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from the JGOFS Arabian Sea Cruises
Aboard the RV T.G. Thompson**

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by

Hyun-Sook Kim, Charles N. Flagg, and Yan Shi
Oceanographic and Atmospheric Sciences Division
Brookhaven National Laboratory
Upton, NY 11973

December 1996

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DEPARTMENT OF APPLIED SCIENCE

BROOKHAVEN NATIONAL LABORATORY

UPTON, LONG ISLAND, NEW YORK 11973

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1 Introduction

Acoustic Doppler current profiler (ADCP) data is part of the core data for the U.S. JGOFS Arabian Sea project, along with hydrographic and nutrient data. Seventeen cruises are scheduled to take place between September 1994 and January 1996 on the R/V T.G. Thompson. They are numbered consecutively from the ship's commissioning with the first JGOFS cruise designated TN039. Table 1 shows each cruise's mission with its start and end dates.

All but the first cruise have been staged from Muscat, Oman. Each cruise is scheduled for a duration of between two weeks and one month. Seven of the cruises, referred to as process cruises, follow a standard cruise track, taking hydrographic, chemical and biological measurements (see Figure 1). The rest of the cruises, which take place generally within the standard cruise region defined by a set track, are for the deployment and recovery of moored equipment and towing of a SeaSoar.

ADCP data are collected using an autonomous data acquisition system developed for ship-of-opportunity cruises, named the AutoADCP system. The system is an extended version of RD instrument's DAS 2.48 using enhancements made possible with "user-exit" programs. It makes it possible to collect ADCP data without the constant monitoring usually necessary, and it ensures constant data coverage and uniform data quality.

This data report presents the ADCP data collection methods and results from the last group of five JGOFS Arabian Sea cruises, TN051 through TN055. The cruises include one SeaSoar, two process, one sediment-trap retrieval, and one mooring retrieval cruises (bold-faced entries in Table 1). The data were processed using the CODAS software, the single most widely used processing program for ship-mounted ADCP system, developed at the University of Hawaii for PCs or UNIX computers. All the ADCP data reside in the CODAS database at Brookhaven National Laboratory, and are generally available to JGOFS investigators through contact with the authors.

Detailed description of ADCP hardware, the AutoADCP data acquisition system, and the collection of navigation and compass data on the Thompson is documented in Section 2. Followed by data collection for each cruise together with a cruise track, Section 3 presents the processing and analysis of velocity and acoustic backscatter intensity data. Section 5 shows results of profile quality diagnosis.

The ADCP data results from previous cruises are documented in three data reports;

Figure 1: Arabian Sea standard cruise track with the station locations, and an array of current meter and sediment trap moorings: The o, +, and * indicate long, intermediate and hydrographic stations. The symbol of ⊗ designates sediment trap mooring. The o centered at 15.5°N, 61.5°E represent the locations of five long-term moorings.

Flagg and Shi (1995), Flagg, Kim and Shi (1995), and Kim, Flagg and Shi (1995).

2 ADCP installation on the R/V Thompson

2.1 ADCP hardware

The ADCP used on the R/V Thompson is a 153.6 kHz ADCP, model VM-150 manufactured by RD instruments at San Diego, CA, with a four-beam concave transducer (serial # 127). The transducer is mounted in a faired pod which protrudes below the hull of the Thompson by about two feet such that the depth of the transducer is nominally 5.9 meters (19 feet). Hence the ADCP transducer is exposed directly to the sea. The transducer pod eliminates or at least reduces the impact of bubble-sweep-down on the ADCP. Experience with this installation during the relatively violent conditions of the last four cruises (Kim, Flagg and Shi, 1996) indicates that this is an excellent installation producing high quality data at all ship speeds.

The ADCP deck unit is installed on a computer rack above a sub-bottom depth sounder in the Thompson's computer lab. The deck unit is connected to the ship's uninterruptable power supply. The AC voltage going into the ADCP deck unit was measured to be 117 volts during the calibration-training cruise TN039. The temperature of the deck unit was 30° Celsius under the air-conditioned environment of the electronics lab during the cruise. However, there were occasional large variations in temperature that may alter the operating environment of the deck unit.

On the R/V T.G. Thompson, the AutoADCP programs were installed on two PCs: One is Delphi 286, and the other is Dell 386 supplied by Brookhaven National Lab. Both computers were connected by the Pathworks network to virtual disks on a DEC 5000-200 UNIX workstation. Delphi 286 was set up to collect the data while Dell 386 was used for real-time presentation of the results. The advantage of the AutoADCP programs installation on both computers is that the data collection could be switched to the Brookhaven PC, when the primary PC suffers a failure.

Standard ADCP data is displayed on the Thompson's Delphi 286. This consists of 5-minute ensemble averaged profiles of U (zonal) and V (meridional) velocities, AGC (automatic gain control) and percentage of good pings. In addition to the data gathering performed by the AutoADCP system, another set of programs written in MATLAB presents

ADCP data in real-time. These programs run on the Dell 386, and make use of the networked virtual disk that is common with the AutoADCP system to access the most recent pingdata files. The real-time displays include vertical sections of U, V and range corrected backscatter intensity. The usual setup displays the last 12 hours of ADCP data, updating the display at 15 minute intervals.

2.2 AutoADCP Data Acquisition System

The AutoADCP system is a modified version of RD instrument's data acquisition system (DAS) version 2.48 for narrow-band ADCPs. The purpose of the modification is to ensure to collect more consistent and high quality data while minimizing interference with other program components. The system was initially developed in collaboration among Brookhaven National Laboratory, University of Rhode Island, and RD instruments. The program expands upon the standard DAS's capabilities to make it possible to automatically start and stop the collection of the data, and to change the configuration of the DAS depending upon the ship's location. The AutoADCP system is also designed to make back-up copies of the pingdata files, and provides a means of restarting the system if the DAS stops collecting data for any reason.

The utility of the AutoADCP is to control ensemble interval, number of bins, bin and pulse size, bottom tracking, and other configuration parameters without an on-board operator monitoring the DAS's performance. The major component of the system is a "user-exit" program named FLAG.EXE. This program is called up at the end of each ADCP ensemble, determines the ship's position, and compares it with pre-defined regions contained in the POSITION.DAT file. When the ship leaves one region for another, the DAS's default configuration file is updated, the computer in turn reboots and the ADCP starts pinging using the new configuration. Provision has also been made for a watchdog timer and automatic backup of pingdata files each time a file is filled.

In order for the ADCP's data acquisition system to collect the data, it is necessary to define the desired system configuration in the file START.CNF. The AutoADCP system determines the appropriate region by comparing the ship's position with the regions defined in the POSITION.DAT file. If necessary, a configuration for the new region is copied into the START.CNF file and the PC is rebooted. Most of the data in the program was obtained using the configuration for the northern Arabian Sea, ARABSEA.CNF file (shown in Table

2).

In addition, the system includes the WOCE standard enhancements to the DAS with another "user-exit" program, UE4.EXE, which was developed by Eric Firing's group at the University of Hawaii. This program is designed to improve upon some features of RD instruments' DAS software. The most important element is that UE4 records the position of the ship precisely at either end of the ensemble. This allows a more accurate computation of the ship's velocity during the ensemble. The UE4 program has been expanded recently so that it now works with the Ashtech GPS attitude sensor that uses phase differential GPS to determine the ship's heading. The Ashtech heading data is not only more accurate than the ship's gyro compass, but also immune to the latitudinal speed and turning errors that degrade gyros. However, because the Ashtech heading data can have gaps, the primary heading information for the ADCP retains the gyro compass. The recorded Ashtech heading data is used on a post-cruise basis to adjust the compass heading as needed.

A third user-exit program is AGCAVE.EXE, which modifies the way the DAS collects acoustic backscatter intensity data. Without the addition of this program, the DAS would record the intensity data (which used to be called amplitude) as a single profile composed of the average of all four beams. This degrades the intensity data because without calibration the individual beams produce slightly different profiles. To address this problem and to allow for post-cruise calibration of the intensity data, AGCAVE.EXE was developed. The program forms ensemble averaged profiles for each beam and stores the results separately in the pingdata data file location normally reserved for "last AGC".

These are the main components in the AutoADCP DAS so that it only requires an occasional check to ensure that the hardware is still functioning. At the end of each cruise the pingdata files were copied to a SyQuest removable hard disk and sent to Brookhaven National Laboratory for processing.

2.3 Navigation

Navigation information for the Thompson was provided by a GPS satellite navigation system. The intent was to use a P-code GPS receiver for the JGOFS cruises. However, permission to use the more accurate system was delayed and the P-code receiver was not used during the first four cruises of the program (Flagg and Shi, 1995). The receiver was made operational in January 1995 in preparation for cruise TN043. It worked successfully for

cruise TN043 through the middle of cruise TN046, and then from cruises TN048 through TN054 (for cruises TN051 through TN054, see Appendix B). The improvement in the navigation quality due to the P-code receiver is significant and quite obvious during the processing of the ADCP data.

Relative accuracy of ensemble-end-point positions using the degraded C/A GPS code had an rms value of about 33 meters for both latitude and longitude. The change in navigation quality is mostly visible in the initial estimates of the reference layer velocities where the P-code data resulted in a factor of four to five reduction in the short-term variance, suggesting a similar reduction in rms short-term position accuracy. During the ADCP data processing, the navigation fixes are smoothed to lessen the effects of the quasi-random navigation errors. With the P-code GPS receiver, the required smoothing to produce high quality results was significantly reduced.

The use of the P-code data was controlled by the UE4 user-exit program where the P-code data stream was set as the primary navigation source. The position data from the Ashtech receiver, when it was available, was used as a backup. The UE4 user-exit program reads the navigation data contained in the NEMA "GGA" message at the end of the ensemble and records the results in the "user buffer" area. With the P-code receiver in the system, the laptop computer used to reformat of the "GGA" message on the earlier cruises was no longer used. The UE4 program also maintained the PC clock to within 2 seconds of the GPS time provided in the GGA message.

2.4 Compass

The primary heading data for the ADCP was provided by the Thompson's gyro compass. Both the latitude and speed corrections for the compass were daily/regularly updated by bridge personnel depending upon the ship's activities (Bill Martin, personal communication). When the ship stops on station, the gyro speed setting is apparently set to zero. On cruise TN044 the compass was augmented with an Ashtech GPS attitude sensor that provided a data stream that could be used during post processing to reduce errors inherent to gyro compasses. The Ashtech was available for cruise TN044, operated only for a day on TN045, and was back to functioning for cruise TN049. But it was not available on the Thompson since cruise TN050.

3 Data Processing and Analysis

Pingdata files from each cruise were shipped in binary format to Brookhaven National Laboratory. They were processed on a Silicon Graphics Indy (SGI) workstation by modified version of the CODAS (Common Oceanographic Data Access System) processing programs for the ship-mounted ADCP originally developed by the ADCP group at the University of Hawaii. These programs consist of two parts, a set of processing and data base programs called CODAS written in C, and a series of MATLAB analysis routines for post-processing and plotting ADCP velocity and backscatter data. The CODAS routines were expanded to handle the backscatter intensity data in keeping with the methods developed by Flagg and Smith (1985) and Flagg et al. (1994). Detailed processing steps are as follows.

3.1 Velocity

The binary pingdata files were scanned to produce listings of the headers and ADCP configurations for each of the pingdata files, and to extract the GPS navigation data contained in the user-buffer area. Using the header listings as a guide to the appropriate ADCP profiles, the ADCP data in the pingdata files were separated into a CODAS data base for each cruise. Editing of the data started with a determination of parameters to flag complete or partial profiles. The basic editing parameter was the minimum percent good which was determined by the ADCP and recorded along with the velocity data. The minimum percent good was set to 30 percent. Four other editing parameters were also used: The first was a bottom search criterion based on the difference between the minimum backscatter intensity and a subsequent maximum. Most of the JGOFS Arabian Sea cruise time was spent in waters considerably deeper than the ADCP's range, so this parameter was often ignored. In shallower water bottom tracking was used which also determined the bottom depth and that data was used to edit the ADCP profiles for bottom interference. The second flagging parameter was error velocity, the difference between vertical velocities calculated from opposite pairs of the four beams in the transducer. The third parameter was the variance of vertical velocity over the entire profile. The last editing parameter was the second order difference in the vertical (i.e., $\partial^2/\partial z^2$) of horizontal velocity components. Collectively, these parameters flag interference from the bottom, from instrumentation suspended from the ship, from large aggregations of fish or scatterers and other, possibly anomalous behavior.

Individual profiles of velocity and backscatter were examined visually and in light of the

flagging parameters. Often they showed high variance of vertical velocity or false bottom indication which was due to diel vertical migration of euphausiids and micrroids. Generally the profiles that showed this vertical migration were kept in the data set. One of the more notable features in data set was the drastic effect that diel migration had on the range of the ADCP. During daylight hours the plankton stayed at depth when the ADCP easily reached 350 to 400 meters. But during the night the plankton moved near the surface, and the range of the ADCP decreased to 200–250 meters. According to the results of a test run during cruise TN039, increasing the ADCP's acoustic output power at night (by increasing pulse length to 32 m) resulted in no increase in range to any noticeable degree. Apparently, there were simply no scatterers left behind in the mad rush out of the low oxygen layer into the subsurface layer where the food (and predators) was.

The heading offset and amplitude scale factors are required for the calibration of the ADCP's orientation and velocity. In order to obtain values for these parameters, the primary source was bottom tracking data collected during 29 hrs run-up the Malacca Straits at an average speed of ~ 12 knots (6.75 m s^{-1}) on an average heading of 308° during cruise TN039. Using a least-square-linear fitting of the ship's track determined from the bottom track velocities to that determined from the GPS positions, heading offset and amplitude scale factors were found to be 1.53° and 1.000, respectively.

Subsequently, the ADCP calibration was checked using another bottom track run along the continental shelf south of Oman during cruise TN039 and water tracking during cruise TN041. From the three hour run along the Oman shelf where the ship was steaming at 4.4 knots on a heading of 261° , the rotation correction was 1.29° while the scale factor was 1.006. The water tracking calibration from TN041 used about 85 right-angle turns produced during several rectilinear patterns made while the ship was making SeaBeam bottom surveys. The water track calibration resulted in a scale factor of 0.999 and rotation correction of 1.39° . While all the calibration runs yielded similar values, we have used the coefficients determined from the bottom track run-up the Malacca Straits since the section covered a long distance under nearly ideal conditions.

Once the ADCP profiles were edited and the velocities scaled and rotated, the navigation data were combined with reference layer velocities to produce smoothed versions of the ship's track and absolute reference layer velocities. In deep water the reference layer spanned bins 5 to 20 (46 to 166 meters) while in the shallow waters of the Oman shelf the reference layer was

defined as bins 3 to 8 (30 to 70 meters). The smoothing of the reference layer velocity was done using a Blackman window convolution filter (Bahr, Firing and Songnian, 1989) with a width of one hour. This filter has a half-power point at about 20 minutes corresponding to a distance of about 8 km at 13 knots. The smoothed reference layer velocity was then added to the ship's velocity relative to the reference layer to produce a smoothed version of the ship's actual velocity. The displacements calculated from the velocity were then fit to the position data to yield a smoothed cruise track. The smoothed velocities and position were then loaded into the data base. At this point in the processing the velocity data in the CODAS data base was ready to be extracted for plotting and analysis.

3.2 Acoustic Backscatter Intensity

Backscatter intensity data were recorded in terms of digital counts from each of the ADCP's four transducers. They were loaded into the CODAS data base directly from the pingdata files along with the velocity data. At the same time, two blank variables, CALIB_AMP and ZOOP_BIOMASS, were also loaded into the data base to make room for parameters to be filled in later.

The first step in processing backscatter intensity is calibrating the intensities from each beam and combining them to produce a single calibrated intensity profile for each ensemble. The calibration procedure is based upon the method outlined in RD instruments' technical bulletin ADCP-90-04 issued in December 1994, which attempts to determine the absolute value of the volume reverberation, Sv, for each depth bin.

The calibration equation for Sv for each beam is:

$$Sv = 10 \log_{10} \left\{ \frac{4.47 \times 10^{-20} K_2 K_s (T_x + 273) (10^{K_c(E-E_r)/10} - 1) R^2}{c L K_1 10^{-2\alpha R/10}} \right\}, \quad (1)$$

where the K 's are calibration coefficients, c is the speed of sound at the transducer in m s^{-1} , L is the pulse length in m, T_x is the transducer temperature in $^{\circ}\text{C}$, α is the sound absorption coefficient in dB m^{-1} , R is the slant range in m, E_r is the intensity reference level, and E is the echo intensity level. Both E and E_r are given in terms of counts. Two of the constants, K_1 and K_2 are determined by RD instruments during instrument checkout. K_1 is the power sent to the transducer and is given by:

$$K_1 = K_{1c} \left(\frac{1.397 V_s - 4.27}{37.14} \right)^2, \quad (2)$$

where V_s is the measured rms AC voltage supplied to the deck unit (117 volts), and the values of K_{1c} supplied by RD instruments for the Thompson for beams 1 to 4 are:

Beam	K_{1c} (Watts)
1	5.424
2	5.647
3	6.609
4	6.172

The system noise factors, K_2 , also supplied by the manufacturer for the Thompson for beams 1 to 4 are:

Beam	K_2
1	2.158
2	2.244
3	1.854
4	2.183

The conversion factor, K_c , from ADCP counts to measured intensity in dB is given by:

$$K_c = \frac{127.3}{T_e + 273}, \quad (3)$$

where T_e is the temperature of the deck unit on the Thompson which was 30°C when measured. The reference thermal transducer noise, E_r , for the beams is given by:

$$E_r = E_{rc} + (292 + 0.133T_e)(1 - a) + (273 + 0.1T_x)(1 - b), \quad (4)$$

with

$$a = \frac{T_e + 273}{T_{ec} + 273}; \quad b = \frac{T_x + 273}{T_{xc} + 273}, \quad (5)$$

where E_{rc} is the measured reference thermal noise, and T_{ec} and T_{xc} are the deck unit and transducer temperatures at the time when E_{rc} was measured. For the Thompson data the values of E_{rc} for each beam were taken to be the minimum backscatter counts recorded during the entire first cruise, minus one count to avoid numerical problems with calculating logarithms. T_{ec} was taken to be 30°C while the values of E_{rc} and T_{xc} for the Thompson were:

Beam	E_{rc} (counts)	T_{xc} ($^{\circ}\text{C}$)
1	12	28.4
2	15	28.1
3	17	28.7
4	16	27.2

The absorption coefficient is given by Urick (1982) as:

$$\alpha = \left\{ 1.86 \times 10^2 S f_t \left(\frac{f^2}{f_t^2 + f^2} \right) + 2.68 \times 10^{-2} \left(\frac{f^2}{f_t} \right) \right\} \left\{ \frac{1 - 6.54 \times 10^{-4} P}{914.4} \right\}, \quad (6)$$

where P is the pressure in atmosphere, f is the frequency of the ADCP which is 153.6 kHz for the ADCP on the Thompson and

$$f_t = 21.9 \times 10^{6-1520/(T_x+273)}. \quad (7)$$

The absorption coefficient for each bin is the average value between the transducer and the bin while the pressure term has a noticeable effect and needs to be included. The transducer temperature is clearly not the correct value to use in this calculation except near the transducer itself, but at this point we have not attempted to refine this value further by using CTD cast results.

This procedure brings the four acoustic beams into close, but not perfect agreement. Typically over the normal range of variability, the beams might differ by one to two dB. As a result, we have taken an ad-hoc approach to ensure that over the length of a section or cruise all the beams will yield the same average backscatter profile. This secondary correction is done using the liner transformation:

$$S_{vc} = a_0 + a_1 S_v, \quad (8)$$

where the scaling a_1 and offset a_0 factors for each beam relative to the mean profile are determined by least squares.

In the past this had been a straight forward procedure, but in the Arabian Sea there was enough biological patchiness that when the ship was on station a single beam occasionally indicated substantially larger concentrations of scatters than the others. Under these circumstances, scatter plots of a single beam's return versus the average of all four beams showed enough scatter to adversely influence the least square calculations. To distinguish those profiles with large inter-beam variations, we calculated the rms difference of each

profile relative to the mean from all four beams. An examination of the time dependence of the rms difference showed that high values were exclusively associated with periods when the ship was on station. The reverse was not necessarily the case. From this behavior we surmise that the distribution of plankton and/or fish can be patchy on the scale of one to two hundred meters. Thus when the ship is still, the anomalous scatters can remain within a beam for a significant portion of an ensemble and increase the recorded backscatter intensity. Figure 2 shows profiles of backscatter intensity differences between beam 1 and beam average when the rms intensity differences were greater than 1.5 dB. (This plot was generated before the secondary corrections were applied which leads to a positive mean offset.) The figure shows that the large beam discrepancies were majorily confined to the ADCP's mid-range between bins 12 to 32. These bins correspond to depths of 114 and 274 meters spanning the thermocline in the Arabian Sea and the depths over which the oxygen concentrations decrease to very small values. It would appear that there are individual large fish, schools of smaller fish, or plankton patches that tend to congregate in and just above the thermocline perhaps waiting to feed on the upward migrating meso-planktonic euphausiids and mictophids.

We thus edited the profiles and include only those whose rms intensity differences were less than or equal to 1.5 dB. The secondary correction factors, determined using an edited set of profiles from the calibration and training cruise were:

Beam	a_0 (dB)	a_1
1	-1.6387	0.9991
2	-0.2789	0.9983
3	0.9646	0.9954
4	-0.0794	0.9926

During the processing, the ensemble averaged backscatter profiles are combined to form a single profile for each ensemble. For those ensembles where the rms differences relative to the mean are greater than 1.5 dB, indicating contamination from anomalous scatter densities, the average profiles are set to nulls. Backscatter differences of a single beam from the mean profiles is shown in Figure 3, which is obtained after secondary correction is applied. Note the change in the scale of the abscissa relative to Figure 2.

Figure 2: Scatter plot of the rms differences greater than 1.5 dB: They are the differences between the partially calibrated backscatter intensity from Beam #1 and the mean intensity of all four beams from cruise TN039. The occurrence of the relatively large difference is restricted to periods when the ship is on station. It appears to reflect inhomogeneities in the small-scale distribution of fish and/or plankton. The bin length is 8 meters and the first bin is centered at a depth of approximately 22 meters.

Figure 3: Scatter plot of the rms differences less than or equal to 1.5 dB. The data were taken from cruise TN039.

4 Data Collection

4.1 TN051

This is the last SeaSoar cruise of the JGOFS Arabian Sea program, conducted during the basin-wide relaxation of the SW monsoon. The R/V T.G. Thompson left Muscat on September 19 and returned to the port on October 9, 1995. The Thompson followed the similar track as other SeaSoar cruises, except it repeated part of the nearshore radiator for more observation on a frontal feature running parallel to the southern JGOFS transect. Bob Arnone was the chief scientist. William Peterson monitored the AutoADCP system.

4.2 TN052

This is mooring recovery cruise. It took place for the purpose of retrieving all five moorings centered 15.5N, 61.6E. The R/V T.G. Thompson left Muscat on 14 October, 1995, heading out to the mooring location. After the recovery, the ship headed towards the coast (17,38N,55.66E) which is further south than the usual track. From the location an ADCP transect was taken along the 1000 meter isobath until the ship returned to Muscat on 25 October, 1995. Daniel Rudnick was the chief scientist for the cruise.

4.3 TN053

Chief scientist William Balch with his scientist group took a sawtooth survey of a front feature over 3 days in the Gulf of Oman, before they headed out on the standard track of the Process cruise. On November 1, 1995, they resumed with the JGOFS cruise track, but they cut the eastern transect off and headed directly toward the long-term station at 10N, 65E. On November 26, 1995, they returned to Muscat.

4.4 TN054

The last Process cruise left Mustcat on November 11, 1995 and returned on December 27, 1995, with Wilford Gardner as the chief scientist. Marine Technicians, Mike Grogan and Tony Burke, were responsible for the AutoADCP system.

The percent good of ADCP measurements was bad particularly during this cruise. The minimum percent good criterion locates usually below the maximum depth range of the vertical diel migration. However, the criterion during this cruise moved up to 200 meters.

This is illustrated in contour section plots of (u,v) and backscatter intensity (Appendix C) as grapped data around 200 m. It is particularly noticed from day-time measurements.

4.5 TN055

The final cruise of the U.S. JGOFS Arabian Sea project – sediment trap recovery departed Mustcat on December 12, 1995, with Warren Prell as a chief scientist. After the recovery, the T.G. Thompson visited at location (10N, 65E) and headed southwest toward the tip of South Africa in the Indican Ocean. The field observations of the US JGOFS Arabian Sea project is officially finished with this cruise. Although the AutoADCP system went to bad towards end of the JOGFS program, it worked excellently overall.

Figure 4: Cruise track for TN051, SeaSoar #4. Numbers along the track represent sections and stations used later for vectors and contour plots in Appendix C.

Figure 5: Cruise track for TN052, current meter mooring retrieval cruise. Duration of this cruise is eleven days.

Figure 6: Cruise track for TN053, Process cruise #6.

Figure 7: Cruise track for TN054, Process cruise #7.

Figure 8: Cruise track for TN055, sediment trap mooring retrieval cruise.

5 Profile Quality

In processing the ADCP data, a set of diagnostic products assessing the data quality is routinely produced. Typically, profiles of horizontal velocity shears, vertical velocity, error velocity, backscatter intensity (amplitude), spectral width and percent good are separated into those for on-station and underway periods. The diagnostic products are depth-averages and standard deviations of the on-station and underway profiles. In general, analysis of these results shows the same acceptable behavior for all the cruises examined. Particularly it shows no different behavior from the analysis of the highest quality data during cruise TN044 and TN049 where both the P-code GPS receiver and Ashtech attitude sensor were available.

Figure 9 shows results of the quality analysis of the data collected during cruise TN053 along the standard cruise track which has short, intermediate, and long term stations (Figure 1). For the statistical results shown in the figure, approximately 4600 ensembles and 4100 ensembles were extracted while the ship was on-station (ship velocity $< 2.5 \text{ m s}^{-1}$) and underway respectively.

Figure 9a and 9b show the first-order vertical differences of horizontal velocities. These diagnostics are intended to illustrate the portions of the profile affected by misalignments of the tracking filters near the surface, in regions of high shear, or in regions of low return signal. The horizontal velocity shears are relatively higher in the upper 150 meters or so, where the maximum values approached 0.5 cm s^{-1} . The shears and the standard deviations below 150 meters remain almost constant with depth. However, near the extreme range of the ADCP below 360 meters the shears show significant variations with substantial increase in the standard deviations. The maximum shear generally encountered near the range are well below the limit of the velocity tracking capability of the filter ($\sim 2.0 \text{ cm s}^{-1}$). Therefore, it should not pose any problem.

Figure 9c and 9d show mean and standard deviation profiles of vertical velocity and error velocity taken during on-station and underway. The vertical and error velocities are expected to be fairly small, and significant values would indicate misalignment of the transducers either relative to the vertical or between themselves. The notable features of profiles in the figure are the uniformity in depth range between ~ 50 and 400 meters. Difference between the average on-station and underway vertical velocity profiles is approximately 0.2 cm s^{-1} . This suggests that the ADCP transducer was out of trim by 0.02 degrees which

is remarkably small. The negative shear value near the surface while underway represents that the passage of the ship through the water is forcing downward water motion in the vicinity of the transducer. The impact of this on the horizontal velocities is unclear. The mean error velocities during underway (Figure 9d) are about 1.2 cm s^{-1} , and higher than those during on-station approximately by 1 cm s^{-1} . This suggests that there may have been less than 0.1 degrees misalignment of beams 1 and 3 relative to beams 2 and 4. Both Figure 9c and 9d show changes in the profiles near 150 meters and the extreme depth range of ADCP. This may be mainly associated with the percent good (Figure 9g) beyond its criterion which is 30%.

The average backscatter intensity (aka amplitude) profiles are presented for both ship's underway and on-station conditions in Figure 9e in terms of digital counts. Figure 9e shows the usual large decrease with depth. These averaged profiles are not filtered using a percent good criterion and include all ensembles selected for this section. Without range correction, the backscatter intensity profiles accentuate the upper water column. The standard deviation profiles indicate maximum variability upper 300 m, reflecting the planktonic diel migration under which a large proportion of the plankton rises from their daytime depths around 300 meters to upper 100 meters during the night.

Figure 9f shows the average and standard deviation of spectral width profiles. The spectral width measures spectral broadening of the returning signal primarily resulted from the short duration of the transmit pulse during transmission. Thus the spectral width is directly related to the uncertainty of the mean Doppler frequency estimate, and in turn related to the uncertainty of velocity measurements. From Figure 9f, the mean spectral width during on-station and underway increases below 130 meters, and the signal-to-noise declines.

The last analysis of the diagnostic set is for the percent good profiles. Figure 9g shows their averages and standard deviations for on-station and underway period. The mean profiles indicate that highly reliable data were obtained in the upper 130 meters. Below the depth, the percent good decreases linearly with depth, and at 400 meters it is virtually zero. Generally below the depth ADCP is subject to the affect of diel migration. However, the decrease occurring from such an unusually shallow depth seems to be a result of slow deterioration of ADCP performance.

Figure 10 presents the average percent good profile as a function of cruise from TN040

to TN055. Figure 10a shows the on- station profiles, and Figure 10b shows the underway profiles. From both figures, the depth of the minimum percent good criterion (30maximum range during cruise TN040. Although there is a slight improvement before cruise TN046, the depth noticeably moved up in time, with the shallowest depth at 200 m during cruise TN054. Thus, the depth for reliable velocity measurements is narrower in range.

Figure 9: Diagnostic profiles of ensemble averaged a) zonal vertical shear, b) meridional vertical shear, c) vertical velocity, d) error velocity, e) backscatter intensity, f) spectral width, g) percent good for underway and on-station ADCP data taken along the standard cruise track for TN052.

96-9-27 9:55

c) W component, ADCP TN052
(Solid: On Station; Dash: Underway)

d) ERROR VELOCITY, ADCP TN052
(Solid: On Station; Dash: Underway)

96-9-27 9:56

e) AMPLITUDE, ADCP TN052
(Solid: On Station; Dash: Underway)

f) SPECTRAL WIDTH, ADCP TN052
(Solid: On Station; Dash: Underway)

g) PERCENT GOOD, ADCP TN052
(Solid: On Station; Dash: Underway)

96-9-27 9:56

Figure 10: The average percent good profile for on-station as a function of cruise from TN040 through TN055.

Figure 11: The average percent good profile for underway as a function of cruise from TN040 through TN055.

6 Acknowledgments

We would like to express our appreciation for the assistance of George White, Mike Realander, Bill Martin, Mike Grogran, William Peterson and the Thompson's crew in the initial set-up the ADCP system and in the continuing data collection. We also thank Eric Firing and Frank Bahr for significant help which we received at early stage in the program. Especially Frank Bahr who has checked on the AutoADCP system and helped the Ashtech receiver available during his cruises. Eric Firing and Julie Ranada were also very helpful for the installation of the CODAS processing system on our UNIX computer.

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Table 1: Cruise schedule for the U. S. JGOFS Arabian Sea Project. The bold-faced entries are the cruises covered by this data report.

Cruise ID	Start Date	End Date	Chief Sci.	Purpose
TN039	09/20/94	10/07/94	L. Codispoti	Calibration and training
TN040	10/11/94	10/25/94	C. Erickson	Mooring deployment
TN041	10/28/94	11/21/94	S. Honjo	Sediment trap and coring
TN042	11/28/94	12/17/94	D. Young	SeaSoar survey #1
TN043	01/08/95	02/04/95	M. Roman	Process cruise #1
TN044	02/08/95	02/25/95	K. Brink	SeaSoar survey #2
TN045	03/14/95	04/10/95	J. Marra	Process cruise #2
TN046	04/14/95	04/29/95	R. Weller	Mooring turn-around
TN047	05/03/95	05/20/95	J. Dymond	Process cruise #3
TN048	06/21/95	07/13/95	K. Brink	SeaSoar survey #3
TN049	07/17/95	08/15/95	R. Barber	Process cruise #4
TN050	08/18/95	09/15/95	S. Smith	Process cruise #5
TN051	09/18/95	10/09/95	R. Arnone	Searsoar survey #4
TN052	10/14/95	10/25/95	D. Rudnick	Mooring retrieval
TN053	10/29/95	11/26/95	B. Balch	Process cruise #6
TN054	11/30/95	12/27/95	W. Gardner	Process cruise #7
TN055	12/31/95	01/15/96	W. Prell	Sediment trap retrieval

Table 2: Listing of the Arabian Sea regional ADCP configuration used for the deep water portion of the U. S. JGOFS Project.

AD,SI,HUNDREDTHS	300.00 Sampling interval
AS,NB,WHOLE	50 Number of Depth Bins
AD,BL,WHOLE	3 Bin Length
AD,PL,WHOLE	16 Pulse Length
AD,BK,TENTHS	4.0 Blank Beyond Transmit
AD,PE,WHOLE	1 Ping Per Ensemble
AD,PC,HUNDREDTHS	1.00 Pulse Cycle Time
AD,PG,WHOLE	25 Percent Pings Good Threshold
XX,OD2,WHOLE	5 [SYSTEM DEFAULT, OD2]
XX,TE,HUNDREDTHS	0.00 [SYSTEM DEFAULT, TE]
AD,US,BOOLE	YES, Use Direct Commands on StartUp
DP,TR,BOOLE	NO Toggle Roll compensation
DP,TP,BOOLE	NO Toggle Pitch compensation
DP,TH,BOOLE	YES Toggle Heading compensation
DP,VS,BOOLE	YES Calculate Sound Velocity from TEMP/Salinity
DP,UR,BOOLE	YES Use Reference layer
DP,FR,WHOLE	5 First Bin for reference layer
DP,LR,WHOLE	20 Last Bin for reference layer
DP,BT,BOOLE	NO Use Bottom Track
DP,B3,BOOLE	NO Use 3 Beam Solutions
DP,EV,BOOLE	YES Use Error Velocity as Percent Good Criterion
DP,ME,TENTHS	250.0 Max. Error Velocity for Valid Data (cm/sec)
DR,RD,BOOLE	YES Recording on disk
DR,RX,BOOLE	YES Record N/S (FORE/AFT) Vel.
DR,RY,BOOLE	YES Record E/W (FORT/STBD) Vel.
DR,RZ,BOOLE	YES Record vertical vel.
DR,RE,BOOLE	YES Record error Good
DR,RB,BOOLE	NO Bytes of user prog. buffer
DR,RP,BOOLE	YES Record Percent good
DR,RA,BOOLE	YES Record average AGC/Bin
DR,RN,BOOLE	YES Record Ancillary data
DR,AP,BOOLE	YES Auto-ping on start-up
XX,LDR,TRI	3 [SYSTEM DEFAULT, LDR]
XX,RB2,WHOLE	192 [SYSTEM DEFAULT, RB2]
DR,RC,BOOLE	NO Record CTD data
XX,FB,WHOLE	1 [SYSTEM DEFAULT, FB]
XX,PU,BOOLE	NO [SYSTEM DEFAULT, PU]
GC,TG,TRI	1 DISPLAY (NO/GRAPH/TAB)
GC,ZV,WHOLE	4 ZERO VELOCITY REFERENCE (S/B/M/L)
GC,VL,WHOLE	-200 LOWEST VELOCITY ON GRAPH
GC,VH,WHOLE	200 HIGHEST VELOCITY ON GRAPH
GC,DL,WHOLE	0 LOWEST DEPTHS ON GRAPH
GC,DH,WHOLE	200 HIGHEST DEPTHS ON GRAPH

GC,SW,WHOLE	YES Set Depths Window to include all bins
GC,MP,WHOLE	25 MINIMUM PERCENT GOOD TO PLOT
SG,PNS,BOOLE	YES Plot North/South Vel.
SG,PEW,BOOLE	YES Plot East/West Vel.
SG,PVT,BOOLE	NO Plot Vertical Vel.
SG,PEV,BOOLE	NO Plot Error Vel.
SG,PPE,BOOLE	NO Plot Percent Error
SG,PMD,BOOLE	NO Plot Mag and Dir
SG,PSW,BOOLE	NO Plot Average SP. W.
SG,PAV,BOOLE	YES Plot Average AGC
SG,PPG,BOOLE	YES Plot Percent Good
SG,PD1,BOOLE	NO Plot Doppler 1
SG,PD2,BOOLE	NO Plot Doppler 2
SG,PD3,BOOLE	NO Plot Doppler 3
SG,PD4,BOOLE	NO Plot Doppler 4
SG,PW1,BOOLE	NO Plot SP. W. 1
SG,PW2,BOOLE	NO Plot SP. W. 2
SG,PW3,BOOLE	NO Plot SP. W. 3
SG,PW4,BOOLE	NO Plot SP. W. 4
SG,PA1,BOOLE	NO Plot AGC 1
SG,PA2,BOOLE	NO Plot AGC 2
SG,PA3,BOOLE	NO Plot AGC 3
SG,PA4,BOOLE	NO Plot AGC 4
SG,PP3,BOOLE	NO Plot 3-Beam Solution
SS,OD,WHOLE	0 Offset for Depth
SS,OH,TENTHS	-90.0 Offset for Heading
SS,OP,TENTHS	0.0 Offset for Pitch
SS,ZR,TENTHS	0.0 Offset for Roll
SS,OT,HUNDREDTHS	45.00 Offset for Temp
SS,ST,HUNDREDTHS	50.00 Scale for Temp
SS,SL,HUNDREDTHS	36.00 Salinity (PPT)
SS,UD,BOOLE	YES Toggle UP/DOWN
SS,CV,BOOLE	NO Toggle Concave/Convex transducer head
SS,MA,TENTHS	30.0 Mounting angle for transducers
SS,SS,HUNDREDTHS	1500.00 Speed of Sound (m/sec)
XX,GP,BOOLE	YES [SYSTEM DEFAULT, GP]
XX,DD,TENTHS	1.0 [SYSTEM DEFAULT, DD]
XX,PT,BOOLE	NO [SYSTEM DEFAULT, PT]
XX,TU,TRI	2 [SYSTEM DEFAULT, TU]
TB,FP,WHOLE	1 FIRST BIN TO PRINT
TB,LP,WHOLE	64 LAST BIN TO PRINT
TB,SK,WHOLE	6 Skip interval between bins
TB,DT,WHOLE	YES Diagnostic TAB mode
DU,TD,BOOLE	NO Toggle use of dummy data
XX,PN,WHOLE	0 [SYSTEM DEFAULT, PN]

DR,SD,WHOLE	4 Second recording drive
DR,PD,WHOLE	3 First recording drive (1=A;2=B ...)
DP,PX,BOOLE	NO Profiler does XYZE transform
SS,LC,TENTHS	5.0 Limit of Knots change
SS,NW,TENTHS	0.5 Weight of new knots of value
GC,GM,TRI	2 Graphic Control 0=lo res, 1=hi res, 2=enhanced
AD,PS,BOOLE	NO YES=SERIAL/NO=PARALLEL Profiler Link
XX,LNN,BOOLE	YES [SYSTEM DEFAULT, LNN]
XX,BM,BOOLE	YES [SYSTEM DEFAULT, BM]
XX,RSD,BOOLE	NO Record Standard Deviation of Velocities per Bin
XX,DRV,WHOLE	0 [SYSTEM DEFAULT, DRV]
XX,PBD,WHOLE	3 [SYSTEM DEFAULT, PBD]
TB,RS,BOOLE	NO HSOW RHPT STATISTIC
UX,EE,BOOLE	YES Enable Exit to External Program
SS,VSC,TRI	0 Velocity scale adjustment
AD,DM,BOOLE	NO USE DMA
TB,SC,BOOLE	NO SHOW CTD DATA
AD,CW,BOOLE	YES Collect spectral width
DR,RW,BOOLE	YES Record average SP. W. /Bin
DR,RRD,BOOLE	NO Record last raw dopplers
DR,RAA,BOOLE	YES Record last raw AGC
DR,RRW,BOOLE	NO Record last SP. W.
DR,R3,BOOLE	NO Record average 3-beam solutions
DR,RBS,BOOLE	YES Record beam statistic
XX,STD,BOOLE	NO [SYSTEM DEFAULT, STD]
LR,HB,HUNDREDTHS	0.00 Heading Bias
SL,1,ARRAY5	0 1 8 NONE 19200 PROFILER
SL,2,ARRAY5	0 1 8 NONE 1200 LORAN RECEIVER
SL,3,ARRAY5	0 1 8 NONE 1200 REMOTE DISPLAY
SL,4,ARRAY5	0 1 8 NONE 1200 ENSEMBLE OUTPUT
SL,5,ARRAY5	0 1 8 NONE 1200 AUX1
SL,6,ARRAY5	0 1 8 NONE 1200 AUX2
DU,1,ARRA6	100.00 100.00 60.00 0.00 0.00 YES D1
DU,2,ARRA6	-100.00 -100.00 60.00 0.00 0.00 YES D2
DU,3,ARRA6	200.00 200.00 60.00 0.00 0.00 YES D3
DU,4,ARRA6	-200.00 -200.00 60.00 0.00 0.00 YES D4
DU,5,ARRA6	200.00 19.00 60.00 0.00 0.00 YES AGC
DU,6,ARRA6	0.00 0.00 60.00 0.00 0.00 NO SP. W.
DU,7,ARRA6	0.00 0.00 60.00 0.00 0.00 NO ROLL
DU,8,ARRA6	0.00 0.00 60.00 0.00 0.00 NO PITCH
DU,9,ARRA6	0.00 0.00 60.00 0.00 0.00 NO HEADING
DU,10,ARRA6	0.00 0.00 60.00 0.00 0.00 NO TEMPERATURE
DC,1,SPECIAL	"FH00001" MACRO 1
DC,2,SPECIAL	"CF64" MACRO 2

DC,3,SPECIAL "E0004020099" MACRO 3
DC,4,SPECIAL "B0009001" MACRO 4
CI,1,SPECIAL "Arabian Sea" CRUISE ID GOES HERE
LR,1,SPECIAL " " LORAN FILE NAME GOES HERE

8 Appendix A. List of Sections

Each cruise is divided into sections and stations, to form either nearly linear transects or coverage over some localized area. In this section, we list the start date, stop date, and the beginning and end positions of each section.

Section List for TN051

Sec	Date		Start		Date		End	
			Year Day	(Lat,Lon)			Year Day	(Lat,Lon)
1	95/09/18	04:50:51	260.202	(23.627,58.566)	95/09/19	23:36:22	261.984	(22.625,60.370)
2	95/09/19	23:41:22	261.987	(22.617,60.370)	95/09/21	20:41:22	263.862	(18.142,58.007)
3	95/09/21	20:46:22	263.866	(18.132,58.007)	95/09/22	07:09:30	264.305	(17.475,59.262)
4	95/09/22	07:14:30	264.302	(17.473,59.252)	95/09/27	07:14:30	269.302	(16.924,60.282)
5	95/09/27	07:19:33	269.305	(16.925,60.282)	95/09/27	23:09:33	269.965	(16.158,61.829)
6	95/09/27	23:14:33	269.968	(16.149,61.824)	95/09/29	00:19:31	271.014	(16.162,61.841)
7	95/09/29	00:24:31	271.017	(16.157,61.850)	95/09/29	11:28:00	271.478	(15.443,63.075)
8	95/09/29	11:33:01	271.481	(15.451,63.082)	95/10/01	23:52:27	273.995	(14.907,64.101)
9	95/10/01	23:57:27	273.998	(14.896,64.102)	95/10/02	11:57:25	274.498	(14.438,65.005)
10	95/10/02	12:02:25	274.502	(14.443,65.003)	95/10/04	00:02:26	276.002	(15.717,61.494)
11	95/10/04	00:07:26	276.005	(15.734,61.494)	95/10/05	19:43:13	277.822	(18.500,57.300)
12	95/10/05	19:48:13	277.825	(18.499,57.300)	95/10/06	06:58:59	278.291	(17.399,57.503)
13	95/10/06	07:04:00	278.294	(17.401,57.506)	95/10/07	01:44:42	279.073	(19.336,58.033)
14	95/10/07	01:49:43	279.076	(19.335,58.033)	95/10/07	22:18:38	279.930	(18.984,59.028)
15	95/10/07	22:23:36	279.933	(18.987,59.025)	95/10/09	23:58:37	281.999	(22.408,60.615)

Section List for TN052

Sec	Date		Start		Date		End	
			Year	Day			Year	Day
				(Lat,Lon)				(Lat,Lon)
1	95/10/14	02:45:50	286.115	(23.640,58.641)	95/10/14	14:29:45	286.604	(22.454,60.823)
2	95/10/14	14:34:45	286.608	(22.438,60.825)	95/10/16	01:49:46	288.076	(15.740,61.746)
3	95/10/16	01:54:46	288.080	(15.740,61.747)	95/10/20	20:08:13	292.839	(15.744,61.193)
4	95/10/20	20:13:14	292.843	(15.746,61.177)	95/10/22	06:38:13	294.277	(17.376,55.661)
5	95/10/22	06:43:14	294.280	(17.386,55.666)	95/10/22	18:57:52	294.790	(17.527,57.578)
6	95/10/22	19:02:53	294.794	(17.538,57.583)	95/10/24	04:37:53	296.193	(21.790,60.108)
7	95/10/24	04:42:53	296.197	(21.801,60.115)	95/10/25	03:48:38	297.159	(23.635,58.578)

Section List for TN053

Sec	Date		Start		Date		End	
			Year Day	(Lat,Lon)			Year Day	(Lat,Lon)
1	95/10/29	03:58:06	301.165	(23.655,58.594)	95/11/01	10:13:51	304.426	(23.793,59.893)
2	95/11/01	10:18:51	304.430	(23.793,59.898)	95/11/06	23:18:51	309.971	(19.167,67.161)
3	95/11/06	23:23:51	309.975	(19.167,67.160)	95/11/10	14:48:51	131.617	(10.086,64.942)
4	95/11/10	14:53:51	313.621	(10.089,64.943)	95/11/13	12:43:32	316.530	(14.473,64.958)
5	95/11/13	12:48:32	316.534	(14.475,64.954)	95/11/18	14:13:45	321.593	(18.514,57.286)
6	95/11/18	14:18:45	321.596	(18.510,57.287)	95/11/19	03:59:31	322.166	(16.404,56.490)
7	95/11/19	04:04:31	322.170	(16.402,56.489)	95/11/24	18:52:45	317.787	(22.334,60.502)
8	95/11/24	18:57:46	327.790	(22.334,60.504)	95/11/24	20:02:45	327.835	(22.480,60.609)
9	95/11/24	20:07:46	327.839	(22.493,60.617)	95/11/26	02:12:46	329.092	(23.684,58.685)

Section List for TN054

Sec	Date		Start		Date		End	
			Year Day	(Lat,Lon)			Year Day	(Lat,Lon)
1	95/11/30	04:40:36	333.195	(23.644,58.608)	95/11/30	18:31:23	333.772	(22.428,59.913)
2	95/12/01	18:36:21	333.775	(22.428,59.913)	95/12/01	13:59:32	334.583	(22.541,61.199)
3	95/12/01	14:04:32	334.586	(22.587,61.204)	95/12/04	07:24:31	337.309	(19.213,67.140)
4	95/12/04	07:29:31	337.312	(19.204,67.156)	95/12/06	03:34:32	339.149	(19.202,67.135)
5	95/12/06	03:39:32	339.152	(19.189,67.140)	95/12/08	02:39:32	341.111	(15.388,68.756)
6	95/12/08	02:44:32	341.114	(15.385,68.772)	95/12/08	11:23:35	341.475	(15.392,68.783)
7	95/12/08	11:28:35	341.478	(15.392,68.775)	95/12/08	21:38:35	341.902	(14.920,66.894)
8	95/12/08	21:43:35	341.905	(14.918,66.892)	95/12/10	05:23:34	343.225	(10.031,64.912)
9	95/12/10	05:28:34	343.228	(10.031,64.911)	95/12/14	01:58:34	347.082	(14.450,64.999)
10	95/12/14	02:03:34	347.086	(14.451,64.999)	95/12/16	01:23:35	349.058	(14.462,64.992)
11	95/12/16	01:28:35	349.062	(14.466,64.984)	95/12/17	13:53:34	350.579	(16.029,62.007)
12	95/12/17	13:58:34	350.582	(16.033,61.999)	95/12/19	11:46:43	352.491	(16.158,62.109)
13	95/12/19	11:51:43	352.494	(16.160,62.101)	95/12/20	10:14:52	353.427	(17.195,59.774)
14	95/12/20	10:19:52	353.430	(17.200,59.767)	95/12/22	07:19:52	355.305	(17.335,59.894)
15	95/12/22	07:24:52	355.309	(17.341,59.879)	95/12/23	01:59:52	356.083	(18.099,58.005)
16	95/12/23	02:04:52	356.087	(18.099,58.005)	95/12/26	02:13:50	359.093	(18.493,57.305)
17	95/12/26	02:18:50	359.096	(18.493,57.305)	95/12/26	14:49:41	359.618	(18.996,59.002)
18	95/12/26	14:54:41	359.621	(18.995,59.002)	95/12/27	18:14:40	360.760	(22.946,59.626)

Section List for TN055

Sec	Date		Start		Date		End	
			Year	Day			Year	Day
				(Lat,Lon)				(Lat,Lon)
1	95/12/31	07:13:17	364.301	(23.655,58.616)	96/01/01	06:34:04	365.273	(20.185,59.070)
2	96/01/01	06:39:05	365.277	(20.177,59.067)	96/01/02	12:54:04	366.538	(17.692,57.874)
3	96/01/02	12:59:04	366.541	(17.693,57.877)	96/01/07	14:12:12	371.592	(16.005,61.493)
4	96/01/07	14:17:12	371.595	(16.002,61.497)	96/01/10	01:24:09	374.058	(10.007,65.003)
5	96/01/10	01:29:09	374.062	(10.003,65.005)	96/01/15	05:19:25	379.222	(-4.625,55.462)

9 Appendix B. Reference Layer Velocity

This section shows zonal (U) and meridional (V) velocities for reference layer, together with navigation data (longitude and latitude), for each cruise. In each plot, x-axis represents duration of cruise in yearday.

96-9-20 15:2

96-9-20 15:0

96-9-20 14:59

96-9-20 11:41

96-9-20 11:23

10 Appendix C. Vector Plots and Contoured Sections

This section presents vector plots and contoured U, V and backscatter plots for individual sections on each cruise. Vector plots include currents at four layers, each of which is averaged between 20 – 50 m, 50 – 100 m, 100 – 200 m, and 200 – 300 m, respectively. Units for U and V are cm s^{-1} , and for backscatter intensity is digital counts.

TN051

JGOFS Arabian Sea

TN051 First Half Cruise (09/18/95 to 10/02/95)

Hourly Averaged Velocity Layer 20m to 50m.

BNL

Thu Dec 14 10:31:28 1995

JGOFS Arabian Sea

TN051 First Half Cruise (09/18/95 to 10/02/95)
Hourly Averaged Velocity Layer 20m to 50m:

BNL

Thu Dec 14 10:31:28 1995

JGOFS Arabian Sea

TN051 First Half Cruise (09/18/95 to 10/02/95)

Layer: 100m to 200m

BNL

Thu Dec 14 10:31:39 1995

JGOFS Arabian Sea

TN051 First Half Cruise (09/18/95 to 10/02/95)

Layer: 200m to 300m

BNL

Thu Dec 14 10:31:44 1995

JGOFS Arabian Sea

TN051 Second Half Cruise (10/02/95 to 10/09/95)
Hourly Averaged Velocity Layer 20m to 50m:

BNL

Thu Dec 14 10:37:10 1995

JGOFS Arabian Sea

TN051 Second Half Cruise (10/02/95 to 10/09/95)

Hourly Averaged Velocity Layer 20m to 50m:

BNL

JGOFS Arabian Sea

TN051 Second Half Cruise (10/02/95 to 10/09/95)

Layer: 100m to 200m

BNL

Thu Dec 14 10:37:21 1995

JGOFS Arabian Sea

TN051 Second Half Cruise (10/02/95 to 10/09/95)

Layer: 200m to 300m

BNL

Thu Dec 14 10:37:26 1995

JGOFS Arabian Sea

TN051 Section 4 (09/22/95 to 09/27/95)
Quarter-hourly Averaged Velocity Layer 20m to 50m

BNL

Thu Dec 14 12:43:59 1995

JGOFS Arabian Sea

TN051 Section 4 (09/22/95 to 09/27/95)

Layer: 50m to 100m

BNL

Thu Dec 14 12:44:04 1995

JGOFS Arabian Sea

TN051 Section 4 (09/22/95 to 09/27/95)

Layer: 100m to 200m

BNL

Thu Dec 14 12:44:09 1995

JGOFS Arabian Sea

TN051 Section 4 (09/22/95 to 09/27/95)

Layer: 200m to 300m

BNL

63

Thu Dec 14 12:44:14 1995

JGOFS Arabian Sea

TN051 Section 6 (09/27/95 to 09/29/95)
Quarter-hourly Averaged Velocity Layer 20m to 50m

BNL

JGOFS Arabian Sea

TN051 Section 6 (09/27/95 to 09/29/95)

Layer: 50m to 100m

BNL

Thu Dec 14 13:57:59 1995

JGOFS Arabian Sea

TN051 Section 6 (09/27/95 to 09/29/95)

Layer: 100m to 200m

BNL

Thu Dec 14 13:58:04 1995

JGOFS Arabian Sea

TN051 Section 6 (09/27/95 to 09/29/95)

Layer: 200m to 300m

BNL

Thu Dec 14 13:58:08 1995

JGOFS Arabian Sea

TN051 Section 8 (09/29/95 to 10/01/95)
Quarter-hourly Averaged Velocity Layer 20m to 50m

BNL

Thu Dec 14 13:46:30 1995

JGOFS Arabian Sea

TN051 Section 8 (09/29/95 to 10/01/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN051 Section 8 (09/29/95 to 10/01/95)

Layer: 100m to 200m

BNL

Thu Dec 14 13:46:39 1995

JGOFS Arabian Sea

TN051 Section 8 (09/29/95 to 10/01/95)

Layer: 200m to 300m

BNL

71

Thu Dec 14 13:46:44 1995

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN051
Section 1

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN051
Section 1

Backscatter Intensity
Arabian Sea Cruise TN051
Section 1

ADCP Velocity: Zonal (U) Arabian Sea Cruise TN051 Section 2

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN051
Section 2

Backscatter Intensity
Arabian Sea Cruise TN051
Section 2

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN051
 Sections 3, 5, 7 & 9

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN051
 Sections 3, 5, 7 & 9

Backscatter Intensity
Arabian Sea Cruise TN051
Sections 3, 5, 7 & 9

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN051
 Section 10

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN051
 Section 10

Backscatter Intensity
Arabian Sea Cruise TN051
Section 10

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN051
Section 11

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN051
 Section 11

Backscatter Intensity
Arabian Sea Cruise TN051
Section 11

Backscatter Intensity
Arabian Sea Cruise TN051
Section 12

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN051
Section 13

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN051
Section 13

Backscatter Intensity
Arabian Sea Cruise TN051
Section 13

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN051
Section 14

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN051
Section 14

Backscatter Intensity
Arabian Sea Cruise TN051
Section 14

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN051
Section 15

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN051
Section 15

TN052

JGOFS Arabian Sea

TN052 Whole Cruise (10/14/95 to 10/25/95)
Hourly Averaged Velocity Layer 20m to 50m

BNL

Fri Dec 15 08:04:24 1995

JGOFS Arabian Sea

TN052 Whole Cruise (10/14/95 to 10/25/95)

Layer: 50m to 100m

BNL

95

Fri Dec 15 08:04:29 1995

JGOFS Arabian Sea

TN052 Whole Cruise (10/14/95 to 10/25/95)

Layer: 100m to 200m

BNL

96

JGOFS Arabian Sea

TN052 Whole Cruise (10/14/95 to 10/25/95)

Layer: 200m to 300m

BNL

70°E
65°E
60°E
55°E
Fri Dec 15 08:04:40 1995

JGOFS Arabian Sea

TN052 Section 3 (10/16/95 to 10/20/95)
Quart-hourly Averaged Velocity Layer 20m to 50m

BNL

Fri Dec 15 08:09:56 1995

JGOFS Arabian Sea

TN052 Section 3 (10/16/95 to 10/20/95)

Layer: 50m to 100m

BNL

Fri Dec 15 08:10:01 1995

JGOFS Arabian Sea

TN052 Section 3 (10/16/95 to 10/20/95)

Layer: 100m to 200m

BNL

100

JGOFS Arabian Sea

TN052 Section 3 (10/16/95 to 10/20/95)

Layer: 200m to 300m

BNL

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN052
Section 1

ADCP Velocity: Meridional (v)
Arabian Sea Cruise TN052
Section 1

Backscatter Intensity
Arabian Sea Cruise TN052
Section 1

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN052
 Section 2

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN052
 Section 2

Backscatter Intensity
Arabian Sea Cruise TN052
Section 2

22.30N
60.85E

15.75N
61.74E

ADCP Velocity: Zonal (U) Arabian Sea Cruise TN052 Section 4

ADCP Velocity: Meridional (V) Arabian Sea Cruise TN052 Section 4

Backscatter Intensity Arabian Sea Cruise TN052 Section 4

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN052
Section 5

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN052
Section 5

Backscatter Intensity
Arabian Sea Cruise TN052
Section 5

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN052
Section 6

ADCP Velocity: Meridional (V) Arabian Sea Cruise TN052 Section 6

Backscatter Intensity
Arabian Sea Cruise TN052
Section 6

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN052
Section 7

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN052
Section 7

Backscatter Intensity
Arabian Sea Cruise TN052
Section 7

TN053

JGOFS Arabian Sea

TN053 Cruise (10/29/95 to 11/26/95)
Hourly Averaged Velocity Layer 20m to 50m

BNL

Fri Dec 15 15:12:15 1995

JGOFS Arabian Sea

TN053 Cruise (10/29/95 to 11/26/95)

Layer: 50m to 100m

BNL

0.0 25.0 50.0
Velocity (cm/s)

55°E 60°E 65°E 70°E 75°E
Fri Dec 15 15:12:21 1995

JGOFS Arabian Sea

TN053 Cruise (10/29/95 to 11/26/95)

Layer: 100m to 200m

BNL

120

JGOFS Arabian Sea

TN053 Cruise (10/29/95 to 11/26/95)

Layer: 200m to 300m

BNL

70°E 75°E
Fri Dec 15 15:12:33 1995

JGOFS Arabian Sea

TN053 Section 1 (10/29/95 to 11/01/95)
Quart-hourly Averaged Velocity Layer 20m to 50m

BNL

JGOFS Arabian Sea

TN053 Section 1 (10/29/95 to 11/01/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN053 Section 1 (10/29/95 to 11/01/95)

Layer: 100m to 200m

BNL

JGOFS Arabian Sea

TN053 Section 1 (10/29/95 to 11/01/95)

Layer: 200m to 300m

BNL

JGOFS Arabian Sea

TN053 Sections 2 to 6
Hcp Averaged Velocity 20m to 50m

BNL

126

Wed Sep 18 15:04:20 1996

JGOFS Arabian Sea

TN053 Sections 2 to 6
Current Velocity: 50m to 100m

BNL

JGOFS Arabian Sea

TN053 Sections 2 to 6
Current Velocity: 100m to 200m

BNL

128

Wed Sep 18 15:04:44 1996

JGOFS Arabian Sea

TN053 Sections 2 to 6
Current Velocity: 200m to 300m

BNL

129

JGOFS Arabian Sea

TN053 Sections 7 to 9
Quart-hourly Averaged Velocity 20m to 50m

BNL

Wed Sep 18 14:34:31 1996

JGOFS Arabian Sea

TN053 Sections 7 to 9
Current Velocity: 50m to 100m

BNL

JGOFS Arabian Sea

TN053 Sections 7 to 9

Current Velocity: 100m to 200m

BNL

Wed Sep 18 14:34:42 1996

JGOFS Arabian Sea

TN053 Sections 7 to 9

Current Velocity: 200m to 300m

BNL

Wed Sep 18 14:34:48 1996

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN053
Section 2a

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN053
 Section 2a

Backscatter Intensity
Arabian Sea Cruise TN053
Section 2a

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN053
 Section 2b

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN053
 Section 2b

Backscatter Intensity
Arabian Sea Cruise TN053
Section 2b

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN053
 Section 3a

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN053
 Section 3a

Backscatter Intensity
Arabian Sea Cruise TN053
Section 3a

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN053
Section 3b

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN053
Section 3b

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN053
 Section 4

Backscatter Intensity
Arabian Sea Cruise TN053
Section 4

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN053
 Section 5a

ADCP Velocity: Meridional ($\bar{v}$)
 Arabian Sea Cruise TN053
 Section 5a

Backscatter Intensity
Arabian Sea Cruise TN053
Section 5a

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN053
Section 5b

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN053
Section 5b

Backscatter Intensity
Arabian Sea Cruise TN053
Section 5b

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN053
Section 6

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN053
Section 6

Backscatter Intensity
Arabian Sea Cruise TN053
Section 6

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN053
Section 7

ADCP Meridional (V)
Arabian Sea Cruise TN053
Section 7

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN053
Section 8

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN053
 Section 8

Backscatter Intensity
Arabian Sea Cruise TN053
Section 8

TN054

JGOFS Arabian Sea

TN054 Cruise (11/30/95 to 12/27/95)
Hourly Averaged Velocity Layer 20m to 50m

BNL

JGOFS Arabian Sea

TN054 Cruise (11/30/95 to 12/27/95)

Layer: 50m to 100m

BNL

162

Tue May 28 09:09:05 1996

JGOFS Arabian Sea

TN054 Cruise (11/30/95 to 12/27/95)

Layer: 100m to 200m

BNL

JGOFS Arabian Sea

TN054 Cruise (11/30/95 to 12/27/95)

Layer: 200m to 300m

BNL

164

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN054
Sections 1 & 2

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN054
Sections 1 & 2

Backscatter Intensity
Arabian Sea Cruise TN054
Sections 1 & 2

23.63N
58.74E

22.50N
61.14E

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN054
Section 3

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN054
 Section 3

Backscatter Intensity
Arabian Sea Cruise TN054
Section 3

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN054
 Section 5

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN054
 Section 5

Backscatter Intensity
Arabian Sea Cruise TN054
Section 5

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN054
 Sections 7 & 8

ADCP Velocity: Meridional (V) Arabian Sea Cruise TN054 Sections 7 & 8

Backscatter Intensity
Arabian Sea Cruise TN054
Sections 7 & 8

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN054
Section 9

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN054
Section 9

Backscatter Intensity
Arabian Sea Cruise TN054
Section 9

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN054
Sections 11 & 13

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN054
Sections 11 & 13

100

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN054
Sections 15 & 16

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN054
Sections 15 & 16

Backscatter Intensity
Arabian Sea Cruise TN054
Sections 15 & 16

17.73N 18.50N
59.90E 57.30E

ADCP Velocity: Zonal (U)
 Arabian Sea Cruise TN054
 Sections 17 & 18

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN054
Sections 17 & 18

Backscatter Intensity
Arabian Sea Cruise TN054
Sections 17 & 18

TN055

JGOFS Arabian Sea

TN055 Cruise (12/31/95 to 01/15/96)

Hourly Averaged Velocity Layer 20m to 50m

BNL

JGOFS Arabian Sea

TN055 Cruise (12/31/95 to 01/15/96)

Current Velocity: 50m to 100m

BNL

JGOFS Arabian Sea

TN055 Cruise (12/31/95 to 01/15/96)

Current Velocity: 100m to 200m

BNL

JGOFS Arabian Sea

TN055 Cruise (12/31/95 to 01/07/96)
Hourly Averaged Velocity Layer 20m to 50m

BNL

0.0 25.0 50.0
Velocity (cm/s)

Thu Sep 19 14:19:51 1996

JGOFS Arabian Sea

TN055 Cruise (12/31/95 to 01/07/96)

Current Velocity: 50m to 100m

BNL

Thu Sep 19 14:20:01 1996

JGOFS Arabian Sea

TN055 Cruise (12/31/95 to 01/07/96)

Current Velocity: 100m to 200m

BNL

JGOFS Arabian Sea

TN055 Cruise (12/31/95 to 01/07/96)

Current Velocity: 200m to 300m

BNL

0.0 25.0 50.0
Velocity (cm/s)

Thu Sep 19 14:20:13 1996

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN055
Section 1

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN055
Section 1

Backscatter Intensity
Arabian Sea Cruise TN055
Section 1

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN055
Section 2

ADCP Velocity: Meridional (V) Arabian Sea Cruise TN055 Section 2

Backscatter Intensity
Arabian Sea Cruise TN055
Section 2

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN055
Section 3

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN055
Section 3

ADCP Velocity: Zonal (U) Arabian Sea Cruise TN055 Section 4

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN055
Section 4

1. 2. 3. 4.

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN055
Section 5a

ADCP Velocity: Meridional (V)
 Arabian Sea Cruise TN055
 Section 5a

Backscatter Intensity
Arabian Sea Cruise TN055
Section 5a

ADCP Velocity: Zonal (U) Arabian Sea Cruise TN055 Section 5b

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN055
Section 5b

Backscatter Intensity Arabian Sea Cruise TN055 Section 5b

ADCP Velocity: Zonal (U)
Arabian Sea Cruise TN055
Section 5c

ADCP Velocity: Meridional (V)
Arabian Sea Cruise TN055
Section 5c

Backscatter Intensity
Arabian Sea Cruise TN055
Section 5c