Improving Acoustic Doppler Current Profiler Accuracy with Wide-Area Differential GPS and Adaptive Smoothing of Ship Velocity

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ABSTRACT

Accurate ship velocity is important for determining absolute currents from acoustic Doppler current profiler (ADCP) measurements. In this paper, the authors describe the application of two methods to improve the quality of ship velocity estimates. The first uses wide-area differential global positioning system (WADGPS) navigation to improve ship positioning. During the cruise, raw global positioning system (GPS) pseudorange data are collected. The pseudorange measurement is the difference between satellite transmission time and receiver reception time of a GPS signal. A few days after the cruise, satellite clock corrections from the Canadian Active Control System and orbital parameters from the U.S. Coast Guard Navigation Center are used to derive WADGPS positions that remove the position degradation effects of selective availability. Two-dimensional root-mean-square (rms) position accuracies reduce from ±34 to ±9 m. The authors' second method of improving the ship velocity applies an adaptive local third-order polynomial smoother to the raw ship velocities. This smoothing method is particularly effective at handling the nonstationary nature of the signal when the ship is starting, stopping, or turning, which is typical of oceanographic cruises. Application of the smoother in this case reduces overall rms noise in the ship velocity by 16%. The combination of both methods reduces the uncertainty due to navigation of a 20-min ADCP absolute velocity from ±0.063 to ±0.038 m s^{-1}—a 40% reduction. These methods also improve the calibration for sensitivity error and ADCP–gyrocompass misalignment angle.

1. Introduction

When bottom tracking is not available, accurate ship velocities from navigation are vital for referencing acoustic Doppler current profiler (ADCP) measurements to earth coordinates. The global positioning system (GPS) continues to be of great assistance in this regard to the shipboard ADCP user. The presence of selective availability (SA) degrades the accuracy of a conventional GPS receiver to about ±50 m root-mean-square (rms) (Hofmann-Wellenhof et al. 1997). The P-code receivers that eliminate SA are available only to the military and selected civilian users, such as the larger University National Oceanographic Laboratory System research vessels. Various differential GPS techniques with respect to a known reference can also remove SA and increase typical GPS accuracy to about ±10 m. For real-time differential GPS, one or more reference stations and a radio data link are required. The U.S. Coast Guard offers differential corrections via radio, but the transmissions are not always available away from the vicinity of major U.S. harbors. Commercial radio differential corrections are available only in certain areas and involve greater expense. GPS users can set up their own differential reference stations on shore in support of a particular project, but this method can be difficult and expensive.

If real-time results are not required, however, a wide-area differential GPS (WADGPS) method can be used in postprocessing to remove the effects of SA. Heroux and Kouba (1995) pioneered the method for Canadian geodetic surveying applications, but the method is useful globally. During the cruise, raw GPS pseudorange data are collected. The pseudorange measurement is the difference between reception time (in the time frame of the GPS receiver) and transmission time (in the time frame of the satellite) of a GPS signal. A few days after the cruise, GPS satellite clock corrections and precise orbital parameters, derived using an international network of GPS receivers, are used to calculate improved WADGPS positions. These positions are as accurate or more accurate than conventional P-code or real-time differential GPS methods.

The ADCP user calculates ship velocity using the best possible positions at the end of each ADCP ensemble averaging interval, typically 2.5 min. The resulting raw ship velocity is noisy and must be smoothed. Conventional linear filtering methods are not appropriate since the ship velocity is significantly nonstationary. One ap-

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proach to this smoothing problem is the reference-layer method, in which measured ADCP-layer velocities relative to the ship are subtracted from raw ship velocity to yield a raw absolute reference-layer velocity (Kosro 1985; Wilson and Leetmaa 1988). This signal is smoothed with a linear time-domain filter and then used to reference the entire ADCP profile.

We apply a locally adaptive polynomial smoothing technique (Fan and Gijbels 1996) to the ship velocity, as an additional step in the ADCP processing, prior to using the reference-layer method. We find that both this initial smoothing of ship velocity and the later application of the reference-layer method are important in reducing the final ADCP uncertainty.

These methods are applied to a recent ADCP dataset collected from R/V *Wecoma* in the vicinity of Cape Blanco, Oregon (Pierce et al. 1997), and we find significant reduction in the final estimated uncertainties of our ADCP velocities. The methods also improve our ability to calibrate for sensitivity error and ADCP/gyrocompass misalignment angle. We were able to verify independently both methods when bottom tracking was available over the continental shelf and slope.

2. Data

ADCP data were collected on the R/V *Wecoma* from 17 to 27 August 1995 (Pierce et al. 1997). This was one of a series of Coastal Jet Separation cruises to study how and why a strong alongshore coastal upwelling jet turns offshore, crosses steep bottom topography, and becomes an oceanic jet (Barth et al. 1999). The cruise was organized around the collection of conductivity–temperature–depth data from a towed undulating vehicle, the *SeaSoar*. The ADCP was an RD Instruments hull-mounted 150-kHz narrowband model, with four beams oriented 30° from vertical. The pulse length was 12 m, the bin width was 8 m, the ensemble averaging time was 2.5 min, and the RD Instruments DAS program was used. The number of pings per ensemble varied from 51 to 149, with a mean of 119. Inherent short-term uncertainty in an ADCP velocity bin ranges from 1 to 3 cm s^{-1}. Conventional GPS navigation from the ship's Trimble 4000AX receiver was integrated into the ADCP data stream at the end of each ensemble using a ''user exit'' program (Firing et al. 1995). For the WADGPS method, a Magellan Field-Pro V receiver recorded raw pseudorange data separately at 1 Hz using Magellan software running on a laptop PC. This additional GPS unit was required because the ship's receiver did not have a Receiver-Independent Exchange (RINEX) output format option. After corrections using the WADGPS method (described herein), these positions were interpolated onto the ADCP ensemble times. The ship's heading was by Sperry gyrocompass.

Data were collected continuously during the 10-day period, in a region extending about 200 km along the coast and 75 km offshore. The focus of the cruise was a series of high-resolution *SeaSoar*/ADCP surveys across the continental margin upstream and downstream of Cape Blanco (43°N). Bottom tracking was available when the ship was in water less than about 500 m deep (42% of the cruise). We use the relatively accurate (±0.01 m s^{-1}) bottom tracking to evaluate the WADGPS and adaptive smoothing methods. Since we experienced a strong along-track gradient of cross-track current (Fig. 1) while out of bottom-tracking range, the methods discussed in this paper are particularly helpful.

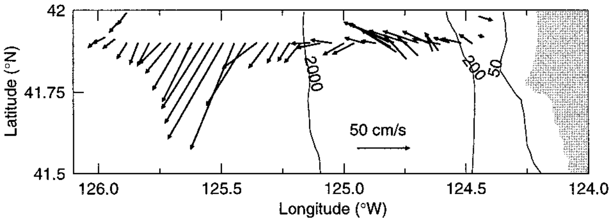

FIG. 1. Final processed ADCP vectors at 18-m depth along a cross-shore line just south of Cape Blanco. Each vector is a 5-km spatial average. The 50-, 200-, and 2000-m isobaths are shown.

3. Wide-area differential GPS

Given the accuracy and availability limitations of conventional real-time single-station differential GPS methods, such as the U.S. Coast Guard system, segments of the GPS community are active in the development and implementation of real-time WADGPS methods (Abousalem 1997). If real-time results are not required, however, WADGPS methods have been available for several years now (Heroux and Kouba 1995).

Most of the detailed information and software required to implement the WADGPS method can now be obtained for nominal fees through the Canadian Geodetic Survey Division (GSD and NRCan 1998). The GSD maintains a network of automated GPS tracking stations across Canada. They also connect with a global network of GPS stations maintained by the International GPS Service for Geodynamics. With a 2–5-day lag time, GSD calculates and makes available, at 30-s intervals, offsets between individual GPS satellite clocks and their network reference clock. These clock corrections effectively remove the dithering effect introduced by selective availability, which is the dominant error source (±50 m).

A smaller source of error, caused by inaccurate orbits, is also reduced by the WADGPS method. GSD offers precise GPS orbit information with a 2–5-day lag. These have an accuracy of about 0.2 m, compared to typical broadcast orbit accuracies of 1 m. Assuming a typical position dilution of precision (PDOP) of 4, position errors due to inaccurate orbits are reduced from about 4 to 0.8 m. Thus, depending on the quality of the receiver, the WADGPS method can be more accurate than P-code or any real-time conventional differential GPS method, both of which use broadcast orbits. Similar postprocessed orbit data are freely available from the U.S. Coast Guard navigation center (NAVCEN 1998), while the GSD charges a nominal fee. We tried both sets of orbits and found identical results. Errors due to ionospheric effects using this WADGPS method are estimated to be about 4 m (Abousalem 1997).

We used the ''gpspace'' software program (GSD and NRCan 1998) for postprocessing the pseudorange data, incorporating clock and orbit corrections and producing improved GPS positions. The program requires the pseudorange data to be in RINEX format (Gurtner 1994), different from the National Marine Electronics Association format used commonly in marine applications. The regular ship's GPS at the time, the Trimble 4000AX, could not produce RINEX output, but most receiver manufacturers now offer RINEX options. In our case, Magellan PC software associated with the Field Pro-V receiver translated from the Magellan proprietary binary format to ASCII RINEX.

The WADGPS method is effective at reducing the familiar nonrandom SA wander (Fig. 2). During this 1-h test at the dock, uncorrected GPS positions measured every 2 s have an rms of ±34 m, while the WADGPS positions are ±9 m rms. WADGPS accuracy while underway is estimated to be ±15 m, calculated by comparing 2.5-min ship velocity from navigation to bottom tracking (section 5).

4. Adaptive local smoothing

Although smoothing by some type of data-adaptive local regression actually dates back at least to Woolhouse (1870) and Spencer (1904), this family of smoothing methods has been rediscovered recently and new theoretical work has been accomplished (Hardle and Schimek 1996). Some varieties of the method have been named ''loess'' smoothers, after a geological term for a deposit of fine clay along a river valley (Cleveland 1979). The approach is to determine a smoothed value $\hat{y}$ at a point x by weighted regression to a local neighborhood of points around x. This group of methods actually includes the familiar moving-average filter. In the case of the moving average, the regression model used is a zero-order polynomial, and the points are weighted with a boxcar.

Consider now fitting data in the vicinity of x using a first-order polynomial, solving for parameters $a(x)$ and $b(x)$ by minimizing

$$\sum_{i=1}^{n} [Y_i - a(x) - b(x)X_i]^2 K[(X_i - x)/h], \qquad (1)$$

where h is the local bandwidth, $X_i \in x \pm h$, n is the number of local data points, and the weighting function K is the tricube function

$$K(u) = \begin{cases} (1 - |u|^3)^3, & |u| < 1, \\ 0, & |u| \geq 1. \end{cases} \qquad (2)$$

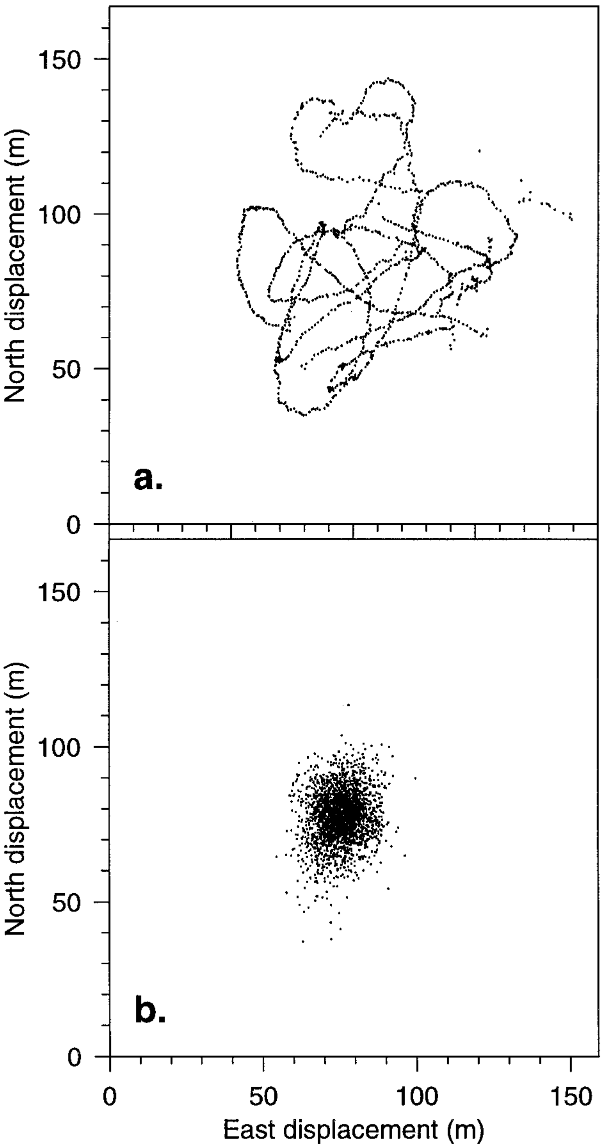

FIG. 2. Stationary test of the postprocessed WADGPS method for 1 h using a 2-s sampling rate. (a) Conventional GPS and (b) WADGPS-corrected positions.

The above regression problem is solved separately for each desired output point x, and then the smoothed value is found: $\hat{y} = a(x) + b(x)x$. In our case, x is time and y is ship velocity, as derived from the GPS positions at the end of each ADCP ensemble. If the underlying function (the true ship velocity) can be well approximated by a first-order polynomial within the local neighborhood of width h, then (1) should perform well.

Many options are available within this family of smoothers, as reviewed thoroughly in the Hardle and Schimek (1996) volume. Bandwidth h can be either fixed or chosen such that the number of local data points n remains constant (nearest neighbor bandwidth). Band-

TABLE 1. Differences between the east–west component of navigation-derived versions of ship velocity and the bottom-tracked ship velocity during the 140-min time period of Fig. 3.

Velocity (m s^{-1})	Mean difference	rms difference	Maximum absolute difference
Raw ship velocity	−0.043	0.201	1.351
First-order polynomial smoothing	0.009	0.172	0.755
Third-order polynomial smoothing	0.002	0.096	0.445
Fifth-order polynomial smoothing	0.004	0.094	0.445

width *h* might be determined using either local or global cross validation. The degree of the polynomial used can be optimized depending on the type of data. A higher-order polynomial will do a better job at following a rapid change in the underlying signal but possibly at the expense of greater noise elsewhere. Mixed-order or adaptive-order polynomial methods are possibilities. Regression functions besides polynomials can also be useful. The software package of Cleveland et al. (1998) is freely available and implements a few types of local regression smoothers (not the type that we adopt herein, however).

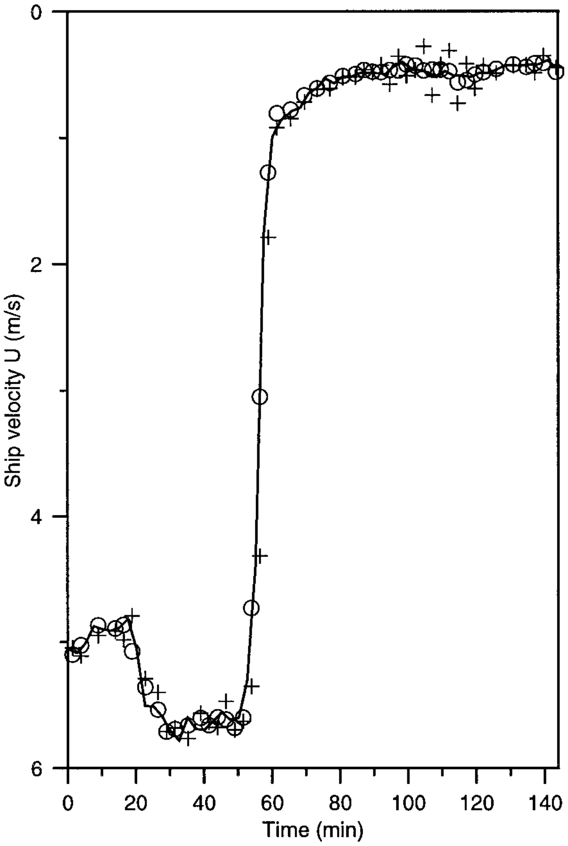

FIG. 3. The curve is the true (bottom tracked) component of ship velocity during this period beginning 1747 UTC 17 August 1995. Crosses are raw ship velocity determined from navigation. Circles are the result of applying the third-order local polynomial smoother to these ship velocities.

As suggested by Fan and Gijbels (1996) for signals such as ours, we test higher-order odd polynomials in addition to (1). We evaluate the results through comparison with the relatively accurate bottom-tracked ship velocity (Table 1). We settle on the third-order polynomial version of (1) as the best balance between simplicity and performance in reducing the mean, rms, and maximum absolute differences:

$$\sum_{i=1}^{n} [Y_i - a(x) - b(x)X_i - c(x)X_i^2 - d(x)X_i^3]^2 \times K[(X_i - x)/h]. \tag{3}$$

Unlike a fixed linear low-pass filter, the smoother is remarkably effective even when ship velocity is rapidly changing (Fig. 3). During this 140-min period, bottom-tracked and raw navigation-derived east–west components of ship velocity have a mean difference of 0.043 m s^{-1} and an rms difference of ± 0.201 m s^{-1}. After application of the adaptive filter, the bias error drops to a negligible 0.002 m s^{-1} and the rms error is reduced to ± 0.096 m s^{-1}. During the entire 98 h of the cruise in which bottom tracking was available, application of the smoother reduces the overall rms ($[0.5(u_{\rm rms}^2 + v_{\rm rms}^2)]^{1/2}$) ship velocity noise by 16%.

We use a fixed bandwidth *h* of 7.5 min for results shown, but the smoother is not sensitive to this choice. We tested values of *h* from 7.5 to 15 min at 2.5-min intervals for the third-order polynomial case. While the 7.5-min case had the best agreement with bottom tracking, final ADCP rms uncertainties varied by only 0.002 m s^{-1} over the range.

These results are probably not too sensitive to the ADCP ensemble averaging time interval—2.5 min in this case. Although a smaller interval would allow more choices for the optimum bandwidth *h*, in our results the exact *h* used is not important. The disadvantage of a smaller ensemble averaging time is that fewer raw ADCP pings are recorded because of the dead time at the end of each ensemble. A shorter ensemble time and *h* might be better on a smaller research vessel, which can experience quicker accelerations than the R/V *Wecoma* (a 56-m ship). The choice of a third-order polynomial for the local regression function should continue to be a reasonable one.

Local regression smoothing methods have much to recommend them for many applications, and have been informally mentioned as rivaling the performance of such adaptive smoothing techniques as wavelets, splines with knot deletion, and various kernel methods (Cleveland and Loader 1996), although we are not aware of any comprehensive formal comparison in the literature. They also have the advantages of simplicity in application and interpretation over other methods. The fact that their theoretical properties remain an active area of research should not preclude their practical application in any number of fields (Hardle and Schimek 1996).

5. Results

The smoothed ship velocity is an improvement, but it still contains noise due to navigational uncertainty. Using a 30–62-m reference layer, we transfer the problem of smoothing ship velocity to the problem of smoothing reference-layer velocity. We combine the ship velocity data and measured ADCP-layer velocities relative to the ship to determine absolute motion of the reference layer (Kosro 1985; Wilson and Leetmaa 1988). The advantage of this step is that our noisy signal is now relatively stationary; conventional filtering techniques are now appropriate. After a robustness step in which outliers are replaced with the median, we low-pass filter in the time domain with a Blackman window:

$$w(x) = 0.42 - 0.5\cos(2\pi x/T) + 0.08\cos(4\pi x/T). \qquad (4)$$

The choice of the filter width T is discussed herein. The resulting smoothed velocities are also integrated back to obtain a new consistent and smooth set of ship positions. This step uses the ‘‘smoothr’’ routine in the CODAS package (Firing et al. 1995). After this, the vertical shear profile for each ensemble is added to the reference layer to determine absolute velocities at all depths.

The resulting uncertainties with and without the prior polynomial smoothing filter confirm that this additional step is ultimately beneficial (Fig. 4). For a filter width T of 20 min, the rms difference, $[0.5(u_{\mathrm{rms}}^2 + v_{\mathrm{rms}}^2)]^{1/2}$, between absolute velocity of the ADCP reference layer from navigation and bottom tracking is reduced from 0.047 to 0.038 m s^{-1} (19% improvement). Figure 4 also shows the improvement of WADGPS navigation over conventional GPS (0.063 to 0.047 m s^{-1} at $T = 20$ min). At full ship speed, 20 min corresponds to a 7.6-km spatial smoothing of the reference-layer velocity. Choosing a longer filter may distort smaller-scale oceanic features (in the absolute velocity) of interest (Fig. 1), while a shorter one results in more noise from navigation. We note that without the added polynomial smoothing filter step, we would have required a T of 70 min (corresponding to a 27-km spatial smoothing) to yield the same rms uncertainty of 0.038 m s^{-1}. This amount of smoothing of the ocean by (4) might be acceptable in some cases, such as in the middle of an ocean basin transect, but here the 27-km length scale would have smeared the velocity structure (Fig. 1).

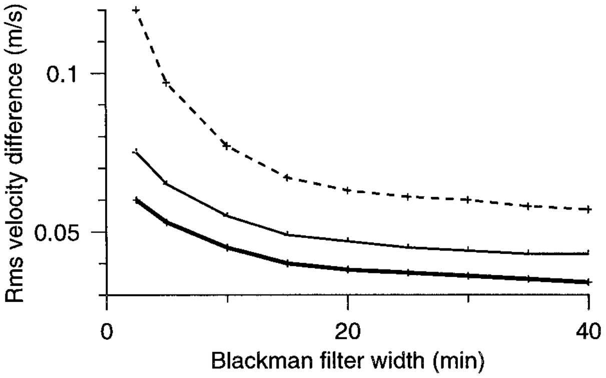

FIG. 4. Root-mean-square difference $[0.5(u_{\mathrm{rms}}^2 + v_{\mathrm{rms}}^2)]^{1/2}$ between absolute velocity of the ADCP reference layer from navigation and bottom tracking vs low-pass filter width T. The uppermost curve uses conventional GPS and ADCP processing methods. The next curve down uses WADGPS positioning. The lowest curve uses both WADGPS positioning and the prior local regression smoothing of ship velocity.

These methods also improve our ability to calibrate for sensitivity error β and ADCP/gyrocompass misalignment angle α (Joyce 1989). We use the bottom-tracking method of calibration and follow many of the recommendations of Trump and Marmorino (1997). Without the methods described in this paper, our α calibration uncertainty is 0.2°. Using the improved ship velocity after applying both methods, α uncertainty is reduced to 0.1°. At highest ship speed, this implies a reduction in the unknown athwart-ship velocity bias from 0.02 to 0.01 m s^{-1}.

Both of these methods are apparently new to the ADCP community and deserve wider recognition. The WADGPS method should be useful for anyone without access to P-code or real-time differential corrections. Additional information, software, and clock–orbit corrections can be obtained from GSD and NRCan (1998). Another promising oceanographic application of the WADGPS method is for Lagrangian drifter navigation (Wilson et al. 1996; Barth et al. 1999, unpublished manuscript). Local regression smoothing methods may be useful tools for the analysis of many different types of data. The 19% reduction in final rms ADCP noise that we observe does not result in either added bias or oversmoothing of the oceanic signal. Software to implement the method is available from the corresponding author (spierce@oce.orst.edu).

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