Acoustic Doppler Current Profiling from the JGOFS Arabian Sea Cruises Aboard the RV T. G. Thompson

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TN047, May 3, 1995 – May 20, 1995

TN048, June 21, 1995 – July 13, 1995

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TN050, August 18, 1995 – September 15, 1995

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by

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DEPARTMENT OF APPLIED SCIENCE

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**Oceanographic and Atmospheric Sciences Division
Department of Applied Science**

**Brookhaven National Laboratory
Associated Universities, Inc.
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 lists start and end dates of each cruise with its mission.

All but the first cruise have been or will be 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 equipments 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 extension of RD instrument's DAS version 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 insures constant data coverage and uniform data quality.

This data report presents the ADCP data collection methods and results from the third group of four JGOFS Arabian Sea cruises, TN047 through TN050. This group includes three process cruises and one SeaSoar cruise (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 PC's 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

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.

authors.

A description of ADCP hardware, the AutoADCP data acquisition system, and the collection of navigation and compass data on the Thompson is given in section 2. Section 3 presents the processing and analysis of velocity and acoustic backscatter intensity data. Section 4 documents data collection for each cruise together with a cruise track. A diagnosis of profile quality is given in section 5.

The ADCP data results from previous cruises are documented in two data reports; the data for cruises TN039 through TN042 is in Flagg and Shi (1995), and for cruises TN043 through TN046 is in Flagg, Kim 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 transducer 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). 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 calm conditions of the first eight cruises indicates that this is an excellent installation producing high quality data at all ship speeds. The ability to produce high quality data was tested during the JGOFS monsoon cruises in this data report, and the impact of high waves on ADCP performance is assessed below.

Installation of the ADCP deck unit was done on a computer rack above a sub-bottom depth sounder in the Thompson's computer lab. The deck unit was 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 and training cruise TN039. The temperature of the deck unit with the depth sounder operating was 30° Celsius under the air-conditioned environment of the electronics lab. 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 have been installed on two PC computers, both of which are connected by a Pathworks network to virtual disks on a DEC 5000-200 Unix workstation. In September 1994, one of the Thompson's PCs (a Delphi 286) was set up to collect the data, while a PC supplied by Brookhaven (a Dell 386) was used for real-time presentation of the results. The AutoADCP programs were installed on both computers so that the data collection could be switched to the Brookhaven PC if the primary PC suffered a failure.

Standard ADCP data is displayed on the Thompson's Delphi 286. The presentation consists of 5-minute ensemble averaged profiles of U (zonal) and V (meridional) velocities, AGC (backscatter intensity) and percentage of good pings. In addition to the data gathering performed by the AutoADCP system, another set of programs was written in MATLAB to present ADCP data in real-time. These programs run on the second computer, 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 high quality data while minimizing interference with other program components. The system was initially developed in a 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 for any reason the DAS stops collecting data.

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 as shown in Figure 2. When the ship leaves one region for another, the DAS's default configuration file, START.CNF, is updated, the computer reboots and the ADCP starts pinging using the new configuration. Most of the data in the program was obtained using the configuration for the northern Arabian Sea, ARABSEA.CNF. Table 2 presents the ARABSEA.CNF file.

Provision has also been made for a watchdog timer and automatic backup of pingdata files each time a file is filled. The utility of the AutoADCP DAS is that ensemble interval, number of bins, bin and pulse size, bottom tracking, and other configuration parameters can be controlled without an on-board operator monitoring the DAS's performance. This makes for a more consistent and robust data set.

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

Figure 2: The ADCP regions of the Arabian Sea, Bay of Bengal, and western portion of the Indonesian Archipelago, which dictate control over the operation of the ADCP through the specification of the appropriate configuration file. The ADCP regions include possible ports of call and the continental shelves as well as the open ocean of the Arabian Sea and Bay of Bengal.

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 which 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 remains 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 records 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 TN050 (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 had 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 (Appendix B) 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 communi-

cation). 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 which 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, but operated only for a day on TN045. It didn't function again until cruise TN049 where it worked throughout the cruise.

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 percent good 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. A 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 micetofids. 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.

For calibration of the ADCP's orientation and velocity, the heading offset and amplitude scale factor are required. 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, a heading offset and amplitude scale factor 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.

When the Ashtech attitude sensor functions, the ensemble averaged difference between the Ashtech heading data and the ship's compass is determined by the UE4 user-exit program, and recorded in the user buffer portion of the pingdata files. When the Ashtech data is available, the individual ensemble velocities are rotated before calibrating for the heading offset and amplitude factor. During cruise TN049, the mean offset between the Ashtech and the ship's compass was -1.23° with standard deviation of $\pm 1.56^\circ$.

This procedure corrects for the various compass errors, but leaves the ADCP heading data relative to new reference frame. It was therefore necessary to determine the angular

offset of the Ashtech antennae relative to ADCP using the bottom tracking. Bottom track data from a 20 hour run near the end of cruise TN049 along the Oman shelf, resulted in an angular offset of 1.335° . The data from the cruise were then rotated by this amount. Note this correction and the mean difference between the compass and the Ashtech are nearly equal and of opposite sign.

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, S_v , for each depth bin.

The calibration equation for S_v for each beam is:

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

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} (°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:

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

where the scaling a_1 and offset a_o 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 3 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 scatters densities, the average profiles are set to nulls. Backscatter differences of a single beam from the mean profiles is shown in Figure 4, which is obtained after secondary correction is applied. Note the change in the scale of the abscissa relative to Figure 3.

Figure 3: 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 4: 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 TN047

The third process cruise, which took place during the pre-summer monsoon period, was for the purpose of turning around the sediment trap moorings and taking sediment cores under the upwelling area off southern Oman. The duration of the cruise was 18 days from May 3 through May 20, 1995. The cruise track was slightly different from the standard one (Figure 5), proceeding directly to the mooring sites hence northwestward to the coast. Jack Dymond and Warren Prell were co-chief scientists during this cruise, while Bill Martin monitored the AutoADCP system.

4.2 TN048

This cruise was the third of the ONR/NRL SeaSoar cruises, starting on June 21 and ending July 13, 1995 in the southwest monsoon. The P-code GPS receiver was up running for better navigation data. Ken Brink was the chief scientist for the cruise. As before the cruise track consisted of two "radiator" seasoar surveys along the main transect and a "bowtie" around the long-term moorings. There was also an abbreviated radiator pattern near the coast and a series of hydrographic stations to investigate a large filament observed near the shelf break.

4.3 TN049

TN049 was the fourth process cruise and was also conducted during the SW monsoon. The cruise followed the standard track line, leaving Muscat on July 17 and returning on August 15, 1995. Richard Barber was the chief scientist and Mike Grogan helped monitor the ADCP and Ashtech unit. During this cruise, the Ashtech receiver functioned intermittently. In the gaps, the velocities were rotated by the average Ashtech heading offset. The

P-code receiver functioned throughout the cruise.

4.4 TN050

The fifth process cruise took place from August 18 through September 15, 1995 at the end of the SW monsoon with Sharon Smith as the chief scientist and Bill Martin responsible for the ADCP. The P-code receiver worked throughout the cruise while the Ashtech receiver did not.

Figure 5: Cruise track for TN047, Process cruise #3. Numbers along the track represent sections and stations used later for vectors and contour plots in Appendix C.

Figure 6: Cruise track for TN048, the 3rd ONR/NRL SeaSoar cruise. Duration of this cruise is three weeks.

Figure 7: Cruise track for TN049, following the standard cruise track.

Figure 8: Cruise track for TN050, the 5th process cruise.

5 Profile Quality

In processing the ADCP data, a set of diagnostic products is routinely produced. Typically, each cruise is broken into sections along the track or subsections of special interest. The diagnostic products include separate underway and on-station profiles of averages and standard deviations of horizontal velocity shears (first differences in the vertical), vertical velocity, error velocity, backscatter intensity, and percent good, based upon the ensemble data.

Figure 9 shows results of the quality analysis of the data collected during cruise TN049 along the standard track (Figure 7) in the SW monsoon. Cruise TN049 is of special interest, because both the P-code GPS receiver and Ashtech attitude sensor were available. Hence the data set should be of the highest quality possible with current technology. For the statistical results in Figure 9, 4700 ensembles were extracted while the ship was on station ($< 2.5 \text{ m s}^{-1}$) and 2330 ensembles when the ship was underway ($> 5.0 \text{ m s}^{-1}$).

The first difference/vertical shear diagnostics shown in Figure 9a and 9b 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 shears were significant only in the upper 100 meters or so, where the maximum values approached 0.5 cm s^{-1} . The standard deviation of the shear was relatively higher between the first and second bins, below 150 meters when underway, and near the extreme range of the ADCP below 360 meters. The maximum shears generally encountered were well below the limit of the velocity tracking capability of the tracking filter ($\sim 2.0 \text{ cm s}^{-1}$) and therefore it should not pose any problem. The higher standard deviations near the surface may reflect the often encountered difficulties with the first bin where signal-to-noise may decrease (note increase in backscatter intensity in Figure 9e) and spectral width increase, Figure 9f, such that the ping-to-ping first bin tracking control may be less than optimal. The "E" command used

the results from depth cells 2 to 5 from the previous ping to determine the initial position of tracking filter during these cruises. In highly sheared near surface conditions, as might be encountered during extreme wind forcing of the SW monsoon, it is quite possible that there was some skew bias introduced by a misaligned tracking filter. The cause for the increased shear standard deviation below 150 meters while underway is unclear. In the lowest 50 meters of the profile where the shear standard deviation is increased substantially appears to reflect noise bias. This should not impact the data products because the percent good over that portion of the profile was well below the acceptance level of 30 percent.

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 the average vertical velocity profile, Figure 9c, are the uniformity with depth below 50 meters, the $\sim 3 \text{ cm s}^{-1}$ difference between underway and on-station profiles suggest that the ship (actually the ADCP transducer) was out of trim by about 0.3 degrees, a remarkably small value. The negative near surface values while underway suggest 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 error velocities on this cruise, Figure 9d, were less than we've seen in some of the previous cruises. The underway values were about 1 cm s^{-1} higher than those from on-station periods. It suggests that there may have been less than 0.1 degrees misalignment of beams 1 and 3 relative to beams 2 and 4. Why the on-station error velocity increases with depth is unclear; this behavior was not evident in some of the earlier cruises.

The average backscatter intensity (aka amplitude) profiles are presented in Figure 9e in terms of digital counts for both underway and on-station conditions. 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 between 100 and 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.

The percent good profiles of Figure 9g indicates that highly reliable data covered the upper 175 meters. Below that, the range is subject to the effects of diel migration. During the night the effective range of the ADCP in the northern Arabian Sea was generally not more than 250 meters. From experiments on earlier cruises doubling the pulse lengths to 32 meters had no measurable effect.

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 TN049.

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c) W component, ADCP TN049
(Solid: On Station; Dash: Underway)

d) ERROR VELOCITY, ADCP TN049
(Solid: On Station; Dash: Underway)

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e) AMPLITUDE, ADCP TN049
(Solid: On Station; Dash: Underway)

f) SPECTRAL WIDTH, ADCP TN049
(Solid: On Station; Dash: Underway)

g) PERCENT GOOD, ADCP TN049
(Solid: On Station; Dash: Underway)

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6 Acknowledgments

We would like to express our appreciation for the assistance of George White, Mike Realander, Bill Martin, Mike Grogan, William Peterson and the Thompson's crew in the initial set-up the ADCP system and in the continuing data collection. We also received significant help from Eric Firing and Frank Bahr 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 Renanda 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	SeaSoar 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 Cyle 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,RRA,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 TN047

Sec	Date		Start		Date		End	
			Year Day	(Lat,Lon)			Year Day	(Lat,Lon)
1	95/05/03	03:47:39	122.158	(23.655,58.615)	95/05/05	02:34:54	124.108	(15.971,61.501)
1a	95/05/03	03:47:39	122.158	(23.655,58.615)	95/05/03	18:43:26	122.780	(22.272,60.312)
1b	95/05/03	18:48:26	122.784	(22.255,60.316)	95/05/05	02:34:54	124.108	(15.971,61.501)
2	95/05/05	02:39:55	124.111	(15.971,61.501)	95/05/07	09:34:53	126.399	(15.990,61.494)
3	95/05/07	09:39:54	126.403	(15.995,61.476)	95/05/07	20:14:54	126.844	(16.615,59.803)
4	95/05/07	20:19:54	126.847	(16.623,59.799)	95/05/07	23:19:54	126.972	(17.197,59.596)
5	95/05/07	23:24:54	126.976	(17.203,59.595)	95/05/10	10:13:01	129.426	(17.206,59.627)
6	95/05/10	10:18:01	129.429	(17.209,59.617)	95/05/10	19:13:01	129.801	(17.386,58.865)
7	95/05/10	19:18:01	129.804	(17.389,58.853)	95/05/12	17:48:02	131.742	(17.356,58.794)
8	95/05/12	17:53:02	131.745	(17.360,58.781)	95/05/13	00:18:03	132.013	(17.694,57.856)
9	95/05/13	00:23:02	132.016	(17.696,57.853)	95/05/15	13:30:54	135.563	(17.827,57.357)
10	95/05/15	23:26:59	134.977	(17.832,57.363)	95/05/16	13:30:54	135.563	(19.238,58.571)
11	95/05/16	13:35:54	135.567	(19.231,58.564)	95/05/19	06:09:02	138.256	(19.272,58.247)
12	95/05/19	06:14:24	138.260	(19.274,58.256)	95/05/20	23:34:00	139.982	(23.375,58.994)
12a	95/05/19	06:14:24	138.260	(19.274,58.256)	95/05/20	09:29:02	139.395	(22.452,60.085)
12b	95/05/20	09:34:02	139.399	(22.464,60.085)	95/05/20	23:34:00	139.982	(23.375,58.994)

Section List for TN048

Sec	Date		Start		Date		End	
			Year Day	(Lat,Lon)			Year Day	(Lat,Lon)
1	95/06/21	05:52:34	171.245	(23.713,58.731)	95/06/21	23:04:57	171.962	(22.494,60.290)
2	95/06/21	23:09:57	171.965	(22.486,60.295)	95/06/23	08:49:58	173.368	(18.739,58.42)
3	95/06/23	08:54:58	173.372	(18.746,58.436)	95/06/26	13:59:59	176.583	(18.751,58.63)
4	95/06/26	14:04:59	176.587	(18.750,58.638)	95/06/27	01:14:59	177.056	(17.392,59.18)
5	95/06/27	01:19:59	177.056	(17.392,59.188)	95/06/29	13:53:15	179.579	(16.929,60.28)
6	95/06/29	13:58:15	179.582	(16.923,60.293)	95/06/30	01:53:17	180.079	(16.162,61.83)
7	95/06/30	01:58:15	180.082	(16.154,61.830)	95/07/01	02:48:15	181.117	(16.167,61.84)
8	95/07/01	02:53:14	181.120	(16.164,61.855)	95/07/01	12:48:15	181.534	(15.444,63.06)
9	95/07/01	12:53:15	181.537	(15.450,63.077)	95/07/03	22:56:23	183.956	(14.906,64.09)
10	95/07/03	23:01:23	183.959	(14.893,64.098)	95/07/04	06:16:23	184.261	(14.435,65.00)
11	95/07/04	06:21:23	184.265	(14.430,65.003)	95/07/06	01:41:23	186.070	(16.511,61.46)
12	95/07/06	01:46:23	186.074	(15.510,61.468)	95/07/08	01:30:18	188.063	(18.500,57.30)
13	95/07/08	01:35:18	188.066	(18.500,57.304)	95/07/09	07:39:59	189.319	(19.341,58.03)
14	95/07/09	07:44:58	189.323	(19.338,58.041)	95/07/10	12:55:46	190.539	(18.999,60.50)
15	95/07/10	13:00:46	190.542	(18.999,60.505)	95/07/11	06:05:44	191.254	(20.425,59.15)
16	95/07/11	06:10:45	191.257	(20.430,59.163)	95/07/11	22:50:44	191.952	(21.913,61.02)
17	95/07/11	22:55:45	191.955	(21.915,61.018)	95/07/13	01:35:45	193.066	(23.676,58.67)

Section List for TN049

Sec	Date		Start		Date		End	
			Year Day	(Lat,Lon)			Year Day	(Lat,Lon)
1	95/07/17	16:29:22	197.687	(23.660,58.620)	95/07/18	02:31:48	198.105	(22.387,59.884)
2	95/07/18	05:34:36	198.232	(22.440,59.915)	95/07/18	11:09:55	198.465	(22.500,61.163)
3	95/07/18	17:34:36	198.732	(22.524,61.236)	95/07/19	11:34:56	199.482	(21.190,63.541)
4	95/07/19	17:29:36	199.729	(21.160,63.604)	95/07/21	02:29:36	201.104	(19.201,67.170)
5	95/07/23	08:54:36	203.371	(19.133,67.184)	95/07/24	23:29:56	204.979	(15.391,68.749)
6	95/07/25	08:29:35	205.353	(15.314,68.679)	95/07/25	18:28:15	205.769	(14.918,66.887)
7	95/07/26	00:22:55	206.016	(14.902,66.846)	95/07/27	05:02:54	207.210	(15.963,63.109)
8	95/07/27	05:02:54	207.210	(15.952,63.124)	95/07/27	16:03:14	207.668	(14.467,64.985)
9	95/07/28	15:36:04	208.650	(14.434,65.029)	95/07/30	07:14:41	210.301	(19.162,67.157)
10	95/08/01	02:19:21	212.096	(10.008,64.893)	95/08/01	23:39:42	212.985	(14.444,65.001)
11	95/08/02	08:29:21	213.353	(14.480,64.950)	95/08/03	19:29:41	214.812	(16.031,62.005)
12	95/08/05	07:44:21	216.322	(15.572,61.500)	95/08/05	12:29:42	216.520	(16.418,61.250)
13	95/08/05	18:49:22	216.784	(16.408,61.229)	95/08/09	10:59:41	220.457	(18.126,58.013)
14	95/08/11	14:59:21	222.624	(18.329,58.029)	95/08/11	18:20:27	222.764	(18.492,57.330)
15	95/08/12	15:18:16	223.637	(18.569,57.386)	95/08/13	00:49:22	224.034	(18.996,58.988)
16	95/08/13	04:39:23	224.193	(18.996,59.027)	95/08/14	02:44:14	225.114	(22.016,59.976)
17	95/08/14	02:44:14	225.114	(22.016,59.976)	95/08/15	03:48:03	226.158	(23.644,58.578)

Section List for TN050

Sec	Date		Start		Date		End	
			Year Day	(Lat,Lon)			Year Day	(Lat,Lon)
1	95/08/18	04:50:46	229.201	(23.651 58.617)	95/08/18	15:26:32	229.643	(22.237 59.88
2'	95/08/18	15:31:32	229.646	(22.390 59.883)	95/08/18	20:31:32	229.855	(22.409 59.88
2	95/08/18	20:36:31	229.858	(22.419 59.895)	95/09/20	09:06:33	231.379	(21.738 62.35
3	95/08/20	09:16:32	231.386	(21.739 62.360)	95/08/21	22:54:40	232.954	(19.898 65.85
4	95/08/21	22:59:49	232.958	(19.893 65.861)	95/08/23	13:54:40	234.579	(19.076 67.09
5	95/08/23	13:59:39	234.583	(19.075 67.093)	95/08/26	08:32:49	237.356	(15.378 68.76
6	95/08/26	08:37:50	237.359	(15.377 68.758)	95/08/27	01:27:49	238.060	(14.905 66.88
7	95/08/27	01:32:50	238.064	(14.903 66.884)	95/08/30	06:46:02	241.281	(9.966 64.898
8	95/08/30	06:51:01	241.285	(9.966 64.898)	95/09/02	19:19:11	244.804	(14.444 65.00
9	95/09/02	19:24:09	244.808	(14.444 64.999)	95/09/08	15:06:50	250.629	(17.402 59.77
10	95/09/08	15:11:50	250.633	(17.140 59.776)	95/09/12	15:30:49	254.646	(18.507 57.31
11	95/09/12	15:35:49	254.649	(18.507 57.318)	95/09/13	08:34:42	255.357	(19.002 58.99
12	95/09/13	08:39:43	255.360	(19.013 58.996)	95/09/14	09:44:19	256.405	(22.641 59.98
13	95/09/14	09:49:20	256.409	(22.641 59.971)	95/09/15	01:20:48	257.056	(23.580 58.81

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.

95-9-5 16:30

95-9-1 10:52

95-10-26 15:5

95-10-31 15:33

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.

TN047

JGOFS Arabian Sea

TN047 Whole Cruise (05/03/95 to 05/21/95)

Layer: 50m to 100m

BNL

Tue Sep 5 17:14:43 1995

JGOFS Arabian Sea

TN047 Whole Cruise (05/03/95 to 05/21/95)

Layer: 100m to 200m

BNL

JGOFS Arabian Sea

TN047 Whole Cruise (05/03/95 to 05/21/95)

Layer: 200m to 300m

BNL

Tue Sep 5 17:14:56 1995

JGOFS Arabian Sea

TN047 Section 3,4,6,8 (05/07/95 to 05/13/95)

Current Velocity 20m to 50m

BNL

JGOFS Arabian Sea

TN047 Section 3,4,6,8 (05/07/95 to 05/13/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN047 Section 3,4,6,8 (05/07/95 to 05/13/95)

Layer: 100m to 200m

BNL

09

25°N

20°N

0.0 25.0 50.0
Velocity (cm/s)

JGOFS Arabian Sea

TN047 Section 3,4,6,8 (05/07/95 to 05/13/95)

Layer: 200m to 300m

BNL

61

JGOFS Arabian Sea

TN047 Section 10,12 (05/15/95 to 05/21/95)

Current Velocity 20m to 50m

BNL

25°N

20°N

62

0.0 25.0 50.0
Velocity (cm/s)

JGOFS Arabian Sea

TN047 Section 10,12 (05/15/95 to 05/21/95)

Layer: 50m to 100m

BNL

63

JGOFS Arabian Sea

TN047 Section 10,12 (05/15/95 to 05/21/95)

Layer: 100m to 200m

BNL

25°N

20°N

64

JGOFS Arabian Sea

TN047 Section 10,12 (05/15/95 to 05/21/95)

Layer: 200m to 300m

BNL

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN047

Section 1a

23.655

58.615

22.272

60.312

BNL

Distance, km

7-SEP-95 08:37:50

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN047
Section 1b

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN047
Section 1b

Backscatter Intensity
Arabian Sea Cruise TN047
Section 1b

22.255
60.316

15.971
61.501
BNL

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN047

Section 3-4-6-8

ADCP Velocity: meridional (V) Arabian Sea Cruise TN047 Section 3-4-6-8

Backscatter Intensity
Arabian Sea Cruise TN047
Section 3-4-6-8

Backscatter Intensity

Arabian Sea Cruise TN047

Section 10

17.832

19.238

57.363

58.571

BNL

ADCP Velocity: zonal (U) Arabian Sea Cruise TN047 Section 12a

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN047
Section 12a

Backscatter Intensity
Arabian Sea Cruise TN047
Section 12a

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN047

22.464 Section 12b 23.375

60.085 58.994

Backscatter Intensity

Arabian Sea Cruise TN047

22.464 Section 12b 23.375

60.085 58.994

BNL

7-SEP-95 09:43:23

TN048

JGOFS Arabian Sea

TN048 First Half Cruise (06/21/95 to 07/04/95)
Current Velocity 20m to 50m

BNL

Fri Sep 1 13:19:05 1995

JGOFS Arabian Sea

TN048 First Half Cruise (06/21/95 to 07/04/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN048 First Half Cruise (06/21/95 to 07/04/95)

Layer: 100m to 200m

BNL

JGOFS Arabian Sea

TN048 First Half Cruise (06/21/95 to 07/04/95)

Layer: 200m to 300m

BNL

JGOFS Arabian Sea

TN048 Second Half Cruise (07/04/95 to 07/13/95)
Current Velocity 20m to 50m

BNL

Fri Sep 1 13:25:28 1995

JGOFS Arabian Sea

TN048 Second Half Cruise (07/04/95 to 07/13/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN048 Second Half Cruise (07/04/95 to 07/13/95)

Layer: 100m to 200m

JGOFS Arabian Sea

TN048 Second Half Cruise (07/04/95 to 07/13/95)

Layer: 200m to 300m

BNL

JGOFS Arabian Sea

TN048 Section 3 (06/23/95 to 06/26/95)

Current Velocity 20m to 50m

BNL

Fri Sep 1 13:45:03 1995

JGOFS Arabian Sea

TN048 Section 3 (06/23/95 to 06/26/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN048 Section 3 (06/23/95 to 06/26/95)

Layer: 100m to 200m

BNL

95

Fri Sep 1 13:45:14 1995

JGOFS Arabian Sea

TN048 Section 3 (06/23/95 to 06/26/95)

Layer: 200m to 300m

BNL

JGOFS Arabian Sea

TN048 Section 5 (06/27/95 to 06/29/95)

Current Velocity 20m to 50m

BNL

97

JGOFS Arabian Sea

TN048 Section 5 (06/27/95 to 06/29/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN048 Section 5 (06/27/95 to 06/29/95)

Layer: 100m to 200m

JGOFS Arabian Sea

TN048 Section 5 (06/27/95 to 06/29/95)

Layer: 200m to 300m

BNL

100

JGOFS Arabian Sea

TN048 Section 7 (06/30/95 to 07/01/95)

Current Velocity 20m to 50m

BNL

101

JGOFS Arabian Sea

TN048 Section 7 (06/30/95 to 07/01/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN048 Section 7 (06/30/95 to 07/01/95)

Layer: 100m to 200m

BNL

Fri Sep 1 11:55:10 1995

JGOFS Arabian Sea

TN048 Section 7 (06/30/95 to 07/01/95)

Layer: 200m to 300m

BNL

JGOFS Arabian Sea

TN048 Section 9 (07/01/95 to 07/03/95)

Current Velocity 20m to 50m

BNL

JGOFS Arabian Sea

TN048 Section 9 (07/01/95 to 07/03/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN048 Section 9 (07/01/95 to 07/03/95)

Layer: 100m to 200m

JGOFS Arabian Sea

TN048 Section 9 (07/01/95 to 07/03/95)

Layer: 200m to 300m

BNL

ADCP Velocity: zonal (U)

Arabian Sea Cruise IN048

23.713
58.731

Section 1

22.494
60.296

7-SEP-95 10:39:53

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN048

Section 1

23.713

58.731

22.494

60.296

7-SEP-95 10:36:51

Backscatter Intensity
Arabian Sea Cruise TN048
Section 1

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN048
Section 2

22.486
60.295

18.739
58.422
BNL

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN048
Section 2

22.486
60.295

18.739
58.422
BNL

Backscatter Intensity
Arabian Sea Cruise TN048
Section 2

22.486
60.295

18.739
58.422
BNL

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN048

Section 4

17.392

59.188

18.750

58.638

Backscatter Intensity
Arabian Sea Cruise TN048

18.750 17.392
58.638 59.188

Section 4

BNL

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN048
Sections 6,8

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN048

Sections 6,8

16.923
60.293

15.444
63.068
BNL

Distance, km

7-SEP-95 12:52:00

Backscatter Intensity
Arabian Sea Cruise TN048
Section 6, 8

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN048

14.893 Section 10 14.435

64.098 65.007

Distance, km 7-SEP-95 13:01:32

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN048

14.893 Section 10 14.435

64.098 65.007

BNL

Distance, km 7-SEP-95 12:57:44

ADCP Velocity: zonal(U)
Arabian Sea Cruise TN048
Section 11

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN048
Section 11

Backscatter Intensity
Arabian Sea Cruise TN048
Section 11

ADCP Velocity: zonal (U)
 Arabian Sea Cruise IN048
 Section 12

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN048
Section 12

Backscatter Intensity
Arabian Sea Cruise TN048
Section 12

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN048
Section 13-14

18.500
57.304

18.999
60.505
BNL

ADCP Velocity: meridional (V) Arabian Sea Cruise IN048 Section 13-14

7-SEP-95 14:26:03

Backscatter Intensity
Arabian Sea Cruise TN048
Section 13-14

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN048
Sections 15,16,17

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN048

Sections 15,16,17

18.999
60.505

23.676
58.670
BNL

Backscatter Intensity Arabian Sea Cruise IN048 Section 15,16,17

TN049

JGOFS Arabian Sea

TN049 Whole Cruise (07/17/95 to 08/15/95)

Current Velocity 20m to 50m

BNL

137

JGOFS Arabian Sea

TN049 Whole Cruise (07/17/95 to 08/15/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN049 Whole Cruise (07/17/95 to 08/15/95)

Layer: 100m to 200m

JGOFS Arabian Sea

TN049 Whole Cruise (07/17/95 to 08/15/95)
Layer: 200m to 300m

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN049

Section 1

23.660

22.387

58.620

59.884

BNL

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 2 and 3

24.440
59.910

21.190
63.541
BNL

ADCP Velocity: meridional (V)
 Arabian Sea Cruise TN049
 Section 2 and 3

Backscatter Intensity
Arabian Sea Cruise TN049
Section 2 and 3

24.440
59.910

21.190
63.541
BNL

30-OCT-95 14:13:50

ADCP Velocity: zonal (U) Arabian Sea Cruise TN049 Section 4

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

Section 4

21.160

63.604

19.201

67.170

BNL

Backscatter Intensity
Arabian Sea Cruise TN049
Section 4

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 5

19.133
67.184

15.391
68.749
BNL

150

7-NOV-95 17:41:16

ADCP Velocity: meridional (V) Arabian Sea Cruise TN049 Section 5

Backscatter Intensity
Arabian Sea Cruise TN049
Section 5

19.133
67.184

15.391
68.749
BNL

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN049

Section 6

15.314

68.679

14.918

66.887

BNL

Distance, km 30-OCT-95 15:32:57

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

Section 6

15.314

68.679

14.918

66.887

BNL

Backscatter Intensity
Arabian Sea Cruise TN049
Section 6

15.314
68.679

14.918
66.887
BNL

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 7

ADCP Velocity: meridional (V) Arabian Sea Cruise TN049 Section 7

Backscatter Intensity
Arabian Sea Cruise TN049
Section 7

ADCP Velocity: zonal (U)
 Arabian Sea Cruise TN049
 Section 8

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

Section 8

15.952
63.124

14.467
64.985
BNL

Backscatter Intensity
Arabian Sea Cruise TN049
Section 8

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 9

14.434
65.029

19.162
67.157
BNL

ADCP Velocity: meridional (V) Arabian Sea Cruise TN049 Section 9

Backscatter Intensity
Arabian Sea Cruise TN049
Section 9

14.434
65.029

19.162
67.157
BNL

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 10

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN049
Section 10

10.008
64.893

14.444
65.001
BNL

166

30-OCT-95 16:13:36

Backscatter Intensity Arabian Sea Cruise TN049 Section 10

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 11

ADCP Velocity: meridional (V) Arabian Sea Cruise TN049 Section 11

Backscatter Intensity
Arabian Sea Cruise TN049
Section 11

14.480
64.950

16.301
62.005
BNL

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

15.571 Section 16.418

61.500 61.250

Distance, km 80-OCT-95 16:25:11

Backscatter Intensity

Arabian Sea Cruise TN049

15.571 Section 12 16.418

61.500

61.250

BNL

8-NOV-95 10:34:50

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 13 and 14

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

Section 13 and 14

16.408

61.229

18.126

57.330

BNL

Backscatter Intensity
Arabian Sea Cruise TN049
Section 13 and 14

16.408
61.229

18.126
57.330
BNL

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

18.569 57.386

Section 15

18.996

58.988

BNL

Distance, km 30-OCT-95 16:34:49

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049
Section 16

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

Section 16

Backscatter Intensity
Arabian Sea Cruise TN049
Section 16

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN049

Section 17

22.016
59.976

23.644
58.578

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN049

Section 17

22.016

23.644

59.976

58.578

BNL

Backscatter Intensity
Arabian Sea Cruise TN049
Section 17

22.016
59.976

23.644
58.578
BNL

TN050

JGOFS Arabian Sea

TN050 Whole Cruise (08/18/95 to 09/15/95)

Current Velocity 20m to 50m

BNL

187

JGOFS Arabian Sea

TN050 Whole Cruise (08/18/95 to 09/15/95)

Layer: 50m to 100m

BNL

JGOFS Arabian Sea

TN050 Whole Cruise (08/18/95 to 09/15/95)

Layer: 100m to 200m

BNL

189

JGOFS Arabian Sea

TN050 Whole Cruise (08/18/95 to 09/15/95)

Layer: 200m to 300m

BNL

190

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN050

Section 1

23.651

22.405

58.617

59.884

BNL

Distance, km 2-NOV-95 09:33:46

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN050
Section 2 and 3

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN050
Section 2 and 3

22.492
61.169

19.898
65.851
BNL

195

Depth, m

Distance, km

7-NOV-95 15:54:

Backscatter Intensity
Arabian Sea Cruise TN050
Section 2 and 3

22.492
61.169

19.898
65.851
BNL

7-NOV-95 16:31:3

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN050

19.893   Section 4   19.076

65.861   67.094

BNL

7-NOV-95 15:11:33

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN050

19.893

Section 4

19.076

65.861

67.094

BNL

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN050
Section 5

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN050
Section 5

19.075
67.093

15.378
68.760
BNL

Backscatter Intensity
Arabian Sea Cruise TN050
Section 5

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN050

Section 6

15.377

14.905

68.758

66.883

BNL

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN050

15.377

Section 6

14.905

68.758

66.883

BNL

Backscatter Intensity

Arabian Sea Cruise TN050

Section 6

15.377

14.905

68.758

66.883

BNL

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN050
Section 7

14.903
66.884

9.966
64.898
BNL

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN050
Section 7

14.903
66.884

9.966
64.898
BNL

Backscatter Intensity
Arabian Sea Cruise TN050
Section 7

14.903
66.884

9.966
64.898
BNL

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN050
Section 8

ADCP Velocity: meridional (V) Arabian Sea Cruise TN050 Section 8

Backscatter Intensity
Arabian Sea Cruise TN050
Section 8

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN050
Section 9

14.444
64.999

17.402
59.775
BNL

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN050
Section 9

Backscatter Intensity
Arabian Sea Cruise TN050
Section 9

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN050
Section 10

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN050

Section 10

17.140

59.776

18.507

57.318

BNL

Backscatter Intensity
Arabian Sea Cruise TN050
Section 10

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN050

18.507

Section 11

19.002

57.318

58.996

BNL

2-NOV-95 12:43:57

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN050

18.507 Section 11 19.002

57.318 58.996

ADCP Velocity: zonal (U)
Arabian Sea Cruise TN050
Section 12

ADCP Velocity: meridional (V)
Arabian Sea Cruise TN050
Section 12

19.013
58.996

22.641
59.987
BNL

ADCP Velocity: zonal (U)

Arabian Sea Cruise TN050

22.641 Section 13 23.580

59.971 58.810

BNL

Distance, km

3-NOV-95 11:30:36

ADCP Velocity: meridional (V)

Arabian Sea Cruise TN050

22.641 Section 13 23.580

59.971 58.810

BNL

Distance, km

3-NOV-95 11:25:03