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Seven Years of SWIPS Measurements, Applications and Development: Where, How and What Can the Technology Do for Us

Jan Buermans, David B. Fissel and Anudeep Kanwar
ASL Environmental Sciences Inc.
#1-6703 Rajpur Place, Victoria, BC, V8M 1Z5 Canada

Email for correspondence: jbuermans@aslenv.com

Introduced in 2004, the Shallow Water Ice Profiling Sonar (SWIPS) instrument has been used for previously inaccessible, high resolution ice draft measurements and monitoring of the water column for ice content.

In the present work, several example deployments of the SWIPS in river- and lake- applications in Canada and in the United States will be described.

SWIP-based ice draft measurements of the floating surface, combined with its capabilities for water column profile measurements, provide the potential for reasonably complete quantitative tracking of all components of fresh water ice systems. Collaborative laboratory and field-based research with the instrument provides quantification and insights into ice processes.

1. Introduction and background

Ice Profiling Sonar (IPS) has been widely used in the Polar ocean regions since 1990 (Melling et al., 1995). ASL has pioneered in the evolution of the acoustic profiling instruments used in this work, recently introducing a fifth generation Ice Profiler instrument (IPS5), which sets the current global standard for autonomous sea ice thickness measurement in remote areas. Applications of the basic profiling technology in fresh- as opposed to salt-water areas were first made on the St. Lawrence River during the 2002-2003 winter season (Chave, et al. 2004).

First introduced in 2004 into annual river ice monitoring programs on the Peace River (Jasek, 2005), the Shallow Water version of the Ice Profiling Sonar (SWIPS), intended for ice measurements in fresh water, has been developed for qualitative and quantitative monitoring and study of ice in river, lake and laboratory environments. Since 2004, a number of SWIP instruments have been deployed around the world in rivers and lakes.

2. Principles of Operation

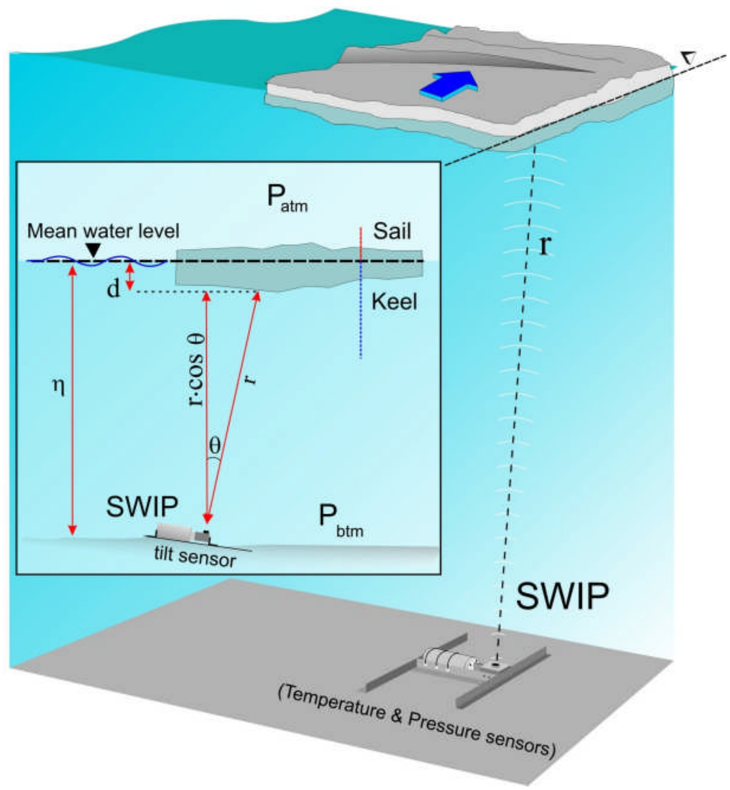

Figure 1. SWIP configuration and measurements parameters are shown above.

The SWIP has been designed as a self-contained or real-time instrument to observe stationary or moving ice through the sonar's field of view (Figure 1). Since SWIP shares its software, firmware, and main electronic components with the IPS, its principles of operation are identical. The SWIP sensors and housing configuration have been optimized for deployment depths of between 2 and 20 m below the surface, looking upward. At intervals set by the deployment software, the acoustic transducer transmits a pulse of programmable duration. The sound travels in the form of a conical beam toward the surface. Some of the sound is absorbed as it travels through the water and some of the sound is reflected by frazil, slush, and thermal ice, the water-air interface or other targets it may encounter. The acoustic transducer listens for these reflections (echos) from the water column. The voltage signal generated by the transducer is amplified to account for spreading and absorption losses and it is then digitized by the analog-to-digital (A/D) converter. This digitized voltage output is referred to as the return strength. With the standard digitization rate of 64 kHz, the instrument has a time resolution of about 16 microseconds (or 25 microseconds if the digitization rate is set to 40 kHz). The attainable resolution in space is of the order of 1 cm.

In target mode, which is designed specifically for ice draft measurements, the SWIP examines the return strength from echoes. Using a well-established algorithm, the instrument then decides which part of the signal is returned from the bottom of the ice or from the water-air interface in the absence of ice. The interval between transmission and receipt of the selected target is referred to as the Travel Time. This parameter is measured and recorded internally onto removable CompactFlash memory or transmitted in real-time over the serial interface. The SWIP can record the maximum Amplitude, the duration (Persistence) and Travel Time of up to a maximum of 5 detected targets. The Travel Time is then used to compute the range (r) to the detected target using a best estimate of the water speed of sound.

In profiling-mode, the SWIP records the return strength, expressed in Counts, for the entire water column. This series of values represents the acoustic backscatter from the water column and can be used to detect frazil ice, investigate slush and explore the ice cover, as well as detect the surface ice and the air/water interface (if present). With the application of the speed of sound, the return strength versus range can be plotted over a period of time.

The SWIP also contains a real time clock and sensors for measuring pressure, temperature and instrument tilt from the vertical on two axes. The frequency of the recording of these auxiliary variables may be controlled by the user. The tilt data allow the calculation of zenith distance from return range. The pressure sensor allows for calculation of the actual depth of the SWIP beneath the water level, as the instrument's depth below water level changes in response to current, set up from wind and possible mooring motion. To complete this calculation, atmospheric pressure must be determined by means of independent instrumentation at the surface, as discussed in more detail below.

The SWIP may be programmed to start data collection immediately, or to wake up at a future time. It may also be programmed to go to sleep for a specific time. It can store acquired data in its removable commercially-available CompactFlash memory and/or send the data over a serial communication port. For real-time communication over a long underwater cable, the instrument is usually supplied with an RS-422 serial communications port.

Table 1**.** Speed of sound in fresh water is shown as a function of water temperature.

Water Temperature(°C)	Sound Speed (c in m/s)
0	1402.39
1	1407.37
2	1412.23
3	1416.99
4	1421.63
5	1426.16
6	1430.59
7	1434.91
8	1439.13
9	1443.25

3. Ice draft and ice thickness computations from SWIP data-Target mode

Ice draft computation, using data obtained from an upward looking sonar deployed in a saltwater environment, is well understood (Fissel et al. 2008). The SWIP parameters measured include Travel Time (from which range(r) to the underside of the ice is computed), tilt in two planes ($tilt_x$ and $tilt_y$), absolute water pressure at the instrument (Pbtm), and near-bottom water temperature. Barometric pressure (Patm) needs to be measured separately. It may also be useful to conduct water column measurements of the speed of sound while the body of water is ice covered. To compute ice draft, this information needs to be entered into Eq. 1 thru 4 below. For salt water applications (Marko, 2006), the critical, accuracy-limiting factor in ice profiling is knowledge of the mean sound speed. The actual speed of sound is only available with accuracy over the full water column at the start and end of a deployment through direct conductivity-temperature-density (CTD) profile measurements for temperature and salinity. For intermediate times, sound speed estimates are obtained as an integral part of the data processing/analysis program. This is done by establishing values of β (Eq.4) which correctly yield zero draft values from Eq. 3 using range, r, and water level, η, values at times when there is unambiguous presence of open water above the SWIP instrument.

$$\eta = (P_{btm} - P_{atm}) / \rho g - \Delta D \qquad [1]$$

Where: η is the water depth above the acoustic transducer

P_{btm} is the hydrostatic (bottom) pressure as measured by the SWIP

P_{atm} is the atmospheric pressure

ρ is density of water

g is acceleration of gravity

ΔD is the physical separation in the vertical direction between the deployed acoustic and hydrostatic pressure sensors

$$\theta = (tilt_x^2 + tilt_y^2)^{1/2} \qquad [2]$$

where: θ is the tilt magnitude with respect to the vertical

$tilt_x$ is the measured tilt angle in the x-plane

$tilt_y$ is the measured tilt angle in the y-plane

$$d = \eta - \beta \cdot r \cdot \cos\theta \qquad [3]$$

where: d is the ice draft

β is a "*to be determined*" factor which accounts for changes over time in the mean sound speed in the upper water column

r is the range to the ice as measured by the acoustic transducer

$$\beta = c_{act} / c_{IPS\mathit{Link}} \qquad [4]$$

where: c_{act} is the actual mean speed of sound in the water column and

$c_{IPSLink}$ is the speed of sound entered in the IPS*Link* software for the instrument deployment.

Without a snow cover and with relatively flat ice, the ice thickness (T_{ice}) can be estimated if the densities of water (ρ_{water}) and ice (ρ_{ice}) are known:

$$T_{ice} = d \cdot \rho_{water} / \rho_{ice} \qquad [5]$$

For fresh water applications, corrections for the time varying speed of sound are generally entirely a function of water temperature. During the cooling and ice covered seasons, depending on thermal stratification in the water column, the measured water temperatures can be used to directly determine the speed of sound of freshwater to a reasonable degree of accuracy. Table 1 lists the speed of sound in fresh water for water temperatures from 0 to 9°C. After ice break-up, thermal stratification in the water column above the SWIP instrument may require the use of the open water episodes to determine the speed of sound, as described above for sea water computations.

4. Ice Draft Measurement Applications in Rivers and Lakes

4.1. BC Hydro Experience's with the SWIP on the Peace River in Alberta, Canada.

Ice in the Peace River has a significant impact upon the operation of BC Hydro's W.A.C. Bennett Dam hydroelectric plant. Effective detection and quantitative characterization of such ice can provide direct input to operational decision-making and for formulating numerical river

Figure 2. The SWIP is being deployed in the Peace River (Marko and Jasek, 2008).

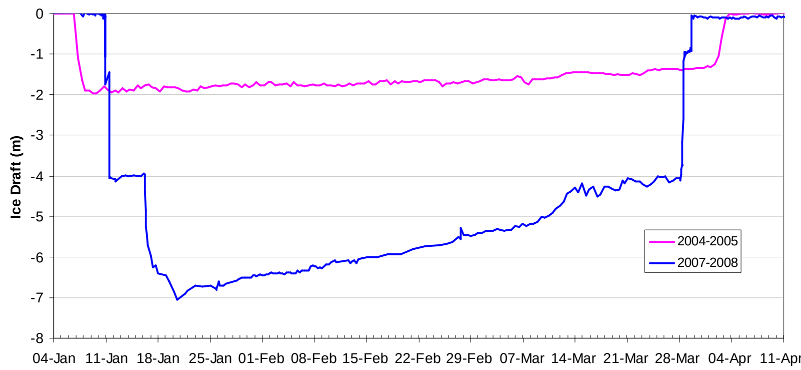

Figure 3. The above figure shows the ice draft time series for the 2004-2005 and 2007-2008 study program from the Peace River SWIP deployments.

ice and flow models. BC Hydro initially deployed a 235 kHz SWIPS instrument for the 2004-05 winter. Since then, the flooding of the town of Peace River downstream of the dam has been avoided. For the 2005-06 winter season, BC Hydro added the high-frequency 546 kHz SWIP to the program. During the 2007-08 winter, an improved design of the heated anchor-ice resistant mooring worked successfully. Data from both a high and low frequency SWIP instrument were available in real-time via a secure website for BC Hydro operations for a portion of the 2008-09 winter. Deployment of the SWIP continued for the 2009-10 and 2010-11 winters. Figure 2 and 3 show a sample SWIP deployment and ice draft data for two separate ice seasons respectively. Frazil ice and slush ice play a big role in the ice dynamics on the Peace River. These aspects are discussed further in the next section.

4.2. Validation of the Canadian Lake Ice Model through the deployment of a SWIP at a Lake, near Churchill, Manitoba, Canada throughout the 2008/2009 and 2009/2010 ice seasons.

To validate and improve the Canadian Lake Ice Model results, in situ measurements of the ice cover were obtained through the 2008/2009 and 2009/2010 ice covered seasons using an upward-looking sonar device Shallow Water Ice Profiler (SWIP) installed on the bottom of the Malcolm Ramsay Lake near Churchill, Manitoba, Canada. Figure 4 shows the deployment of the instrument after the ice was thick enough to work on. Figure 5 shows water level and ice cover

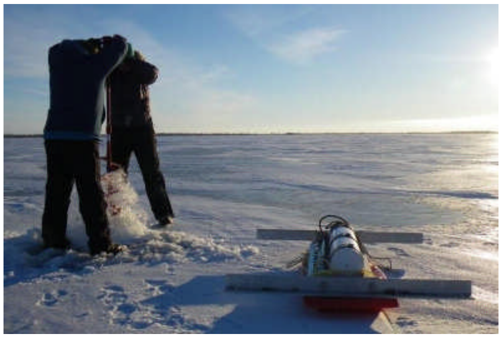

Figure 4. The crew is making a hole for the 2010 SWIP deployment.
Courtesy of Laura Brown, University of Waterloo.

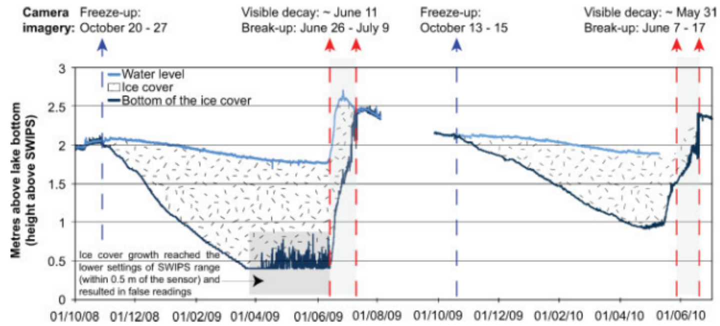

Figure 5. Water level and ice cover ranges as measured by the SWIP (Brown, 2011).

ranges for the two seasons measured so far. The SWIP identified the arrival and break-up of the ice cover. It was used to collect ice draft measurements (Brown, 2011).

The late season ice thickness tended to be underestimated by the simulations with break-up occurring too early. However, the evolution of the ice cover was simulated to fall between the range of the full snow and no snow scenario, with the thickness being dependent on the amount of snow cover on the ice surface (Brown, 2011).

4.3. Ice observations in Lake Erie, 2010-2011, Michigan, USA.

"The Great Lakes Environmental Research Laboratory (GLERL) deployed four SWIPS ice profilers at 4 separate locations in the central basin of Lake Erie (Figure 6, stations 1-4) over the winter of 2010-2011 to measure the ice growth, decay, and thickness in the lake. This data will be analyzed and used to improve a coupled ice-lake model for the lake. The annual variability of Lake Erie ice, temperature, and currents will be investigated by comparing the observations with simulations made for other periods with extensive winter observations. Finally, the impact of ice on surface heat flux, temperature, and lake circulation will be determined.

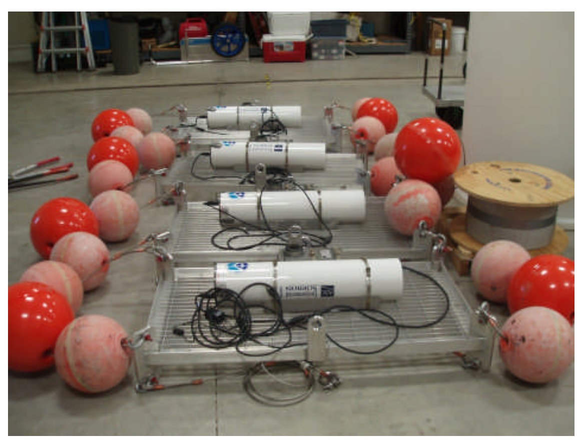

Figure 7. This figure shows the 4 SWIPS units with external battery packs mounted on sleds prior to deployment
-Courtesy of Nathan Hawley, GLERL

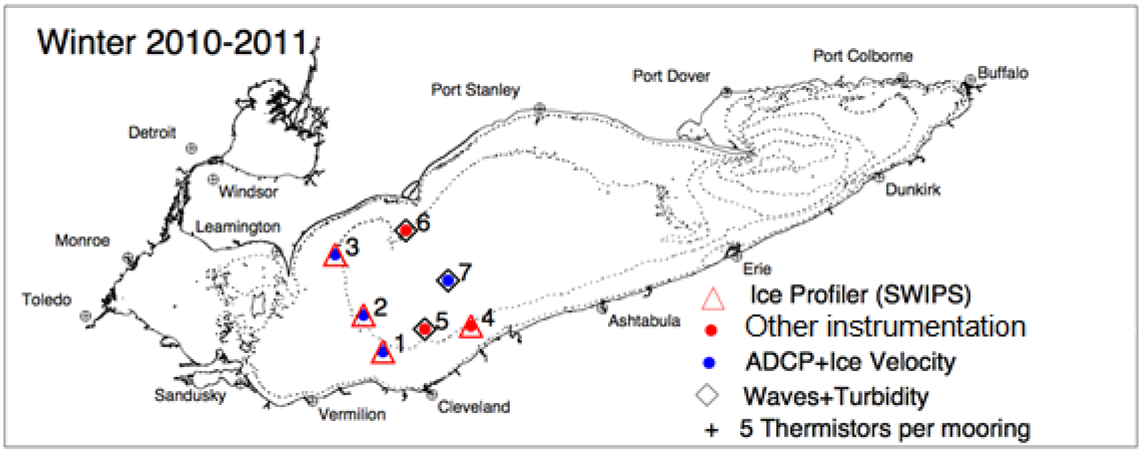

Figure 6. Mooring locations for 2010-2011 - *Courtesy of Nathan Hawley, GLERL*

The SWIP units were mounted on sleds (Figure 7) 1-3 meters above the bottom in water depths of approximately 18m. The units were deployed between October 25 and November 4, 2010 and retrieved between May 31 and June 22, 2011. Sampling was done in 3 phases (Figure 8): a wave phase from October 19 through December 11 with about 3 million pings individual pings, an ice phase from December 12 through April 30, and a second wave phase from May until the end of the deployment. During Phase 2 of the deployment, it sent out one ping every second for 140 days collecting a total of about 12 million pings. All of the units were still recording data when retrieved, and they each recorded over 6 Gbytes of data.

Satellite observations show that two distinct periods of ice cover occurred during the deployments – the first from January 19 until February 15, and the second from February 27 until March 14. A period with little to no ice cover occurred from about February 15- February 27." (Hawley, 2011)

	Phase 1	Phase 2	Phase 3	
Start Date	Oct 19, 2010 00:00:00	Dec 12, 2010 00:00:00	May 1, 2011 00:00:00	
Duration	54.0000 days	140.0000 days	30.0000 days	
Phase type	Wave Profiling	Ice Profiling	Wave Profiling	Continue to end of FLASH
Main Amp Hrs	29.17	48.64	16.21	
Tx Amp Hrs	0.35	1.17	0.19	
Pulse Len	68 uS	68 uS	68 uS	
DigRate	64 kHz (0.0110 m/smpl)	64 kHz (0.0110 m/smpl)	64 kHz (0.0110 m/smpl)	
Gain	1	1	1	
PingPeriod	10.0 sec	1.0 sec	10.0 sec	
Base Ping Rate	2 Hz	1 Hz	2 Hz	
Sensor Period	60.0 sec [6 pings]	10.0 sec [10 pings]	60.0 sec [6 pings]	
Burst Period	3600.0 sec [60 sensors]	10.0 sec [1 sensors]	3600.0 sec [60 sensors]	
Burst Length	1024.0 sec [2048 pings]	1.0 sec [1 pings]	1024.0 sec [2048 pings]	
Range	25.00 m [2281 smpl]	25.00 m [2281 smpl]	25.00 m [2281 smpl]	
Lockout	2.00 m [182 smpl]	2.00 m [182 smpl]	2.00 m [182 smpl]	
Max. Targets	3	3	3	
Start Amp.	35000	10000	35000	
Stop Amp.	25000	9000	25000	
Min Persist	62 us [4 smpl]	62 us [4 smpl]	62 us [4 smpl]	
Target Storage	Burst Profiles & Targets	Burst Profiles & Targets	Burst Profiles & Targets	
Mega Bytes	346.3 Mb	5920.3 Mb	192.5 Mb	

Figure 8. The above figure shows the deployment configuration of the GLERL SWIP

4.4. Automated ice thickness measurements in support of community-based ice monitoring SWIP deployment in Koksoak River near the Northern Village of Kuujjuaq, Quebec Canada.

"The Climate Research Division of the Science and Technology Branch of Environment Canada @ Ouranos fostered the installation of an automated underwater ice thickness measuring system at a site near *Kangiqsualujjuaq* (George River) to contribute to the Kativik Regional Government community-based ice monitoring program and supply ground-truth data for the RADARSAT-2 ice monitoring activity, The thickness measurements will be made available to community residents via the northern outreach website for the network at the Canadian Cryospheric Information Network. Local residents will be engaged in the installation, maintenance and interpretation of the data stream during annual maintenance visits.

In October 2009, a team of researchers and divers installed a Shallow Water Ice Profiling System (SWIP) on the Koksoak River near the Northern Village of Kuujjuaq on Little Elbow Island, a well travelled river crossing for Kuujjjuamiut (Figure 9).

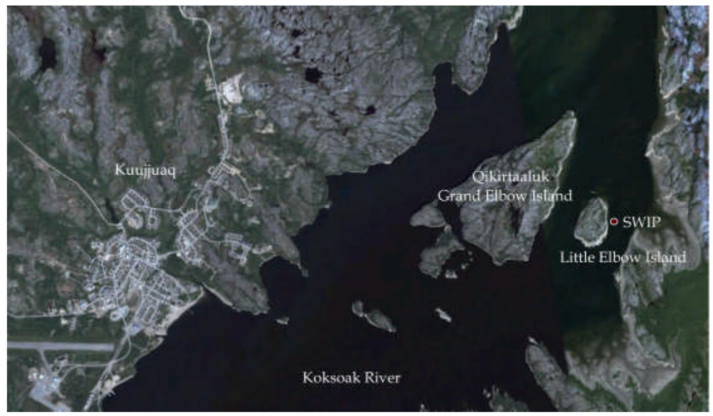

Figure 9. The above map shows the mooring location of the SWIP *-Courtesy of Ross Brown, Environment Canada*

The instrument was housed in a pre-fabricated mooring station with steel ballast plates and a Teflon sheeting at approximately 45 degree (pyramid structure), a design used for the deployment of a SWIP on the Peace River, Alberta (ASL, BC Hydro, 2007). The teflon sheets were used to reduce anchor ice bond strength accompanied by the angled sides which reduce the perpendicular impacts of supercooled frazil ice crystals. This design has been shown to reduce the rate of anchor ice accumulation. A steel structure insulated battery box was fabricated to house the external battery which was then attached to a cable then to the SWIP. Anchor plates with teflon cable ties were fabricated to act as anchors for the SWIP cable underwater.

Two divers from the Kuujjuaq dive team installed the underwater unit while another boat was used to feed the cable to shore and up a steep cliff on the Eastern side of Little Elbow Island to an area well past the high tide mark where the battery box was installed.

The unit was configured into five phases at which time, data will be collected until the end of the available memory. Table 2 illustrates the phase configuration and main parameters.

Table 2. Deployment parameters for various phases

Phase Date	**Duration**	**Phase Type**	**Ping Period**	**Max Targets**
September 21, 2009	3 days	Ice Profiling	2.0 seconds	5
October 24, 2009	83 days	Ice Profiling	1.0 second	5
January 15, 2010	120 days	Ice Profiling	2.0 seconds	5
May 15, 2010	31 days	Ice Profiling	1.0 seconds	5
June 15, 2010	92 days	Ice Profiling	2.0 seconds	5

The five (5) phase configuration is designed to capture more data during ice accumulation periods and ice depletion periods, therefore, Phase two (starting October 24) and phase 4 (starting June 15) have a higher frequency of measurements to capture a higher degree of change during these periods.

In late January 2010, real-time development capability of the SWIP began the development stage. The purpose of the real-time capability is to provide the residents of Kuujjuaq an ice thickness measurement in near real-time from the deployed SWIP unit. To facilitate this, the SWIP has been tested and configured with an external logging unit and an Iridium satellite transceiver. The development of this technology is in collaboration with ASL who will develop a web based data retrieval system and community data delivery mechanism.

During the summer of 2010, the project team will travel to Kuujjuaq to download the 2009/2010 data from the SWIP and to redeploy the unit with the real-time components." (Brown, 2011)

5. Other applications: Acoustic observation of suspended frazil ice and slush

5.1. Background

Frazil ice is a collection of small, loose, randomly-oriented ice crystals in water. Frazil ice is the first stage in the formation of ice and it forms in open, turbulent and super-cooled water at low air temperatures. Hydrodynamic drag in turbulent and fast flowing water can distribute the small crystals throughout the water column. As the ice crystals increase in size and also start to stick together, buoyancy forces will become more important and will carry the crystals to the surface. When these larger ice crystals coagulate and concentrate at the air-water interface (or at the water-ice cover interface), this mixture of ice and water is referred to as slush ice.

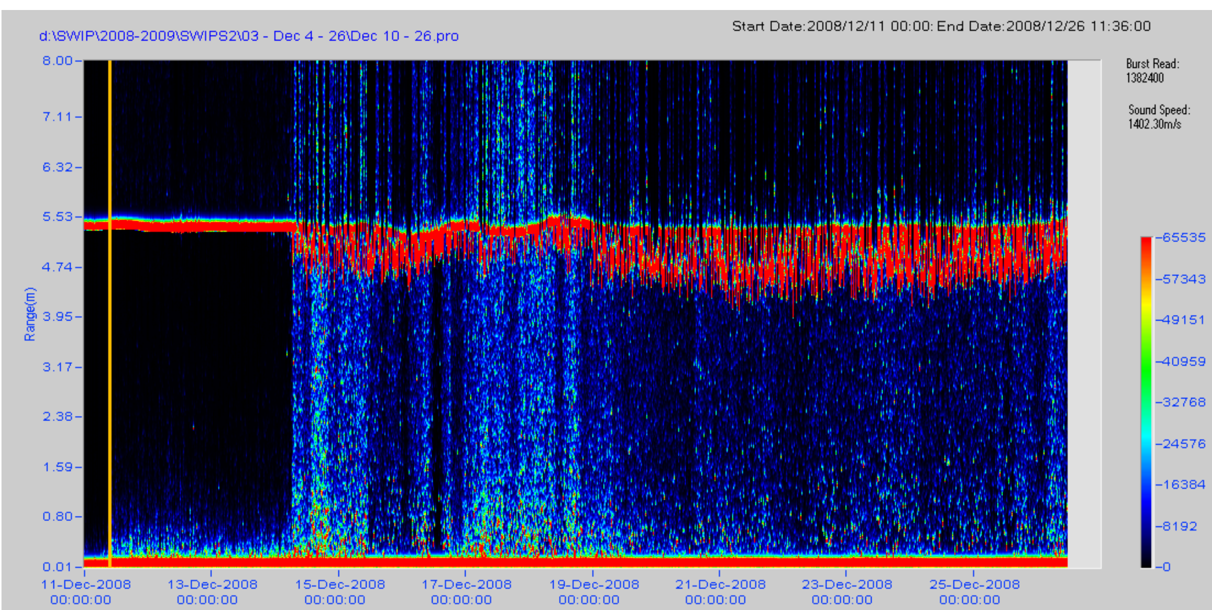

Figure 11. The above SWIPS (545 kHz) echogram shows suspended and surface ice during the ice formation period on the Peace River (Jasek, 2010).

5.2. Frazil ice observations

In the profile-mode, the SWIP records echos from the entire water column. The data shown in Figure 11 as recorded by BC Hydro's SWIP includes echos from pings one second apart from a 15-day period (about 1,300,000 individual pings) just prior to the arrival of the 2010/11 ice cover on the Peace River. The color scale indicates the strength of the echo returns. The air-water interface and the water-ice interface are very strong acoustic reflectors both shown in red. Any acoustic returns shown beyond the water level of about 5.5m are reflections and should be discarded. On or about Dec 14, weaker echos (light blue) appear in the entire water column while ice pans appear at the surface. These weaker echos are from frazil ice.

Some work has been done to look at frazil with two separate frequencies (545 and 235 kHz) (Marko and Jasek, 2009) and (Marko and Jasek, 2010). BC Hydro plans to deploy a 4-frequency SWIP instrument for the 2011-12 ice season.

The reflected acoustic power can be quantified and derived from the amplified transducer voltage measured. In absolute terms, the links between the voltage output and the acoustic power detected from any given range are quantifiable in terms of known or measureable system parameters such as gains, A/D conversion rates, driving voltages and transducer transmitting and receiving efficiencies. A comparison of detected acoustic power relative to the similarly-calculated "outgoing" acoustic power at the range of the target provides the basis for ice or other target characterization. A version of the SWIP is being developed that will output the acoustic measures from the profiles using the instrument parameters. Additional studies are underway to determine frazil characteristics (mean particle size and concentration) from these acoustic measures.

5.3. Slush Ice Observations

Slush is mostly a mixture of water, ice crystals, and air bubbles and its acoustic properties, including its intrinsic speed of sound, can be expected to exhibit considerable variability. Some attempts have been made to measure the speed of sound within the slush ice in the field and results appear variable. We suspect the speed of sound in slush is 10 to 20% less than in clear fresh water. Interpretation of backscatter from within the slush ice is more since the speed of sound and attenuation within it can be quite variable. The physical properties of slush ice are the subject of further collaborative research studies.

In the case of the mixed ice cover (thermal ice, slush ice and frazil ice) of the Peace River, the slush layer under the thermal ice generally is limited to 1-2 meters thickness over the winter but can erode to 0.5 to 1.5 meters in the latter months of the ice covered season (Jasek, 2010). Locally, there can be areas where slush is being eroded more rapidly or is even being deposited depending on the water velocity. The ice drafts measured by the SWIP include the frazil slush layer if it is present. Lower acoustic frequencies (longer wave lengths) penetrate the lower ice cover and appear to allow useful extraction of qualitative or semiquantitative data on changes inside the slush layer. These changes are likely to be significant in characterizing the seasonal ice cover and its interactions with water column frazil ice (Buermans et al, 2010). This topic is the subject of further study in collaboration with research partners and SWIP users.

6. Conclusions and Future directions

The introduction of the Shallow Water Ice Profiler (SWIP) instrument for use in a number of river and lake high-resolution ice monitoring programs has been described in this paper. The SWIPS has been developed for monitoring and study of river, lake and laboratory ice environments by providing detailed real-time quantitative information on the ice cover draft and the extent of frazil ice. The SWIP instrument provides two measurement modes: draft of floating ice in target mode and high resolution measurement of suspended ice crystals over the full water column in profile mode.

These SWIP-based ice draft measurements of the floating surface, combined with its capabilities for water column profile measurements, provide the potential for reasonably complete quantitative tracking of all components of fresh water ice systems.

Collaborative laboratory and field based research is providing quantification and insights into river frazil ice processes (Ghobrial et al., 2009). The forthcoming introduction of the multiple-frequency SWIP instrument, with up to four discrete acoustic frequencies, will provide the framework to achieve improved quantitative understandings of frazil ice, and in particular, information on the size of the frazil ice particles and the total concentration of frazil ice in the water column. This multi-frequency SWIP will provide new insights into the acoustic properties of slush ice and thermal ice.

To determine river frazil ice concentrations, development and verification of algorithms for converting SWIPS acoustic backscatter values, simultaneously recorded at two or more frequencies into actual estimates of the suspended ice volumes and frazil particle size distributions is necessary. Some initial success in this regard has been reported by Marko and Jasek (2010) in analyses of multiple Peace River annual data success by assuming that the strengths of acoustic backscattering by populations of discoidal frazil particles could be treated by summing over acoustic power returns from independently-acting spherical targets of equal volume. By and large, the particle concentration, radius and fractional volume estimates derived from the Peace River data were consistent with those data and the utilized measurement frequencies satisfying these criteria. To facilitate applications to other situations (e.g. higher concentrations of larger frazil particles) and to verify and improve upon the obtainable frazil characterizations, ASL Environmental Sciences has initiated laboratory measurements and calibrations on both spherical and discoidal neutrally buoyant pseudo-frazil particles. The information extracted from these forthcoming laboratory tests, to be carried out simultaneously at four different acoustic frequencies, are intended to provide the basis for development and verification of a more general algorithm which could be applied to quantitatively characterize frazil populations. The field verifications might be most practicably accomplished by simultaneously recording high resolution video data on frazil conditions under stationary river ice above a SWIPS monitoring site.

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