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(Supplementary)

What is the Relative Importance of Frazil and Anchor Ice in a Freezing River and Do We Have the Measurement Tools and Data to Answer that Question?

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Abstract

Unexpectedly low frazil concentrations in freezing rivers (Marko et al., 2015) have been interpreted (Marko et al., 2017) as evidence for the dominant role of *in situ* anchor ice growth in the formation of annual river ice covers. This interpretation has been shown to be consistent with river thermodynamics and the detailed characteristics of time-variations in both river frazil and anchor ice contents. Nevertheless, without specific technical objections, skepticism regarding the importance of *in situ* anchor ice growth has persisted in a sector of the river ice research community. This skepticism reflects, in part, the assumption in most river ice models that high concentrations of water column frazil rise to the surface to form the seasonal ice cover. Additionally, the data supporting the new results were obtained by an unfamiliar multifrequency acoustic profiling methodology and appeared to contradict the higher concentrations previously deduced (Ghobrial et al., 2013) with a, nominally, simpler acoustic technique. This situation, potentially indicative of continuing uncertainties in river ice measurements and understandings, is addressed by a critical review of frazil measurement alternatives. It is shown that currently available modern field data on river frazil content are almost completely limited to results obtained with, alternatively, applications of multifrequency- and single-acoustic frequency methodologies. In both of these approaches, critical calibration and verification tests were carried out in laboratory tanks. Reviews of these tests and subsequently obtained results are provided to facilitate assessing the current status of frazil measurements and their implications for river ice production.

Weaknesses and uncertainties were identified in both approaches. However, unresolved and debilitating errors were found to be confined to the single frequency approach. Particular difficulties in the latter case were introduced by inadequate ice mass measurements and uncontrolled frazil growth which favoured production of frazil concentrations too high to be relevant to river applications. These defects in the laboratory data were compounded by reliance on tenuous and contradictory connections to link laboratory and field frazil data. This approach, effectively, tried to use ice mass and acoustic measurements in a cold room test tank to produce a universal regression for estimating the frazil content of any river from acoustic backscattering measurements. Major conflicts were apparent with observed frazil variabilities and fundamental understandings of acoustic backscattering dependences. An equivalent examination of the credibility of the multifrequency acoustic approach, on the other hand, identified abundant direct and indirect verifications of consistency and accuracy. These verifications included laboratory tests on stable frazil surrogate targets and field measurements on seasonal frazil. In both cases, close agreement was achieved with a detailed scattering theory which was, itself, previously verified with state-of-the-art acoustic instrumentation. Additional inferences of widespread *in situ* anchor ice production suggested by the frazil content results were separately verified by independent acoustic, visual and water level observations. The estimated anchor ice growth rates were quantitatively compatible with both the estimated variations in frazil content and with a simple thermodynamic anchor ice growth model. Although additional independent testing is to be encouraged, these results suggest that the multifrequency approach presently offers a solid basis for continuing studies of freezing river environments.

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1.Introduction

ASL Environmental Sciences Inc. has been building acoustic profiling instruments for more than two decades. This activity was an outgrowth of its much longer (since the Company's founding in 1977) involvement in the science of cold region marine and freshwater environments. Since 2004, such efforts have included introducing and refining a line of Shallow Water Ice Profiling Sonar (SWIPS) instruments broadly intended to resolve outstanding issues in river ice growth and behaviour. A particular issue, the absence of reliable quantitative data on frazil ice formation, a critical step in the growth process, motivated relatively intense efforts. Reports on the obtained results have been circulated through a series of journal publications (Marko and Jasek, 2010 a,b; Marko and Topham, 2015; and Marko et al., 2015). This work led to a broad, largely SWIPS-based, refinement of understandings of frazil growth which, we believe, represents a significant alteration of prevailing conceptions. Our results were recently made available to SWIPS users and others as an ASL Technical Report (Marko et al., 2017). This form of distribution, as opposed to publication in the journal which disseminated earlier work, reflected the difficulties encountered navigating a split panel of reviewers which objected to use of "unverified" technology and excessive speculation.

It has become obvious that there is a segment of the river ice community which is both wedded to a dominant paradigm on the role of frazil ice and skeptical of slightly complex but relatively standard acoustic methodologies. Penetration of such attitudes into the scientific communication process can undermine confidence in potentially powerful tools for studying rivers and other ice-infested environments. Lack of access to information obtained with such tools could continue to restrict research to the unproductive pathways which originally triggered calls for new technological developments.

The present Report tries to rectify this situation through a brief review and evaluation of the history of frazil-related measurements. By default, driven by the lack of success obtained with other approaches, attention is quickly focused on the acoustic methodologies which have been successful in similar, non-ice related, applications. Most attention is given to two specific long term research efforts which, we believe, have provided the primary evidential bases for contending views on frazil ice. In both cases, weaknesses and strengths of the works and their origins are identified and explored to, hopefully, facilitate informed judgements on the questions raised in the title of this Report.

2. Background

Over the past few decades, organized efforts to understand, model and control freezing rivers have repeatedly cited (Daly, 1984; 2013) a crucial need for developing capabilities for accurate measurements of water column frazil content. These calls reflected the apparent ubiquity of frazil occurrences prior to appearances of surface ice as well as, primarily, laboratory evidence that ice cover development proceeds through the buoyant rising of frazil ice (Daly and Axelson, 1989). Although this point of view was built into most numerical river ice models, information on frazil particle sizes, and numbers was sparse and, until the early years of the present century, continued to be obtained by manual and photographic sampling techniques. Most of this work was carried out in laboratory flumes and in laboratory and outdoor tanks, supplemented by small numbers of field observations (Carstens, 1966; Gosink and Osterkamp, 1983).

Instruments designed to estimate frazil content have utilized: water resistivity (Tsang, 1985); flow through screens (Daly and Rand, 1990); and calorimetry (Lever et. al. (1992). These methods offered neither sensitivities nor response times suitable for practical field- or laboratory-applications. Initial successes in these regards were obtained by Pegau et al. (1996) using optical methods in a freezing Arctic lead. The latter work employed both a laboratory-calibrated commercial transmissometer and a three frequency optical absorption meter. Estimates of frazil concentration, expressed as fractional volume (F), were obtained at concentrations up to 0.005% from a transmissometer attached to a CTD profiler. No information on particle sizes was obtained with this approach. The careful laboratory calibrations essential to this work were deliberately limited to frazil concentrations low enough to avoid the presence of flocs and aggregates as well as possibilities for significant multiple scattering (i.e. light paths representing successive scattering by more than one frazil particle).

More recent optical work (Clark and Doering, 2006; MacFarlane et al., 2013) focused on determining relative occurrence probabilities for frazil particles of different sizes and shapes but yielded no information on water column frazil mass content. As in all previous approaches, this methodology returned data over short (cm) ranges within small, well-defined, sampling volumes.

Acoustic profiling techniques were only introduced into the frazil measurement problem a little more than a decade ago, although similar methods had been in use since the 1980's for remote current measurements and for quantifying water column biological and suspended sediment content. These techniques utilized the favourably low attenuation rate of sound propagating in water to allow simultaneous sampling of large portions of the water column using backscattered acoustic pulses. Introduction of this technology into river frazil studies was first suggested in 2004 by Brian Morse of Laval University who requested that ASL Environmental Sciences modify its IPS4 Ice Profiler instrument (typically used for ice draft measurements) to allow continuous recording of acoustic backscattering data. This enhancement allowed access to acoustic returns from targets at all water column levels. The resulting retrofitted IPS4 instrument enabled direct observations of suspended frazil variations (Morse and Richard, 2009) but was handicapped by the relatively low signal to noise ratios characteristic of the narrow acoustic beams required to optimize draft measurement accuracy. At about the same time, ASL produced a purpose-built broad beam single frequency (254 kHz) Shallow Water Ice Profiling Sonar (SWIPS) instrument with sensitivities suitable for detailed frazil monitoring. This instrument was deployed by BC Hydro in the Peace River over the 2004-2005 winter. The obtained results (Jasek et al., 2005) included: documentation of growth and changes in both the surface ice cover and in water column frazil contents. The acquired data readily allowed distinctions to be made between the characteristics of suspended particulate ice as detected, alternatively, prior to and after ice cover consolidation. Significant impacts of anchor ice growth were also detected in terms of both returns from ice accumulations on the instrument and by its effects in physically destabilizing the instrument platform.

The consensus opinion of the research community, at that time, was that the "new" technology should be directed at addressing the absence of credible estimates of water column frazil mass. This task was assumed to require use of multifrequency profiling techniques similar to those used in acquiring equivalent biological- and sediment-profiling data. To facilitate this effort, ASL expanded SWIPS capabilities to include acoustic frequencies both higher and lower than employed in the 2004-2005 Peace River program.

Two specific research programs were initiated in Canada to explore acoustic frazil content measurement capabilities. Both programs used similar SWIPS instruments but diverged significantly in the utilized methodologies. One of these efforts was centred in the University of Alberta Water Resources Engineering (UAWRE) Group while the other consisted of ongoing instrument development work at ASL Environmental Sciences and continuation of its collaboration efforts with BC Hydro. The approaches taken and the results achieved in these two programs will be discussed in Section 3 following an outline of the multifrequency profiling approach which, we believe, was originally intended to be the basis of both research programs. The key steps in each program will be identified along with the corresponding objectives, underlying rationales, and respective weaknesses and strengths. It is our intention that this summary and commentary should facilitate critical assessments of the assumptions and methods which undergird two very different approaches to quantifying and interpreting river frazil processes.

3. Acoustic profiling of suspensions of small targets

3.1 Multifrequency Acoustic Methodology

Most acoustic methods for estimating per unit volume particle contents ultimately draw upon the relationship:

$$s_v(\nu) = \sum_{1}^{n} N_i \sigma_i(\nu, a_i) \ , \qquad [1]$$

to connect backscattering coefficients $s_v(\nu)$ measured at a frequency ν to the per unit volume concentration of particles of type “i”, N_i, characterized by a backscattering cross section $\sigma_i(\nu, a_i)$ where a_i denotes a particle dimension (typically, a particle radius). The back scattering coefficient and cross section quantities, respectively, represent the per unit volume and per unit area fractions of incident acoustic energy which are scattered directly back toward an acoustic source by such particles. Given knowledge of the relationship $\sigma_i(\nu, a_i)$, simultaneous measurements of $s_v(\nu)$ at several different frequencies can allow separate estimation of N_i and a_i.

In frazil content applications, this estimation approach usually has been limited to utilizing measurements at two or three frequencies. In the two frequency case, measured backscattering coefficients, $s_v(\nu_a)$ and $s_v(\nu_b)$, allow evaluation of just two parameters on the right hand side of Eq.1: N and a* corresponding to a concentration of N identical particles/unit volume characterized by a single, representative, radius a*. Making such parameter determinations requires knowledge of the relationship $\sigma(\nu, a)$.

Measurements at three frequencies and assumption of the ubiquitous lognormal form of particle size distributions allow still more realistic characterizations in terms of quasi-continuous distributions of particle size parameters. This approach assumes backscattering coefficients take the form;

$$s_v(\nu) = N \int_0^{\infty} g(a)\sigma(a, \nu)da \ , \qquad [2]$$

where, again, a denote$_s$ a radius parameter determining both particle volume and backscattering cross sections, σ. The factor g(a) is a lognormal probability distribution satisfying:

$$\int_0^{\infty} g(a)da = 1 \ , \qquad [3]$$

expressed as:

$$g(a, a_m, b) = \left[(2\pi)^{0.5} ba\right]^{-1} e^{-\{0.5(\ln(a/a_m)/b\}^2} . \qquad [4]$$

The two additional parameters in Eq. 4 are: the median effective radius, a_m and b which governs radius variance or the “spread” of the distribution. The three parameters N, a_m, and b can be determined from simultaneous measurements of $S_v(\nu)$ at three different frequencies.

In both the two and three frequency cases, knowledge of the population parameters allows straightforward calculation of F, the fractional portion of the water column occupied by frazil ice. In the two frequency case, where a_o denotes the radius of the assumed uniformly sized particle distribution:

$$F = (4/3) N \pi a_o{}^3 . \qquad [5a]$$

The three frequency results yield values of F given by:

$$F = N \int_0^\infty (4/3)\pi g(a, a_m, b) a^3 da , \qquad [5b]$$

for optimal values of N, a_m and b.

Considerations of the efficacy and accuracy of such methods have largely focused on the reliability of the relationship $\sigma_i(\nu, a_i)$ assumed to link particle backscattering cross sections to incident frequencies and particle dimensions. These relationships are sensitive to frequency and target properties such as particle shape, size and intrinsic mechanical properties such as the speeds of sound in the material. Fortunately, key sensitivities can be dealt with through the widespread applicability of a modern algorithm for calculating theoretical cross sections of spherical targets. The algorithm is the basis of all precise calibrations of acoustic receivers and transmitter. Moreover, cross sections of most non-spherical targets deviate only fractionally from those calculated with this algorithm for spheres with radii, a_e, equal to an “effective radius”: i.e. the radius of a sphere of volume equal to that of the object. Moreover, the extents of these deviations only become significant when the particle size/acoustic wavelength ratio exceeds an approximate threshold value. In frazil content applications, proper choices of measurement frequencies could, in principle, allow accurate estimates to be based upon a well-established relationship $\sigma(\nu, a)$. Such estimates could utilize either the single term version of Eq. 1 (for 2-frequency measurements) or Eq. 2 when measurements are made at three frequencies. Of course, some cautions are required to avoid the complications introduced, primarily near the river surface, by floc and aggregate formation.

Other, possibly more important, restrictions on measurement validity are imposed by the basic assumptions underlying Eqs. 1 and 2. These assumptions all concern the independence of individual scattering events. This independence allows the detected returns of acoustic energy to be expressed as the sum of energies scattered by individual targets. Failure of this assumption occurs when the combination of the numbers of particle targets per unit volume and their individual cross sections dictate that significant fractions of the detected returns have been scattered two or more times (multiple scattering) by different targets. The consequences of this failure become evident in both the added complexity of signal return strength on particle numerical densities and, for extremely large strengths and densities, through attenuation of the acoustic power incident on targets and receivers. Such effects would confound accurate acquisition of $S_v(\nu)$ vs range data: becoming particularly problematic in measurements at higher frequencies giving rise to large σ(ν, a) values. As noted above, Pegau et al. (1996) took explicit precautions to avoid such problems in transmissometer calibrations. Assessing the importance of these effects in field estimates of frazil content has not been helped by the absence of reliable independent estimation procedures. Consequently, self-consistency remains an essential requirement for acoustically derived results: i.e. estimated fractional volumes must be low enough to rule out invalidation by non-linear multiple scattering and attenuation effects.

3.2 Acoustic Profiling at UAWRE

A research program was initiated at the University of Alberta in 2008 to calibrate and use ASL SWIPS instrumentation for frazil content measurements. The first stage of this work was carried out in a small 0.8 m by 1.2m by 1.5 m cold room tank. Two ASL single frequency (235 and 546 kHz) upward-looking (vertical beam) SWIPS instruments were mounted side by side on the tank floor in 1.5 m of water. Eight propellers on the interior walls and floor (Ghobrial, 2012) raised turbulence levels to facilitate frazil formation. Almost 50 separate frazil production events were studied in detail. In each case, SWIPS pulsed acoustic return data were acquired, near-simultaneously at each acoustic frequency, at 1 Hz pulse repetition rates. Analyses focused on acoustic data acquired near the end of each frazil event since independent frazil content data were only acquired upon event termination. This acquisition involved raising three gridded wire baskets, with a mesh size of 1.8 mm, from the floor of the tank. The ice masses collected in each basket were drained and weighed to estimate per unit volume contents of water column frazil (fractional volume) representative of immediately preceding acoustic measurements. Particle size information gathering was limited to microscope examinations of crystals manually selected after each of 12 growth events. The number of particles documented in this way (316) was not sufficient to yield size probability distributions but indicated the predominance of disk-shaped particles with a 1.97 mm mean sampled diameter and variance of 0.89 mm. More quantitative, particle size distribution, data were collected (Ghobrial et al., 2013) with optical imaging techniques (McFarlane et al. 2013) during an unspecified number of events. These results found the diameters of the disk-shaped particles to be distributed lognormally with a 0.80 mm mean value over a range between 0.04 mm and 5.08 mm. It was recognized that, given the 1.8 mm collection mesh size, the fractional volumes estimated for such distributions were likely to be lower than actual values.

Initial comparisons were made between measured mean water column s_v values at two different acoustic frequencies, ν_H and ν_L (denoting high (H) and low (L) frequencies) and values calculated using Rayleigh Theory or a close variant. Such theories imposed an upper limit of approximately 29.1 on $s_v(\nu_H)/s_v(\nu_L)$. Measurements (Ghobrial et al., 2012) indicated this ratio rose with time during an event: starting out well below this limit but rising, first, to about 50 and then to above 90 prior to event termination. It was concluded that, under such circumstances, combined use of $s_v(\nu)$ values measured at two different acoustic frequencies (i.e. the "two-frequency" approach) would not offer a laboratory-verified route to estimating frazil content. Given the discussions of Section 3.1, this failure was the likely consequence of the combinations of sizes, shapes and concentrations characterizing the frazil particles. Thus, large, non-spherical particles would be expected to significantly alter the Rayleigh-like character of the $\sigma_i(\nu,a_i)$ relationship while high particle concentrations would have introduced multiple scattering and attenuation effects. Either or both of these changes could have invalidated the applicability of Eqs. 1 and 2.

The origins of such problems were apparent in the observation (Ghobrial et al., 2013) that acceptable $s_v(\nu_H)/s_v(\nu_L)$ ratios were recorded at the lower end of the tested, nominally 0.012% to 0.135%, fractional volume range. (As noted above, incomplete sieving dictated that these bounds underestimated the actual lower and upper limits of the testing.) This range was similar to the ranges reported for other laboratory studies: 0.065% to 0.61% (Ettema et al., 2003); 0.01%-to 1% (Ettema et al., 1984); and 0.1% to 0.17% (Ye et al. 2004). Nevertheless, even the lowest nominal UAWRE laboratory value was about 3 times higher than the first reasonably credible field estimate of frazil fractional volume, 0.005% (Pegau et al., 1996). Although the latter estimate was made in a marine setting, an identical value was also reported by Marko and Jasek (2010c) on the basis of two-frequency analyses of 2009 Peace River SWIPS data. Comparisons with these earlier results would have suggested the possibility that most of the UAWRE laboratory tests were being carried out on frazil fractional volumes larger than likely to be encountered in actual field situations.

It was surprising that subsequent analyses did not follow up on the noted feasibility of two frequency SWIPS measurements for frazil events associated with F ≤ 0.025%. Under such conditions, the corresponding experimental ratios, $s_v(\nu_H)/s_v(\nu_L)$ might have satisfied a basic requirement for Rayleigh Theory applicability and the nominal values of F would have been, at worst, only about 5 times larger than earlier field estimates (Pegau, 1996; Marko and Jasek, 2010c). Instead, perhaps to accommodate the full set of tank data and/or due to difficulties encountered in field-use of the low acoustic frequency SWIPS instrument[1], a "single frequency" approach was applied over the full range of tested fractional volumes. This choice necessitated dealing with the reality (noted in section 3.1) that acoustic estimation of fractional volumes generally requires measures of, at least, two frazil population parameters. Multifrequency methods employ a well-established theory to directly extract such parameters from S_v values simultaneously measured at two or more frequencies. A single frequency approach can, in principle, yield the equivalent of a two frequency frazil characterization if relevant additional data are available from some other source. Such data could be obtained through independent field measurements of one of two population characterization parameters[2], N or a_{mean}. The approach taken in the UAWRE program was to seek essential additional information through empirical connections between the acoustic backscattering properties of frazil as measured in, alternatively, the laboratory tank and freezing rivers. Key laboratory results obtained with this approach using the most sensitive ν_H = 546 kHz acoustic frequency are depicted in Fig.1 in the form of experimental F vs. $S_v(\nu_H)$ data (where $S_v(\nu_H)$ =10 log $s_v(\nu_H)$ denotes the logarithmic version of the backscattering coefficient). The plotted F and $S_v(\nu_H)$ data pairs were, respectively, derived from sieve and acoustic measurements made at the ends of 32 different frazil growth events. These data are accompanied in the Fig. by a corresponding "empirical curve" derived from these data using the basic power law form:

$$F = \alpha(10^{(\beta+\delta S_v)}) \, , \qquad [6]$$

where α is a known function of known acoustic measurement parameters and β and δ are the coefficients of a least squares logarithmic regression. The resulting empirical relationship was intended to provide a

[1] No explanation was offered for this difficulty which was unexpected since the instrument functioned well in laboratory tank depths comparable to those of the field deployments. As well, quality SWIPS data have been have obtained by other users at frequencies at least as low as 125 kHz and in waters as deep as 10 m.

[2] It is not feasiblel to independently "measure" the particle numerical density parameter, N, appropriate to a two parameter population description. It is an "effective' numerical density. Consequently, independent inputs to single frequency frazil content would likely be confined to a mean frazil radius a_{mean}.

means for directly converting field S_v measurements into fractional volumes in situations where ice conditions could be assumed to be identical to those attained in the test tank. Separate empirical curves were derived for high and low acoustic frequency $S_v(\nu)$ data. Focus in subsequent applications and in this review was largely given to acoustic data acquired at ν_H = 546 kHz.

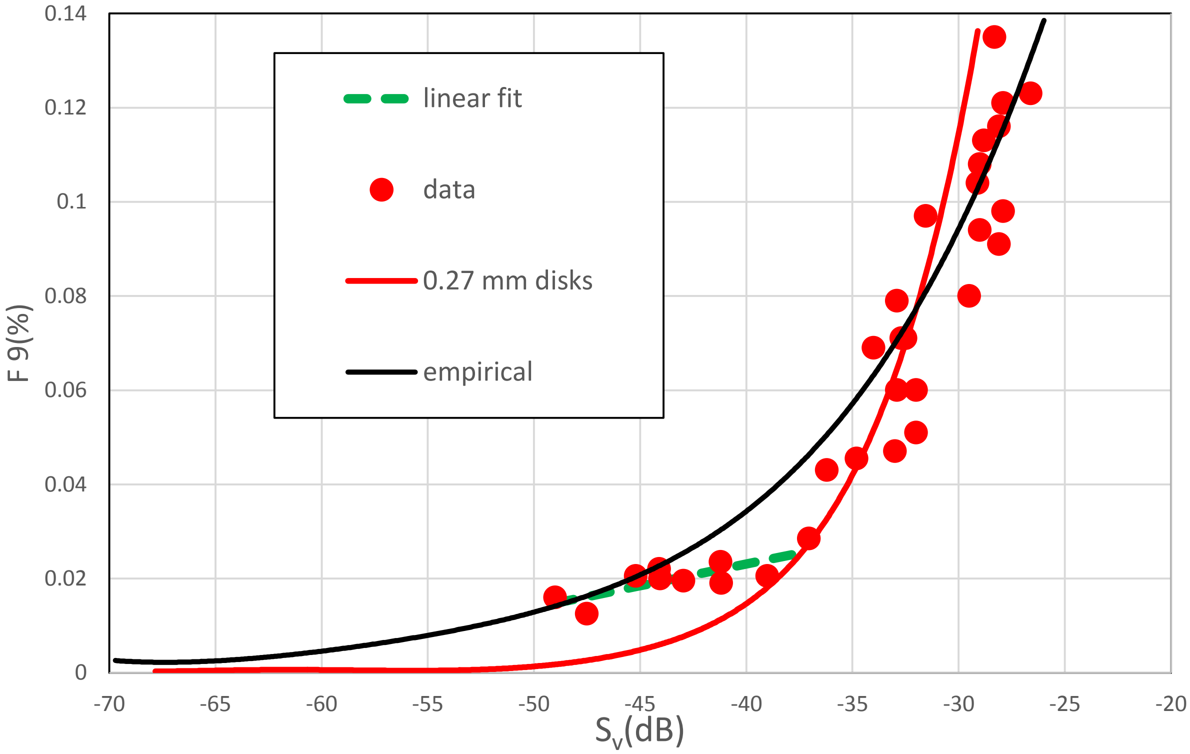

Fig.1. (Adapted from Ghobrial, 2012) Plots of UAWRE test tank frazil fractional volume (F) vs. backscattering coefficient (S_v) data and a resulting least square "empirical" regression fit to Eq. 6. Additional curves include a linear regression applied to data points for F < 0.03% and a curve to represent optimal theoretical (F, S_v) results calculated for using the Coussios (2002) theoretical cross section for a population of identical frazil disks of radius=0.27 mm.

Unfortunately, fully reliable frazil field S_v data were not available in the literature at the outset of the UAWRE research. It is now apparent that the great bulk of the laboratory work was carried out on frazil present in fractional volumes large enough to produce backscattering strengths well beyond levels usually attained in actual river settings. Thus, current best estimates, derived from 455 kHz and 774 kHz data acquired in the 2011-2012 Peace River program (Marko et al., 2015), suggest that the upper limit for S_v at the 546 kHz test tank frequency was, approximately, -37 dB. This value is just 1 dB above the largest S_v value, -38 dB, reported in the UAWRE North Saskatchewan River measurements (Ghobrial, 2012). Consequently, only that fraction of the empirical tank data plotted in Fig. 1 for nominal fractional volumes < 0.03% was likely to be relevant to characterizing river frazil populations. Since approximately two thirds of the tank data were acquired for F ≥ 0.03%, the empirical relationship derived using all data points was least representative in, precisely, the data regime of interest. In fact, as indicated by the included straight broken-line curve in Fig. 1, the empirical data in the field-relevant, low fractional volume, regime, were most closely represented by a simple linear regression. Use of the latter regression to interpret field S_v data in this regime would have lowered fractional volume estimates from those derived with the logarithmic regression curve by, roughly, a factor of two.

Several other factors further complicated applications of the empirical approach. One such limitation was the resolution attainable in the $F < 0.03\%$ regime. The total range of variation in this regime, approximately 0.01%, represented a fractional volume increase of less than 50%. Since this increase was coincident with a 12 dB increase in S_v values (a sixteen-fold increase in s_v), F was a relatively weak and noisy "signal": seriously limiting the accuracies of frazil contents estimated from S_v data. Specifically, the 0.0026% standard error in the $F < 0.03\%$ data regime, corresponding to 3.3 dB changes in S_v, represented about 25% of the total range of variation in fractional volume.

Restriction of usable empirical results to fractional volumes < 0.03% also vitiated critical steps in a work program which, because of the chosen empirical approach, had to use laboratory results to justify their own applicability to river acoustic measurements. These justifications drew upon two basic assumptions. One of these was that that the relative "shapes" of particle size probability distributions did not change during frazil growth. The second, and much more consequential assumption, was that the size distributions attained in the test tank were quantitatively expressible in a convenient form due to an underlying, almost exclusive, dependence of backscattering on frazil fractional volume.

The possibility of continuity in the "shapes" of river frazil particle size distributions during frazil growth events was suggested by Osterkamp and Gosink (1983) on the basis of time-lapse field photography data. This "similarity", presumably equivalent to relatively fixed values of the parameters a_m and b in Eq. 4, was also reported (Ghobrial et al., 2013), without elaboration, to have been observed with optical methods (McFarlane et al., 2013) in the UAWRE tank measurements. Contrary field data were reported (Marko et al.; 2015, 2017) (Section 3.3) showing significant changes occurring in size distribution parameters during individual frazil events. Such changes would not be inconsistent with other UAWRE tank measurements (McFarlane et al., 2015) which identified strong dependences of mean particle size on turbulence intensity. The latter results would suggest that the variations in turbulence levels, which are likely to accompany complex frazil growth events (Marko et al., 2017), could undermine size distribution stability. Further doubts in this regard were raised by the empirical data in the only portion of Fig. 1 relevant to river frazil measurements: i.e. where $F < 0.03\%$. Similarity in this data regime would have required that increases in fractional volume occur through progressive increases in the numbers of particles/unit volume, N, as opposed to changes in the, presumably, fixed shape-controlling statistical parameters a_m and b. Since N appears as a multiplicative factor in both s_v (Eq. 2) and F (Eq. 5a,b), the observed, roughly, 50% relative increase in F, should have been accompanied by a, logarithmically equivalent, 2.3 dB, increase in S_v. The much larger, 12 dB, observed increase suggests that relative size probability parameters varied with fractional volume during either individual frazil events or from event to event. It was suggested (Ghobrial et al., 2013) that this result might be evidence that the "sieving technique was not as sensitive as high frequency sonar to concentrations below (0.025%)". While this suggestion has merit, it also calls attention to the fact that this experimental shortcoming introduced major uncertainties into the only body of tank data of potential use for estimating river frazil content.

The second, more far-reaching, justification for the utility of tank results was based upon claimed similarities between the empirical F vs S_v curves and relationships derived by applying Rayleigh-like theories to hypothetical populations of nearly identically-sized particles. In the latter case, pairs of S_v and F values were calculated as a function of disk radius using, for the S_v calculation, the logarithmic form of the one term version of Eq.1 and a theoretical expression (Coussios, 2002) for disk backscattering cross sections. An F vs. S_v relationship of this type is plotted in Fig. 1 for the most favourable, 0.27 mm, choice of disk radius. Unfortunately, the magnitudes of corresponding representative and empirical values of F differ by almost an order of magnitude in the most relevant $F < 0.03\%$ and $S_v < -37$ dB data regime. Rough similarities in the shapes of the hypothetical distribution curve and its empirical-counterpart were confined to the $F > 0.03\%$ and $S_v > -37$ dB range which contained the bulk of the empirical data but was irrelevant for river applications. Additionally, it was shown that, inclusion of similar representative curves for disk diameters of 0.21 mm and 0.35 mm completely enveloped all empirical points in the latter data regime. The appearance of similarities was hardly surprising since F was defined in all cases, through Eqs. 1 and 6, to be an exponential function of S_v. Closer examination, however, shows that, even in the best represented (high F and high S_v) regime, the slope of the plotted representative curve was twice that of its empirical counterpart. Given the logarithmic horizontal plotting axis, this difference indicates that the fractional volumes represented by the hypothetical uniform disk size relationships were much stronger functions of S_v than indicated by the empirical relationship. In short, there was no close functional correspondence here. Nevertheless, it was argued that, by reproducing the bounds of the river-irrelevant empirical data with a modest spread of disk radii, one could conclude that "the population of frazil ice can be represented by a single dominant size which implies that the backscattered signal is mainly a function of concentration (rather than concentration and particle sizes)".

The empirical curve plotted in Fig. 1 was applied to Peace River (Jasek et al., 2011) and North Saskatchewan River (Ghobrial, 2013) S_v data to obtain corresponding estimates of F. For the Peace River, this procedure yielded typical and peak fractional volumes of, respectively, 0.015% and 0.033%. Peak values of F for 8 separate North Saskatchewan River frazil intervals were found to range between 0.012% and 0.049%. The claim of equivalent representation in terms of, alternatively, the empirical F vs. S_v relationship and "representative" populations of uniformly sized, Rayleigh-like, particles was then employed to justify applying laboratory tank results to interpret river S_v data. The intention was to show that a representative hypothetical F vs. S_v curve could closely reproduce estimates of F previously derived from the empirical curve of Fig.1. It was claimed that such a demonstration would further support the assertion that measured backscattered coefficients were primarily functions of fractional volume.

In principle, given such a dependence, the 0.27 mm disk radius Rayleigh-like curve in Fig.1 should have, on its own, allowed equivalent extraction of fractional volumes from North Saskatchewan River (or Peace River) S_v data. Inspection of Fig.1, however, indicates that this approach would not yield estimates compatible with results obtained using the empirical curve. The difficulty was that, as noted above, the Rayleigh-like curve in Fig.1 (optimized to fit all the (S_v,F) data) fell an order of magnitude below the empirical data points in the river-relevant $F < 0.03\%$, $S_v < -37$ dB data regime (which encompassed all North Saskatchewan River S_v data). The resulting matching problem was addressed by tuning the Rayleigh-like curve by reducing disk radii to values in the 0.13 mm-0.19 mm range (roughly 60% below the optically estimated mean disk radius). Such changes were equivalent to leftward-shifts of the 0.27 mm hypothetical distribution curve of Fig.1 which raised values of F for S_v values in the river-relevant (-50 dB $< S_v <$ --37 dB) data range. The need for such an adjustment, in itself, appears to contradict prior assertions that the empirical tank curve could both be represented by Rayleigh-like scattering from a population of 0.27 mm radius disk particles and be used (Jasek et al., 2011) to estimate F from Peace River S_v data.

Although no comparisons of the tuned hypothetical and empirical F vs. S_v curves were presented, the use of smaller disk radii would have greatly degraded prior matching with the river-irrelevant tank (S_v, F) data. As well, given the extremely small sizes of the tuned radii, the adjustments would have required corresponding particle numerical densities to be so large ($N \approx 10^8$ m^{-3}) as to invalidate the independent scattering assumption embedded in Eq. 1. Such numerical densities would have been two to three orders of magnitude larger than values previously reported (Daly, 1984; Marko et al., 2015) as typical of observed frazil populations. Nevertheless, it can be assumed that, as required to match the empirical data, the tuned Rayleigh-like curves closely approximated the empirical curve in the critical F < 0.03%, S_v < -37 dB data regime associated with the North Saskatchewan River data. Consequently, the values of F derived with the tuned representative curve were usually well within 50% of corresponding values based upon the empirical curve and, likewise, exhibited similar time variations. In our view, this agreement was simply a demonstration of the curve-fitting flexibility offered by a Rayleigh-like distribution with two adjustable parameters.

Ghobrial et al. (2013), on the other hand, concluded that: "If the suspended frazil ice particles in the North Saskatchewan River were significantly different in size and shape than those produced in the laboratory it is unlikely that the theoretical and empirical time series ….would agree so closely". This conclusion was based upon a claimed equivalence between a uniformly-sized frazil disk population with unphysically high numerical densities and diameters ≈ 0.3 mm in a flowing river and an incompletely characterized frazil distribution with a 0.8 mm mean diameter in a laboratory tank. The latter distribution had been previously represented by another uniformly-sized distribution of disks with diameters just slightly smaller than 0.6 mm. No evidence was presented to allow judgment on the quality of the F values extracted from the North Saskatchewan River data other than that these values were, as intended by the applied radius reductions, very similar to those obtained using the suspect empirical curve. The degree of agreement was taken to be sufficient to, again, confirm "that the sonar signal is largely a function of concentration". This powerful and scientifically revolutionary, assertion, thus, provided the basis for justifying both the relevance of hypothetical Rayleigh-like populations and the usefulness of empirical tank acoustic results. Specifically, if all the above assertions were valid, fractional volumes in any river could be read directly off the empirical curve in Fig.1 for corresponding measured S_v values.

In our view, the circularities and inconsistencies introduced in reaching the above conclusions preclude credible use of the UAWRE empirical methodology to derive frazil content estimates from river acoustic backscattering data. The proposed approach violates, without explanation, long-confirmed understandings of acoustic backscattering derived through methods which, repeatedly, have been successful in other, non-ice-related, applications (Sheng and Hay, 1988; Thorne and Campbell; 1992 and Stanton, 1989). Most specifically, there was no evidence presented that could lead one to ignore the extremely strong dependence of backscattering on the dimensions of the frazil particles present in the test tank and in the two surveyed rivers. No consistent links were demonstrated to exist between frazil populations in any river and those attained in the UAWRE tank. Finally, the value of the data employed in developing or exploring the proposed methodology was seriously undermined by an inadequate but critical independent verification procedure and by the unfortunate prevalence of measurements on frazil populations too concentrated to be representative of natural rivers.

3.3 Acoustic Profiling by ASL Environmental Sciences and BC Hydro

Initial circulation of the UAWRE results motivated unplanned additions to ASL's instrument development activities and its involvement in BC Hydro Peace River field programs. These efforts reflected expressed concerns that commonplace acoustic profiling procedures could, somehow, be considered inapplicable to frazil measurements. A broad claim (Ghobrial et al., 2012) that "it is not possible to measure and quantify all the acoustic and material characteristics of suspended material required to directly model the volume backscatter strength S_v for particle concentrations" contradicted a large body of evidence but, still, called for quantitative refutation.

To do this, ASL initiated an extensive laboratory program of backscattering measurements at 4 different acoustic frequencies between 125 kHz and 769 kHz using populations of suspended targets of a common size and shape. In each case, particles were drawn from one of 9 different species of disk- and spherically-shaped polystyrene target particles suspended in brine, with a density adjusted to match that of polystyrene value, within a 1.77 m by 0.96 m by 0.69 m test tank. Our choice of non-ice targets with sizes and shapes similar to those of frazil crystals avoided the target characterization and uncontrolled growth difficulties encountered in the UAWRE study. The objective of the testing was to establish the extent to which backscattering sensitivities to particle sizes, shapes, composition and volume concentration were explicable in terms of a credible theoretical formulation of backscattering strength. Use of less than perfect, but still mostly satisfactory, frazil surrogates avoided stability and verification issues: offering a basis for testing theoretical linkages between basic target and target population descriptors and acoustic backscattering coefficients.

Specifically, precise knowledge was in hand on particle dimensions, mass densities and key material parameters (longitudinal and shear wave speeds of sound in the target material) for populations of identical disk-shaped particles of known concentrations. Additionally, the inclusion of a single species of spherical particles with individual volumes identical to those of one disk species allowed testing of the convenient "effective radius" concept. This concept assumed the theoretical cross sections of spherical particles to be representative of cross sections of non-spherical particles having the same volume. Cross sections deduced from backscattering coefficient measurements on each species were compared with theoretical expectations from a modern version of the Rayleigh Theory as modified by (Anderson, 1950 and Faran, 1951). This Theory was encapsulated in a convenient algorithm by Chu (Marko and Topham, 2015) expressing backscattering cross sections for elastic spheres of any material in any fluid as functions of radius, mass density, intrinsic speeds of sound and acoustic frequency. The Chu algorithm is at the core of standard precision acoustic calibration methodologies. Its applications to frazil problems allowed exploitation of the effective radius concept which is consistent with evidence that, at sufficiently small values of the particle size to acoustic wavelength ratio, backscattering cross sections in a given fluid are primarily functions of acoustic frequency, particle volume and target material properties.

The immediate intention of the work was to assess the extent to which knowledge of target particle size, shape, concentration, composition and acoustic measurement parameters allows accurate recovery of target population information from acoustic backscattering data. Given the assertions made in the UAWRE work, focus was given to: 1) establishing the degree to which a reliable theory can support such recovery for realistic particle population parameters and convenient acoustic frequencies; and 2) to identify conditions under which such capabilities become significantly degraded. The research program consisted of a series of measurements of s_v at 4 acoustic frequencies (125, 200, 455 and 769 kHz) for several successively higher particle concentrations. Initial interests were in both the extent to which s_v maintained linearity with respect to particle concentration in accord with Eqs. 1 and 2) as well as in the dependences of these extents on acoustic frequency, particle size and concentration (fractional volume) parameters.

Key insights were obtained from measurements on the 1 mm diameter disks associated with effective radii equal to the radii (0.295 mm) of the similarly studied 0.59 mm diameter Microbead spheres. Co-plots of the two bodies of data showed that persistence of nearly identical linear concentration dependences below a common threshold concentration was confined to the two lowest acoustic frequencies (125 and 200 kHz) (Figs 2a,b). At higher concentrations, > 6×10^6 m^{-3}, s_v increased with concentration at a greater than-linear rate. At 455 kHz, non-linearity was, again, confined to particle concentrations > 6×10^6 m^{-3}. In this case, however, the slope of the 1 mm disk line, the measure of average individual particle cross sections, was noticeably lower than that associated with the spherical particle data. In other words, the cross sections of individual disks were smaller than expected from spheres of equal volume.

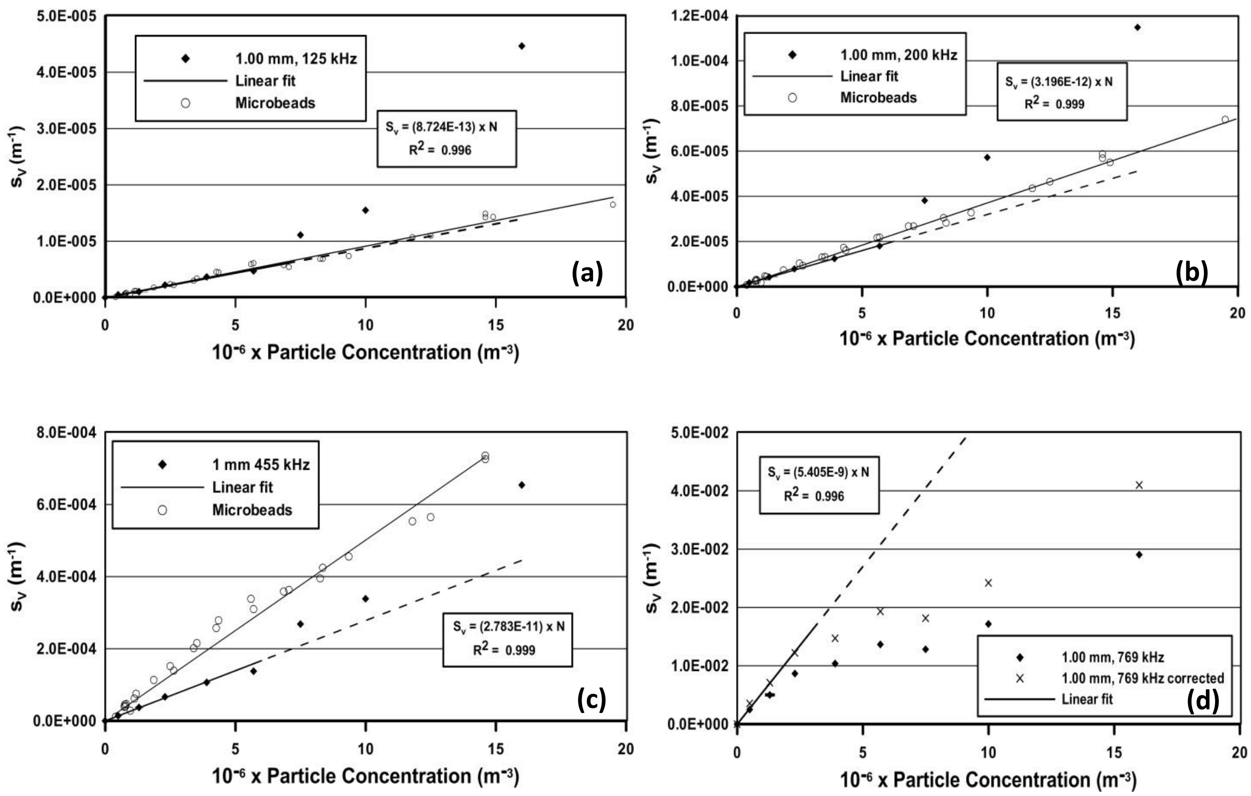

Fig. 2. Plots of S_v as a function of w = 1.00 mm Glitter particle concentrations and corresponding linear representations based upon measurements at: (a) 125 kHz; (b) 200 kHz; (c) 455 kHz and (d) 769 kHz. Estimated measurement uncertainties are depicted in each plot by horizontal bars positioned one standard error above and below a representative linear regime data point. Data in (d) include additional entries representing values obtained after corrections (described in text) for attenuation. Microbead data and associated thinner solid line linear fits are also included in (a), (b) and (c) to illustrate differences in, disk- and effective radius sphere target results.

Contrary behaviour was evident in the 769 kHz results (Fig. 2d). In this case, disk s_v values were roughly two orders of magnitude larger than those associated with equal volume spheres. This strange result was a consequence of a "giant resonance" phenomenon previously observed in polystyrene spheres (Hay and Schaafsma, 1989) of radius a when the quantity ka approached and exceeded unity (where $k_1 = 2\pi/\lambda$ and λ is the wavelength of sound in the fluid). This phenomenon was identified (Heffner and Marston, 2000) as unique to target materials characterized by shear wave sound speeds below those characteristic of the speed of sound in the surrounding fluid. Such conditions do not occur in ice targets and, consequently, the resulting anomalously strong 769 kHz scattering by 1mm and larger polystyrene disks was not relevant to evaluating frazil scattering properties. This quirk of the surrogate particle material put an upper limit on testable combinations of k_1w, where w denotes disk diameter. Comparisons of theoretical cross sections calculated using effective radii for tested disk species with w < 1 mm showed (Fig.3) generally good agreement with values estimated from the linear portions of corresponding s_v vs N curves.

Extensions of measurements to disks with diameters of 1.6, 2.39 and 3.15 mm (Fig. 4) showed similar results at the two lowest frequencies. Specifically, the measured cross sections were close to theoretical expectations derived using the effective radius assumption and the linear regimes associated with these cross sections persisted up to concentrations of 6 X 10^6 m^{-3}, 3 X 10^6 m^{-3} and 1 X 10^6 m^{-3}, respectively. However, at the two highest acoustic frequencies and for the largest, 6.35 mm, disk species, complex interplays of non-linear concentration dependences and the anomalous polystyrene-specific returns ruled out relevance to measurements on similarly-sized frazil particles.

Plotting of measured cross sections as functions of k_1a_e and $k_1w/2$ facilitated identifying acceptable combinations of acoustic frequency and particle dimensions (i.e. which produce measured cross sections in accord with theoretical expectations) satisfying the inequalities: $k_1a_e < 0.7$ and $k_1w/2 < 1.2$. The weaknesses and the strengths of the attained agreements as a function of k a_e are illustrated in Fig. 5 which compares theoretical individual particle backscattering cross sections, with the measured quantities as derived from the low, linear, portions of the tested disk concentration ranges. Experimental deviations from theory on the order of a few dB were confined to the lower and upper ends of plotted k_1a_e.range. The deviations at low k_1a_e (also evident in Figs 3a-b) were, initially, surprising since the corresponding measurement and particle parameters were well within the range associated with classic Rayleigh Theory. In part, this result reflected the lower signal to noise ratios typical of lower acoustic frequencies. Additionally, however, late in the experimental program, a more significant error source was detected during measurements carried out on mixtures of different suspended particle species. Such measurements confirmed that s_v values associated with such mixtures could be accurately predicted from knowledge of mixture composition and individual species cross sections. These results also provided evidence that the deviations from theoretical values detected at very low k_1a_e values were artifacts of the employed stirring procedures. The impacts of this effect were confined to the lowest acoustic frequency and could be eliminated by improving test preparation procedures.

Unfortunately, there was no equivalent way to assure compliance with theory at the high end of the tested k_1a_e regime. In this regime, as indicated in Fig 2c, the underlying effective radius assumption was beginning to break down and, at still larger k_1a_e values, polystyrene-specific deviations became prominent. Nevertheless, the data in Fig. 5 suggested that the Faran cross section theory was capable, even at values of k_1a_e approaching 0.7, of reproducing experimental backscattering cross sections for disk targets with 30-40% accuracy or, in logarithmic terms, to better than +/-1.5 dB. Such results were consistent with earlier acoustic profiling applications which quantitatively deduced water column sediment and zooplankton concentrations from multi-frequency backscattering data using similar theoretical formalisms. In this case, correct representations of individual particle cross sections required only use of parameters describing target material mass density and sound speed parameters as well as the effective radii of individual particles.

The next stage of the ASL research extended the promising laboratory results into the real world of freezing rivers. This extension involved developing RUNSWIPS data processing and extraction software which used Faran Theory relationships to convert multi-frequency backscattering coefficients into frazil content estimates. Data for doing this were available from the 2011-2012 BC Hydro Peace River monitoring program which deployed SWIPS and ancillary sensors in approximately 5 m of water. SWIPS data were collected at frequencies of: 125 kHz, 235 kHz, 455 kHz and 774 kHz. Transmission and reception of energy at 235 kHz utilized an isolated transducer mounting displaced by 18 cm from the single transmission head accommodating the transducers operating at the other three frequencies. The results obtained in this study were reported in detail in Marko et al., 2015.

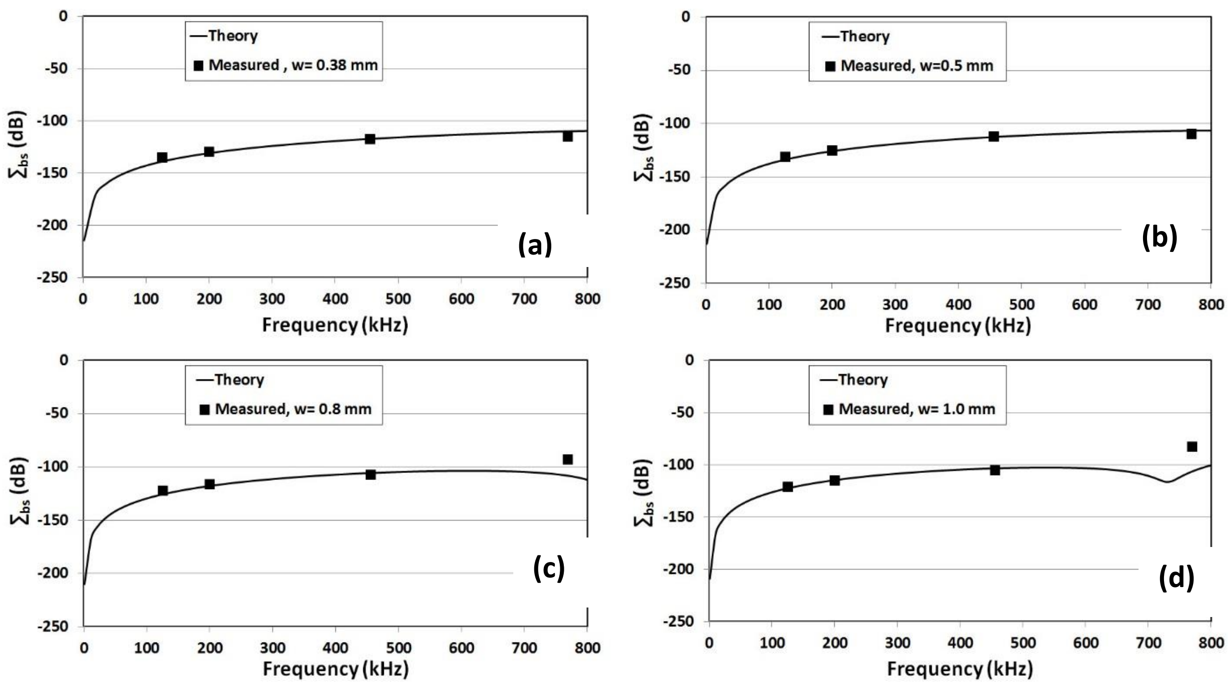

Fig. 3. Plots of theoretical and measured values of Σ_{bs} (equivalent to S_v) as a function of acoustic frequency for brine suspended Glitter particles with widths (w): (a) 0.38 mm; (b) 0.50mm; (c) 0.80 mm; and (d) 1.00mm. "Theory" values were calculated using the Faran (1951) formulation in conjunction with the corresponding "effective radii" of the particles and the optimal polystyrene sound speed parameters.

Unfortunately occasional and still unexplained instabilities in the 235 kHz returns frustrated original plans to base frazil content extractions primarily on 125, 235 and 455 kHz data. These plans reflected laboratory evidence that deviations between measured and theoretical backscattering strengths increased at higher acoustic frequencies. Such increases were, largely, due to effects specific to the utilized polystyrene targets as well as to greater high frequency sensitivities to non-sphericity. Nevertheless, three frequency extractions had to be carried out using the, theoretically less favourable, 125, 455 and 774 kHz combination of frequencies[3]. The extraction process utilized the RUNSWIPS algorithm to compute and utilize successive 10 minute running averages of s_v values at all three frequencies as measured in 4 cm thick horizontal water layers positioned at selectable heights above the common transducer plane. In each case, the logarithmic (S_v) versions of s_v^{meas} (125),s_v^{meas} (455) and s_v^{meas} (774)) were compared to theoretical values computed using the logarithmic version of Eq. 2. The quantity g(a) was expressed as a function of effective radius, a_e, in terms of different combinations of the parameters: N, a_m and b which, respectively, specified the number of frazil particles/unit volume; a median effective radius; and a parameter descriptive of the width of the assumed lognormal size distribution. The comparisons utilized the quantity, q, which was minimized in the optimization process. This quality index represented the sums of squared differences (in $(dB)^2$)between theoretical and measured S_v values. It is expressed as:

$$q = \sum_{i=1}^{i=3} \left[S_v^{meas}(v_i) - S_v^{theo}(v_i) \right]^2 , \qquad [7]$$

where $S_v^{meas}(\gamma_i)$ and $S_v^{theo}(\gamma_i)$ denotes measured and theoretical logarithmic s_v values at the three utilized acoustic frequencies γ_i = 125 kHz, 455 kHz and 774 kHz for each tested combination of N, a_m and b. The

[3] In some intervals, the instability problems encountered at 235 kHz were absent. Frazil contents, determined using 125, 235 and 455 kHz data, were then found to reproduce results obtained with125, 455 and 774 kHz data.

theoretical backscattering cross sections in this expression were calculated from the Faran Theory using the Chu algorithm assuming standard ice values of longitudinal and shear wave sound speed and mass density. Typical distributions of particle numerical densities are plotted in Fig.6.

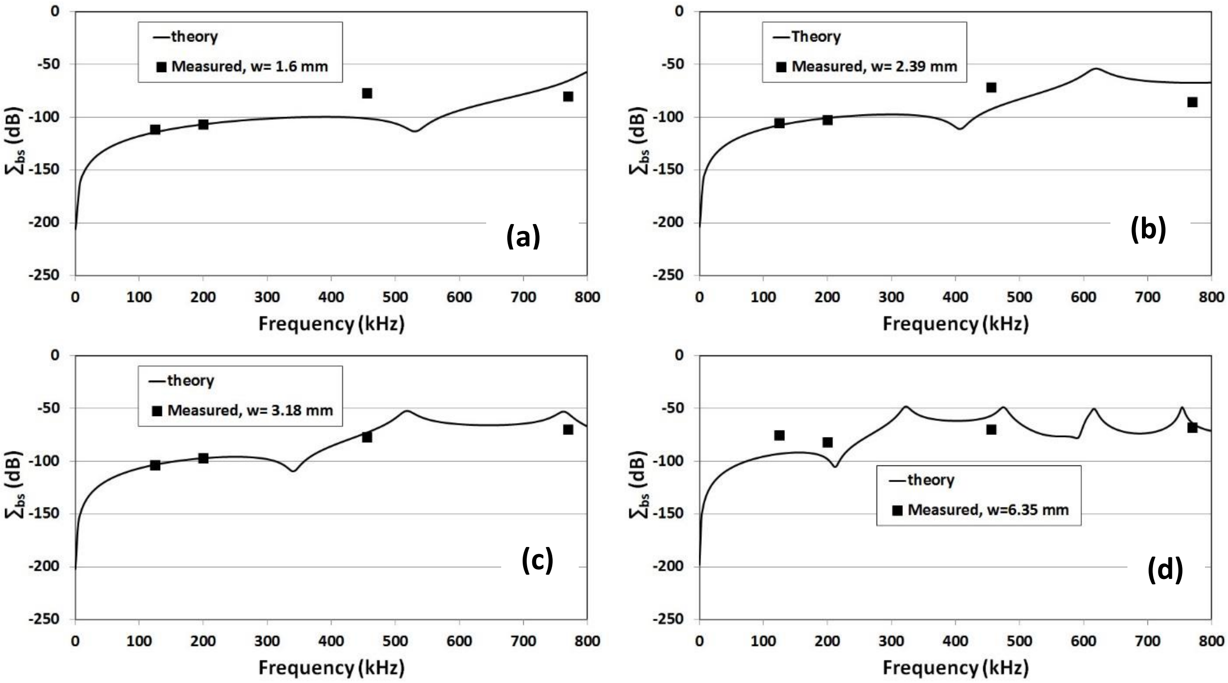

Fig. 4. Plots of theoretical and measured values of $\Sigma_{bs} = S_v$ as a function of acoustic frequency for brine suspended Glitter particles with widths (w): a) 1.6 mm; b) 2.59 mm; c) 3.18 mm; and 6.35 mm. "Theory" values were calculated using Eqs. 2-4 in conjunction with the corresponding "effective radii" of the particles.

Unfortunately, no additional data were available to provide an independent basis for evaluating the accuracy of the obtained fractional volume estimates as calculated from Eq. 5b using optimal values of N, a_m and b Representative results obtained from applications of RUNSWIPS to data acquired during a November, 2011 supercooling interval are displayed in Fig.7. These results provide frazil-population and quality parameter data corresponding to measurements at four different heights/ranges above the plane of the SWIPS transducers. The plotted quantities, reading downward from the top of the Fig., denote: fractional volume (F); numerical per unit volume density of frazil particles (N); quality index (q); median effective radius of frazil population (a_m) and the width parameter (b) descriptive of lognormally distributed frazil effective radii).

From a methodological point of view, the most significant plotted quantity was the quality factor, q, which tells us how closely the standard theory, when applied at each of three acoustic measurement frequencies, duplicates the S_v values measured at such frequencies. The typical results in Fig. 7, show (except at the highest water column levels frequently contaminated by flocs and surface ice) q values which were almost always below 5 $(dB)^2$, and usually satisfied $q < 1$ $(dB)^2$. Such results suggest that Faran Theory correctly reproduced S_v values simultaneously measured at three different frequencies within an uncertainty which ranged upward from a small fraction of 1 dB to approximately 1.3 dB. It is notable that this level of theoretical/measurement consistency was achieved with inclusion of two frequencies, 455 kHz and 774 kHz, which, on the basis of the laboratory testing, were expected to be less than ideal for measurements made in the presence of large frazil disks. It is not unreasonable to suggest that the q parameter results provided a level of methodological verification which is, at least, equivalent to that which could be expected from independent physical measurements of the quantity F.

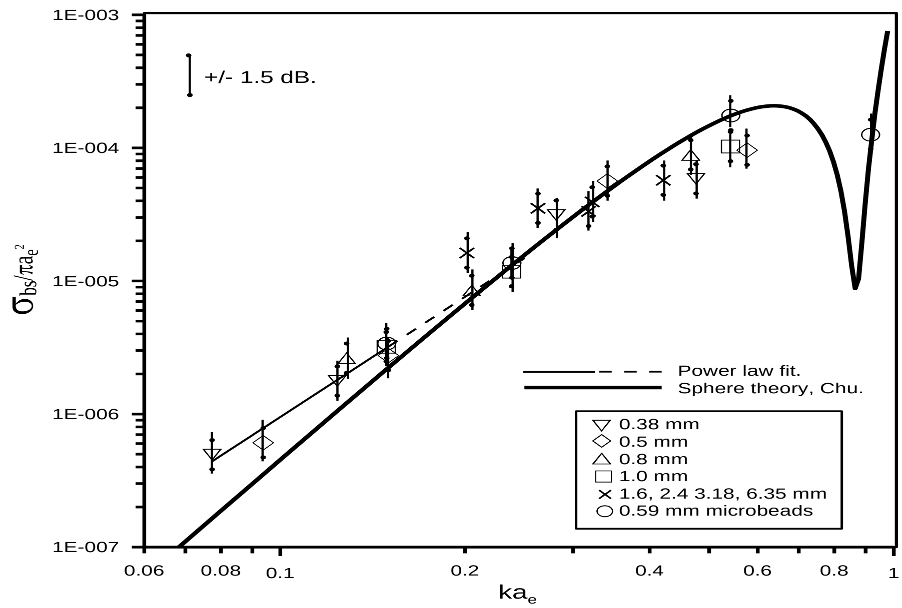

Fig.5. Deduced backscattering cross sections (normalized by dividing by πa_e^2) plotted as a function of ka_e for the indicated disk diameters and the microbead spheres. The included curves represent an optimized power law fit and theoretical expectations based upon the Chu algorithm and the Faran Theory.

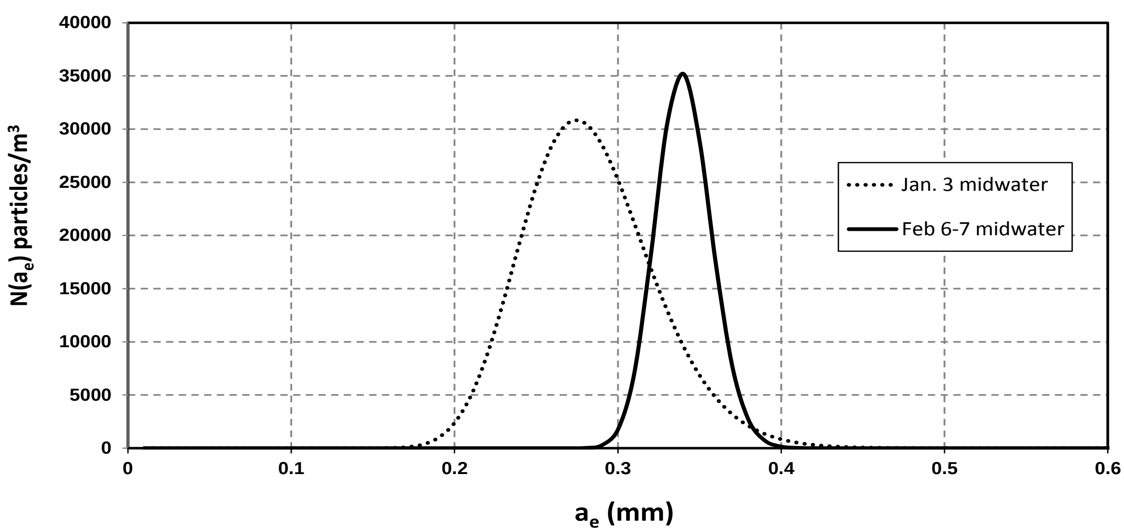

Fig. 6. Numbers of particles per m^3 as at midwater (2.3 m) ranges for the Jan. 2-3 and Feb. 6-7 frazil study intervals.

Principal interests in the extracted frazil parameters included 1) the magnitudes and time- and vertical position-dependences of frazil fractional volume; and 2) the changes observed in the effective radius distributions both during individual frazil intervals and due to interval to interval differences. In the first case, peak fractional volumes were observed to fluctuate from interval to interval but tended to vary between 0.0035% and 0.008%: most typically, being close to the 0.005% value reported by Pegau et al. (1995) and Marko and Jasek (2010c). The latter value was, roughly, an order of magnitude smaller than the single frequency UAWRE estimates derived from Peace and North Saskatchewan River S_v data.

Perhaps more significantly, the estimates were more than an order of magnitude below fractional volumes simulated (Jasek et al., 2011) for the Peace River using the highly regarded CRISSP1D numerical ice model (Shen, (2005).

Other extracted parameters, specifying the median effective radii and widths associated with the underlying lognormal size distributions, showed consistent and similar behaviour at different heights in the water column. Significantly, median effective radii, ranged between 0.2 mm and 0.4 mm and similar variations were noted in the width parameters defining the assumed lognormal distributions. Assuming disk/thickness ratios of 10:1, typical effective radius values, 0.3 mm, corresponding to, roughly, 1.1 mm diameter disks, were only slightly larger than the mean disk diameter values optically estimated in the UAWRE test tank. Changes in the parameters a_m and b during the course of individual frazil events or between different intervals were inconsistent with assumptions made in the UAWRE program on the relative constancy of particle size distribution “shapes” in laboratory grown- and river-frazil populations. Particle numerical densities were in the 10^5 m^{-3} to low 10^6 m^{-3} range and below the thresholds for non-linear behaviour identified by Marko and Topham (2015).

Nevertheless, publication of the Marko et al. (2015) results encountered considerable skepticism. Much of this reaction was triggered by the attained low values of F relative to earlier measurements either made in laboratory settings or, in the case of the UAWRE work, based upon laboratory acoustic calibrations. More significantly, the newer estimates were believed to be too low to be compatible with prevailing theories of river ice cover formation based upon frazil suspensions being the primary source of river surface ice growth. The suggested alternative, namely, that growth and subsequent surfacing of riverbed anchor ice was the major surface ice source, received mixed but wary levels of support.

Subsequent efforts to develop this interpretation further began with additional reviews of the 2011-2012 Peace River data directed at documenting major instances of anchor ice presence and/or evidence that such ice rises to the river surface in substantial quantities. This work demonstrated both sustained coverage of the SWIPS instrument by a thickening ice layer and appearances of strong, very localized, targets in the water column during diurnal clearing periods. The latter targets were fully consistent with rising slabs of anchor ice. These results stimulated subsequent detailed analyses of frazil profile, frazil content, water temperature and water level data with respect to expectations from a CRISSP1D ice model tuned to reproduce observed amounts of surface ice without allowances for anchor ice growth. Detailed thermodynamic and physical analyses not only confirmed the, roughly, two orders of magnitude difference between observed and simulated frazil fractional volumes but also highlighted the reality that the simulations could not reproduce the highly episodic nature of the observed variations. The episodic behaviour was, to our knowledge, not observed in laboratory tanks or flumes but was also evident in the North Saskatchewan River results of (Ghobrial et al., 2013) where such variations were primarily interpreted in terms of variations in nearby surface ice conditions.

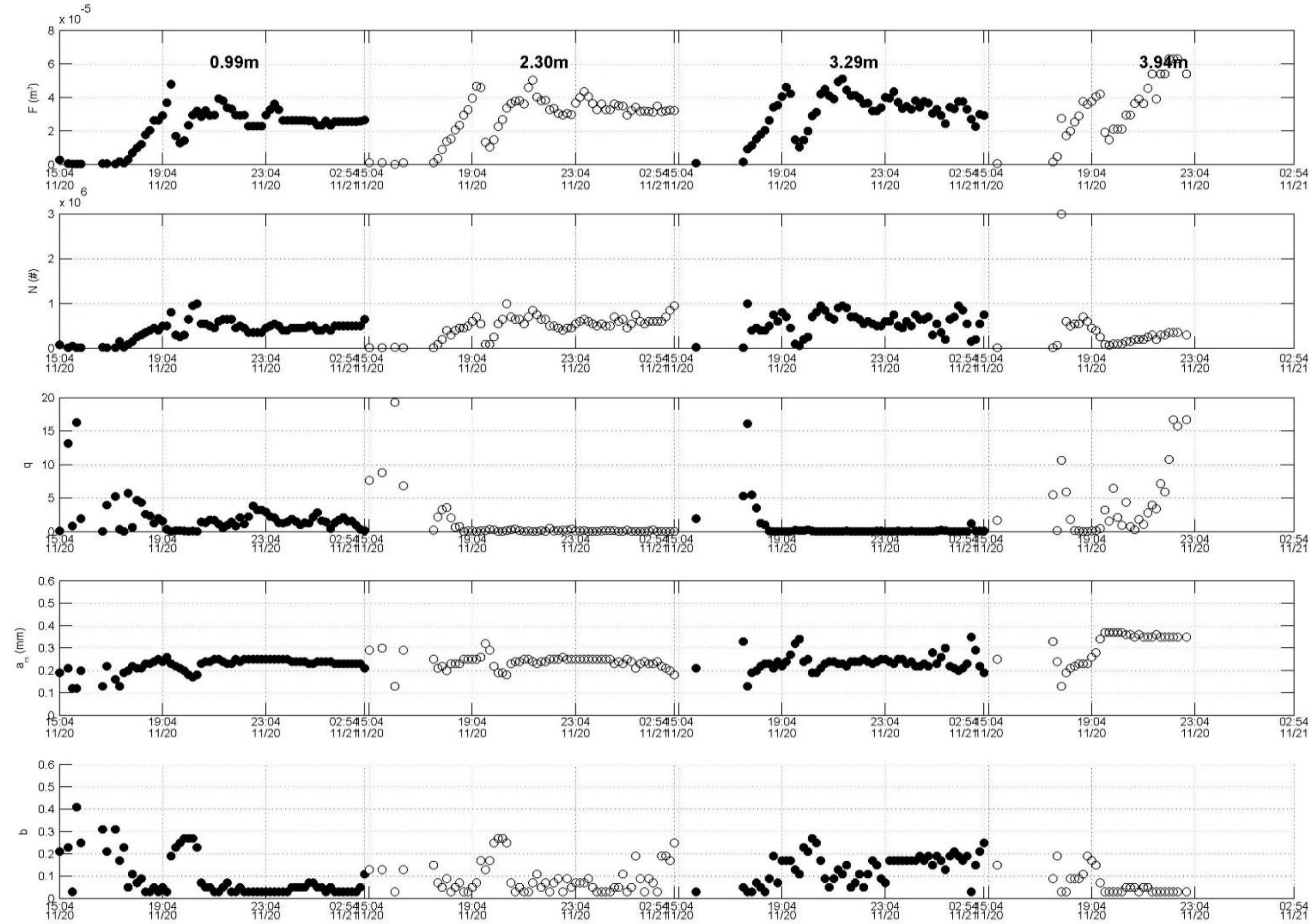

Fig. 7. Plots of frazil parameter, F, N, q, a_m and b values corresponding 4 indicated measurement range as derived from RUNSWIPS extractions carried out on SWIPS channel 1, 3 and 4 data from the Nov. 20-21 frazil interval . Data was limited to ranges centred no further than 3.94 m from the transducer plane to avoid interference with near-surface ice.

The analyses of the 2011-2012 data led to the conclusion that quantitative details of the observed variations in water column frazil content and anchor ice presence on and near the SWIPS instrument were inexplicable in the absence of:

1) Dominant *in situ* anchor ice growth on the riverbed during all supercooling intervals;
2) Suppression of water column frazil growth by latent heat from *in situ* anchor ice production;
3) Irregular resumptions of water column frazil production following partial or full clearance of riverbed anchor ice and its movement to the river surface.
4) A strong, inverse, dependence of anchor ice stability on the cooling rate: i.e. *in-situ* anchor ice is more stable when grown under moderate as opposed to strong supercooling conditions.

Support for these assertions was based upon examinations of the energy balances immediately preceding and following frazil initiation as derived from, respectively, the rates of change in water column temperature and frazil concentration. An overwhelming shortfall in the rate of latent heat release from frazil formation provided telltale signatures of *in situ* growth. Physical evidence for this growth included SWIPS signals arising directly from anchor ice on the instrument and drifting upward toward the river surface as well as unique short duration elevations of local water levels. The timings of latter features (Fig. 8), immediately following peaks in frazil content, were consistent with expected accompanying brief increases in riverbed anchor ice roughness. The latter increases were initiated by renewed anchor ice growth (Jasek et al., 2015) which lowers water column frazil content from its immediately preceding peak value. These results were described in detail by Marko et al. (2017).Direct observations of large scale surfacing of anchor ice pans in the Peace River were reported by Jasek et al. (2015) and Kalke et al. (2015).

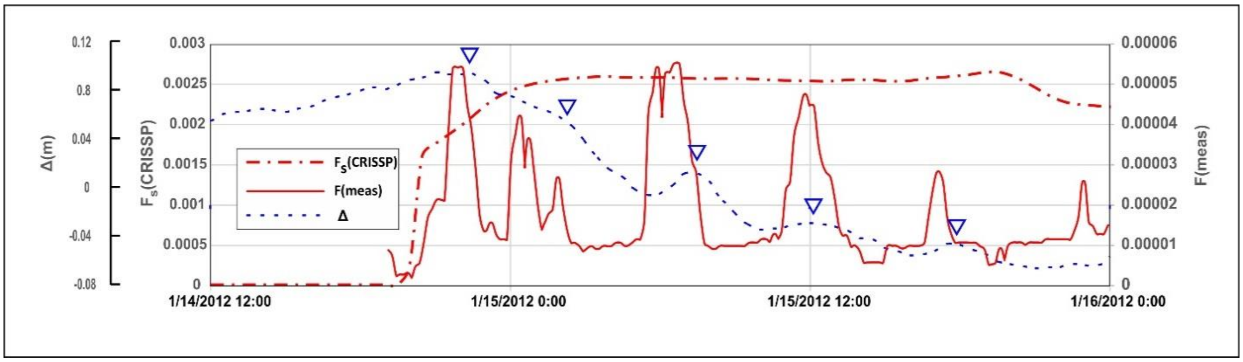

Fig.8. Comparisons of Interval 3 fractional volumes (Marko et al., 2015) as measured (F(meas)) and simulated (F_s(CRISSP)). The plot of F_s(CRISSP) was shifted ahead in time by 15 h to allow approximate coincident positioning in time with F(meas). The two quantities are, respectively, representative of regions 2.3 m above the SWIPS instrument and water column mean values. The additional, blue, curve represents Δ, the difference between 10-point running averaged local water levels and levels simulated in the absence of anchor ice formation by the CRISSPID model. Inverted triangles denote the central positions of the local anchor ice-generated water level peaks.

4. Water column frazil: what the data tell us and how we can learn more

In Section 3 we have summarized and, as objectively as possible, critically evaluated two bodies of work directed at developing verified acoustic methodologies for quantitatively assessing water column frazil content. In both cases, key portions of the work were carried out in a test tank and, when applied to actual river acoustic data, found frazil contents to be below expectations based upon a standard ice model which neglects anchor ice formation. Each set of results currently stands alone as a rare body of quantitative evidence supporting the opposing possibilities that river frazil contents could be high enough (UAWRE results) or are much too low (ASL/BC Hydro results) for surface frazil accretion to be the principal source of river ice cover growth. The roughly order of magnitude disagreement between the two alternative estimates can and has been taken as evidence of continuing major uncertainties in frazil measurement technologies and, more generally, in the nature of the mechanisms governing ice cover growth. We do not believe this to be the case.

The UAWRE results (described in Section 3.2) relied on extremely simple techniques, i.e. mechanical collection and weighing of ice and water column averaging of single frequency acoustic backscattering data, to derive relationships for estimating frazil contents from river acoustic data. Reliance upon single frequency acoustic measurements introduced unavoidable ambiguities which precluded confident content estimation. Efforts to work around such difficulties relied upon unproven and inconsistent assumptions and assertions which were at variance with well-established understandings of acoustic scattering. Ultimately, the utilized approach was reduced to relying on the assertion that the sizes and shapes of frazil particles in rivers did not differ “significantly” from those associated with frazil produced in the laboratory. All estimation efforts were seriously undermined by the quality and limited relevance of the underlying empirical data. Specifically notable shortcomings included inadequate collection of independent (i.e. non-acoustic) ice mass information and a heavy emphasis on measurements made at fractional volumes much higher than normally attained in supercooled rivers.

In hindsight, perhaps the most graphic evidence of fundamental differences between natural river and test tank ice conditions was the apparent absence of laboratory observations of anchor ice presence. This absence was notable since anchor ice growth routinely accompanies supercooling in river settings. There are good reasons for believing (Marko et al., 2017) that the observed (Marko et al., 2015) “anomalously” low levels of river frazil content were consequences of latent heat released by *in situ* anchor ice growth. It is, thus, significant that all prior reports of anchor ice growth in laboratory situations have been based upon work carried out in flumes and controlled flow channels (Doering et al., 2001; Kerr et al., 2002 and Qu and Doering, 2007). These situations were all likely to be associated with the larger net flow velocities which are believed to be required for *in situ* anchor ice growth (Pietrovich, 1956; Marko et al., 2017). The absence of such growth in the UAWRE test tank favoured relatively unconstrained frazil production and consequently unrealistically high frazil fractional volumes.

Observed variations in frazil size parameters (Marko et al, 2015) and the strong particle size dependences of Rayleigh-like scattering dictate that tank/river population differences, alone, can introduce order of magnitude errors into fractional volume estimates based upon empirical test tank data. When combined with other measurement uncertainties, this reality should rule out use of the UAWRE single frequency approach to either confirm or disprove reported (Marko et al., 2015, 2017) large discrepancies between simulated and measured river frazil contents. In terms of methodology, it is possible that frazil content estimates could be obtained using a single acoustic frequency, provided that additional provisions are made for simultaneous independent measurements of at least one frazil population parameter. It is hard to see how this approach would offer any simplicity, convenience or cost advantages relative to multifrequency measurements.

Tank tests were also a critical part of the ASL/BC Hydro research effort which identified discrepancies between modelled and estimated frazil contents. In that case, however, no assumptions of similarity between laboratory and river ice growth conditions were required. Testing was limited to examining the particle and measurement parameter dependences of acoustic scattering by stable frazil surrogates. Particular interests were in identifying the conditions under which such dependences were accurately described by a tractable theory. The uses of polystyrene as a frazil surrogate and brine as the host fluid did introduce complications. One of these complications, arising from the mechanical properties of the material, produced irrelevant, extremely strong, scattering at large values of the product k_1a_e. This effect restricted laboratory testing to combinations of particle and measurement parameters such that k_1a_e remained below a threshold value. Near-threshold measurements incurred the largest (30-40%) observed deviations from theory. Difficulties associated with physical sampling of particle concentration were limited to the lowest, and least theoretically problematic, acoustic frequency and could be eliminated by improved pre-test stirring procedures. The overall implication of the laboratory results was that a standard theoretical formulation, based upon the effective radius concept, could accurately describe acoustic scattering by individual, frazil-like, particles within relevant ranges of particle dimensions and acoustic frequency. Particle size-dependent limits on applications of this theory were established corresponding to particle numerical densities as low as 2×10^6 m^{-3} for larger particles and as high as about

2×10^7 m^{-3} at the lower end of the tested size regime. Exceedance of these thresholds introduced non-linear behaviour which was not easily accessible to theoretical interpretation.

The theoretical formulation, employing ice and freshwater rather than polystyrene and brine parameters, was incorporated into an algorithm which extracted frazil population parameters from backscattering coefficients measured at 3 different acoustic frequencies. Applications to Peace River field data, yielded theoretical agreement with measured S_v values in each channel to within or only slightly above the 1 dB accuracies of transducer calibrations. Although no independent field confirmations of the obtained estimates were available, it is extremely unlikely that such close correspondences with a widely accepted theory were fortuitous. Given the deficiencies cited above in the only modern alternative body of field estimates, the Marko et al. (2015) Peace River fractional volume results represent the best, if not the only, available basis for comparing reality with current understandings. Laboratory data suggest possible systematic errors in these estimates were unlikely to exceed 20% (half of the errors encountered in tests on problematically large particles).

The principal significance of these results lies in their pronounced deviations from CRISSP1D simulations which did not include allowances for anchor ice growth. These deviations, explored in detail by Marko et al. (2017), established a necessity for massive amounts of *in situ* anchor ice growth during supercooling intervals. Such growth had visible impacts on SWIPS profile and water level data which were fully compatible with expectations from a detailed growth model. Predicted movements of this ice toward the river surface were observed in the SWIPS acoustic profile records and later confirmed by visual observations (Jasek et. al., 2015, Kalke et al. 2015).

In sum, a relatively standard application of acoustic backscattering technology has been demonstrated to provide a basis for significantly modifying a prevailing conceptual model which attributes the bulk of river ice growth to surface accretion of water column frazil. This model has been previously called into question on the basis of morphological studies carried out in smaller river settings (Kempema et al., 2008 and Kempema and Ettema, 2015) which suggested significant river ice fractions have their origins in *in situ* anchor ice growth. The present review suggests that the only available, defensible, body of field data in a larger river (Marko et al.; 2015, 2017) requires that such growth is the dominant initial source of surface ice production.

This conclusion, does not address the full complexity of the exchanges among multiple river ice components which accompany seasonal ice growth. Surface ice and frazil ice, the two most observable of these components, are both intimately linked to anchor ice. In answering the questions embedded in the title of this report, it is clear that there are sufficient data to support revisions of the prevailing conception of frazil-centred ice cover development. However, those data, indicative of the dominant role of *in situ* anchor ice growth, are limited in scope and need further quantitative enhancement through planned, well instrumented, field research programs. Such programs would be directed at major gaps in knowledge including the dependences of *in situ* growth on river-velocity, -depth and -bottom composition. Acoustic profiling instrumentation has much to offer in such efforts: being capable of yielding high quality, long term, remotely sensed data on all three major river ice components. When employed in conjunction with comparably high quality water and atmospheric data collection tools, acoustic profiling can provide a fundamental basis for quantitative studies of freezing river environments.

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