Waves and Seiches in Flathead Lake, Montana: Measurements of a Quiet Lake by Differential Travel-Time Current Measurements

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Abstract

Measurements of velocity and pressure at the south end of Flathead Lake, Montana, reveal lake level fluctuations due to wind set up and seiches. Short period wind wave events, typically of single day duration, were recorded several times during the study period in the fall of 2004. The wind waves are fetch limited, in most cases with periods below 3 second but with significant wave heights that can exceed 50 cm during episodic storm events. Pronounced diurnal and longer period changes due to river influx and controlled drawdown through a hydroelectric dam across the exit river are clearly evident in the record. Broad scale upward fluctuations in lake level due to lake level regulation and seiches have exposed fragile portions of the shore to wind waves that have caused extensive lake wide erosion.

The background motion of the lake is typically less than 2 cm/s, the waves are often relatively small with short periods, and the water is clear, making this a difficult environment for current and wave measurement. MAVS (Modular Acoustic Velocity Sensor) acoustic differential travel-time measurements detected and recorded these small signals cleanly and well above the instrument noise level.

I. Introduction

Monitoring Flathead Lake is a demanding example of current meter use where the water is very clear, the velocities may be very small, and the sensitivity of the shoreline of the lake to erosion is significant. The large environmental and economic impact of shoreline damage and loss puts a premium on precise, accurate measurements across a broad range of time scales.

Lake levels vary under the influence of wind, seiches, river influx, and lake level regulation by Kerr Dam, located six kilometers downstream of the natural lake outlet (Figure 1). Some of the variations are seasonal while others have diurnal or hourly periods. These fluctuations locally redistribute wave energy across the shoreline, exposing more fragile regions to erosion and vegetation loss by wind waves [1]. Bank erosion due to the vertical displacement of wave energy has reconfigured the near-shore zone lake wide, causing variable shoreline retreat ranging from tens of meters to over a kilometer [2, 3].

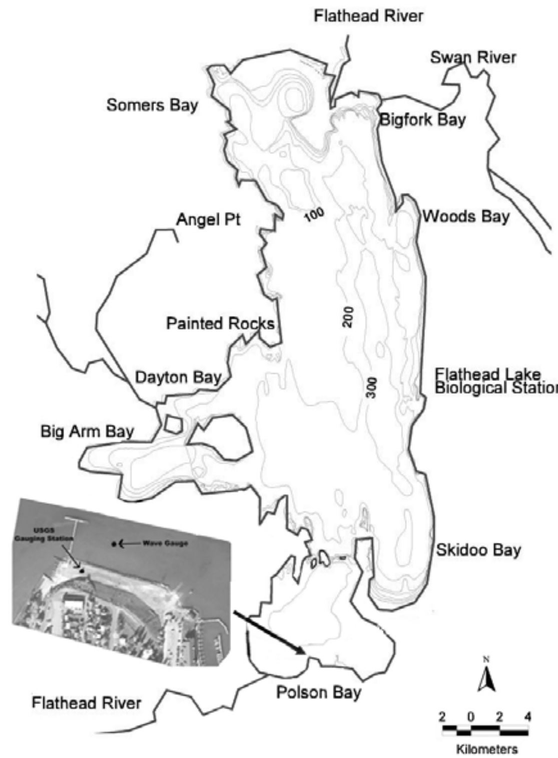

FIGURE 1 - Flathead Lake, Montana, is 50 km long and 12 to 20 km wide. Mountains to the east and west topographically funnel winds along the long axis of the lake. The study site was in Polson Bay at the south end of the lake. The depth contours are feet.

Large differences in shoreline loss result from small changes, 30 cm or less, in lake level [1]. Kerr Dam operations attempt to hold the lake level at an elevation of 881.78 m, without exceeding that limit during the summer months. However, comparison between the USGS gauging station at the south end of the lake (No. 12371550, Flathead Lake at Polson, MT) and the MAVS, which was deployed approximately 100 m from the gauging station (Figure 1), clearly shows that the response of the USGS gauge is too slow to capture hourly or even daily changes in lake level (Figure 2). Managing lake levels and understanding the physical processes causing lake level fluctuations and the

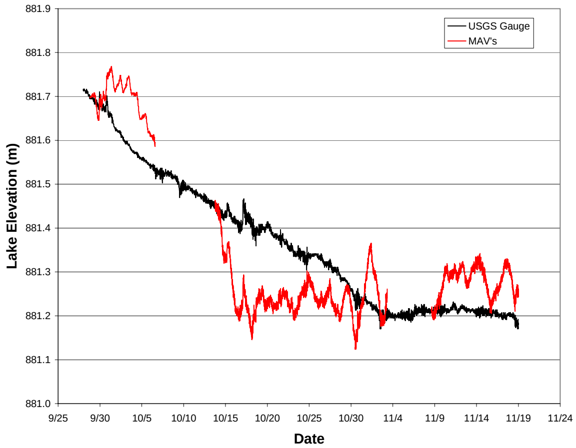

FIGURE 2 – Lake Level Time-Series. The USGS lake level record from the Polson gauging station (No. 12371550, Flathead Lake at Polson, MT) is shown in black and the MAVS pressure record, which tracks lake level, is shown in red. Both traces cover the period of the three deployments, September 28 to November 19, 2004. Both instruments track the downward trend over the duration of the study, but the response time of the gauging station is clearly too slow to record hourly or even diurnal signals. A time constant of several days to a week is indicated.

resulting erosion of the shoreline requires measurements that accurately and precisely record velocity and pressure across a range of time scales from days to seconds.

II. Field Location and Instrumentation

Flathead Lake is located in northwestern Montana. It is approximately 50 km long and 12 to 20 km wide. The average depth is 20 m, with a 100 m to 120 m trench along the eastern side of the lake and shallower water to the west. Polson Bay, the study site at the south end of the lake, is shallow, averaging 5 m to 10 m, and is isolated from the rest of the lake by a string of islands. The flat and dissipative near-shore terrain at the north end of the lake is susceptible to small changes in lake level [2]. Mountain ranges to the east and west topographically funnel the wind along the long axis of the lake [2]. Some of these features are shown in Figure 1.

The period of a seiche excited by wind set up along the long axis of the lake can be estimated from

$$T = 2L\big/\sqrt{gh}$$

T is the seiche period, L is the length of the lake, g is the acceleration due to gravity, and h is the average depth [4]. In practice, the period will depend on the bathymetry, the shape of the shoreline, and other

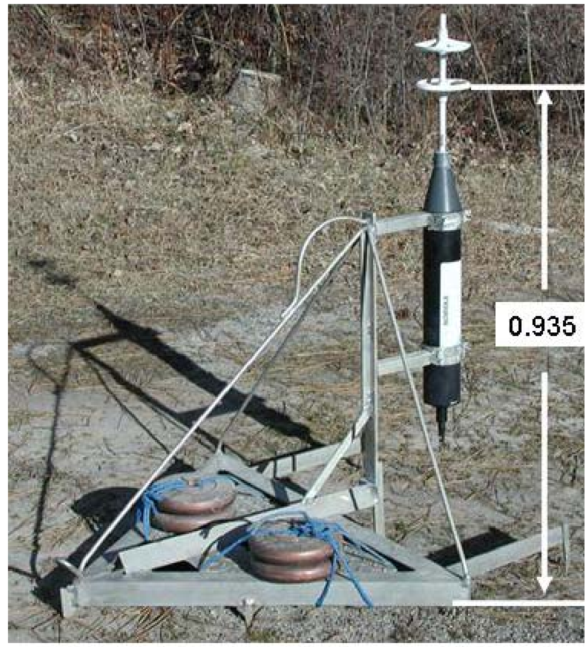

FIGURE 3 – MAVS on the Flathead Lake Bottom Frame. The height of the MAVS velocity sensor is 0.94 m above the bottom. The pressure sensor in the conical end cap is 0.68 m above the bottom. The frame was deployed in 3.5 m depth on a flat bottom in Polson Bay.

factors. For a 50 km lake with an average depth of 20 m the seiche will have a period of approximately 2 hours. Similarly, the cross-lake seiche will have a period of approximately 30 minutes. The expected seiche period in Polson Bay is also approximately 30 minutes. Depending on the direction of the wind, additional oscillation frequencies may be present in the lake and in the bay.

During the fall of 2004, we deployed an acoustic current meter, MAVS, near the south end of Polson Bay at a depth of 3.5 m. The sensor was mounted on a light bottom frame (Figure 3) and recorded velocity, pressure, and temperature during three deployments: September 28 to October 6, October 13 to November 8, and November 8 to November 19. During the first deployment measurements were made continuously at 2 Hz. During the second and third deployments data were acquired in 128 second bursts of 4 Hz measurements every 10 minutes.

The pressure sensor has a range of 20 dbar with a resolution of 5 millibar. This is a depth resolution of approximately 5 mm. Importantly, the pressure sensor measures absolute rather than gauge pressure; the reference pressure is a sealed vacuum and is not dependent on the internal temperature of the pressure housing. The measurements are sensitive to both atmospheric pressure and lake level changes. Diurnal fluctuations in atmospheric pressure are common, but at

FIGURE 4 – MWAVES time-series showing the statistical evolution of the wave field in Polson Bay during the first deployment, September 28 to October 6, 2004. Wave action at the south end of the bay was negligible except for a 36 hour period beginning late in the evening of September 29. Significant wave height, $H_{1/3}$, peaked at 30 cm during the evening of September 30. Note the rapid spin-up from calm conditions. Wind speeds recorded at the Flathead Lake Biological Station, on the east side of the lake and 25 km north of the study site, reached 20 m/s, about 40 kts, during the afternoon of September 30. Wave periods when waves were present remained between two and three seconds throughout the deployment with the direction of propagation varying from the north-northwest to the south-southwest (0° indicates eastward propagation and 90° indicates northward propagation in the plot). Note that the wave period and direction of propagation have little physical meaning during periods of near-zero significant wave height.

the latitude and elevation of Flathead Lake would typically be an order of magnitude less than the observed changes in pressure. Consequently, we attribute the observed diurnal pressure fluctuations largely to changes in the level of the lake.

MAVS is an acoustic differential travel-time current meter with accuracy of 0.1 cm/s and an electronic noise floor of 0.05 cm/s [5-9]. Because the sensor uses forward transmission of sound along a 10 cm path between transducers, it does not require scatterers in the water to function and works without difficulty in very clear water. Short acoustic pulses, 15 cycles at 1.8 MHz, are transmitted from both ends of the path simultaneously and the difference in the arrival times of the fourteenth negative-going zero crossings detected in the receivers is resolved to an accuracy of 40 picoseconds. The velocity measurement is thus independent of the amplitude of the received signal and this makes the technique insensitive to both turbidity and bubbles. These characteristics strongly recommend this technique for such environments as a lake where the water is generally very clear but can become roiled with sediment and bubbles during wind wave events.

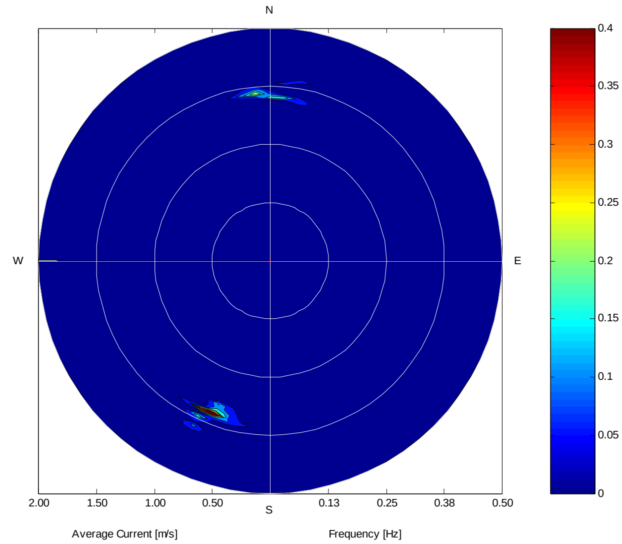

FIGURE 5 – MWAVES directional wave spectrum for 20:00 on September 30, 2004. This was the time of greatest significant wave height during the first deployment. The plot indicates that 2.8 second waves were propagating to the south-southwest, reflecting off the wall at the south end of the lake, and propagating back to the north.

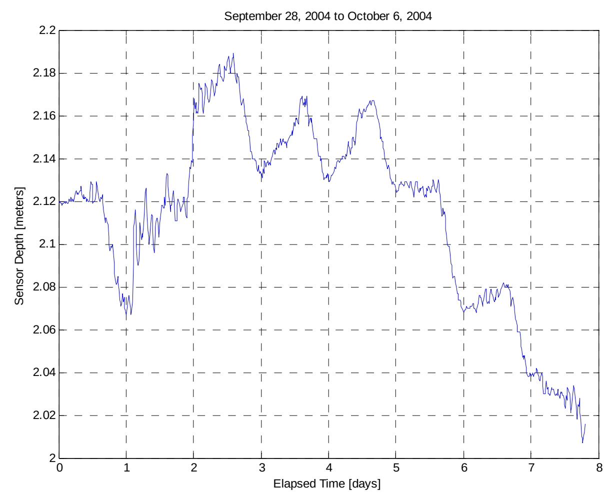

FIGURE 6 – Pressure Time-Series. The MAVS pressure record for the first deployment, which began on September 28 at 19:30, is shown in blue. Note the persistent diurnal signal, with minima in the evening and peaks in the morning. The 2 hour seiche is episodic and most clearly apparent between 2 and 2.5 elapsed days. Trends of longer duration are also present.

Directional wave spectra can be calculated from the velocity and pressure measurements using MWAVES [10]. The software provides full spectral information for each burst as well as a time-series of significant wave height, wave period, and propagation direction, charting the statistical evolution of the wave field over the course of the deployment. Figure 4 shows the statistical time-series for the first of the three deployments. Figure 5 is a directional wave spectrum showing surface wind waves propagating to the south

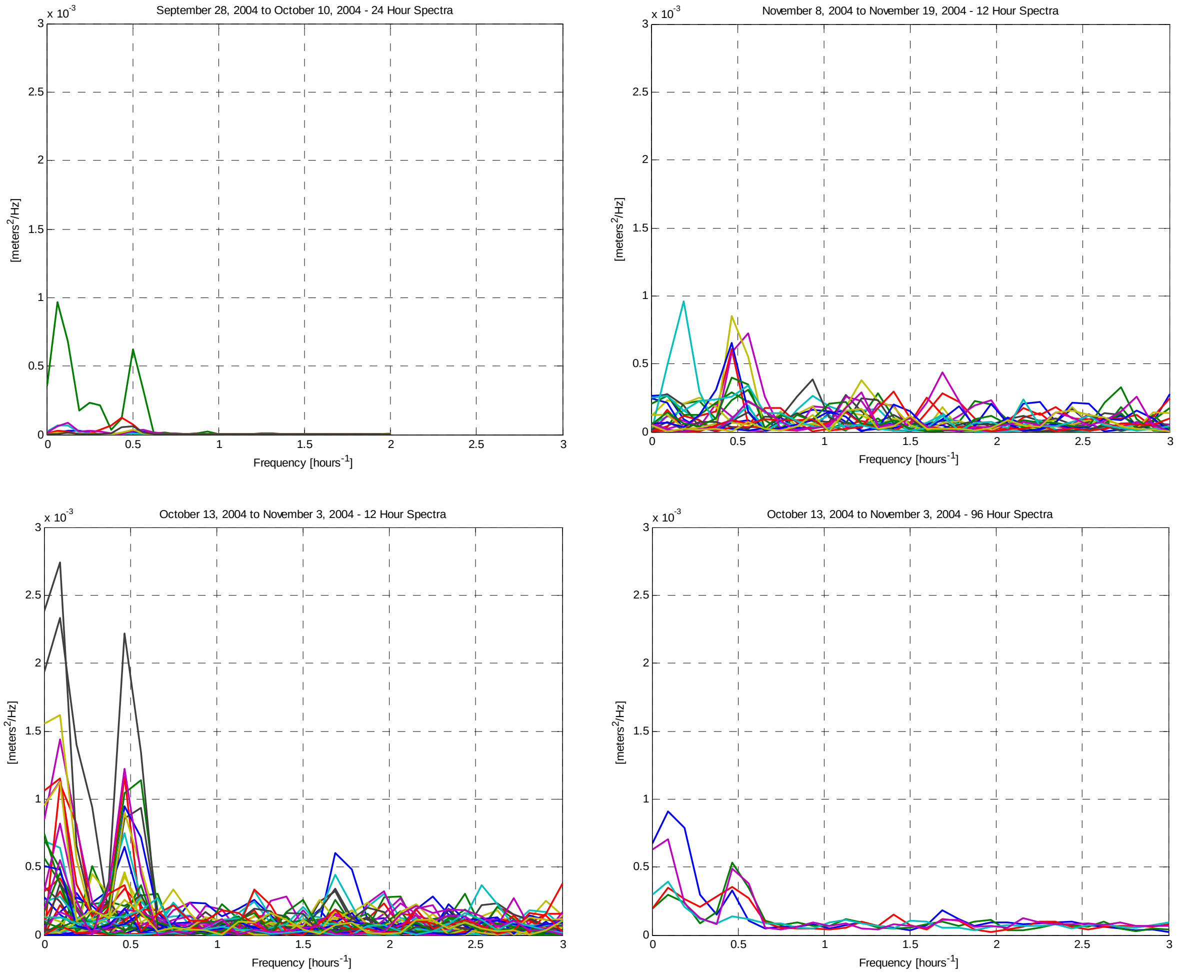

FIGURE 7 – Pressure Spectra. The spectra were calculated for sequential portions of the pressure time-series for each of the three deployments. Because of different deployment durations and sampling schedules, spectra were calculated from 24 hour time-series for the first deployment (upper left panel) and 12 hour time-series for the second and third deployments (lower left and upper right). Note the persistent 2 hour seiche (0.5 hr^{-1}). An intermittent 35 minute signal (1.7 hr^{-1}) is present during the second and third deployments. There is also a persistent peak at 0.1 hr^{-1} (10 hours, the lowest frequency resolved) where we would expect the diurnal signal, but this is a questionable region for 12 and 24 hour time-series. To verify the presence of the signal, pressure spectra for the long duration second deployment were re-calculated from 96 hour time series (lower right panel). The diurnal signal is still present in the lowest frequency bins.

southwest, reflecting from the wall at the south end of the lake, and propagating back to the north.

IV. Seiche

The first deployment MAVS pressure record in Figure 6 shows fluctuations on hourly, daily, and longer time scales. We have interpreted these fluctuations to be changes in lake level. The pattern of diurnal fluctuations, with minima in the evening and peaks in the morning, is suggestive of controlled flow variations through Kerr Dam that are intended to increase power generation during peak hours.

A spectral analysis of the pressure time-series is shown in Figure 7. Spectra were calculated for sequential portions of the pressure time-series for each of the three deployments. Several features are persistent over time with spectral variability evident. The signals are not strong, but they are detected well above the noise level of the MAVS.

The expected seiche for the long axis of the lake is strongly and persistently detected above the spectral background noise during each of the three deployments. This is the variable strength 0.5 hr^{-1} (2 hours) signal. The seiche peaks above 2×10^{-3} m^2/Hz during the second deployment, but is more typically present at strengths near or below 1×10^{-3} m^2/Hz. What may be a cross-lake or Polson Bay seiche, the period is approximately 35 minutes, is irregularly present during the second and third deployments. Its peak strength is 0.5×10^{-3} m^2/Hz.

A longer period signal, which we interpret to be the diurnal fluctuations in lake level apparent in the time series, is also strongly and persistently detected in all three deployments. We note that the first frequency bin above zero is centered on 0.09 hr^{-1} (~10 hours),

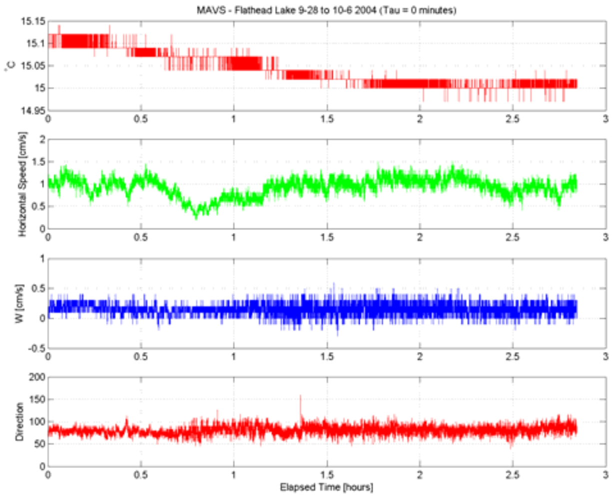

FIGURE 8 – Three hour time-series of unfiltered MAVS measurements. Measurements were made continuously at 2 Hz during the first deployment. Each individual measurement is shown. The 0.1 cm/s digitization of velocity is clearly visible in the vertical velocity trace (blue). The average vertical velocity of 0.2 cm/s is an uncorrected zero point offset. The horizontal speed (green) is the square root of the sum of the squares of the east and north components. Velocity varies from a minimum of 0.3 cm/s to a maximum of 1.5 cm/s. Small fluctuations in the signal are cleanly resolved throughout. Temperature during this period drops from 15.1 °C to 15.0 °C.

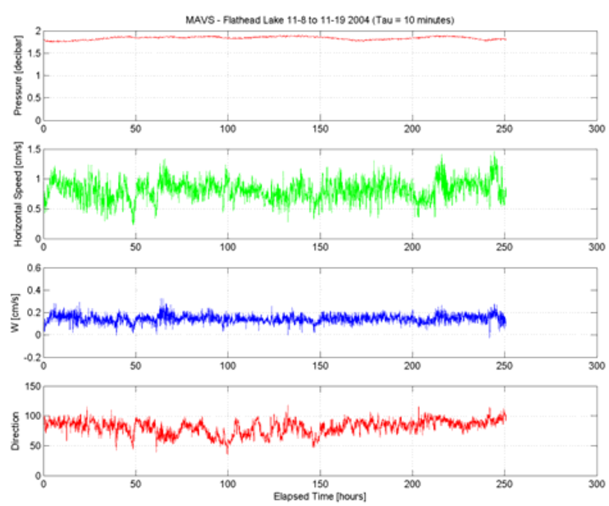

FIGURE 9 – MAVS data for the third deployment after smoothing with a 10 minute Butterworth filter. The filtered data show low frequency variations in pressure of about 0.1 dbar, a depth change of ~10 cm. No average velocities greater than 1 cm/s were observed.

preventing detailed resolution of this part of the spectra. However, the calculations using the 96 hour time-series demonstrate the presence of a significant pressure signal at and below this frequency.

V. Detailed Time-Series

Unfiltered measurements provide a window through which to study the capabilities and behavior of an instrument. A three hour time-series of unprocessed, 2 Hz, MAVS measurements is plotted in Figure 8. The data were acquired during the first deployment and show a very low instrument noise level. The noise is only visible because the signal levels were also very low during this period. The velocity signal in the lake at this time is comparable in magnitude to the thermal currents we have measured in buckets with MAVS.

The very low inherent noise of MAVS, combined with the absence of any threshold or dead band, permits accurate and detailed measurements in a quiet lake where the currents can be slower than 1 cm/s and the vertical wave velocities less than 0.3 cm/s. Upon this background and with this instrument, low amplitude seiches and small wind waves can be reliably detected and observed by filtering the data to reduce digitization granularity (Figure 9).

VI. Wind Wave Events

There were several short wind events during the third deployment. A portion of one of these is shown in Figure 9. Wave velocities on November 10, recorded at a depth of less than 2 m, are quite modest by ocean standards, yet this represents the strongest event during the period from November 8 to November 19, with significant wave heights reaching 6 to 8 cm. This event would have been undetectable by less sensitive current sensors.

A much larger and more sudden storm event was observed during the second deployment. Significant wave heights exceeded 0.5 m on October 17, 2004 at 03:50. Polson Bay was flat calm only 90 minutes earlier (Figure 10). Wave events of this magnitude are not uncommon and, when combined with lake level fluctuations, can cause severe erosion with a significant and rapid loss of shoreline.

VII. Conclusion

Wind set up, dam operations, and seiche oscillations in lakes can play a significant role in shoreline erosion by exposing fragile and otherwise protected backshore environments to the action of wind waves. These processes occur across a range of time scales that spans five orders of magnitude.

The detection and documentation of these physical processes requires sensitive, low noise current and pressure sensors that can be deployed for extended durations at relatively high sampling rates. MAVS is demonstrably capable of detecting and logging the

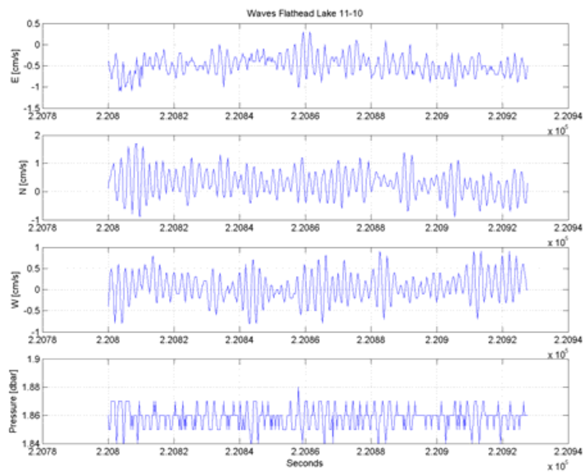

FIGURE 10 – Two minute record, one burst, from the wind wave event of November 10, 2004. The event lasted for 10 hours beginning at elapsed hour 65 in Figure 9. Unfiltered velocity measurements show a north-south component of wave velocity with a 1 cm/s amplitude and a 2.17 second period. While the significant wave height, $H_{1/3}$, briefly reached 8 cm during this event, it was probably no greater than 2 to 4 cm when this burst was recorded.

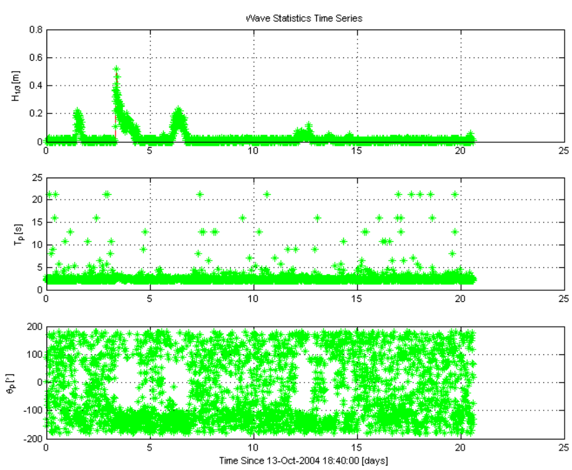

FIGURE 11 – MWAVES time-series showing the statistical evolution of the wave field in Polson Bay during the second deployment, October 13 to November 8, 2004. Significant wave height exceeded 0.5 meters at 03:50 on October 17, 2004. The spin-up time from flat calm conditions to this peak was only 90 minutes. The relaxation time was over a day. Such strong, sudden onset events are not uncommon.

velocities and pressure fluctuations of these lake processes. Continued study of Flathead Lake, Montana, using a mobile array of independent MAVS systems is currently planned. Seiche amplitudes exceeding those recorded in Polson Bay are expected in less isolated portions of the lake. Accurate lake wide measurement of lake level changes in near real-time is essential to maintaining operational lake levels at or below federally mandated maximum elevations.

Acknowledgments

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