Instrument for Detecting Suspended and Surface Ice Runs in Rivers

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A second generation underwater acoustic instrument for river ice studies has been designed, developed, and deployed in the Peace River in Northern Alberta, which is hydraulically regulated by upstream hydropower projects. The data are being collected to support studies related to ice jam occurrences and winter hydropower operations.

The new upward looking sonar instrument was deployed on the riverbed in November 2005 and 2006. The instrument package contained a 545 KHz sonar transducer, as well as temperature-, 2-axis tilt- and pressure- sensors as well as onboard heaters to prevent anchor ice formation. The original instrument deployed in October 2004 and November 2005 was a 235 KHz unit. The sonar instruments measure the distance to the water surface or the undersides of drifting or stationary ice. By computing the difference between the acoustically-derived distance to the ice and an independently measured water level, the draft of the floating ice can be determined at one second sampling intervals. The instruments can also record the profile of acoustic backscatter returns through the body of the river water column allowing detection of the presence and depth of suspended frazil ice. The higher frequency of the second generation unit was intended to facilitate detection of smaller particles of frazil ice.

This paper describes the presence of suspended frazil ice as detected both prior to, during and after the formation of the winter ice cover by the higher frequency instrument. Relative concentrations of suspended ice and the concentrations and thicknesses of surface ice pans were measured by the instrument as the surface ice run developed from the initial annual supercooling event to near full coverage of the river surface by ice floes. Variations in returns from the suspended frazil during and after formation of the ice cover were found to be linked to air temperatures, water levels and flow velocities as well as to ice front movements.

Problems encountered with anchor ice interference in some portions of the measurement program will be discussed.
1. Introduction

Floating frazil ice pans and suspended individual or aggregated crystals of frazil ice in fresh water bodies often have significant impacts upon water supply, hydro electric, fisheries and other management activities. Effective detection and quantitative characterization of such ice can provide direct input to operational decision-making and for formulating numerical river ice and flow models (Shen et al., 1995; Shen, 2006) underlying modern flow management (Jasek, 2006).

The results presented here were obtained in freshwater during B.C. Hydro’s 2005-2006 and 2006-2007 winter Peace River monitoring programs utilizing SWIPS (Shallow Water Ice Profiler Sonar) instruments developed by ASL Environmental Sciences Inc. from the company’s IPS4 Ice Profiler platform. The SWIPS is an upward looking sonar instrument that acquires acoustic backscatter data from, roughly, 2 cm deep, horizontal, slices of an insonified water column. Suspended particles such as frazil ice crystals, the water surface, bottom of floating frazil ice pans and the water surface can be detected. The location of the monitoring program is shown in Figure 1.1 and the basic instrument set-up and components are depicted in Figure 1.2.

1.1 The 2004-2005 SWIPS Deployment

Detailed information on this instrument can be found in Jasek et al. 2005, where data collected during the 2004-2005 were also presented. That study showed that the instrument could provide insights into freeze-up ice processes such as: frazil ice particle formation and suspension; frazil ice pan formation: formation of the river ice cover and secondary consolidations during the ice cover stabilization process. It also provided insights into undercover frazil erosion, deposition and transport of frazil ice during the ice covered period. Later in the winter, it detected a moving layer of larger granular pieces of ice under the stationary ice cover. The acoustic beam was also able to penetrate the slushy underside of frazil pans and the stationary ice cover providing some sense of the porosity of the lower reaches of these features as they changed with time. Finally it provided measurements of the thinning rate and thermal break-up of the ice cover as warm water and the thermal break-up front approached and passed the SWIPS location.

The instrument deployed in 2004-2005 used a frequency of 235 kHz (SWIPS 1) and although it detected frazil ice in the water column, the theoretical minimum particle diameter detectable with this frequency was calculated to be about 2 mm. As frazil nucleation occurs at the < 1mm size it was evident that a higher frequency SWIPS was needed to gain insight into the frazil evolution process and to detect its earliest presence.

Prior to formation of a stable local ice cover, occasional interruptions of data collection and changes in instrument position were encountered due to formation and deposition of anchor ice on the instrument and its platform.
2. SWIPS data collection on the Peace River during the winter of 2005-2006

A second, higher frequency (545 kHz) instrument (SWIPS 2) was added to the monitoring program in the fall of 2005 in order to better detect smaller suspended frazil particles. Due to the previous year’s anchor ice problems, the SWIPS 2 was outfitted with 100 watts of heating strips built into the epoxy potting surrounding instrument’s transducer head. The SWIPS 1 (235 kHz) unit was also deployed with 100 W of external heating strips which were, in this case, attached to the transducer’s aluminum support plate.

2.1 Overview of the 2005-2006 ice season and anchor ice interference with the SWIPS 1 & 2

The 2005-2006 ice season on the Peace River can be characterized as the warmest on record. The stationary ice cover was in place for only 34 days, Feb 28 to Apr 3. For comparison, the average winter ice cover duration is 95 days at this location (Jan 5 to Apr 10).

Supercooling at our monitoring sites was first noted for a brief Dec 5 to 9 period in 2005 (Figure 2.1), shortly after the SWIPS 1 and 2 were deployed on Nov 24. The heat was turned on the SWIPS 2 on Dec 1 in anticipation of supercooling but unfortunately interference from the heater electronics with the data electronics started on Dec 2. The source of this interference was not discovered until the Dec 13 download when the SWIPS2 heater was disconnected for the rest of the season. Despite the interference it could be determined that anchor ice blocked the SWIPS 2 signal from Dec 5 17:00hrs to Dec 8, 10:30hrs. It was impossible to assess if the heater was working properly at the time or if it significantly affected the duration of anchor ice adherence duration on the SWIPS 2. Although the SWIPS 1 was in shallower water, where anchor ice obstructions might have been expected to pose greater problems the instrument continued to collect data through the supercooled Dec 5 to 9 period without any evidence of external heating on acoustic signal quality. Heater interference with transducer signals occurred in the SWIPS 2 and not in the SWIPS 1 instrument because of the use of separate communication and heater power supply cables in the latter case. The next supercooling periods, on Jan 4 and 10 were only a few hours in duration and did not introduce anchor ice problems at either instrument.

A sustained supercooling period began on Jan 12 which was interrupted by only brief intervals of warming until the formation of the ice cover occurred on Feb 27-28. The latter event was the latest local freeze-up on record and, thus, provided a lengthy period for monitoring frazil activity but, as well, exposed the monitoring instruments to lengthy episodes of anchor ice formation leading to frequent physical movements of the instruments and data-taking interruptions. The anchor ice did not block signal detection at the, still, heated SWIPS 1 instrument even after the start of the Jan 12 supercooling period but did tilt the unit 62 degrees from vertical at 23:13, Jan 17. In fact, these accumulations flipped the unit upside down a few hours later (03:44, Jan 18), ending useful data collection by this instrument for the rest of the season. The, now unheated, SWIPS 2 experienced blockage of the acoustic beam by anchor ice between 04:20, Jan 15 and 22:20, Jan. 23 and again between 00:00, Jan 29 and 14:30, Feb 1. On the later date, the anchor ice tilted the unit significantly (61º) from vertical and definitive acoustic returns from the water surface were lost. The SWIPS 2 unit remained relatively stable and free from anchor ice interference for the rest of the ice season. Although the severely tilted beam precluded obtaining easily interpretable data from the undersurface of the formed ice cover, signal returns from
shorter ranges provided important insights into suspended frazil transport as the ice front approached the monitoring site and during and after local ice cover formation.

2.2 Comparison of profile data from the SWIPS 1 and SWIPS 2 during the winter 2005-2006

Evidence of frazil detection during the 2004-2005 program motivated the inclusion of the 546 kHz SWIPS2 unit in the 2005-2006 study. The higher frequency of this unit was intended to increase detection sensitivity based upon expectations that the scattering cross-sections of frazil particles with radii, \( a < \lambda/2\pi \), where \( \lambda \) is the acoustic wavelength, followed a Rayleigh Law proportionality to the fourth power of acoustic frequency. After corrections for different system gains, SWIPS2 return signal strengths were anticipated to exceed SWIPS1 returns from common targets by 33.6 dB. The resulting sensitivity increases are evident in comparisons (Figures 2.2 and 2.3) of, roughly, 4.5 days of coincident SWIPS1 and SWIPS2 profile data. The Figures present target strengths vs. range results for successive returns from bursts of 120 1 s-separated pings emitted at half-hour intervals during a Jan 9-13, 2006 time interval associated with cold air temperatures and supercooling (Figure 2.4). Three separate intervals of frazil detection were apparent in the data, each characterized by essentially range-independent average target strengths at ranges (heights) > 1m above the bottom-mounted transducer. Detection durations were relatively brief, about 3 hours, in the first and second intervals (initiated around 08:00, Jan 10 and 08:00, Jan 12 respectively) but a third, more intense, event followed at about 17:00 on the Jan 12 and persisted almost to the end of the depicted period. Averaged over a 2.5 hour period, the strongest of the SWIPS1 water column returns (Figure 2.2) in the latter period were comparable to the maximal returns observed with the same instrument during the 2004-2005 program. This level was approximately 30.7 dB +/- 3 dB below corresponding SWIPS2 return levels (Figure 2.3), in accord with anticipated sensitivity differences. This was interpreted as validation of the Rayleigh scattering assumption and its underlying restrictions on target size, suggesting that detected particle diameters were, very roughly, \( \leq 0.8 \) mm.

Figures 2.5 and 2.6 each show 2 minutes of profile data from the SWIPS 1 and 2 respectively on January 13 at about 18:00 hrs. Although frazil ice pans are easily visible in both datasets, the SWIPS 2 data show higher contrast between the frazil pans and the underlying water column even in the presence of higher returns from suspended frazil. The higher frequency SWIPS 2 unit thus performed well in both detecting suspended frazil content and in quantifying frazil ice pan concentrations and thicknesses. Unlike the lower frequency SWIPS1 unit, the SWIPS2 does not have a capability for distinguishing between such pans and the usually harder fragments of detached border ice which sometimes appear among them.

2.3 Suspended frazil intensities, ice pan thicknesses and concentrations prior to the formation of the ice cover - winter 2005-2006

Two periods were encountered in which initial absences of interference by anchor ice allowed SWIPS2 observations of evolving ice runs from initial supercooling and appearances of suspended frazil, to the formation of surface ice and increasing concentrations of surface ice. Data from these intervals, Jan 9-16 and Jan 25-29, are shown in Figures 2.7 and 2.8 respectively. Anchor ice obstructions did arise in the later portions of both periods: becoming significant on
Jan 14 and Jan 28 as indicated by the appearance of intense (red) returns adjacent to the river bottom transducer in the Figures. Total interference and blockage by anchor ice occurred on Jan 15, at about 04:30 hrs and late on Jan 30. Given the successful avoidance of such obstructions in the heated SWIPS1 instrument, it is reasonable to expect that similar avoidance would have been likely if disconnection of the SWIPS2 heaters not been necessary to avoid interference with return signal degradation.

Vertically averaged suspended ice target strength, surface ice concentration, and average ice pan thicknesses were computed for these two periods and plotted in Figures 2.9 and 2.10 respectively. Each data point in these cases corresponds to 2 minutes of SWIPS2 data sampled at 1 Hz every 30 minutes. Air temperature and solar radiation collected at the Water Survey of Canada gauge about 7 km downstream as well as the water temperature at the SWIPS site are included in the same Figures. The latter data in Figure 2.9 show that the Jan 9-16 period was characterized by moderately cool air temperatures between -5 and -15 °C. It appeared that suspended frazil formed and increased in intensity as long as air temperatures remained below -10 °C. Frazil production also corresponded well with measured supercooling (Figure 2.9d). There was a brief period of suspended and surface ice on Jan 10 (Figure 2.9a, b) but, since air temperatures were mostly > -10 °C for times between Jan 10 and the early morning hours of Jan 12, no suspended or surface ice was detected during this period. A more significant frazil ice evolution period started in the early hours of Jan 12, peaked on Jan 13 and continued on with decreasing intensity until Jan 15 when anchor ice formation obstructed the SWIPS2 signal. Maximum surface ice concentration and ice pan thickness reached about 90% and 0.55 m respectively. However, on a daily average basis the maximum surface ice concentration was about 60%.

Solar radiation (Figure 2.9c) appeared to reduce both suspended and surface ice in the mid day period of Jan 12 (Figure 2.9a, b) although similar mid-day effects on Jan. 13 were confined to the suspended component as surface ice concentrations reached a peak value. The Jan 13 observations may have been, at least partially, a consequence of curtailed supercooling due to the additional insulation at the water-ice interface provided by higher surface ice concentrations. Generally, data from the Jan 12 to 15 period showed that suspended frazil ice peaking prior to surface ice concentrations in accord with theoretical expectations.

The Jan 25 to 29 period was characterized by cooler air temperatures relative to the Jan 10 to 15 period, -10 to -20 °C (Figure 2.10c) compared with -5 to -15 °C respectively. Some surface ice runs were noted on Jan 26 prior to suspended ice production and supercooling but may have been associated with mobilized border ice fragments. Supercooling resumed later on Jan 26 producing increases in suspended and surface presence and in frazil pan thickness until the early hours of Jan 27. At that time, a 2.5 hours period was noted during which all three of these quantities were significantly depressed: 160 counts to 60 counts for frazil intensity: 65% to 30% for surface ice concentration, and 0.4 m to 0.2 m for frazil ice pan thickness. We have no ready explanation for this period in terms of environmental factors such as air temperatures, water temperatures or solar radiation. Subsequently, suspended frazil once again showed typical correspondences with surface ice concentrations, solar radiation and air-water temperatures. After the surface ice concentration leveled off at 85% late on Jan 29 and into Jan 30, the suspended frazil content dropped to near-zero levels despite cold air temperatures. Although the likely cause of this
A decrease in frazil intensity was the additional insulation provided by increased frazil ice pan coverage, a gradual decrease in the instrument’s sensitivity due to the slow build-up of anchor ice may also been a factor in the apparent decrease in suspended ice intensity. Ice pan thicknesses in this period were no longer increasing: showing a net decrease from 0.5 m to 0.35 m. Possible explanations for this change could be buoyancy-driven compaction of loose slush beneath the ice pans and/or acoustic beam obstruction effects caused by anchor ice. Maximum surface ice concentration and ice pan thickness reached about 85% and 0.55 m respectively. On a daily average basis, the maximum surface ice concentration also reached 85%.

2.4 Suspended frazil intensities during ice front approach and ice cover formation - winter 2005-2006

Figure 2.11 shows the suspended frazil intensities and water levels at the SWIPS2 during the ice cover formation period. The backwater effect from the approaching ice front started early on Feb 26. By interpolating ice front position from observed values the ice front would have been, approximately, at river km 400, or about 10 km downstream of the SWIPS2. Interpolating between the timings of the ice front as observed at, respectively, this location and upstream of our monitoring site suggests that the front would have reached the SWIPS site at about 24:00 hrs on Feb 28. This time coincides well with the termination of the sharp rise in river levels. The rising river levels were also accompanied by a dramatic decrease in the suspended frazil intensities (Figure 2.11) in spite of a contemporary drop in air temperatures from -7 to -26 °C (Figure 2.12). This decreased frazil intensity could be explained by an expected drop in water velocity and turbulence in the 10 to 15 km long backwater upstream of the ice front. This reduction in turbulence may have been enough to allow the suspended frazil to rise to the water surface. It is unfortunate that, due to the end of January tilting event, the beam of the SWIPS2 was not pointing vertically upward at this time, precluding detection of a corresponding increase in surface ice pan thickness as well as an accompanying increase in surface ice coverage in the backwater region. Both of these effects would have tended to lower local concentrations of suspended frazil.

Rising frazil intensities appeared to be associated with consolidation events as noted in Figure 2.11. Such events can be inferred from the peakings of water levels which corresponded closely with increases in suspended frazil intensity. These results suggested that an active ice front could provide a potent source of suspended frazil for ice covered downstream areas.

2.5 Suspended frazil intensities during the ice covered period - winter 2005-2006

The river was ice covered at the SWIPS site from Feb 28 to Apr 3. The SWIPS 2 unit functioned well although the severely tilted beam prevented monitoring of the stationary ice undersurface equivalently to levels achieved with the SWIPS 1 in 2004-2005. SWIPS 2 was able to successfully monitor the suspended ice intensities throughout the 2006 ice covered period. Both vertically and time integrated average intensities as well as time integrated vertical profiles of frazil intensities were obtained.
2.5.1 Description of frazil intensities and comparison with air temperature

There appear to be both diurnal and longer time scale components of variability in the frazil intensities shown in Figure 2.12. Focusing on data obtained subsequent to the Feb 28 to Mar 3 consolidation period, the non-diurnal component of the frazil intensity increased more or less linearly until Mar 15. Even during the warm spell of Mar 8 and 9, the long term frazil trend was an increasing one. From Mar 15 to 17 there was a significant decrease in suspended frazil even though a cold spell occurred from Mar 14 to 16. The Mar 18 to 23 period could be characterized as very large daily fluctuations (compared to the Mar 3 to Mar 17 period) with a medium intensity but a flat long term trend. After Mar 23 a long term decreasing trend in frazil intensity was evident until Mar 28 after which increased frazil intensity was noted with two peaks about 2 days apart (Mar 29 and 31) until ice clearance on April 3. This (longer than diurnal) variability and increase may have been related to the recession of the ice front which accelerated after Mar 27.

Marko et al (2006) noted that there appeared to be some correlation of frazil intensity with negative air temperature with higher suspended frazil intensities corresponding to colder air temperatures. This behavior was mostly indicative of the March 10 to 20 period. However, the minimum daily air temperatures appeared to lag the frazil peaks by about 4 hours as shown in Figure 2.12. Since this phase shift was consistently apparent in the presence of significant changes in ice front location, it is reasonable to conclude that the diurnal fluctuations in air temperature upstream of the ice front were not responsible for similar temporal scale frazil fluctuations at the SWIPS2 site where, otherwise, effects of the time-varying times of travel from the shifting ice front might have been expected to be detectable. There is also no known, alternative, mechanism which would allow supercooling of water through a snow covered river ice cover. In particular, heat fluxes through the snow and the solid ice and slush under-layer of the river cover make local frazil nucleation extremely unlikely.

2.5.2 River flow arriving from upstream

The river flow during the winter at the SWIPS location is dominated by regulation activities at the Peace Canyon generating station. Inflows downstream of Peace Canyon are typically less than 5% of the total volume and are relatively constant throughout the late winter months. The most downstream non-ice affected gauge during Feb-Mar 2006 was the Peace River at Alces River gauge near the BC-AB Border (about 225 km upstream of the SWIPS). The river discharge for that gauge (Figure 2.13) shows diurnal fluctuations resulting from the daily generation pattern out of Peace Canyon. The only major tributary downstream between this gauge and the SWIPS is the Smoky River which was discharging at a constant 50 m$^3$/s rate during this time (Figure 2.13). Also shown in the Figure is the water depth given by the Solinst water level logger at the SWIPS site. There appears to be a lag of about 30 to 40 hours in the diurnal fluctuations between the gauge at Alces and the SWIPS location which is consistent with river velocity.

The daily average discharge out of Peace Canyon is relatively constant during the ice covered period (except for the decrease on Mar 1). However, there are some long term trends in the water levels at the SWIPSs site that cannot be explained as a result of tributary inflows. These are most certainly associated with channel storage effects as the ice front moves upstream and downstream.
Figure 2.14 shows the depth at the SWIPS site and the ice front position and shows that when the ice front moves upstream the depth at the SWIPS decreases and when it moves downstream the depth at the SWIPS increases. We have no rating curve (with ice effects) available to convert the water level at the SWIPS to a discharge but judging from the decrease in flow and water level on March 1 it would appear that discharge variations attributable to changes in ice front position could have magnitudes on the order of several hundred m$^3$/s. The effect of channel storage on the discharge at the SWIPS location should be negligible during periods when the ice front is neither receding nor advancing. Two such periods can be seen, in Figure 2.14, to be centred on, roughly, Mar 12 and Mar 21, yet water levels on these two dates differ by approximately 0.5 m. This discrepancy is a likely a consequence of temporal differences in hydraulic capacity due to frazil erosion and redistribution that have been documented in previous annual Peace River monitoring programs (Trillium Engineering and Hydrographics Inc. 2004).

2.5.3 Relationship between frazil intensity and river flow

Figure 2.15 shows the integrated frazil intensities along with the water level at the SWIPS 2. The most striking feature of the data is that the diurnal water level fluctuation peaks correspond almost exactly with the diurnal frazil fluctuation peaks. Furthermore, the higher the daily water level fluctuation the higher the increase in the frazil fluctuation peak. On average the frazil peaks tend to lead the water level peak slightly which is consistent with the fact that the maximum velocity occurs on the leading edge of a river wave and not at the crest. It would thus appear that the frazil fluctuations are flow-related as opposed to being a direct consequence of air temperature change. It is interesting to note that, even though the long term trend in the Mar 10 to Mar 15 period was toward decreasing water levels (and flow) due to channel storage associated with upstream advances in the ice front, the corresponding trend in frazil returns was an increasing one. This suggests abrupt or short term discharge changes were much more effective at mobilizing frazil relative to longer term changes in flow. On the other hand there would have been an increase in frazil supply at the ice front as it advanced which would have also tended to increase measured frazil intensities during this period.

2.6 Vertical distributions of frazil intensity in 2005-2006

The 2005-2006 results, acquired at the higher SWIPS2 acoustic frequency were characterized by the continuous presence of significant frazil returns which often exceeded their strongest pre-stabilization counterparts, particularly at heights above pre-stabilization water levels. This situation is illustrated by the six-hour averaged profiles plotted in Figure 2.17 for stabilized ice cover periods associated with, respectively, near minimal and near maximal return strengths. The two other curves in the Figure represent data acquired at times which preceded ice formation and followed break-up and clearance, respectively. The latter, baseline, responses show zones of strong close-in returns with dimensions (1m) essentially identical to those observed beneath the mobile ice cover (Figure 2.16). The smaller dimensions of such zones in the stabilized ice cover profiles, indicative of compression of the turbulent bottom boundary layer, may be a consequence of the presence of the additional boundary layer at the stabilized ice cover. The sharp rises at the upper ends of the stabilized ice cover curves encompassed water column heights up to, roughly, 1m below estimated contemporary river water levels.
Unfortunately, use of profile data for extracting the detailed composition of water column particulate ice content remains problematic in the absence of the multi-frequency results needed to separately estimate particle number densities and size distributions. Thus, the observed sharp rise in target strength at heights greater than 5.5 m could be a consequence of increases in either or both particle numbers and sizes. An intriguing possibility in this respect arises from the well known (Martin, 1981) tendency of frazil particles to sinter or bond together: increasing buoyancy to drag force ratios and, consequently, probabilities for presence in upper portions of the water column. This possibility, alone, because of the sixth power particle diameter dependence of Rayleigh scattering cross-sections, could account for rising target strengths at the upper ends of the stabilized ice cover curves (Figure 2.17). A clarification of this and other frazil population composition issues clearly requires expanded measurement programs. Initial assessments of needs in this respect were facilitated below by more detailed explorations of the 2005-2006 data to explore empirical relationships between frazil-related SWIPS target strengths and the environmental factors most likely to affect the properties and distributions of suspended ice particles. Results of these assessments will be presented elsewhere (Marko and Jasek, to be published).

3. SWIPS data collection on the Peace River during the winter 2006-2007

Due to the physical stability issues encountered in the 2005-2006 season due to anchor ice accumulations on both deployed SWIPS instruments, some efforts were given to redesign of the SWIPS2 instrument housing and mooring systems prior to its deployment in November, 2006. This deployment and its restriction to the higher (545 kHz) of the two tested acoustic frequencies was intended to take advantage of the SWIPS2 instrument’s capabilities for both detecting suspended frazil ice and for more precisely establishing ranges associated with the very porous bottom portions of frazil ice pans (Figure 2.2 and 2.3). The lower frequency, SWIPS1, unit penetrated well into the ice pans, making it significantly more difficult to establish the slush/water boundary (Figures 2.5 and 2.6). The higher frequency model also had a smaller beam angle (6° compared to 11°) offering higher horizontal resolution pans (0.5m compared to 1 m at a 5 m depth) in distinguishing between open water and floating frazil ice. Additionally, pending definitive resolution of physical stability issues, it was judged prudent to invest limited resources in the single unit most likely to provide the greatest quantity of relevant data.

The disadvantages of not deploying the lower frequency (235 kHz) unit were that no further information would be gained on temporal porosity variations in the observed ice pans and ice cover. It was recognized that changes in suspended frazil particle size (growth and decay) could not be studied in detail at a single acoustic frequency unit and access to contemporary SWIPS1 data would have, at least, provided a measure of the fractional content of the SWIPS2 returns which were associated with larger mobile ice particles that, typically, appear in late winter under stationary ice covers.

3.1 SWIPS housing and mooring design for 2006-2007 ice season

Three different elements in the design were envisioned to improve instrument stability and reduce anchor ice formation and interference.
1. The shape of the instrument housing was sloped to reduce perpendicular-to-flow cross-sectional areas where anchor ice was known to first form (Figure 3.1). Initially, a cone-shaped housing was considered prior to eventual fabrication of a pyramidal stainless steel mount which replaced the concrete blocks used in all earlier deployments.

2. Heating was applied to the unit in excess of the 100 Watts of heating strips applied around the transducer heads in 2005-2006. Specifically, in the 2006-2007 deployment, an additional 500 Watt heater was installed inside the hollow metal pyramid structure to heat entrapped water it. It was intended that this water would rise to the top of the pyramid and help to reduce or possibly eliminate the anchor ice adherence both near the sensor and on the instrument mount itself.

3. A second mooring cable was attached to the housing and anchored on the opposite river bank (Figure 3.2). The idea behind this was that even if the unit was moved or picked up by anchor ice it would reduce the chances of the instrument from tilting substantially or tipping over upside down as it did in 2005-2006.

Photographs of the SWIPS deployment platform are shown in Figures 3.3 to 3.5.

3.2 Loss of SWIPS due to anchor ice adhesion in November 2007
The instrument was deployed on Nov 3, 2006 and programmed to collect 120 profiles at a rate of one per second every half hour. The x- and y- tilt sensors collected data once every half an hour just before each set of 120 burst profiles.

The first significant supercooling occurred on Nov 17, 2006 and despite the mitigative features of the system, stability problems were more severe than in either of the two previous winter monitoring programs. Figure 3.6 shows that the instrument tilted significantly shortly after the appearance of suspended frazil ice in the water column late in the evening of Nov 16 and into the morning of Nov 17. Tilts up 60 degrees from vertical were recorded. Only the x-tilts are shown in Figure 3.6, the y-tilts were less dramatic. Each horizontal bar on the x-tilt plot corresponds to 2 minutes of 1-sec data collected every 30 minutes in the profile plot above it. The red (strong return) areas in the profile plot represent either the water surface, floating pan ice or anchor ice located at various distances from the unit. Based on these profiles and the x-tilts, it appears the range to strong return targets varied significantly between each set of burst profiles. Eventually the signal was completely blocked by the anchor ice on Nov 18. Figure 3.7 shows profile and x-tilt data for Nov 22 to 23. Despite occasional and short lived anchor ice clearances, the SWIPS2 platform continued to be jostled in the presence of abundant frazil and anchor ice. Increases of x-tilt magnitudes to 80.1 degrees and were followed by the disappearance of both far and near field insonified targets at about 21:11 hrs on Nov 23. This disappearance was taken as indicative of the severing of the communications cable.

In order to gain more detailed insight what may had been happening to the instrument platform prior to communications cable severance, the returns on Nov 23 were inspected with greater resolution as depicted in Figure 3.8. Four sets of data shown in this Figure: as recorded at half hour time separations. Each horizontal bar of x-tilts corresponds to the 120 seconds of burst data
above it. The x-tilt values are instantaneous values at the start of each burst set and it is likely that tilt values varied considerably within each 120 s burst. Significant second to second changes in range to hard targets indicates that the unit was floating or partially floating or waving around in the flow, probably in a neutrally- or near-neutrally-buoyant state. Given the heating applied to the mount and instrument, post-mortem calculations and the data in Figure 3.8 suggest that the cable segments which, together, spanned the entire river width became buoyant due to anchor ice adhesion. This change eventually lifted the instrument off the river bed. Eventually the cable accumulated enough buoyancy to begin capturing frazil ice pans and creating a river-wide ice boom. Calculations suggesting that the 4 mm and 10 mm steel diameter cables would certainly fail under such circumstances were confirmed by inspections of the frayed ends of the cables, (Figures 3.9 to 3.12).

5. Plans for 2007-2008
The plans for 2007 deployment include getting rid of the far side cable and increasing the mass of the SWIPS housing substantially to prevent movement by anchor ice. Heaters will be installed once again and the near-bank mooring and communications cables will be weighted to the river bottom to discourage lifting by anchor ice accumulations.

6. Conclusions
Extension of SWIPS profiling and draft measurement to higher acoustic frequencies offers powerful new capabilities for monitoring ice in and on the surface of freezing rivers. Initial results show the existence of consistent correlations between major environmental parameters, seasonal events, the distribution of frazil suspended in the water column and the formation of surface frazil ice pans. Quantitative spatial and temporal variations in the size distributions of suspended frazil ice would appear to be accessible to measurement through near-simultaneous profiling at several acoustic frequencies.

The higher frequency SWIPS 2 (545 kHz) unit had distinct advantages over the lower frequency SWIPS 1 (235 kHz) unit. It was able to detect smaller suspended frazil particles and more precisely defined the draft depth of frazil ice pans.

SWIPS 2 data during frazil ice evolution episodes showed an increase in suspended frazil ice concentration and in surface frazil ice pan concentration and thickness tended to follow supercooling with suspended frazil concentrations eventually decreasing again when surface ice concentrations exceeded about 65%. Reductions in both suspended ice and surface ice presence were also noted during increases in solar radiation as long as the surface ice was below 65% concentration. At higher surface concentrations, only suspended ice concentrations showed a response to solar radiation. Also noted was a decrease in pan thickness with time after suspended ice began to decrease to negligible levels. This may have been the result of slush compaction under the ice pan due to the buoyancy force and/or been, simply, an artifact of anchor ice obstruction of the SWIPS acoustic beam.

During the approach of the ice front, the SWIPS 2 unit recorded a significant decrease in suspended frazil despite cold air temperatures. This could indicate that suspended ice may come
out of suspension within the backwater upstream of the ice front due to lower turbulence. Shortly after the ice front advanced upstream of the SWIPS location sharp increases in suspended frazil coincident with sharp spikes in water levels indicated that the consolidation process was able to mobilize frazil back into suspension.

Under an ice cover, particularly strong relationships were detected, for the first time, linking short term variations in water levels or water flow speeds and the intensities of returns from frazil ice suspended in the water column.

The vertical distribution of frazil intensity obtained from SWIPS 2 suggested higher upper layer concentration under an ice cover and a more uniform vertical distribution under open water conditions.

The most substantial remaining obstacle to achieving a routine monitoring capability appears to be assuring the physical stability of the instrument on the river bottom during periods of intense local frazil production in periods preceding ice cover formation. A combination of externally applied heating and suitable weighting of instrument platform and instrument and power cables holds good prospects for demonstrating this capability in upcoming 2007-2008 tests.

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Figure 1.1 Geographic location of SWIPS unit and meteorological stations.
Figure 1.2 SWIPS unit and data logger installation.

Figure 2.1 Location of SWIPS, ice front and hourly air temperature at the Town of Peace, water temperature at the SWIPS and anchor ice interference durations and notes. SWIPS 1 and 2 were deployed on Nov 24, 2005. (Stationary ice cover present above dark blue line)
Figure 2.2 SWIPS 1 Profile date for Jan 9-13, 2006.

Figure 2.3 SWIPS 2 Profile date for Jan 9-13, 2006.

Figure 2.4 Water Temperatures at SWIPS location for Jan 9-13, 2006.
Figure 2.5 SWIPS 1, 120 seconds of data during suspended frazil and frazil ice pan period on Jan 13, 2006. The SWIPS 1 was in about 3.2 m of water.

Figure 2.6 SWIPS 2, 120 seconds of data during suspended frazil and frazil ice pan period on Jan 13, 2006. SWIPS 2 was in about 4.9 m of water.
Figure 2.7 SWIPS 2 profile data for Jan 9-16, 2006.

Figure 2.8 SWIPS 2 profile data for Jan 25-29, 2006.
Figure 2.9 a) Surface ice concentration and frazil pan thickness, b) surface ice concentration and suspended frazil intensity, c) air temperature and solar radiation, d) water temperature and suspended frazil intensity Jan 9 to 15, 2006.
Figure 2.10 a) Surface ice concentration and frazil pan thickness, b) surface ice concentration and suspended frazil intensity, c) air temperature and solar radiation, d) water temperature and suspended frazil intensity Jan 25 to 29, 2006.
Figure 2.11. Frazil intensity and water level at the SWIPS site during ice front approach and consolidation process in 2006.

Figure 2.12. Suspended frazil intensity, air temperature and ice front position in 2006.
Figure 2.13. Discharge 225 km upstream from SWIPS, discharge contribution from the Smoky River just upstream of SWIPS and water level at the SWIPS in 2006.

Figure 2.14. Water Level at SWIPS and the ice front position in 2006.
Figure 2.15. Frazil intensity and water level at the SWIPS site during the ice covered season in 2006.
Figure 2.16. Six-hour averaged target strength (counts) vs. height (m) above the transducer at indicated times. Square- (triangle-) denoted data were obtained with vertical (tilted) beams.

Figure 2.17. Six-hour averaged SWIPS2 target strength vs. height above the transducer under the indicated conditions. Again, squares (triangles) denote vertical (tilted) beam data.
Figure 3.1. Design of SWIP2 mount for 2006 deployment. Pyramid shaped mount was hollow with 3.2 mm steel construction.

Figure 3.2. SWIPS 2 mooring, communications and heater cables for 2006 deployment.
Figure 3.3. ASL Technician Matt Stone installs SWIPS 2 and 500 watt heater (far right) into pyramid shaped housing.

Figure 3.4. Complete instrument platform ready for deployment. Pipe in foreground (downstream side) holds an independent pressure transducer and water temperature sensor/logger. Communication, two heater and two mooring cables are also attached (top).
Figure 3.5. 100 Watts of heater strips around SWIPS transducer head.

Figure 3.6. SWIPS 2 anchor ice interference on Nov 16 to 18, 2006.
Figure 3.7. SWIPS 2 anchor ice interference on Nov 22 to 23, 2006. Communications cable was severed and the instrument was lost at about 21:11 hours on Nov 23.

Figure 3.8. SWIPS 2 anchor ice interference on Nov 23, 2006 shown in high resolution. There are 4 sets of 120 seconds of data shown taken about half an hour apart.
Figure 3.9. Severed communications and two heater cables on left bank.

Figure 3.10. Severed left bank mooring cable.
Figure 3.11. Severed right bank mooring cable

Figure 3.12. Right bank mooring cable was coiled up suggesting it snapped and recoiled after failing in tension.