Ice Measurements in Cook Inlet, Alaska with an Acoustic Doppler Profiler

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ABSTRACT

Ice conditions were measured in Lower Cook Inlet, Alaska using Acoustic Doppler Profilers with an innovative data analysis method. PND Engineers, Inc., deployed three bottom-mounted upward-looking Nortek Acoustic Wave and Current (AWAC) profilers near Iniskin Bay. The instruments were configured to collect current profiles and wave data alternating with experimental “diagnostic” water-ice interface profiles. Analyzing these measurements together with the surface current velocity time series and assumed ice block shape allows estimation of the ice block size, mass, and velocity. Descriptions of the instrumentation and data processing are presented in this paper. This mission was the first application of this recently developed technique for ice measurements in Cook Inlet’s harsh environment.

KEY WORDS: Ice thickness; waves, currents; ADCP; Cook Inlet

INTRODUCTION

Sea ice strength and thickness of are important factors affecting engineering of coastal and offshore structures. Ice kinematics are also important (but less understood), partly due to the lack of data about the speed and movement of ice blocks and sheets under the influence of wind, waves, and currents. Ice thickness data is also important for safe vessels navigation, downtime at docks, and mooring design.

To measure the ice draft thickness, current speed and direction, as well as wave height and direction in vicinity of the proposed Pebble Project marine facilities in Cook Inlet, Alaska, PND Engineers, Inc., deployed three bottom-mounted oceanographic instruments. The instruments are upward-looking Nortek Acoustic Wave and Current (AWAC) profilers with Acoustical Surface Tracking (AST). The AWAC AST measures the distance to the ice bottom edge and the pressure from which mean sea level can be determined. By determining the difference between these measurements, the ice keel draft can be calculated. The ice block size is calculated using the current speed data combined with the time series of the distances to the bottom of the ice.

The instruments were originally deployed at three sites on the seafloor in the Lower Cook Inlet at the mouth of Iniskin and Iliamna bays (Figure 1 and Figure 2) at depth ranges from 14 to 24 meters (MLLW) on November 2010. They were then recovered and redeployed for a second period in January 2011 and retrieved in April 2011.

PROJECT SITE LOCATION CHARACTERISTICS

Cook Inlet is an estuary with high tide ranges, approximately 4 meters near the entrance and over 12 meters further north near Anchorage. Inskin and Iliamna bays are shallow estuaries on the west side of Lower Cook Inlet. Inskin Bay is deeper along its western shoreline with a maximum depth of 24 meters (MLLW). The inner portion of Inskin Bay is dominated by mudflats. Iliamna Bay is shallower than Inskin Bay with a maximum depth 13 meters at the mouth of the bay. Mudflats at the upper portion of Iliamna Bay are exposed at low tides.
Cook Inlet, because of its unique environment, is “an ice-making machine” (Nelson, 1998). The proposed project site is located in an area that has moderate snow fall, extended periods with air temperatures less than -18°C, a freezing index of 1900 C days per year, and high tides. Maximum thickness of the pack ice varies from less than two feet to six feet. Large volumes of shore fast ice can form during the cold months. Isolated beach ice with thickness greater than 40 feet were observed grounded in Upper Cook Inlet and East Foreland in the past (Hutcheon 1970). Relatively thick beach ice is the last to melt in Cook Inlet in spring. Most ice is melted by the end of April.

INSTRUMENTATION

The data was collected with Nortek’s bottom-mounted AWAC. One 600 KHz and two 1 MHz instruments were used for deployment. Each Nortek AWAC has four acoustic transducers—one vertical and three slanted at 25 degrees. The AWAC is also equipped with a temperature sensor for sound speed corrections, and a pressure sensor.

The upward-looking AWAC is mounted on a gimbaled tripod approximately 0.6 meters above the seafloor. Pop-up buoy systems were used for retrieval. Tilt sensor pingers were attached to the deployment tripods to monitor the AWAC tripod angle after deployment on the sea floor. Figure 3 shows the tripod configuration used for this project. The system is battery powered and remotely located, without a cable connected to shore.

Figure 3. AWAC Bottom-Mounted Tripod Configuration

Acoustic Doppler profilers work by transmitting sound along beams and then listening to the echoes returned by sound scattering particles in the water. By measuring the Doppler shift and time travel of the echoes, the instrument can calculate velocities in the water column. To calculate wave parameters, the wave orbital velocities below the surface are measured along with water elevations measured by a pressure gage and an upward-looking sound transducer.

The AWAC pressure sensors record a value of absolute pressure. To determine the water surface elevation above the bottom, the measured water pressure is adjusted to account for atmospheric pressure fluctuations. A time series record of barometric pressure is required to make these corrections. The barometric pressure data logger made by Onset Computer Corporation was installed at the site to collect atmospheric pressure during the AWAC deployments.

The AWAC AST was configured to profile current velocities in 1-meter depth cells every 30 minutes with a two-minute averaging window. Each instrument was configured to collect waves in bursts of 1024 wave samples at 1 Hz for 17 minutes every hour. To collect ice information AWAC systems were configured to collect specific “diagnostic” data in bursts of 512 echo profile samples at 1 Hz rate (8.5 minutes) every 60 minutes with 2.4 cm vertical resolution. The wave and diagnostic bursts alternate on 30-minute interval.

The Nortek Internal Processor (NIP) was activated on all three instruments for the purpose of increasing internal logging memory and to collect diagnostic mode data used for ice analysis. The NIP is a self-contained, single-board processing unit installed within the AWAC unit.

The AWAC internal compass is sensitive to all magnetic fields and it is very important to check and calibrate the AWAC internal compass sensor in close proximity to the deployment site and with all instruments attached to the deployment frame. The calibration procedures consist of rotating of the deployment tripod 360° around the z-axis of the AWAC. All instruments’ compasses were successfully calibrated with an error margin of less than 1.5°.

Water density and sound speed in sea water were calculated using measured temperature and salinity. The AWAC instrument records water temperature data during each burst with a built-in temperature sensor. Surface water salinity measurements were taken during each deployment visit with handheld conductivity probes made by YSI Incorporated. Based on these measurements the average salinity was 30 parts per thousand (ppt), with a range of 28 ppt to 31 ppt. It was assumed that there was no stratification in the water column and that the salinity did not change significantly throughout whole deployment period. This is obviously incorrect due to some inflow of fresh water from the land; however, it was not practical to measure salinity in the water column at every burst throughout whole deployment period.

DATA ANALYSIS

Throughout the entire deployment period each AWAC collected more than 730,000 ice, current, and wave profiles, samples, with sampling once a second. A total of 5.5 GB of data was collected. All collected data was converted and processed using proprietary Nortek software, including the AWAC-AST, QuickWave, and STORM programs.

Ice Measurement Method

The AWAC AST measures the height of the water-ice interface using data from the single vertical beam and the pressure time series. The ice keel draft estimation process involves differencing these measurements. The method used includes the assumption that the floating ice is in isostatic equilibrium with the water and that the ice freeboard is no more than 10% greater than the ice keel ice. The mass of each measured ice block can also be calculated using the surface currents recorded by the AWAC and the passing time of the ice block. However, this is also done with the vast assumption that the ice block movement is not affected by the wind and that the ice block shape is close to square.

The Nortek’s pioneer ice processing beta version software uses “leading edge” techniques for the water-ice detection. The leading edge detection method, as stated by Nortek, is a more effective technique to detect water-ice interface compared to “maximum peak” detection in locating water-air interface.
The calculated sea level was corrected for atmospheric pressure using the barometric pressure gage data installed near the deployment sites.

**Instrument Limitations and Analysis of Uncertainty**

The ice thickness measurements are based on the AWAC’s acoustical and pressure sensors. Several corrections to both types of data were used to adjust for instrument error.

The AWAC pressure sensors have an accuracy limitation, which is approximately +/- 0.5% of full scale (FS), which equates to an approximately +/- 0.14 meters possible margin of error for a 28-meter-deep deployment, and an approximately +/- 0.1 meters possible margin of error for a 18-meter deployment. The assumed instrumentation accuracy is per Nortek standard specifications.

Pressure sensors may also experience errors due to water temperature variations. Nortek documentation reports that the temperature sensitivity of some tested pressure sensors ranges from 0.004% FS/°C to 0.01% FS/°C. The AWAC recorded temperature ranges from -1°C to 6°C throughout the winter deployment. The temperature-induced variations. Nortek documentation reports that the temperature pressure sensor error would be less than 0.02 meters.

The accuracy of the ice keel measurements is limited to the native vertical resolution of the AST window, which is 0.024 meters.

The AST estimates the distance to the surface by measuring the two-way travel time of the short pulse transmitted to the surface together with an estimate of the speed of sound. The estimated profile is based on the fixed salinity specified at deployment and the measured temperature by the AWAC thermistor. A fixed salinity value of 30 parts per thousand (ppt) was derived from averaging numerous surface water salinity measurements with the handheld conductivity probe. Measured salinity values fluctuated from about 28 ppt to 31 ppt depending on the tide stage and the season. It was assumed that there was no stratification in the water column and that the salinity did not change significantly throughout the winter deployment period. This is obviously a simplifying assumption; however, it is impossible to calculate accurate salinity in the water column without measuring it every burst throughout the entire deployment. The 3 ppt salinity fluctuation plays a relatively minor role in sound velocity in well-mixed waters, so the variability in salinity is not anticipated to significantly contribute to errors in the acoustic data.

The tilt of the instrument also affects AWAC’s AST range data at the surface. All three AWAC instruments were deployed in gimbaled tripods; still all three instruments experienced minor variations in the tilt due to the currents and sediment erosion under tripods and settlement into the sea floor. Tilt variations for each instrument was less than 5 degrees throughout the whole deployment. Nortek’s software uses time series data of the AWAC’s tilt sensors to correct the range to estimate vertical distance from the instrument to the water surface or the ice keel; however, residual errors associated with this factor still persist.

A single approximate value of residuals error was estimated for each AWAC unit using the times when there was no ice. The differences between the AST distance and pressure reading should be zero when there is no ice present. However, after application of one fixed offset to the AWAC data, there are the various sources of transient errors that may emerge from inaccurate calculations of speed of sound, tilt, and/or water density.

The estimated threshold of the instrumentation accuracy was set 0.1 meters. All data measurements below 0.1 meters of the mean ice keel depth are considered to be noise threshold associated with variation of density and the water due tides and weather, and sensor accuracy limitations.

### Surface Data

Surface currents were analyzed for each current profile time series. The surface current is assumed to be the average of the currents in the top 6 meters, measured at a spacing of 1 meter vertically. Currents at the Port Site 1 AWAC site location were approximately 20–25 percent stronger compared with those at the White Gull location. The Entrance location currents were twice as slow compared with those at the Port Site 1 site. Table 1 summarizes measured current speed statistics. Surface current roses based on current speed (m/s) and direction (from) are presented in Figure 4, superimposed on a nautical chart.

**Table 1. Surface Current Speed Descriptive Statistics - November 2010 to April 2011.**

<table>
<thead>
<tr>
<th>STATISTICS</th>
<th>Port Site 1 AWAC</th>
<th>White Gull AWAC</th>
<th>Entrance AWAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>1.2</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Average</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Median</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

![Figure 4. Surface Current Speed Roses superimposed on NOAA Nautical Chart # 16648 (soundings in fathoms)](image)

### Wave Data

During the deployment period from November 2010 to April 2011 the Port Site 1 AWAC recorded seven wave events exceeding 1 meter significant wave height. The significant wave height (Hs) is the average of the third-highest wave in record of time. On three occasions the maximum wave height (Hmax) exceeded 2 meters. Waves at Port Site 1 are mostly approaching from the south.

For the same deployment period the White Gull AWAC instrument recorded nine wave events exceeding 2 meters of Hs. On one occasion the Hmax exceeded 4 meters. Most of the time waves arrived at the White Gull location from the southeast direction.

Between November 2010 and April 2011 the Entrance AWAC recorded three wave events exceeding 3 meters of Hs. On one occasion the Hmax exceeded 5 meters. Most of the time waves arrived at the Entrance measurement site from the southeast direction with several smaller wave storms from the northwest.
The wave height statistics are summarized in Table 2.

<table>
<thead>
<tr>
<th>STATISTICS</th>
<th>Port Site 1 AWAC</th>
<th>White Gull AWAC</th>
<th>Port Site 1 Entrance AWAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Height (meters)</td>
<td>Hs</td>
<td>Hmax</td>
<td>Hs</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.4</td>
<td>2.4</td>
<td>3.0</td>
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<tr>
<td>Average</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
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<tr>
<td>Median</td>
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<tr>
<td>Standard Deviation</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

ICE RESULTS

Port Site 1

The time series of the mean ice keel thicknesses and water temperature for the Port Site 1 location is presented in Figure 5. Horizontal red lines on the chart display the noise threshold of the instrument. Ice thickness below the red line (around 0.1 meters) is considered to be a noise associated with the sensor’s accuracy limitations and variation of salinity, density, and temperature of the water due to tides and weather. Air temperature from the weather station at Port Site 1 for the whole deployment period is presented in Figure 6. Horizontal red lines on the chart display the seawater freezing temperature (about -1.6°C for 30 ppt).

The first measurable ice at Port Site 1 appeared on December 3, 2010. On December 16, 2010, an AWAC data burst revealed nearly continuous ice cover from a drifting ice field with an irregular bottom and variable ice keel depth up to 1 meter. The time series of ice keel depth for the AWAC burst on December 16, 2010, is presented in Figure 7. The horizontal axis covers the entire 512-second burst duration (8.5 minutes), while the vertical axis represents distance from the AWAC’s transducer. An image from the Port Site 1 weather station shows long periods of clear water and a massive ice block with an ice keel depth over 1 meter and more than 67 meters in length. An ice block of this size has a mass of about 70 tons. An image of the ice condition of this event is presented in Figure 8. Note that the image frame is covering an area slightly to the south from the Port Site 1 AWAC location, and the AWAC deployment location is to the left and is not visible in the image.

The time series of ice keel depth for the AWAC burst on December 22, 2010, (Figure 9) shows long periods of clear water and a massive ice block with an ice keel depth over 1 meter and more than 67 meters in length. An image of the ice condition of this event is presented in Figure 10.
On January 20, 2011, the Port Site 1 data bursts reveal nearly continuous ice cover from drifting ice fields with irregular bottoms and variable ice keel depths up to 1.3 meters.

The largest ice block observed at Port Site 1—30 meters in length with an ice keel depth reaching 2.5 meters—was recorded on February 14, 2011. An ice block of this size has a mass of about 30 tons. The time series for the individual burst is presented in Figure 11, showing long periods of clear water and ice fields of significant sizes, suggesting that the ice block was a conglomeration of two or more blocks frozen together. Images of the ice conditions on February 14 and February 15 are presented in Figure 12.

Illustrative example bursts of ice keel depth with associated Port Site 1 images from around the same time are presented in Figure 7.20 through Figure 7.25, revealing a wide variety of ice conditions during this period. The horizontal axis covers the entire 512-second burst duration, while the vertical axis represents the distance from the AWAC’s transducer.
White Gull Site

The time series of the mean ice keel thicknesses and water temperature for the White Gull location is presented in Figure 18. Horizontal red lines on the chart display the noise threshold of the instrument. Ice thickness below the red line (around 0.1 meters) is interpreted to be a noise associated with the sensor’s accuracy limitations and variation of salinity, density, and temperature of the water due to tides and weather.

Example bursts of ice keel depth for the White Gull AWAC for January 1, 2011, are presented in Figure 20 showing periods of clear water, a thin, newly developed ice layer, and drifting ice blocks with irregular bottoms with ice thickness up to 0.6 meters. The horizontal axis covers the entire 512-second burst duration, while the vertical axis represents the distance from the AWAC’s transducer.

The first measurable ice at the White Gull site appeared on December 13, 2010. The largest ice block observed at the White Gull location during deployment No. 1, with an ice keel depth reaching 0.8 meters and more than 65 meters in length, was recorded at 1:03 Alaska Standard Time (AST) on December 26, 2010. Ice blocks of this size have a mass of about 60 tons. The time series of individual bursts is presented in Figure 19 showing long periods of clear water and ice fields of significant sizes.

Figure 15. Example Bursts from the Port Site 1 AWAC for February 13, 2011.

Figure 16. Ice Conditions at Port Site 1 on February 13, 2011.

Figure 17. Example bursts from the Port Site 1 AWAC for February 15, 2011.

Figure 18. Ice Condition at Port Site 1 on February 15, 2011.

Figure 19. Time Series of Mean Ice Keel Thickness vs. Water Temperature at the White Gull Site from November 2010 – January 2011.

Figure 20. Example Bursts from the White Gull AWAC for December 26, 2010.
Pressure

Water Temperature

The time series of the mean ice keel thicknesses from November 2010 to March 2011 for the Entrance site is presented in Figure 21. The horizontal red line on the chart represents the noise threshold of the instrument.

Unfortunately, diagnostic AST data from the White Gull AWAC for deployment No. 2 exhibited an excessively high noise level at each surface detected. Presumably, the leading edge detection method used for processing all AWAC ice data is not suitable for processing the 600 kHz AWAC data deployed at the White Gull location. Apparently, Nortek’s post-processing software fails to correctly track the ice bottom for the 600 kHz unit when there is an intense concentration of suspended sediment in the water column.

Ice data from the White Gull AWAC for its second deployment is not available.

**Entrance Site**

The time series of the mean ice keel thicknesses from November 2010 to March 2011 for the Entrance site is presented in Figure 21. The horizontal red line on the chart represents the noise threshold of the instrument.

The first measurable ice at the Entrance AWAC site appeared on January 20, 2011, at 9:00 (AST).

The largest ice block observed at the Entrance site had an ice keel depth reaching 6 feet, and was observed at 18:07 00 (AST) on January 22, 2011. The time series of individual bursts for this time is presented in Figure 22 showing long periods of open water and drifting ice fields with irregular bottoms and variable ice keel depths. The horizontal axis covers the entire 512-second burst duration, while the vertical axis represents the distance from AWAC’s transducer.

**CONCLUSIONS**

Measurement of ice properties with an ADP instrument is effective, but requires careful planning and analysis methods. Throughout the deployment period the AWAC instruments collected adequate and high-quality wave, current, and ice keel depth data. The ice keel depth measurements resolution is within +/-0.1 meters. The following is recommended for future ice keel measurements using AWAC instruments:

1. An accurate atmospheric pressure record in close proximity to the deployment site is an important component for pressure corrections procedures.
2. Extending the mooring pressure record several hours before the deployment and several hours after the recovery allows more accurate measurement of the AWAC pressure offset.
3. As much knowledge as possible of the sound velocity profile throughout water column at the deployment site should be obtained for more accurate ice keel draft corrections.

The diagnostic AST data from the White Gull AWAC from the second deployment period was excessively noisy for processing using the “leading edge” method, and was not presented in this paper. The raw diagnostic data is not at fault—rather, different processing techniques are required to process diagnostic AST data from the White Gull 600 kHz AWAC.

A significant advantage of this instrument is in its ability to measure ice keel depth simultaneously with the current speed profile.

Current measurements were used to calculate the ice block size and mass based on the ice block passing time. More accurate estimation of the ice block size using these instruments would be possible by installing several instruments in a linear array.
The collected AWAC data is consistent with the photography and temperature readings.

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REFERENCES


