Measurement of Freeze-Up and Break-Up Ice Velocities

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ABSTRACT

Records of discharge on northern rivers are typically the poorest during break-up and freeze-up events. An earlier paper (Prowse *et al.* 1986) reviewed a number of techniques that could be used to improve velocity measurements, and hence discharge estimates, during such periods. The "shore-survey" technique was identified as the one to be most suitable for incorporation into existing hydrometric programs. This paper reviews and updates the details of this technique with a special emphasis on margins of error.

INTRODUCTION

In the 1986 proceedings of the Eastern Snow Conference, Prowse *et al.* (1986) reviewed a number of techniques to obtain measurements of velocity and ultimately discharge during periods of pronounced ice activity, particularly freeze-up and break-up. The major objective of this earlier paper was to encourage agencies operating water data-collection programs to adopt some of these new techniques. Unfortunately, such techniques have not become part of regular monitoring programs. Periods of freeze-up and break-up can amount to several weeks on large northern rivers and on more southerly rivers where the winter season is characterized by multiple freeze-up and break-up events. The implications of this are most pronounced in regions where the annual maximum flow is concomitant with break-up.

As outlined in Prowse *et al.* (1986), the quality of freeze-up and break-up discharge records are poor because conventional techniques and equipment have been developed primarily for use under open-water conditions and are poorly suited for application during periods of significant ice activity.

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[1] NHRI Contribution No. CS-91075

For example, rapidly varying flow and ice conditions during break-up (and freeze-up) make it impossible to establish consistent stage-discharge relationships, as traditionally employed for open-water periods. Furthermore, the situation is exacerbated by frequent equipment failures due largely to the effects of ice scour and flooding.

As part of an ongoing research study of break-up processes on northern rivers, the authors have evaluated and used many of the techniques outlined in Prowse *et al.* (1986). Given the operational set-up of hydrometric agencies, the "shore-survey" approach would seem to be the best suited for inclusion in current data-collection programs, particularly with the recent advent of more automated and less expensive survey equipment. The following reviews and updates the use of the "shore-survey" method with a special emphasis on margins of error associated with different aspects of the technique.

Figure 1 Digital theodolite, infra red electronic-distance measuring unit and on-board data acquisition system, positioned along the Liard River, N.W.T. Canada.

BASIC APPROACH

The following description assumes the use of a two-person survey team and a "total-station" theodolite (digital theodolite with electronic-distance measuring unit [EDM] and automatic data acquisition)(Figure 1). One person operates the total-station while the second follows water-level fluctuations with a rod-mounted prism reflector. The advantage of using a total-station system is that records of floe travel and water level can be simply and rapidly obtained. This is particulary important during the early phases of breakup when instantaneous discharge can be rapidly changing largely as a result of ice-jam surges.

The basic approach involves the tracking of a moving-ice floe by the theodolite over a time interval "t" (Figure 2). At the beginning of each floe survey, instrument height with respect to water level "d_E" is automatically obtained using vertical angle information from the theodolite and distance information from the EDM-rod-mounted prism (survey time <30 s). The instrument is then focused on a distinct feature of a floe (preferably as close the water level as possible) at a desired point in the cross-section and somewhat upstream of the survey site. The initial time "t_1", horizontal angle "β_1" and vertical angle "α_1" are automatically recorded and the floe is tracked downstream for a desired period whereby the final time "t_2" and associated angles "β_2" and "α_2" are again automatically recorded. A new measurement set can then begin.

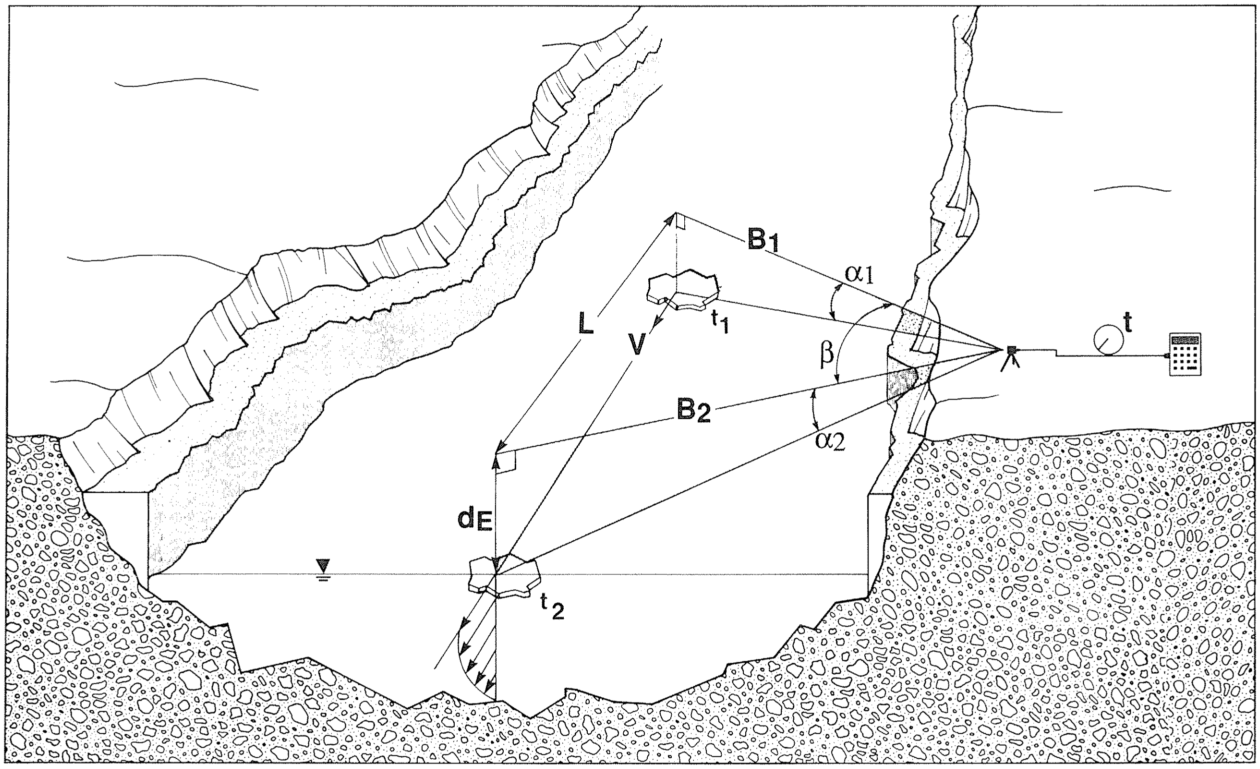

Figure 2 Schematic of the "shore-survey" ice-floe velocity measurement technique.

Following completion of the entire survey, the time and angle measurements are then used to compute ice velocities according to the following. First, the horizontal distance from the instrument to the initial ice floe location "B_1" is obtained from:

$$[1] \quad B_1 = \frac{d_E}{\tan \alpha_1}$$

Similarly, the horizontal distance to the final floe location "B_2" is obtained from:

$$[2] \quad B_2 = \frac{d_E}{\tan \alpha_2}$$

The downstream distance traversed by the floe "L" can then be calculated using the cosine law:

$$[3] \quad L^2 = B_1^2 + B_2^2 - 2B_1B_2 \cos(\beta_2 - \beta_1)$$

and finally, the average surface velocity "$\overline{V}$" is given by:

$$[4] \quad \overline{V} = \frac{L}{t_2 - t_1}$$

SHORE-SURVEY MEASUREMENT ERRORS

The following details the measurement components and their associated sources of error in the estimation of ice-floe velocity:

t	time:	i) instrument resolution ii) synchronization (human)
β	horizontal angle:	i) instrument resolution ii) sighting error (human)
d_E	instrument height:	i) prism-rod position error (human) ii) instrument resolution iii) sighting error (human)
α	vertical angle:	i) instrument resolution ii) sighting error (human)

Intuition and sensitivity analysis (not detailed here) reveals that the resolution of vertical angles α_1 and α_2 are of primary significance in resolving desired error bounds for estimates of ice-floe velocity. Due consideration must also be given to the resolution of swept horizontal angle β_2-β_1, and instrument height d_E. The resolution of tracking duration t is found to be less significant but its importance will vary according to the actual ice-floe velocities and the total time used for tracking. It is important to note that the selection of an optimum tracking time must compromise between the advantages of measurement frequency and the representativeness of the derived ice-floe velocity estimates.

To better illustrate the significance of vertical angle measurement error, its effect on floe-travel distance (and thus average floe-velocity) was examined for varying instrument-height/river-width ratios (d_E/B). Assuming

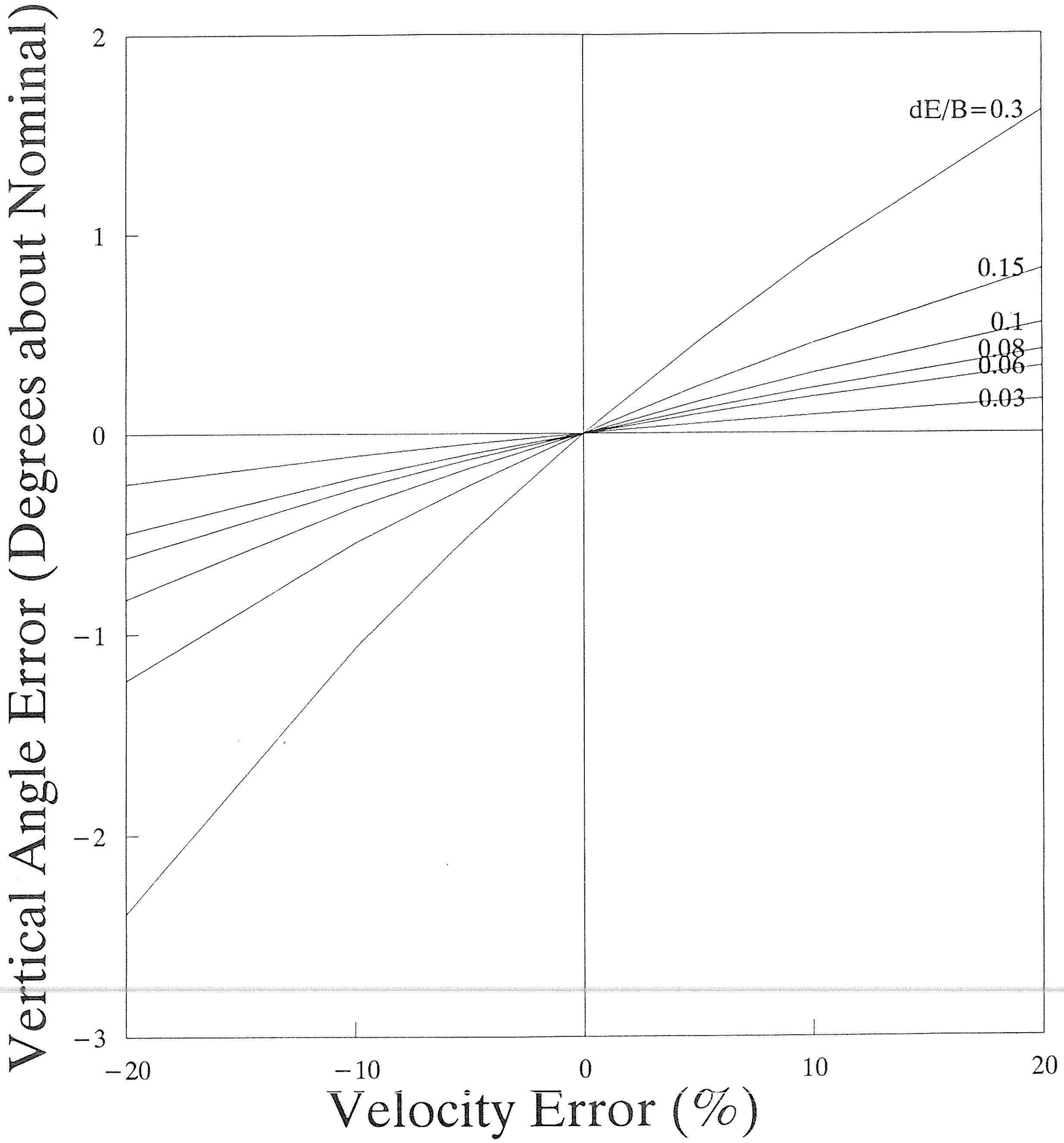

Figure 3 Ice-floe velocity error as a function of d_E/B and vertical angle resolution.

d_E, β and t are absolutes, Figure 3 shows that for low d_E/B, large errors in ice-floe velocity result from relatively small errors in the ability to resolve α. For high d_E/B, that is, a high vantage point with respect to river width, similar errors in resolving α result in a much lower error in estimating ice-floe velocity. In general, the error bias about nominal indicates undershooting the target by a small fraction yields less error than that produced by overshooting a similar amount. Also note that Figure 3 is representative of errors associated with nominal sightings at mid-channel. The advantages of a high vantage point are obvious, as is the requirement of sighting on the ice-floe at or near the water line.

INSTRUMENT OPTIONS

The above discussion illustrates the importance of being able to sight precisely a particular spot on the ice-floe and then be able to track it successfully over some distance. Thus, this leads the discussion to consider only instruments having high quality sighting optics and suitable magnification. In terms of angle measurement, it is obvious from Figure 3 that the vertical angle resolution need not be extremely high (e.g. 1'arc). Indeed less expensive instruments giving a vertical angle resolution of approximately ±10'arc, but still having high quality optics and power, are more than adequate for this application.

Digital theodolites derive their angular measurements electronically using opto-electric sensors and gray-code logic, thus data is easily and conveniently displayed and recorded. Traditional high-resolution optical theodolites resolve angles using expensive optical verniers which are time consuming to read and, although the state-of-the-art digital device may also be able to resolve 1'arc, it is also very expensive. At present many agencies involved with hydrometric data gathering have reasonable inventories of optical theodolites. This invites the possibility of conversion. An optical theodolite having high-quality sighting optics could have both horizontal and vertical circles coupled mechanically to opto-electric sensors at minimal cost. For example, at a d_E/B of 0.1 (Figure 3) the required α resolution at mid-channel for a desired ice-floe velocity error of ±10% is $\approx \pm 0.5$'arc. Sensors having this level of angular resolution are inexpensive as would be the associated electronics. Note that such a conversion would allow the operator to maintain highly accurate sightings and to obtain sufficiently accurate <u>automatic</u> angular measurements. With such a conversion, however, there remains the need for an EDM device to obtain rapid and automatic water-level (instrument height) measurements to accompany the ice-tracking measurement.

INTERPRETATION OF ICE-FLOE VELOCITY

As outlined in Prowse *et al.* (1986), the conversion of a series of ice-floe velocity measurements into an estimate of discharge must take into account a number of complicating factors. Firstly, ice-floe velocity and water-surface velocity may significantly differ due to the effects of wind drag and inter-floe friction. Second, surface velocity must be related to a mean vertical velocity and therefore, knowledge of channel characteristics which will modify the vertical velocity profile is essential. Third, the presence of ice can: i) complicate the estimation of a mean vertical velocity; ii) cause difficulty in estimating "effective" stage from observed stage; and iii) complicate the referencing of floe streamlines with respect to the bed profile, largely because of the formation of shear walls. For details regarding the accommodation of the above factors see Prowse *et al.* 1986.

CONCLUSION

The authors hope that the above restatement and elaboration of the shore-survey technique for estimating instantaneous ice-floe velocity (discharge) will encourage agencies to experiment with it, and possibly adopt it as standard practice. Implementation could begin with selected sites, perhaps those where ice related flooding is of particular concern. Instrumentation options have been reviewed whereby optical theodolites, which may already exist with hydrometric data collection agencies, could be converted inexpensively into coarse digital instruments.

LITERATURE CITED

Prowse, T.D., Anderson, J.C. and Smith, R.L 1986: Discharge measurement during river ice break-up. Proc.43rd Eastern Snow Conference, 55-69.