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WHP Hydrographic Operations and Methods – July 1991

Acoustic Doppler Current Profiling Measurements and Navigation

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1. Introduction

Shipboard Acoustic Doppler Current profiler (ADCP) measurements are not difficult to make. A good system, properly set up, can and usually should be left to run continuously throughout a cruise with no intervention beyond changing the floppy disk when they are full. The following discussion is intended primarily to help ADCP users ensure that they have a good system to with and that it is properly set up. This note is intended to supplement, not supplant, the information provided by ADCP manufacturers. In particular, the new ADCP user is advised to read first the "Practical Primer" published by RD Instruments, for an introduction to the principles and terminology of Doppler profiling. Before embarking on a cruise, the user should also become familiar with the relevant manufacturer's manuals and technical bulletins.

The present note begins with a bit of motivation: a list of some of the potential scientific benefits from shipboard ADCP systems (Section 3.) and the related navigational instruments (Section 4.). Recommendations for the configuration and operation of a shipboard ADCP are given in Sections 5. and 6., and in calibration methods are summarized in Section 7.. The steps required to process ADCP data are listed in SEction 8.. The note concludes with a discussion of the accuracy of shipboard ADCP measurements (Section 9.). Appendices list sources of GPS information (Appendix A), describe the publicly available software developed at the University of Hawaii (Appendices B and C), and give recommendations for using the obsolescent Transit navigation system (Appendix D).

2. Scientific rationale for ADCP measurements

ADCP measurements can make important contributions at moderate cost to almost any hydrographic cruise, and to the WHP cruises in particular. With an ADCP one can map current structure along the cruise track with high vertical (10–20 m) and horizontal (2 km) resolution. Having both horizontal components of the velocity vector gives a more complete and realistic picture of the currents at the time of the cruise than can be obtained from the geostrophic cross-track component. This helps in mapping the circulation and in interpreting tracer measurements. Accumulating ADCP sections from many cruises, one can statistically describe the upper ocean vertical shear field as an aid in interpreting drifter measurements. In some regions, the ADCP velocity field will be the best available reference for geostrophic calculations. At low latitudes, geostrophic calculations from single cruises are unreliable, and direct current measurements are essential if one is to know the upper ocean currents. This appears to be true in strong nearshore current regimes as well. A significant part of the upper ocean current structure is ageostrophic; unlike geostrophic calculations, the ADCP measures the actual current field. The measured currents include increase with increasing sonar frequency, but at the expense of decreased profiling range. Because the WHP is primarily concerned with large-scale phenomena, the two lowest-frequency models, operating at 75 kHz and 150 kHz, are much more appropriate for WHP work than are any of the higher frequency models. The VM-75 might indeed be the most suitable of all for the WHP, but few have been installed (probably because the transducer is so large and awkward) and I have no experience with them. The most common model, the VM-150, can serve the WHP well.

The depth range of a given profiler is determined by the density of scatterers, the presence of bubbles under the transducer, and the noise generated by the propellers and by flow along the hull. In moderate weather (winds less than about 20 knots), typical maximum profile depths for an RD Instruments model VM-150 are about 280 to 450 m when the ship is on station, and 180 to 400 m when underway. The greater ranges are achieved near the equator, in coastal regions, and at high latitudes when winds are light; the poorer ranges result from higher winds and/or lack of scatterers as in the middle of the subtropical gyres. A profiler can be rendered useless when the ship is steaming into head seas and clouds of bubbles are frequently swept under the transducer.

3.2 Data acquisition system

Shipboard ADCPs are always operated in conjunction with a computer running a program that controls the profiler and records the profiles. The usual functions of this DAS include vector averaging sequences (ensembles) of profiles in geographical coordinates, recording the ensemble averages on disk or tape, and plotting them on the screen. DAS programs are usually quite complex, and few have been written. Most users of RD Instruments profilers also use the RDI DAS, which runs on an AT-class PC. It is well recognized that this DAS is not perfect, but until a substantially better one is developed and thoroughly tested, continued use of the RDI DAS is probably advisable. Despite its faults it serves its purpose, and it has the virtue of being a standard.

3.3 Transducer installation

ADCP transducer installations are not yet well understood. Some experimentation has been done and at least one poor installation has been successfully redesigned (Leaman et al., 1989), but it seems that no one can predict accurately how well a new installation will work. The least understood aspect of the problem is noise: what the sources are and how it can be minimized. Propeller cavitation seems to be the major noise source on some ships, and flow noise may be the biggest problem on others. On some ships the noise increases uniformly with ship speed, and on others there is a distinct threshold speed above which it increases drastically. Reverberation (or “ringing”) of the transmitted pulse has been a crippling noise source in at least one installation.

Bubbles in the water in front of the transducer absorb sound, so a good transducer installation is one that keeps the transducer in bubble-free water. A faired housing projecting below the hull is often used for this purpose, but some such installations are still subject to bubble problems; and some installations flush with the hull, such as on the Wecoma, seem to be relatively free from obstruction by bubble layers. Perhaps the shape of the hull is a major factor determining how much air is entrained in the water flowing under the hull.

An essential requirement for any installation is that the transducer be rigidly mounted; its orientation relative to the ship must be constant. Ideally this constant orientation should be maintained even when the transducer is reinstalled.

Easy access to the transducer is highly desirable, but sometimes difficult to achieve. Mounting the transducer at the bottom of a well that extends up through the ship to above the waterline is ideal, because it provides access when the ship is at sea. Such a well must be designed carefully to ensure that the transducer is solidly mounted, however.

Transducers made by RD Instruments are fragile; water is kept away from the ceramic elements only by a thin layer of urethane. Barnacles can and often do attach themselves to this urethane and gradually cut through it, causing leaks and complete failure of the transducer. One way of preventing this is to protect the transducer by mounting it behind an acoustic window, typically made of rubber or plastic. The effects of windows are not well understood, however, and they must be tested carefully in each installation to see that they are not causing unacceptable loss of profiling range or other degradation of the signal. Another way of attacking the barnacle problem is to flood the transducer well or sea chest with fresh water whenever the ship is in port. Exposure to fresh water for a day should kill any barnacles that have become attached since the previous port call. This method has been tried only recently, and it is too early to evaluate its effectiveness.

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4. Navigation

Navigation for our purposes requires instruments to measure three quantities: ship's heading, ship's velocity relative to some vertical average of the water column (reference layer), and position fixes. Heading is needed only for transforming the ship's velocity into geographical coordinates. Measurement of the ship's velocity relative to a reference layer, such as from an ADCP, is needed for dead reckoning between position fixes. Even when fixes are calculated almost continuously, as by GPS and LORAN receivers, relative velocity measurements can improve navigation by reducing the effect of short-term errors in the fixes.

4.1 Heading

During the early 1990's, heading will normally be provided by the ship's gyrocompass. It can be transmitted by either of two methods: stepper control signals, which are essentially digital commands that would ordinarily go to a stepper motor; or by synchro signals, which are analog AC voltages carried on 5 wires: two carry a constant reference voltage and the other three carry voltages that vary with the sine of the angle being transmitted. Stepper signals specify angles modulo 1°, with a precision of $\frac{1}{6}°$. A stepper decoder must always be initialized when power is turned on to specify the integer degree, and noise can cause the decoder to lose count of the degrees. Synchro-to-digital conversion tends to be more robust than stepper-to-digital conversion and is therefore preferred for the ADCP. A synchro transmitter can sometimes be added to a compass that uses a stepper to drive its repeaters. This was done on the Moana Wave at minimal cost when the ADCP was installed.

Synchro transmitters can be connected directly to the gyrocompass shaft, in which case the gear ratio is 1:1, or they can be connected through a gear train with a ratio of up to 360:1 (synchro revolutions per ship revolution). The advantage of a 1:1 synchro is that there is no ambiguity, and no need to initialize the heading in the ADCP at power-up. The disadvantage is that accuracy may be lower than for any other transmission configuration. In practice it can still be quite adequate, around 0.1°. I recommend that this be checked at the dock by slewing the compass and noting the heading as received by the ADCP. This procedure provides an end-to-end check of the data transmission, including both the synchro transmitter on the compass and the synchro-to-digital converter in the ADCP.

If heading is available only via stepper or via a synchro with gear reduction, then *it is imperative that the heading as recorded by the ADCP* (and displayed on the screen with the RDI DAS) *be checked frequently against the heading on the master compass.* The stepper-to-digital converter can lose one or more counts every now and then, with devastating effect on ADCP accuracy. Such loss of counts indicates a malfunctioning repeater or other source of noise on the stepper lines. This should be corrected immediately. Gear-reduced synchro conversions can also lose counts, but the only time I have seen this problem it was caused by inadequate filtering in the first version of the ADCP synchro-to-digital converter board, which has since been corrected. The problem that remains, with both gear-reduced synchro and stepper, is determining the *exact* offset between the compass heading and the synchro or stepper reading. (The offset is called the "heading bias" in the RDI DAS). This should be done first at the dock. For a 360:1 synchro, assuming the gear mechanism is properly aligned with the gyrocompass output shaft, the heading bias will be either an integer number of degrees or an integer plus 0.5°, depending on the polarity of the reference voltage wires. Similarly, with proper alignment the ambiguity in stepper output is the integer degree, so only integer heading biases should be required. This should be verified for each installation, however.

A simple gyrocompass points not due north, but along the axis of the total rotation vector: the sum of the earth's rotation and the rotation of the compass due to its relative motion on the earth's surface. The difference from due north is typically of order 1° for a ship, and is a function of latitude and of the north component of the ship's velocity. Most gyrocompasses can compensate for this error, given correct settings of two dials, one for latitude, one for speed. It is suggested that the scientific party discuss this with the Captain at the start of the cruise, emphasizing that for ADCP purposes there is no limit to the desired heading accuracy, and that therefore the compensation should be kept as accurate as possible. (Don't go overboard; it is not necessary to get the latitude to the degree or the speed to the knot; but it is good to keep the latitude correct to a few degrees, limited by the crudeness of the compensator knob, and to adjust the speed compensator when the ship makes a major speed change.) The Captain can also be queried about his knowledge of the accuracy of the particular compass, when it is checked for drift, how accurate the check is, etc. For example, the ship's officers may routinely use star sights to check the compass, and may in this way track its drift to 0.5° or so throughout a cruise (given clear skies and calm seas). If so, this is useful information.

4.2 Velocity relative to a reference layer

Whenever an ADCP is available, it should be used as the speed log; it will almost certainly be the best available if it has been installed and calibrated properly. The reference layer should be chosen so that it is expected to be as smoothly varying as possible along the cruise track. Hence one wants the thickest layer that usually contains good data, and that perhaps omits the first few depth bins near the surface. I normally use ADCP bins 5–20, corresponding to about 50–170 m with 8-m bins. If I were expecting bad weather and poor ADCP range I might reduce the range to bins 5–15, or perhaps 3–15. However, there is nothing to be gained by frequent fiddling with the bin range.

4.3 Position fixes

Because most WHP cruises will be outside the range of Loran C, satellite navigation will be the primary source of position fixes. The Global Positioning System (GPS) is now approaching 24-hour 2-dimensional coverage and the need for the older Transit navigation system is dwindling. If Transit navigation must be used anyway, see Appendix D.

A good GPS receiver with a serial interface should be used on every WHP cruise. GPS receivers are cheap enough now that it would be feasible as well as advisable to carry a spare. There appears to be little advantage for WHP ADCP work in getting the most expensive models, since the fix accuracy of the cheap ones is about the same. Some 2-channel sequencing receivers—including the Magnavox 5400 and 1100 series—sometimes show positions oscillating with a 4-second period and with a peak-to-peak amplitude of up to 60 m. Multichannel continuously tracking receivers, such as the new and inexpensive 6-channel Magnavox 4200, are likely to be much better.

Differential GPS methods can provide very high accuracy that is nearly unaffected by Selective Availability (the deliberate degradation of GPS accuracy provided to civilian users), but require reference receivers within a thousand kilometers or so of the ship. The reference data must be either logged or transmitted in real time to the ship. Because of the cost, complexity, and range limitations, it seems unlikely that differential GPS will be used on many WHP cruises, if any.

For ADCP purposes, GPS fixes should be recorded as near as possible to the end of each ADCP ensemble. Note that one must be careful to record fixes, not dead reckoned positions. In terms of the standard NMEA-0183 data blocks, this means message "GGA". There may be a modest advantage in recording fixes more often, particularly for ADCP calibration. GPS quality information (which is included in message "GGA") should also be recorded. Horizontal dilution of precision (HDOP) is most relevant, although position dilution of precision (PDOP) will do if HDOP is not readily available. The number of satellites used should also be recorded. Regardless of the number of satellites available, it seems wise to operate a shipboard GPS receiver in the altitude-hold mode (in which the antenna height is specified), so that only the horizontal position of the antenna is calculated from the satellite measurements. With the antenna height specified accurately, two-dimensional fixes can be calculated when only three satellites are in view; and when more than three satellites are available, two-dimensional fixes can be calculated more accurately than three-dimensional fixes.

4.4 Integrating navigation with the ADCP

The integration of satellite navigators into the ADCP system is not absolutely essential, but it is highly recommended. Its benefits include improved navigation quality, reduced data storage requirements because fixes are recorded only when needed, and convenience because ADCP and navigation data are recorded in the same file. To achieve all of these benefits there must be 2-way communication between the DAS and the satellite navigator: the DAS sends ADCP speed log information to the navigator, and receives fixes from the navigator. Because GPS fix accuracy does not depend on information about the ship's velocity, the ADCP speed log function is not critical in a GPS-based system, however.

With the present RDI DAS, integrating navigation into the ADCP system requires a "user exit" program which effectively becomes a part of the DAS. I have written one such program to work with the Magnavox 1100 series (1102, 1105, 1107, 1157, with or without GPS), and have recently added partial support for GPS receivers that use the NMEA-0183 data format (Appendix C). Full support of this modern format will be available soon. ADCP users may request this program from me and use it as is, if appropriate, or use it as a starting point for their own versions. I would simply caution that user exit programs can easily disturb the DAS (and possibly crash the machine), so care and testing are needed with any new version.

User exit programs to handle navigation are also available from RD Instruments and probably from other sources. Before a user exit program is used on a WHP cruise, it should be checked to see that it provides the necessary functions when working with the available satellite navigators, and then it should be tested in place with the DAS and the navigators. Instructions for the setup of the navigator should perhaps be posted near the navigator, so that navigation logging will not be disrupted by incorrect or inappropriate navigator settings.

5. ADCP setup

The following recommendations apply to the common RD VM-150 instruments. They are suggestions based on my experience to date and are certainly subject to argument and to revision; but they may provide a useful starting point. For definition of terms, consult two publications available from RD Instruments: the VM operation and maintenance manual, and "Acoustic Doppler Current Profilers, Principles of Operation: A Practical Primer". The user is also referred to these manuals, to the new DAS manual, and to RD Instruments Field Service Bulletins and Technical Notes for additional information, suggestions, and updates.

Before going into the details, here is a general recommendation: keep it simple and consistent. It is usually best to set up a single reasonable configuration and stick with it rather than make frequent changes. Configuration changes tend to complicate data processing and interpretation more than they can possibly improve the data quality.

Firmware: It is important to keep the ADCP firmware reasonably up to date. Some firmware changes will require hardware modifications as well, in which case one must remember to get any spare boards modified along with the profiler itself. The upgrades announced by RDI in March, 1989, are extremely important, and should be performed before any WHP work is done. A lesser but still significant upgrade, to firmware revision 17.07, was announced in late 1990. It involves mainly the bottom tracking, but includes some improvements in water tracking as well.

Depth (range) parameters: The blanking interval should be at least 4 m, not the 2 m that was the original default. I prefer a depth bin length of 8 m, and a pulse length of either 8 or 16 m; the longer pulse increases the maximum range by a few tens of meters in some cases, at the expense of vertical resolution. Note that very short bins and/or pulses have disadvantages (shorter range, higher variance and bias) and no real advantages. The limits on effective vertical resolution are set by the spreading of the beams, their angle from the vertical, and often the pitch and roll of the ship. The number of bins should be set so that the percent good pings has nearly always dropped below 25% by the last bin. With 8-m bins, 50–60 bins are usually adequate.

Temporal sampling: The profiler should be kept pinging as frequently as possible. It does this by default so long as the ensemble averaging is done in the DAS, not the profiler. The operator can assist by not using an outrageous number of depth bins (don't use 128 bins if the data are never going to be good beyond bin 60), and by using GPIB rather than serial communications between the profiler and the DAS computer. Bottom tracking is also a factor: turn it off when the water will be consistently beyond bottom tracking range, so that all pings can be devoted to water tracking. The DAS ensemble averaging interval should normally be somewhere in the range of 1–20 minutes. An interval as short as 1 minute gives a very large data set to process as the price for improved spatial/temporal resolution, which might sometimes contain interesting signal. The higher resolution may be helpful in editing also, although the disadvantage of additional data to look at may overwhelm the theoretical advantage of resolution. As a compromise, I have always liked a 5-minute ensemble averaging time, and that is what I recommend for most WHP work. I have never used a longer interval, and have used shorter intervals only in special circumstances such as when mapping the flow around islands and in some calibration maneuvers.

Compensation for heading, pitch, and roll: Compensation for heading, that is, vector-averaging of pings in earth coordinates, should always be done. Compensation for pitch and roll should be done *if one is sure the pitch and roll sensors are reliable.* The improvement to the data from pitch and roll compensation is usually small. The damage that can be done by a malfunctioning vertical-axis gyro providing incorrect attitude measurements is large.

Reference layer used in ensemble-averaging: The ensemble-averaged profile should always be calculated after removal (and separate averaging) of the vertical mean over a reference layer. I have usually used bins 5–20, although one could use 2–20 or 2–15. The top bin tends to be less accurate and more variable than the others and is therefore excluded from the reference layer. The last bin of the layer should be set so that it is usually well within the profiling range of the instrument. The benefit of the reference layer calculation does not depend critically on the layer used, however, so long as the layer contains good data on each ping.

Error velocity editing: Error velocity screening by the DAS is a potentially useful filter for outliers. A threshold should be chosen to make only a slight reduction in the percent good; only a few outliers should be eliminated. The RDI recommendation of 100 cm/s is a reasonable starting point. I have never used less than 60 cm/s.

Sound speed: For non-obvious reasons, the constant of proportionality between the Doppler shift and the water speed involves the speed of sound *at the transducer* only. Ordinarily, one should let the DAS calculate it from the temperature measured at the transducer and a reasonable salinity specified in the configuration. Sound speed changes by about 0.1% for each psu change in salinity, so it is not necessary to keep changing the salinity in the configuration; keeping it within 0.5 psu or so will make it a very small source of error. The most important thing is to monitor the temperature measured by the profiler and displayed by the DAS. If it drifts away from sea surface temperature then the thermistor has failed. One must then configure the DAS to use a specified sound speed, and one must calculate this from sea surface temperature and correct it in the DAS whenever there is a significant change. Sound speed changes by 0.3% per °C at 0°C, and by 0.13% per °C at 30°C. Recalculating sound speed for each 1°C change in sea surface temperature would be a reasonable procedure.

Three-beam solutions: Whether to use 3-beam solutions to improve the depth range depends on the characteristics of the particular installation. If the error velocity is consistently small, even at the bottom of the profile where the percent good is dropping rapidly, then the 3-beam solutions will be similar to the 4-beam solutions and can be used. I have not done the algebra needed to quantify this.

Bottom tracking: Bottom tracking should be turned on when the bottom is within range. When bottom tracking is used, bottom track pings should be interleaved 1:1 with water track pings. With other ratios there is increased likelihood of aliasing and serious error in the bottom track measurement. The direct command for 1:1 interleaving is "FH00001".

What to record: Always record all ensemble-averaged velocity components: N/S, E/W, vertical, and error. Always record percent good, AGC level, and ancillary data. If 3-beam solutions are used, then record percent 3-beam. Ordinarily there is little point in recording any of the "last raw" variables. Beam statistics can be helpful, take little space, and should therefore be recorded. Standard deviation of velocity is not calculated correctly in the DAS as of this writing, and so should not be recorded. Spectral width is optional. I have not made much use of it so far, but I do record it. If a user-exit program is in use, the correct number of bytes to record (from a memory block called the "user buffer") must be specified.

Graphical display: The display does not affect what is recorded, and so is may be set to the taste of the operator.

Direct commands: There is presently one ADCP water tracking parameter that cannot be set from the DAS and that in many cases should not be left at its default. The "E" command controls ping-to-ping tracking. By default the processing filter is positioned based on the average frequency in the top 30% of the bins in the previous pings (with a variable weight for increasing lags). If the near-surface shear is large, as in the equatorial undercurrent for example, then this default ensures poor positioning and consequent bias errors in the top few bins, until the bin-to-bin tracking loop corrects the initial error. The solution is to tell the ping-to-ping tracker to use only a few bins (5 in this example) starting with bin 2; the direct command for this is "E0005020199". As far as I know there is no good reason not to use this command routinely; it should do quite well in positioning the tracker regardless of whether there is large shear in the upper 100 m. However, with regard to this and all other direct commands, the user is cautioned to check the manufacturer's technical bulletins for changes and new recommendations.

6. ADCP operation

The first principle of operation is to set the instrument up and then let it run as long as possible without interruption. If an interruption is needed, it should be done right after a profile (that is, the ensemble average of the individual single-ping profiles) has been written to disk, and it should be kept as brief as possible. Avoid interruptions when the ship is accelerating. Interruptions are less destructive of absolute velocity accuracy when GPS is available than with the less frequent Transit fixes, but still should be avoided.

The DAS display should be checked occasionally to see that the ADCP system, including the integrated navigation instruments, is working normally. Usually the graphical display is preferred, both for monitoring the instrument and for viewing the current structure. With GPS navigation integrated into the DAS by a user-exit program, and with a 5-minute ensemble averaging interval, the real-time absolute velocity estimate is often quite good (to 10 cm/s or so), so I normally choose the DAS option to reference the velocity profile to the navigation. Occasionally the position fix jumps and consequently the velocity profile is off-scale for one ensemble—this is a minor inconvenience and nothing to worry about.

The most important things to monitor are:

Heading: check that it agrees with the ship's compasses.

Temperature: check against sea surface temperature to ensure that the DAS is using the right sound speed to calculate velocity.

Velocity: check for reasonableness in the region where the percent good is greater than 25%.

Beam statistics: check that all four numbers are roughly the same, indicating that all four beams are performing equally.

The last item in this list is not available from the graphical display; one must switch to the tabular display, which can be done with only a very brief interruption. In the tabular display, the velocities and signal strengths are given for each beam from the last ping of the ensemble. Because there is no averaging, the numbers are highly variable.

7. Calibration

The basic methods of calibration are explained by Joyce (1989) and Pollard and Read (1989) and will not be repeated here in detail. Briefly, there are two methods: comparing the ship's displacement measured from bottom tracking with that measured from GPS, and comparing the acceleration relative to the water measured with the ADCP to the acceleration over the ground measured with GPS. These two methods should give identical results for the transducer orientation (relative to the gyro compass), but they can give scale factors that differ by something like 0.5%. Therefore the bottom track method is a useful supplement to the water track method, but cannot replace it.

The bottom track calibration method is straightforward and will not be discussed. Here are some notes about the acceleration method:

When to do it: Any substantial acceleration of the ship during good GPS coverage can be used, so usually most calibration points are obtained in the course of a normal hydrographic cruise when the ship stops on station and then gets back underway. Additional calibrations can be obtained at very low cost in ship time by slowing the ship by at least 6 knots for about 20 minutes at any time between stations or on deadheads.

Navigation: Good quality GPS is essential. It is also important that the fixes be obtained within a very few seconds of the end of each ADCP ensemble. If fixes are not being logged with a user exit program, then they should be logged externally very frequently (up to once per second), and the ADCP time (which comes from the DAS PC clock) must coincide with GPS time. The ADCP time can be adjusted in post processing. If necessary, this adjustment can be determined to within a few seconds from the GPS fixes and the ADCP data alone.

Schuler oscillations: One source of error is the Schuler oscillation of the gyro compass. Everything I have read indicates that the oscillation is excited mainly by the meridional component of acceleration of the ship on the time scale of the oscillation (84-minute period). If so, then calibrations should be more accurate on zonal cruise tracks than on meridional tracks, and on the latter should be more accurate when the ship stops than when it gets underway. It is not yet clear that these effects are detectable in the data I have looked at. Also, it is not clear to me how the amplitude of the oscillation should vary from one compass to another; the oscillations reported by Pollard and Read (1989) are larger than I seem to see on other ships and larger than I expect based on the calculations of Stansell (1973).

The assumption underlying most discussions of ADCP calibration is that gyrocompass error may drift with time over a period of days to weeks, but at any time is independent of heading (apart from the short-term Schuler oscillation). *This assumption has recently been demonstrated false in at least one case:* a standard Sperry Mark 37 compass has been shown to have a difference of 1.5° between the errors on north versus south headings. I do not know yet whether this dependence of the error on heading is a symptom of compass failure, how long it has been occurring, or how commonly it might occur on other compasses.

Software for performing calibration calculations (both methods) is included in the UH data processing system (Appendix B).

8. Data processing

Processing ADCP data well is not a trivial task, but neither is it so difficult that it should limit the collection or use of ADCP data. In this section I will list the operations that any ADCP data processing system is likely to perform; some components and characteristics of the particular software system developed at University of Hawaii are described in Appendix B. Developing this type of software requires considerable time and effort, so I suggest that new ADCP users consider adopting existing systems rather than developing their own from scratch. The UH system was developed with this in mind and is readily available (Appendix B. This may be true of other systems as well.

8.1 The basic functions

In the following, "profile" will refer to the recorded ensemble-average of single-ping profiles. The basic functions that must be performed are:

Scan the raw data files to ensure they are readable, to identify gaps or other problems, and to extract information needed to correct the recorded profile times in case the PC clock was in error.

Load the data into a database suitable for processing and analysis.

Correct the profile times. This can be done as the profiles are loaded into the database.

Evaluate the quality of the dataset as a whole by calculating and plotting diagnostic statistics. Signal strength (as measured by the Automatic Gain Control: AGC), percent good pings, error velocity, vertical velocity, and the vertical derivative of the horizontal velocity components are informative. It is useful to compare these variables between on station and underway periods.

Edit the profiles.

Calibrate the profiler-gyrocompass combination. Scale factor and rotation calibrations must be determined from all available data as a function of time during the cruise and then used to correct the velocity data.

Reference the relative velocity profiles by calculating the ship's position at the end of each profile and the average velocity of the ship during the profile.

Adjust depth for the difference between the actual vertically averaged sound speed (calculated from hydrographic data) and 1470 m/s, the nominal sound speed assumed by RDI in converting pulse travel times to ranges.

Grid and plot the absolute velocity field in useful ways, such as contoured sections of each horizontal velocity component and maps of velocity vectors at each of several depths.

The order given above is reasonable, but does not have to be followed exactly. Data processing is often done iteratively, beginning with a quick pass (minimal or no editing and calibration). Editing does not have to be done all at once. For example, clipping the bottom of the profiles can be delayed until the data are extracted for plotting.

9. Accuracy

Shipboard ADCP measurements are inherently complicated, and their accuracy cannot be reduced to a single number. One must instead characterize the accuracy of various products calculated from ADCP measurements, as a function of many variables. For example, one might estimate the uncertainty in transport across a given 1000-km section in the top 200 m, or one might estimate the uncertainty in the velocity at 50 m relative to the velocity at 80 m, averaged over 5 minutes. The main source of error in the transport measurement would probably be uncertainty in the orientation of the transducer in geographical coordinates. The main source of error in the relative velocity measurement might be the inherent limitation in short-term accuracy of the Doppler measurement. In the following discussion I will not give a complete characterization of ADCP system error, but I will try to cover the main points that are relevant to WHP ADCP work.

9.1 Errors in relative velocity

Accuracy of the ADCP in measuring currents relative to a vertical mean is thought to be of order 1 cm/s. This accuracy is very difficult to measure, however, and so the estimate is based primarily on theory and simulations (RD Instruments Technical Bulletin ADCP-89-06). Larger errors discussed by Chereskin et al. (1989) have been greatly reduced in new or upgraded instruments.

When measuring currents relative to the ship, small deviations in transducer geometry lead to current errors proportional to the ship's speed. These errors are constant and can be removed by in situ calibration procedures described by Kosro (1985), Joyce (1989), and Pollard and Read (1989). Errors in sound speed used in calculating velocity from Doppler shift are similar but may be time varying and are therefore not as easy to remove. For example, if the salinity is off by 1 psu and the temperature by 1°, the combined error could be 0.2% in sound speed and hence in velocity. With a ship speed of 5 m/s the error is then 1 cm/s in the along-ship velocity component. Very small quantities of bubbles in the water can also reduce sound speed dramatically; it is not clear yet whether this effect can be observed in shipboard ADCP measurements. In addition, Pollard and Read (1989) found day-to-day differences in the amplitude calibration parameter of as much as 1%. They suggest that this may be due to signal processing subtleties combined with variations in the density of scatterers, but this has not been confirmed.

9.2 Errors in absolute velocity

Calculating absolute currents in geographical coordinates by adding the motion of the ship to the relative ADCP profiles introduces two more sources of error: (1) fix inaccuracy causes errors in the ship's velocity, and (2) the combined errors of the compass and of the transducer orientation about the vertical axis cause errors in the transformation from ship coordinates (starboard and forward) to geographical coordinates (east and north). The second of these error sources is often the more troublesome, since it leads to errors in the cross-track velocity component that are proportional to the ship's speed and that may persist indefinitely if not identified and removed. The first error source—fix inaccuracy—does not lead to bias on large space scales, but does limit the horizontal resolution of the absolute current measurement. That can be a major problem in narrow, swift coastal currents.

The biggest problem with future GPS accuracy is the deliberate degradation by the US Department of Defence under their long-announced policy of Selective Availability (SA). This was begun in March 1990 and temporarily discontinued in August. It may be reimposed at any time. Civilian accuracy (using the CA code) gives a 95% confidence circle with a radius of about 40 m without SA or 100 m with it (Zachman, 1988.) Without SA, the 95% confidence level for ship velocity is therefore about 20 cm/s averaged between fixes 5 minutes apart, and 3 cm/s averaged over 30 minutes. For a given velocity accuracy, the required averaging time with SA increases by a factor of 2.5, so averaging for one hour gives an accuracy of 4 cm/s. Clearly, even with SA, fix accuracy is not a problem for measuring currents on large scales along a cruise track. Fix accuracy becomes a significant limitation for looking at horizontal scales of about 10 nm or less when the ship is underway at 10 knots.

The above estimates of velocity error due to GPS error do not take into account the sequential correlation of position errors; they are based on a white spectrum of position errors. In fact, a time series of GPS fixes from a stationary antenna is nonstationary and its spectrum is not white. Position errors can drift over a period of hours, jump abruptly when the constellation changes, or oscillate with periods as short as 4 seconds. The character of the errors changes from hour to hour and from day to day; presumably some of this variability is caused by experimentation with SA and will diminish as the satellite constellation is completed and the system is declared operational. In any case, sequential correlation of fix errors reduces short-term velocity errors at the expense of longer-term errors. The ill effect of very high frequency oscillations, such as the 4-second oscillation observed in some receivers during the period of SA, can be eliminated by burst sampling and averaging over an integral number of oscillation periods.

The last error source to be discussed here is the one that appears to place the most severe limits on the accuracy of volume transports calculated from ADCP sections and on the usefulness of the ADCP for referencing geostrophic sections: it is the error in the angle between the transducer axis and true north. In situ calibration methods (Pollard and Read, 1989; Joyce, 1989) can be used to calculate this error at various times, places, and headings. If the error were constant, there would be no limit on the accuracy with which it could be measured and corrected. Unfortunately, gyro compasses are not perfect, but can have errors in the range 0°–2°. One of these errors, the Schuler oscillation, is well understood and usually relatively harmless; it is a heavily damped oscillation of 84-minute period excited primarily by meridional accelerations. Another error source is the transmission of the heading from the compass to the ADCP, usually via a synchro control transmitter and a synchro-to-digital converter. This error can be measured at the dock by slewing the compass. With good components it should be minimal, 0.1°–0.2°. (This level of accuracy has been verified on the Moana Wave.) Remaining errors are said by Sperry personnel (Robin Congdon, personal communication) to be less than 0.2°, but ADCP calibrations obtained on several Moana Wave cruises indicate that the compass error can shift by about a degree over periods of a few days to a month. (See also Section 7..) Such drifts have been observed via star sights also on the R/V Franklin and on the Discovery (Pollard and Read, 1989).

9.3 Calibration accuracy

A calibration point can be obtained whenever the ship's velocity changes substantially during good GPS coverage. With nearly continuous GPS coverage, this means we can anticipate two calibration points per CTD station, or 6 per day with a typical WOCE schedule of 3 stations per day. Experience on several cruises has shown that the standard deviation of the calibration points (without SA) was typically 0.8° in angle and 1.5% in amplitude. This means that to get a target calibration accuracy of 0.2° with 95% confidence required 64 calibration points, which could be obtained in 11 days. This can be shortened by getting additional calibration points between stations, at a cost of about 15 minutes of ship time per pair of calibration points (which would not be independent, and so perhaps should be treated as a single point).

The standard deviation of the calibration points is determined by fix errors, by short-period variability in the compass (for the angle error) and the ADCP scale factor (for the amplitude factor error), and by spatial and temporal variations in the ocean reference layer velocity along the ship's track during each calibration maneuver. Although I have not studied this thoroughly, it appears that the main contributors are usually the fix error and the ocean variability, and that the latter is probably dominant for GPS fixes without SA. With SA in effect, the standard deviation of the calibration points would be at most doubled; this would happen if ocean variability were negligible and if fix errors were uncorrelated over 5–10-minute intervals. The number of calibration points required for a given level of accuracy would then be increased fourfold. Fortunately, much of the time the SA errors have a decorrelation time scale considerably longer than 10 minutes (although some receivers are subject to very high frequency oscillations in calculated position). Still, the effect of SA on calibration may be more disturbing than its direct reduction of accuracy in calculating absolute currents along a section.

Calibration errors, whether of amplitude or of orientation relative to north, cause absolute velocity errors proportional to the ship's speed. Hence typical calibration errors are of little importance on station and of major importance underway. The average speed of a typical ship (e.g. the R/V Knorr) on a meridional line, such as the P16 leg from Tahiti to Hawaii, is about 4 kts with small-volume stations only, or 3 kts with large-volume work. The resulting error in zonal velocity from the target 0.2° calibration error is then only 0.7 cm/s in the former case, and 0.5 cm/s in the latter. Heading uncertainty may be larger over periods shorter than the 11 days required for the 0.2° calibration, and the uncertainty in the cross-track velocity component will be correspondingly larger.

The long-run solution to the orientation problem is likely to be the use of GPS carrier phase interferometry in place of the gyro compass to measure the ship's attitude. In principle this should provide heading accuracy of about 0.1°, enormously simplifying the calibration problem and increasing the accuracy of the cross-track velocity component. This technique is under development, and I am optimistic that GPS heading measurements will be available to enhance ADCP accuracy for a significant fraction of the WHP.

9.4 Sampling

Shipboard ADCPs do not successfully measure the velocity in each depth bin on every ping. Near the bottom of the profiling range, for example, the profiler may get a valid velocity in only half of the pings. Under adverse conditions, especially when a ship is steaming into head seas, the percentage of good pings may fall well below 100% even at the top of the profile. This can lead to a large bias in the ensemble-averaged velocity, because the loss of signal may be correlated with the ship's velocity and/or attitude. On one ship I have worked with a bias of up to 1 m/s appeared when the ship steamed into heavy weather and the percent good pings at the top of the profile dropped to 50% or less. This bias was in the direction the ship was steaming, indicating that pings were lost when the ship sped up and the signal returned when the ship slowed down.

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A Sources of GPS information

Many interesting and useful reprints of conference and seminar presentations are available from Magnavox Advanced Products and Systems Corporation, 2829 Maricopa St., Torrance, California, 90503, phone: (213) 618 1200.

A variety of informative publications are sold by Navtech Seminars, Inc., 1900 N. Beauregard St., Suite 106, Alexandria, VA 22311, phone: (703) 931 0500. Among other things they have compiled a survey of available GPS receivers. I do not know how recently this has been updated, however, and the market is changing rapidly.

For periodic updates on all facets of GPS technology and its applications, there is now a magazine dedicated to the subject: *GPS World*, published bimonthly by GPS World Corporation, and distributed free of charge to qualified individuals (which would probably include most people reading this). If you can't find a copy lying around, write to GPS World, Aster Publishing Corp., PO Box 10955, Eugene Oregon, 97440-9972, or phone (503) 343 1200.

GPS constellation status and general news can be obtained with a computer and modem by dialing into the public bulletin board of the US Naval Observatory. The number is (202) 653 1079. Use upper case only, and set your modem for 7 data bits, 1 stop bit, even parity.

Similar information plus almanac data can be obtained from the "Yuma" bulletin board operated by General Dynamics Services Company for the US Air Force Space Systems Division. This board is easier to use than the Naval Observatory board and accepts upper and lower case, 8 data bits, 1 stop bit, no parity. The number is (505) 679 1525. æ

B The UH ADCP data processing system

The University of Hawaii ADCP data processing system has been developed and used over several years. It has been used by several groups in addition to mine to process more than two ship-years of ADCP data. Some of this processing has been done at sea in near real time by people with no more than a few hours of training by my group. However, this required considerable time and effort by the new users; the system is large and its use involves many steps. A description of the system and an example of its use are given by Bahr et al. (1990).

The software may be obtained from me by request: telemail to e.firing/OMNET or Internet email to efiring@soest.hawaii.edu. The standard distribution package includes all source code, documentation, and a sample dataset illustrating all stages of processing. The source code is internally documented and external documents have been written for many of the major operations. These are now being assembled into a users manual that will describe all data processing procedures.

B1 Hardware

The UH system is designed to run on a variety of machines starting with a simple PC-compatible and including VAX-VMS and most UNIX machines. The reasons for specifying this degree of machine independence are:

- Hardware is changing rapidly, and one wants to be able to take advantage of improvements as they occur, with minimal cost in software modification and maintenance.

- Portable software can be used by more members of the community than can machine-specific software; it can contribute to a pool of common software.
- PC-compatibles are so cheap, ubiquitous, and physically portable that they can always be taken along when travelling or going to sea. With software that runs on a PC, one can always process data in near real time at sea.

The minimal configuration for the UH system is a PC with 640K of RAM, a math coprocessor, and a 40-Mbyte hard disk. The system has been used extensively with such machines and also with Sun-3 and Sun-4 machines. A Postscript-compatible laser printer is recommended for plot output, although an HPGL plotter (laser is preferred, pen is usable) can also be used.

B2 User interface

Most routines in the UH system are governed by ASCII control files that are designed for readability and therefore help document the processing of each data set. All control files can contain unlimited comments; standard sample control files start with a comment block that explains the parameters in the file and gives examples. Each parameter (or list) in a control file is preceeded by a descriptive key word, which identifies the parameter to both the machine and the operator. Control files for complicated routines have optional parameters; when not needed for a particular operation they can be omitted, shortening and simplifying the file.

Many routines also use intermediate ASCII data files that are also designed to be human-readable, with headers and comments. For example, files listing satellite fixes are edited, both mechanically and by hand, by prefixing the character "%" as a comment indicator to lines with bad fixes that are to be ignored in future steps. Additional comments can be used to explain why a fix was deemed bad.

One commercial program is used as part of the UH system. Matlab (by the MathWorks, Inc.; available for the PC, 386-PC, Sun, Vax, and several others) provides easy plotting and interactive calculations.

The first step in processing a new dataset with the UH system is to run a batch file (or UNIX script) that builds a directory tree for the new dataset with subdirectories for each of the processing steps. These subdirectories are then filled automatically with example control files and Matlab program files ("m-files"). The operator need only copy his raw data files into the appropriate subdirectory, modify the sample control files as needed, and run the processing programs.

B3 Database

A typical one-month cruise generates about 10 Mbytes of binary ADCP data which include many variables, both scalars and arrays. The variables included in a dataset can change from one cruise to another. The size and complexity of ADCP datasets therefore warrant the use of a database system rather than a simple fixed file format. To fill this need, Ramon Cabrera, Julie Ranada, and I have developed CODAS (Common Oceanographic Data Access System): a set of machine-independent subroutines for the storage and retrieval of oceanographic and other scientific data. It is designed for maximum storage efficiency combined with fast random or sequential access. It is flexible enough to comfortably accommodate data from a wide variety of instruments, such as the Acoustic Doppler Current Profiler (ADCP), the CTD, current meter moorings, and pressure gauges, together with auxiliary observations and instrument configuration parameters.

CODAS is hierarchical. Data are organized into profiles, each of which may consist of several arrays (for example, one for each of three velocity components) and other data (flags, data collection parameters, notes, etc.) Profiles are collected together in blocks, each of which is an independent, self-describing unit of data. The internal description of each variable in a block includes the name, units, and scale factors. A profile is located within a block via a profile directory that is part of the block. Blocks are catalogued in a block directory.

A CODAS database contains only two kinds of files: a set of data block files, and a single block directory file. The data block files are independent units and contain all the information required to make a block directory file. Hence, data blocks from different sources can be combined into a working database by running a utility program that generates a new block directory file.

CODAS was written in C with care taken to make it portable among modern machines. It has been used on IBM PC-compatibles, a VAX 750, an Alliant, and Sun workstations. Data blocks are normally stored in the binary format of the machine on which they were created or are actively being used. When moved to another machine and assembled into a new database, they are automatically translated to the new binary format if necessary (as in going from a PC to a Sun, for example).

Storage space is minimized. The user is free to use 1, 2, or 4 byte integers, floating point, double precision, or ASCII. However, use of the most compact format for each variable is encouraged, because the system (optionally) automatically converts and scales array data from any number format to floating point when reading, and the reverse when writing. Storage space is allocated as needed when the data are stored; there is no need to waste space by specifying fixed array lengths, for example. The extensive directory structure adds only a few percent of storage overhead.

B4 Editing

The premises behind the UH editing system are:

- Because of the volume of ADCP data, automated scanning for possible problems is essential.
- We do not yet know enough to design a purely automated editing system; an operator must be able to review the results of the scanning and decide exactly how the editing

should proceed.

- Because editing is sometimes done iteratively, and one might sometimes want to undo a step, the eventual changes to the database should be kept to a minimum and should be reversible where possible.
- The editing process should be self-documenting.

The main problems to be removed by editing are usually limited to interference from the bottom reflection in shallow water, interference from the hydrographic wire during CTD stations, and diminishing accuracy at the bottom of the profile. With a poor installation or a poor choice of setup parameters, it may also be necessary to reject data from the top depth bin(s).

In the UH system, suspect profiles or bin ranges are identified primarily by running a program ("FLAG") that tests each profile in a given time range for several conditions and writes an ASCII file listing cases in which user-specified thresholds are exceeded. The variables being checked include error velocity, the variance in the vertical of the vertical velocity component, the signal strength, and the second vertical difference of each of the velocity components. Large values of the error velocity coinciding with large second differences in the vertical velocity component and in at least one of the horizontal velocity components indicate interference by something like a hydrographic wire. On the Moana Wave, for example, this occurs occasionally during CTD stations, is usually confined to a few depth bins among the top ten, and is usually quite subtle—the horizontal velocity component glitches are typically only 5–10 cm/s. A local maximum of the signal amplitude indicates either a scattering layer or the bottom, when the bottom is deeper than about 30 m. When the bottom is very shallow it does not cause an amplitude maximum, but it usually leads to high variance in the vertical velocity profile, hence our use of this statistic.

After running the FLAG program, one normally uses Matlab to look at sequences of profiles ("stagger plots") that are suspect, to make a final decision about what to edit. In many cases the output of the FLAG program can be used with little modification to control the programs that modify the database; in other cases a difficult judgement must be made.

Once the decisions have been made, editing is done on the database. In the case of bottom interference, the appropriate portions of the FLAG output file are used to specify the last bin of each profile for which velocity data will be considered valid, and this bin number is recorded in the database with each profile. If there is a problem in the top depth bins, caused, for example, by inadequate blanking interval or by ringing of the transducer installation, then the first bin of the profile for which the data are acceptable may be recorded with each profile. Otherwise, by default this is bin 1. When the velocity in individual bins is judged bad, a file listing these bad bins is used to control a program that sets the appropriate bits in an array of flag bytes. (This is a recent improvement in the system. Previously we set the actual velocity values themselves to a bad flag value.)

Additional editing is normally done when the data are accessed. Typically one specifies a percent-good criterion, and the access program flags as bad any velocities for which the recorded percent-good is below the threshold. We usually use 30%.

Although our editing system is quite thorough, flexible, and effective, it can also be confusing and difficult to use; we plan major improvements.

B5 Calibration

Routines are available for both the bottom-track and the acceleration method of determining the calibration factors. For the bottom track method the user must select the time ranges with continuous bottom track and navigation data. An interactive Matlab routine is then used to edit the navigation data and write the least-squares, best-fit calibration factors to a file. For the acceleration calibration method, a program automatically selects the accelerations for which GPS data are available and calculates the calibration factor for each acceleration. This is written to a file along with quality statistics. This file is input to a Matlab routine which edits, plots, and writes out a statistical summary.

B6 Navigation

Position fixes, GPS or Transit, are automatically screened and merged by an editing program. Rejected fixes are simply commented in the file, so that they can be manually reinserted if desired. Additional manual editing is also done, in an iterative fashion, by commenting out questionable fixes.

Calculation of absolute velocity profiles involves the intermediate calculation of the absolute velocity of a reference layer (we use bins 5 to 20, about 50–170 m) in the usual way (e.g., Kosro, 1985; Wilson and Leetmaa, 1988). Averaged between fixes, the velocity of the reference layer is just the difference between the velocity of the ship over the ground, determined from the fixes, and the velocity of the ship relative to the reference layer, from the ADCP profiles. This initial estimate of the reference layer velocity, which is constant between fixes, is then smoothed by convolution with a Blackman window function $w(t)$ (Blackman and Tukey, 1958) of width T,

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

Since the function being filtered is piecewise constant, the convolution can be evaluated efficiently by analytic integration over each constant piece. The choice of filter width depends on the characteristics of the data: the quality of the fixes and the expected amplitude and time scales of the currents being surveyed. When GPS is good and there are small-scale current features of interest, T might be as short as 15 minutes. In the worst case of poor Transit quality and no GPS, T can be up to 12 hours.

Our method of smoothing the reference layer velocity is probably not optimal in many cases; its main virtue is simplicity. The biggest problem is that it does not take into account nonuniform motion of the ship; smoothing is done in the time domain only. In a region of large spatial current gradients, this guarantees errors when the ship changes course or stops for a station. Usually this error has little effect on the outcome of data analysis. The problem is likely to be worst, and hardest to fix with a simple algorithm, when the ship reverses course in a region of large along-track gradient of the cross-track current—for example, when approaching a coast along which flows a western boundary current. Time-domain smoothing of the reference layer velocity then causes a systematic underestimate of the maximum speed of the current.

Estimates of reference layer velocity as a function of time are plotted routinely (using Matlab) in 2-day intervals along with the ship's position. This reveals outlying fixes or intervals of bad GPS that have to be edited out, and also helps one choose a smoothing filter width. The plots resulting from the final iteration of this process serve to document some important aspects of the ADCP data set: the spatial coverage, the quantity and quality of position fixes, and the degree to which major current features have been resolved by the smoothed reference layer estimate.

The smoothed estimate of the reference layer velocity over the ground is added to the velocity of the ship relative to the reference layer to give the final estimate of the ship's velocity, which is then integrated over each interval of nearly continuous ADCP data and fit to the ensemble of position fixes within the interval to generate the ship's track. The ship's position and velocity for each profile are written back to the ADCP database. We could add the ship's velocity to the velocity profile and store the resulting estimated absolute profile, but for the present we choose instead to do this calculation as needed when plotting and analyzing the data.

B7 Gridding and plotting

ADCP profiles typically give velocity estimates at nominal 8-m intervals in the vertical. We use nearby CTD profiles, when available, to correct these depths for the difference between nominal and true sound speed. Additionally, the profiles are interpolated to any user-specified grid in depth or density coordinates. The interpolation can be done using integration to reduce aliasing and to give an average velocity over a given layer. The integrated velocity is also available for use in transport calculations.

In the horizontal, one typically wants to average profiles in latitude or longitude bins. The approach taken by the UH system involves two steps. First, a program searches the database to find the time ranges corresponding to user-specified latitude-longitude grid. Second, these time ranges (edited or modified if necessary) are used to control the data access and averaging process. Additionally one may specify the use of only underway data or only on-station data. Another option is to calculate transport by integrating horizontally.

Standard plots for viewing the data are of two types: vector maps and contoured sections. For the former we use Matlab or a custom vector mapping program. For contouring we use a dedicated contour program. The vector and contour programs, unlike the rest of the processing system, have not yet been adapted and compiled on a PC; we usually run them on a Sun workstation with hardcopy from a Postscript printer.

C The UH "user exit" program

The main functions of MAG1157, the University of Hawaii "user exit" program, are:

1. Provide the best available position and absolute ship's velocity estimates to the RDI DAS for recording and for use in the real-time display.
2. Record all transit fixes with quality information. Record the PC clock time when the transit fix time mark is received, for correction of the ADCP profile time in post processing.
3. Record GPS fixes with quality information at the end of each ensemble.
4. Permit the calculation of the absolute velocity of a reference layer twice per ensemble; this requires recording GPS fixes at the beginning, middle, and end of the ensemble, and averaging the reference layer velocity over each half of the ensemble.
5. Allow the ADCP to serve as the speed log for the satellite navigator; once per ping, transmit a message containing the velocity of the ship relative to a reference layer.
6. Send all data recorded by the DAS out over a serial port to be recorded by another computer. This duplicates a DAS function, but unlike the DAS, MAG1157 neither adds extra characters to the transmitted data structures nor delays the start of the next ensemble while transmitting the data.

MAG1157 communicates with the 1100 series navigators through the bidirectional port A by sending and receiving the Magnavox proprietary message formats. For example, quality messages and GPS fixes must be requested when needed; Transit time marks and fixes are transmitted by the navigator as soon as they are complete, without being requested. Additional GPS information may be received from the 1100 series' unidirectional port B, which should be set to send message "option 1" once per second. This permits MAG1157 to average groups of 4, 8, or 16 fixes, so as to eliminate aliasing of the 4-second-period position oscillations that often occur.

Because GPS fix accuracy does not depend on information about the ship's velocity, there is no real need to send speed log information to a GPS-only receiver, unless one wants the receiver to dead-reckon during gaps in GPS coverage.

D Transit satellite navigation

If at all possible, Transit fixes should be obtained with a dual-channel receiver such as the Magnavox 1107 or 1157. Dual-channel accuracy can be similar to GPS with Selective Availability (SA; the deliberate degradation of civilian GPS). Single-channel accuracy is several times worse. The accuracy of Transit fixes depends critically on the accuracy of the ship's meridional velocity component used to calculate the fix, so using the ADCP as the speed log for the navigator can result in much more accurate fixes than would be obtained otherwise. The receiver should be set to calculate set and drift from the satellite fixes plus the ADCP velocity (2-axis speed log) input and gyrocompass heading. Omega navigation, if present, should usually be ignored, and in particular should *not* be used to calculate ship's velocity or set and drift for the Transit fix calculation.

All Transit fixes should be recorded, along with the primary quality information: satellite number, elevation, Doppler counts, and iterations. Fixes can then be mechanically edited if the satellite elevation was too low (less than 7° or so) or too high (above 70°), if the iterations exceeded 3 (indicating some inconsistency in the data), and if the Doppler counts were fewer than about 20 (indicating that interference between satellites or some other factor caused incomplete data collection.)

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