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ESTIMATING ABSOLUTE CURRENT VELOCITIES BY MERGING SHIPBOARD DOPPLER CURRENT PROFILER DATA WITH LORAN-C DATA

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Abstract

The output of a shipboard-mounted Doppler Current Profiler (DCP) is a profile of water velocity, in various depth bins, relative to the ship. To obtain absolute water velocities, some independent measure of the absolute ship's velocity must be used. The most common measure of ship's velocity is derived from LORAN-C navigation. Unfortunately, LORAN-C derived velocities are not as accurate as Doppler estimates. A process involving a reference layer concept and numerical filtration to obtain estimates of absolute water velocities is described. The cost of using this process is the loss of information concerning the variation of absolute water velocities at periods less than $\sim 1/2$ hours. Once the problem of inaccurate navigation is solved, there are still two problems that can affect the quality of absolute water velocity estimates. These problems arise from small errors in the heading ascribed to the ship and to the speed calibration of the Doppler system.

Introduction

Shipboard-mounted Doppler Current Profilers (DCP's) are rapidly becoming a standard oceanographic instrument. The basic operation of these systems will not be discussed here [see (1) and (2)]. This talk will discuss the conversion of Doppler data from the basic output data of a system, which are estimates of the water velocity in various depth bins relative to the ship, into estimates of absolute water velocities relative to the earth. It should be emphasized that the processes described herein only apply to estimates of absolute water currents. Another product derivable from the Doppler output is current shear which is invariant through all the processes described in this presentation.

Figure 1 is an example of a one-minute averaged Doppler profile taken by an Ametek/Straza DCP 4400 - 300 KHz system in the Sargasso Sea in August of 1984. This profile represents the basic output of a Doppler system. What is shown is the velocity of the water, in various depth bins, relative to the ship. Obviously, the motion of the ship provides the largest component of these velocities.

FIGURE 1: A one-minute averaged profile (100 pings) of the water velocity in each depth bin relative to the ship. This is the primary output of a Doppler System.

FIGURE 2: The same profile as shown in Figure 1 with a reference layer calculation made. The results are velocity estimates of the ship relative to the reference layer and of the water in each depth bin relative to the reference layer.

One method of deriving an estimate of the ship's velocity solely from the Doppler data is the use of a reference layer concept. The ship's

velocity is common to all depth bins, so if a subset of the bin velocities is averaged, then the negative value of this average represents an estimate of the ship's velocity relative to the reference layer. If the reference layer average velocity is subtracted from every bin velocity estimate, a profile of water velocities relative to the reference layer results. The result of this step on the profile shown in Figure 1 is shown in Figure 2. If there is some reason for assuming the average motion in the reference layer is actually zero, then the process of obtaining absolute velocities is complete; but this is practically never the case. There is one situation where this step would be sufficient. If the ship is operating in shallow water and the Doppler system pings the bottom as well as the water column, then the bottom return can be used as a reference layer of known zero velocity.

Invariably, the reference layer will be moving; therefore, some independent measure of ship's velocity is needed to convert the profiles into absolute velocities. Figure 3 shows the profile used in Figure 2 after the absolute motion of the ship, derived from LORAN-C navigation, has been folded in. Two things are apparent from Figures 1, 2 and 3. One: the shear, or shape of the profile, is unaffected by these steps. As was said previously, if shear is the desired product then it is not necessary to worry about the motion of the ship. Two: the reference layer step is handy in that it gives a good first degree estimate of the ship's motion which can be compared to ship's heading and speed data as a check on whether the Doppler is working properly. If the ship is going quite fast in relatively quiescent water, then the reference layer step will be quite reliable. But in the case shown here, with the ship traveling at about 5 knots in a 2 knot current field, the use of navigation is required.

FIGURE 3: The same profile as shown in Figures 1 and 2 with an independent estimate of the absolute ship's velocity added. The results are estimates of the absolute velocity of the water in each depth bin.

At first thought, the use of a reference is an intermediate step that is not necessary if the absolute motion of the ship, derived from navigation, is to be used. The navigation estimates are much noisier than the Doppler estimates forcing some form of smoothing. A representative of the Doppler data needs to be smoothed in the same manner to avoid filter effects during ship's maneuvers. The Doppler estimates of ship's velocity relative to the reference layer handles this job nicely.

The next section will discuss the particular problems involved in using LORAN-C derived estimates of absolute ship's velocity. It should be kept in mind that other estimates are available. The use of bottom-reflected Doppler data can be very effective in shallow water. The new GPS satellite system now coming on line is very promising. But for the next few years, LORAN-C navigation will be the most readily available form of accurate navigation.

Merging LORAN-C Data with DCP Data

Figure 4 shows 24 hours of one-minute (100 ping) averaged Doppler estimates of ship's velocity relative to the reference layer. The data is from the same cruise as the data shown in Figures 1, 2 and 3, and the reference layer is the same 40 to 80 m shown in Figure 2. The "NIGHT" bar indicates the period of local darkness which does not affect the quality of the Doppler data but does, as will be shown, affect the quality of the LORAN-C data. This 24 hour section of data was chosen because the ship made five course reversals during this period. Course reversals are useful because water motion estimates should be invariant during a turn.

FIGURE 4: Twenty-four hours of one-minute averaged estimates of the velocity of the ship relative to the reference layer from the Doppler data.

The derivation of absolute ship's velocities is fairly straightforward. The LORAN-C system used was a Northstar-7000 which produced a position estimate every three seconds. These data were averaged for 1.0 minutes and then a velocity estimate was made by using the difference, in cm, of position from the minute after the minute of interest minus the position from the minute before the minute of interest and dividing by 120 seconds. An option available on the Northstar-7000 allows the user to smooth its output by using the seven minutes of data prior to each estimate. It was decided not to use this feature since this is not a symmetric filter and the LORAN-C data would not react to ship's turns in the same manner as the Doppler. Therefore, the LORAN-C data shown here will be noisier for periods less than seven minutes than normal usage, with the filter, would indicate. Figure 5 shows the same 24 hours of data shown in Figure 4 only it is of 1.0 minute LORAN-C derived estimates of absolute ship's velocity. It is obvious that these estimates are much noisier than the Doppler estimates. It is also clear that the U (east) component is much noisier than the V (north) component and that both components are noisier at night. Analysis of this data indicates that the V component is accurate to about 10 cm/s (ranging from ~ 7 cm/s to ~ 14 cm/s) and the U component is accurate to about 28 cm/s (ranging from ~ 13 cm/s to ~ 40 cm/s). The difference in noise levels between the components is probably due to geography (the position of the ship relative to the two LORAN-C broadcasting stations) and the increase of noise at night is probably related to nighttime ionosphere effects. On the plus side, the basic accuracy of the LORAN-C estimates is supported by the same general character of the two ship's velocity estimates --in particular, the course reversals are as obvious in the LORAN-C estimates as they are in the Doppler estimates.

FIGURE 5: Twenty-four hours of 1.0 minute estimates of the absolute velocity of the ship relative to the earth from the LORAN-C data. This is the same time period shown in Figure 4.

Figure 6 then shows 24 hours of 1.0 minute estimates of the water (reference layer) velocity estimates for the same period, found by subtracting the Doppler ship's velocity estimates (Figure 4) from the LORAN-C ship's velocity estimates (Figure 5). It is evident that all the LORAN-C noise passed through this subtraction, badly contaminating the water velocity estimates. Also, the basic accuracy of the two systems is supported since the ship's course reversals do not affect the estimates of the water velocities.

FIGURE 6: Twenty-four hours of 1.0 minute estimates of the absolute velocity of the reference layer found by subtracting the Doppler estimates (Figure 4) from the LORAN-C estimates (Figure 5).

Because the LORAN-C data noise does vary with component and with time of day, some very sophisticated smoothing could be performed using filters with different characteristics for each component and during different times of day. This was not done because it was felt that it would not be worth the effort. Therefore, it was decided to find one smoothing process that could be applied to the entire data set. The data set from which the examples were taken was a 10 day experiment. During this experiment the ship did a lot of maneuvering, so spectra of ship's velocity estimates are informative. Figure 7 shows spectra of 10 days of 1.0 minute U (east) component estimates of the LORAN-C absolute ship's velocity (SHIP-NAV), of the Doppler relative ship's velocity (SHIP-DCP) and of the reference layer velocity (REF. Lay.). The SHIP-NAV spectrum has been raised one decade for clarity. Two vertical bars are indicated on the spectra. These bars are at frequencies that correspond to periods of 8.33 minutes and 33.33 minutes. At an average ship's speed of 5 kts, these periods correspond to length scales of 1.25 km and 5 km respectively. The "red" nature of the two ship's velocity spectra is a result of the types of maneuvers the ship was put through. An interesting aspect of the SHIP-DCP spectrum is that it does not reach a noise floor. From this observation it can be

SHIP-NAV SPECTRUM RAISED ONE DECADE

FIGURE 7: Spectra of 10 days of 1.0 minute estimates of the U (East) component of: ship's absolute velocity (SHIP-NAV), ship's velocity relative to the reference layer (SHIP-DCP), and absolute velocity of the reference layer (REF. LAY.). The SHIP-NAV spectrum has been raised one decade for clarity.

concluded that the accuracy of the Doppler estimates of the ship's relative velocity is less than 2.4 cm/s. It is felt from other tests that the Doppler accuracy is about 1 cm/s. When the SHIP-NAV spectrum is analyzed, a noise floor is quite apparent. The break from a "red" spectrum to a "white" one occurs at a frequency of about 3×10^{-3} Hz or about 6 minutes. The SHIP-NAV spectrum looks good down to this point and this explains why the NAVSTAR-7000 has a 7 minute smoothing option in its electronics. But when the REF-LAY spectrum is examined, it is apparent that this spectrum reaches a noise level at a frequency corresponding to a period of 30 to 35 minutes indicating that there are some artificial variations in the LORAN-C estimates between 8 and 35 minutes. Indeed, when the two series were filtered with a symmetric low-pass tapered-cosine filter with a one-half amplitude cut off frequency corresponding to 8.33 minutes, there was a great deal of energy in the 8-35 minute band in the SHIP-NAV velocity that was not present in the SHIP-DCP velocity. There is a small possibility that some of this could be real, that the ship is affected by shear-less (over a depth of 80 m) oscillations that would show up in the LORAN-C data but not in the Doppler data. But examination of the data indicated that the amount of SHIP-NAV energy in this band was so great that it probably was due to some sort of electronic "wow" in the LORAN-C

system. It was therefore concluded that both the SHIP-NAV and the SHIP-DCP data series needed to be smoothed with a symmetric low-pass tapered-cosine filter with a one-half amplitude cut-off frequency corresponding to 33.33 minutes. As was stated previously, filtering both ship's velocity records is necessary to avoid having any filter effects show up in the reference layer velocity estimates during any kind of ship's maneuvering.

Figure 8 shows the data shown in Figures 4, 5 and 6 after the filtration has been applied. Notice that all the features in the SHIP-DCP data appear in the SHIP-NAV data, but some energy still exists in the SHIP-NAV data that does not exist in the SHIP-DCP data and is passed through to the WATER (reference layer velocity) data. For example, the period from 0700 to 0800 GMT in the U (east) component. Figures 5 and 6 show this to be the time of greatest noise in the LORAN-C estimates. Therefore, the filter still did not smooth the data enough. Periods like this are rare and the filtration process has already sacrificed all information as to water velocity variations at length scales less than 5 km so it was decided to leave the data in this form.

FIGURE 8: The same 24 hours of 1.0 minute estimates of absolute ship velocity (SHIP-NAV), relative ship velocity (SHIP-DCP), and absolute reference layer velocity (WATER) shown in Figures 4, 5 and 6 after a symmetric low-pass tapered-cosine filter was applied that had a one-half amplitude response at a frequency corresponding to a period of 33.33 minutes.

Therefore, when merging LORAN-C data with Doppler data to obtain absolute water velocities, much of the inherent accuracy and spatial resolution of the Doppler data needs to be sacrificed in order to match it up with the relatively noisy LORAN-C data. Again, it must be stated that this process does not affect the shear data. The full accuracy and spatial resolution of the Doppler system is available if it is shears that are being examined.

Heading and Speed Calibration Errors

The previous section discussed the problems of converting Doppler relative velocities to absolute velocities using noisy but basically accurate navigation data. Unfortunately, noisy navigation is not the only problem faced when converting Doppler relative velocities into absolute velocities. Even if the navigation data were perfect, there are some small problems that can bias the absolute estimate significantly. The two problems that will be briefly discussed are those relating to a heading error and to a Doppler speed calibration error.

In the Introduction, it is stated that the basic output of a Doppler system is a profile of the water velocities relative to the ship. This is a simplification. In reality, the basic product is a profile of water velocities relative to the transducer head in the coordinate system defined by the transducer head. In order to convert this data into water velocities relative to the ship in earth coordinates (as in Figure 1) precise information is needed about the transducer coordinate system (Beam orientations), the transducer's alignment with respect to the ship, and the ship's alignment with respect to the earth (pitch, roll and heading). An error in any of these alignments can lead to an error in the estimates of the relative velocities that can become quite significant when converting relative velocities to absolute velocities.

As a simple example of this type of problem, assume all the alignments are exact except for the pitch. Assume that when the pitch sensor reads 0.0° , the transducer array is actually tipped up by 1.0° . If the ship is steaming at 250 cm/s (5 kts) then the Doppler system will interpret 1.7% $[100 \times \sin(1^\circ)]$ of the ship's horizontal speed as a vertical component. Therefore, the Doppler system will estimate that the ship is rising vertically above the sea surface at a rate of 4.25 cm/s. This is an obvious error and can be corrected fairly easily; other errors are not as easy to assess.

Figure 9 is a diagram demonstrating aspects of the type of errors found in calculating absolute water velocities in the presence of a heading error. In this figure it is assumed that the navigation data is perfect, that the speed of the ship relative to the reference layer (V_s) is always constant at 250 cm/s, and that the absolute velocity of the reference layer (V_w) is always 100 cm/s either parallel or perpendicular to the ship's heading. The heading error is set at 5° ccw, which means that the ship is progressing 5° to the left of what the Doppler system records. The three panels on top depict a situation where the water motion is perpendicular to the ship's heading. The first panel shows the ideal situation where there is no heading error and the estimated water velocity would be correct. The second and third panels show what would be calculated for a water velocity when the ship, with the 5° heading

error, steams east (90°) then west (270°). As can be seen, the direction attributed to the water velocity would not change much but there would be a large variation in the water velocity magnitude estimates.

DIRECTION ERROR

FIGURE 9: A diagram indicating the types of errors that can be caused by a heading error. This figure is explained in the text.

The variation of the water velocity for a course reversal is shown since this is the only way to determine if there is an error. The measured currents should be constant during a course reversal, but, as can be seen in the upper portion of Figure 9, if there is a heading error and the water motion is perpendicular to the ship's apparent course, then a large magnitude but small direction shift will occur in the water velocity estimates. On the other hand, as can be seen in the lower part of Figure 9, if the current is parallel to the apparent ship's course, then a course reversal will estimate the water velocities with a small magnitude shift and a large direction shift.

So the conclusion to be drawn from Figure 9 is that an error in the heading will cause an error in the absolute velocity attributed to the water. The characteristics of the resultant error will vary with the relative orientation of the water velocity and the ship's course. In this case, a course reversal will indicate a maximum water velocity magnitude shift when the water velocity is perpendicular to the ship's apparent course and a maximum direction shift when the water velocity is parallel to the apparent ship's course.

In Figure 10 the heading is considered accurate but the Doppler is assumed to underestimate the speed of the ship relative to the reference layer by 10% (25 cm/s). Examination of this figure shows that a course reversal will indicate a maximum water velocity direction shift when the water velocity is perpendicular to the ship's course and a maximum magnitude shift when the water velocity is parallel to the ship's course. Note that the varying

SPEED ERROR

FIGURE 10: A diagram indicating the types of errors that can be caused by a calibration error in the Doppler speeds. This figure is explained in the text.

response on the water velocity estimates of a speed calibration error is exactly the opposite of the varying response to a heading error.

Figures 9 and 10 demonstrate the effect of heading and speed errors during course speed reversals on the estimation of absolute water velocities. It is felt that course reversals are the only way to find these errors. Unfortunately, one course reversal is not enough to quantify these two sources of error because of the two different and varying responses on the velocity estimates. Several course reversals, in different directions, are needed. This takes time which weakens any assumption about the constancy of the water currents being estimated. This is a nasty little problem for which there is no easy solution.

During the 10 days of the experiment from which the data shown in this presentation was drawn there was one period of 41 hours and another of 17 hours where the ship performed a "star pattern" maneuver. The ship ran 10 km legs back and forth across a common center point at different angles. The estimated water currents appeared fairly constant during both of these periods. By assuming the basic water flow was constant over the entire period of each "star pattern", an attempt was made to quantify both the heading and speed calibration errors by numerically searching for that pair of heading offset and speed offset that minimized the variance of the speed and direction of the estimated water velocity. The result was a heading error 1.2 degrees ccw and a speed error of -2.4%. The heading error was not a surprise because a 1 to 2 degree offset between the bridge gyro and scientific lab gyro repeaters had been noted during the experiment and the watch officers had noticed a small error during the preceding cruise. But the speed error was a surprise. Previous tests had

shown the Doppler to be a very accurate speed estimator, though none of these tests utilized a set of repeated course reversals. There are several sources of speed error. At the start of this section, the effects of a pitch error were discussed. If there is a pitch error and some of the ship's relative velocity is estimated as a vertical component, then obviously the horizontal component is affected. There could be some error in the electronics, e.g., the transmitted signal may not be exactly 300 KHz. The sound speed at the transducer is a critical factor in converting Doppler shifts to relative velocities. The Ametek/Straza System calculates sound speed by measuring temperature to the nearest degree and using an average salinity. The effect of a roll error has not been evaluated or estimated. All these problems are small and it would be difficult to see how they could cause a 2.4% speed error. Another possible source of error is the alignments of the beams within the transducer array. These alignments have not been tested independently of the manufacturers production procedures. In all, a 2.4% speed error is surprising, but there are many small sources of error that could add up to a big enough problem. On the other hand, the assumption that the currents under the "star patterns" were constant for up to 41 hours was pretty weak, so the estimated speed error of 2.4% might itself be in error.

It should be clear that, in estimating absolute velocities, there are other sources of error besides noisy navigation data. The process of estimating absolute velocities is one that demands a lot of careful, painstaking work.

Conclusion

The conversion of Doppler data into estimates of absolute water velocities is a tricky process. The worst aspect of the problem is the relatively poor accuracy of LORAN-C navigation. The price paid for the necessary mutual smoothing of the LORAN-C and Doppler estimates of ship's velocity is the loss of shorter period resolution of water velocity variations. Another aspect of the problem are the effects of small errors in the alignment of the beams relative to the transducer array, the array relative to the ship, or the ship relative to the earth. Examples of the effects of the ship's heading error and Doppler calibration error indicate that small errors in alignment can have significant effects that are difficult to quantify.

I would like to point out that if noisy LORAN-C navigation appears to be the weakest aspect of an integrated Doppler system, the strongest aspect seems to be the Doppler concept itself. I cannot prove it, but I feel that the process of sending a narrow-band acoustic signal out along a narrow beam, and estimating the Doppler shift of the range-gated return signal to obtain radial velocity estimates in various

range bins, is not only the core of the Doppler Profiler concept, but is probably the most accurate and reliable part of a Doppler Profiler System.

References

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