NOAA Technical Report NOS CO-OPS 075

Water Level and Wave Height Estimates at NOAA Tide Stations from Acoustic and Microwave Sensors

Microwave water level sensors at La Jolla California.

Silver Spring, Maryland

June 2014

noaa National Oceanic and Atmospheric Administration

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

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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.

NOAA Technical Report NOS CO-OPS 075

Water Level and Wave Height Estimates at NOAA Tide Stations from Acoustic and Microwave Sensors

Joseph Park

Robert Heitsenrether

William V. Sweet

June 2014

U.S.DEPARTMENT OF COMMERCE
Penny Pritzker, Secretary

National Oceanic and Atmospheric Administration
Dr. Kathryn Sullivan, NOAA Administrator and Under Secretary of Commerce for Oceans and Atmosphere

National Ocean Service
Dr. Holly Bamford, Assistant Administrator

Center for Operational Oceanographic Products and Services
Richard Edwing, Director

NOTICE

Mention of a commercial company or product does not constitute an endorsement by NOAA. Use of information from this publication for publicity or advertising purposes concerning proprietary products or the tests of such products is not authorized.

TABLE OF CONTENTS

TABLE OF FIGURES

EXECUTIVE SUMMARY

The National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) is transitioning the primary water level sensor at the majority of tide stations in the National Water Level Observation Network (NWLON) from an acoustic ranging system to a microwave radar system. The primary motivation for this transition is the significant reduction in infrastructure and maintenance costs associated with the microwave sensor, which in ice-free conditions requires no contact with the water surface. The acoustic system requires a protective well that extends from above the highest water level to below the lowest water level and system maintenance requires disassembly, cleaning and dive operations. Installation of a new acoustic system requires nontrivial infrastructure to support the protective well.

To assess the relative performance of these two sensor systems, CO-OPS initiated a program to compare performance of the acoustic and microwave systems at operational NWLON stations finding statistically equivalent performance at sites with little or no wave energy. At sites with wave energy (expressed in the standard deviation statistic of the water level estimate) a persistent bias was noted with acoustic water level estimates lower than that of the microwave sensor. This report is the culmination of a study to identify and assess these differences.

Water level data from acoustic and microwave sensors covering a period of 19 months at tide stations on both the Atlantic and Pacific coasts are analyzed. Comparison of the acoustic and microwave data reveals that the majority of differences are accounted for by errors in the acoustic system, primarily from undiagnosed temperature gradients and wave-induced water level draw-down. It is also demonstrated that water level resonance inside the acoustic protective well can distort the water level spectral variance, and that the microwave sensor captures water level variability with higher fidelity than the acoustic system when waves are present. The overall results indicate that the microwave sensor is better suited than the acoustic system for water level measurement in locations where temperature differences between the sensor and water are significant or where waves or tidal flows draw down water levels inside the well.

We also note that wave height estimates as envisioned by the Integrated Ocean Observing System (IOOS) National Operational Wave Observation Plan (2009) using the NWLON standard deviation statistic are more accurately rendered with the microwave sensor than with the acoustic system.

It should be noted that the results of this study do not constitute a general recommendation to replace acoustic sensors with microwave sensors. Just as the acoustic system has limitations from temperature and hydraulic draw-down effects, microwave sensors have limitations such as sidelobe interference, false targets and signal scattering from heavy rain. Such an assessment is a site-specific determination, and should include long term comparisons of sensor data.

INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) manages the National Water Level Program (NWLP) to meet NOAA mission requirements for coastal water level information. The NWLP is a major observational program within NOS and serves as a Federal component of the Integrated Ocean Observing System (IOOS, 2013) and the Global Sea Level Observing System (GLOSS, 2013). A fundamental component of the NWLP is the National Water Level Observation Network (NWLON), a network of more than 200 long term, continuously operating water level stations around the United States including island possessions, territories and the Great Lakes.

Since the early 1990s the primary water level measurement system at most NWLON stations has been an acoustic time-of-flight range sensor (NOAA, 1991). The sensor is coupled to a sounding tube that guides an acoustic pulse to the water surface. The system is self-calibrating in the sense that it monitors the effective sound speed between the transducer and an acoustic reflector at a known distance (1.219 m), thereby adjusting for temperature changes in sound speed. However, this assumes that the temperature near the transducer is representative of the mean temperature along the entire tube, and a potential error source arises from the strong temperature dependence of acoustic celerity (Porter, 1996; Hunter, 2003). When the sounding tube is longer than several meters and the temperature difference between the upper section of the tube and the water surface is greater than several degrees, water level errors of several centimeters are possible.

The sounding tube is further enclosed in a vented protective well, a 15.24 cm (6 inch) diameter pipe extending below the water surface terminated with a brass orifice to restrict water mass transport in/out of the well. The orifice is a 5.08 cm diameter (2 inch) opening designed to work with the protective well to impose a mechanical low-pass filter on pressure induced water level variations inside the well. The primary source of these high frequency oscillations is a natural resonance of the well from buoyancy forces driven by pressure differences at the top and bottom of the well. In addition to these water level oscillations inside the well, wave-induced hydraulic pressure changes from hydrodynamic flow across the orifice are known to draw down or pile up water inside the well introducing another potential error (Shih and Rogers 1981). Parallel plates are added to the bottom of the orifice configuration to impose laminar flow past the orifice and to limit vertical accelerations. However, this does not preclude the development of a pressure differential and associated water level draw down.

From a logistical perspective, installation and maintenance of the protective well requires nontrivial infrastructure and yearly servicing including dive operations, and there is potential for the well to be damaged from flotsam or vessel impacts. Nonetheless, it should be noted that the protective well and acoustic sensor are a significant improvement over the earlier float/stilling well configurations in use prior to the early 1990s.

Microwave Water Level (MWWL) Phase II Analysis

The emergence of microwave water level sensors without temperature dependence or hydraulic pressure effects and with substantially reduced installation and maintenance costs has motivated NOAA to transition from acoustic systems to microwave sensors where possible (Heitsenrether, 2009). However, the microwave sensors have limitations such as signal scattering/blockage from rain or flotsam, and a variable surface area footprint dependent on sensor beamwidth and range from the water which introduces a spatial filter (Heitsenrether, 2008).

NOAA field evaluations comparing the two sensors find statistically equivalent performance at stations with little or no surface wave energy and small thermal gradients along the sounding tube. At stations with persistent surface waves larger than roughly 0.5 - 1 meter significant wave height, monthly mean water levels consistently reveal lower levels observed with the acoustic sensor. Boon et al. (2009) also reported differences between the acoustic and microwave system response with wave conditions, and presented evidence of an asymmetric water level distribution when waves are present (Boon, 2012).

To assess these differences, the *Microwave Water Level (MWWL) Phase II* project was designed to collect collocated acoustic and microwave water level data at NWLON stations where wave energy is known to be persistent (Park, 2013; Park, 2013a; Hensley, 2013; Park, 2013b; Heitsenrether, 2013). Site selection was based on comparison of empirical cumulative distribution functions (ECDF) of water level standard deviation over a period of 1 year. Figure 1 shows the ECDF at select NWLON stations with coastal exposure. Bay Waveland, Miss. and Port Townsend, Wash. are typical of stations protected from wave energy. In the intermediate regime are Monterey, Calif. and Lake Worth, Fla., while stations that represent high amplitude Aquatrak σ and wave energy include La Jolla, Calif., Duck, N.C., Wrightsville Beach, N.C., and Santa Monica, Calif. Based on the ECDF analysis, four NWLON stations with intermediate and high energy wave environments were selected for Phase II data collection and analysis: Duck, N.C., Lake Worth, Fla., La Jolla, Calif., and Monterey, Calif.

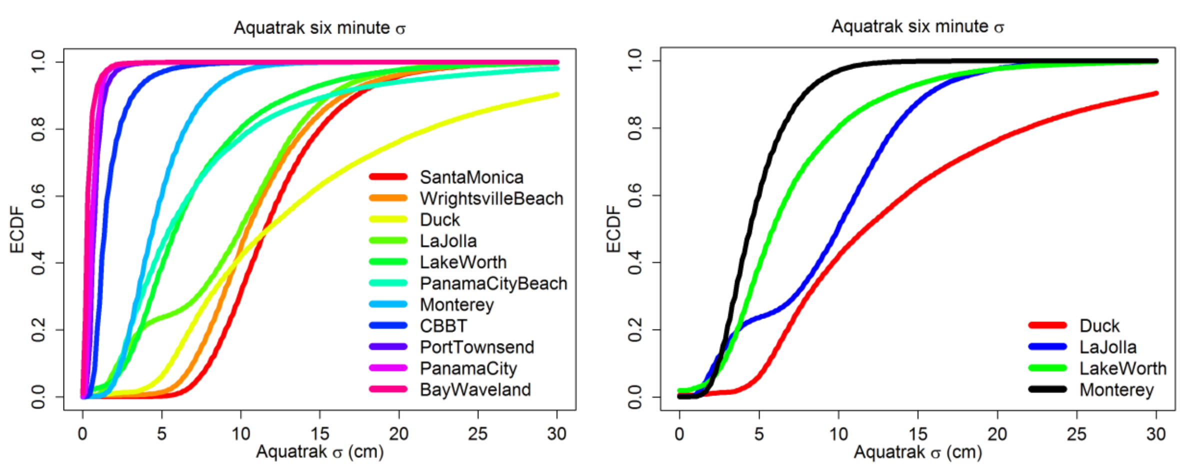

Figure 1. Empirical cumulative distribution functions of Aquatrak Data Quality and Assurance Procedure (DQAP) σ over a period of 1 year at coastal NWLON stations (left). Empirical cumulative distribution functions of Aquatrak DQAP σ over a period of 1 year at four NWLON stations selected for Phase II analysis (right).

Wave Height and Tide Gauge Standard Deviation

NWLON data products recorded every six minutes include the standard deviation (σ) of 181 water levels sampled at 1 Hz. The σ statistic is known to be correlated with significant wave height such that, as surface wave amplitude increases, there is an observed increase in water level standard deviation σ, although the relationship has been viewed primarily as a source of error in the water level measurement (Shih and Rogers1981; Boon, 2012). However, as part of the TOPEX/Poseidon validation experiments, a direct relationship between significant wave height ($H_{1/3}$) and standard deviation was established (Morris, 1995; Parke, 1995). It was concluded that standard deviation of the NOAA water level estimate is a good first order measure of significant wave height with the proviso that the protective well and low-pass filter can bias the wave height estimates, and that, below a threshold wave height, the relationship would degrade such that in protected waters estimates of wave height would not be viable.

Parke and Gill (1995) evaluated this dependence for the acoustic system as part of the TOPEX/Poseidon validation at Platform Harvest finding a linear increase of water level standard deviation values in the range of 10 - 20 cm for significant wave height of 1 m. This is consistent with data presented in sections *Water Level Standard Deviations and Significant Wave Height* and *Additional Analysis Results*. For example, at Duck, N.C. standard deviation values in the range of 7 - 20 cm correspond to significant wave heights of 1 m.

Given that the NWLON continuously monitors coastal water levels at numerous stations covering the United States coastline, a robust relationship between significant wave height and water level standard deviation could provide wave height estimates useful to coastal interests. Taking note of this, the Integrated Ocean Observing System (IOOS) plan for a surface wave monitoring network recognized that nondirectional wave data extracted from NWLON water level standard deviation can augment directional wave observations and are particularly useful in understanding the transformation and dissipation of waves as they traverse shallow and complex local bathymetry (IOOS, 2009).

Objective

The intent of this report is to assess comparative performance of the acoustic and microwave sensors in response to wave and temperature forcings for NOAA water level measurement, and to attribute these differences to known physical responses of the sensor systems. The following sections describe the sensors and give particular attention to models of the leading error sources for the acoustic system. Data from Duck, N.C. and Lake Worth, Fla. are used to illustrate the sensor characteristics and error estimates. Supporting data from all four Phase II test sites are presented in the appendix *Additional Analysis Results*.

SENSORS

Acoustic Water Level

The acoustic system is described by Edwing (NOAA, 1991) and is fundamentally a time-of-flight sensor encased in a protective well. The acoustic ranging sensor is coupled to a sounding tube that guides an acoustic pulse to the water surface, and the system is self-calibrating in the sense that it monitors the effective sound speed between the transducer and an acoustic reflector at a known distance (1.219 m), thereby adjusting for temperature induced changes in sound speed. However, this assumes that the temperature near the transducer is representative of the mean temperature along the entire tube, and a potential error source arises from the strong temperature dependence of acoustic celerity if this assumption is violated (Porter, 1996; Hunter, 2003). When the sounding tube is longer than several meters and the temperature difference between the upper section of the tube and the water surface greater than several degrees, water level errors of several centimeters are possible. Two temperature sensors (thermistors) are attached to the sounding tube to monitor temperatures along the tube with the upper sensor close to the acoustic transducer and the second sensor located above the highest astronomical tide. These temperature data are not used in the water level estimate, but are collected so that temperature corrections can be applied in post processing (discussed in section *Acoustic Temperature Dependence*).

The sounding tube is enclosed in a vented protective well, a 15.24 cm (6 inch) diameter pipe extending below the water surface terminated with a 5.08 cm (2 inch) diameter brass orifice to restrict water mass transport in/out of the well (Figure 2). The depth of the water inlet is referred to as the submergence depth, Y_o.

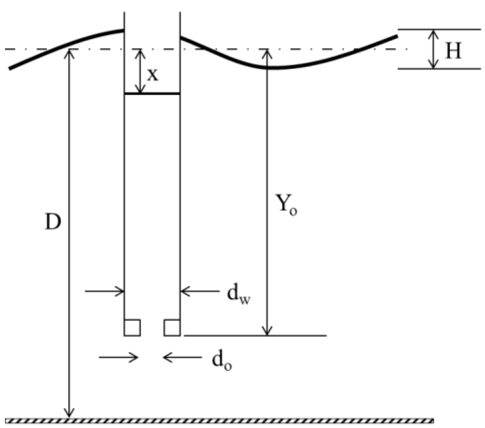

Figure 2.
Schematic diagram of Aquatrak protective well. The water depth is D, the instantaneous water level from the mean is x, submergence depth Y_o, well diameter d_w, orifice diameter d_o and wave amplitude H.

Applying the kinematic equation of motion to this system results in the classic second order (nonlinear) expression for a physical system with mass, potential and kinetic energy transfer, and damping (Serway, 2003):

$$\frac{d^2\mathrm{x}}{dt} + \frac{1}{2}\left[\zeta + \frac{\mathrm{f}}{\mathrm{d_w}}\right]\frac{d\mathrm{x}}{dt} + \omega_o{}^2\mathrm{x} = {}^{-\mathrm{P}}/_{\rho} \qquad (1)$$

where $\zeta = \frac{\left(\frac{d_W}{d_O}\right)^4}{Y_o\, C_d^{\,2}}$ is the damping factor with C_d the orifice discharge coefficient, f the frictional resistance to vertical flow in the well ($f = F(C_d, d_w)$), resonance frequency $\omega_o = \sqrt{\frac{g}{Y_o}}$, gravitational acceleration g, density ρ, and P the pressure at the orifice.

When waves or other water level perturbations pass around the air-water interface, the response of the water level inside the pipe is delayed from frictional and inertial forces, depending on the diameter of the well, the submergence depth, and the period and amplitude of the perturbations. The mismatch between the instantaneous water level inside and outside the well results in a buoyancy-driven oscillation of water level inside the well. Ignoring frictional effects and dependence of the protective well diameter, the natural (resonant) period of oscillation is

$$T_n = 2\pi\sqrt{\frac{Y_o}{g}} \qquad (2)$$

For typical submergence depths of 4 to 6 m at coastal locations the first order estimate of T_n ranges from 4 to 5 seconds. The water inlet orifice is sized to work with the protective well to impose a mechanical low-pass filter on these pressure induced water level variations and has a cutoff period of approximately 5 seconds. The damping factor is controlled by the mass flow rate through the orifice which numerically can be expressed as $\zeta = d_w/d_o$ where d_w and d_o are the diameters of the protective well and orifice, respectively.

The dynamic response of water levels inside the protective well are solutions to equation 1, and significant effort was expended in the 1980s with a series of laboratory, field, and numerical experiments to design the protective well based on hydrodynamics of water level frequency response in the well (Shih, 1981; Shih and Rogers, 1981). Figure 3 reproduces the dynamic water level response inside the well, *R*, to surface wave excitation of height *H* and period *T* from the work of Shih (1981).

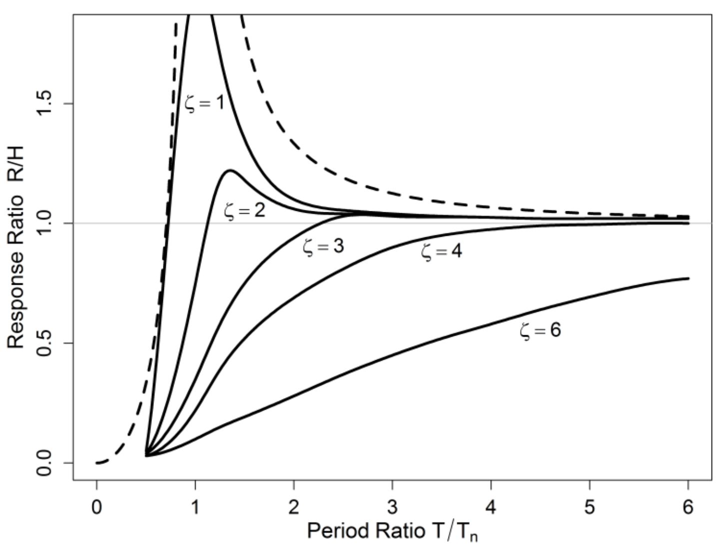

Figure 3.
Dynamic water level response inside a protective well to surface waves of height H and period T. R is the water level amplitude, T_n is the resonant period of the well and $\zeta = d_w/d_o$ is the damping factor where d_w and d_o are the diameters of the protective well and orifice, respectively. The dashed line represents the theoretical response in the absence of damping.

Examination of Figure 3 reveals why the orifice has a diameter of d_o = 5.08 cm. With a protective well diameter of d_w = 15.24 cm the value of ζ is 3, corresponding to a critically damped response. It is important to realize that Figure 3 represents the response to a specific set of parameters: H = 0.3 m, orifice submergence depth 3.0 m, water depth 7.6 m. Changing these parameters alters the shape and amplitude of the response curves and it is obvious that the single system design represented in Figure 3 will behave quite differently under varying parameter regimes. For example, increasing the orifice submergence depth increases the amplitude response R near resonance ($T = T_n$).

In addition to the resonant oscillations, Bernoulli's principle dictates conservation of pressure and velocity (v) at the inlet orifice:

$$\frac{v^2}{2} + g\,Y_o + \frac{P}{\rho} = C \qquad (3)$$

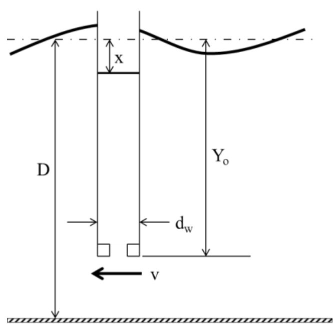

Figure 4.
Schematic of protective well orifice with a hydraulic current of velocity v across the orifice.

When tidal or wave driven currents are significant across the orifice, the pressure reduction is known to draw down water level inside the well. This effect was quantified by Shih and Rogers (1981) as a function of wave height and period as shown by the functional relationship in Figure 5. One can use this function to assess water level differences between the microwave and acoustic systems in response to wave forcing. Again, it should be noted that, while this curve applies to general combinations of wave height and period, and protective well and orifice diameter, it is specific to an orifice discharge coefficient of C_d = 0.8, submergence depth 3 m, and water depth of 9.14 m. Deviations from this parameter regime will alter the response of this model.

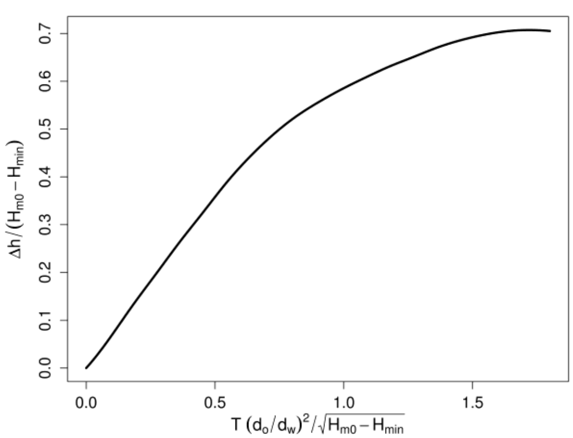

Figure 5.
Relationship between water level draw-down in centimeters (Δ h) and surface wave forcing. T is the wave period, d_o/d_w the ratio of orifice to protective well diameter, H_{m0} the significant wave height in meters, and H_{min} a minimum threshold wave height below which wave effects are not important.

Microwave Water Level

The microwave sensor operates at a frequency of 26 GHz with a beamwidth of 8 to 10^{o} depending on the antenna. There is no contact with the water surface and no dependence on pressure, hydrodynamic flow, or density of the water. The sensor is remarkably insensitive to temperature variation (0.2 mm/^{o}K, 5 mm maximum) and has accuracy of 0.03% of the measured range. However, microwave sensors have limitations such as signal scattering/blockage from rain, ice or flotsam and sidelobe interference from pilings or other infrastructure, and, as the range to the water changes, the surface area imaged by the sensor also changes, which introduces a changing spatial filter (Heitsenrether, 2008).

Details of the sensor can be found in the NOAA Limited Acceptance Test Report (NOAA, 2011). Boon et al. (2012) estimated sensor accuracy for NOAA water level estimates finding a quadratic increase of sensor error with wave height. They also identified an asymmetric distribution of water levels when wave height increased. This asymmetry is consistent with the development of a Rayleigh distribution of water level in the presence of waves.

Wave Height and Period

Hourly significant wave height (H_{m0}) and period at Duck were obtained from a Nortek bottom mounted acoustic waves and current (AWAC) sensor operating at 1 MHz deployed on the same depth contour as the acoustic and microwave sensors (6 m) but located approximately 500 m northward.

DATA

The MWWL Phase II project targeted four NWLON stations for data collection and analysis: Duck, N.C.; Lake Worth, Fla.; Monterey, Calif.; and La Jolla, Calif. The data period spans April 2012 through November 2013. Raw range-to-water data were sampled from both the microwave and acoustic sensors at 1 Hz. These raw 1 Hz data are used in power spectral density (PSD) estimates and to estimate range to water by application of the NOAA Data Quality and Assurance Procedure (DQAP) (NOAA, 2013c). This algorithm samples 181 consecutive 1 Hz values centered on each hour and 6 minute interval (minutes 0, 6, 12, 18, 24, 30, 36, 42, 48, 54) to compute an initial mean and standard deviation. Data points greater than 3 standard deviations from the mean are discarded, and a final mean and standard deviation are computed from the remaining points. These range data are transmitted by satellite to NOAA's Center for Operational Oceanographic Products and Services, where they are converted to water level by subtracting the range estimates from the reference datum, which are then disseminated in near-real time on the Internet and stored in the NWLON archives.

An example of the data for April 2012 at Duck is shown in Figure 6, where the upper panel plots the difference between the hourly acoustic and microwave water levels, the middle panel the temperature difference between the two thermistors, and the lower panel significant wave height. The water level differences are acoustic minus microwave, so that a positive differential implies the acoustic system reported a higher water level, a negative one that the acoustic level is lower. The temperature differences are upper thermistor minus lower thermistor, such that a negative differential represents a higher temperature along the sounding tube than at the acoustic transducer.

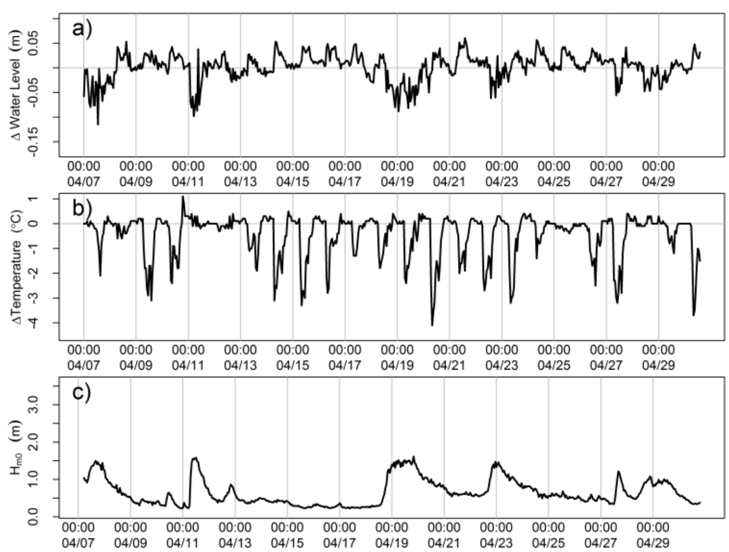

Figure 6.
Hourly data from Duck, N.C. in April 2012. a) Water level difference between the acoustic and microwave sensors. b) Temperature difference between the upper and lower thermistors of the acoustic sounding tube. c) Significant wave height. Times are Coordinated Universal Time (UTC).

Two inferences are apparent from examination of Figure 6. Positive water level differences are related to negative temperature differentials along the sounding tube, and negative water level differences are related to significant wave height. Each of these observations is examined in the following sections, but we first establish some general characteristics of the sensors with spectral analysis.

ACOUSTIC AND MICROWAVE FREQUENCY RESPONSE

Examination of water level power spectral density (PSD) estimates under different wave conditions reveals some fundamental response characteristics of the two systems. PSDs are estimated from raw 1 Hz water level data with a periodogram smoothed by a modified Daneill smoother of span 600 points resulting in a spectral amplitude 99% confidence interval of 1.1 dB (Bloomfield 1976). Resultant PSDs for four distinct wave regimes are shown in Figure 7. Panels a, b and c show spectra from waves of increasing height, all with dominant wave periods in the 7 to 15 second range. Panel d plots the response to a short period (4.1 second) wave field generated by the passage of a cold front on April 27, 2012 (discussed in *Standard Deviation and Significant Wave Height*).

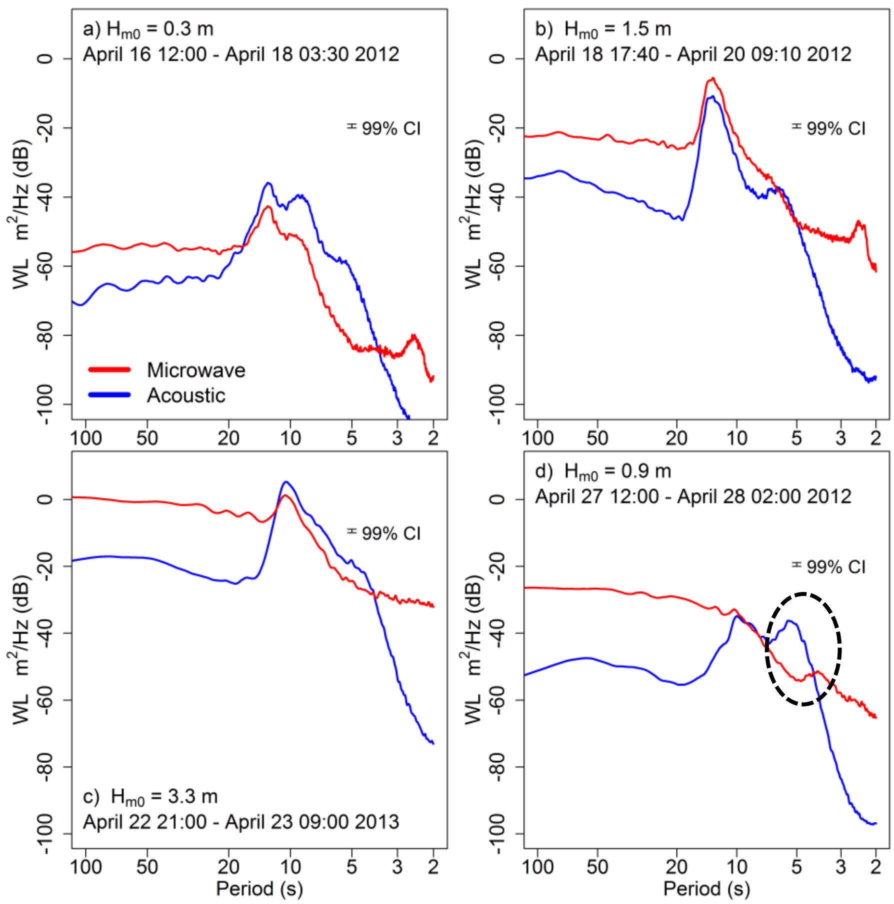

Figure 7.
Power spectral density estimates of 1 Hz water level data from the acoustic and microwave sensors at Duck, N.C. a) Low wave conditions. b) Intermediate to high wave conditions. c) Very high wave conditions. d) A locally generated, short duration swell with a dominant period of 4.1 seconds. Spectral distortion from the well resonance is highlighted.

Perhaps the most obvious characteristic is high frequency attenuation of the acoustic system at periods shorter than about 5 seconds owing to mechanical filtering from the water inlet orifice. Another robust feature observed across multiple data sets and environmental conditions is enhanced response of the microwave sensor to water level variance from low to intermediate/high wave conditions in the wind wave frequency band (periods of 5 to 20 seconds). This can be seen by comparison of panels a and b. In panel a, the wave height is low and the microwave sensor water level variance is 5 to 10 dB less than that of the acoustic system in the wind wave band. In panel b, the wave height has increased by a factor of 5, and the microwave water level response is roughly 5 dB greater than that of the acoustic system. This 'inversion' of water level variance translates into a superior water level sensitivity for the microwave sensor in the low to intermediate/high wave regime and led to identification of the microwave sensor as a higher fidelity water level sensor in the presence of waves (discussed in *Standard Deviation and Significant Wave Height*).

Although the sensitivity of the microwave sensor to water level dynamics is greater than the acoustic system for low to intermediate/high wave conditions, we see in panel c that when waves are very high the acoustic sensor reports higher variance in the 4 to 12 second band. NOAA is continuing to collect and analyze data in the high wave regime to ascertain if this is a consistent characteristic between the two sensors.

Resonance of the protective well is a notable feature in panel d. It is clear that the 4.1 second dominant wave period is captured by the microwave sensor, while the acoustic system responds with a broad peak centered on a period of 5 seconds. This can also been seen in panel a, where the acoustic spectra has a 'knee' at a period of 5 seconds while the microwave presents no such energy. It is also likely that the broad peak centered on a period of 5 seconds in panel b can be attributed to the protective well resonance.

Data from Lake Worth, Fla. where short period surface wave energy is common, show extreme distortions of spectral amplitude due to this resonance as shown in Figure 8, (see also Figure 34 and Figure 36 in *Additional Analysis Results: Lake Worth*).

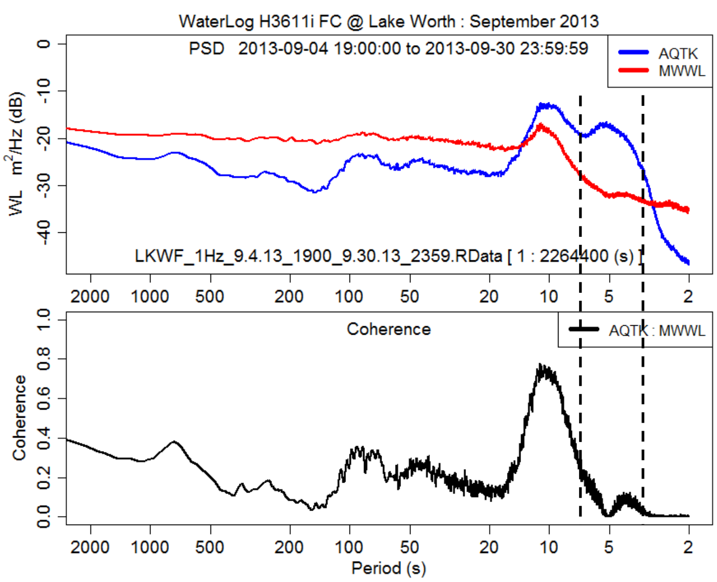

Figure 8.
PSD of 1 Hz water level data from Lake Worth during September 2013. Resonance of the protective well is presented as a large distortion of the spectral variance centered on a period of 5 seconds. The lack of coherence between the acoustic and microwave water levels at 5 seconds indicates that this resonant energy is a distortion.

That this resonant spectral energy is a distortion is verified by the lack of coherence between the acoustic and microwave water levels spanning the period of the protective well resonance. These distortions have the potential to bias the water level estimates since they represent energy inside the protective well due to resonance, not variance due to the true dynamics of the water surface. These resonance features are consistent with the dynamic response of the protective well being forced by combinations of parameters (wave height and period, orifice submergence depth, water depth, orifice discharge coefficient), which deviate from the ideal design represented in Figure 3 such that the critically damped response is not realized.

At periods longer than 20 seconds the microwave sensor consistently measures higher water level variance than the acoustic system. At these long periods we are no longer dealing with direct, wind generated ocean surface waves, but are sampling infragravity waves and other nonlinear processes associated with subharmonics of wind waves, internal waves, edge-waves trapped on the shelf, or other forcings (Munk, 1950). It is not presently known whether this response represents a higher fidelity sampling of low frequency variability, a limitation imposed by the acoustic system mechanical filter or microwave sensor, or some other effect. However, a consistent feature is that the shape of the spectral coherence at these long periods generally follows the shape of the acoustic spectra. This suggests that the protective well affords some level of noise rejection at very low frequencies. Nonetheless, values of coherence at these long periods are consistently low, indicating systemic differences in the sensing modalities of the two sensors.

ACOUSTIC TEMPERATURE DEPENDENCE

In previous work investigating the relationship between temperature and accuracy of the acoustic ranging system, Porter and Shih (1996) described the system and the presently used correction algorithm, and assessed impacts with a case study at the La Jolla, Calif. tide station. Their data reveal water level errors of the order of 5 cm arising from temperature induced sound speed errors. Hunter (2003) conducted a comprehensive analysis of the temperature dependence, again finding the dominant error arising from uncertainty in sound speed.

It is worth noting that the current NWLON temperature correction algorithm makes a significant assumption concerning representation of the physical environment. The correction is:

$$\Delta S = h(0.0018\,\Delta T) \qquad (4)$$

where ΔS is the water level correction, h is the range from the acoustic transducer to the water surface and ΔT the difference between the temperature measured near the transducer and the temperature measured closer to the water surface. The factor 0.0018 is a constant relating the sound speed in an adiabatic ideal gas to temperature in units of degrees Celsius.

This correction contains no dependence on the location of the temperature measurements. For example, for a given range to the water h, the correction ΔS computed from ΔT measured over a distance of 1 cm is the same as for ΔT measured over a distance of 10 m. The assumption is that a stepwise constant temperature difference, one temperature at the sensor and another constant temperature along the sounding tube, accurately represents the effective temperature profile along the sounding tube. This first order assumption may be valid in certain cases; however, in cases where the actual temperature profile is not well represented by a spatially independent temperature difference, the correction from equation 4 is known to be poor (Vogt, 1986; Park and Shabbir, 2013). NOAA is currently exploring the use of additional thermistors and a spatially dependent algorithm to improve sound speed corrections. Note that for the data analyzed here, the temperature differences are less than 4.2 ^{o}C, with mean and maximum sound speed changes of 0.6 and 2.5 m/s, respectively, resulting in temperature corrections of up to 7.2 cm. Temperature corrections exceeding 5 cm are not uncommon.

As previously noted from inspection of Figure 6, a relation between positive water level differences of the acoustic and microwave sensors and negative temperature differences of the two thermistors is evident. Even though the temperature correction of equation 4 is based on a simplistic physical model, it is the currently accepted algorithm and is used to compute temperature corrections for the data shown in Figure 6. These corrections are then compared with the observed water level differences as shown in Figure 9. The acoustic temperature corrections are largely coherent with the positive water level differences with pronounced disagreement primarily arising when significant wave height is greater than 0.5 m. These discrepancies are attributed to increased thermal mixing within the protective well driven by wind stress and pneumatic pumping from water level variance, since the protective well is vented at the top to allow ambient pressure equalization. The extent to which these positive water level differences are captured by the correction of equation 4 can be examined with linear regression of the positive sea level differences, with the temperature corrections for data having wave height below a certain threshold. With a threshold of $H_{m0} < 0.5$ m the regression finds a linear dependence of $c = 0.86$ m/^{o}C with $r^2 = 0.49$: ($p < 1E\text{-}9$), where c is the regression coefficient and p the p-value.

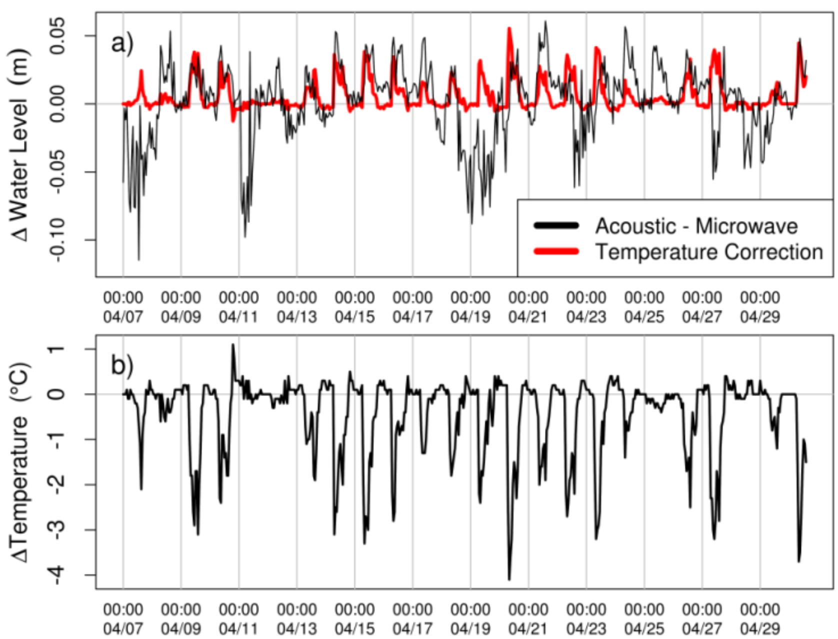

Figure 9.
Hourly data and temperature corrections from Duck in April 2012. a) Water level difference between the acoustic and microwave sensors (black) and acoustic temperature water level error estimates (red). b) Temperature difference between the upper and lower thermistors of the acoustic sounding tube.

These data, along with data presented in *Additional Analysis Results* confirm that temperature induced errors of acoustic water level are a significant disadvantage of the acoustic system in relation to the microwave system.

MECHANICAL FILTER WATER LEVEL DRAW-DOWN

To evaluate water level draw-down in the acoustic system, the functional relation of Figure 5 is applied to the data of Figure 6, with results presented in Figure 10. One can see that the envelope of the draw-down model captures the overall negative water level differences; however, there are differences at short time scales (several hours) as positive water level differences are observed during wave events, for example during the period April 11, 2012. It is not known whether these positive water level differences represent an error of the microwave sensor when water level variability is high (Boon, 2012), or whether they are a response of the acoustic system protective well and orifice. Given the nonlinear response of the protective well to wave forcings and known issues of water level pile-up in the well, it is likely that these short timescale differences are driven by resonance of water levels from a loss of damping in the acoustic system protective well.

To assess the draw-down model, one can regress the envelope of negative water level differences against the predicted draw-down. The water level difference envelope is obtained from low-pass filtering the magnitude of the differences with an 18 hour moving average filter, and the result is $c = 0.30$, $r^2 = 0.55$: ($p < 1E\text{-}9$). Copious examples of water level draw-down driven by wave-induced hydrodynamic flow are presented in *Additional Analysis Results*.

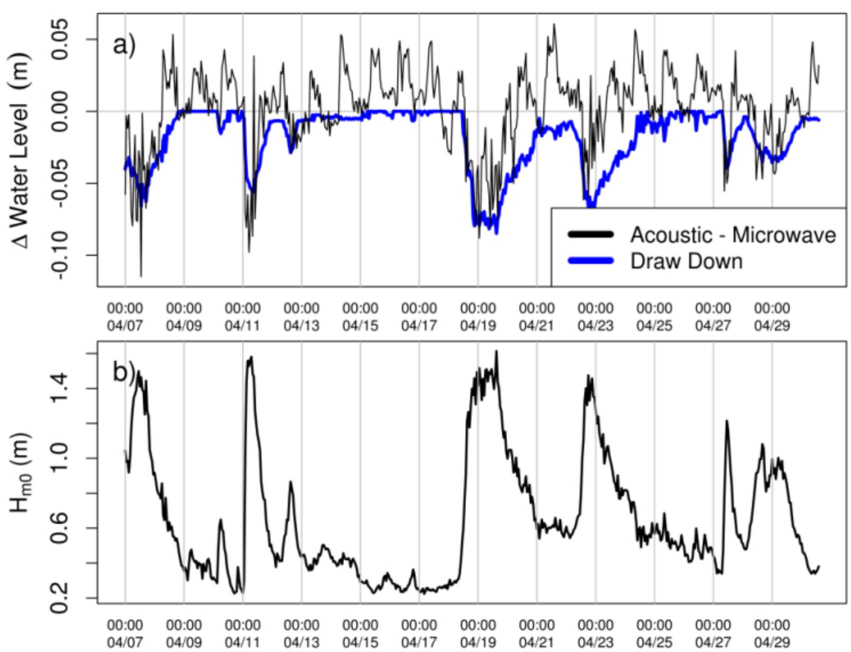

Figure 10.
Hourly data and draw-down corrections from Duck in April 2012. a) Water level difference between the acoustic and microwave sensors (black) and protective well draw-down estimates (blue). b) Significant wave height.

Not accounting for wave driven water level reductions in the acoustic sensors can impact long term water level statistics. For example, integration of the negative water level differences in Figure 10 results in an estimated 1.1cm reduction in mean sea level between the acoustic and microwave water levels over the April 2012 record. This closely matches the observed difference in sensor range shown by probability densities of the sensor range differences in Figure 11. Probability density functions (PDF) were computed based on subsets of the range data partitioned according to three regimes of acoustic DQAP standard deviation: Low ($0 < \sigma < 1/3$), Med ($1/3 < \sigma < 2/3$), and High ($\sigma > 2/3$).

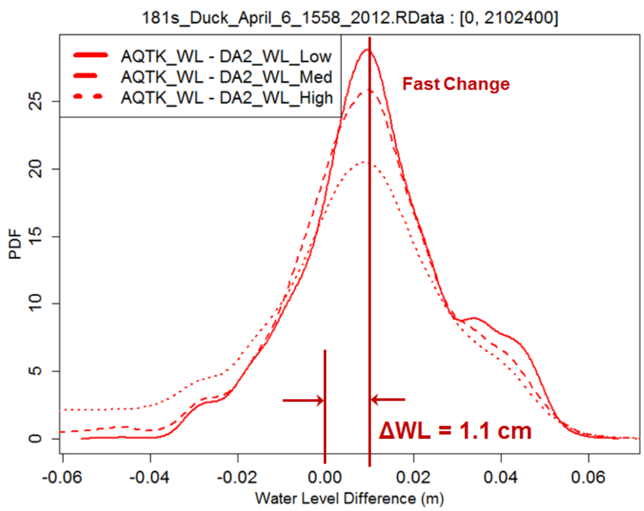

Figure 11.
Probability density functions of range to water difference (acoustic - microwave) for April 2012 at Duck. Density functions are shown for:
Low ($0 < \sigma < 1/3$)
Medium ($1/3 < \sigma < 2/3$), and
High ($\sigma > 2/3$)
partitions of the data.

One of the objectives of Phase II testing was to evaluate the microwave sensor in two different internal operating modes: Fast Change and No Filter (Park, 2013; Park, 2013a). In No Filter mode the sensor reports raw range data, while in Fast Change mode the sensor implements a low-pass filter with a time constant of roughly 5 seconds. Fast Change mode is the standard operating mode for CO-OPS deployments as recommended by the Limited Acceptance Report (NOAA, 2011).

Two additional observations from the probability densities are that in Fast Change mode, modal values of the partitioned PDFs are conserved, and that as σ increases the tail of the PDF increases for negative range-to-water levels. The first observation validates stability of the microwave sensor mean estimates with respect to the Aquatrak as a function of water level energy, while the latter suggests the emergence of an asymmetric water level distribution consistent with the transition from non-wave (Gaussian) to wave water level statistics (Rayleigh). However, since the low σ data correspond to lower wave heights it is expected that there should be a decrease in the modal values so that the bias from the center of the distribution should decrease if wave draw down is the driver.

Figure 12 presents probability density function estimates of range to water level differences for April 2013 for both No Filter and Fast Change modes. The data were partitioned into Low, Medium, and High subsets based on acoustic DQAP standard deviation (σ). Several pertinent observations can be made. First, the bias of the Fast Change distributions (1 cm) matches the estimated difference in mean water level from the draw-down model for April 2013 (see Figure 27 in *Additional Analysis Results*). Second, Fast Change mode preserves modal values of the probability distributions, while No Filter mode introduces a peak probability dependence on water surface variance with lower values of σ corresponding to smaller deviations from zero difference. This is the behavior one would expect if wave-induced draw-down is affecting the acoustic water level estimates. Again, we note in Figure 12 that as water level energy increases there is the emergence of an asymmetric tail at negative range to water levels which is consistent with the emergence of wave-like statistics (Rayleigh) from non-wave (Gaussian) distributions.

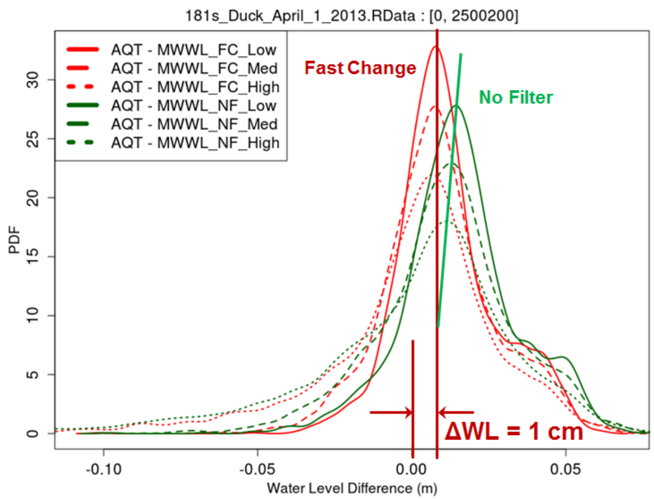

Figure 12.
Probability density functions of range to water level difference (acoustic - microwave) for April 2013 at Duck. Density functions are shown for:
Low (0 < σ < 1/3)
Medium (1/3 < σ < 2/3) and
High (σ > 2/3)
partitions of the data.

The reason for this modal invariance in Fast Change mode is not known, but it does support the recommendation of the Limited Acceptance Report to deploy microwave sensors in Fast Change mode, *if the Aquatrak is assumed to be a valid reference*. It should be noted that in the next section, *Standard Deviation and Significant Wave Height*, comparisons of both the acoustic and microwave systems with independent water level measurements from local wave gauges find that the microwave system captures water level variability with higher fidelity than the acoustic system. Therefore the assumption that the Aquatrak is a preferred reference requires further scrutiny. In fact, examination of Figure 16 in the next section provides evidence that the microwave sensor in No Filter mode performs better as a measure of water level variance in the presence of waves than the microwave sensor in Fast Change mode, which performs better than the Aquatrak. Therefore, the assumption of the Aquatrak as a valid reference is questionable.

Generally, these water level differences are consistent with the monthly mean differences that motivated the restriction of microwave sensors to limited fetch, low wave energy environments (NOAA, 2012b). Based on the data presented here and in *Additional Analysis Results*, it is clear that the acoustic system is poorly suited for environments with significant tidal or wave-induced hydrodynamic flows. At stations where these conditions prevail, the microwave sensor provides water level estimation with higher accuracy than the acoustic system.

STANDARD DEVIATION AND SIGNIFICANT WAVE HEIGHT

A comparison of wave gauge hourly H_{m0} with water level standard deviations of the acoustic and microwave gauges over 24 days in April 2012 at Duck is shown in Figure 13, suggesting a robust relationship between wave height and water level standard deviation.

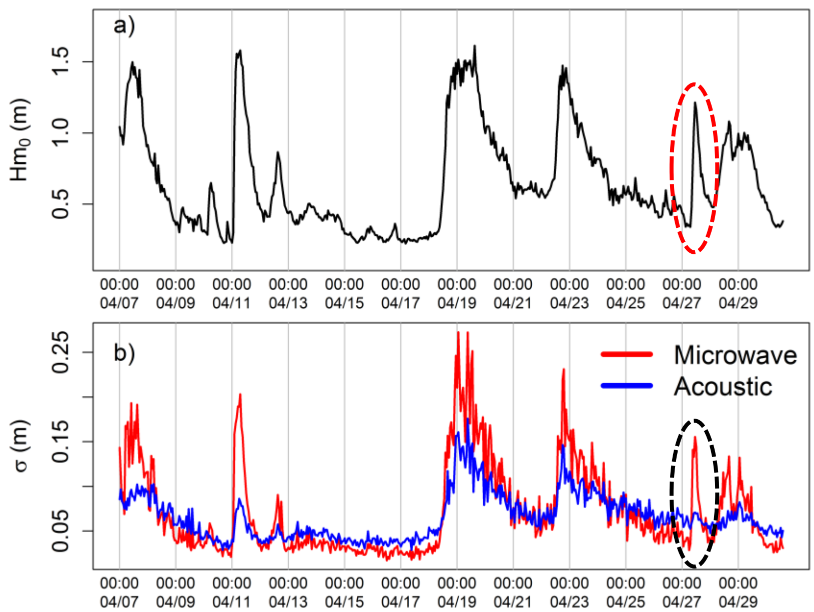

Figure 13.
a) Hourly significant wave height (H_{m0}) during a 24 day period in April 2012 at the Duck, N.C.
b) Hourly NWLON standard deviations. Note the lack of response of the acoustic system to the event on April 27.

Direct estimation of H_{m0} from σ would utilize the canonical definition:

$$H_{m0} = 4\,\sigma \qquad (5)$$

However, one can recognize that several factors contribute to deviations from this ideal. One is that we are relating H_{m0} estimated from the wave gauge over a period of 1 hour with a single σ estimated over 181 seconds for both the acoustic and microwave sensors. Other factors include the spatial separation between the wave gauge and water level sensors, and water level measurement system mechanics, e.g., the acoustic protective well introduces nonlinear filter to the water level variance and this response is known to depend on wave height, period, and water depth (Shih and Rogers, 1981). Further, the microwave sensor images a variable footprint on the water surface depending on the sensor-to-water distance and implements some internal smoothing of the 1 Hz data. Therefore, it is not expected that NWLON water level σ will explicitly satisfy equation 5, but one can hope for a linear scaling and seek a parameter α that best relates water level σ to H_{m0}:

$$\widehat{H}_{m0} = \alpha\,\sigma \qquad (6)$$

where $\widehat{H}_{m0}$ is the estimate of H_{m0} and α a factor that minimizes the residual $H_{m0} - \widehat{H}_{m0}$.

Fitting this linear model over the 24 day period results in $\alpha = 6.53$ and $\alpha = 11.08$ for the microwave and acoustic sensors, respectively, with resulting wave height estimates $\widehat{\mathrm{H}}_{\mathrm{m0}}$ shown in Figure 14. The mean error of these first order estimates can be represented with the RMS residual over the period and finds values of $\varepsilon_\mu = 0.14$ m and $\varepsilon_A = 0.21$ m for the microwave and acoustic sensors, respectively.

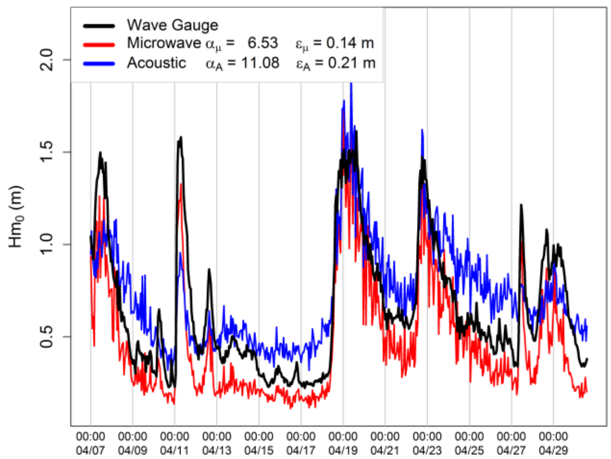

Figure 14.
Hourly significant wave height (H_{m0}) and estimates of wave height ($\widehat{\mathrm{H}}_{\mathrm{m0}}$) from a linear model of H_{m0} regressed onto water level standard deviations (σ) over 24 days of April 2012 at Duck. α is the fit coefficient, ε the RMS residual between wave gauge H_{m0} and estimated wave height ($\widehat{\mathrm{H}}_{\mathrm{m0}}$).

To assess the dynamics of this linear scaling on a finer temporal scale one can regress hourly σ over a sliding window of length 24 hours with the resultant fit and correlation coefficients shown in Figure 15. Correlation and fit coefficients are only shown if the p-value of the fit exceeds the 99% confidence level. The dashed line quantifies an ideal model of $\mathrm{H}_{\mathrm{m0}} = 4\,\sigma$, and we see that in a linear least squares sense the microwave sensor comes closer to this definition than the acoustic sensor. Both models find a significant dependence (p-values < 0.01) during times of wave activity, and note that, in concordance with the expectation of Parke and Gill (1995), when wave activity is low (days 14, 17, 24-27) the model fails to be statistically significant, although there are exceptions (days 9 and 30). Generally, the predictive skill of the acoustic system is less robust than that of the microwave system with consistently lower r^2 values and fit coefficients farther away from the ideal.

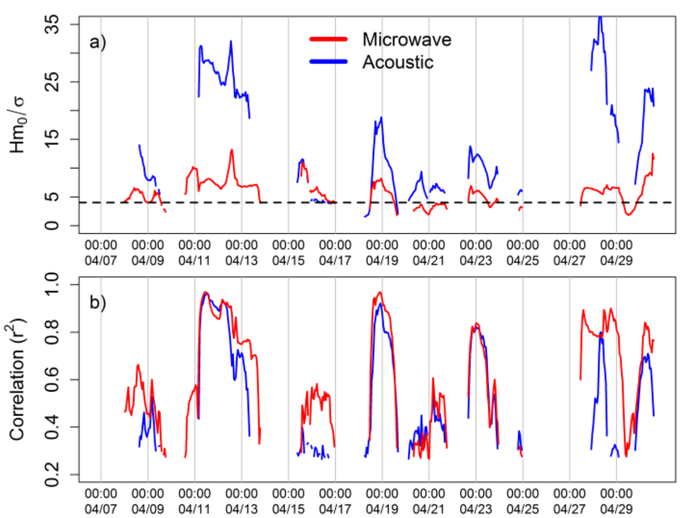

Figure 15.
Linear regression of significant wave height (H_{m0}) onto microwave and acoustic standard deviations shown in Figure 13 over a 24-hour sliding window. a) Fit coefficients. The dashed line shows the ideal model of $\mathrm{H}_{\mathrm{m0}} = 4\,\sigma$, corresponding to the accepted definition of significant wave height. b) Correlation coefficients. Values are shown only if the p-value exceeded the 99% significance level.

Figure 16 presents linear regression results for σ for all three sensors (Aquatrak, microwave Fast Change, and microwave No Filter) in April 2013. Consistent with previous results, the microwave sensor more closely matches the canonical definition of wave driven water level variance. It is interesting to note that No Filter mode performs best.

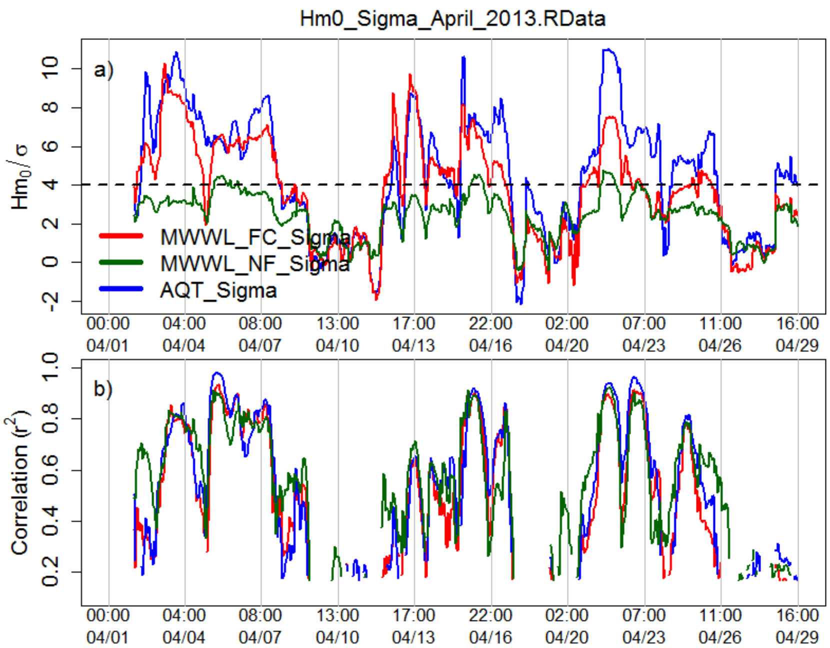

Figure 16.
Linear regression of DQAP σ and significant wave height for the acoustic and microwave sensors during April 2013. a) Fit coefficients b) Correlation coefficient. Values are shown only if the p-value exceeded the 95% confidence interval. The dashed line shows the canonical definition of $H_{m0} = 4\,\sigma$.

A re-examination of the acoustic and microwave water level σ shown in Figure 13 reveals that the microwave sensor exhibits a greater dynamic range than the acoustic system. During times of low σ the microwave response is lower in amplitude than that of the acoustic system, whereas during time of high σ the microwave response is higher. This suggests that in terms of water level variations the microwave sensor has a higher sensitivity than the acoustic system, which is consistent with the spectral analysis presented in *Acoustic and Microwave Frequency Response*.

Another difference evidenced in Figure 13 during day 27 is that the microwave sensor exhibits a pronounced response to a short term wave event while the acoustic system presents only a minor indication. Examination of meteorological data (NOAA, 2012) reveals that a cold front moved through the area on April 27 with a change in wind direction from 270^o to 10 to 60^o (offshore to onshore) with wind speeds during the period increasing from 5 to 10 m/s (10 to 20 knots). These conditions are consistent with the formation of locally generated, short period wind waves. Wave gauge records over this period reveal an average wave direction of 64^o, height of 0.9 m, and period of 4.1 s. Water level PSDs encompassing this event are shown in panel d of Figure 7 and we observe that, at periods between 2 and 4 seconds, the acoustic system is attenuated from the low-pass mechanical filter by roughly 20 dB in relation to the microwave response, an amplitude ratio of 10 to 1. The microwave response reveals a small (3 dB), but statistically significant broad peak between 3 and 5 seconds corresponding to the wave gauge report of a 4.1 second period.

The combination of meteorological, wave gauge, and water level PSDs suggests that the wave event on April 27 was primarily locally generated, short period wind waves that the acoustic system filtered out, but which drove the protective well into a resonant water level oscillation at a period of 5 seconds. This resonance introduces distortion into the spectral variance and at some point will contribute to increased error of the water level estimate.

DISCUSSION

As part of a modernization effort for NOAA's National Water Level Observation Network, acoustic ranging water level systems are being transitioned to microwave radar sensors. From a cost, maintenance, and support perspective, the microwave sensor is more efficient than the acoustic system since it requires no infrastructure in contact with the water, although it has limitations to be considered. When used without a protective well, flotsam or surface ice can lead to erroneous water levels. It is also known that ice accumulation in the antennae as well as scattering from heavy rain can degrade sensor performance. The use of a protective antenna cover (end cap) to prevent ice buildup inside the antenna does effectively mitigate the ice problem but introduces another where moisture accumulation on the cover impedes the signal (Park, 2013). The microwave beampattern also needs evaluation to ensure that interference from pilings/mounting structures does not impede imaging the water surface, and in surface wave sensing applications the footprint of the beam introduces a spatial filter (Heitsenrether, 2008).

Two benefits of the microwave sensor are that it is insensitive to temperature and does not rely on a hydraulic pressure measurement. With regard to temperature effects, the analysis finds that from one half to two thirds of water level differences between the acoustic and microwave sensors can be attributed to speed-of-sound errors in the acoustic system. An improved temperature correction algorithm would find higher proportions. Temperature errors of 5 cm and greater are common at La Jolla and Duck, as are temperature errors of 2 to 4 cm at Lake Worth (*Additional Analysis Results*).

When a wave-induced water level draw-down model for the acoustic protective well is applied, the analysis finds that one half to three fourths of the negative water level differences can be attributed to wave-induced pressure changes. Even though differences in water level response as a function of wave height are reasonably captured by the hydrodynamic draw-down in the protective well, there are exceptions during high wave events when a water level pile-up is observed (not discussed here). Based on the nonlinear response of the protective well, a leading hypothesis for these observations is resonance of the protective well due to a loss of damping. Further study is needed to clarify this behavior.

Spectral analysis demonstrates that resonance of the protective well can introduce large distortions to water level variance centered on periods of 5 seconds. Suppression of this resonance was a primary objective of the orifice and low-pass filter; however, the highly dynamic and variable parameter regimes of the nearshore wave zone can invalidate assumptions inherent in the one design protective well. These distortions have potential to bias the water level estimate, and further study is needed to identify the extent of such impacts.

NWLON data products recorded every six minutes include the standard deviation (σ) of 181 water levels sampled at 1 Hz. The σ statistic is known to be correlated with significant wave height, but has been largely ignored as a wave height measure and viewed primarily as an error metric of water level estimates. To assess the link between water level standard deviation and significant wave height a linear model at the 99% significance level finds that the microwave sensor estimates significant wave height, and therefore water level variability, with higher fidelity than the acoustic system.

CONCLUSION

The MWWL Phase II project has collected collocated acoustic and microwave water level data at four NWLON stations on both the Pacific and Atlantic coasts in intermediate and high wave environments. The data analyzed here cover the period from April 2012 through November 2013. Data from Monterey fail to show any significant differences between sensors due to the temperate climate, shielding of the protective well from insolation, and harbor water level oscillations (*Additional Analysis Results*). The other three stations (La Jolla, Duck, and Lake Worth) provide consistent results which can be encapsulated as: The majority of water level differences between acoustic and microwave sensors are attributed to systemic errors of the Aquatrak system. The leading errors are:

1) Speed-of-sound errors from undiagnosed temperature gradients along the sounding tube.

2) Water level draw-down errors from wave-induced hydrodynamic flow across the protective well orifice.

3) Resonance of water level inside the protective well from buoyancy driven pressure fluctuations.

The microwave sensor is insensitive to temperature and is not influenced by hydraulic pressure, as is the case for pressure sensors and water level inside the Aquatrak protective well. It is also shown that the microwave sensor measures water level variance in medium and high wave conditions with higher fidelity than the acoustic system.

Although the microwave sensor has significant advantages, there are important performance issues to be considered including beampattern, signal scattering, blockage, and false targets. Further research is needed to attribute increased water level variance observed by the microwave sensor at periods exceeding the wind wave band (20 seconds), and additional work is warranted to clarify the positive water level differences (pile-up) when waves are very high.

In summary, the data analyzed here spanning 19 months at stations on the Pacific and Atlantic coasts demonstrate that when wave or temperature forcings are present, the microwave sensor exhibits superior performance as a water level sensor in comparison to the Aquatrak.

REFERENCES

Bloomfield, P. (1976). Fourier Analysis of Time Series: An Introduction. 1st ed., Wiley, 471 pp.

Boon (2009). Boon J., Heitsenrether R. and Bushnell M., Microwave-acoustic water level sensor comparisons: sensor response to change in oceanographic and meteorological parameters. Proc. Oceans 09, October 26-29, Biloxi, MS.

Boon (2012). Boon J., Heitsenrether R., and Hensley, W., Multi-sensor evaluation of microwave water level error. Proc. Oceans 12, October 14-19, Hampton Roads, VA.

Breaker (2010). Breaker L.C., Tseng Y., Wang X., On the natural oscillations of Monterey Bay: Observations, modeling and origins. Progress in Oceanography, 86, 380-395.

GLOSS (2013). Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organisation and the Intergovernmental Oceanographic Commission. The Global Sea Level Observing System. http://www.gloss-sealevel.org/ (2013).

Heitsenrether (2009). Heitsenrether R., Using Microwave Range Sensors for Long Term Remote Sensing of Ocean Surface Dynamics. AMS 17th Conference on Atmospheric and Oceanic Fluid Dynamics, June 8-12, Stowe, VT, https://ams.confex.com/ams/17Fluid15Middle/webprogram/Paper154150.html.

Heitsenrether (2008). Heitsenrether R., Understanding the impact of surface waves on Microwave Water Level measurements. Proc. Oceans 08, September 15-18, Quebec City, QC.

Heitsenrether (2013). Heitsenrether R., Installation of a Microwave Radar Water Level Sensor Test Platform at Lake Worth, FL NWLON station. NOAA Center for Operational Products and Services, September 2, 2013. http://intranet.nos-tcn.noaa.gov/media/wikidocs/OSTEP/201308_LakeWorthMWWLInstallTripReport_final.pdf.

Hensley (2013). Hensley W., Test System Install: OSTEP and DET Return of the Jedi, USACE FRF Duck NC, NOAA Center for Operational Products and Services, May 2013. http://intranet.nos-tcn.noaa.gov/media/wikidocs/OSTEP/Trip\%20Reports/2013_01_15_OSTEP_DET_TripReport.pdf.

Hunter (2003). Hunter J. R., On the Temperature Correction of the Aquatrak Acoustic Tide Gauge. Journal of Atmospheric and Oceanic Technology, Vol. 20, pg. 1230--1235.

IOOS (2013). Integrated Ocean Observing System, NOAA, http://www.ioos.noaa.gov/.

IOOS (2009). Integrated Ocean Observing System, A National Operational Wave Observation Plan. Integrated Ocean Observing System (IOOS) plan for a surface-wave monitoring network for the United States, http://www.ioos.noaa.gov/library/wave_plan_final_03122009.pdf.

Kruger (1999). Kruger J., and Dunning D., Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. Journal of Personality and Social Psychology, Vol 77(6), pg. 1121-1134 http://psycnet.apa.org/journals/psp/77/6/1121/.

Morris (1995). Morris C. S. and DiNardo S. J. and Christensen E. J., Overview of the TOPEX/Poseidon Platform Harvest verification experiment. Marine Geodesy, Vol. 18, pg. 25--37.

NOAA (1991). Edwing R., Next Generation Water Level Measurement System NGWLMS Site Design, Preparation, and Installation Manual. http://tidesandcurrents.noaa.gov/publications/NextGenerationWaterLevelMeasurementSystemMANUAL.pdf.

NOAA (2011). Heitsenrether R. M. and Davis E., Limited Acceptance of the Design Analysis WaterLog H-3611i Microwave Radar Water Level Sensor. U.S. Department of Commerce, NOAA Technical Report NOS CO-OPS 061, March 2011. http://tidesandcurrents.noaa.gov/publications/Technical_Report_NOS_CO-OPS_061.pdf.

NOAA (2012). NOAA, Meteorological Observations, Duck NC, Station ID: 8651370, http://tidesandcurrents.noaa.gov/data_menu.shtml?bdate=20120427\&edate=20120428\&metinterval=\&unit=1\&shift=g\&stn=8651370+Duck\%2C+NC\&type=Meteorological+Observations\&format=View+Plot.

NOAA (2012b). Microwave Water Level Transition to Operations (TOP) Committee. Chair: Manoj Samant, Center for Operational Oceanographic Products and Services.

NOAA (2013b). NOAA, Duck, NC Station ID: 8651370 http://tidesandcurrents.noaa.gov/stationhome.html?id=8651370.

NOAA (2013c). NOAA, Environmental Measurement Systems Sensor Specifications and Measurement Algorithm. http://tidesandcurrents.noaa.gov/publications/CO-OPS_Measure_Spec_07_July_2013.pdf.

Munk (1950). Munk W. H., Origin and generation of waves. Proc. 1st International Conference on Coastal Engineering, ASCE, Long Beach, CA, pg. 1--4.

Parke (1995). Parke M. E. and Gill S. K., On the sea state dependence of sea level measurements at platform Harvest. Marine Geodesy, Vol. 18, pg. 105--111.

Park (2013). Park J. and Heitsenrether R., Microwave Water Level Transition to Operations (MWWL TOP) WaterLog H-3611 Test Plan Part II: Sensor Response to Dynamic Water Levels, January 24 2013, NOAA Center for Operational Products and Services http://intranet.nos-tcn.noaa.gov/media/wikidocs/ED/DET/MWWL/WaterLogCharacterizationTestPlan_Part_II_v0.3.pdf.

Park (2013a). Park J., Heitsenrether R., et al., Microwave Water Level Transition to Operations (MWWL TOP) Part II Field Test: Sensor Response to Dynamic Water Levels Installation Plan, NOAA Center for Operational Products and Services, August 29 2013. http://intranet.nos-tcn.noaa.gov/media/wikidocs/ED/DET/MWWL/MWWLPartIIFieldTest_InstallationPlan_v5.pdf.

Park (2013b). Park J. et al., MWWL Phase II Installation: La Jolla and Monterey CA. NOAA Center for Operational Products and Services, October 28, 2013. http://intranet.nos-tcn.noaa.gov/media/wikidocs/ED/DET/MWWL/MWWL_PhaseII_Installation_LaJolla_Monterey_v0.2.pdf.

Park and Shabbir (2013). Park J., and Shabbir A., Temperature Gradient Effect on the Sound Path Measurement of Aquatrak Acoustic Tide Gauge, NOAA Center for Operational Products and Services. http://intranet.nos-tcn.noaa.gov/media/wikidocs/ED/DET/Aquatrak/AquatrakTemperatureProfiles_Shabbir_2013.pdf.

Park and Heitsenrether (2013). Park J., and Heitsenrether R., WaterLog H-3611i Test Results Part I: Sensor Characterization, NOAA Center for Operational Products and Services. http://intranet.nos-tcn.noaa.gov/media/wikidocs/ED/DET/MWWL/WaterLog_Phase_I_TestResults_v0.11.pdf.

Porter (1996). Porter D. L. and Shih H. H., Investigation of Temperature Effects on NOAAs Next Generation Water Level Measurement System. Journal of Atmospheric and Oceanic Technology, Vol. 13, pg. 714--725.

Serway (2003). Serway R. A. and Jewett J. A., Physics for Scientists and Engineers. Brooks/Cole. Ed. 9, pg. 468--471.

Shih and Rogers (1981). Shih H. H. and Rogers D., Error analysis for tide measurement systems utilizing stilling wells. NOAA Tech. Rep., U.S. Department of Commerce, NOAA, Office of Ocean Technology and Engineering Services.

Shih (1981). Shih H. H., The Water Level Response Inside an Open Protective Well to Surface Wave Excitation. NOAA Tech. Rep., U.S. Department of Commerce, NOAA, Office of Ocean Technology and Engineering Services, September.

Vogt (1986). Vogt C. J.,Croucher A. and Mooney J., The Aquatrak Water Level Sensor Field Test at Shady Side, Maryland. The Johns Hopkins University Applied Physics Laboratory, STD-N-494, Submarine Technology Department, December.

Wilson (1965). Wilson B.W., Hendrickson J.A. and Kilmer R.E., Feasibility study for a surge-action model of Monterey Harbor, California. U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, MS, Contract Report No. 2-136, http://www.dtic.mil/dtic/tr/fulltext/u2/684953.pdf.

APPENDIX: ADDITIONAL ANALYSIS RESULTS

Duck, North Carolina

The Duck NWLON station is located at the U.S. Army Corps of Engineers Field Research Facility (FRF) (NOAA, 2013b). A map and description of the test setup is given in Boon et al. (Boon, 2012). The work by Boon et al. is the continuation of several years of microwave sensor deployments at Duck, which contributed valuable data characterizing response of the microwave sensors in a high wave environment (Boon, 2009).

The microwave sensor is located 8.66 m above mean water so that one can expect a single measurement accuracy of ±3 mm. The acoustic sensor is located 7.0 m above mean water level and is calibrated to a single range measurement accuracy of ±3 mm when there is zero temperature gradient between the sensor and water. Hourly significant wave height and period were obtained from a bottom mounted acoustic waves and current (AWAC) sensor operating at 1 MHz deployed on the same depth contour as the acoustic and microwave sensors (6 m) but located approximately 500 m northward.

PSD estimates of 1 Hz water level data from April 6 - 30, 2012 are shown in Figure 17. Spectral features are consistent with the other data with high coherence in the wind-wave band. The low-pass filter response of the protective well is evident.

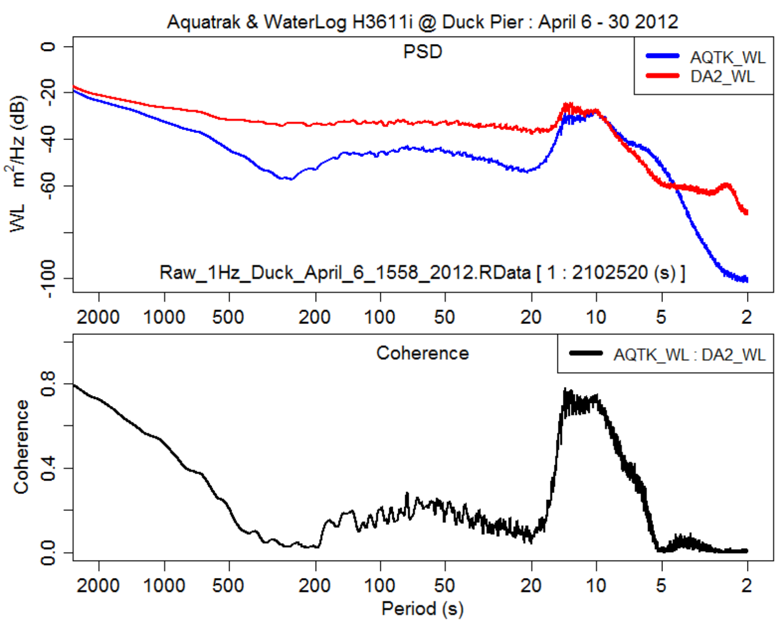

Figure 17.
PSD and coherence of acoustic and microwave water level data at Duck, N.C. in April 2012.

PSD estimates of 1 Hz water level data from February 1 - 18, 2013 are shown in Figure 18. Spectral features are consistent with the other data with high coherence in the wind-wave band and a significant distortion from the protective well resonance that is incoherent with the microwave data.

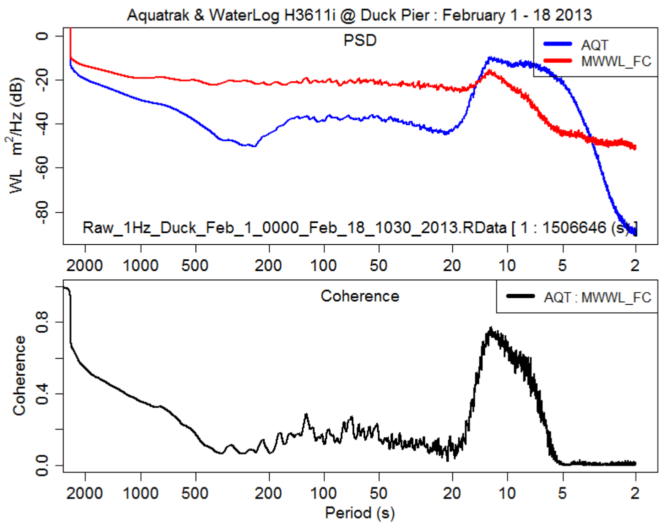

Figure 18.
PSD and coherence of acoustic and microwave water level data at Duck, N.C. for February 1 - 18 2013.

Application of the wave draw-down model (Figure 5) for data covering February 1 - 18, 2013 at Duck is shown in Figure 19. With the exception of the large positive water level difference at the peak of the wave event early on February 8, the draw-down model captures the water level differences quite well and water level differences exceeding 5 cm are common. The large positive water level difference exceeds 10 cm and occurs during a period of extreme wave heights, $H_{mo} \approx 4$ m, an area that needs additional investigation. However, there is little doubt that water level measurement in the presence of 4 m waves challenges the state-of-the-art in water level estimation. The leading hypothesis is a pile-up of water level inside the well due to extreme pressure fluctuations driving the nonlinear resonant response of the well. The large spectral distortion at the resonant period of the well (Figure 18) supports this hypothesis.

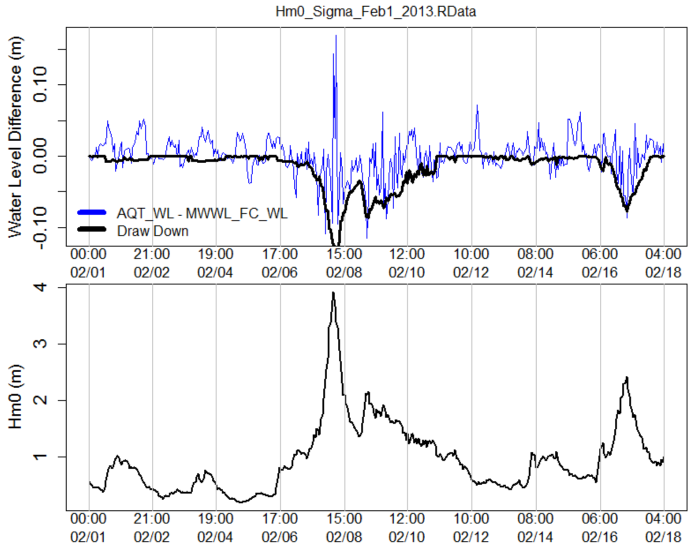

Figure 19.
Water level difference (acoustic - microwave, blue) and water level draw-down estimate (black) and significant wave height at Duck, N.C. for February 1 - 18 2013.

PSD estimates of 1 Hz water level data from February 18 - 28, 2013 are shown in Figure 20. Spectral features are consistent with the other data with high coherence in the wind-wave band and a significant distortion from the protective well resonance that is incoherent with the microwave data.

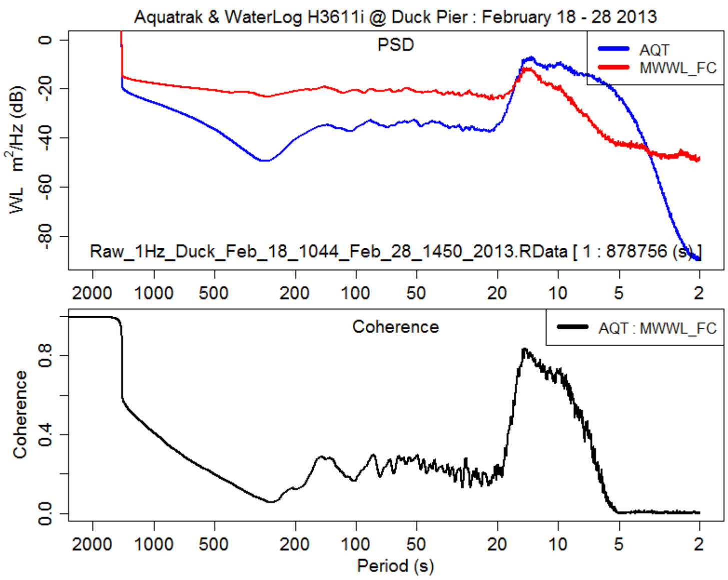

Figure 20.
PSD and coherence of acoustic and microwave water level data at Duck, N.C. for February 18 - 28 2013.

Application of the wave draw-down model (Figure 5) for data covering February 18 - 28, 2013 at Duck is shown in Figure 21. The draw-down model captures the negative water level differences with reasonable accuracy. The large spectral distortion at the resonant period of the well (Figure 20) suggests that the acoustic water levels will be highly variable and this is thought to contribute to deviations from the draw-down model.

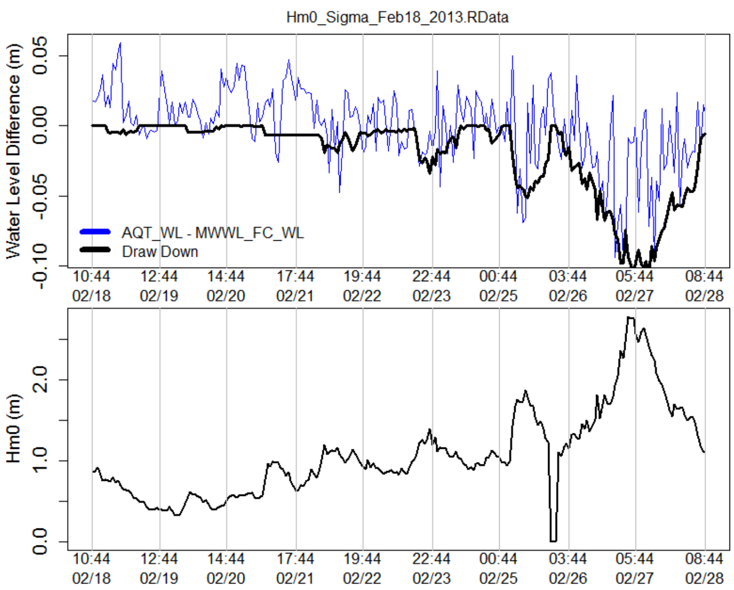

Figure 21.
Water level difference (acoustic - microwave, blue) and water level draw-down estimate (black) and significant wave height at Duck, N.C. for February 18 - 28 2013.

Figure 22 plots sensor water level difference, acoustic temperature difference, and significant wave height for April 2013 at Duck. During times of low wave energy (H_{m0} < 1 m), positive water level differences are consistent with the temperature differentials. During periods of significant wave activity negative water level differences are largely coherent with significant wave height. However, during periods of high waves positive water level differences are observed.

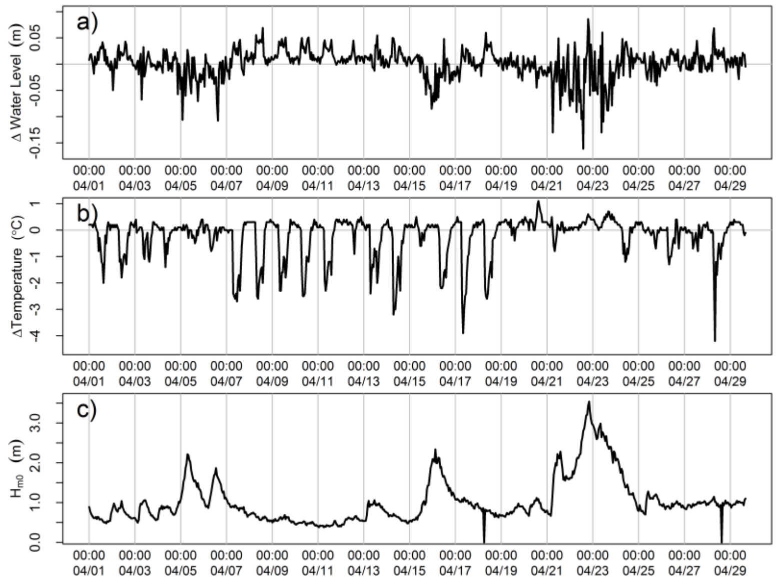

Figure 22.
Hourly data from Duck, N.C. in April 2013. a) Water level difference between the acoustic and microwave sensors. b) Temperature difference between the upper and lower thermistors of the acoustic sounding tube. c) Significant wave height.

Application of temperature corrections (equation 4) for the data shown in Figure 22 are presented in Figure 23. During periods of low waves temperature corrections account for the majority of the positive water level differences with a linear regression of c = 0.82, r^2 = 0.59 (p < 1E-9).

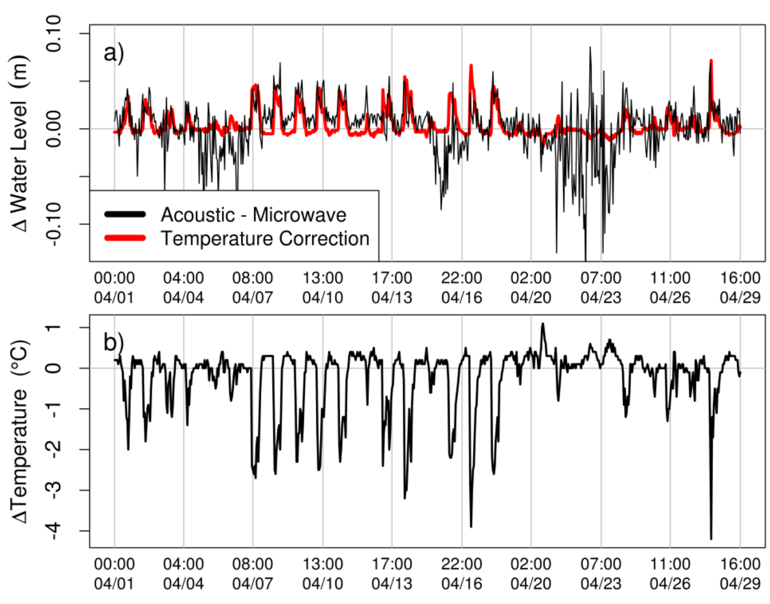

Figure 23.
Hourly data and temperature corrections from Duck, N.C. in April 2013. a) Water level difference between the acoustic and microwave sensors (black) and acoustic temperature water level change estimates (red). b) Temperature difference between the upper and lower thermistors of the acoustic sounding tube.

Figure 24 plots sensor water level differences with wave draw-down estimates, and significant wave height at Duck in April 2013. The envelope of the draw-down model captures the behavior of the negative water level differences with some exceptions, particularly when wave heights are high. Regression of low-pass filtered water level differences with the draw-down model find c = 0.31, r^2 = 0.76 (p < 1E-9).

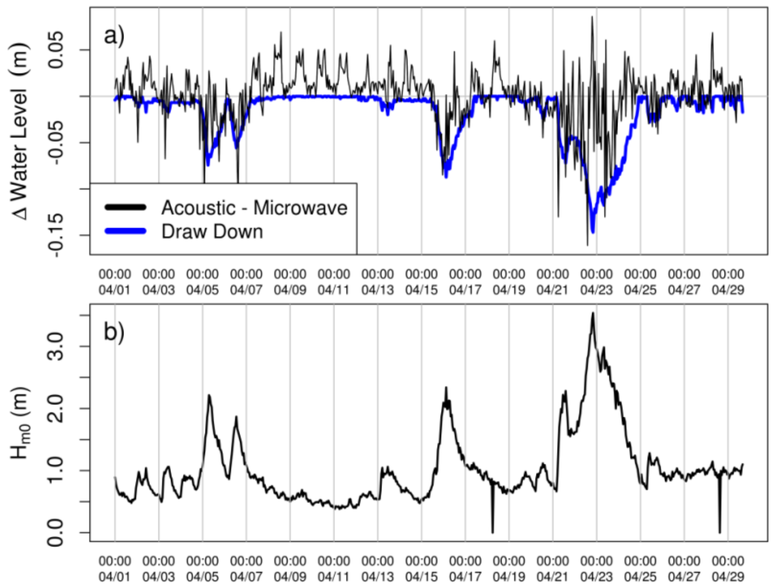

Figure 24.
Hourly data and draw-down corrections from Duck N.C. in April 2013. a) Water level difference between the acoustic and microwave sensors (black) and protective well draw-down estimates (blue). b) Significant wave height.

Figure 25 plots PSD estimates for water level data during a period of low surface variance (April 9 - 11, 2013) for the Aquatrak and microwave sensors operating in both Fast Change and No Filter modes. These responses are consistent with other data revealing good coherence between the acoustic and microwave sensors in the wind wave band, lower variance of the microwave sensor in Fast Change mode, roll-off of the acoustic system at short periods and evidence of the protective well resonance.

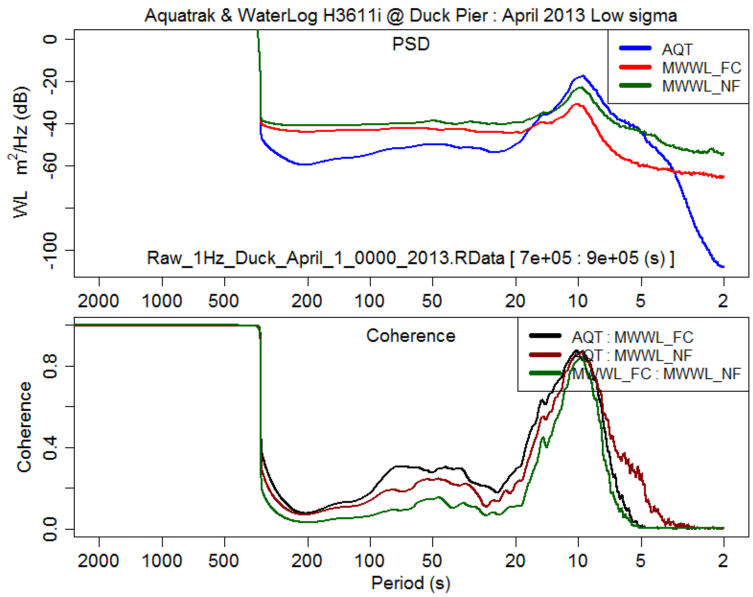

Figure 25.
PSD and coherence of acoustic and microwave water level data at Duck, N.C. for April 9 - 11, 2013, a period of low surface energy.

PSD estimates for all three water level sensors covering April 1 - 28, 2013 are shown in Figure 26. Spectral response is consistent with other observations.

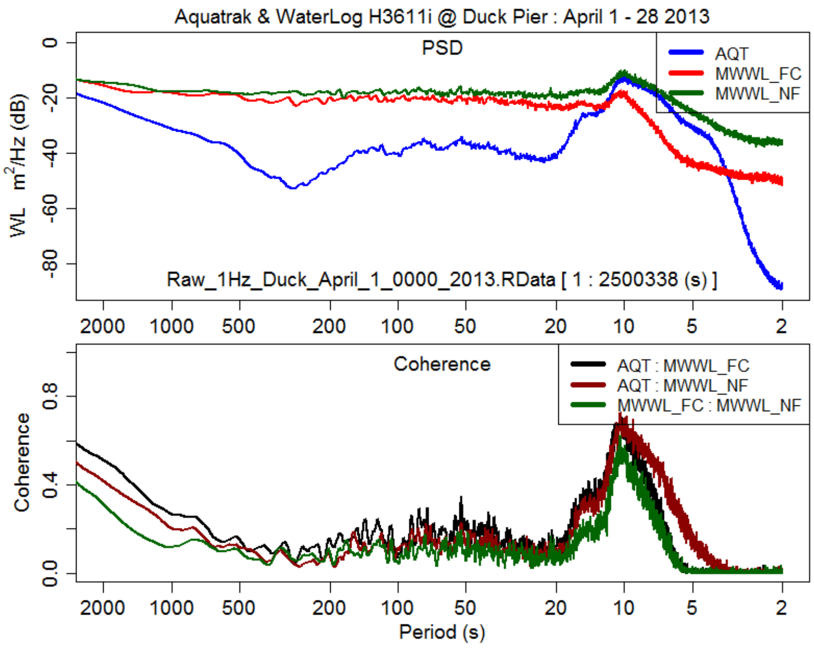

Figure 26.
PSD and coherence of acoustic and microwave water level data at Duck NC for April 2013.

Water level differences, estimated draw-down, and significant wave height for October 2013 are shown in Figure 27. Negative water level differences are captured by the draw-down model, and one should take note of the magnitude of water level differences (15 cm) during the large wave event on April 9.

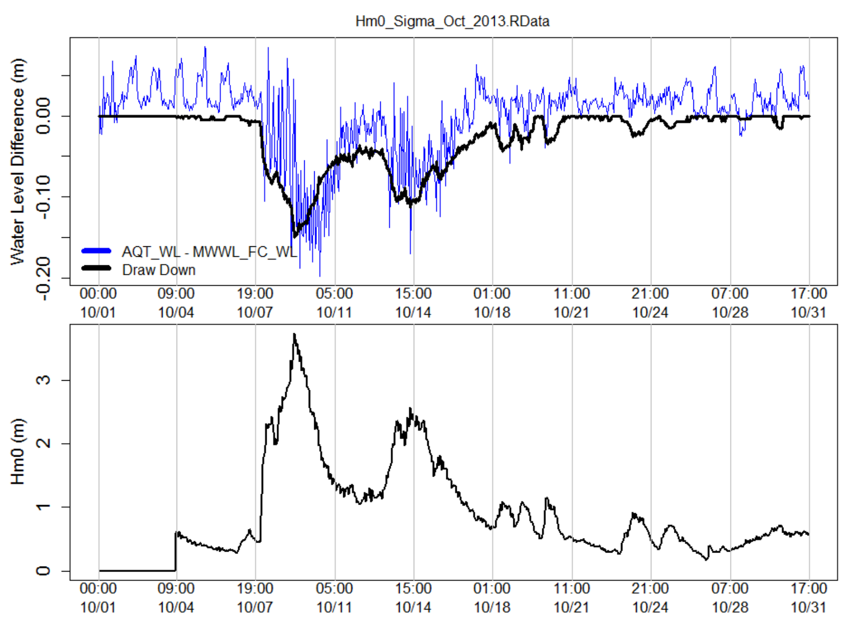

Figure 27.
Hourly data and draw-down corrections from Duck, North Carolina in April 2013. a) Water level difference between the acoustic and microwave sensors (blue) and protective well draw-down estimates (black). b) Significant wave height.

La Jolla, California

The La Jolla tide gauge is located on the Scripps Oceanographic Institute research pier. The Aquatrak system is located on the south side of the pier receiving direct sunlight to the protective well throughout the year. The protective well is one of the longest in use, and these two features result in significant Aquatrak temperature errors. The Phase II test plan did not install a wave gauge but relies upon the Coastal Data Information Program (CDIP) wave gauge at the pier. Figure 28 show the CDIP wave height and period at Scripps Pier for October 2013, indicating small to medium wave events on October 10th and 28th, and small waves from the 2nd through the 4th.

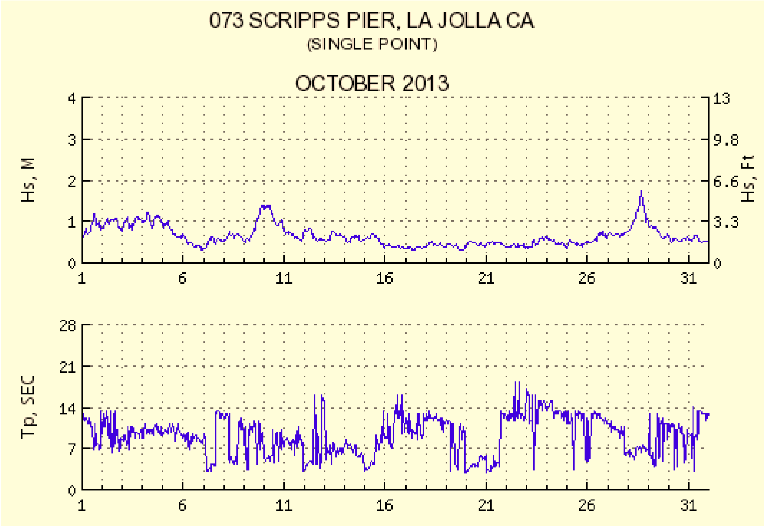

Figure 28.
CDIP significant wave height and period at Scripps Pier.

A power spectral density estimate of the microwave sensor data over the month of October is shown in Figure 29. This might be considered a prototypical spectra for ocean waves with dominant energy in the wind-wave band. (Although the peak near 110 second periods is not representative of open ocean spectra, and likely represent infragravity waves generated by shelf interactions with wind-wave forcing.)

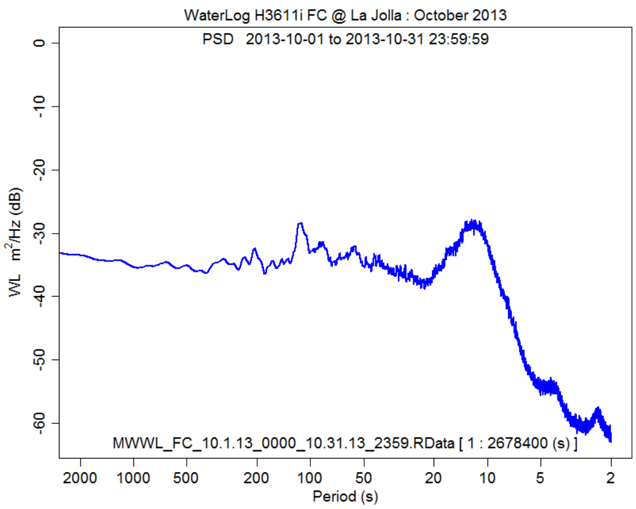

Figure 29.
PSD estimate of microwave water level for October 2013 at La Jolla.

Figure 30 plots water level differences with the acoustic temperature corrections and wave draw-down estimates, and careful inspection reveals that the acoustic system temperature and draw-down errors account for the bulk of the water level differences.

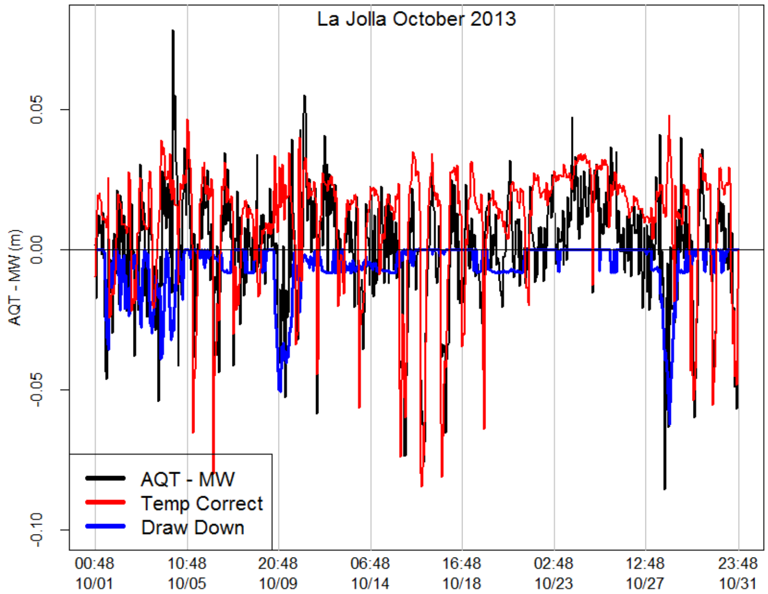

Figure 30.
Black: Sensor water level difference (acoustic - microwave), Red: acoustic temperature corrections and Blue: wave-induced draw-down at La Jolla for October 2013.

To better assess the water level differences and corrections for October 2013, Figure 31 separately plots the sensor water level differences (top) and the combined temperature and draw-down corrections (bottom). Even a casual observation suggests a high degree of correspondence, and a linear regression of the two finds a correlation coefficient of 0.74 with r^2 of 0.47.

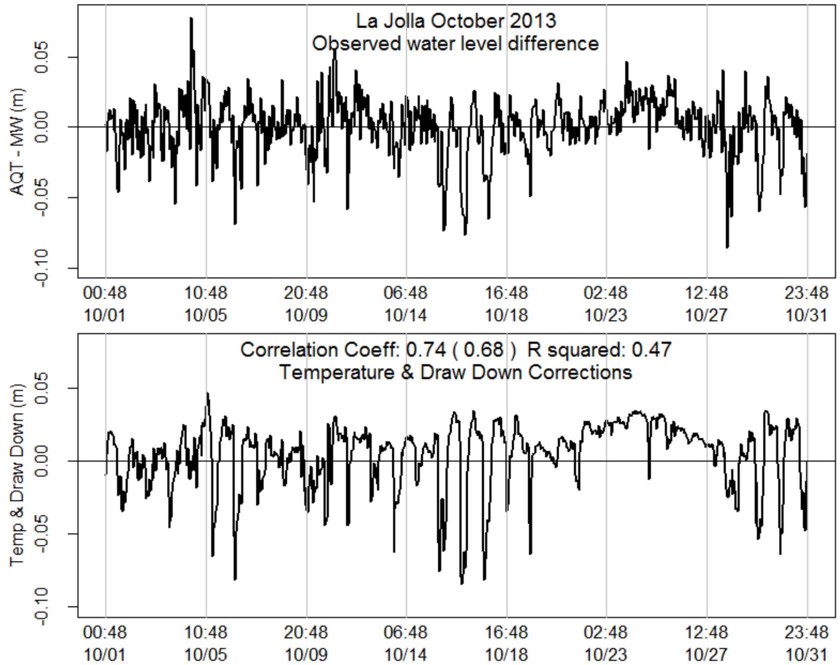

Figure 31.
Observed water level difference (top) and combined temperature and draw-down corrections (bottom) at La Jolla for October 2013.

Lake Worth, Florida

Lake Worth is an intermediate wave environment, but does experience large wave events from both Northeasters and Hurricanes. Data at Lake Worth are available from September through November 2013. Figure 32 plots PSD estimates for the acoustic and microwave sensor for September 2013. The large spectral distortion of the acoustic sensor at a period of 5 seconds is incoherent with the microwave observations, and provides compelling evidence that resonance of the protective well is contributing to the distortion.

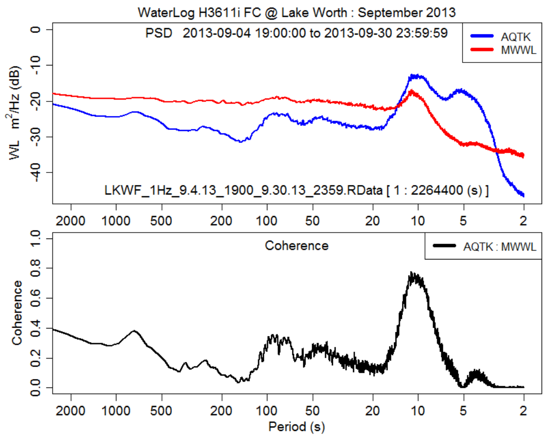

Figure 32.
PSD and coherence of acoustic and microwave water level data at Lake Worth for September 2013.

Figure 33 shows a comparison of significant wave height with microwave standard deviation in the upper panel and the sensor water level differences with acoustic temperature and wave draw-down corrections in the lower panel. Lake Worth resides in a subtropical climate and acoustic temperature corrections are not normally applied. However, Figure 33 shows that temperature errors of 2 - 4 cm are common. Waves were generally small (less than 1 m) for the month, however wave events of 1 m height did occur on the 16th and 28th with the draw-down model correctly attributing the observed draw-down. The wave event on the 19th was smaller, but still produced a noticeable draw-down. Given the extreme distortions of spectral energy at 5 seconds, it is likely that resonance of the protective well contributes to deviation from the modeled draw-down.

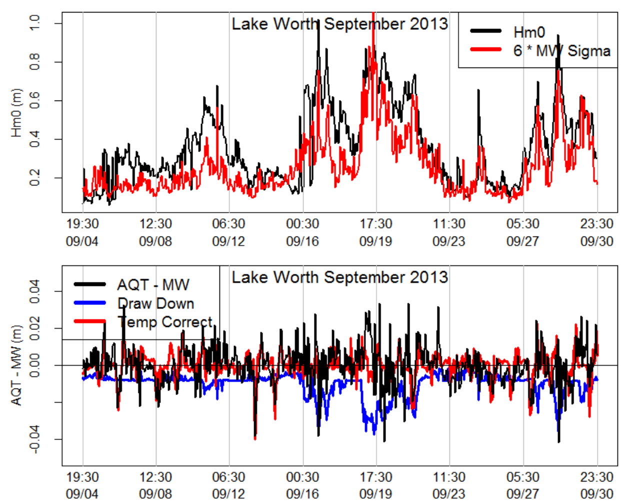

Figure 33.
Significant wave height and microwave DQAP standard deviation (top) at Lake Worth in September 2013. Water level difference (acoustic - microwave) with acoustic temperature and wave draw-down corrections (bottom).

Figure 34 presents PSD estimates for the acoustic and microwave sensor for October 2013. The extreme spectral distortion of the acoustic sensor from 4 to 8 seconds is incoherent with the microwave observations indicating that resonance of the protective well is contributing this distortion.

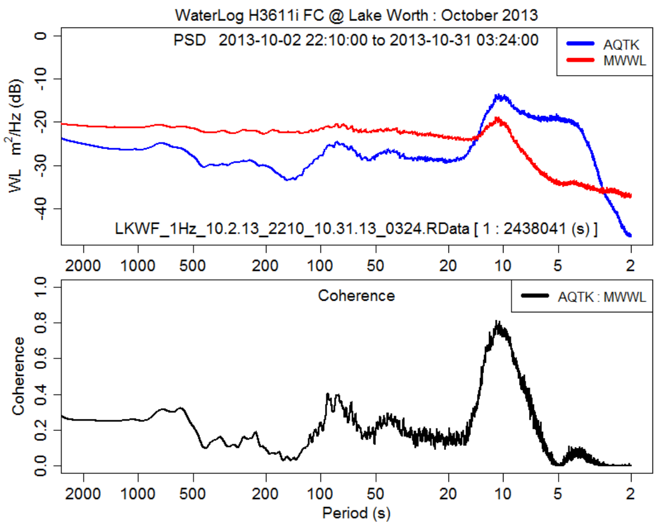

Figure 34.
PSD and coherence of acoustic and microwave water level data at Lake Worth for October 2013.

A comparison of significant wave height with microwave standard deviation, and water level differences with acoustic temperature and wave draw-down corrections for October is shown in Figure 35. Temperature errors of 2 to 4 cm are common. Waves were generally small during October, less than 0.6 m, and the draw-down model over-predicts draw-down during the three small wave events. This can be addressed with adjustment of the minimum wave threshold to the draw-down model. The wave event on the 30th is accurately captured by the draw-down model.

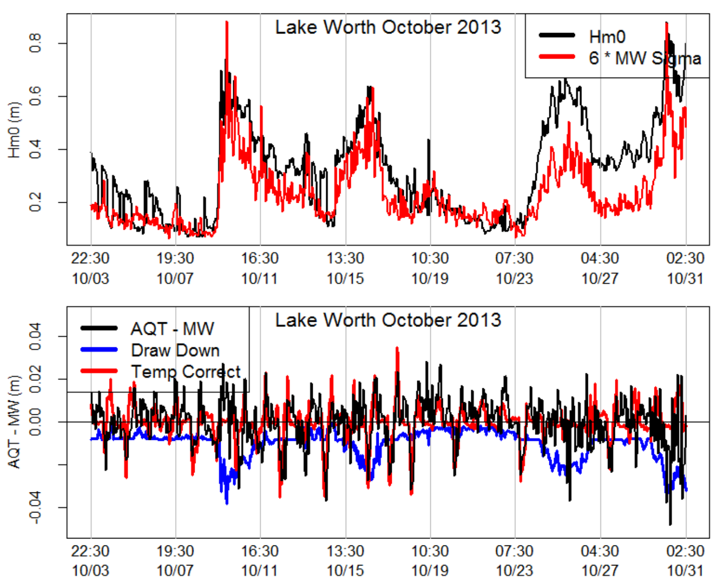

Figure 35.
Significant wave height and microwave DQAP standard deviation (top) at Lake Worth in October 2013. Water level difference (acoustic - microwave) with acoustic temperature and wave draw-down corrections (bottom).

PSD and coherence estimates for the acoustic and microwave sensor for November 2013 are shown in Figure 36. At this point, a consistent picture of spectral distortion from the protective well resonance is clear.

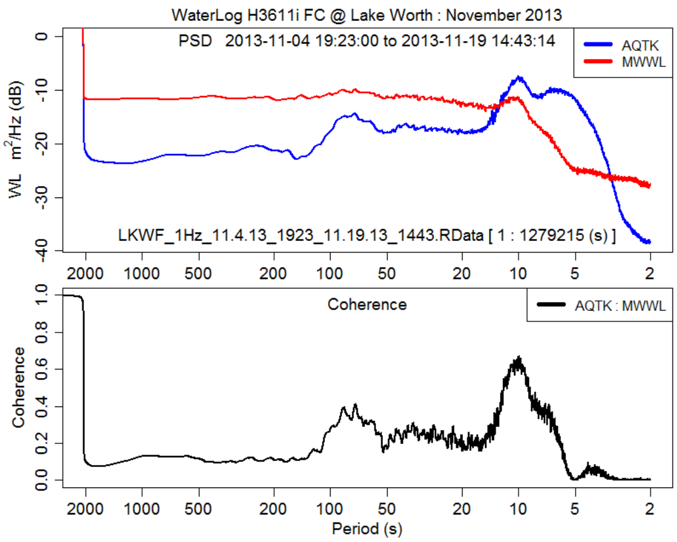

Figure 36.
PSD and coherence of acoustic and microwave water level data at Lake Worth for November 2013.

Figure 37 plots comparison of significant wave height with microwave standard deviation in the upper panel and sensor water level differences with acoustic temperature and wave draw-down corrections in the lower panel. There were three wave events in November that exceeded 1 m significant wave height, and during each wave event the draw-down model captures the observed water level differences. Oscillation of water levels from the protective well resonance is thought to account for the observed pile ups during wave events. Temperature corrections are essentially absent during the month.

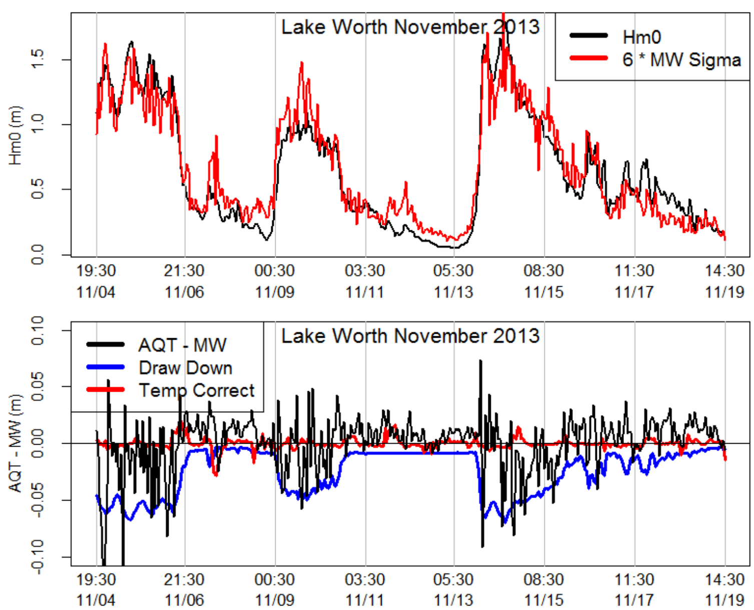

Figure 37.
Significant wave height and microwave DQAP standard deviation (top) at Lake Worth in November 2013. Water level difference (acoustic - microwave) with acoustic temperature and wave draw-down corrections (bottom).

Monterey, California

Monterey was selected as an intermediate wave environment although breaking waves at the sensor site are rare due to the semi-enclosed nature of Monterey Harbour and wharf inside the breakwater. Analysis finds that the bulk of the water level variance is due to Bay and harbor water level oscillations, with no coherence to offshore waves at Bay modes (periods longer than 15 minutes) but good correlation at periods shorter than 2 minutes. Based on analysis of data covering the period September 14 - November 29, 2013, the following conclusions are supported:

1) Water level differences suggest that temperature issues associated with the Aquatrak sound speed dependence are not a primary error source at Monterey.

2) Water level differences between the acoustic and microwave sensors exhibit a tidally-locked component 90^o out of phase with water level amplitude. Flood tide produces a negative difference (microwave level higher than acoustic level) while ebb tide presents a positive water level difference (acoustic higher than microwave). Since the acoustic sensor is closer to shore, it is suggested that this component represents the mean surface slope.

3) Wave induced draw-down in the Aquatrak is not a primary error source for wave heights less than 0.5 m.

4) There is good correlation between microwave DQAP standard deviation and significant wave height (H_{m0}) measured at the sensor. For offshore waves at the Monterey Canyon CDIP buoy there is a frequency dependent relationship between water level variance and wave height with water level oscillation periods longer than 15 minutes uncorrelated with offshore wave height.

5) Spectral analysis presents a robust and persistent set of water level resonant modes (seiche). Dominant components are seen at periods near 36, 27 and 2 minutes with amplitudes in the range of 0.45 m. The longer period modes represent bay-wide resonances, while the 2 minute mode likely represents a resonance within Monterey Harbour. Other notable resonances are found at periods of 22, 19, 16, 11, 9 and 4 minutes. This harmonic structure is consistent with measurements and models of resonance in Monterey Bay (Wilson, 1965; Breaker et al, 2010). Water level amplitudes of individual modes range from 30 to 475 cm, therefore, if several modes were to synchronize constructively water level variations well in excess of 1 m are plausible.

6) The selection of Monterey as an intermediate wave site based solely on the CDF of σ (Figure 1) was misleading since the water level variance is coupled to Bay and Harbor modes.

7) Monterey is a good site to investigate total water level issues and the impact of non-tidal and wave-forced oscillations on errors in water level and tidal predication.

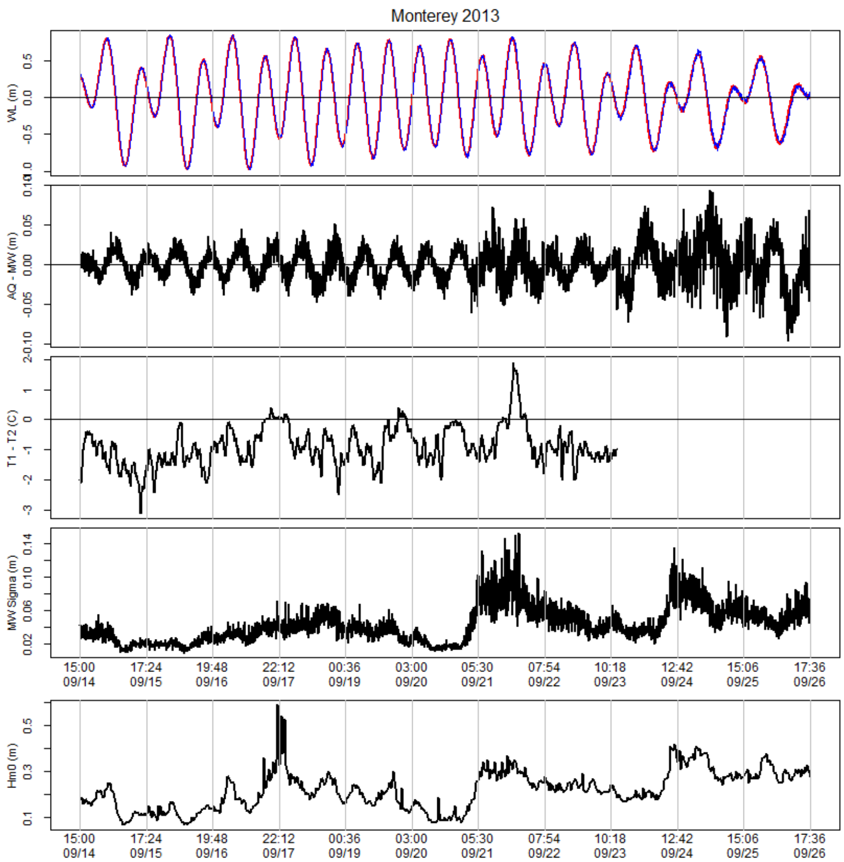

Figure 38.
Monterey data for September 14 - 26, 2013. WL is the demeaned DQAP water level, microwave data are red, acoustic data are blue. AQ - MW is the water level difference. T1 - T2 is the temperature difference of the two thermistors. MW Sigma is the DQAP standard deviation (σ) of the microwave data. Hm0 is the significant wave height.

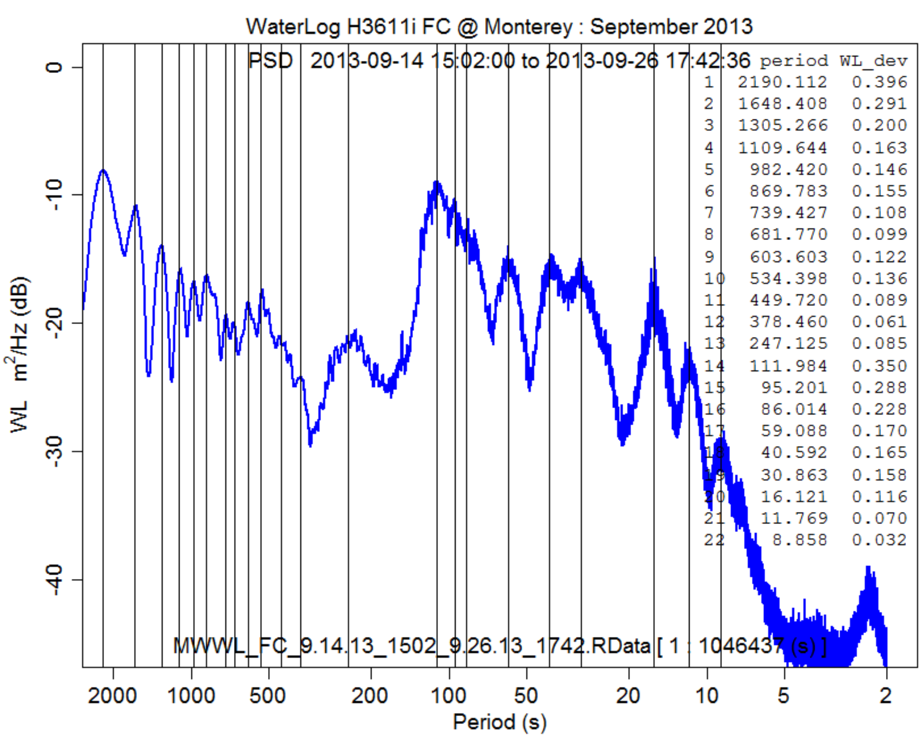

Figure 39.
PSD estimate of microwave water level at Monterey for September 14 - 26, 2013. Vertical lines mark frequencies of interest. The inset table lists the period of oscillation in seconds for each vertical line and the corresponding water level oscillation amplitude in meters.

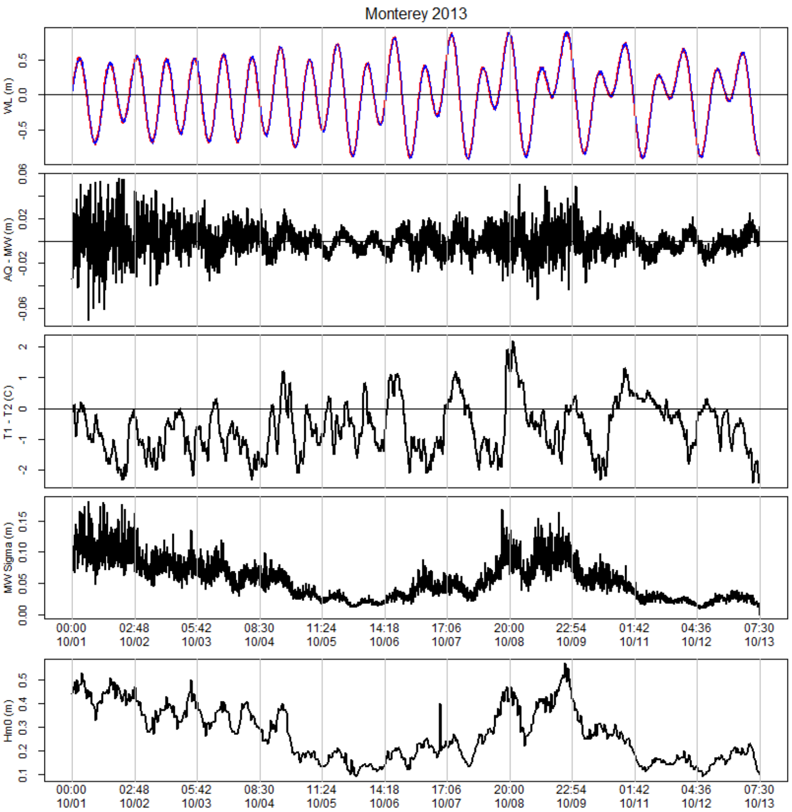

Figure 40.
Monterey data for October 1 - 13, 2013. WL is the demeaned DQAP water level, microwave data are red, acoustic data are blue. AQ - MW is the water level difference. T1 - T2 is the temperature difference of the two thermistors. MW Sigma is the DQAP standard deviation (σ) of the microwave data. H_{m0} is the significant wave height.

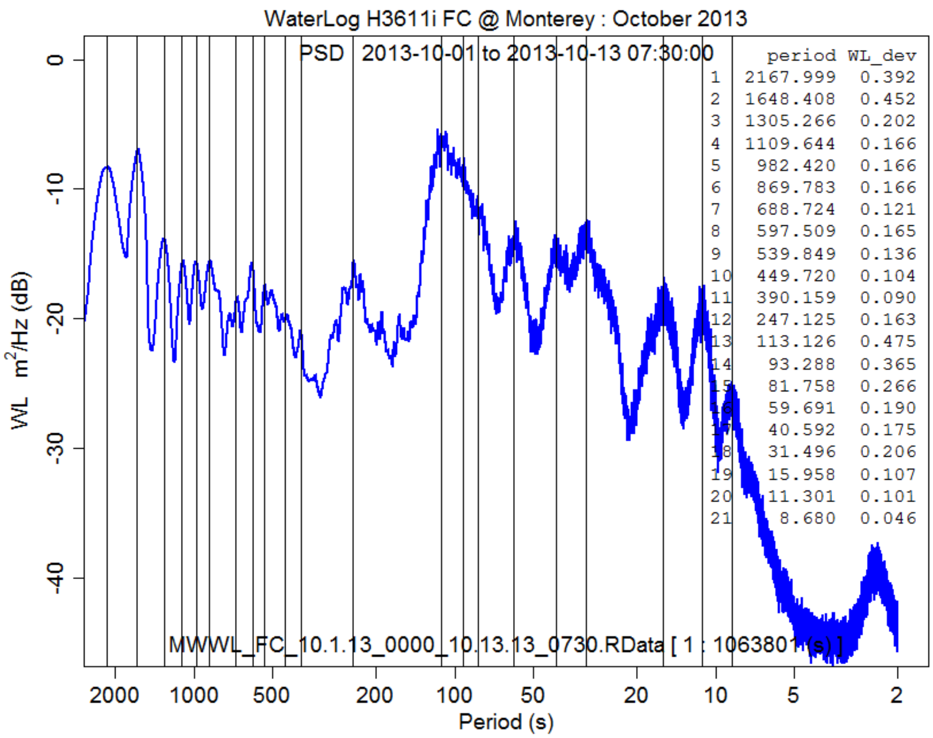

Figure 41.
PSD estimate of microwave water level at Monterey for October 1 - 13, 2013. Vertical lines mark frequencies of interest. The inset table lists the period of oscillation in seconds for each vertical line and the corresponding water level oscillation amplitude in meters.

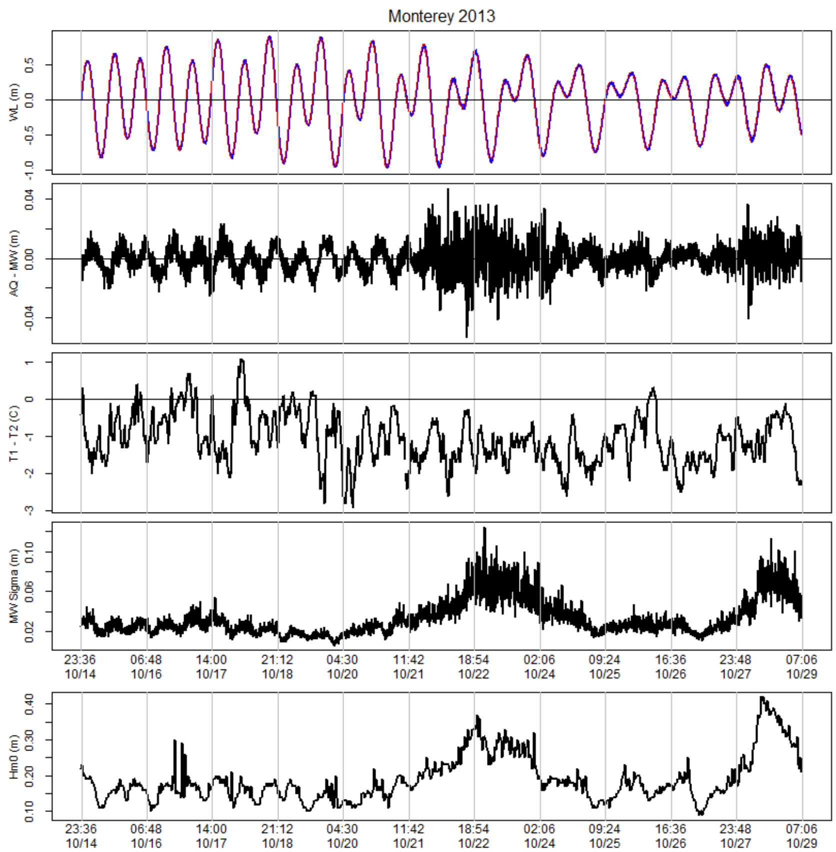

Figure 42.
Monterey data for October 14 - 29, 2013. WL is the demeaned DQAP water level, microwave data are red, acoustic data are blue. AQ - MW is the water level difference. T1 - T2 is the temperature difference of the two thermistors. MW Sigma is the DQAP standard deviation (σ) of the microwave data. H_{m0} is the significant wave height.

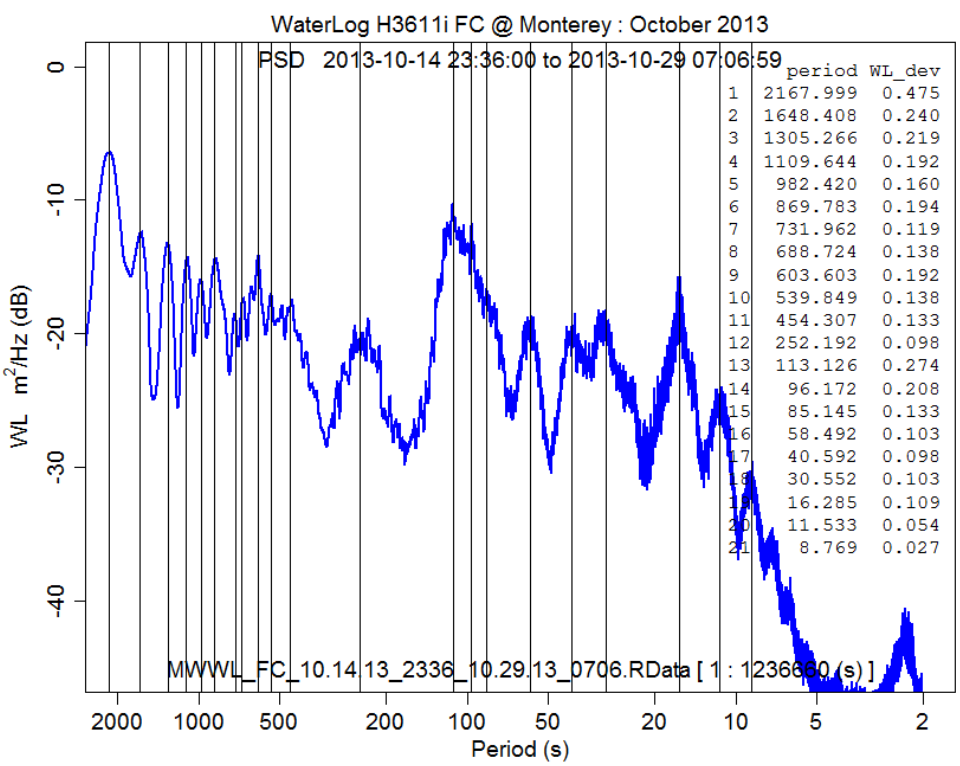

Figure 43.
PSD estimate of microwave water level at Monterey for October 14 - 29, 2013. Vertical lines mark frequencies of interest. The inset table lists the period of oscillation in seconds for each vertical line and the corresponding water level oscillation amplitude in meters.

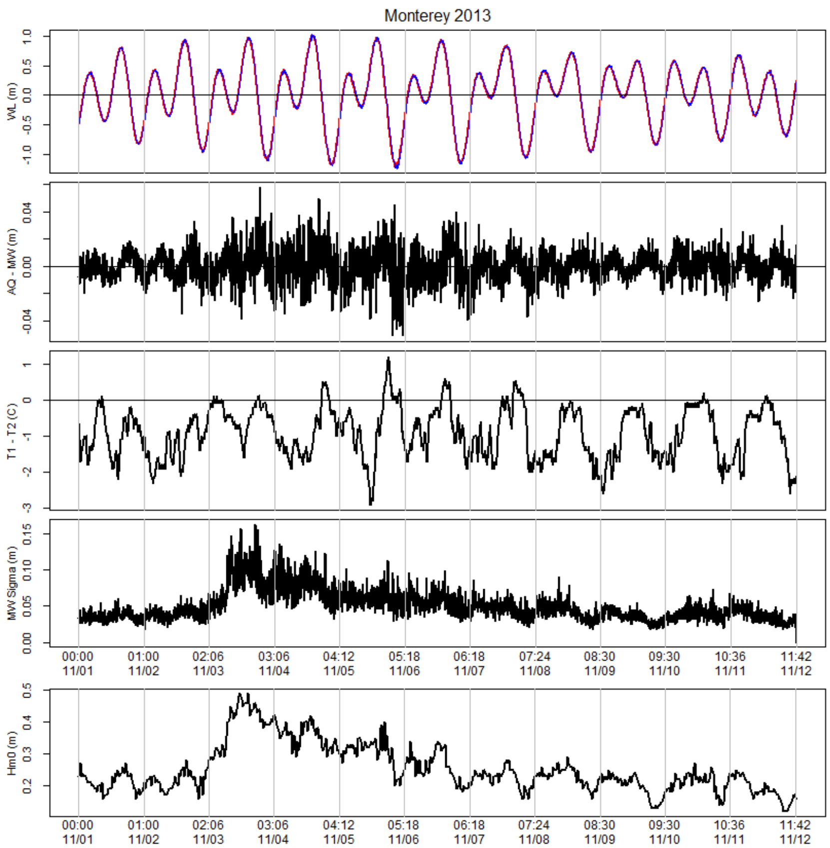

Figure 44.
Monterey data for November 1 - 12, 2013. WL is the demeaned DQAP water level, microwave data are red, acoustic data are blue. AQ - MW is the water level difference. T1 - T2 is the temperature difference of the two thermistors. MW Sigma is the DQAP standard deviation (σ) of the microwave data. H_{m0} is the significant wave height.

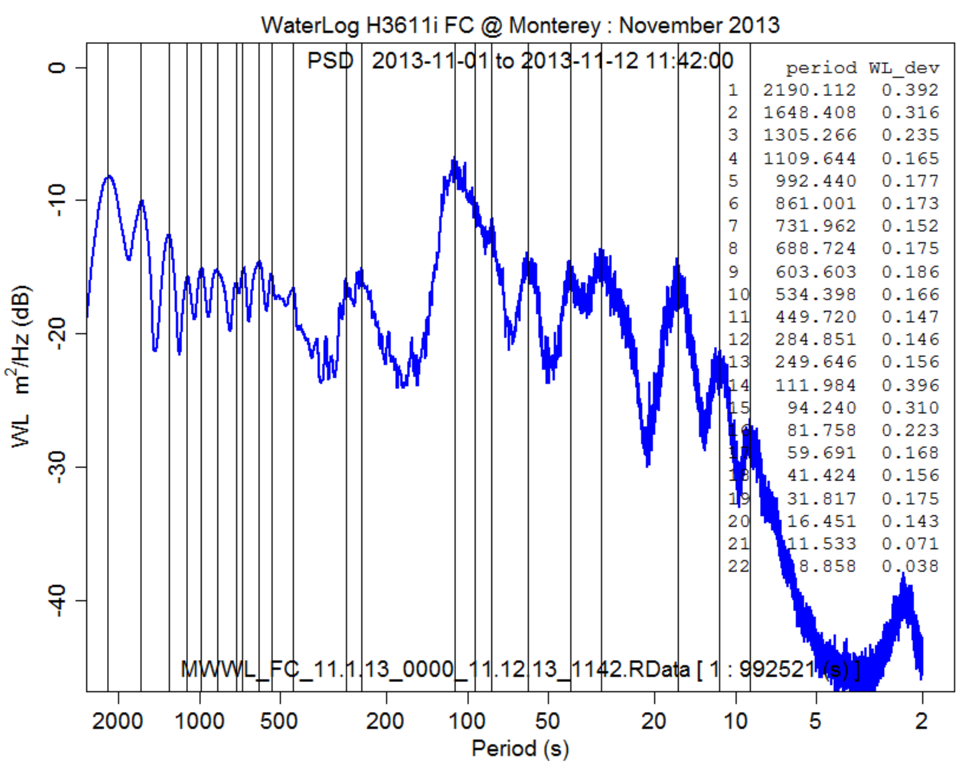

Figure 45.
PSD estimate of microwave water level at Monterey for November 1 - 12, 2013. Vertical lines mark frequencies of interest. The inset table lists the period of oscillation in seconds for each vertical line and the corresponding water level oscillation amplitude in meters.

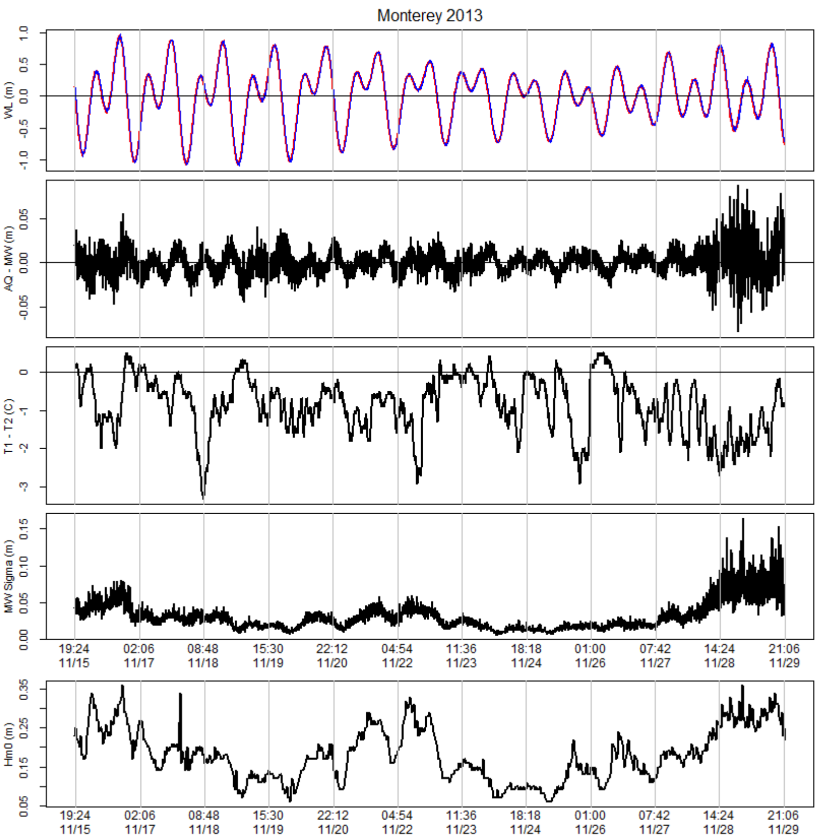

Figure 46.
Monterey data for November 15 - 29, 2013. WL is the demeaned DQAP water level, microwave data are red, acoustic data are blue. AQ - MW is the water level difference. T1 - T2 is the temperature difference of the two thermistors. MW Sigma is the DQAP standard deviation (σ) of the microwave data. H_{m0} is the significant wave height.

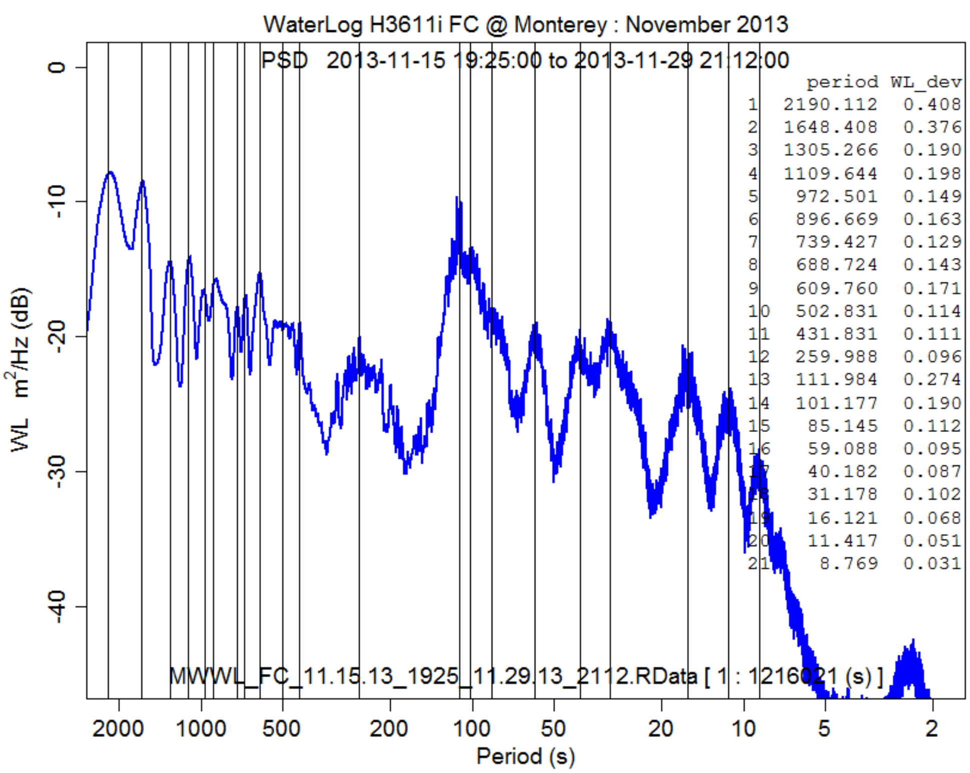

Figure 47.
PSD estimate of microwave water level at Monterey for November 15 - 29, 2013. Vertical lines mark frequencies of interest. The inset table lists the period of oscillation in seconds for each vertical line and the corresponding water level oscillation amplitude in meters.

ACRONYMS AND SYMBOLS

AWAC	Acoustic Waves and Current
CDIP	Coastal Data Information Program
CO-OPS	Center for Operational Oceanographic Products and Services
CDF	Cumulative Distribution Function
dB	Decibel
DQAP	Data Quality and Assurance Procedure
ε	Root Mean Square Residual
FRF	U.S. Army Corps of Engineers Field Research Facility
GLOSS	Global Sea Level Observing System
$H_{1/3}$	Significant Wave Height
H_{m0}	Significant Wave Height
IOOS	Integrated Ocean Observing System
MWWL	Microwave Water Level
NOAA	National Oceanic and Atmospheric Administration
NWLON	National Water Level Observation Network
NWLP	National Water Level Program
PDF	Probability Density Function
PSD	Power Spectral Density
σ	Sample Standard Deviation
TOPEX	Ocean Topography Experiment
WL	Water Level