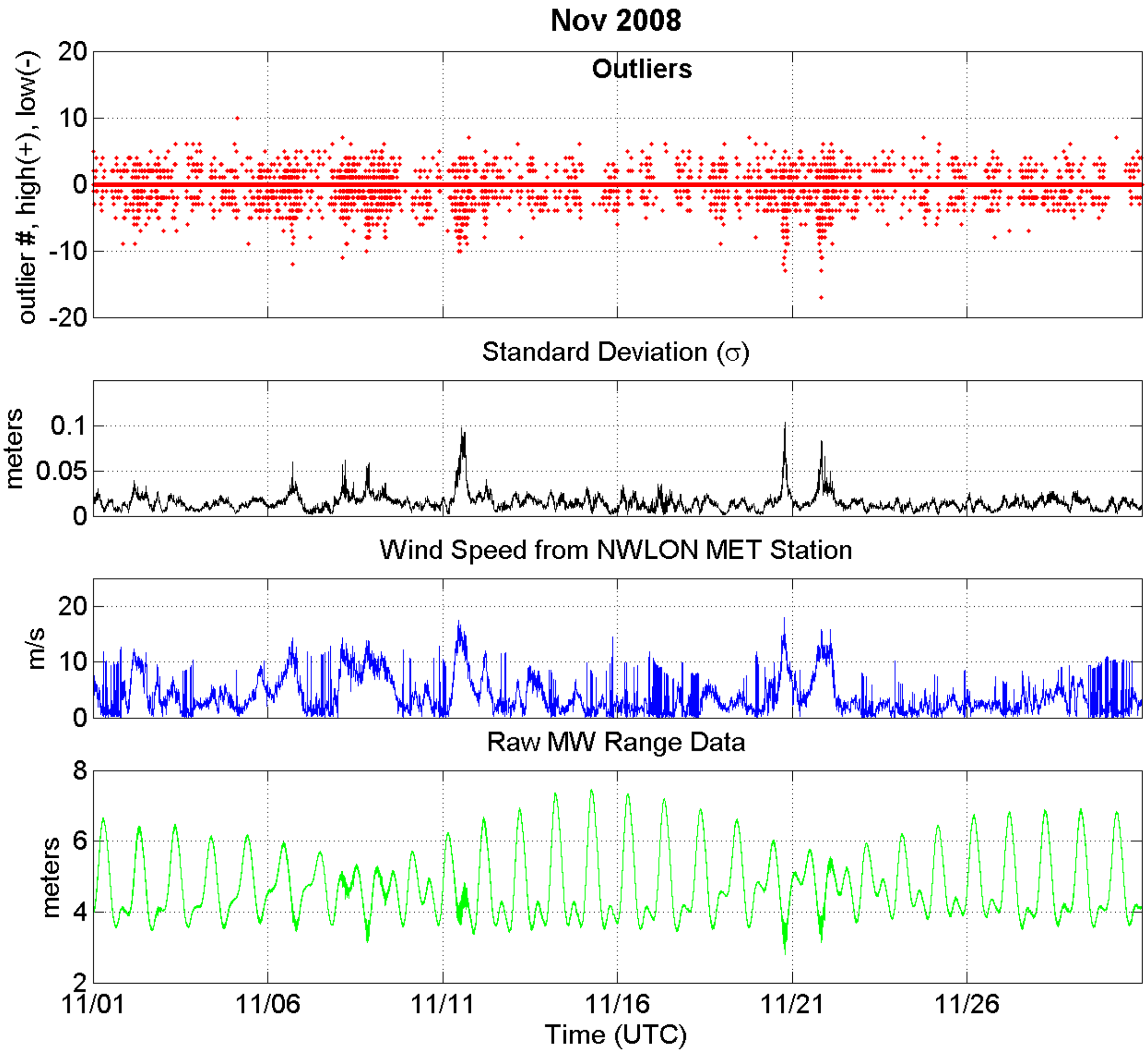

Figure 17. Time series of number of outliers and standard deviations calculated from 6-min blocks of 1-Hz WaterLog® range data, along with coincident wind speed collected at the nearby NWLON meteorological station and the raw 1-Hz WaterLog® range measurements.

The scatter plot of 6-min WaterLog® water level sigma values versus corresponding 6-min wind speed measurements from the Port Townsend site (fig. 18) was generated using 9 months of data from November 2008 through July 2009 (wind measurements were not available at this site until after a meteorological station was deployed in late October 2008). The plot shows a clear trend between sigma and wind speed. During this data collection period, there was only one confirmed bad 6-min water level data point in the record, which can be seen in the scatter plot as the outlying sigma value that is slightly less than 0.18 m. These data represent typical sigma values over a range of varying wind-induced surface roughness at Port Townsend. Based on results from the scatter plot, along with all time series plots included in appendix A, it is reasonable to assume that all 6-min sigma values should be 0.15 m or less, and that any values larger than 0.15 m likely indicate a bad data point. OSTEP recommends that a sigma threshold of 0.15 m be applied during QC processing of WaterLog® water level measurements collected at Port Townsend and other sites with similar coastal characteristics.

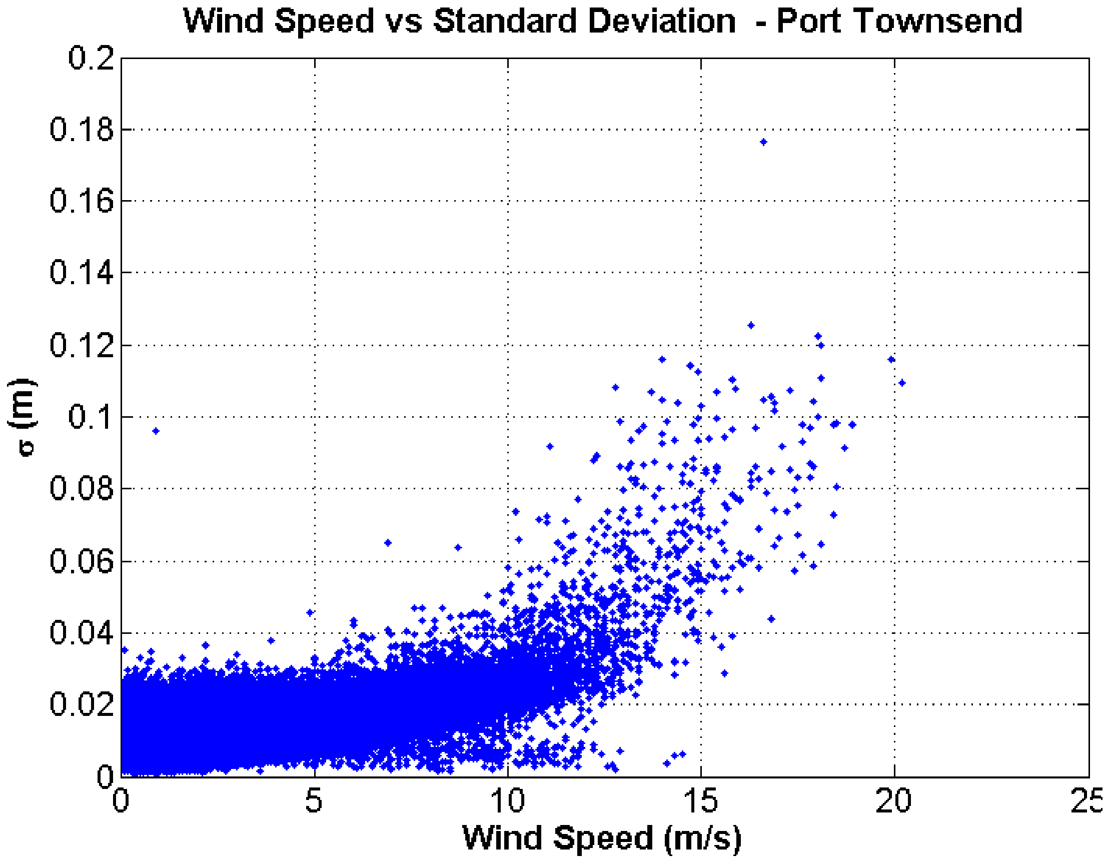

Figure 18. Scatter plot of wind speed versus WaterLog® range series standard deviation using 9 months of data (November 2008 through July 2009) at Port Townsend.

Number of Outliers

The **MW_OUTLIER_FLAG** in table 3 involves checking the number of 1-Hz points in a 6-min block of data that are likely outliers from the distribution of true water level observations. If a particular 6-min block of 1-Hz water level values contains a high number of outliers (also called 'wild points' or 'spikes'), the data point may be bad, so the **MW_OUTLIER_FLAG** should be set. Outliers may result from random sensor noise that creates spurious spikes in a data record, or, in the case of microwave radar outliers, from false echoes reflected off obstructions that transit beneath a sensor's antenna (e.g. boats, birds, or large debris floating in the water after a storm). For the data processing methods that CO-OPS currently employs for obtaining 6-min values from the raw 1-Hz record, it is assumed that 1-Hz water level observations are normally distributed. The mean of the 6-min block of data is calculated first, followed by the standard deviation of the 1-Hz series. An outlier is then defined as a data point that falls outside of ±3 sigma values from the series mean. In accordance with the standard CO-OPS DQAP procedure, if any outliers are detected in a 6-min water level series, they are removed and then the mean is recalculated (as previously stated, the only difference in the application to microwave radar sensors here is that a 360-s window has been used rather than the 181-s window used with an Aquatrak acoustic sensor record). If the number of outliers in a 6-min block of 1-s data is a large percentage of the total number of data points, the resulting 6-min value will likely be corrupted because of the high number of wild points and therefore not a true representation of water level.

To determine the outlier number threshold used to set the **MW_OUTLIER_FLAG**, similar analysis for determining sigma threshold (as discussed earlier) was conducted. Time series of outlier numbers generated from 6-min blocks of 1-Hz WaterLog® water level records, shown in fig. 17 and appendix A (top panel plots, red line dots), were used to determine an outlier number threshold that would indicate a suspect/bad data point. In these plots, the number of outliers above the mean water level plus 3 sigma (upper bound) is shown as a positive number, and the number of outliers below the mean water level minus 3 sigma (lower bound) is shown as a negative value. The total number of outliers for a 6-min period is the sum of the number of outliers above the upper bound and below the lower bound. The 18 months of data collected at Port Townsend indicate that good water level measurements in this type of environment typically have fewer than 15 outliers in a 6-min block (360 data points). OSTEP recommends that, for sites with coastal environments similar to Port Townsend, if the number of outliers is greater than 15 (approximately 4% of the 1-Hz samples), the **MW_OUTLIER_FLAG** is set to indicate the possibility of a bad data point.

Sensor Flat Line

The **MW_FLAT_FLAG** value in table 3 represents a QC flag set to indicate a bad data point resulting from the "flat lining" of a water level sensor. Although such flat lines are rarely observed throughout WaterLog® sensor data collected in laboratory and field tests to date, when either a sensor malfunction or a problem with the sensor-to-DCP interface occurs, the resulting data record becomes a series of repeated zeros, which creates a section of the time series that appears as a flat line. Similarly, if a single water level value is repeated in the raw 1-Hz data series, this indicates a sensor malfunction due to the sensor locking onto a single value and repeating. Because the WaterLog® sensor has no protective well and senses a larger horizontal area (sensor footprint) of open sea surface, a 6-min block of true 1-s subsequent sea surface values over an open sea surface region covered by the sensor's footprint probably would not be constant, especially at 1 mm measurement resolution. Therefore, a series of repeated values probably indicates bad data. When a 6-min series of 1-s water level data points stays at a constant value, the resulting standard deviation of the series is zero. In other possible scenarios, a series of subsequent 6-min water level values that remain constant may also indicate bad data due to sensor flat lining, and in some cases, sensor standard deviation may not be zero, but just very small. For example, a fixed structure or some type of obstruction located in the WaterLog®

sensor's field of view may result in a constant water level value repeated over several 6-min data points with the standard deviation of the 1-Hz record being small—close to sensor resolution but not zero.

As a result of these possible scenarios, it has been suggested that two conditions be checked to determine if the **MW_FLAT_FLAG** is set. The two conditions must be checked in order and the flag is set if either condition is met. First, the value in **MW_SIGMA** is checked, and if **MW_SIGMA** = 0.0 m, then **MW_FLAT_FLAG** is set. If the flag is set based on this first condition, then the second condition does not need to be checked. If the MW_SIGMA does not equal zero, then the second condition must be checked. This is the same flat line condition that is currently implemented for NWLON primary water level sensors (29). If a 6-min water level data value is identical to the two values before and the two values after that value, then **MW_FLAT_FLAG** is set.

Rate of Change Check

The **MW_ROFC_FLAG** value in table 3 is a QC flag set when the rate of change between subsequent 6-min water level values is significantly larger than the expected change in magnitude of the water level from an actual physical oceanographic process. Similar to the indicator provided by the outlier check previously described, a sharp increase or decrease between subsequent 6-min values can indicate a sensor malfunction, or in the specific case of a microwave radar sensor, a sharp change may suggest that multiple signal transmissions are being reflected and received from an obstruction in the sensor's signal path. Because these systems are more susceptible to problems related to signal interference from obstructions in the water, it is important to apply the rate of change QC check to microwave radar sensor measurements, as the sensor transmits signals through the open air with no protective well. The rate of change QC check and the outlier check are necessary, since an obstruction may remain in place under a microwave radar sensor's signal transmission path for an extended period. If an obstruction is located in the microwave radar sensor's signal path and remains in the path for the majority of a 6-min sampling period, a high number of subsequent false echoes in one 6-min block may not be statistically detected as outliers, and therefore the **MW_OUTLIER_FLAG** is not automatically set.

The rate of change threshold represents the maximum water level change that is acceptable between subsequent 6-min water level measurements at a particular site. Where $\mathbf{dWL_{max}}$ is the maximum rate of change threshold, $\mathbf{WL_i}$ is the current 6-min water level data point being processed, $\mathbf{WL_{i-1}}$ is the previous 6-min water level data point, and "abs" indicates absolute value, the criteria for setting this flag is:

If $\mathrm{abs}(\mathbf{WL_i} - \mathbf{WL_{i-1}}) > \mathbf{dWL_{max}}$, then the **MW_ROFC_FLAG** flag is set.

The maximum threshold value ($\mathbf{dWL_{max}}$) depends on the water level characteristics at each measurement site under consideration, regardless of any similarities in characteristics with the Port Townsend test site that have been discussed here, such as enclosure from the open ocean, short fetch, and small waves. The typical rates of water level changes at an individual site resulting from processes on time scales ranging from those of tidal- and meteorological-forced water level changes need to be considered, as well as first difference distributions of historical 6-min water level records at a particular site. Water level first difference distributions calculated from the Port Townsend test site show that first difference distributions from 1 year of Aquatrak and WaterLog® sensors' 6-min water level series look similar. Therefore, a long-term record of

NWLON Aquatrak acoustic sensor data from a site where a microwave radar sensor may be deployed can be used to determine a reasonable rate of change threshold for a microwave radar sensor. Plots of first difference distributions from Port Townsend water level data in fig. 19 show a wide distribution that is approximately symmetric, and most differences are within ±0.1 m. The example first difference distribution for the Mobile Bay NWLON station in fig. 20 shows a significantly narrower shape, with most difference values lying within minimum and maximum values of approximately ±0.05 m; however, there are some difference values that are as large as ±0.1 m. Based on these observations, a reasonable rate of change threshold for Mobile Bay is ±0.15 m.

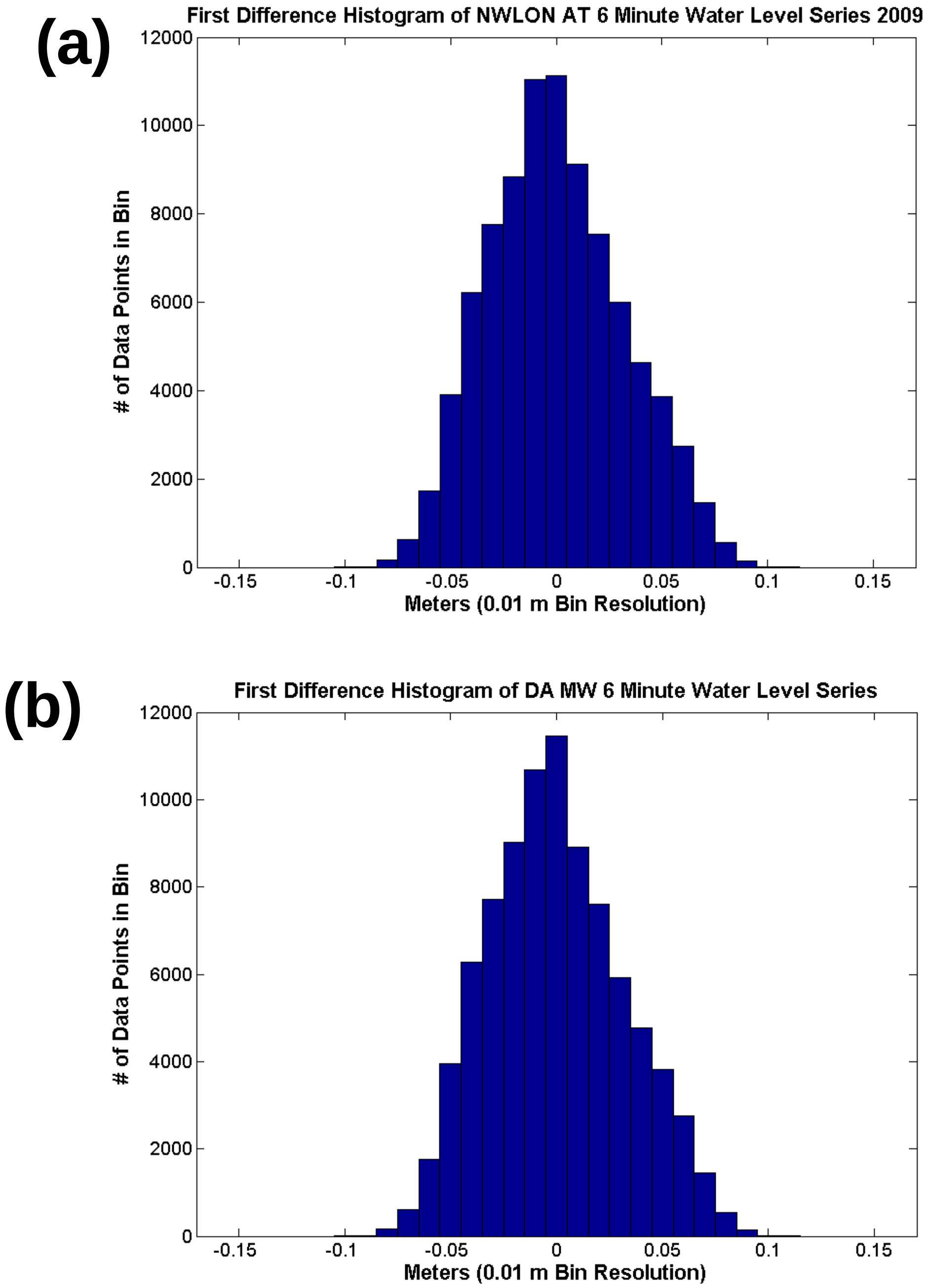

Figure 19. First difference distributions calculated from 1 year of 6-min water level data (2009) from the NWLON Aquatrak sensor (a) and the test microwave radar Design Analysis (DA) WaterLog® sensor (b) both at the Port Townsend, WA site.

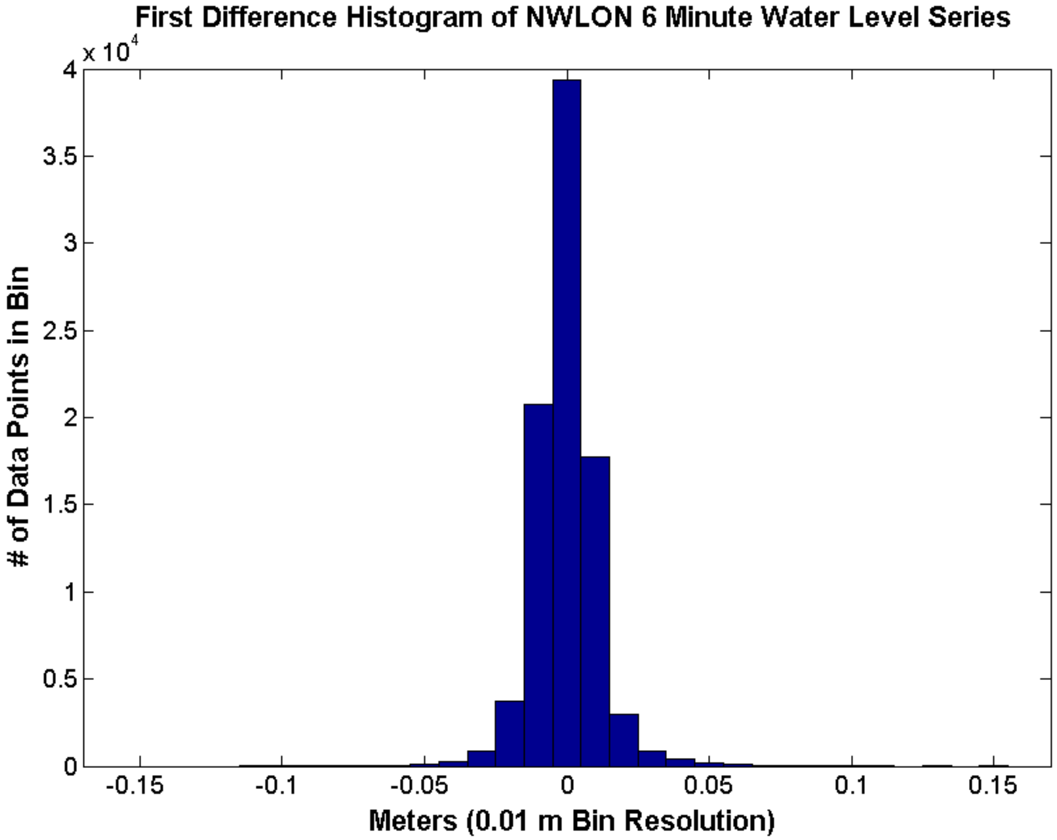

Figure 20. First difference distributions calculated from 1 year of 6-min water level data (2009) from the NWLON Aquatrak acoustic sensor (top) at Mobile Bay Coast Guard Station.

4.0 Microwave Radar Sensor Pre-deployment Test Procedure

4.1 Introduction

In preparation for the microwave radar sensor field testing that has taken place over the last several months [13,14], the OSTEP team conducted a series of basic laboratory tests at the CO-OPS Chesapeake, VA facility to confirm that microwave radar sensors were functioning properly and configured optimally before field installation. Analysis of field results to date reveals a significant improvement in the understanding of sensor functioning and suggests that the original OSTEP microwave sensor pre-deployment laboratory test procedure should be refined and improved. Eventually, this procedure will evolve into an SOP, and software tools to assist with data analysis are currently being developed. In addition to field data analysis, a few sensor problems encountered along the way have also highlighted the need for more a rigorous pre-deployment test procedure. In response, OSTEP developed a clearly defined, standard microwave radar sensor pre-deployment test procedure and the related data analysis. Adherence to this four-step laboratory test procedure will likely improve future microwave sensor field installations. Although field testing is underway as this document is being prepared, the expanded pre-deployment test is the first iteration of an evolving procedure that may be further refined and appended as the test effort progresses.

The following sections describe the new pre-deployment procedure that comprises four different types of basic laboratory tests to be conducted on new microwave sensors: 1) fixed target, 2) time response, 3) range calibration, and 4) water level measurements in a small tank or pool. The description of each test includes the analysis products generated from the resulting data collected, along with guidelines for interpretation.

These pre-deployment tests are the first critical step in a successful microwave radar sensor deployment. A full understanding of both the capabilities and limitations of any sensor is a prerequisite for development of methods, techniques, and procedures that analyze and interpret the data collected.

4.2 Fixed Target Test – Observing Sensor Resolution and Characterizing Sensor Noise

The first pre-deployment laboratory test conducted for each sensor involves setting up a microwave sensor in a secure mount to aim horizontally at a flat fixed target and allowing the sensor to record 1-Hz range measurements for an extended period. Although the initial result confirms whether the sensor measures a reasonable range value based on the known sensor-to-target range, the main objective of this test is to obtain a time series from which an observed sensor resolution can be obtained and any sensor noise (beyond digitization) can be detected and quantified.

Microwave radar sensors include a manufacturer-specified accuracy and resolution. Absolute accuracy is the sensor’s ability to provide an observation that is consistent in magnitude with an absolute reference standard. Unlike accuracy, resolution refers to the smallest amount of input signal change that the instrument can detect reliably. Resolution is determined by the instrument noise, which includes digitization noise resulting from bit resolution and may also include additional electronic noise that can result from several different factors. When sensor resolution is dominated by digitization noise, resolution can be determined as a function of bit resolution, where the resolution of N bits means that the full range of the sensor is partitioned into 2^N equal segments. For example, the Miros SM-094 microwave sensor has 8-bit resolution, and it partitions range measurements into 0.375-m bins, which implies dividing range measurements into $2^8 = 256$ increments, resulting in a sensor resolution of $0.375/256 \approx 0.001$ m. Whether the sensor can actually measure to a resolution and/or accuracy of 0.001 m is another matter.

All of the manufacturers' resolution specifications for the selected microwave sensors are 1 mm or less, indicating that resolution and sensor noise should be dominated by digitization noise. However, some results to date have detected microwave sensors with noise levels higher than those expected only from digitization noise. In previous lab testing, some microwave sensors with higher than expected noise levels produced range measurements to a fixed flat target that were within accuracy specification (±1 cm). However, when these noisier sensors were deployed in the field, if the target was roughened sea surface, noise with a significantly larger magnitude (including frequent spurious spikes) was present in the data record. These previous observations of sensors with noise levels higher than specified digitization resolution demonstrate poor performance in the field, and further emphasize the importance of carefully observing sensor resolution and quantifying sensor noise before field measurements are taken.

For the initial fixed target test, the microwave sensor is secured in a horizontal mount, set up to aim directly at a flat fixed target placed a short distance away. The resulting sensor signal path should be as close to normal as possible to the flat target. The flat target requires an area larger than the sensor's footprint width, which increases linearly with range and can be calculated from a manufacturer's specified beam spreading angle. To ensure a small footprint-to-target area ratio and a relatively strong return, the target-to-sensor range needs to be relatively short, (2 m-3.5 m) but not less than 1 m, which is the default blanking distance of the Miros sensor.

The simple fixed target test (fig. 21) can be successfully conducted outdoors, although conducting it indoors minimizes motion of the sensor and/or target, which may be induced by environmental variability. After the setup is complete and the sensor is confirmed to be measuring reasonable range-to-target values with both sensor and target secure enough to avoid significant movement of either, 1-Hz measurements are recorded for 8-12 hours. Leaving the sensor set up to record overnight is recommended to decrease the likelihood of obstructions moving between the sensor and target and to increase the likelihood that everything stays fixed.

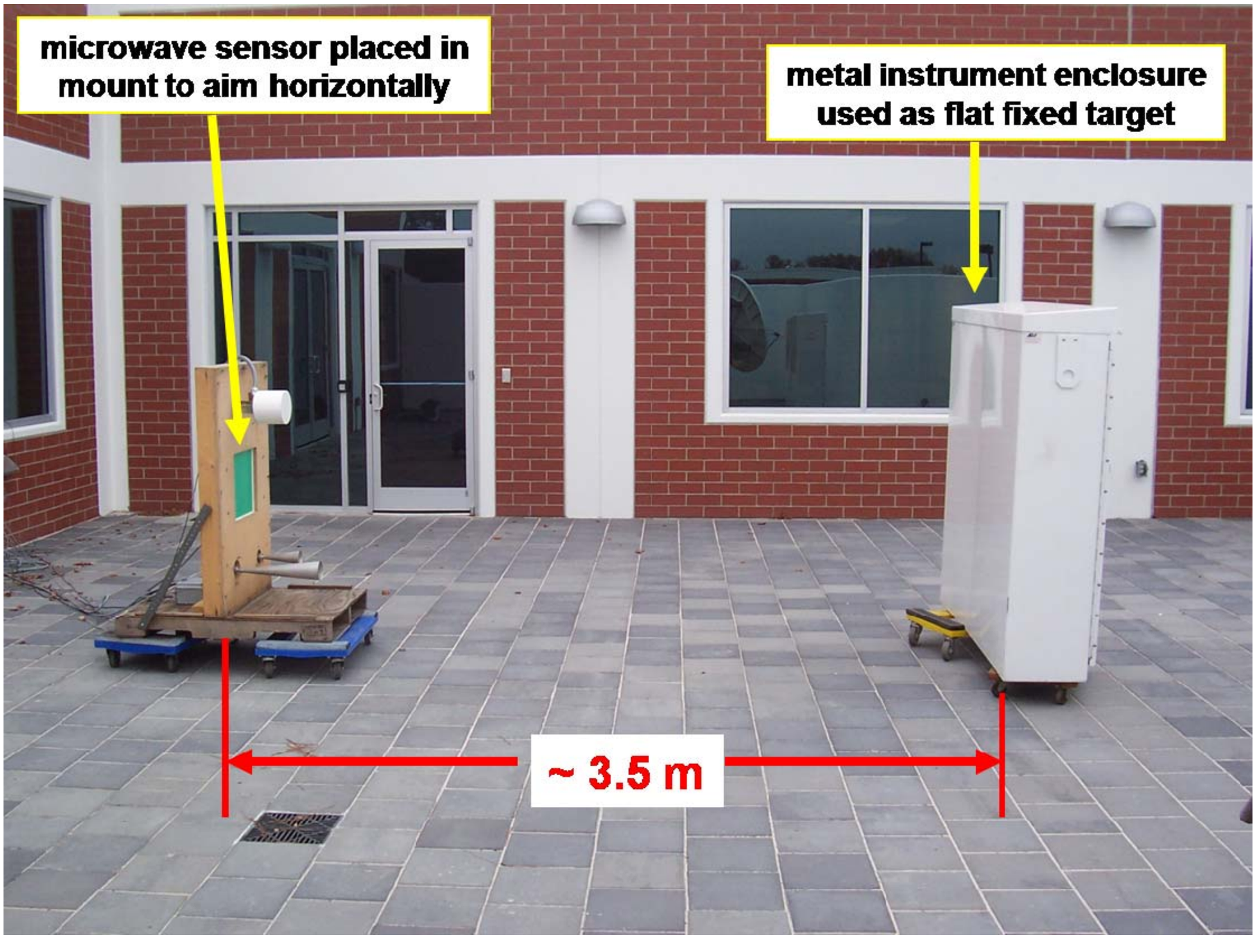

Figure 21. Example of a fixed target test setup. This same setup can also be used to conduct the time response test discussed in section 4.3.

After 1-Hz range is recorded for 8-12 hours, it is critical to look carefully at the entire resulting time series. Several intermediate quick checks of the range values shown on the sensor or DCP displays may provide a confirmation that the sensor *seems* to be operating within resolution and accuracy specifications; however, subtle issues with sensor noise will most likely not be detected without additional observations of the recorded time series. OSTEP recommends that three data analysis products be generated from fixed target test 1-Hz range series: 1) a set of simple time series plots displaying longer periods of data (1 hour or more), 2) distribution of first differences and resulting average observed resolution, and 3) the frequency spectra of a few selected 1-hour periods.

First, a plot of the entire 8-12 hour time series is generated, with the *X*-axis representing time and the *Y*-axis range to target. The plot's *Y*-axis limits are centered on the known sensor-to-target range and should only cover the range plus or minus a few multiples of the sensor-specified resolution value. Such a plot indicates any obvious unusual behavior, such as large deviations in range measurements or high frequency noise. A few wild points or spikes in the records are not significant as long as they are only individual spikes that total an extremely small percent of the entire number of samples. Small, long-term changes in range may result from slight environmental variability, such as changes in temperature or airflow. If such range changes occur, the test data are still useful, as the focus here is on high frequency sensor noise.

Then, if the entire time series plot looks reasonable, additional time series plots are generated—zooming in on the *X*-axis with a few selected 1-hour periods of the 1-Hz range record. Figure 22 shows range time series plots for two Miros microwave sensors, (a) a sensor operating within resolution and accuracy specifications and (b) a sensor functioning within accuracy specifications but with noise levels that are clearly higher than those expected from digitization noise alone.

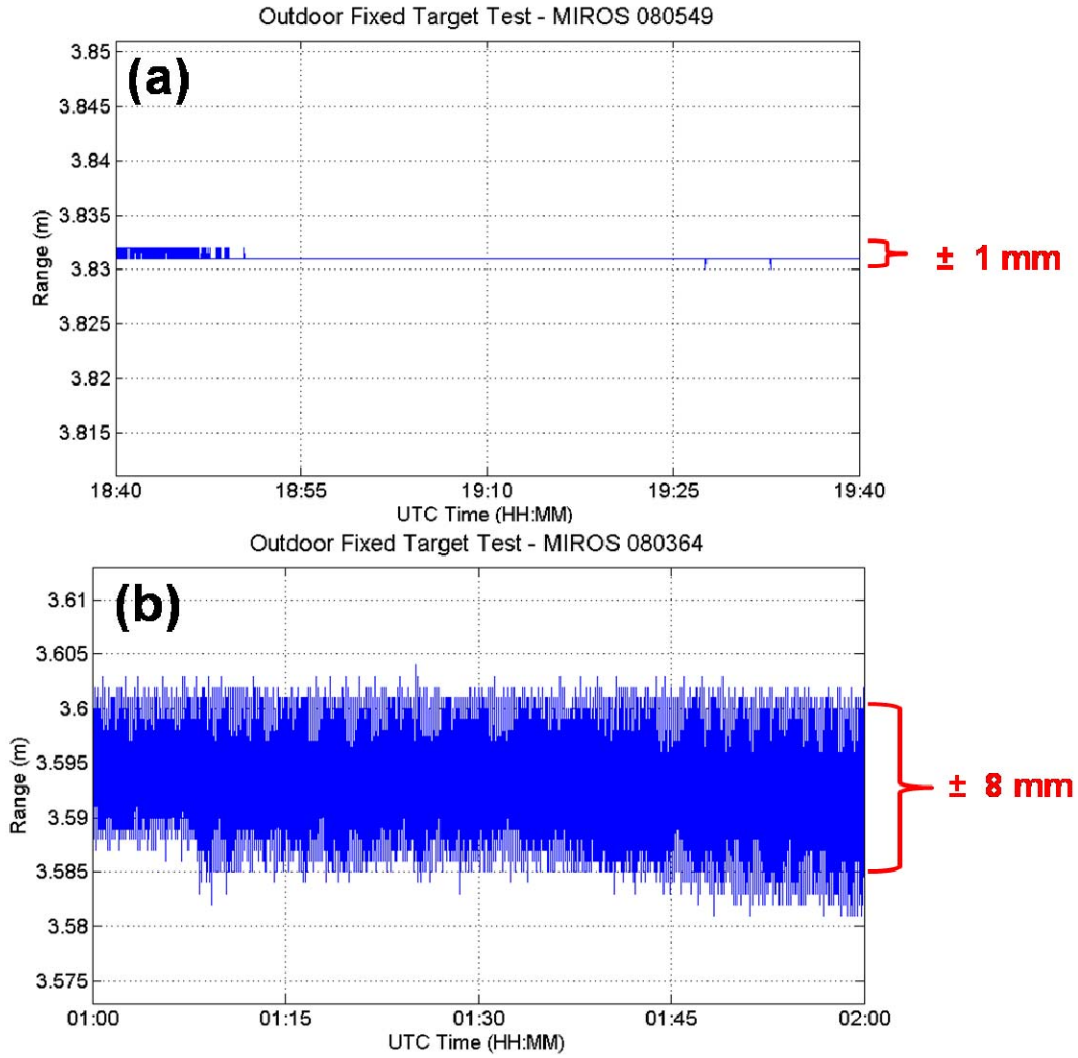

Figure 22. One hour of 1-Hz microwave sensor range time series collected during a fixed target test from (a) a Miros sensor operating within resolution specifications and (b) a noisy Miros sensor functioning within accuracy specifications, but with higher than expected noise levels.

Next, 1 hour of data representative of the whole test period is selected and used to derive a first difference distribution and an observed resolution. If there is uncertainty about which 1-hour period to select, multiple 1-hour sections of data can be selected to determine if repeatable results are obtained. Calculating a first difference series for a select 1-hour period of 1-Hz range data involves iterating through the entire series and calculating the absolute difference between subsequent 1-Hz points. For a range time series, *R*, consisting of *N* samples, the resulting first difference series, *dR* of length *N-1,* is expressed as:

$$R(t) = \sum_{t=1}^{N-1} |R_t - R_{t+1}|$$

where *i = 1,2,3….N-1.* These first difference values in *dR* can be sorted into 1-mm value bins and plotted in a histogram to observe first difference distribution; the mean value of the series *dR* represents an average observed resolution. Figure 23 shows sample first difference distributions and average resolution derived from the two sensors' range series shown in fig. 22, fig. 23 (a) the sensor within resolution specification, and fig. 23 (b) the noisier sensor. An average observed resolution larger than the specified value, which is obviously the case in fig. 23 (b), may indicate a source of electronic noise in the sensor. Such results should be shared with a sensor vendor to obtain further evaluation and explanation of additional noise. The presence of electronic sensor noise could indicate that sensor repair is necessary prior to field deployment.

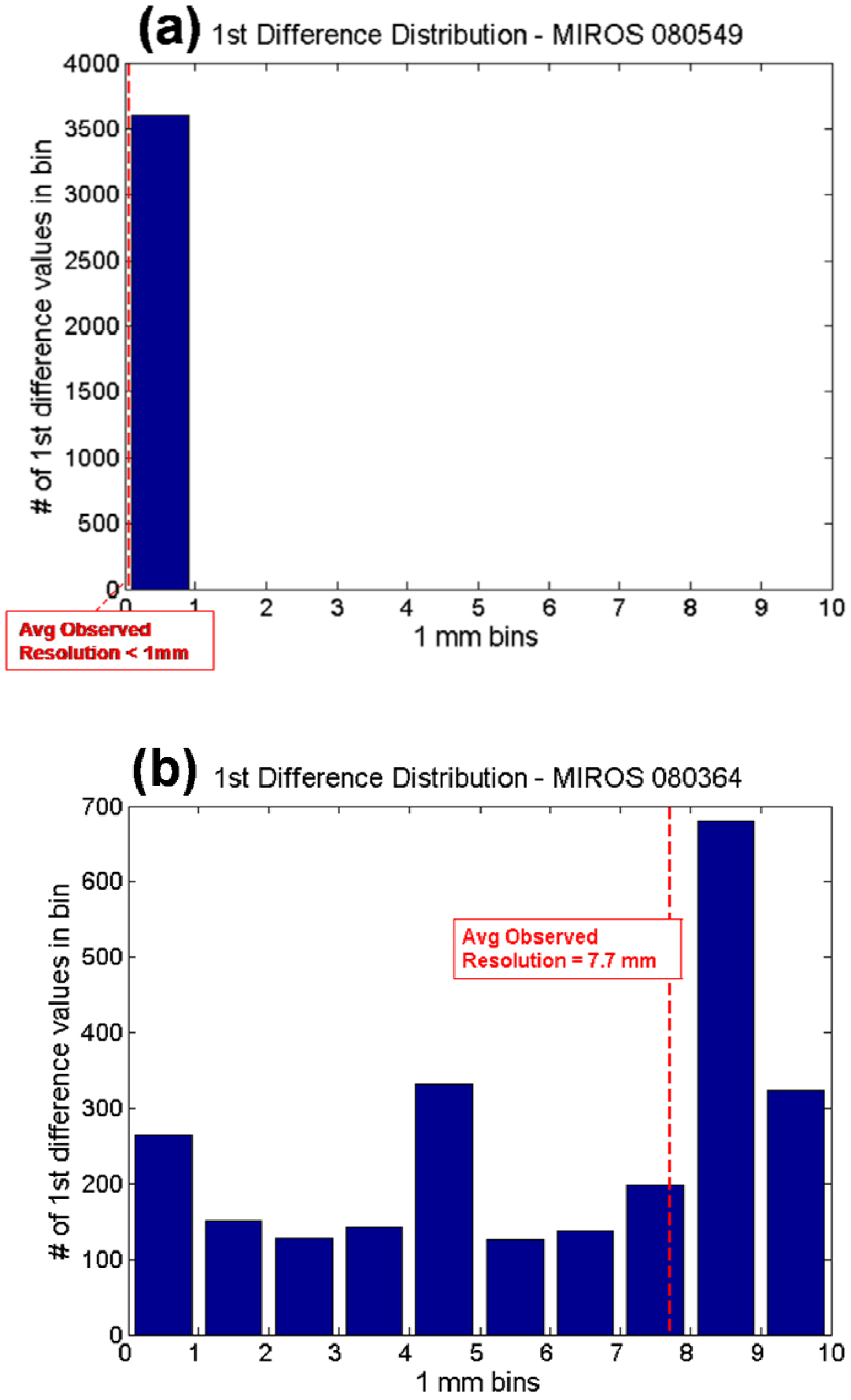

Figure 23. First difference distribution (blue bars) and average observed resolution (red dashed line) calculated from the two sensors' range series shown in fig. 22, (a) a sensor operating within resolution specifications and (b) a noisy sensor that is functioning within accuracy specifications but with higher than expected noise levels.

Finally, the selected 1-hour time series (or multiple 1-hour periods) are used to calculate a frequency spectrum to determine the distribution of the sensor noise in the frequency domain. This distribution indicates whether sensor noise is white or concentrated in a particular frequency band. Results might assist in determining the source of any excess electronic noise. Figure 24 shows frequency spectra calculated from the two sensors' range series shown in fig. 22. In this example, the noisy sensor (blue line) clearly shows high variability near 0.2 Hz.

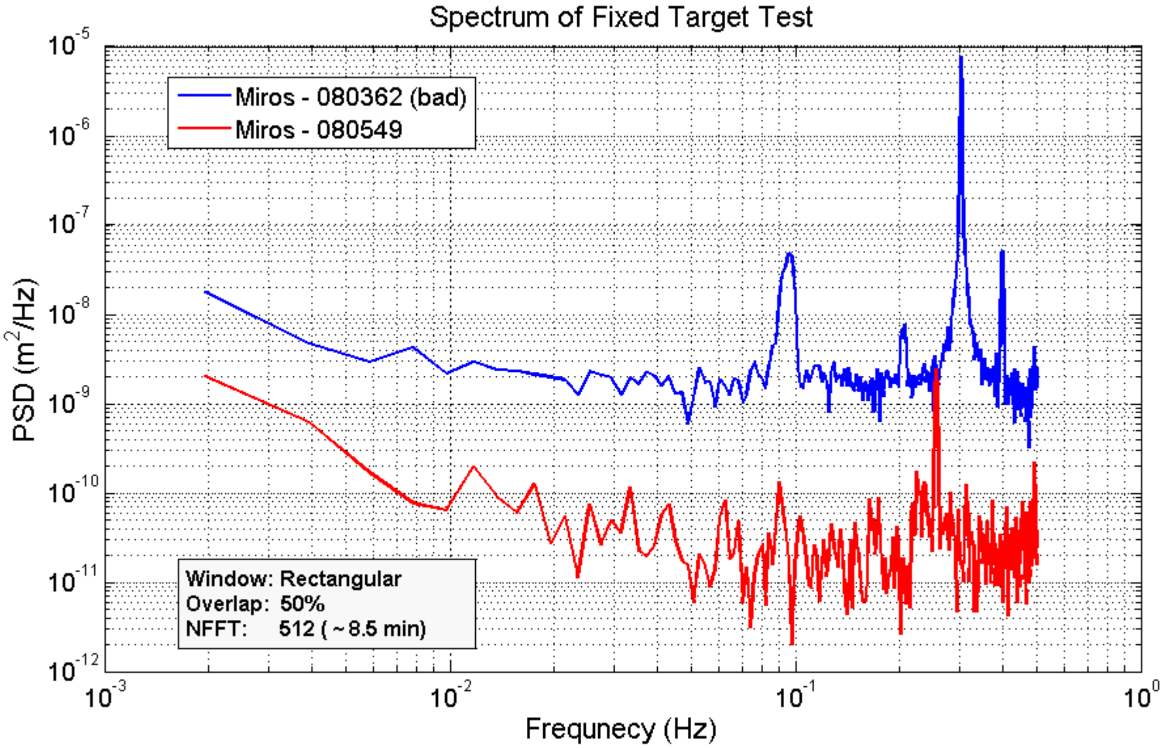

Figure 24. Frequency spectra calculated from the two sensors' range series shown in fig 22. Spectrum of noisy sensor (blue) has levels significantly higher than the spectrum of the good sensor (red line) and a sharp peak at 0.2 Hz.

4.3 Time Response Test

After a microwave sensor's noise has been quantified by collecting measurements with the sensor and target in fixed positions, the next laboratory test involves moving the sensor to induce gradual increases and decreases in sensor-to-target range. Results confirm whether the sensor can track short, gradual range changes and quantify the sensor's response time. A time response of 1 s to 3 s is preferred for microwave radar sensors; however, OSTEP has not been able to change configuration parameters of the Ohmart/VEGA sensor to shut off the sensor's automated temporal filtering processes. As a result, this sensor still demonstrates an approximately 60-s time response.

The setup for this test is similar to that previously described for the fixed target test. The microwave radar sensor is secured in a horizontal mount, aiming directly at a flat fixed target a short distance away. However, the sensor mount is placed on a roller or wheeled device to allow for slow, horizontal motion. The setup shown in fig. 21 can be used for a time response test, with the sensor mount placed on two small carts with wheels. Although its absolute range measurement accuracy is less than that of a microwave sensor, the Laser Technology, Incorporated (LTI) Universal Laser Sensor (ULS) can respond to range changes much faster than 1 s, providing an excellent reference for the true start and stop times of induced sensor mount motions. The LTI laser sensor is installed in the same mount configuration as the microwave radar sensor and has a clear view of the same flat fixed target. Initially, the target should be approximately 3-4 m away from the sensors.

Once both the microwave and laser sensors are mounted and confirmed to be recording reasonable ranges to the target, the sensors are allowed to continue recording range while remaining in place for at least 1 min. Next, the sensor mount on wheels is manually moved forward slowly and smoothly toward the target over approximately 1 m for 3-5 s at a constant speed. It is recommended that both the distance and time over which the sensor mount is manually moved are within one less order of magnitude of the recommended values (1 m over 3-5 s); however, their accuracy is not as critical. Measuring 1-m increments on the floor with tape may help to guide distance of the motion, using a stopwatch to guide the time of the motion. Such methods are only to guide the manual motions, while the laser sensor's range record will ultimately be used as the reference for comparison. Once the sensor is in its new position, approximately 1 m closer to the target, the sensors are again allowed to record range while remaining still for at least 1 min. Next, the gradual motion of approximately 1 m over 3-5 s is repeated, this time while moving the sensor mount backwards, away from the target, back into its original position. This forward and backward motion is repeated 2-3 times, while leaving sensors motionless for at least 1 min at each end point. The back and forward motions can also be repeated while changing the total distance traversed by the mount to 2 m. Plots of the resulting range time series indicate if the microwave sensor responds to distance chances in a reasonable amount of time and ensure that the sensor can reasonably track gradual changes in range.

During previous field testing, OSTEP detected one bad WaterLog® microwave sensor that seemed to lock onto and repeat a single water level value for extended periods, followed by sudden jumps to subsequent values, which resulted in step-like features in the measured water level series. A simple time response test like the one described in this section could have detected this problem before the sensor was deployed to the field.

Based on the configuration of the microwave and laser sensors in the mount, there will likely be a difference in the two sensors' absolute zero points. This offset can be removed by plotting a demeaned range series and observing only change in range. The offset can also be estimated by calculating the difference between the two sensors' range averaged over 1 min with no motion and then applying it to the rest of the series to align the two sensors' ranges. The latter technique was used to align the microwave and laser sensors' range measurements in the sample time response test results shown in fig.25. The plot zooms in on three particular sensor motions that took place during the test. The WaterLog® microwave radar sensor used during this test was run with default configuration settings, which include a 5-s damping constant (typically set to zero seconds in a field deployment to decrease response time). Results indicate the microwave sensor in this test adequately tracks range changes and has the expected response, lagging the laser sensor by approximately 5 s.

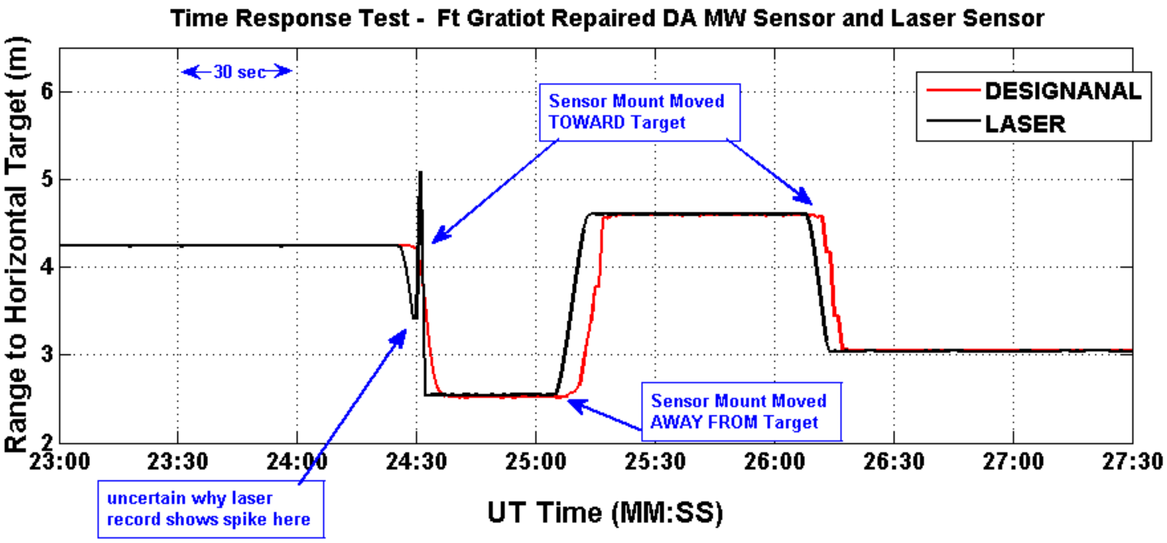

Figure 25. Range-to-fixed target measured by a LTI ULS (black line) and a Design Analysis WaterLog® microwave sensor (red line) during a time response test. Excluding the unusual random spike occurring at approximately 24:30, the laser record is a good representation of true motion times. The Design Analysis sensor tracks the motions well, in this case with an approximately 5-s time response due to a default 5-s damping coefficient that remained enabled during the test.

4.4 Range Calibration Test

The next pre-deployment test to conduct is a basic range calibration that involves collecting range measurements to a fixed target over a series of discrete sensor-to-target ranges. Comparing microwave sensor range measurements to a reference measurement of true range indicates if the sensor is operating within accuracy specifications, or if its raw range data requires the application of correction coefficients.

Once again, the sensor is fixed in a mount aligned to point horizontally toward a flat fixed target. Special care is taken to align the sensor transmission path to be as close to normal as possible to the flat target face. Then, the sensor and target are set up on a continuous flat plane, such as a flat concrete pad. Figure 26 shows a set up for one particular range calibration test conducted at the Chesapeake facility. To assist in precise sensor-target alignment, both the sensor and target were placed atop a long, straight I-beam that was set across two level concrete pads.

OSTEP recommends that the microwave sensor collect range measurements across at least five discrete nominal sensor-to-target ranges (2 m, 4 m, 6 m, 8 m, and 12 m) for at least 1 min at each range (with absolutely no motion of either target or sensor). Collection of measurements across a longer series of ranges may be necessary, depending on initial results or a sensor's particular deployment location. It is acceptable to position the target within a few centimeters of the nominal measurement ranges when conducting the test, as long as a very accurate reference measurement of true sensor-to-target range (within a few millimeters) is made at each target position. This can be obtained by either using a highly accurate reference sensor that is positioned close to the microwave sensor, possibly aligned in the same mount, or by precisely marking off positions of the target face on the ground (or whatever structure the target is placed atop) and then collecting tape measurements of each sensor-to-target range after data collection has been completed (or multiple types of reference measurements can be obtained during a test). If there is uncertainty in the exact location of a microwave sensor's zero range point or in any distance offset between the microwave sensor and reference sensor being used, offsets and zero points should be obtained by initially collecting range data with the target at a short range from the sensor(s), approximately 1 m. The close range measurements can be used to obtain offsets between each microwave radar and reference sensor and/or the offset from the microwave radar sensor's zero range point to some structure in the test setup from which target range can be easily measured manually. An example of such a structure is the flat edge of a sensor mounting plate or mounting box. Any sensor offsets that are estimated using close range target measurements can be applied to the rest of the calibration range data set to obtain absolute range.

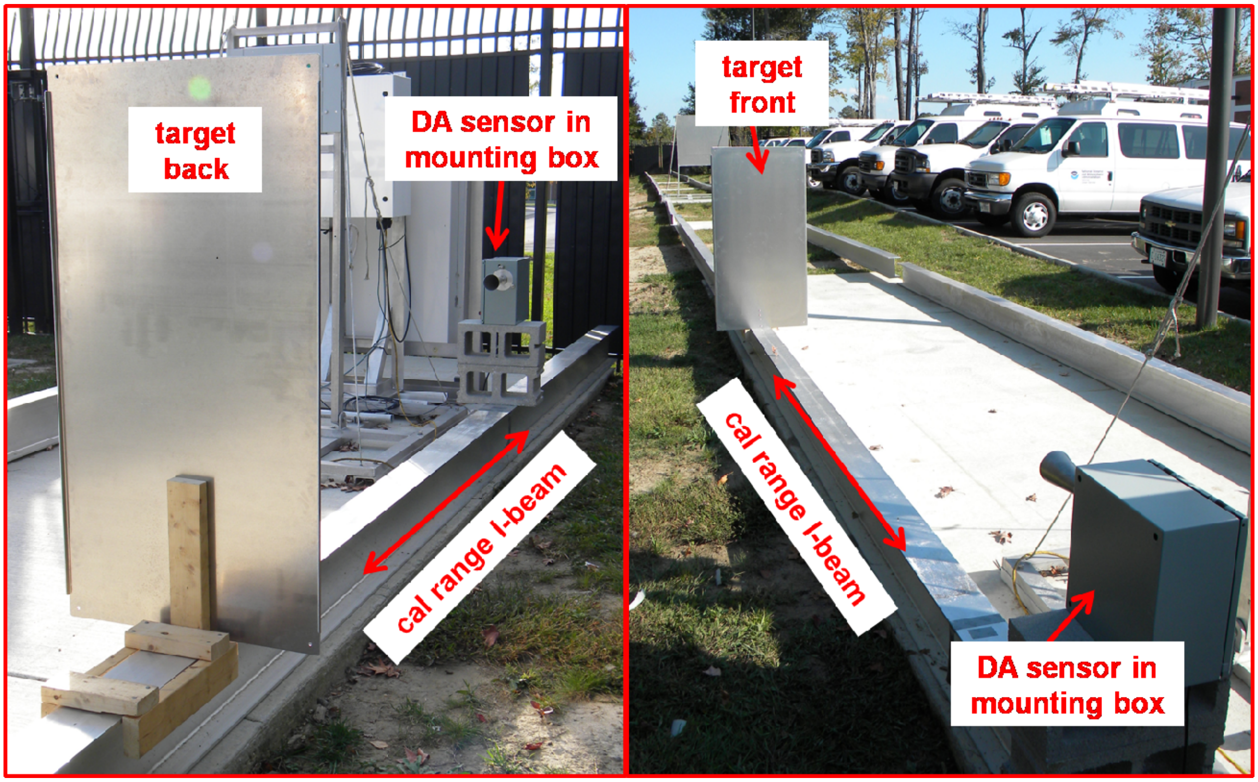

Figure 26. Example of a calibration test setup for a particular test conducted with a Design Analysis (DA) WaterLog® microwave sensor.

Analysis of the range calibration test involves observing the difference between microwave radar sensor range and the reference measurement of true range for the series of eight sensor-to-target range placements. If all points in the difference series are within ±1 cm (plus any potential measurement uncertainty in reference range measurements), results indicate that the sensor passes the test and can proceed to the next pre-deployment test and possibly field testing. If differences are larger than ±1 cm (sensor offsets are present) and there is a clear relationship between the differences and true range, the test should be repeated to see that the same results are obtained. If a consistent relationship between sensor offsets and true range occurs across two tests, a set of correction coefficients can be obtained by conducting a polynomial fit to the offset versus true range series. The order of the polynomial fit depends on the nature of the particular relationship that is present. It may be possible to obtain successful microwave radar sensor water level measurements when applying a set of empirically-derived correction coefficients to a raw range series. However, if a range calibration test indicates that application of a correction factor is necessary, results should be shared with a sensor vendor. Feedback from sensor developers should be obtained before any further testing occurs.

4.5 Measuring Water Levels in Small Tank

A final pre-deployment laboratory test includes a microwave radar sensor set up to measure water levels in a small tank or pool to confirm a sensor's ability to properly process signals reflected from a water surface, which is a target similar to that encountered in the field. This type of test can be conducted using OSTEP's recently developed pool testing facility shown in fig. 27. The test facility consists of a round, 3.7 m (12-ft) diameter outdoor pool from which water can be added or removed and an overhead sensor mount where microwave sensors can be placed above the center of the pool looking downward, approximately 2.5 m above the pool's water surface. For microwave sensors with beam angles of 10 degrees or less, the same test can be conducted using a much smaller tank placed underneath the overhead mount seen in fig. 27. For example, OSTEP could use one of the smaller tanks (which are approximately 0.7 m (2.3 ft) in diameter and 1 m deep) located in the Chesapeake Instrument Lab.

A series of range-to-water surface measurements are made, while slowly raising and lowering water levels in the tank. If the test is conducted in the CO-OPS Chesapeake facility courtyard area, as shown in fig. 27, water level changes can be generated using the outdoor spigot and hose to fill the tank, then using a hose or continuous tube to remove water by siphoning. After microwave sensor measurements are collected, a simple plot of the resulting range time series is generated to confirm that water level changes were tracked smoothly with no unusual features in the series, such as repeated values during times of steady water level changes (step-like characteristics) or random spikes. Reference water level values can be measured using numerous methods in the tank for comparison, including recording visual observations of water level against markings on the tank wall or a placing a high resolution pressure sensor at the bottom of the tank. Figure 28 shows a sample time series of microwave sensor range measurements collected during a successful pool test.

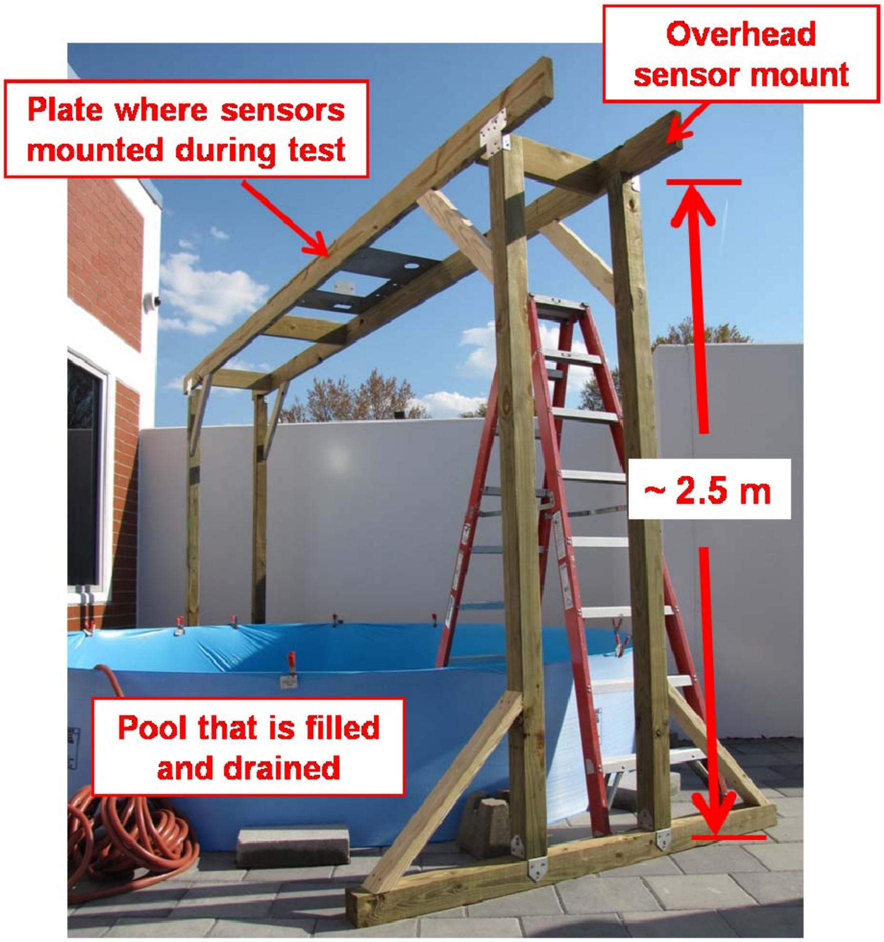

Figure 27. Test pool and overhead sensor mount located in the courtyard of the CO-OPS Chesapeake facility. The same results can be obtained using the overhead sensor mount shown here and a smaller tank.

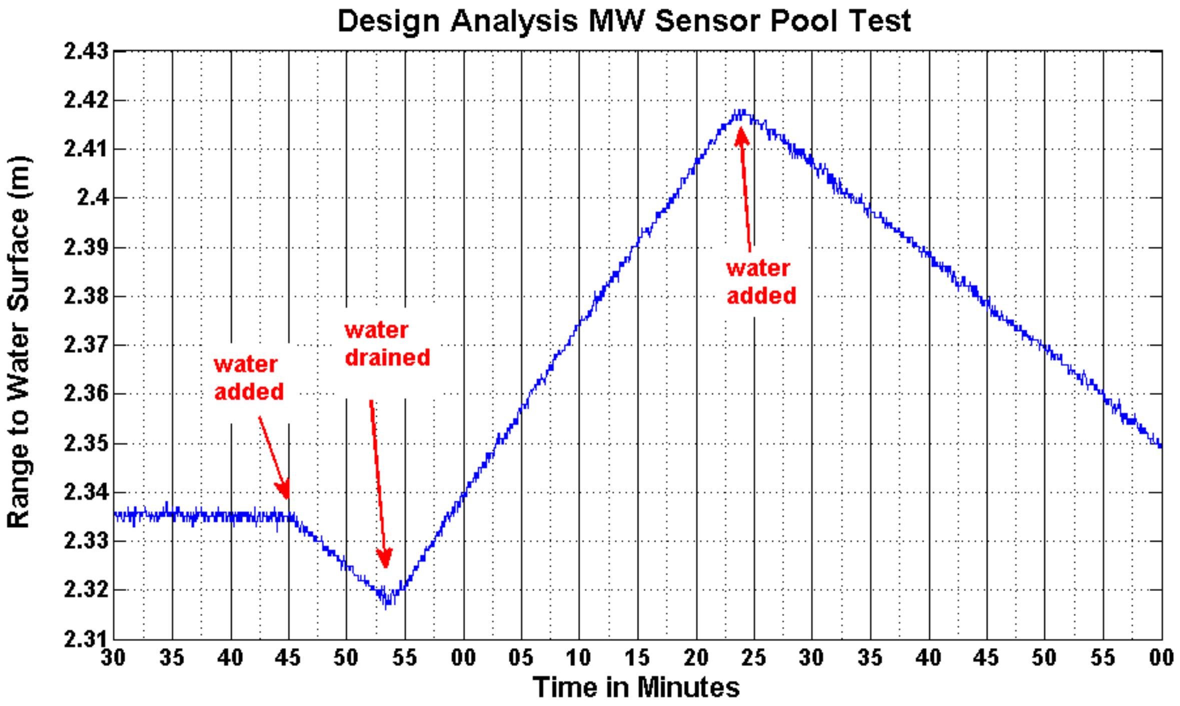

Figure 28. Test pool and overhead sensor mount located in the courtyard of the CO-OPS Chesapeake facility. The same results can be obtained using the overhead sensor mount shown here and a smaller tank.

5.0 Summary and Recommendations

Over the past 2.5 years, significant progress has been made on the CO-OPS effort to test and evaluate the use of microwave radar to measure water levels in oceanographic field applications. OSTEP has gathered a unique and valuable data set from numerous laboratory and field tests. Analysis results obtained from this extensive test data set have led to an enhanced understanding of microwave radar sensors' functional capabilities, measurement accuracy, performance response to environmental variability, and performance limitations. Many of OSTEP's results to date confirm several significant advantages of microwave radar sensors, which have been previously identified throughout the sea level community.

Application of previously established sensor selection criteria to the extensive microwave water level test data suggests that the Design Analysis WaterLog® H-3611i is best suited at the present time for meeting CO-OPS' unique mission requirements, data acquisition operations, and data product applications for environments similar to Port Townsend, WA. Several specific aspects particular to each sensor also influenced the selection, such as a small signal spreading angle and the 10-16-volt input (see table 1). All four sensors tested by OSTEP have demonstrated good performance, and several other institutions and organizations have been successful in collecting accurate, high quality water level observations using microwave radar sensors other than the WaterLog® unit. Manufacturers continue to develop newer versions of each sensor, and testing of those and other sensors may continue. Therefore, newer versions of these sensors may still be considered for use in CO-OPS operational water level stations.

Some uncertainty remains regarding aspects of the WaterLog® versus Aquatrak water level measurement comparisons in the presence of a dynamic, open ocean environment such as Duck; however, the microwave radar sensor is most likely at a disadvantage in large wave environments due to the sensor's open air transmissions with no protective well. Also, since stronger long and cross shore currents are likely to be present in coastal regions that experience larger surface wave action [1], the Aquatrak sensing system is more susceptible to water level draw down inside the protective well, which further complicates interpreting Aquatrak versus WaterLog® comparisons. Although fully understanding the limits of WaterLog® and Aquatrak sensing systems in the presence of larger and longer surface gravity waves is a work in progress, most observations from the Port Townsend, WA, Money Point, VA, and Fort Gratiot, MI test sites indicate that monthly RMSDs of the Aquatrak and BEI 6-min water level records versus those of the WaterLog® are less than 1 cm, and differences in monthly mean sea levels are within ±5mm. All field test sites are located in semi-enclosed, fetch limited coastal regions with small surface wave environments. Furthermore, tidal water level products generated from using CO-OPS standard processing tools with 1.5 years of Port Townsend data provide further confirmation of adequate sensor performance.

Additional testing and analysis are needed before issuing a final microwave radar test and evaluation report. Since most periods of field test data collected by OSTEP to date have indicated that microwave radar sensors meet accuracy requirements, this report was compiled to recommend limited acceptance of the WaterLog® microwave radar water level sensors for use in coastal regions with characteristics similar to those of the field test sites described here: semi-enclosed, fetch limited coastal regions with a small wave environment (unlikely to experience waves with heights greater than 1 m and periods greater than 10 s). Many current NWLON sites, as well as prospective new NWLON sites, are located in regions with these conditions, where use of microwave radar sensor technology would result in significant benefits, including less time and funds required for installation, fewer maintenance requirements, and avoidance of certain challenges that are common in other currently used water level measurement systems. Challenges that can be avoided include the impact of temperature-induced sound speed gradients in an Aquatrak sounding tube on sensor accuracy, complications with Aquatraks' protective well parallel plates silting in shallow regions with large tidal signals, and the impact of vertical density gradients in the water column on pressure sensor accuracy.

To support the transition of WaterLog® microwave radar sensors to an operational status, OSTEP performed extensive analyses of test results to date, including lessons learned and problems encountered along the way, using them to develop a four-step pre-deployment laboratory test procedure and a list of required analysis products to generate and document. These tests and analysis results are the first critical step in a successful microwave radar sensor deployment. This pre-deployment test procedure was specifically designed to improve future microwave radar sensor field installations and avoid common sensor configuration issues that may occur.

Additionally, several time response laboratory tests conducted with WaterLog® sensors, along with 18 months of continuous raw 1-Hz WaterLog® water level data from Port Townsend, were used to identify modifications to CO-OPS software that performs initial quality control of NWLON data upon ingestion into the DIS. Specific QC flags that were modified include the sigma, outlier, rate of change, and flat line flags.

Before proceeding with plans for operational deployments of WaterLog® sensors, CO-OPS must conduct a careful environmental assessment of a prospective deployment location using all available data. A combination of average wind, surface wave, and tidal conditions for a prospective WaterLog® site need to be compared to sites where microwave sensors have previously demonstrated accurate measurement capability. After a careful environmental assessment of a region has been conducted and documented, personnel from CO-OPS OD, ED, and staff should review the assessment of the prospective location before proceeding with any proposed deployments.

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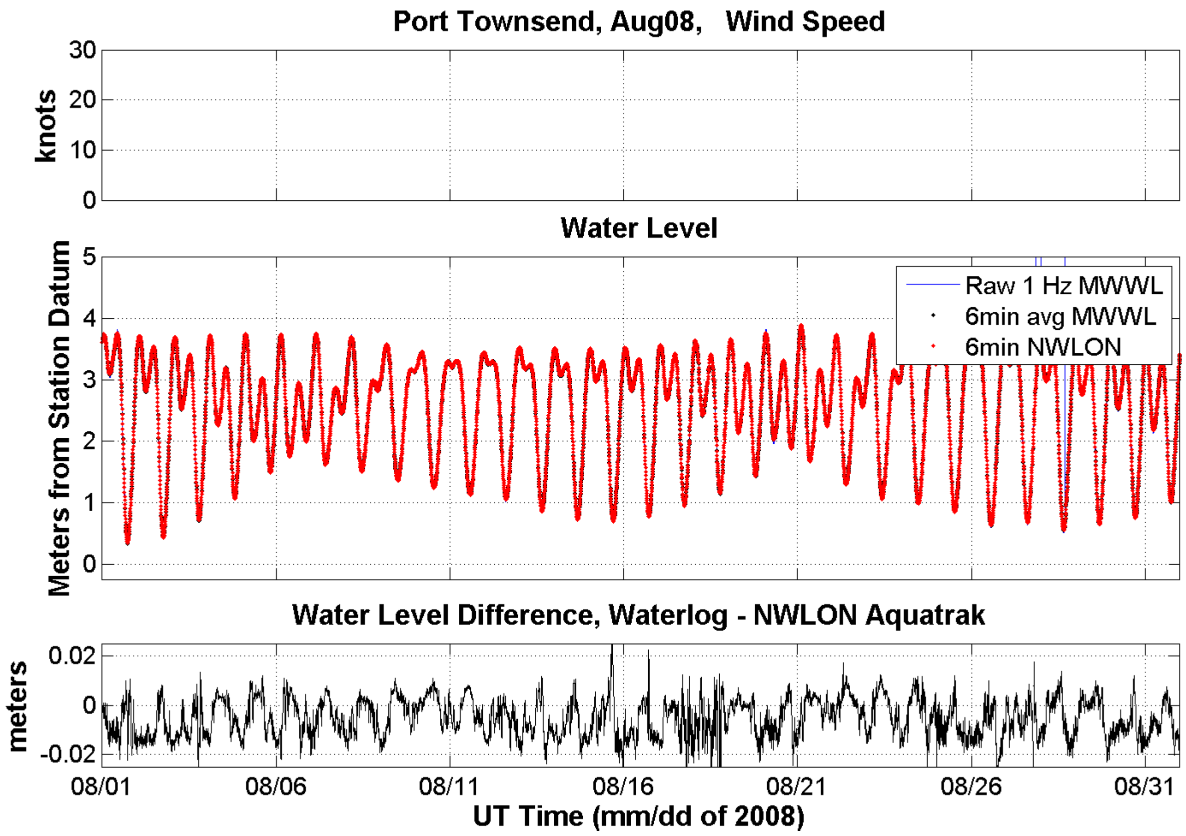
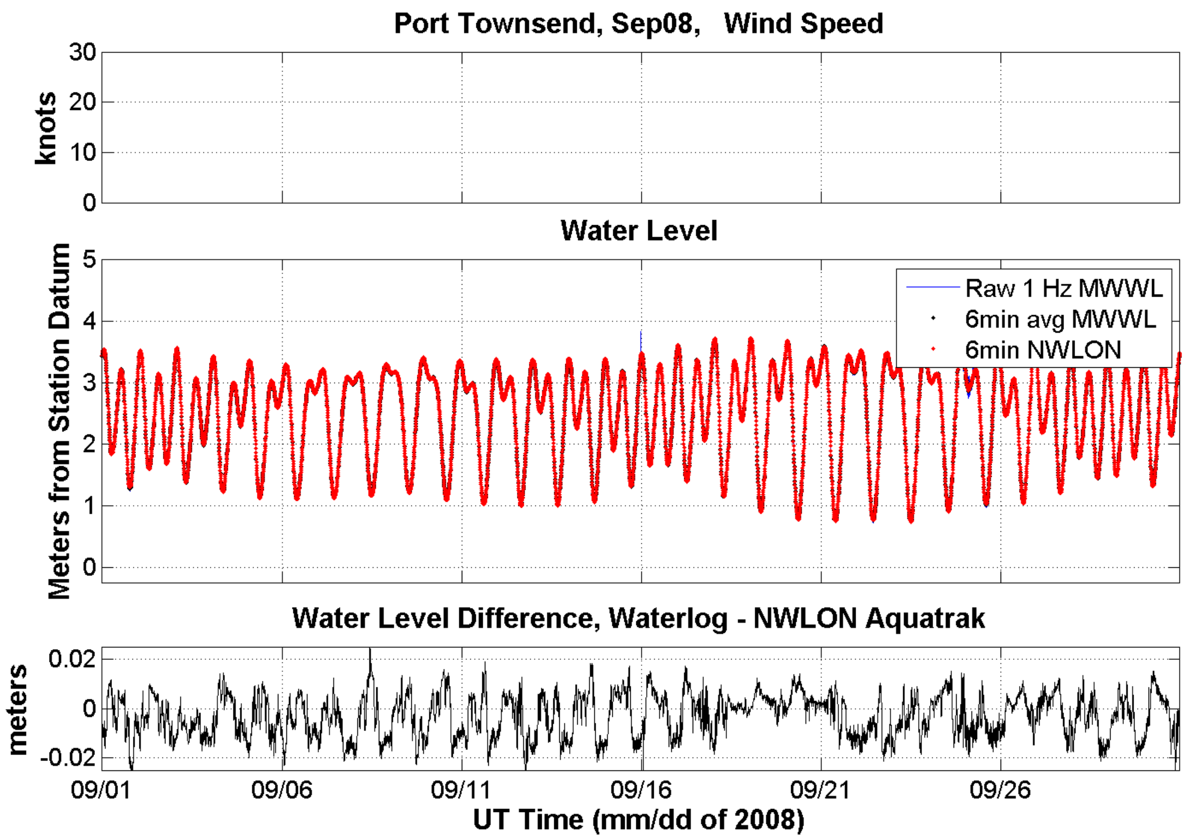
List of Appendices

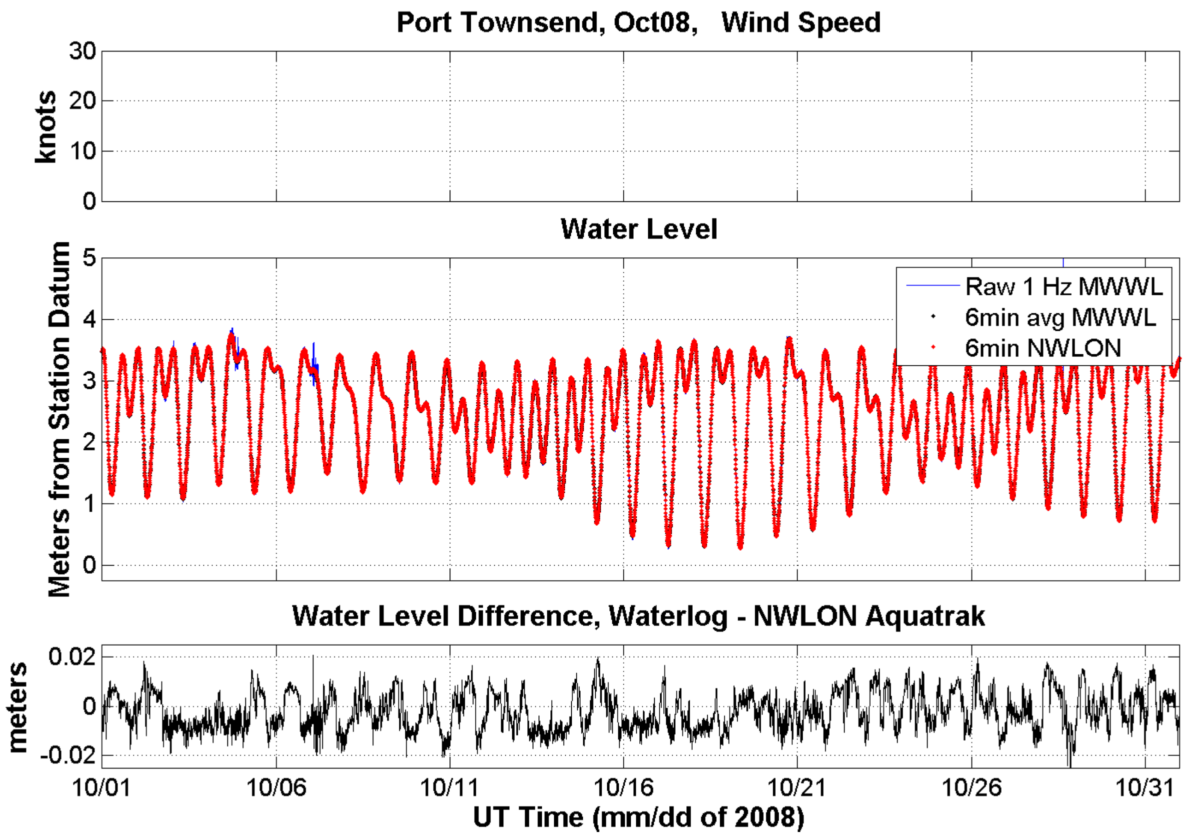
Appendix A.
Monthly Time Series Plots of All MWWL and MET Data at Port Townsend, WA




Port Townsend, Sep08, Wind Speed

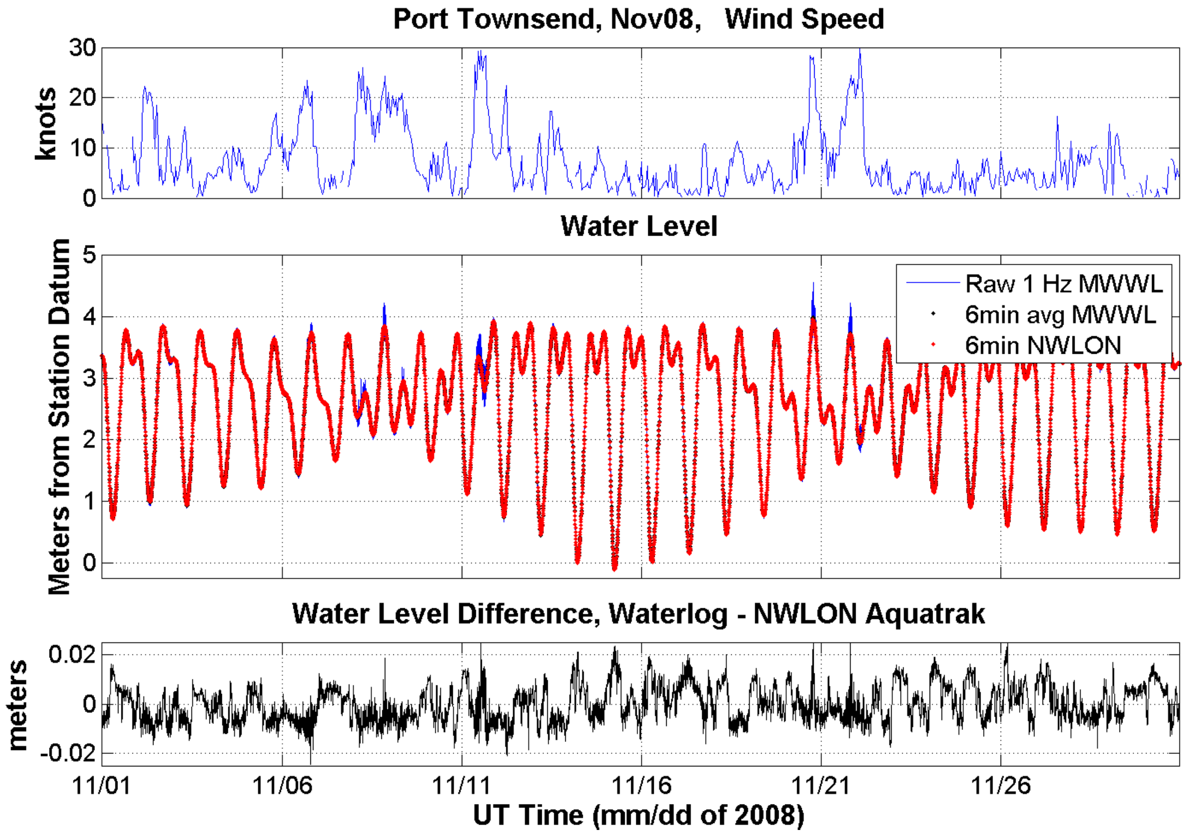
Water Level

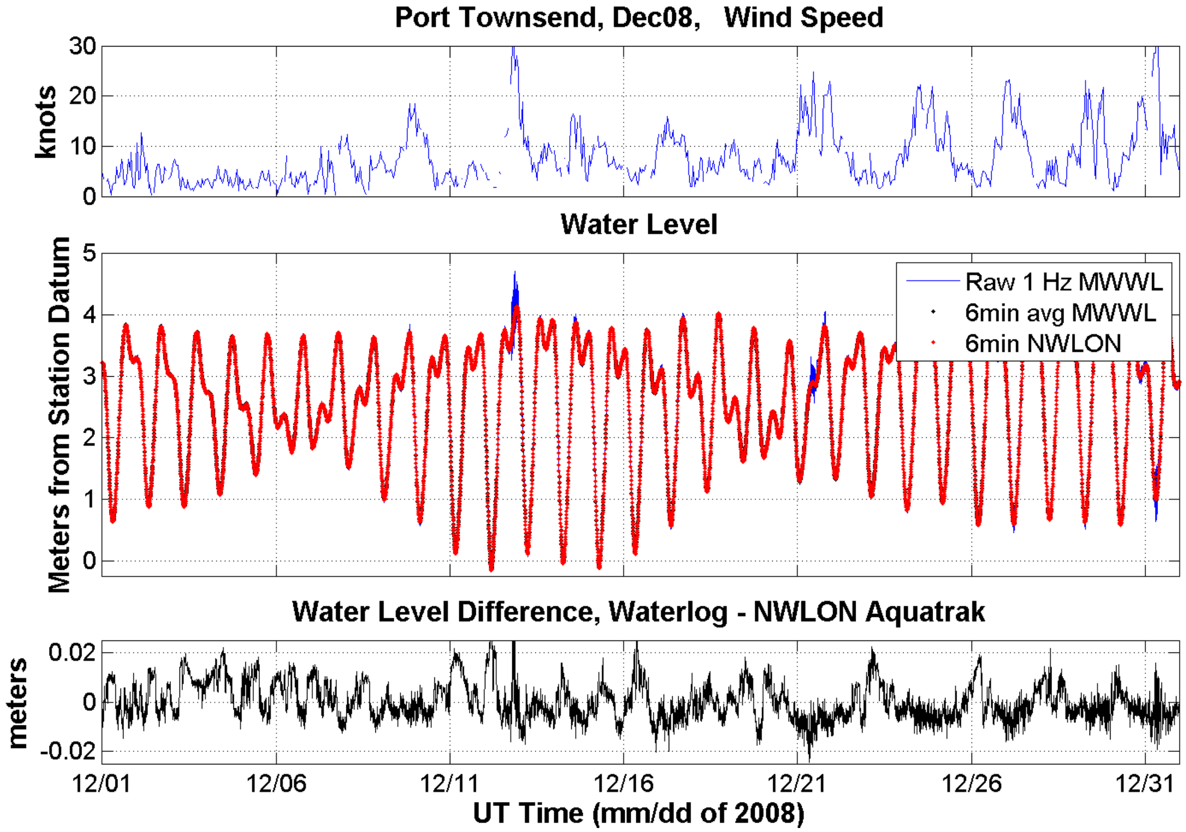
Water Level Difference, Waterlog - NWLON Aquatrak

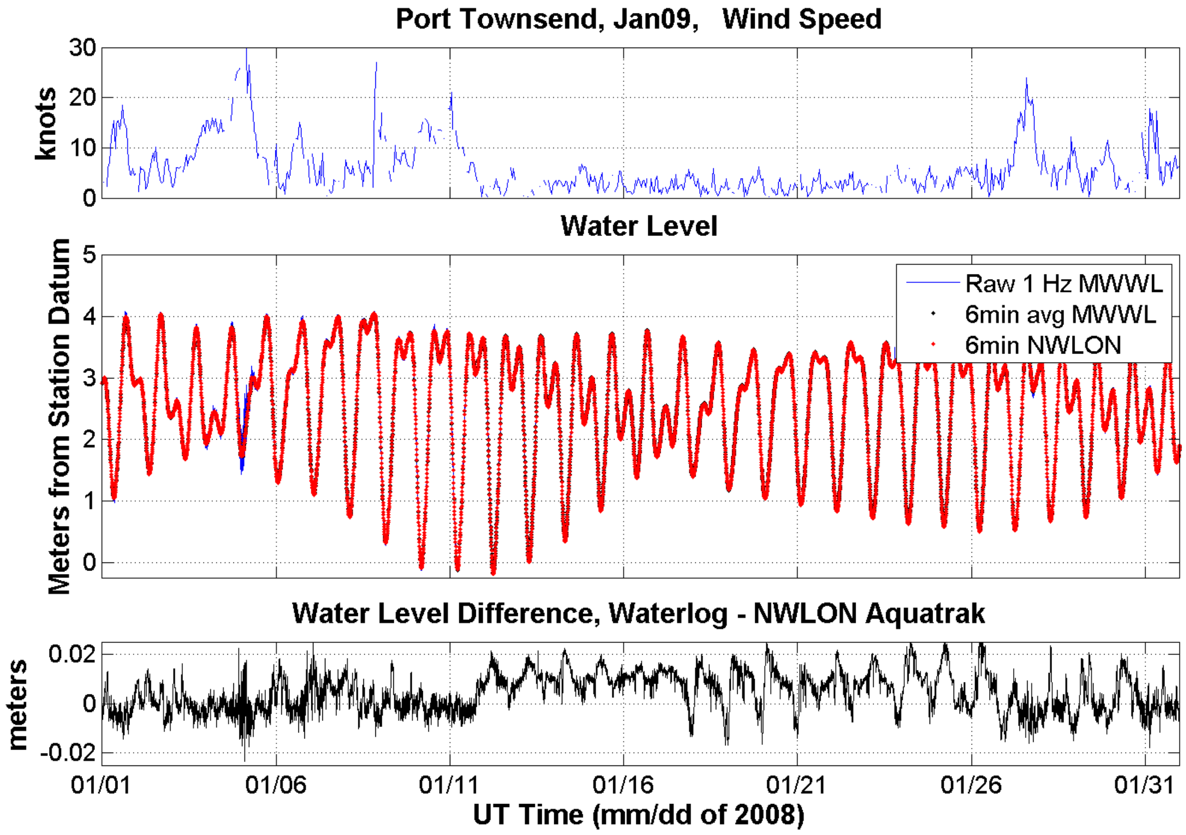

Port Townsend, Oct08, Wind Speed

Water Level

Water Level Difference, Waterlog - NWLON Aquatrak

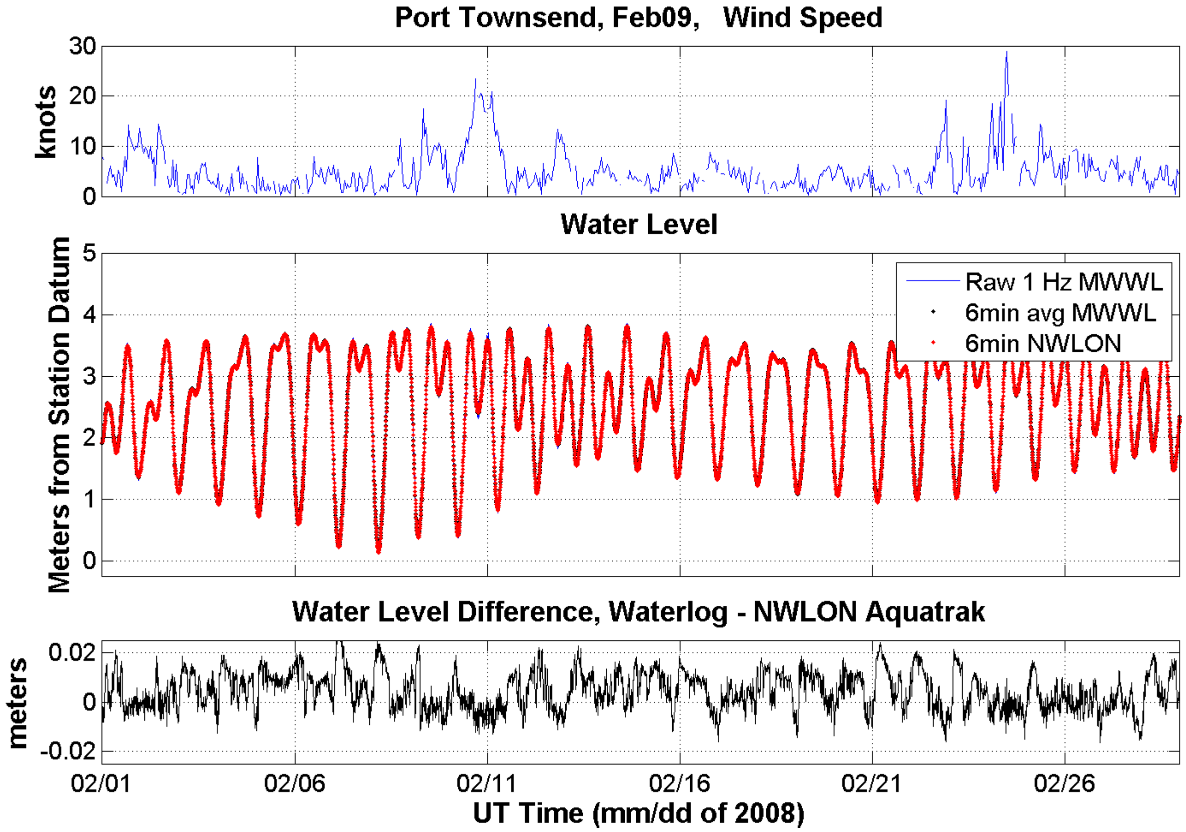

Port Townsend, Nov08,   Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
11/01
11/06
11/11
11/16
11/21
11/26
UT Time (mm/dd of 2008)


Port Townsend, Dec08,   Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
12/01
12/06
12/11
12/16
12/21
12/26
12/31
UT Time (mm/dd of 2008)


Port Townsend, Jan09, Wind Speed

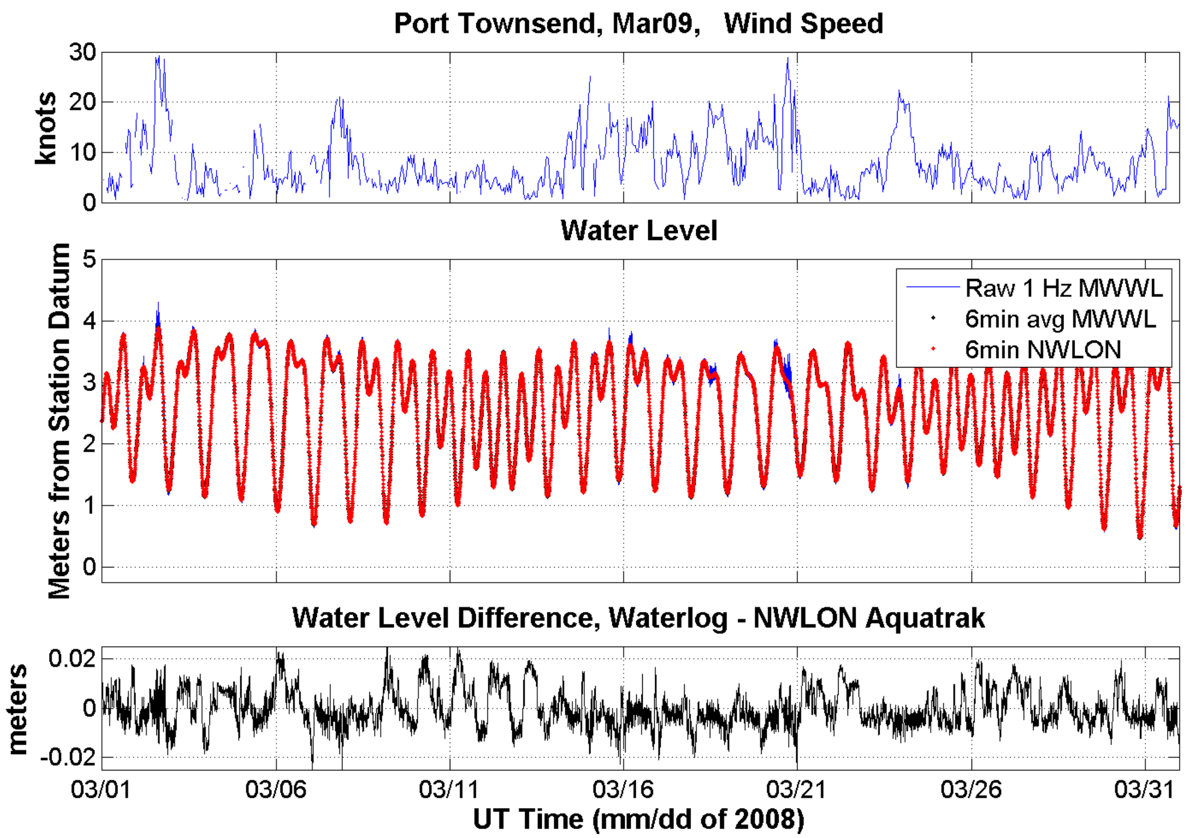
Water Level

Water Level Difference, Waterlog - NWLON Aquatrak


Port Townsend, Feb09, Wind Speed

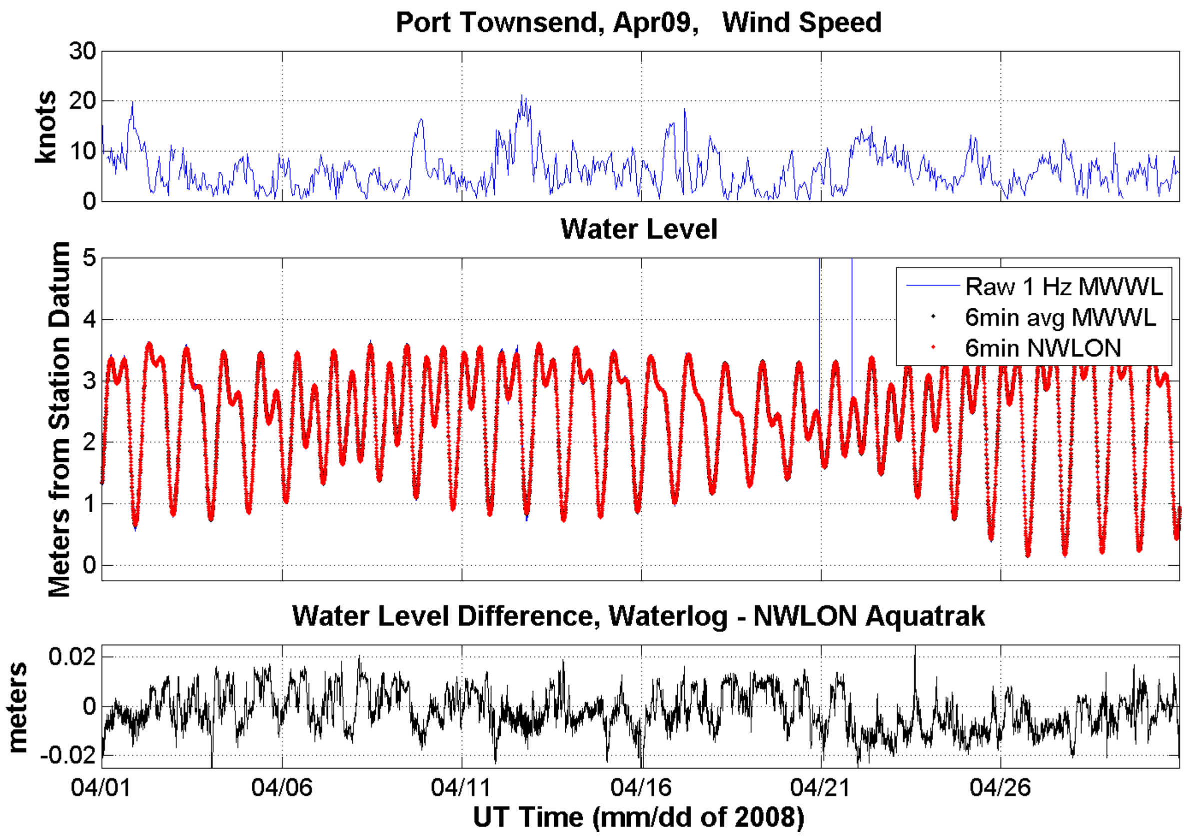
Water Level

Water Level Difference, Waterlog - NWLON Aquatrak


Port Townsend, Mar09,   Wind Speed

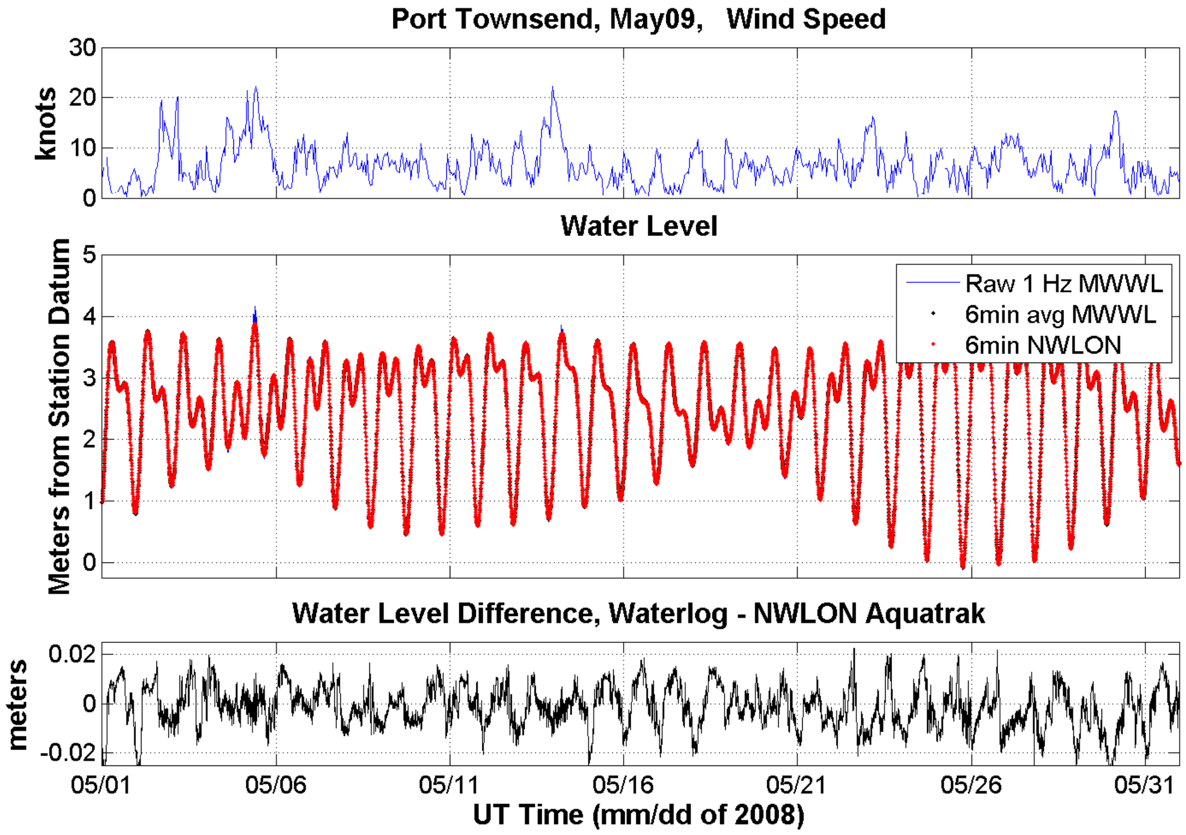
Water Level

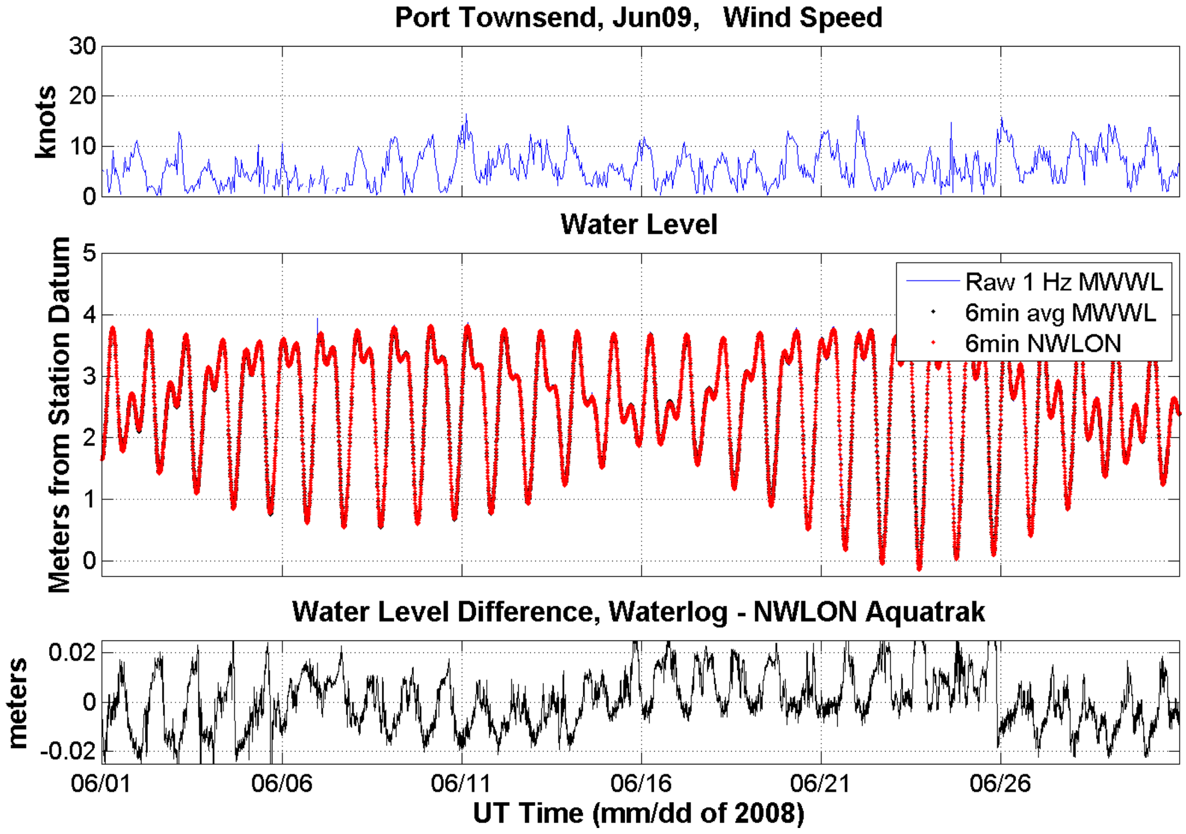
Water Level Difference, Waterlog - NWLON Aquatrak

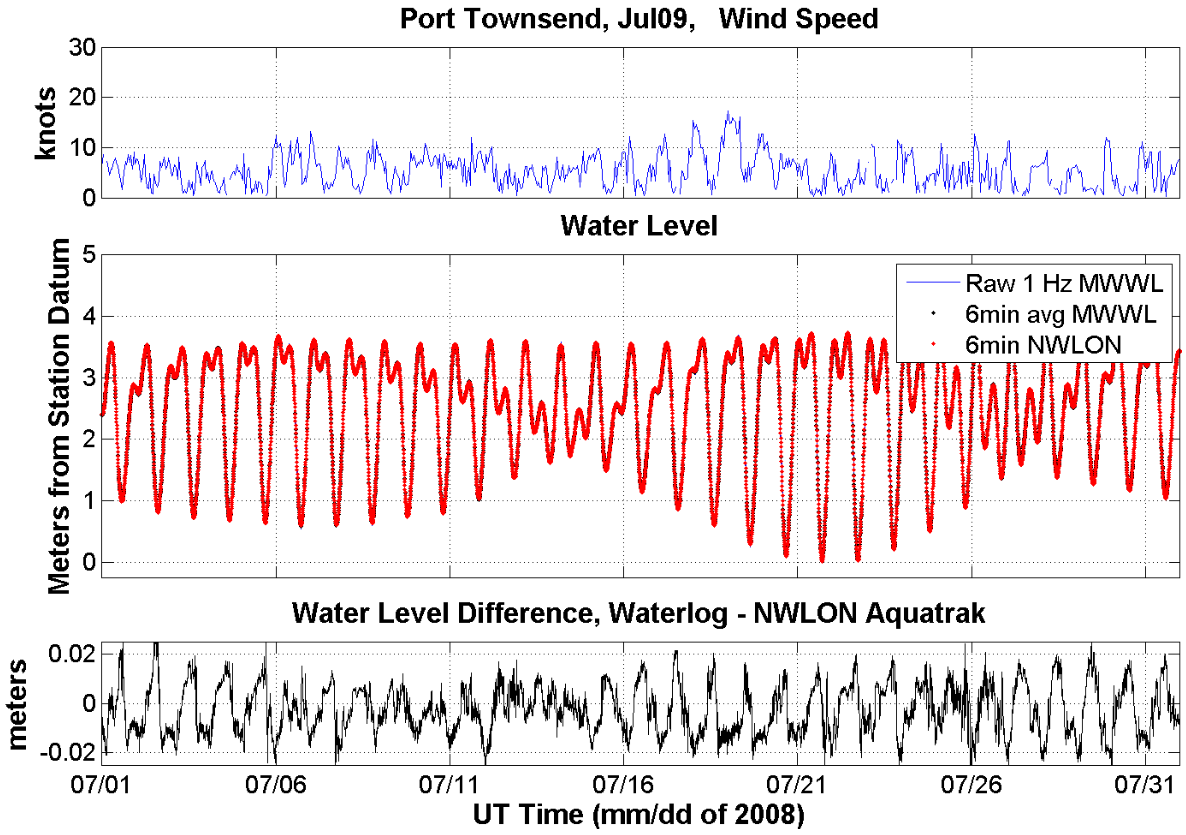

Port Townsend, Apr09,   Wind Speed

Water Level

Water Level Difference, Waterlog - NWLON Aquatrak


Port Townsend, May09, Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
05/01
05/06
05/11
05/16
05/21
05/26
05/31
UT Time (mm/dd of 2008)


Port Townsend, Jun09, Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
06/01
06/06
06/11
06/16
06/21
06/26
UT Time (mm/dd of 2008)


Port Townsend, Jul09, Wind Speed
knots
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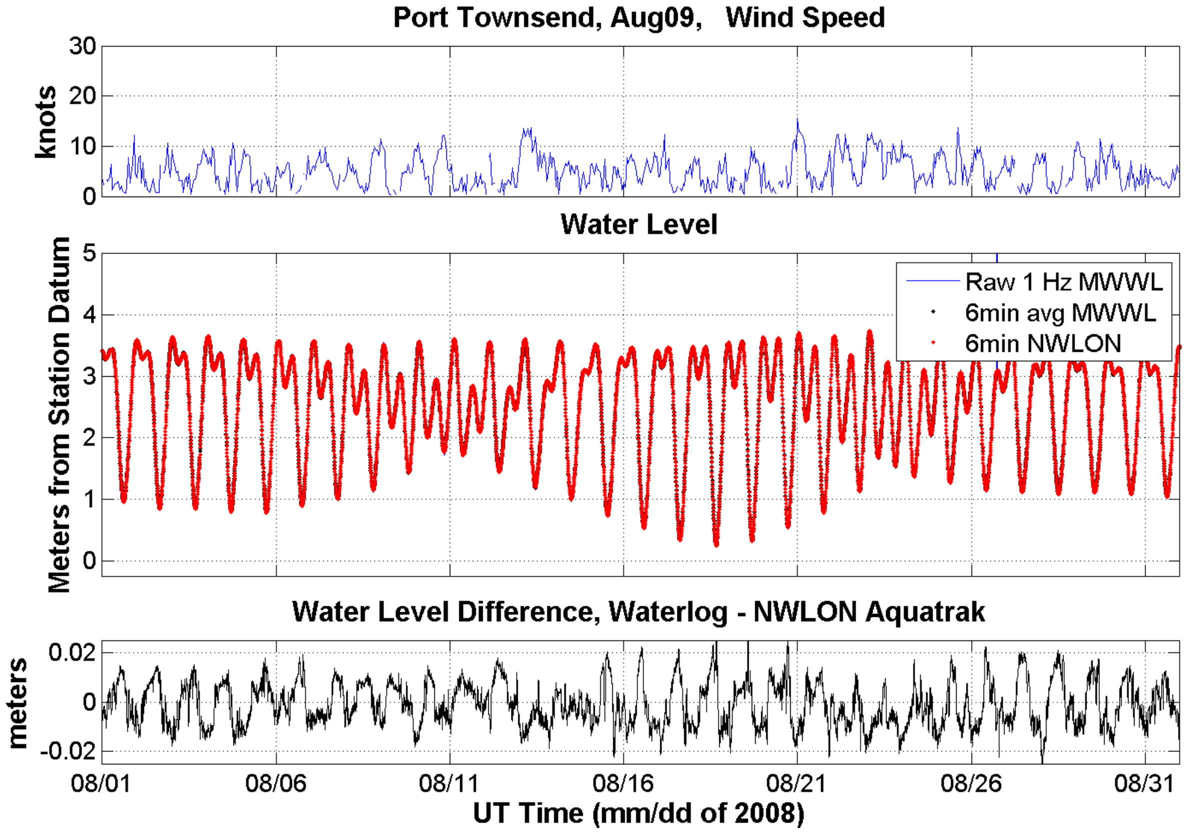
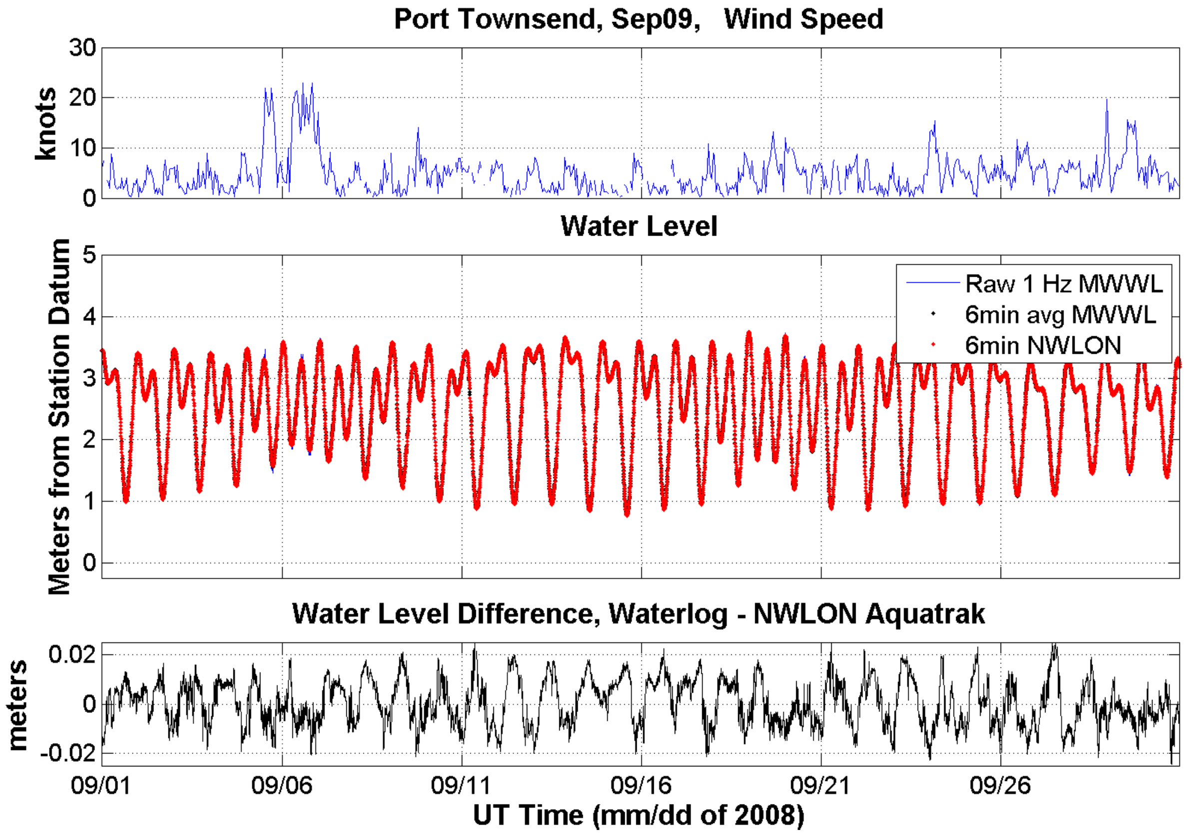
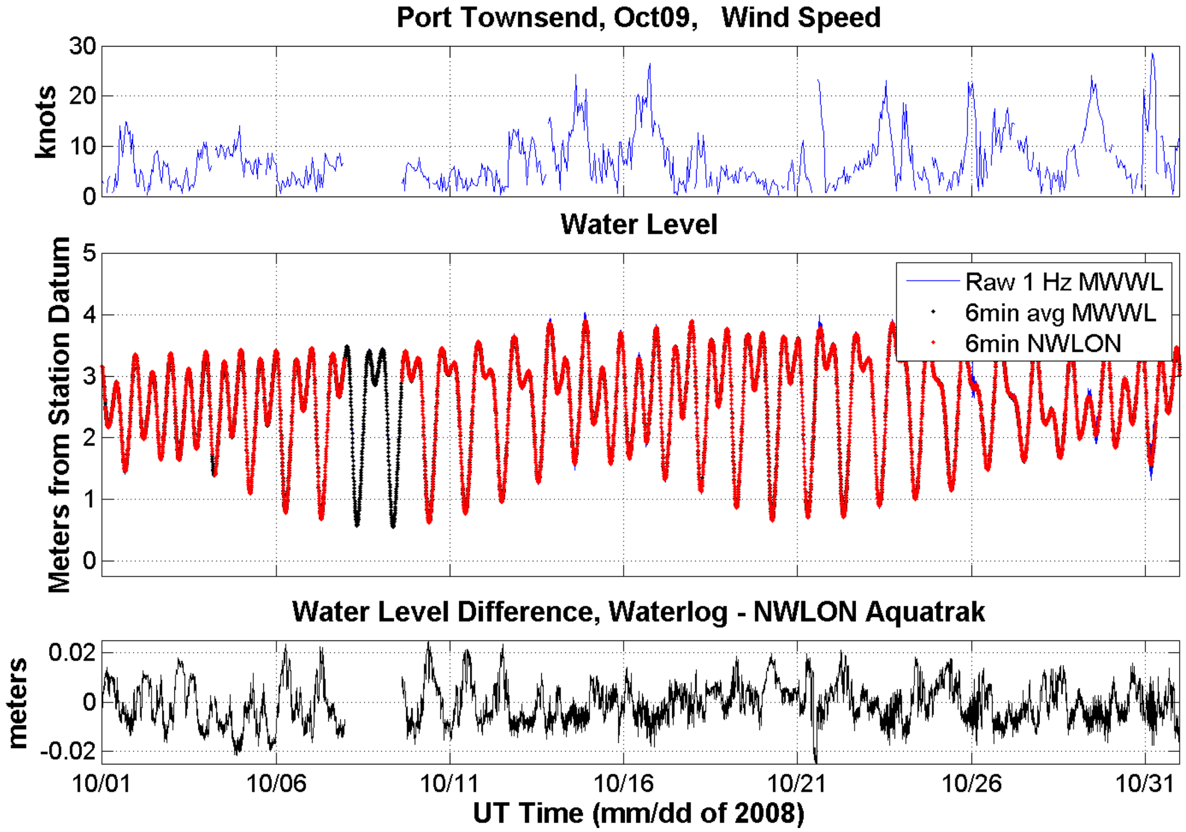
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
07/01
07/06
07/11
07/16
07/21
07/26
07/31
UT Time (mm/dd of 2008)


Port Townsend, Aug09, Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
08/01
08/06
08/11
08/16
08/21
08/26
08/31
UT Time (mm/dd of 2008)


Port Townsend, Sep09, Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
09/01
09/06
09/11
09/16
09/21
09/26
UT Time (mm/dd of 2008)


Port Townsend, Oct09, Wind Speed
knots
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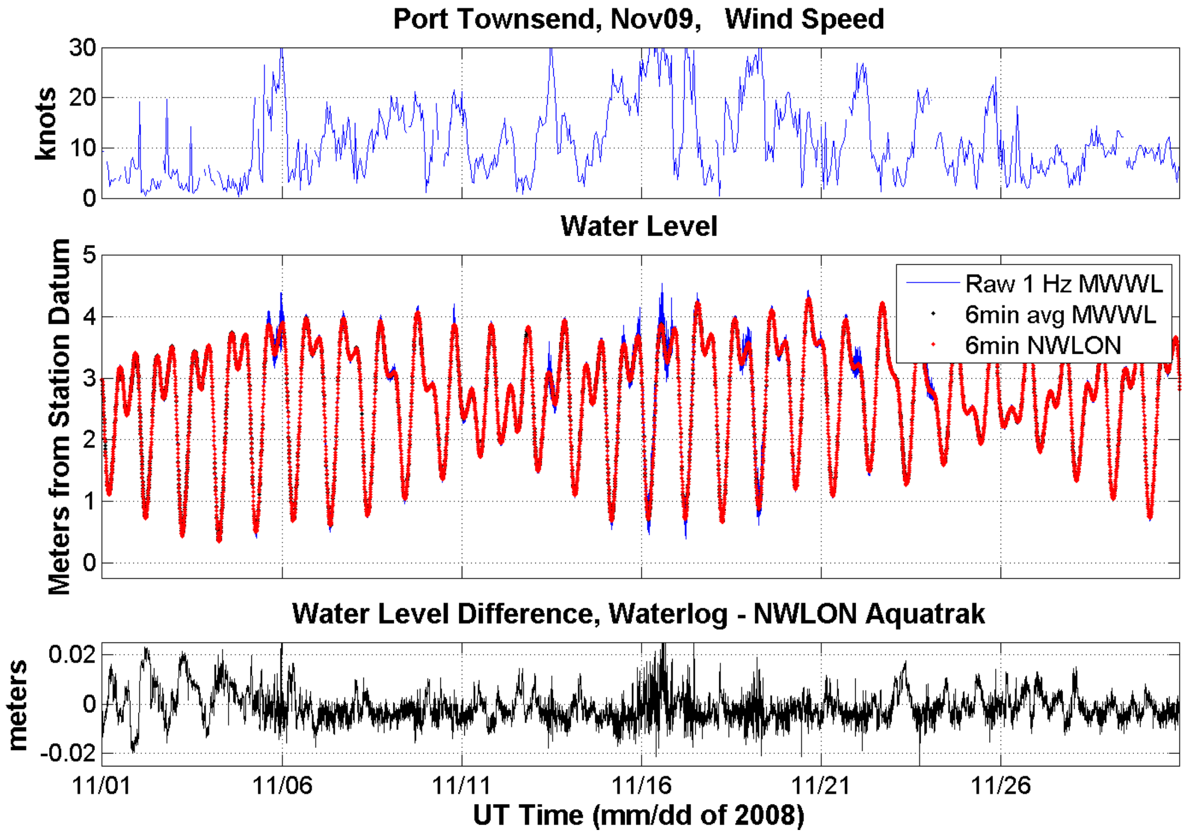
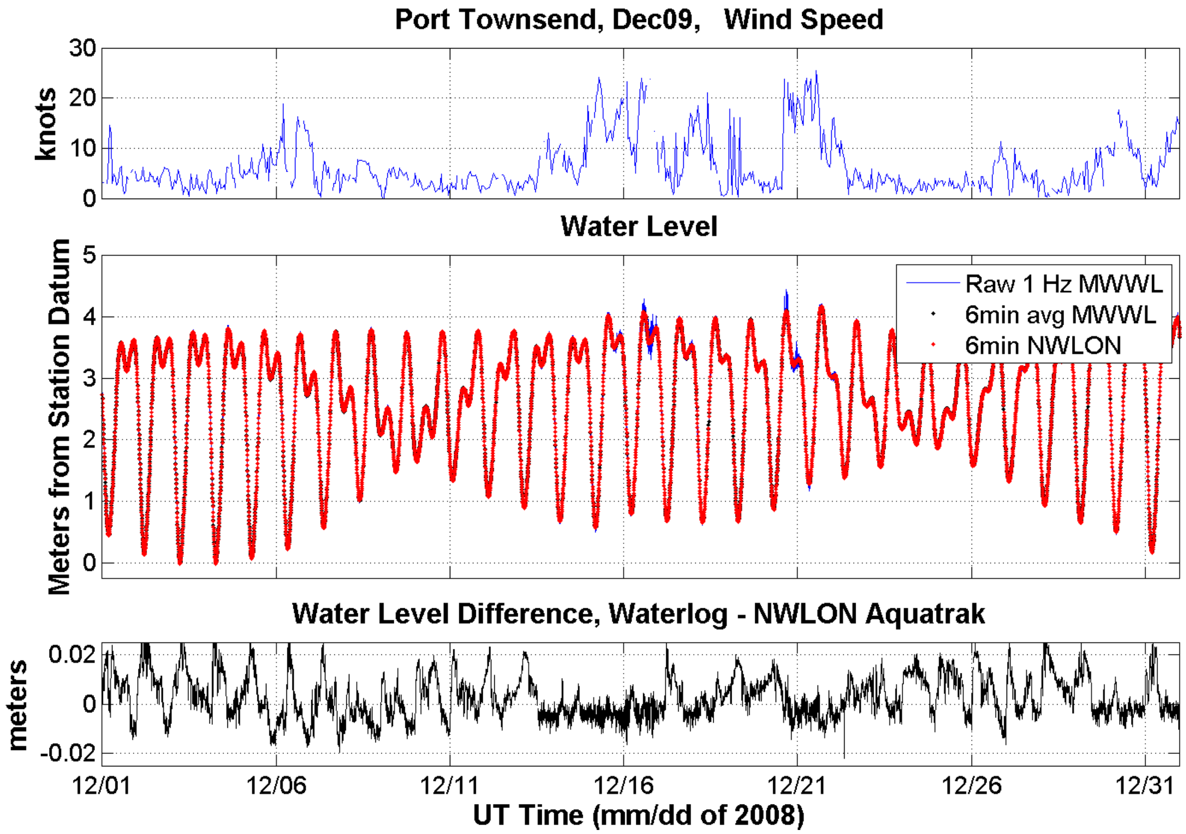
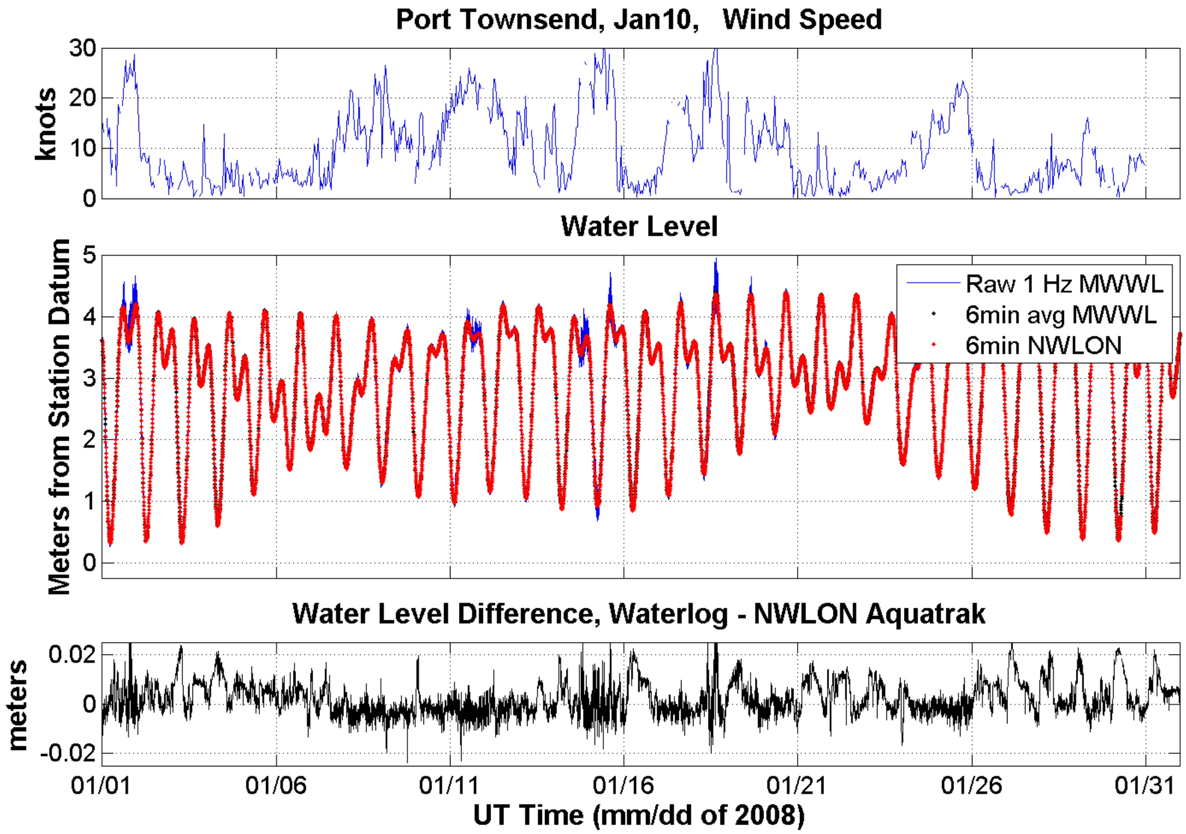
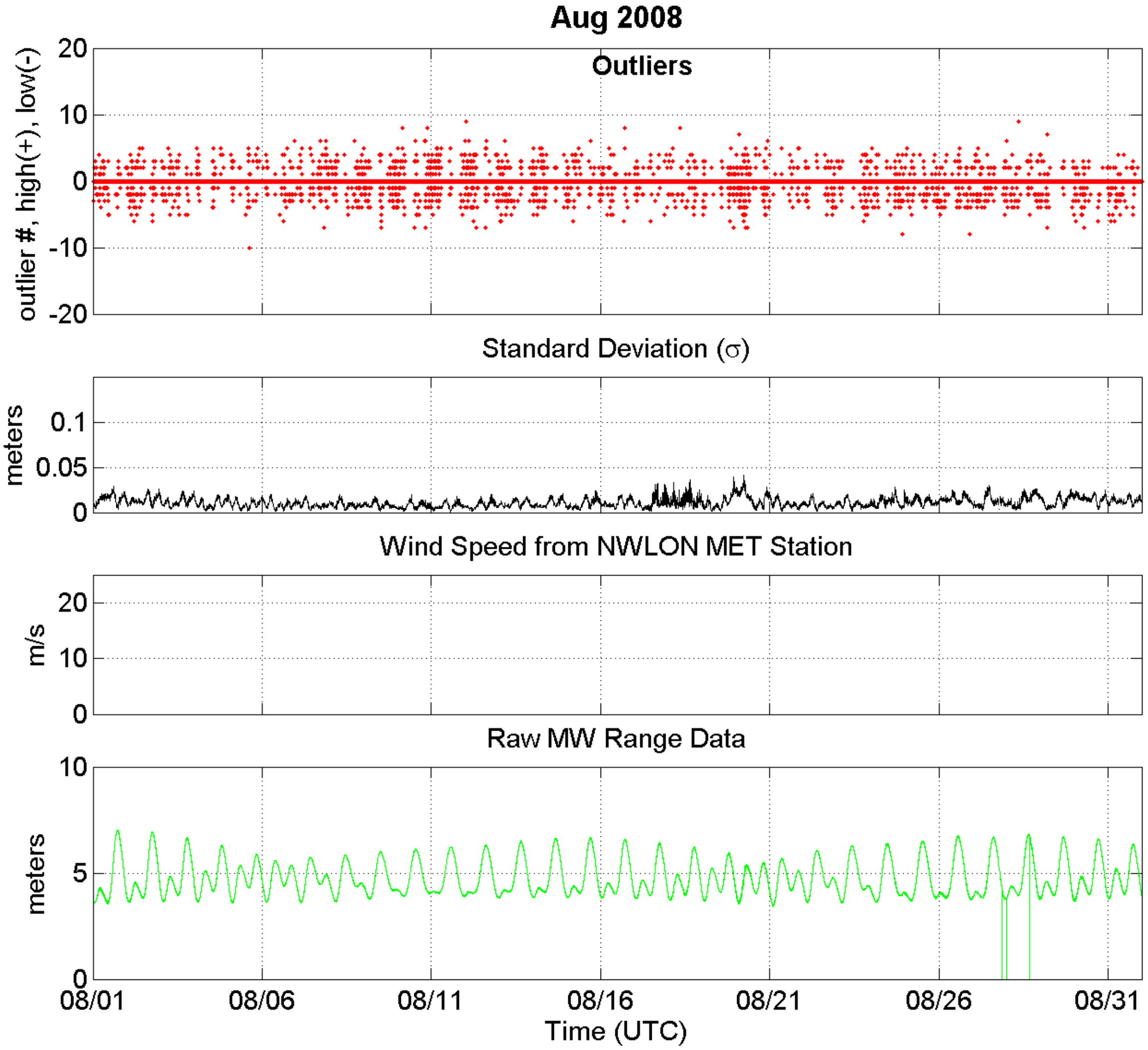
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
10/01
10/06
10/11
10/16
10/21
10/26
10/31
UT Time (mm/dd of 2008)

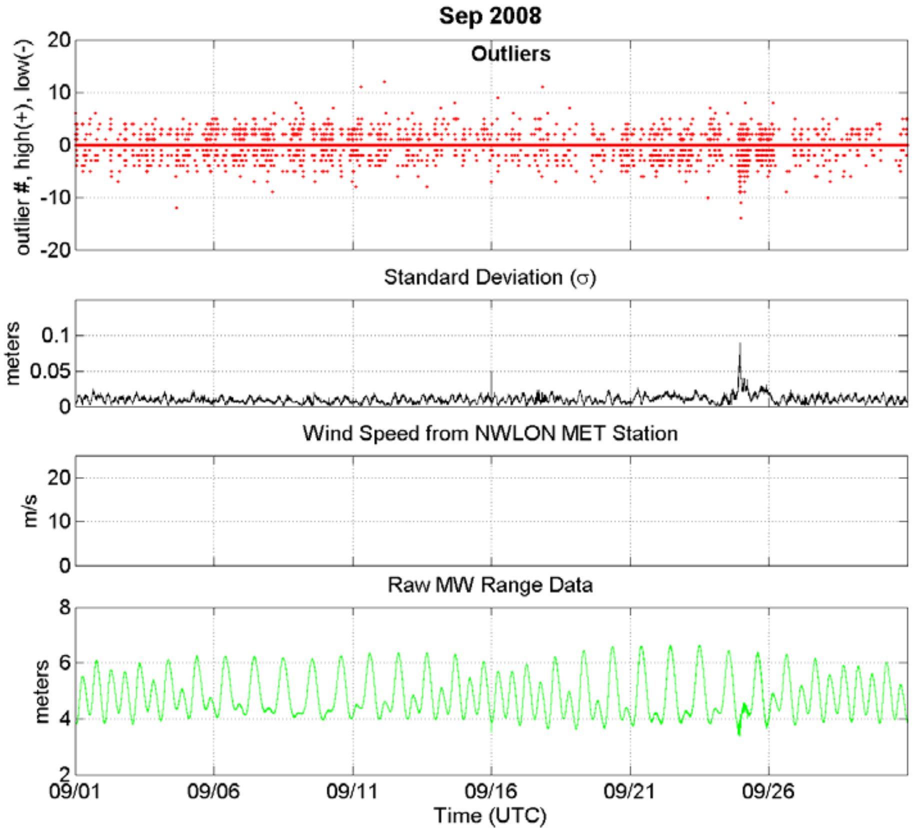

Port Townsend, Nov09,   Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
11/01
11/06
11/11
11/16
11/21
11/26
UT Time (mm/dd of 2008)

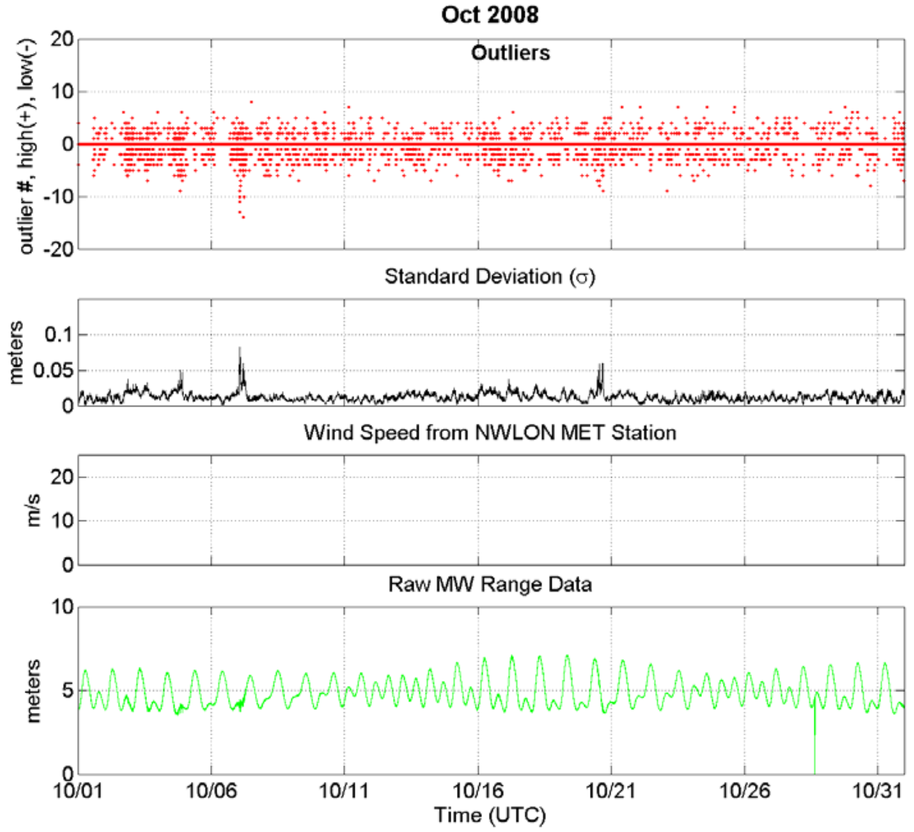

Port Townsend, Dec09,   Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
12/01
12/06
12/11
12/16
12/21
12/26
12/31
UT Time (mm/dd of 2008)

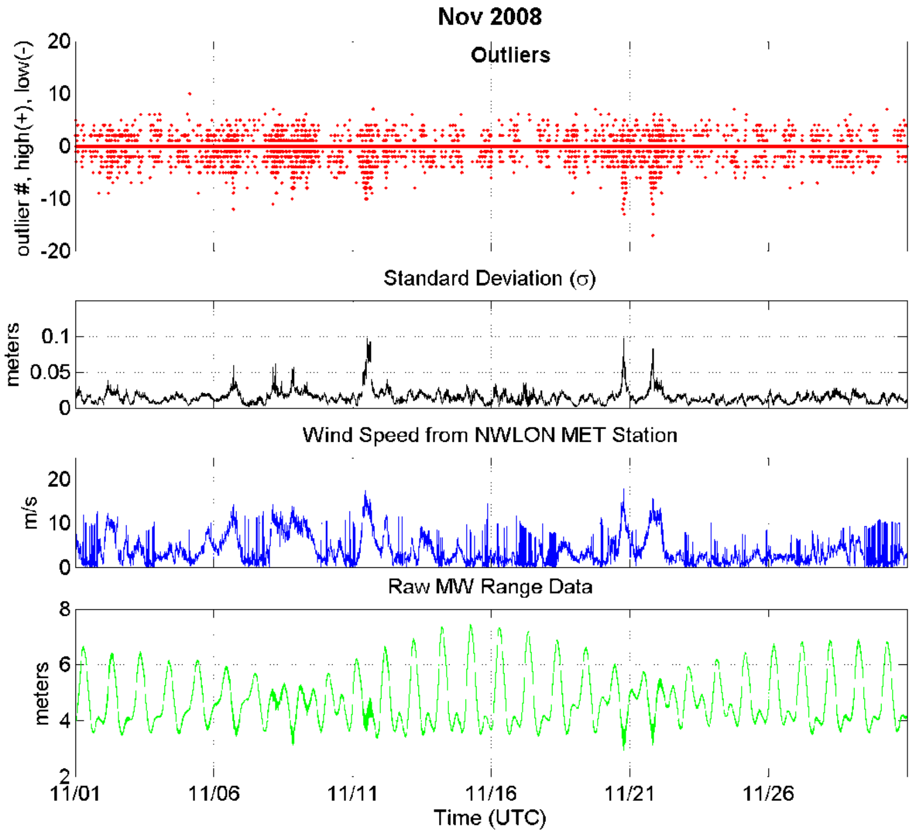

Port Townsend, Jan10, Wind Speed
knots
30
20
10
0
Water Level
Meters from Station Datum
5
4
3
2
1
0
Raw 1 Hz MWWL
6min avg MWWL
6min NWLON
Water Level Difference, Waterlog - NWLON Aquatrak
meters
0.02
0
-0.02
01/01
01/06
01/11
01/16
01/21
01/26
01/31
UT Time (mm/dd of 2008)

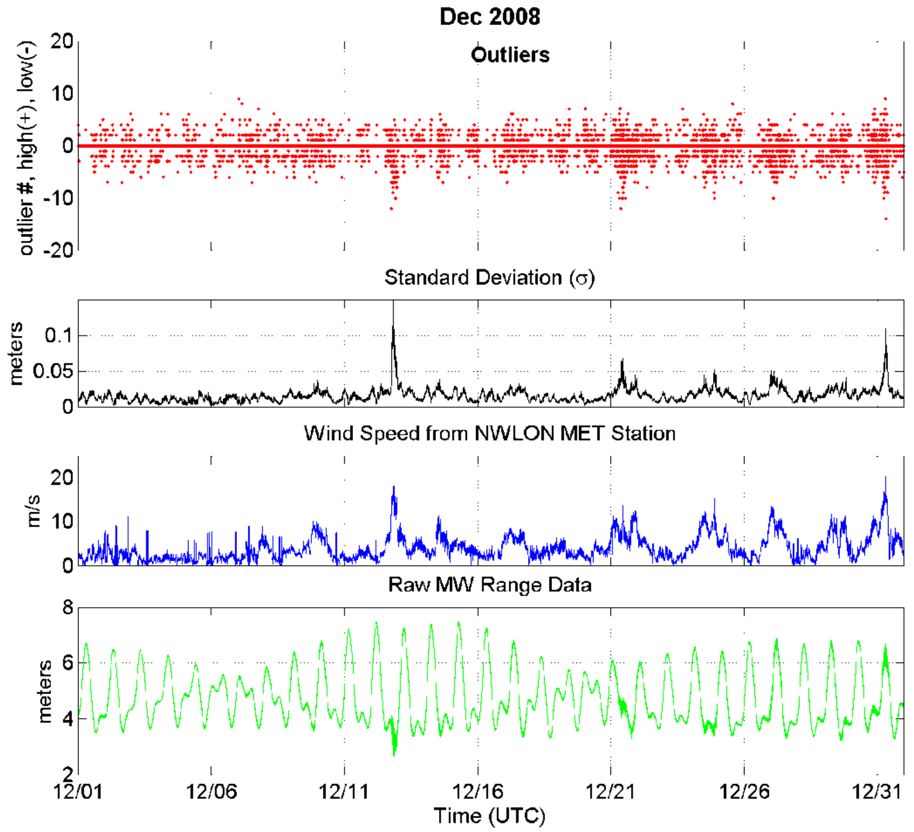
Monthly Outlier and Standard Deviation Plots Derived from Microwave Radar Data at Port Townsend, WA




Sep 2008
Outliers
outlier #, high(+), low(-)
20
10
0
-10
-20
Standard Deviation (σ)
meters
0.1
0.05
0
Wind Speed from NWLON MET Station
m/s
20
10
0
Raw MW Range Data
meters
8
6
4
2
09/01
09/06
09/11
09/16
09/21
09/26
Time (UTC)


Oct 2008
Outliers
outlier #, high(+), low(-)
20
10
0
-10
-20
Standard Deviation (σ)
meters
0.1
0.05
0
Wind Speed from NWLON MET Station
m/s
20
10
0
Raw MW Range Data
meters
10
5
0
10/01
10/06
10/11
10/16
10/21
10/26
10/31
Time (UTC)


Nov 2008
Outliers
outlier #, high(+), low(-)
20
10
0
-10
-20
Standard Deviation (σ)
meters
0.1
0.05
0
Wind Speed from NWLON MET Station
m/s
20
10
0
Raw MW Range Data
meters
8
6
4
2
11/01
11/06
11/11
11/16
11/21
11/26
Time (UTC)


Dec 2008
Outliers
outlier #, high(+), low(-)
20
10
0
-10
-20
Standard Deviation (σ)
meters
0.1
0.05
0
Wind Speed from NWLON MET Station
m/s
20
10
0
Raw MW Range Data
meters
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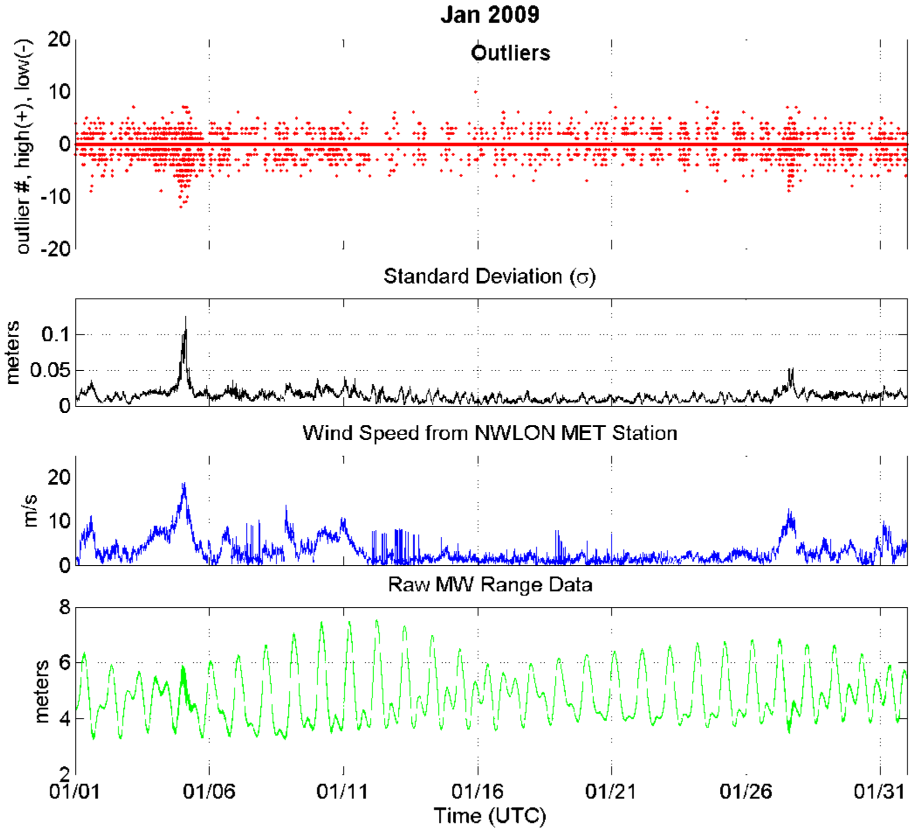
6
4
2
12/01
12/06
12/11
12/16
12/21
12/26
12/31
Time (UTC)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m/s
20
10
0
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meters
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4
2
01/01
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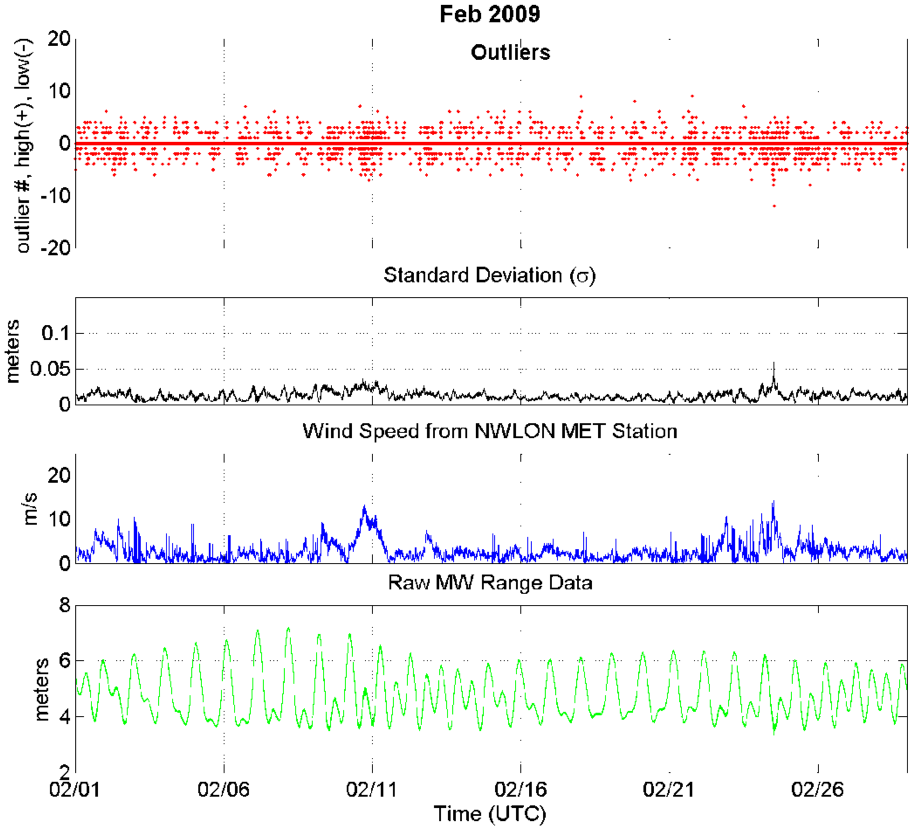
Time (UTC)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meters
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Wind Speed from NWLON MET Station
m/s
20
10
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4
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02/01
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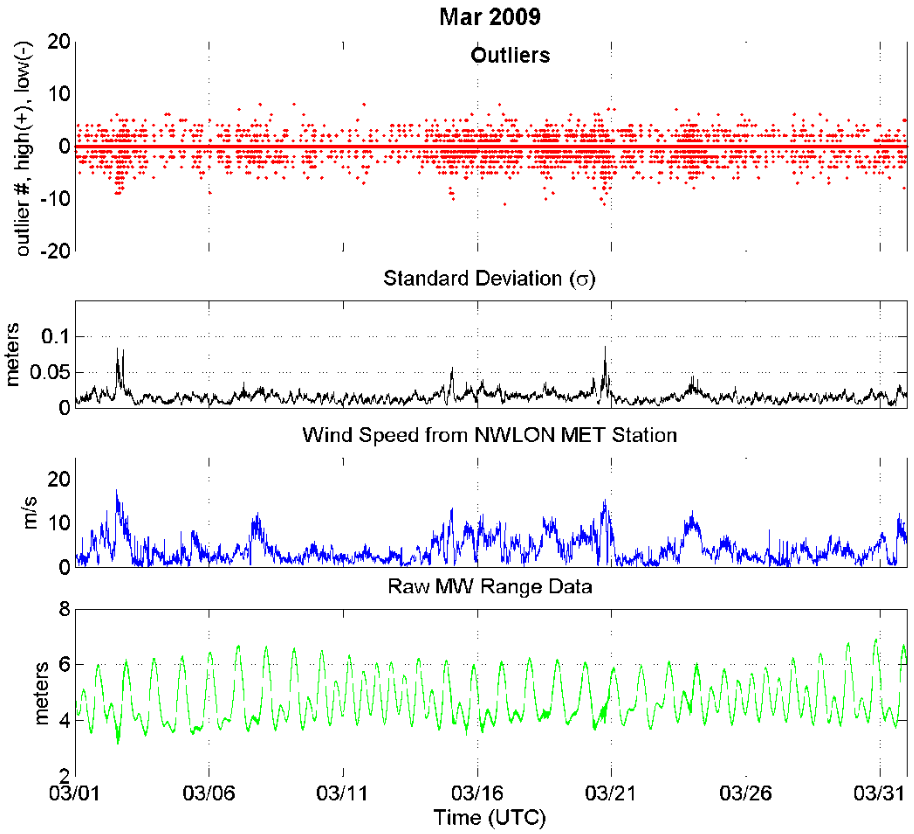
02/21
02/26
Time (UTC)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meters
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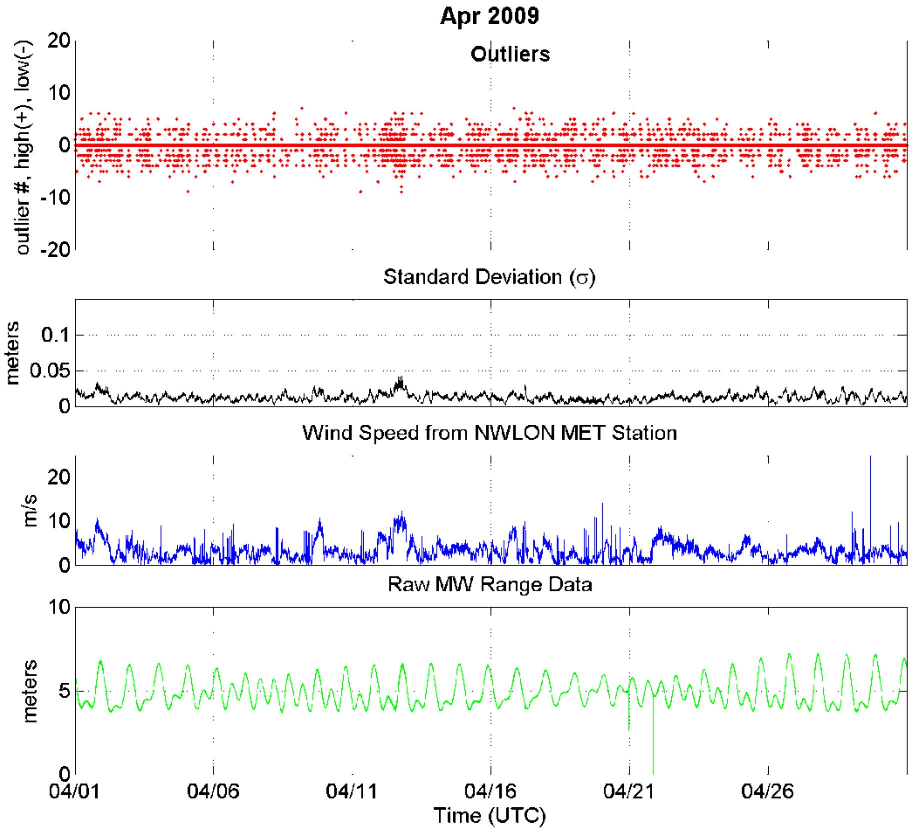
0.05
0
Wind Speed from NWLON MET Station
m/s
20
10
0
Raw MW Range Data
meters
8
6
4
2
03/01
03/06
03/11
03/16
03/21
03/26
03/31
Time (UTC)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0.05
0
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m/s
20
10
0
Raw MW Range Data
meters
10
5
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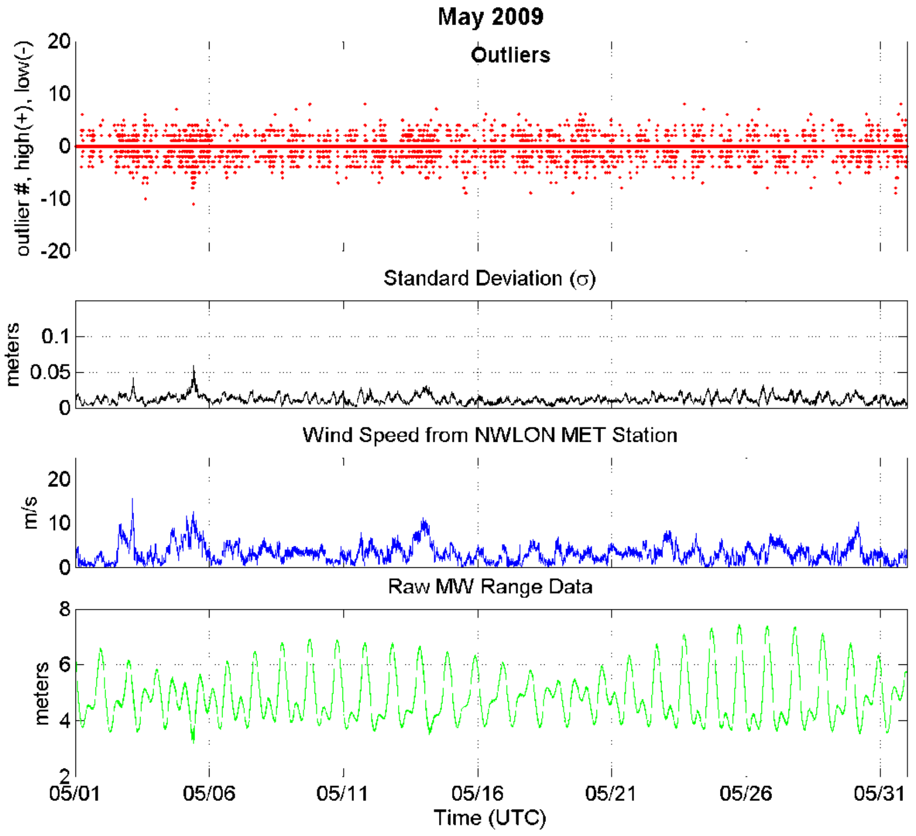
04/01
04/06
04/11
04/16
04/21
04/26
Time (UTC)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Standard Deviation (σ)
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Wind Speed from NWLON MET Station
m/s
20
10
0
Raw MW Range Data
meters
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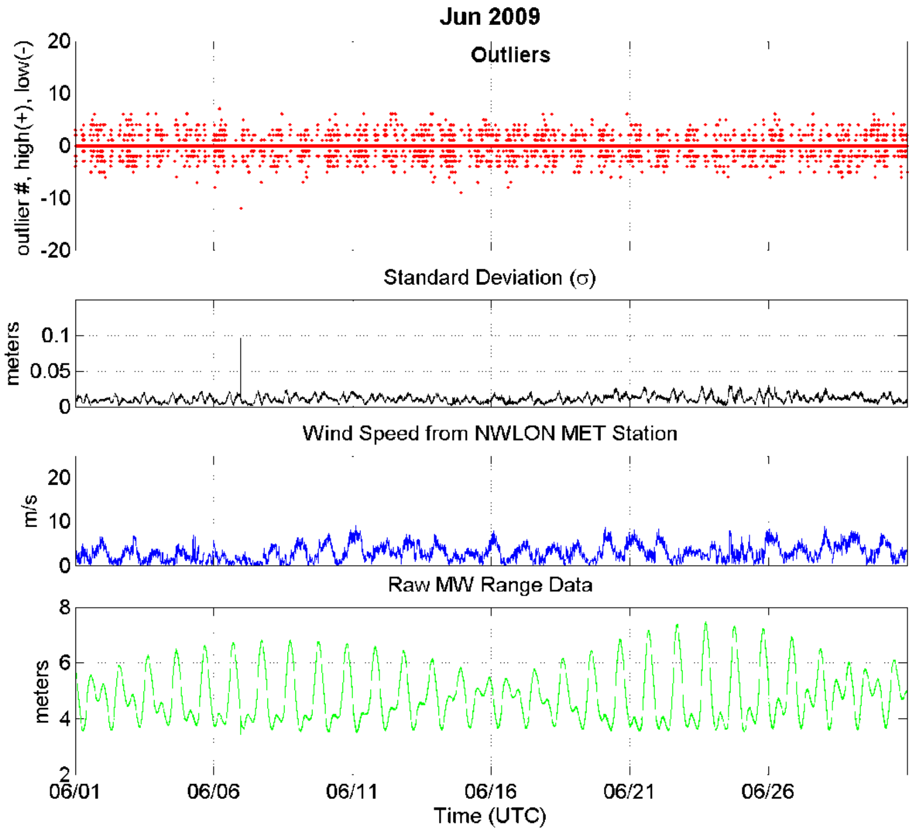
4
2
05/01
05/06
05/11
05/16
05/21
05/26
05/31
Time (UTC)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0
Wind Speed from NWLON MET Station
m/s
20
10
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meters
8
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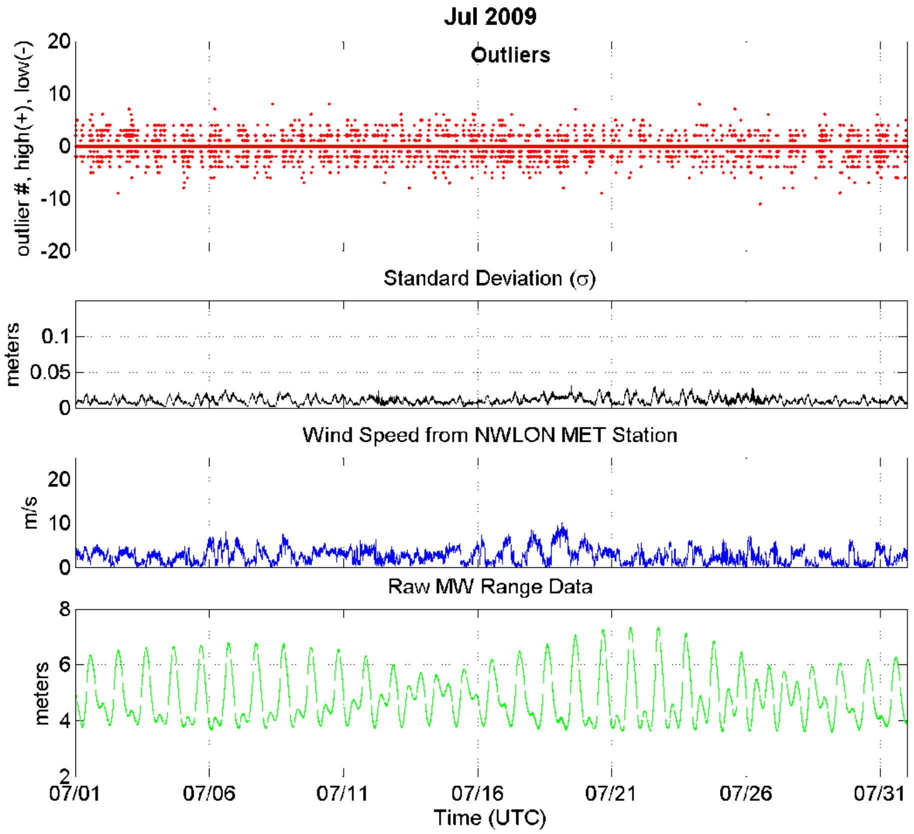
4
2
06/01
06/06
06/11
06/16
06/21
06/26
Time (UTC)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m/s
20
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meters
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2
07/01
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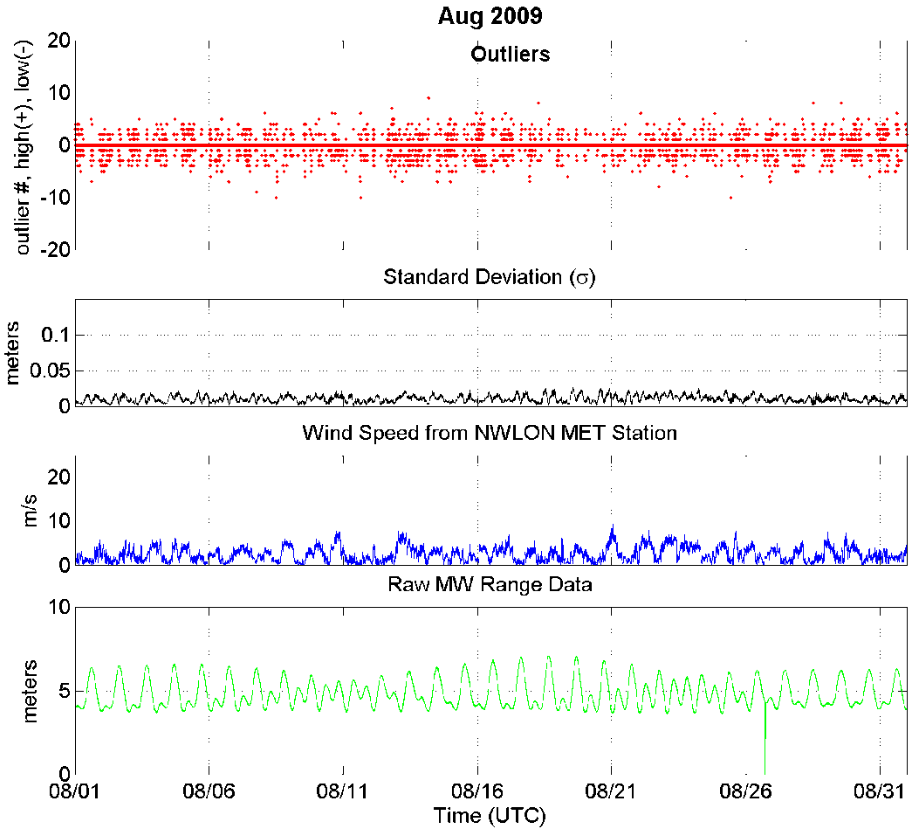
07/31
Time (UTC)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m/s
20
10
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Raw MW Range Data
meters
10
5
0
08/01
08/06
08/11
08/16
08/21
08/26
08/31
Time (UTC)

Appendix B. Requirements for Ingestion and Processing of 6-minute and Hourly GOES Transmitted Water Level Data Measured by a Microwave Radar Sensor

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Version 2.0

Introduction

The Center for Operational Oceanographic Products and Services (CO-OPS) is adding microwave radar sensors to its suite of instruments that measure water levels. Implementation of this new technology requires changes to the CO-OPS database and related processing software necessary to enable the ingestion of Geostationary Operational Environmental Satellite (GOES)-transmitted, near real-time water level data measured by a microwave radar sensor. This document outlines requirements to guide the CO-OPS Information Systems Division (ISD) in implementing these changes.

The desired products resulting from processing and ingesting microwave radar sensor data are the same 6-minute data archive and displays currently generated from water level data measured by Aquatrak acoustic sensors and float/shaft angle encoder systems at current National Water Level Observation Network (NWLON) stations. However, to maintain the same water level observation products after introducing the new microwave radar measurement technology, modifications to data processing methods are required, including the application of new quality control (QC) flags to incoming water level data measured by a microwave radar sensor.

This document describes how a microwave radar sensor is integrated into an operational NWLON station, how final datum-referenced water level values are calculated from initial microwave radar sensor measurements that are transmitted via NOAA's GOES system, and finally, the derivation of values in each column of the microwave radar sensor table that currently exists in the CO-OPS database.

The first microwave radar sensors introduced into operational NWLON stations transmit 6-minute near real-time data via the GOES system. Detailed descriptions of both 6-minute and hourly GOES transmitted data can be found in NOS CO-OPS Technical Reports 058 and 059 [1,2]. These two documents are based on memoranda by Philip J. Libraro from the CO-OPS Engineering Division (ED) and were updated in April 2010.

NWLON Station Setup for Initial Operational Microwave Radar Sensor Deployments

The CO-OPS water level database system refers to an Aquatrak primary sensor as ‘A.’ Currently, CO-OPS refers to a microwave radar sensor as ‘Y’ with the ultimate goal of replacing the currently used Aquatrak acoustic sensors with the newer microwave radar sensors. Microwave radar sensors will then provide primary water level measurements in NWLON stations, with bubbler pressure sensors providing backup measurements. However, to successfully reach this goal, CO-OPS is gradually introducing microwave radar sensors into operational stations. For the first few operational deployments (the first two are scheduled to be installed in the Mobile Bay Storm Surge Network in July-August 2010), the microwave radar sensors will serve as second backup water level sensors at stations with a typical NWLON system setup: an Aquatrak acoustic sensor providing primary measurements and a bubbler pressure sensor providing backup measurements.

To obtain a final water level value from each microwave radar sensor’s initial raw data measurement, CO-OPS applies a datum offset and a sensor offset, similar to the requirements for an Aquatrak acoustic sensor (more details and a related formula are provided in table 1 and the descriptions of microwave radar sensor that follow). However, in an operational system with both an ‘A’ and a ‘Y’ sensor recording to the same Data Collection Platform (DCP), an error results when datum offsets are applied. Therefore, it has been proposed that the two sensors record to separate DCPs in operational stations that involve both an ‘A’ and a Y’ sensor, which is the case in the first few operational deployments of microwave radar sensors where microwave radar sensors will serve as a second backup sensor. At these stations, the primary Aquatrak acoustic sensor records to one DCP and both the backup bubbler pressure sensor and microwave radar sensor record to a second, separate DCP.

Deriving Values for the Columns of the Microwave Radar Sensor Table

ISD recently confirmed that a table for a microwave radar sensor type already exists in the CO-OPS database. The table was previously implemented based on specifications in a Razor ticket (#273) that was originally submitted on December 4, 2003 by Manoj Samant of the CO-OPS ED. Table 1 contains the single string descriptions for each column that ISD provided.

Table 1. Single string descriptions for the microwave radar sensor

SENSOR_ID	single, constant numbers
STATION_ID	single, constant numbers
INFERRED	interpolations that fill in data gaps
MICROWAVE_WL	final, derived water level value
MW_SIGMA	standard deviation
MW_OUTLIERS	number of points that fall outside of ±3 standard deviations
SENSOR_TEMP	recommend removal from table
BOX_TEMP	recommend removal from table
MW_FLAG	water level minimum/maximum check
MW_SIGMA_FLAG	set when sigma indicates bad data
MW_OUTLIER_FLAG	bad water level data point
MW_FLAT_FLAG	bad data due to flat lining
MW_ROFC_FLAG	difference between subsequent 6-min values indicating bad data
DATA_SOURCE	source of the data

Descriptions of where each value can be obtained or how a value can be derived are provided in the following paragraphs.

SENSOR_ID, STATION_ID both are single, constant numbers that are included in each GOES transmission (see [1,2] for location in GOES transmitted message).

The **INFERRED** column is allocated for 'inferring' (or interpolating) water level data during periods when there is an unexpected data gap or sensor dropout, possibly due to a station outage or sensor malfunction. The procedure for inferring water level data at a station location where a microwave radar sensor is providing primary water level measurements is the same procedure currently used at a station location where an Aquatrak sensor is providing primary water level measurements.

MICROWAVE_WL is the final water level value derived from the initial water level (IWL) value transmitted via GOES. The IWL value is calculated by averaging 360, 1-Hz raw microwave radar sensor range data points in the DCP before transmission.

Note that microwave sensors are typical radar (**RA**dio **D**etection **A**nd **R**anging) object detection systems that use electromagnetic waves (in the microwave frequency band) to identify the range to a target. A microwave radar sensor is deployed above the sea surface, on a piling, pier, or structure that extends into the water column. The microwave radar sensor is aimed downward, oriented to transmit signals in a direction normal to the mean plane of the water's surface. The initial measurement is the range to the water's surface and is inverted to convert from range to water level.

Before a microwave radar sensor is installed in the field, a laboratory calibration test is conducted to obtain a vertical distance between the sensor's zero range point and a flat, easily referenced structure on the sensor's hardware or mounting enclosure, which can serve as a good geodetic leveling point (in most cases, the leveling point is the top of a microwave radar sensor's square mounting enclosure). This value is referred to as the sensor offset (**SO**), and once it is obtained during a pre-installation laboratory calibration procedure, the value is provided to ISD and remains constant. After the sensor is installed in the field, the vertical distance between its leveling point and the local established tidal bench mark needs to be determined. This value is referred to as the datum offset (**DO**) and is obtained by a geodetic survey conducted by CO-OPS Field Operations Division (FOD) personnel after sensor installation. As with the **SO**, once determined, the **DO** value remains constant and is provided to ISD after the FOD geodetic survey. The formula that is applied to obtain a final water level value (or **MICROWAVE_WL**) as a function of the initial water level value in the GOES transmission (IWL), the SO, and DO is:

$$\mathrm{MICROWAVE\_WL} = -\mathrm{IWL} - \mathrm{SO} + \mathrm{DO}$$

NOTE: Be certain to include the first negative sign in front of the IWL term to ensure that range is converted to water level!

MW_SIGMA refers to the standard deviation derived from the block of 360 (1-Hz) data points that were used to calculate the transmitted IWL data point. The **MW_SIGMA** value is computed within the DCP before data are transmitted via GOES and can be found in the GOES transmitted data [1,2]. Similarly, the **MW_OUTLIERS** value is also calculated in the DCP using the block of 360 (1-Hz) raw data points and represents the number of points in the data block that fall outside ±3 standard deviation values from the mean. The **MW_OUTLIERS** value is also transmitted in the GOES message. Both the **MW_SIGMA** and **MW_OUTLIERS** values are used to determine whether or not QC flags in the ISD table are set.

Because it is not necessary to consider temperature measurement when processing water level data measured by a microwave radar sensor, it has been recommended that the **SENSOR_TEMP** and **BOX_TEMP** columns be removed from the table. If the columns remain in the table, dummy/null values should be used.

The **MW_FLAG** value in sensor table 1 is the water level minimum/maximum check. This QC flag is applied to microwave radar sensor measurements the same way that it is applied to acoustic sensor measurements. Minimum and maximum water level value tolerances are specified for a specific station location. Then, the flag is set for a given 6-minute water level if the value is above the maximum tolerance plus 3 m or is below the minimum tolerance minus 3 m.

MW_SIGMA_FLAG is set when the value of **MW_SIGMA** indicates a bad water level data point. The criterion for setting the flag is: if **MW_SIGMA** is >0.15 m, then the flag is set.

MW_OUTLIER_FLAG is set when the value of **MW_OUTLIERS** indicates a bad water level data point. The criterion for setting the flag is: if **MW_OUTLIERS** is >15, then the flag is set.

MW_FLAT_FLAG is set if one of two conditions is met.

> **Condition 1:** Check the **MW_SIGMA** value. If **MW_SIGMA** equals 0.0 m, then the **MW_FLAT_FLAG** is set. There is no need to check Condition 2. If the value does not equal zero, then Condition 2 must be checked.
>
> **Condition 2:** If a 6-minute water level data value is identical to the two values before and the two values after that value, then **MW_FLAT_FLAG** is set. This is the same flat line condition currently implemented for NWLON primary water level sensors.

MW_ROFC_FLAG is set when the difference between subsequent 6-minute values of **MWWL_WL** (also known as 'first difference') indicates a bad water level data point.
NOTE: this flag is particularly important when applying QC to microwave radar sensor data because this is an open air sensor with no protective well. Suspect/bad data results from a microwave radar sensor whenever an object (boat, bird, large floating debris, etc.) transits underneath a sensor's signal path for more than a few seconds. Where WL_i is the current water level data point being processed, WL_{i-1} is the previous water level data point (from 6 minutes ago), and abs indicates absolute value, the criterion for setting this flag is:

$$\text{If } \mathrm{abs}(WL_i - WL_{i-1}) > 0.25 \text{ m, then the flag is set.}$$

DATA_SOURCE indicates the source of the data. As previously mentioned, the data source is GOES transmissions for the first operational installations of microwave radar sensors. ISD can use this information to set the **DATA_SOURCE** accordingly.

References

[1] Libraro, PJ. Format of 6-minute Data Transmitted by NOAA's National Environmental Satellite, Data, and Information Services (NESDIS) Geostationary Operational Environmental Satellite (GOES). NOAA Technical Report NOS CO-OPS 058. Center for Operational Oceanographic Products and Services, NOS, NOAA, Silver Spring, MD. April 2010.

[2] Libraro, PJ. Format of Hourly Data Transmitted by NOAA's National Environmental Satellite, Data, and Information Services (NESDIS) Geostationary Operational Environmental Satellite (GOES). NOAA Technical Report NOS CO-OPS 059. Center for Operational Oceanographic Products and Services, NOS, NOAA, Silver Spring, MD. April 2010.

Acronyms and Abbreviations

CIL	Chesapeake Instrument Laboratory
cm	centimeter
CO-OPS	Center for Operational Oceanographic Products and Services
CORMS	Continuous Operational Real-time Monitoring System
DCP	data collection platform
DHQ	diurnal high water inequality
DIS	data ingestion system
DLQ	diurnal low water inequality
DMS	database management system
DPAS	Data Processing and Analysis Subsystem
DQAP	data quality assurance processing
ED	Engineering Division
FRF	Field Research Facility
Gt	great diurnal range of tide
Hz	hertz
ISD	Information Systems Division
LTI	Laser Technology, Incorporated
m	meter
MHHW	mean higher high water
MHW	mean high water
min	minute
MLW	mean low water
MLLW	mean lower low water
mm	millimeter
Mn	mean range of tide
MSL	mean sea level
MTL	mean tide level
MWWL	microwave water level
nfft	Nonequispaced Fast Fourier Transform
NWLON	National Water Level Observation Network
NOS	National Ocean Service
NOAA	National Oceanic and Atmospheric Administration
OD	Oceanographic Division
OSTEP	Ocean Systems Test and Evaluation Program
PORTS®	Physical Oceanographic Real-time System
PRO	Pacific Region Operations
QC	quality control
RMSD	root mean squared difference
s	second
SOP	Standard Operating Procedure
ULS	Universal Laser Sensor
USACE	U.S. Army Corps of Engineers