Uncertainty of ADCP spatial velocity distributions

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Uncertainty is assessed for the spatial distribution of depth averaged velocity estimated from a four-beam Acoustic Doppler Current Profiler (ADCP) asynoptic spatially intensive survey of a 6 km river reach. Kriging was used to interpolate the irregular data on to a uniform grid. Uncertainty due to ADCP single-ping error, macroturbulent velocity fluctuations, and kriging interpolation is evaluated. Specifically, the uncertainty of an estimate of mean streamwise velocity from a single-ping velocity measurement in a single bin (σ_V) is evaluated using ADCP error velocity (σ_ε) for error, and an empirical predictor for root-mean-square turbulence intensity (σ_S) for real fluctuation: $\sigma_V^2=\sigma_\varepsilon^2+\sigma_S^2$. Average σ_ε and σ_S in the reach were 0.22 m/s and 0.17 m/s, respectively. The resulting average single-ping single-bin σ_V was 0.30 m/s, and corresponding average uncertainty of depth average velocity (σ_U) was calculated to be 0.089 m/s. Depth average velocity interpolation uncertainties, as represented by kriging standard deviations, ranged from 0.38 m/s to 0.68 m/s in the reach, thus interpolation uncertainty far exceeded estimated measurement uncertainty. Finally, shear velocity uncertainty (σ_{u^*}) was also estimated. For σ_V = 0.30 m/s and depth equal to the mean channel depth of 5.7 m, σ_{u^*} was 0.045 m/s.

Keywords: ADCP uncertainty, spatial distribution, river, acoustic noise, turbulence intensity

1 INTRODUCTION

Spatial distributions of velocity in rivers have been mapped based on four-beam Acoustic Doppler Current Profiler (ADCP) survey throughout a large river reach [1]. The data were asynoptic, in that an irregular spatial survey with closely spaced sections was collected over a period of time. It was assumed that flow was stationary. Kriging was used to interpolate the irregular data on to a uniform grid. However, a mean velocity spatial distribution from an asynoptic survey is subject to errors associated with single-ping ADCP errors and the fact that instantaneous measurements represent both the mean velocity and macroturbulent velocity fluctuations. In other words, instantaneous data display variance due to both measurement error and real fluctuations, thus an instantaneous measurement may be a poor realization of the local mean velocity. It was previously assumed [1] that kriging would provide sufficient spatial smoothing to overcome this variance. Alternatively, [2] suggested that repeat transects are necessary to reduce ADCP velocity uncertainty. However, repeat transects will necessarily limit the spatial range of the survey, particularly if flow is sufficiently unsteady to limit survey time. In this paper a more rigorous assessment of uncertainty in the spatial velocity maps generated from asynoptic ADCP surveys is presented.

2 METHOD

2.1 Measurements

An RD Instruments 1200 kHz Rio Grande ADCP operated in Water Mode 1 was utilized to survey nearly 6 km of river. ADCP positions were recorded using a Real Time Kinematic Differential Global Positioning System. A total of nearly 30000 vertical profiles were collected using individual pings in 25 cm depth bins, a sampling frequency of 2 Hz, and a radial ambiguity velocity of 3.59 m/s. Depths ranged from 1.5 m to 17 m and depth average velocities ranged from zero to greater than 3 m/s (Figure 1). Refer to [1] for more details on measurement methods.

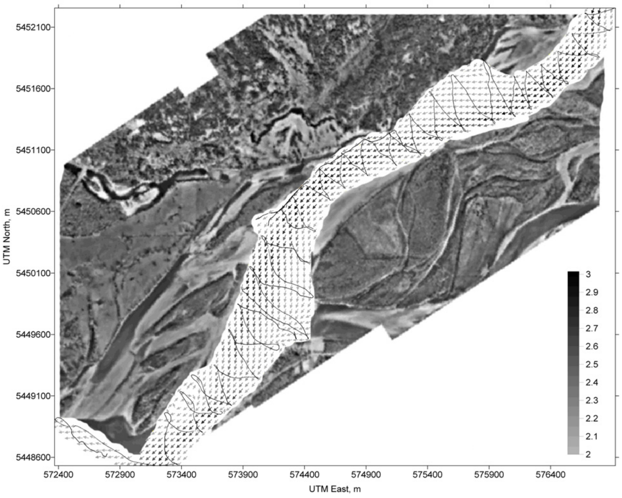

Figure 1: Depth average water velocity (m/s) in 6 km reach of Fraser River, June 24-25, 2006. Spatial distribution kriged to 25 m grid spacing, every second vector shown. Model variogram was fit to observed variogram. Black line shows boat track, where raw data were collected. Air photo from early spring 2006, courtesy Michael Church.

2.2 Uncertainty Assessment

Velocity measurement uncertainty was evaluated using estimates of both measurement error and turbulent velocity fluctuations. Specifically, the uncertainty of an estimate of mean streamwise velocity from a single-ping velocity measurement in a single bin (σ_V) was evaluated using ADCP error velocity (σ_ε) for error, and an estimate of root-mean-square turbulence intensity (σ_s) for real fluctuation:

$$\sigma_V^2 = \sigma_\varepsilon^2 + \sigma_S^2 \quad (1)$$

where σ denotes standard deviation, and σ_ε and σ_s are assumed independent. ADCP error velocity is based on the difference between two redundant measurements of vertical velocity in a depth bin, and accounts for both Doppler noise and heterogeneity of actual velocities between beams. Turbulence intensity was estimated using the empirical equation presented by [3]:

$$\sigma_S = 2.04 u_* \, exp\left(-0.97 \frac{y}{h}\right) \quad (2)$$

where u_* is the shear velocity, y is the elevation above the channel bed, and h is the flow depth. Equation 2 was developed for uniform flow conditions, thus its application requires an assumption of reasonably uniform flow. Furthermore, application of Equation 2 requires a prediction of local u_*, which was obtained from a log-law fit to the velocity measurements themselves (see [1]).

The validity of Equation 2 for the present conditions was tested using a 7 minute (>800 pings) stationary profile located in the centre of the reach, for which u_*=0.120 ± 0.035 m/s. The mean σ_s from Equation 2 over all bins in all pings was 0.22 m/s. Alternatively, σ_s was estimated directly as $\sigma_S = \sqrt{\sigma_V^2 - \sigma_\varepsilon^2}$, using the observed measurement variance in each bin for σ_V and observed average σ_ε in each bin. Observed σ_s averaged across all bins was 0.27 m/s, which compared reasonably well with the prediction from Equation 2.

Finally, the uncertainty of depth average velocity (σ_U) was calculated from single-bin uncertainty, utilizing the dubious assumption that N measured velocities in each vertical profile were independent:

$$\sigma_U = \frac{1}{N}\sqrt{\sum_{i=1}^{N} \sigma_{v_i}^2} \quad (3)$$

In fact, measured velocities at adjacent bins are correlated due to the fact that each bin employs Doppler backscatter from a triangularly weighted window with a width equal to two bins. In other words, neighbouring bins employ overlapping measurement volumes.

2 RESULTS

The ADCP error velocity (σ_ε) was recorded for every bin of every ping. Average σ_ε in the reach was 0.22 m/s, with a standard deviation of 0.18 m/s. Values of σ_ε tended to increase towards the bed in deeper profiles, presumably due to greater velocity heterogeneity between beams. The expected root mean square error in single bin, single ping velocity due to Doppler noise alone (σ_D) can be estimated for a given water mode (signal transmission and processing algorithm), bin size, and ambiguity velocity using the RD Instruments software PlanADCP. For the current deployment, σ_D was predicted to be 0.18 m/s, suggesting that error was increased due to beam heterogeneity by an average of 0.13 m/s.

The single bin, single ping estimate of σ_s from Equation 2 averaged 0.17 m/s in the reach, with a standard deviation of 0.07 m/s. As can be seen from Equation 2, estimated turbulent fluctuations were greatest near the channel bed in areas of high shear stress.

The resulting average single-ping single-bin σ_V was 0.30 m/s, with a standard deviation of 0.16 m/s. Given that both σ_ε and σ_S increased towards the bed, σ_V was greatest near the channel bottom.

The uncertainty of depth average velocity σ_U was calculated throughout the reach from the distribution of σ_V using Equation 3. The average value of σ_U was 0.089 m/s, with minimum and maximum values of 0.023 m/s and 0.386 m/s, respectively (Figure 2). Values of σ_U were least in deeper areas of the river, due to increased averaging from multiple bins.

Depth average velocity interpolation uncertainties were evaluated using the kriging standard deviations (σ_k). Kriging variance is calculated as the difference between the kriging model variance and the weighted covariance between adjacent points and the estimate location. In effect, σ_k is an estimate of the degree of spatial autocorrelation in the data that could be utilized during kriging. If there is little spatial autocorrelation, then σ_k approaches the standard deviation of the raw spatially distributed data. Values of σ_k ranged from 0.38 m/s to 0.68 m/s in the reach (Figure 3). Kriging standard deviations were least in locations near available raw data, and greatest in interpolated areas. The standard deviation of the spatially distributed depth average velocity data was 0.73 m/s, thus kriging variance approached the variance of the data in locations without data. This implies that spatial correlation in the data was of insufficient range to allow for accurate kriging interpolation between transects, particularly if transects were widely spaced. It appears that interpolation uncertainty exceeded estimated measurement uncertainty.

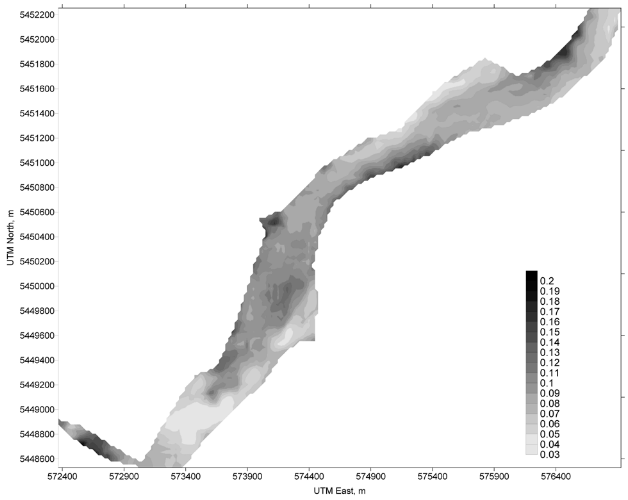

Figure 2: Calculated uncertainty of depth average water velocity (σ_U) (m/s). Spatial distribution interpolated by kriging to 25 m grid spacing using modeled variogram fit to observed variogram.

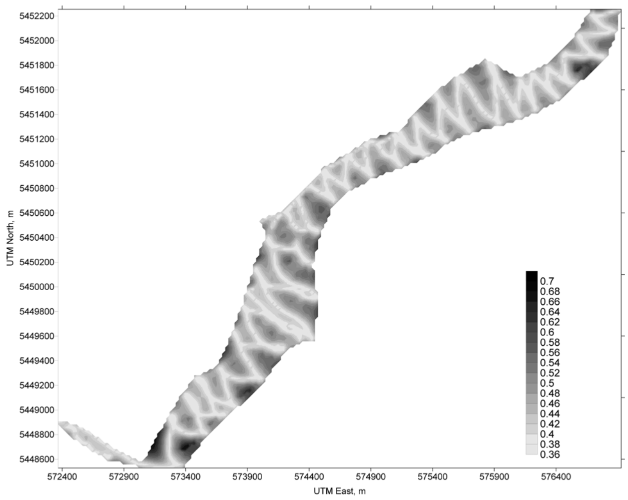

Figure 3: Kriging standard deviation (σ_k) of interpolated depth average water velocity (m/s). Spatial distribution interpolated by kriging to 25 m grid spacing. The standard deviation of observed depth velocity throughout the reach was 0.73 m/s, and kriging standard deviations ranged from 0.38 m/s to 0.68 m/s.

Finally, shear velocity (u_*) was estimated from a log-law fit to the velocity profile, with values ranging from 0.03 m/s to 0.18 m/s. Uncertainty of shear velocity (σ_{u*}) is independent of u_* and roughness, but σ_{u*} does depend on depth and the associated number of bins in the vertical profile. For σ_V = 0.30 m/s and depth equal to the mean channel depth of 5.7 m, σ_{u*} was 0.045 m/s. Averaging at least 10 pings for each velocity profile reduces σ_{u*} to < 0.02 m/s for all depths (Figure 4).

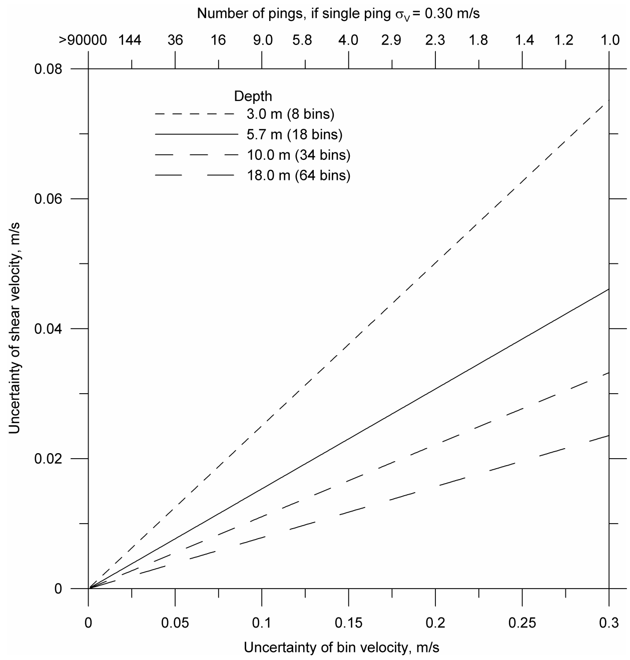

Figure 4: Uncertainty in estimated shear velocity (m/s), depending on number of bins in the vertical profile (depth), and number of pings in an ensemble average of pings (assuming single ping, single bin σ_V = 0.30 m/s).

3 DISCUSSION AND CONCLUSIONS

Uncertainty of spatial velocity distributions measured by asynoptic ADCP survey appears to be dominated by interpolation. For the present data:

- Estimated mean uncertainty due to turbulence = 0.17 m/s
- Mean uncertainty due to ADCP measurement error = 0.22 m/s
- Resulting mean single ping single bin uncertainty = 0.30 m/s
- Corresponding depth average velocity uncertainty = 0.09 m/s
- The standard deviation of measured depth average velocities = 0.73 m/s, and the kriging standard deviations approached this value in locations devoid of measurements.

In order to minimize this uncertainty, more spatially intensive measurements would be required, with reduced spacing between transects. The relative advantages of repeat transect surveys versus spatially dense asynoptic surveys for accurate estimation of spatial distributions requires further investigation.

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