Balearic Islands Coastal Observing and Forecasting System

The route to routine standard VM-ADCP operations on the SOCIB catamaran *B/O SOCIB*

10/02/16

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Summary

Delivered in 2012, the R/V SOCIB is the new research catamaran for Balearic Islands Coastal Observing and Forecasting System (SOCIB). One of its observational requirements were upper ocean currents, whilst underway, to a standard expected by suitably equipped research vessels internationally. The objective of this report is to inform scientific users, technicians and data managers of the principles, components and limitations of upper ocean current profiling operations on board R/V SOCIB, and to act as a historical record of the process of achieving this capability for the vessel's operators.

In this report, the vessel mounted acoustic Doppler current profiler (VM-ADCP) capabilities of R/V SOCIB are presented. After a brief discussion of ADCP principles, the report begins by presenting early tests (December 2012), following delivery/acceptance of the vessel and its arrival in its home port of Palma de Mallorca, Section 2. These initial tests were limited to system tests of the electronics, whilst alongside, and short duration inspections of current profiles whilst at sea in and around the bay of Palma at a variety of vessel speeds. The report then discusses the critical importance of high quality navigation and heading data in section 3, before introducing the calibration procedures for installation errors in section 4. Section 5 presents a collection of VM-ADCP data from two of R/V SOCIB's scientific research cruises indicating the world class data collection capability on board the vessel. The considerations of problems specific to small vessels are addressed in section 6, where the role of pitch and roll are specifically examined. In sections 8 and 9, real-time and delayed mode VM-ADCP data processing is discussed and SOCIB's routine operating procedures are presented. Finally, in section 9, the envisaged routes to dissemination for the SOCIB Data Centre Facility (DCF) are presented and discussed.

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1. Introduction to the principles of the vessel mounted ADCP

The Acoustic Doppler Current Profiler (ADCP) has become a commonplace instrument found on many oceanographic research platforms, from fixed moorings to large research vessels and even unmanned surface and sub-surface vehicles (**Figure 1**). The vessel mounted ADCP (VM-ADCP), is generally mounted in a recess in the hull of the vessel. The ADCP is designed to send a pulsed sound signal into the water column and derive information about the water current velocities by analysis of the return echoes from particles in suspension in the water column. Described simply, the VM-ADCP instrument generally has four transducer heads, arranged in a square formation, each looking downwards and diagonally outwards at a small angle from vertical (typically either 20° or 30°).

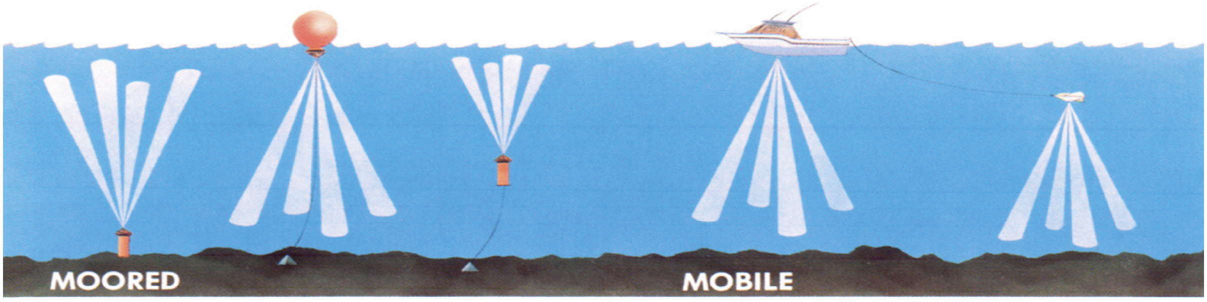

Figure 1: *Cartoon of typical deployments of the ADCP instrument, fixed on the left to mobile on the right*

Simultaneously the transducer heads emit a pulse of sound approximately every second (depending on water depth and user determined instrument settings). The return echoes are electronically range gated, according to an expected time of two-way travel, into a series of depth bins. For each bin the frequency of sound of the return signal at each transducer head is compared to the transmitted sound frequency. The apparent change in frequency between the transmitted pulse and the return echo is directly related to the speed at which the reflecting particles in the water are approaching the transducer head, by what is known as the Doppler effect. We are all familiar with the Doppler effect, for example recall the apparent change in note of a police car siren as the car approaches you and then goes past and away from you. By having four transducer heads pointing in different directions the speed of the particles in all three space dimensions can be calculated (i.e. magnitude and direction of the velocity vector). In principle only three transducer heads are necessary, but a fourth gives an estimate of the error in the calculated velocities.

Typically if a Teledyne RDI VM-ADCP instrument is fitted to a vessel, as it is on B/O SOCIB, then data is recorded, replayed and processed on board the survey vessel using the RDI developed software VmDas (**Figure 2**) and WinADCP (**Figure 3**). VmDas is RDI's data acquisition and playback software. Raw ADCP data or averaged data can be examined in tabular view, as a velocity profile or as a ship track plot. VmDas also enables the ADCP data to be replayed and reprocessed if required; allowing different averaging intervals, or coordinate transformations to a different heading source (provided this was supplied as a nmea input originally) or to a different fixed heading correction. WinADCP is RDI's real-time and post data collection visualisation software, it allows real time analysis and playback of data in the form of contour plotting, profile plotting, time series plotting, sub-sectioning, exporting of RDI ADCP data to ascii (.txt) files or matlab (.mat) files and some statistical calculations.

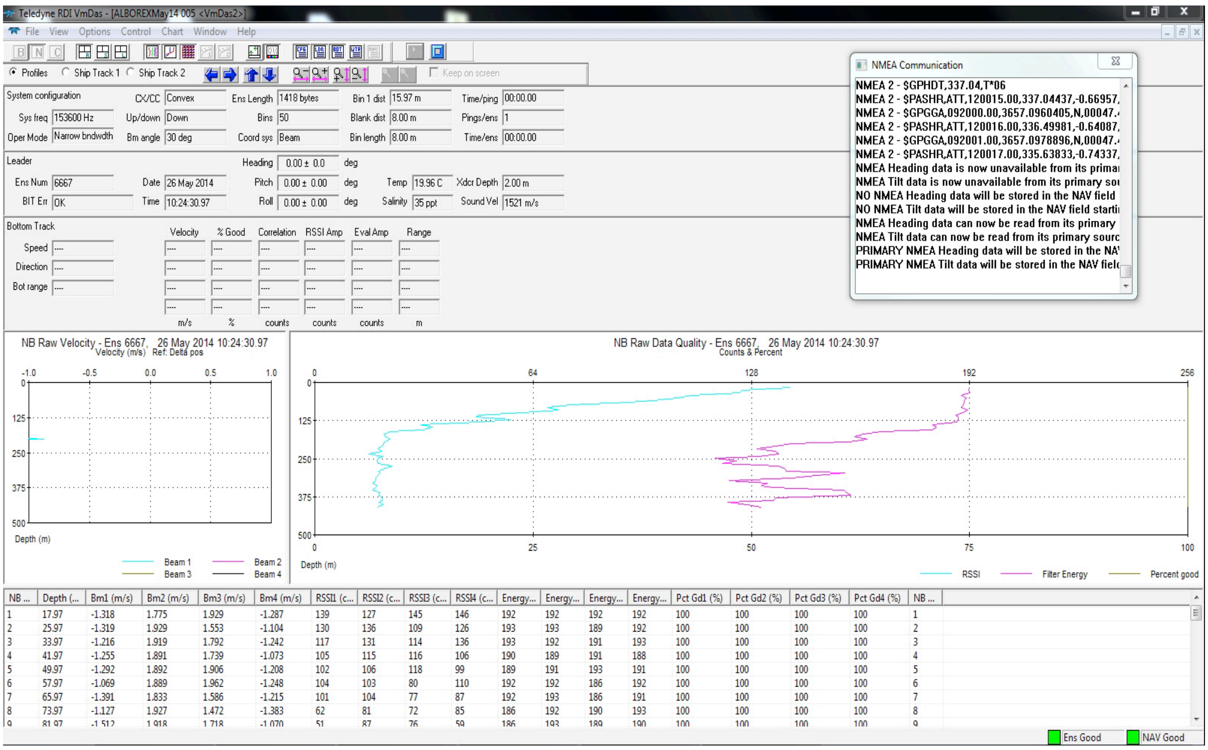

Figure 2: *A typical VmDas main screen*

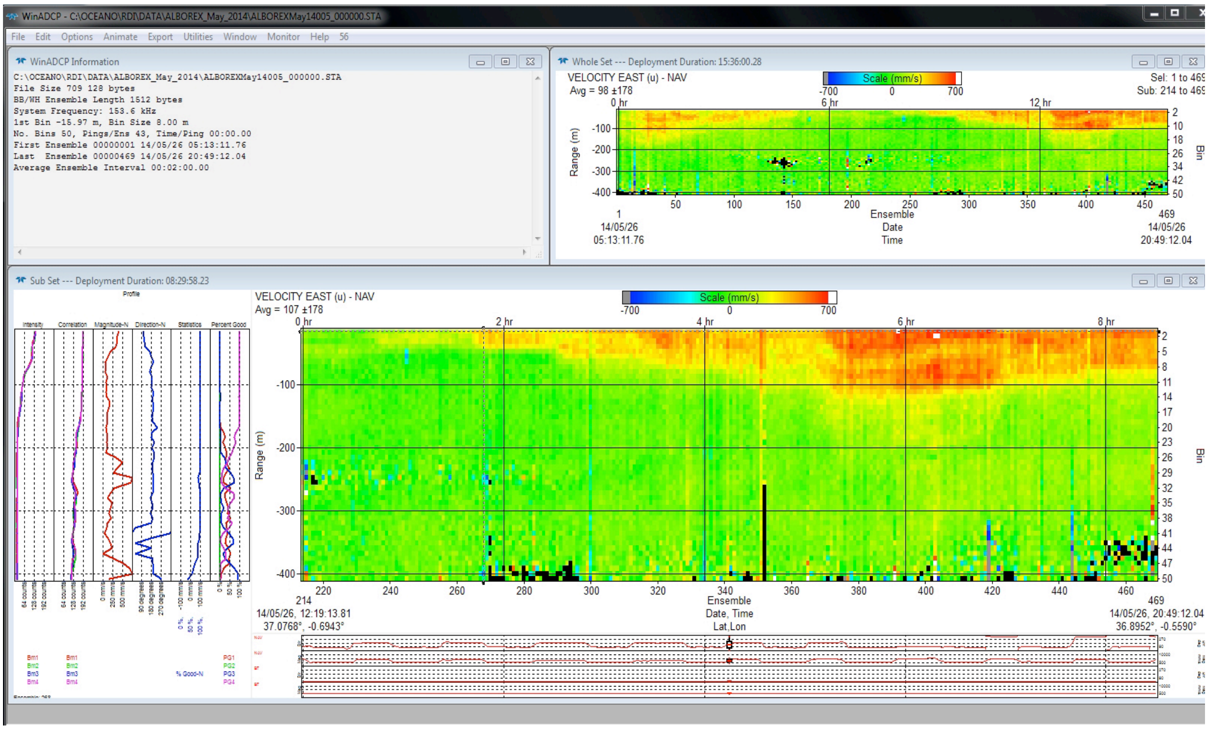

Figure 3: *A typical WinADCP main screen*

There are three principle sources of systematic error when attempting to derive ocean currents from a VM-ADCP instrument. The first is the knowledge of the vessel's velocity over the ground, the second is the error in the knowledge of the vessel's attitude, and the third is the error in the fixed components of relative attitude of the VM-ADCP to the attitude of the vessel. Typically a vessel's velocity through the water is between one and two orders of magnitude greater than the currents we are trying to measure and therefore these sources of error can easily dominate the signal.

Typical bridge GPS navigation instruments will have an accuracy of 1-2 metres or better, leading to a random error in the 1 Hz determination of the vessel's velocity of 1-2 ms^{-1} or better. Averaging the ping by ping VM-ADCP profiles to 2 minute and 10 minute ensemble average profiles reduces the positional ship velocity calculation errors by a factor of the square root of the number of pings in the ensemble. So we can expect to measure ocean currents to around 10 cm s^{-1} or better. To improve on this, a GPS navigation system incorporating the use of differential corrections is required, reducing the 1 Hz positional error to 10-20 cm or better and the error in the 2 minute or 10 minute vessel velocity to typically 1-3 cm s^{-1}. A suitable navigation system is now available on B/O SOCIB through a new 3D GPS system that will be discussed later (section 3).

As for the second of the sources of error, traditionally a ship's gyro-compass data stream is input to the VM-ADCP hardware for heading reference. Ship's gyros will 'wander' in a damped oscillatory manner following rapid changes in direction. Furthermore, gyros typically exhibit a sinusoidal heading dependent error of the order of a few degrees; so at a steaming speed of 5 m s^{-1} (~ 10 knots), these errors rotate the apparent vessel velocity and create a spurious few 10s of cm s^{-1} cross track velocity from the along track velocity component. These errors are well understood and can be corrected using high resolution 3D GPS systems but these are still only commonplace on the larger research vessels. 3D-GPS systems use ultra-short baseline multi-antenna signal phase shift techniques to map the position of a constellation of GPS satellites relative to the vessel. SOCIB is now equipped with the very latest 3D GPS instrument to accurately determine heading, pitch and roll; unlike early 3D-GPS systems, the data from this instrument show very little noise, and therefore the data can be used directly without the need to correct a gyro-compass, again this will be discussed later (section 3).

Correcting for the third source of systematic error, is a matter of calibration. The fixed components of attitude of the VM-ADCP relative to the attitude of the vessel are a function of the installation of the VM-ADCP transducer and electronics in the vessel. This calibration needs to be monitored regularly, and particularly after any replacement of the transducer head in the hull, or any major changes in the electrical/electronic systems on board the vessel. Again, calibration procedures will be discussed in detail later (sections 3 and 4).

2 Preliminary tests (SOCIB)

B/O SOCIB is a well equipped research vessel with a 150 kHz, RDI Ocean Surveyor, VM-ADCP transducer located in the port hull just forward of the accommodation bulkhead (http://www.socib.es/?seccion=observing Facilities&facility=vessel) in front of the fuel tanks at a depth of ~ 2 m. The RDI deck unit is mounted in the computer rack on the port "dry" side of the Laboratory. It is connected to PCLAB02 computer for VMDas control and WinADCP software. The deck unit currently has firmware upgrades to VMDas 23.17 and PCLAB02 runs TeleDyne RDI software VmDAS v1.46 (© 1998-2009).

Vessel speed / Sea state	Light	Heavy sea on the bow	Heavy Sea astern
0 knots	**> 500 m**	Not tested	Not tested
8 knots	**> 320 m**	**< 100 m**	**< 300 m**
12 knots	**< 250 m**	Not tested	Not tested
15 knots	**< 150 m**	Not tested	Not tested
16 knots	Not tested	Not tested	**> 100 m**
18 knots	Not tested	**< 50 m**	**~ 100 m**
20 knots	**< 120 m**	Not tested	Not tested

***Table 1**: The VM-ADCP acoustic ranges measured and/or inferred from the December 2012 trials on SOCIB.*

During her acceptance trials in Vigo, B/O SOCIB did not go into water deeper than around 120 m, and so it was only known that RDI considered the VM-ADCP data to be good to this depth. On the 19th and 20th of December 2012 we had an opportunity to spend some time in waters of up to 500 m depth outside the Bay of Palma. Our objective was to carry out speed versus potential data quality trials, and depth range trials. This was assessed by the real time examination of the percentage of good return echoes as recorded by VmDAS, RDI's ADCP instrument handling and data recording software. The results were limited to the acoustic performance reported by RDI's VM-

DAS software, but they were very encouraging. They suggested that SOCIB's VM-ADCP installation should function with a similar performance to installations on much bigger world class research vessels. Furthermore they suggested that it is likely that meaningful ocean current information may be obtained at much higher ship speeds than can be obtained by these larger world class research vessels; **table 1** summarises these early results.

Using an initialisation file setup for 4 metre depth bins, the short term average data showed the mean percent good falling below 25%, in a region between 160-250 m water depth and then recovering before falling off again below ~310 m. The consistent dropout region between ~ 160 and 250 m was associated with a drop in returned signal intensity. As we discussed in section 1, the ADCP relies on acoustic return signals from particles in the water column to determine the motion of the water; at 150 kHz, these particles need to be individuals greater than ~ 10 mm in length or dense populations of ~2-3 mm or larger through diffuse scattering. In the open ocean such particles are assumed to be predominantly small zooplankton. It is likely, therefore, that this drop in signal strength was a result of a lack of zooplankton in the water column at that depth. During daylight, most larger zooplankton will have migrated to depth, leaving only the smaller but more abundant zooplankton up near the surface.

Using an initialisation file modified for 8 metre bins, reduced the problem of the weak signal return layer above 250 m, but it did not remove the problem altogether, raw ping by ping echoes now typically dropping out between ~ 220-250 m. These results are typical of a lack of biological scattering particles. At this longer range (100 x 8 m bins) the drop out below ~ 310 m as described above, now returned with a strong signal nearer the bottom, ~ 525 m, indicating that the lack of signal below ~ 310 m might also have been a biological artifact rather than the limitation of the instrument or its position in the hull.

8 knots:

The VmDAS software showed very similar results to those found whilst on station, indeed there was some suggestion that there was greater range before the deeper dropout of signal, perhaps ~ 320 m, but this was most likely due to a change in the deep zooplankton layer thickness and position in the water column.

12 knots:

At this speed, the shallow drop out at ~170 m was still apparent and in the STA files there was no indication that data quality should be significantly deteriorated above this. However the return to good data below this absent zooplankton layer, at about 250 m, had disappeared clearly indicating that the acoustic range of the VM-ADCP at speeds of 12 knots or more is reduced to less than 250 m.

15 knots:

At 15 knots, the raw ping by ping data began to show dropouts in one beam or more as shallow as ~ 135 m. The STA files also indicated that the practical useful depth for velocity determination would now be reduced to ~ 150 m.

20 knots:

Remarkably, there was little apparent deterioration in the raw data signals from those at a speed of 15 knots. The STA files indicated that, at least acoustically, the practical useful depth for velocity determination was now reduced to perhaps 110 - 120 m.

On the 20th December, the weather was significantly more blustery with a strong wind from the south-west, force 5 or 6. Out into the bay of Palma, waves were 1-2 m which would be expected to build up a reasonable swell. This gave us an opportunity to examine the effect of rougher seas on the acoustic range of the VM-ADCP installation. SOCIB began with a steaming speed of ~15 knots. 15 knots, however, was not good with the period of the waves, so the master tried several speeds for a while and 18-19 knots was found to be more comfortable.

18 knots into a rough sea state:

The effective range of the STA files (25% good 4 beam returns) was ~ 50 m at most, and sensible velocity determination would not be expected over much of this; a significant reduction in useful range from the day before.

18 knots running with the rough sea astern:

B/O SOCIB runs very smoothly with the weather astern, but at this speed she was beating the waves and generating her own chop. Here, although much better than when running into the sea state, the STA files showed 60-70 % good 4 beam returns to bottom depth of 69 m. Slowing to 16 knots improved this to ~ 100 %.

8 knots into a rough sea state:

SOCIB slowed to ~ 8 knots and the effective range was clearly in excess of the bottom (~ 70 m water depth at this point) with the STA files showing around 50% good 4 beam returns, so in deeper water we could perhaps expect ~ 100 m range.

8 knots running with the rough sea astern:

The STA files showed a full 100% good 4 beam returns to bottom depth of ~ 70 m and every reason to suppose that in deeper waters we would get very similar ranges to fully calm conditions.

3 Navigation and attitude

In this section we look at the provision of 3D GPS heading data, and differential GPS positioning for R/V SOCIB; accurate knowledge of vessel position and attitude are essential to separate the measured water currents from the movement of the vessel.

3.1 3D-GPS and installation considerations

Accurate knowledge of ship's heading and velocity are a central requirement for current measurements using a VM-ADCP. This is because the velocity of the ship is normally at least one order of magnitude larger than the currents that you are trying to observe. Inherent errors in gyro-compass headings, typically 1° or greater, can result in spurious velocities in underway VM-ADCP data of many cm/s. Thankfully gyro-compass error is largely well understood and slowly varying, i.e. of the form

$$E_g = (\theta_{180} - \theta_0)|\cos\phi| + \theta_0 \ ,$$

where, θ_{180}, θ_0 and ϕ are the heading errors at 180° and 0° and the gyro heading respectively. There is also a latitude dependence, so the parameters of any error model will change during long north-south passages (several degrees).

3D-GPS systems provide a much more accurate measure of ship's heading and are used in preference to correct for gyro error. However, traditionally, 3D-GPS data was inherently noisy at raw 1 second resolution (e.g Ashtech ADU-2 and earlier systems) and therefore it was generally smoothed first to the ADCP enemble profile averaging period before use. The level of noise in more recent 3D-ADCP systems (e.g. Ashtech ADU-5) has reduced significantly, to the point that many departments and laboratories now use these data as the primary heading feed for their VM-ADCP data recording in VmDAS.

3D-GPS systems work on an 'Ultra-Short-Baseline' navigation principle; i.e. the phase differences between the signals received simultaneously by a number of antennas 'seeing' the same constellation of GPS satellites is used to determined the three dimensional orientation of the antennas to a fraction of a degree. Most current systems use 4 antennas to work out the orientation and altitude. However the new Trimble-Ashtech ADU800 system uses a 3 antenna setup by effectively assuming that the altitude is not required or is only slowly varying. This new method allows for greater accuracy in the determination of orientation through reduced uncertainty in the calculations. Having negotiated a favourable discount, a Trimble-Ashtech ADU800 system was ordered early in March 2013.

Just before and just after SOCIB's first science cruise in February 2013, some time was spent on the bridge top looking at possible sites for the ADU800 three antenna 3D-GPS system to be placed (**figure 4**). The bridge-top dimensions are ~ 4 m fore to aft and ~ 3.5 m port to starboard. A fore and aft mounting on the blue fairing on the starboard (port) side of the bridge-top for antennae #1 and #2 appeared to be the most obvious solution. Antenna #3 could then be placed approximately half way along the port (starboard) side blue fairing on bridge-top; this allows the ideal distances specified in the installation instructions which are the same perpendicular distance from the line of antennas #1 and #2 as the separation between #1 and #2.

***Figure 4**: Rear view of the bridge (top left), forward view of the bridge top (top right), and rearward view of the bridge top (bottom).*

The ADU800 system was delivered to SOCIB early in April 2013, and was fitted during July 2013, with antennae #1 and #2 on the starboard side and antennae #3 on the port side as described above (**figure 4**). The electronics unit was mounted in the computer racking on the bridge and the serial communications ports were fed into the serial multiplexer (MUX) to provide availability in the scientific laboratory. On the 30th July the system was setup and tested: this was not as simple as it should have been, because the new user manual still had a number of errors, the important lessons learnt were as follows:

1) The set up commands are $PASHS,ABX,10,2+0 or $PASHS,ABX,10,2+1 (the latter only if RTK position corrections are being input on COM port 2). The two versions of the manual had errors here.
2) The ADU800's calibration procedure, called with the command $PASHS,3DF,CLB, took a significant time, much longer than we had been led to believe. At the time no explanation was found for this, however following the fitment of antenna grounding plates, discussed later, the calibration procedure now only takes a few minutes. If the calibration takes a long time it is most probably due to poor or noisy signals being received by one or more of the antennas.
3) The calibration procedure and values can be checked with the command $PASHQ,PAR,3DF. We recommend this is done reasonably regularly, an early example is as follows in **table 2**:

```
$PASHQ,PAR,3DF
==============================+==================================
 3D ATTITUDE STATUS           |
------------------------------|
 SOLUTION STATUS              | FIXED
 CALIBRATION STATUS           | CALIBRATED
------------------------------+----------------------------------
 3D ATTITUDE SETTINGS         |
------------------------------|
 OPERATION MODE               | ON
 MAX TT UPDATE RATE [Hz]      | 10
 THE NUMBER OF LINES          | 2
 HEADING ANGLE OFFSET [deg]   | 0.00
 PITCH ANGLE OFFSET [deg]     | 0.00
 ROLL ANGLE OFFSET [deg]      | 0.00
----------- LINE-1 -----------|
 RTK ENGINE (RTK1-RTK3)       | RTK2
 XYZ COMPONENTS [m]           |
 CALIBRATED COMPONENTS [m]    | 0.000 3.613 0.006
------ RTK2 ARROW SETUP ------|
 DATA SOURCE                  | CALIBRATED
 BASE LINE LENGTH [m]         | 3.613 RMS:0.010
 INITIAL ELEVATION [DEG]      | 0
 MAX. ELEV. DEVIATION [DEG]   | 15
----------- LINE-2 -----------|
 RTK ENGINE (RTK1-RTK3)       | RTK3
 XYZ COMPONENTS [m]           |
 CALIBRATED COMPONENTS [m]    | -3.615 1.807 0.015
------ RTK3 ARROW SETUP ------|
 DATA SOURCE                  | CALIBRATED
 BASE LINE LENGTH [m]         | 4.041 RMS:0.010
 INITIAL ELEVATION [DEG]      | 0
 MAX. ELEV. DEVIATION [DEG]   | 15
==============================+==================================
```

***Table 2**: An example ADU800 setup calibration sheet.*

On the 31st of July, a morning sea trial was carried out off the bay of Palma to collect bottom track ADCP data referenced to gyro heading and referenced to ADU800 3D-GPS heading. These data were to enable a comparison, primarily by carrying out short bottom track calibrations as described in section 2.2. During this short sea trial it was noticed that the ADU800 instrument would occasionally stop putting a heading into the HDT message whilst still providing a perfectly good ATT message for significant periods of time (many minutes). On one of these occasions this caused the VM-ADCP to stop acquiring a heading reference altogether. We also noticed that the solution status in the calibration details (see above) read FLOAT instead of FIXED when the HDT value was absent. Trimble-Ashtech technical support were contacted and their response suggested that this was a multipath reception problem with one or more of the antennas. The obvious culprit was antenna #1 (**figure 5** left) which had an electronics unit next to it and partially over-shadowing. Over the next few weeks the antennas were swapped over such that antennae #1 and #2 were on the port side and antennae #3 is now the starboard side.

***Figure 5**: ADU800 Antenna 1 (left image), Antenna 2 (centre), and Antenna 3 (right)*

Frustratingly this did not solve the problem. As a result Trimble-Ashtech technical support were contacted again and it was suggested that I make a visit to their offices in Nantes, France in August 2013. This was a very productive visit and solved a number of problems on both sides. The standard proposed and subsequently purchased

Antennas were not an ideal design for mounting on a small vessel. Unless they are mounted on long, > 1 m, poles they are susceptible to multiple reflections from the deck below them. Other more expensive Antennas have built in metal grounding plates to avoid this problem. As a result, grounding plates were fabricated and fitted to our antenna layout by the autumn of 2013, as shown in **figure 6**. This modification cured all our problems with the ADU800 system and we have experienced very reliable near 100% 3D-GPS data coverage on all subsequent cruises to date.

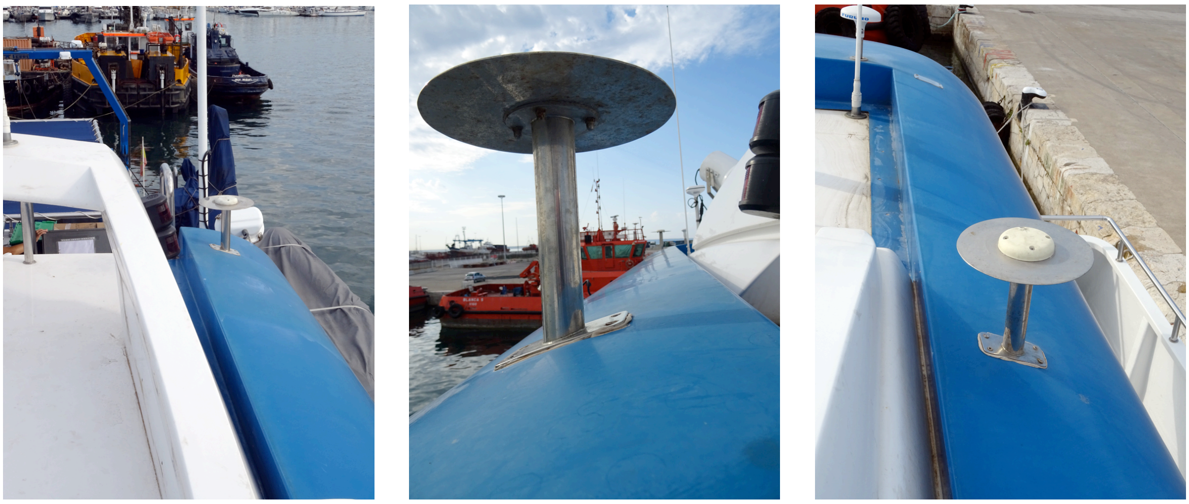

Figure 6*: Relocated and modified ADU800 antennas on B/O SOCIB, showing the fabricated grounding plates underneath the original antennas.*

3.2 Differential GPS data feed

Early discussions were held about the options for a differential corrections data feed for the Furuno GPS navigator and the new Ashtech ADU800 system. The conclusions were that SOCIB already has access to very high accuracy RTK (Real Time Kinematic correction - phase difference differential corrections) data for beach studies, and that it might be possible to make these data available to the SOCIB catamaran. In fact it turned out that the useful range for these RTK corrections from the base station is believed to be only some 10 nautical miles or so. However, the ADU800 system uses the regularly available DGPS corrections as a standard setup for its positioning of antenna #1. On the 30th and 31st of July the ADU800 position data were monitored, and recorded for significant periods of time. The data clearly showed that Ashtech's claim of DGPS positional accuracy to ± 25 cm is good; in fact for periods of a few minutes the accuracy appears to be considerably better, perhaps < ± 10 cm. This level of accuracy is more than sufficient to determine vessel speed to within a few cm s^{-1} over a 2 minute ensemble period, generally considered to be the target bearing in mind the VM-ADCP instrument accuracy limit of ~ 1 cm s^{-1}. The ADU800 is therefore the navigation feed that is now configured by the VmDAS ADCP acquisition software as default.

4 Calibration for instrument installation

Bottom track .STA files are examined for mis-alignment calibration checks. The ancillary navigation and bottom tracking data are saved as text files through WinADCP, file names of the form 'RadMedFeb130nnBTwinADCP.txt' where nn is the sequential number of the STA files as given in the previous diary of events. The text files are read into Excel and sections of the data copied and pasted into a prepared Excel VM-ADCP calibration spreadsheet. The sections of data pasted into the spreadsheets are chosen on the basis of relatively constant ship velocity and bottom depth.

The spreadsheet calculations follow the standard theory for VM-ADCP installation calibration from bottom track information (**figure 7**), which is as follows (Joyce, 1989; Pollard and Read, 1989).

AU_g and AV_g are the velocity components of the bottom past the VM-ADCP as measured by the VM-ADCP and U_s and V_s are the velocity components of the vessel from GPS navigation data. Now trigonometry tells us that

$$\frac{V_s}{U_s} = \tan(\alpha - \phi) = \frac{\sin(\alpha - \phi)}{\cos(\alpha - \phi)} = \frac{\sin\alpha\cos\phi - \cos\alpha\sin\phi}{\cos\alpha\cos\phi + \sin\alpha\sin\phi}$$

but, $\cos\alpha = \dfrac{U_g}{\sqrt{U_g^2 + V_g^2}}$, and $\sin\alpha = \dfrac{V_g}{\sqrt{U_g^2 + V_g^2}}$,

$$\therefore \quad \frac{V_s}{U_s} = \frac{V_g \cos\phi - U_g \sin\phi}{U_g \cos\phi + V_g \sin\phi}$$

cross multiply, divide through by $\cos\phi$ and rearrange to show that the misalignment angle ϕ is given by

$$\underline{\tan\phi = \frac{V_g U_s - U_g V_s}{V_g V_s + U_g U_s}}$$

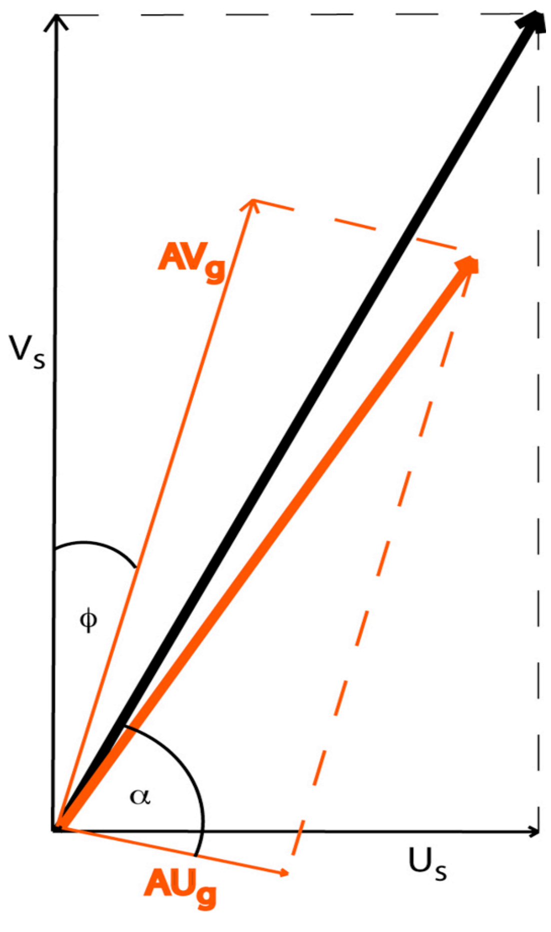

***Figure 7**: Vector diagram for deriving the calibration of a VM-ADCP for mis-alignment angle, ϕ, and amplitude factor, A.*

Now observe also that

$$U_s = AU_g \cos\phi + AV_g \sin\phi$$

and

$$V_s = AV_g \cos\phi - AU_g \sin\phi$$

$$\therefore \quad \tan\phi = \frac{V_g\left(AU_g \cos\phi + AV_g \sin\phi\right) - U_g\left(AV_g \cos\phi - AU_g \sin\phi\right)}{V_g V_s + U_g U_s}$$

which, after expanding, simplifying, dividing through by $\sin\phi$ and inverting both sides becomes:

$$A = \frac{\left(V_g V_s + U_g U_s\right)}{\left(U_g^2 + V_g^2\right)\cos\phi}$$

Following the successful installation of the ADU800 3D-GPS system on B/O SOCIB, bottom track calibration tests have been used to set the mis-alignment angle typically to -45.5 ° and the amplitude factor to 1.0080; although other values of amplitude factor in the range 1.0060-1.0120 have been considered appropriate on some cruises. Typical calibration test results with these offsets already applied are given in **Table 3**.

She-Bex May '15 Bottom track file No. / Calibration variable	Mis-alignment angle ϕ	Std. deviation ϕ	Amplitude factor A	Std. deviation A
15001	0.0135	± 0.1811	1.0003	± 0.0049
15003	0.0026	± 0.2914	1.0013	± 0.0030
15004	0.0005	± 0.2220	1.0012	± 0.0023
15006	0.0556	± 0.1687	1.0011	± 0.0040
15007	-0.0206	± 0.1904	0.9989	± 0.0067
15010	-0.1544	± 0.3513	1.0003	± 0.0034
15012	0.1514	± 0.1908	1.0000	± 0.0020
15013	-0.1683	± 0.1157	1.0009	± 0.0026

***Table 3**: Bottom track calibration results obtained during May 2015*

The calibration results in **Table 3** show that there is rarely any statistically significant suggestion that these offsets should be changed. However it is important to monitor these values by carrying out further calibration tests in bottom tracking mode at least two or three times during a scientific cruise.

5 SOCIB VM-ADCP data quality

In this section, VM-ADCP data are presented from two of B/O SOCIB cruises in order to demonstrate the development stages of the VM-ADCP capability. At each stage the quality of VM-ADCP derived current data is discussed, culminating in the presentation of the world class capability now available on B/O SOCIB.

SOCIB Medess (2-4 December 2013)

At the beginning of the SOCIB Medess (RadMed) cruise 2-4 December 2013, the VM-ADCP configuration file RadMedDec13_LoResBT8m.txt was used with the following configurations set:

Transducer depth = 2 m
Blank beyond Transmit = 8 m (As determined in the acceptance trials)
Number of bins = 50
Bin Thickness = 8 m
LoRes - long range (narrowband) mode
Bottom tracking = on
Maximum bottom track distance = 400 m
Ping as fast as possible

EA Heading alignment set to -44.42 as had been determined in the RDI calibration specified in the acceptance trial notes the previous year, before the ADU800 installation.

STA files = 120 second ensembles
LTA files = 600 second ensembles

The northern, leg 1, Medess line of CTDs was completed across the Ibiza Channel during the afternoon and evening of the 2/12/13, before we turned around off the coast of the Spanish mainland to repeat the line overnight in a continuous VM-ADCP only mode at ~ 10 knots. The weather was rough, force 5-6 and with 2 metre plus swell waves, but we were still achieving ~250 m of depth penetration with the VM-ADCP whilst steaming. Both sections across the Ibiza Channel showed a strong southward flowing northern current just off the Spanish shelf edge and a general northward surface flow on the Ibiza side of the channel. However there was a strong suggestion that the two sections had a residual offset due to a remnant calibration issue (**Figure 8**); this resulted in an apparently much weaker southward flowing northern current on the overnight return leg (ensemble 340 onwards).

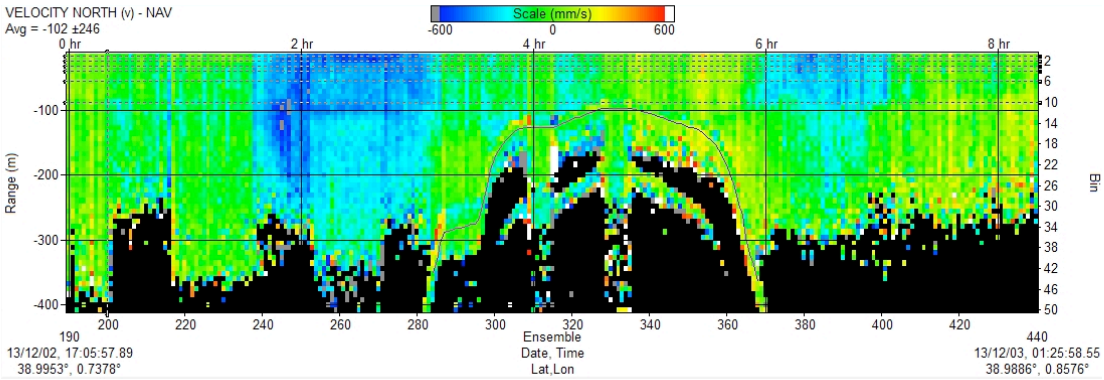

Figure 8: *WinADCP contoured section for the T1 leg repeat run east-west-east across the Ibiza Channel. The north velocity component is shown relative to Ashtech ADU800 navigation, heading, pitch and roll. A residual calibration offset is clearly visible of up to around 10 cms^{-1} to port of the vessel direction.*

Calibration calculations suggested adding a further ~ -1.08 degrees to the heading offset. The cofiguration file was modified, with the following heading offset change in its configuration:

Transducer depth = 2 m

Blank beyond Transmit = 8 m (As determined in the acceptance trials)

Number of bins = 50

Bin Thickness = 8 m

LoRes

long range (narrowband) mode

Bottom tracking = on

Maximum bottom track distance = 400 m

Ping as fast as possible

EA Heading alignment set to -45.50

STA files = 120 second ensembles

LTA files = 600 second ensembles

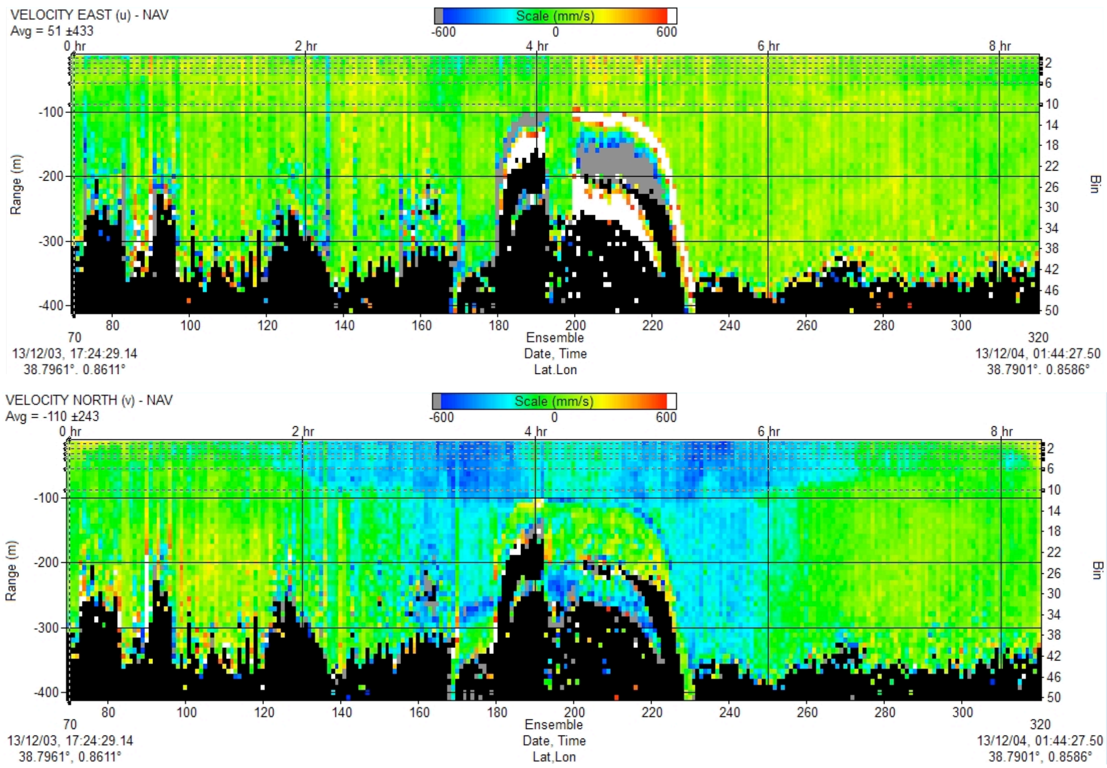

Figure 9: *WinADCP contoured sections for the T3 leg repeat run east-west-east across the Ibiza Channel. Velocity component east (top) and velocity component North (bottom) relative to Ashtech ADU800 navigation, heading, pitch and roll, are contoured.*

Medess leg 3 was carried out with this new misalignment angle and was repeated overnight in a west-east direction in a continuous VM-ADCP only mode at ~ 6 knots as the swell was still substantial and we were heading largely into it. The calibration angle of -45.5 had removed any offset in north-south component velocities from the repeat track (**Figure 9**). There was still a suggestion of a difference in the small east-west velocity component between tracks, but this probably resulted from the lack of an amplitude factor correction applied in VMDas.

Figure 9 provides a very clear indication of the high quality VM-ADCP data obtainable from SOCIB; despite a poor sea-state and very different steaming speeds, there is a remarkable line of symmetry centred on the turn-around over the Spanish mainland continental shelf.

SOCIB PERSEUS Alborex (24 May - 1 June 2014)

During the PERSEUS Alborex cruise between the 24th May and 1st June 2014, the VM-ADCP configuration file was setup with the following configuration:

Transducer depth = 2 m

Blank beyond Transmit = 8 m (As determined in the acceptance trials)

Number of bins = 50

Bin Thickness = 8 m

LoRes

long range (narrowband) mode

Bottom tracking = off

Ping as fast as possible

EA Heading alignment set to -45.50.

STA files = 120 second ensembles

LTA files = 600 second ensembles

Velocity Scale factors set to 1.0060 (determined from previous cruise calibrations)

The mis-alignment angle correction, known as the velocity scale factor in RDI's configuration files, can only be set by editing the configuration file in a text editor. The application of mis-alignment angle and amplitude factor in the VM-DAS software are described and demonstrated in detail in the SOCIB VM-ADCP standard operating procedures.

With the cruise's 1st CTD survey more than half completed, an overnight VM-ADCP box survey over the eastern and south-eastern side of the CTD survey area was carried out. This survey showed the strongest eastern currents associated with an anticyclonic Algerian current eddy were just south of the centre of the survey region; with core velocities of > 1 m s^{-1} (~ 2 knots). This current turned largely southwards, south of the eastern extremity of the CTD survey area (**Figure 10**). Outside of the region of strong currents we can see that the heading alignment and amplitude scale factor used result in the recording of background VM-ADCP derived currents of no more than a few cm s^{-1} regardless of vessel course.

Later bottom track data collected into and out of Cartagena, were examined for calibration values. Derived ϕ (misalignment angle) and A (scaling factor) were as follows:

ϕ (misalignment angle)	A (scaling factor)
-0.1607 ± 0.1508	1.0023 ± 0.0020
-0.1416 ± 0.7463	1.0007 ± 0.0067

These suggested increasing the scaling factor to 1.0070 or even 1.0080, but with significant uncertainty. The derived mis-alignment angle suggested that we should slightly increase the rotational heading offset magnitude from -45.50 °, however again with considerable uncertainty; so no further correction was applied to either the scaling or the misalignment angle.

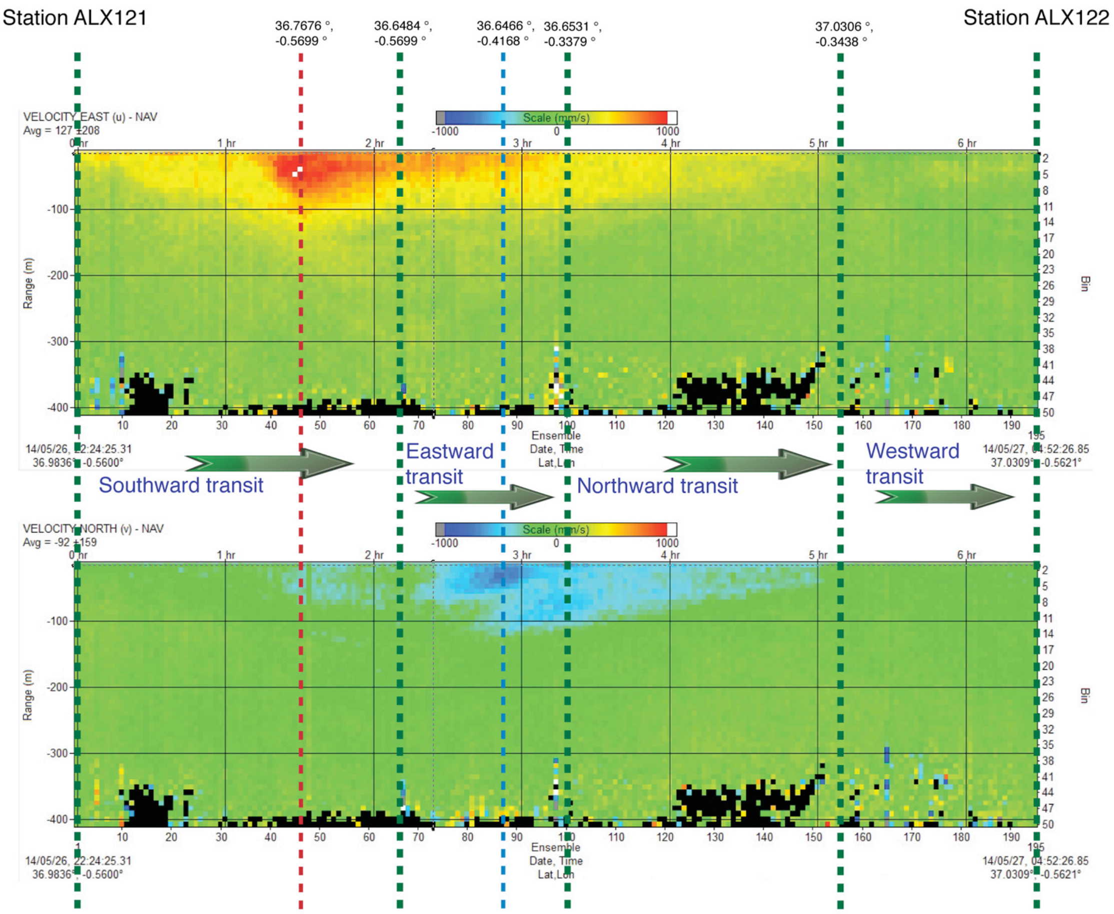

Figure 10: *East component (top) and north component (bottom) of the VM-ADCP velocity profiles contoured for the overnight box survey ALBOREXMay14006_000000.STA. Green dotted lines are the start, stop and turning points of the survey. The red and blue dotted lines give the points of core maximum east and south currents, showing the curvature of the current jet from eastwards to south-eastwards.*

The assumed salinity for sound speed range determination does not appear in the .txt configuration files and therefore it does not seem possible to apply both an amplitude factor and a more realistic Mediterranean surface salinity than the VM-DAS default 35.000 ppt, if an amplitude factor correction is made. This salinity value along with temperature measured by the transducer head, is used to calculate a sound speed value to make the range gated bin depth and bin thickness calculations. The effect is small, but nonetheless in this region of the Mediterranean a setting of 37 or even 38 might be considered more appropriate in the top 400 m of the water column. However, we should consider that as a general guide, sound speed increases by ~ 1.4 m s^{-1} for every 1 psu increase in salinity and ~ 4 m s^{-1} for every 1 °C increase in temperature.

Therefore a low input salinity value will reduce the assumed sound speed value and help to balance out the 2-3 degree decrease in temperature with depth that the transducer measured temperature cannot account for; in summer this temperature gradient is stronger still with the development of a strong seasonal thermocline.

In the future we will try to work with Teledyne RDI to put the mis-alignment angle correction back into the VM-DAS GUI. It was possible to make this correction in the earliest versions of VM-DAS, but it was removed because too many operators were using it incorrectly; failing to note that it would be a number very close to one, typically less than 1% different from 1.000.

6 Small vessel considerations

Small vessels (< 50 m in length) are rarely equipped with VM-ADCPs. The reasons for this fall into two categories, firstly the practical limitations in vessel complement, and secondly the technical or sea-keeping characteristics of smaller vessels. In the first case, traditionally VM-ADCP operation and data processing on a research vessel has been the task of one or more physicists and has required dedicated expert knowledge or training. On a small vessel, berth space is much more limited, for example on B/O SOCIB there are 16 berths in total for scientists, technicians and crew, and many small research vessels have to cope with a considerably smaller complement. Hence there is a requirement on small vessels for a more routine non-expert operation of the VM-ADCP instrument . Later we describe the routine operating procedures that have been developed and adopted on board B/O SOCIB, these enable world standard VM-ADCP data acquisition by non-expert members of the vessel complement.

The technical or sea-keeping considerations on a small vessel relate to the way in which even moderate sea-states can have a large impact on vessel attitude. Kosro (1985), in his PhD thesis, examined the effect of the real-time correction for independent measure of heading, pitch and error. These corrections to earth coordinates have to be applied on an individual profile by profile basis before any ensemble averaging because the vessel attitude is constantly changing; and may not even have a non-zero average. 30 years later, it is now much simpler to carry out such correction with the availability of accurate GPS, and highly accurate 3D GPS systems. Kosro, and others in the intervening years, found that, on a well designed large ocean going research ship, the error induced by not correcting for pitch and roll, by having a full 3D attitude data feed into the VM-ADCP deck unit, was typically less than ~ 1 cm s^{-1}; and depth penetration problems due to poor return echoes in increasingly rough sea-states were a more dominant problem in high seas.

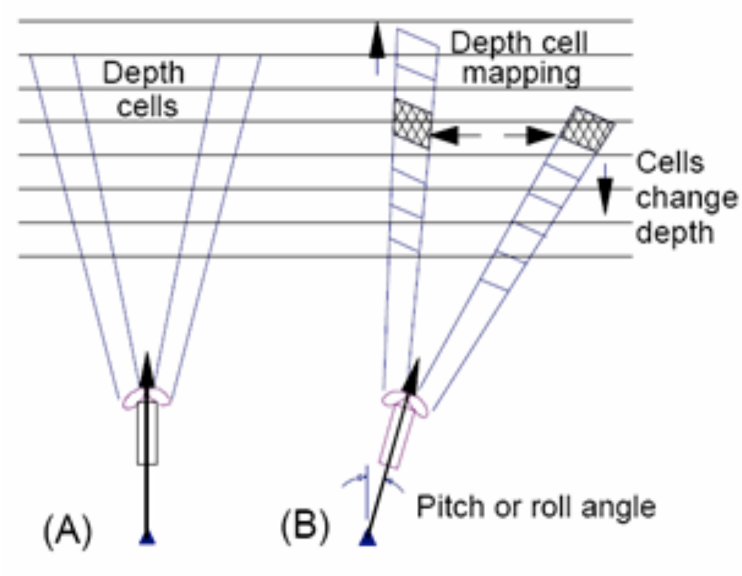

Figure 11: *Simplified diagram showing the effect of significant pitch and roll angles on effective ADCP bin depths; in this case a moored upward looking ADCP.*

However, on smaller platforms, such as coastal research vessels and in future, perhaps unmanned surface vehicles, vehicle attitude can be significantly more severe even in light to moderate states. In addition to the problem of correctly assigning measured water velocities into their constituent components, u, v and w, significant pitch and roll changes the relative depth of the range gated acoustic bins of the four transducer beams (**Figure 11**).

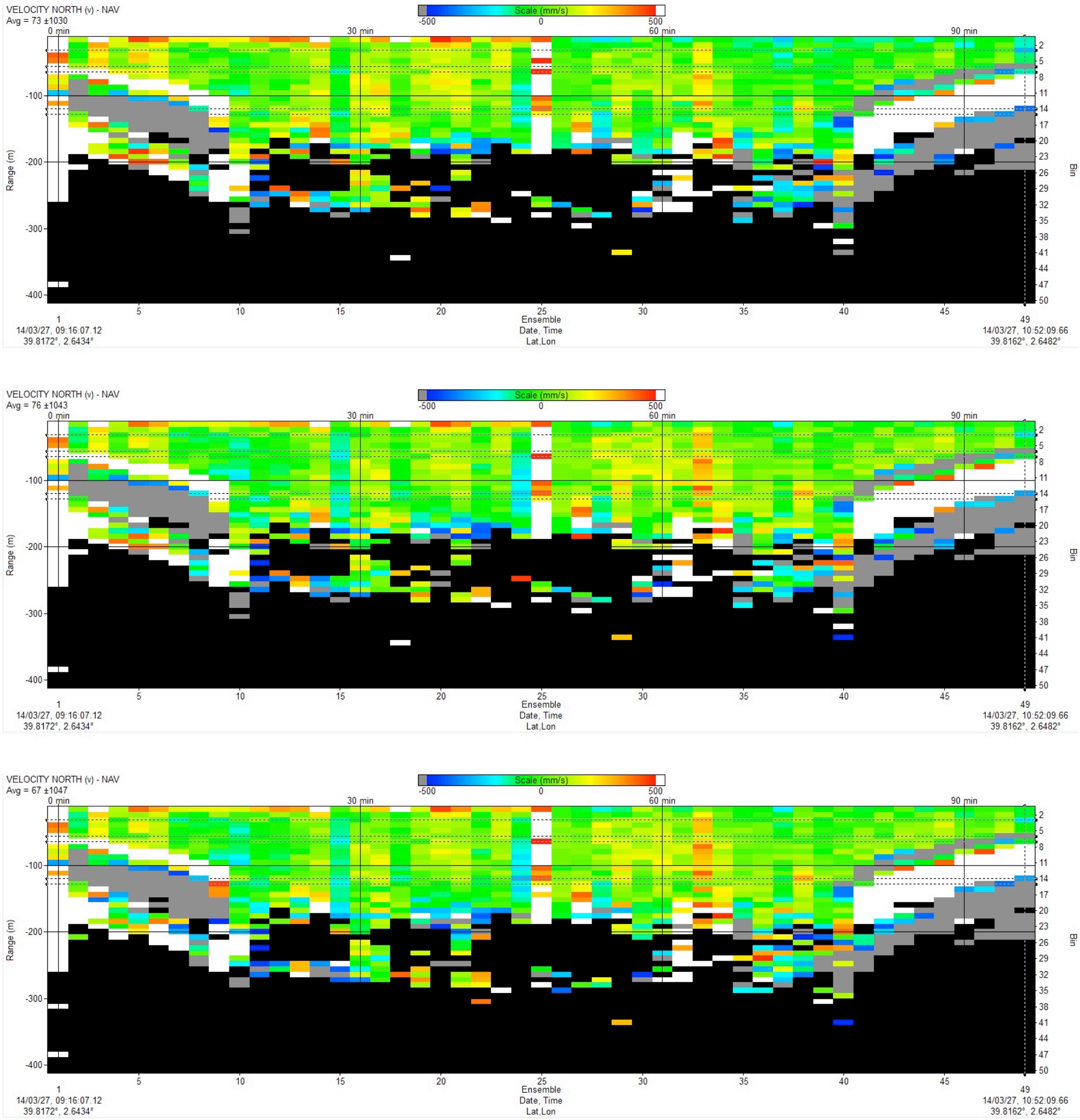

Figure 12: *A return section, displaying northward component velocities, out from and returning to Puerto Söller of approximately 45 minutes duration in each direction: with heading offset and real-time heading correction, but no amplitude correction (top), with heading offset and correction, and amplitude correction (middle) and, with heading offset, real-time roll, pitch and heading correction, and amplitude correction (bottom).*

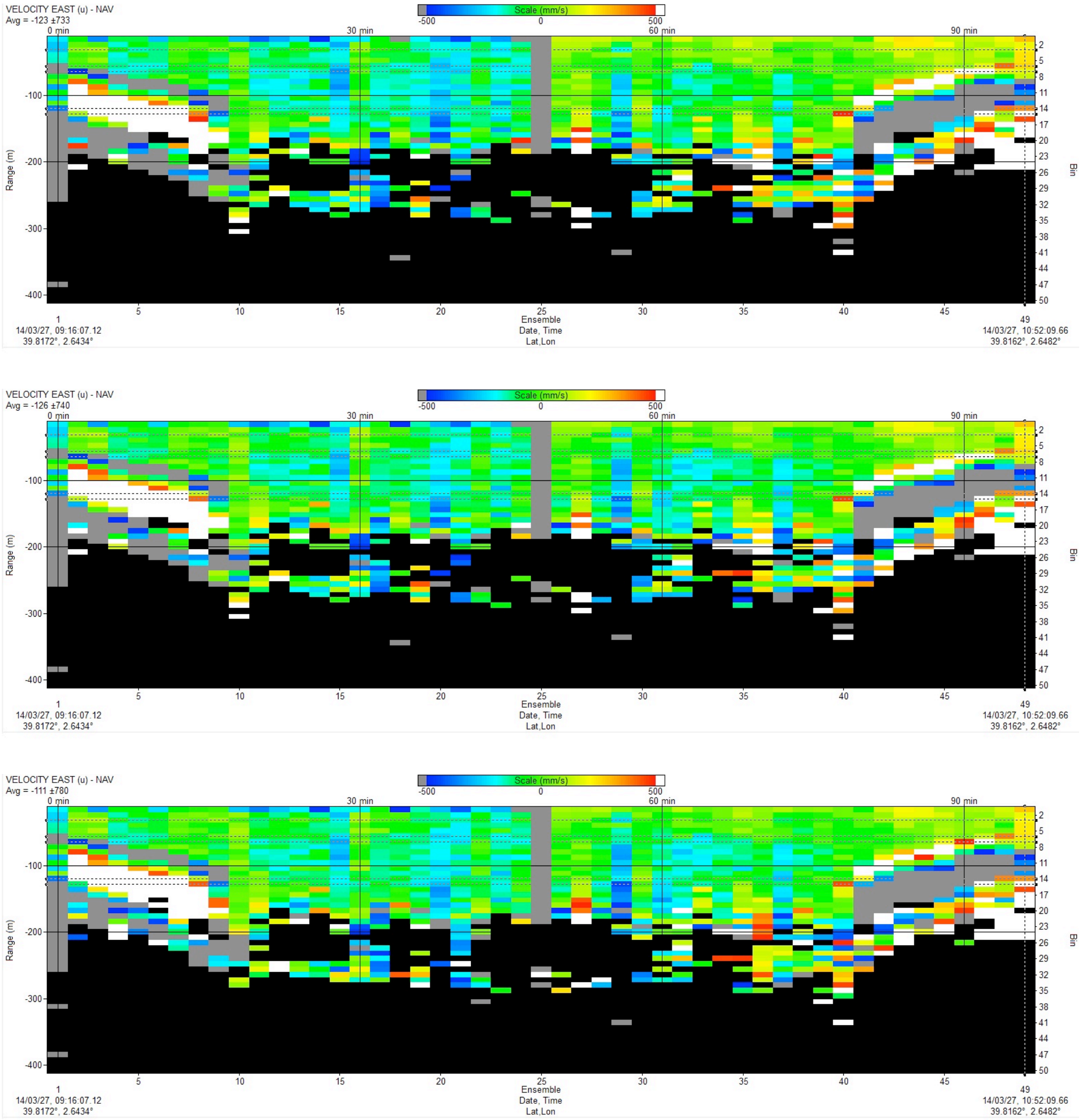

Figure 13: *A return section, displaying eastward component velocities, out from and returning to Puerto Söller of approximately 45 minutes duration in each direction: with heading offset and real-time heading correction, but no amplitude correction (top), with heading offset and correction, and amplitude correction (middle) and, with heading offset, real-time roll, pitch and heading correction, and amplitude correction (bottom).*

Of course it is very difficult to find a demonstration of definitive improvement in using a full roll, pitch, heading correction from a modern 3D-GPS system as fitted to B/O SOCIB and discussed in section 4; however, in **Figure 12** (north component velocities) and **Figure 13** (east component velocities) we show a number of repeat sections in moderately poor weather conditions, out from and returning to Puerto Soller on the west coast of Mallorca. In this case, the heading correction, phi = -45.5°, and the amplitude correction when applied, A = 1.0120 (see section 5 for a full description of these calibration terms). Inspecting the figures very closely it is possible to see that the application of a calibration amplitude factor reduces the otherwise apparent differences between derived current components when travelling in opposite directions, even in this dataset recorded in a poor sea-state. It is more difficult, but still just possible, to also see how the correction to full roll, pitch and heading information from the 3D-GPS system continues to reduce the differences between derived current components when travelling in opposite directions., on a small coastal vessel like B/O SOCIB.

7 Routine operating procedures

In this section the VM-ADCP processing and analysis steps are presented and described. These are broken down into two sub-sections representing the raw data handling and operational near real-time data presentation and data processing.

Routine VM-ADCP data processing takes the following 5 steps (sometimes these are combined into just 4 steps):

Step 1: Initial data read. The respective RDI binary file, normally either the .STA or .LTA ensemble averaged file, but occasionally a user may wish to read the raw individual pings .ENX file, must be read into the users preferred data format. The resulting data matrix or matrices need to recognise that there are both two dimensional water track profile data and one dimensional navigation and bottom track data.

Step 2: Replace velocity 'data' with an absent value or flag if variable "2+bmbad" is greater than 25% (% of pings where >1 beam return echo is bad and therefore no velocity computed). Align ensemble time with spot navigation data and heading data.

Step 3: Merge the VM-ADCP data with a 3D-GPS correction. This involves converting adcp component velocities to speed and direction so that the heading correction can be applied as a vector rotation, then converting speed and direction back to east and north component velocities.

Step 4: Apply the calibration misalignment angle, ø, and scaling factor, A. This should be checked on every science cruise, as discussed in section 4, if at all possible.

Step 5: Subtract the vessel velocity from the adcp data. Vessel velocity should be calculated from spot positions at the beginning and end of each adcp profile ensemble period. The end product is the absolute velocity of the water.

7.1 Raw data processing

On the R/V SOCIB catamaran, a "Quick Guide" to typical real-time routine operating procedures (ROP) are provided as follows:

ROP 1: The VM-ADCP is controlled from PCLAB02. First make a new data directory under 'c:OCEANO/RDI', for example 'c:OCEANO/RDI/SocibRadMedMarch2013/'. This is where the VmDAS software will be pointed to write the collected data files.

ROP 2: Locate the water track and bottom track initialisation files, in directory 'c:OCEANO/RDI/OS150 Khz Configuration files'. These initialisation files should be preset to :-

Transducer depth = 2 m
Blank beyond Transmit = 8 m (As determined in the acceptance trials)
Number of bins = 50
Bin Thickness = 8 m
Lo-Res long range (narrowband) mode

Bottom tracking = on (Bottom tracking = off in water track file)
Maximum bottom track distance = 400 m (N/A in water track file)
Ping as fast as possible

EA Heading alignment set to -45.5 as had been determined on cruises during 2013/14/15.

Velocity Scale Factor set to 1.0080 as had been determined on cruises during 2014/15.

STA files = 120 second ensembles
LTA files = 600 second ensembles

ROP 3: There is no requirement for bottom track recording of data at every opportunity, but once a day or 2 or 3 times during the cruise over long flat < 200 m continental shelves (in this region of the Mediterranean ~100 m is more likely) would be desirable.

ROP 4: The VM-ADCP deck unit is in the computer racking on the 'dry' port side of the laboratory. The VM-ADCP is turned on by flipping the white switch on the left hand side of the RDI deck unit.

ROP 5: On PCLAB02, the VmDAS software should be started by clicking on the screen icon. Select 'collect data' under the 'File' menu item. 'Load' the required initialisation file (see **SOP 2**). 'Edit data options' operates on the initialisation settings, change the 'recording' options, choosing a file name format and browsing for the new data directory that you have setup under **SOP 1**. Make sure the sequential file number is either 1 for the first file in a cruise or the next sequential number if restarting data recording manually. Note, if you have not changed the initialisation file and are simply restarting recording this sequential number will have automatically updated by 1. To begin data recording close the edit windows, save a copy of the initialisation if wished, then under 'control' choose 'go'. Choosing 'stop' under the 'control' option will stop data recording and choosing 'go' again will restart data recording with the sequential file number incremented by 1.

ROP 6: Real-time WinADCP visualisation can be achieved by clicking on the WinADCP icon, selecting the currently recording file ending with .STA, .LTA, or .ENX, and selecting 'monitor'. If this is required I would suggest using a monitoring time interval of 120 seconds rather than the default 5 seconds.

ROP 7: When not in 'monitor' mode, WinADCP ancillary data output in ascii format can be selected to produce a .txt file of navigation, bottom track and bottom depth data. Selected bottom track data can then be entered into the attached example excel calibration spreadsheet, and the VM-ADCP calibration parameters can then be checked.

There is also a full guide to eight standard operating procedures (SOP). Here a number of the quick guide routine procedures are amalgamated into a single operating procedure that is discussed in detail with accompanying figures. Diagnostic tests, calibration procedures and visualisation are discussed in detail in further standard operating procedures.

7.2 Operational / near real-time data presentation

Ideally, a number of general further steps should be carried out before the real-time data from VmDAS/WinADCP are disseminated widely, these are given below:

NRStep 1: By default RDI ADCP current velocities are reported in mm s^{-1}, by convention for ocean currents these should be scaled to cm s^{-1} or to m s^{-1} if strict SI rules are to be followed, whilst doing so it is worth multiplying the backscatter amplitudes by 0.45 to convert to a nominal db value.

NRStep 2: RDI's VmDAS software records the difference between PC time and the GPS navigation time. If the PC is not connected to a time server, then the time variable should be corrected to GPS time by combining the PC clock time and the PC-GPS offset.

NRStep 3: Depending on how the ADCP has been setup, it may be necessary to add an offset depth for the depth bins. The first bin depth is calculated as follows, the depth of the transducer in the ship's hull (~2 m in SOCIB) plus the blank beyond transmit distance (8 m) plus half the bin thickness chosen in the instrument setup.

NRStep 4: In most scientific cruise situations there will be a mixture of VM-ADCP data collected whilst steaming and data collected whilst stationary carrying out other observations, for example making a CTD cast. Generally it will be necessary to examine these two modes of data collection separately and in different manners. To obtain a rapid current velocity section, averaging profiles in distance travelled, typically 4-5 km averages, will give the appearance of removing the on-station data and allow a geographically referenced presentation of the data to be made.

8 Advanced analysis and presentation

VM-ADCP data have been used to determine many features of ocean circulation and these data both support and provide the focus for leading edge papers in all oceanographic journals. The list of derived knowledge from delayed mode VM-ADCP analysis continues to grow. Here we suggest some routine delayed mode processing and presentation steps which can be carried out by an expert data centre such as SOCIB's DCF and which help to promote the exploitation of VM-ADCP data.

DMStep 1: Removing data spikes and anomalies. Two types of spike or anomaly typically exist, the first is simply an erroneously large apparent current vector at one depth in a profile. This is caused usually by a large acoustic scatterer swimming through a beam, but it could be indicative of some acoustic interference if it happens with any sort of regularity. If large, these spikes can be removed by setting maximum velocity tolerances, otherwise only manual editing will remove them. The second type of spike affects a whole profile and is due to very rapid changes in speed and direction of the vessel, some examples can be seen in the data sections presented earlier when stopping for a CTD station or accelerating off a CTD station. Again, if large they can be caught by setting maximum velocity tolerances but otherwise manual editing is necessary.

DMStep 2*:* Plotting vectors, both maps and profiles. Very often, the most influential way to present and view VM-ADCP data is in the form of vector plots. If the VM-ADCP data have been collected during a spatial survey, or repeated sections, it is often instructive to present data in the form of a horizontal vector map at some chosen depth levels. Software tools have been developed at SOCIB using Matlab (drive.google.com/OCEANOGRAPHY/SHIP/PHYSICAL/ADCP/Codes (Matlab)), and some examples are shown in **figure 14.** Alternatively, vectors can be presented in the form of depth sections replacing the need for separate east and north component velocity contours. In this case the vector direction on the page is pre-defined to indicate 2 dimensional direction of flow; for example in an east-west section an upward component to the vector direction might typically be defined as representing the northward component of velocity and vice versa. Software is still under development at SOCIB for this, however an historic example of this type of presentation is shown in **figure 15**.

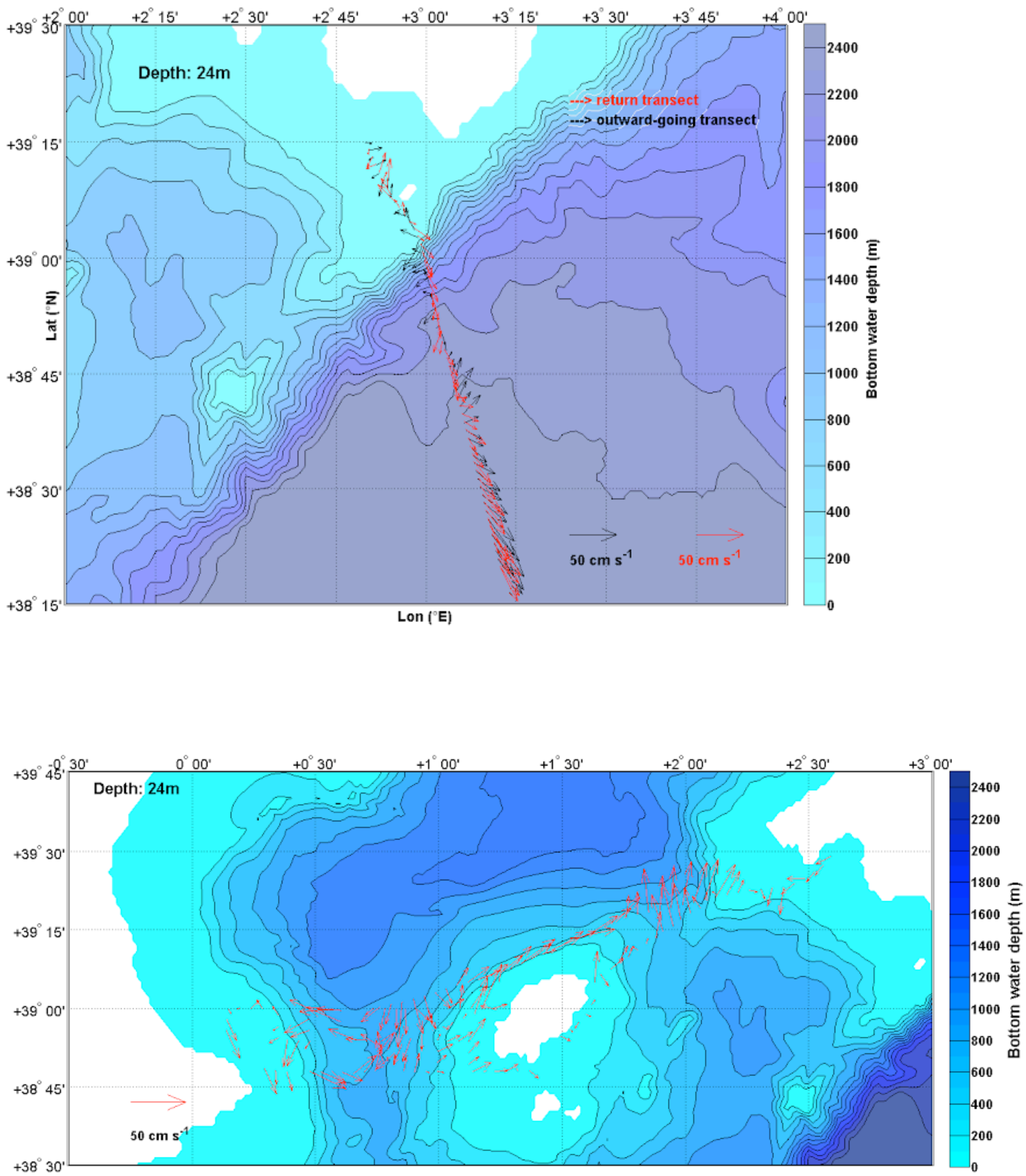

Figure 14*: VM-ADCP velocity vectors at 24m bin depth, using SOCIB Matlab tools. Repeated transects south of Mallorca (top), and a survey of the Ibiza and Mallorca channels (bottom).*

DMStep 3: Overlaying bottom depth. In shallow water it will be desirable to overplot bathymetry from the echosounder data in order to cut off the spurious current velocities apparent in VM-ADCP data associated with the signal returned from the bottom topography, sometimes this will also require some manual editing of the last bin above the bottom depth. This can also be carried out using the VM-ADCP determined bottom depth in RDI's WinADCP software, however in poor weather or for some bottom types, a scientific precision echo-sounder may be more reliable.

DMStep 4: Removing tidal velocities. Several numerical model based or satellite based model tides exist and are freely available academically. In addition, harmonic tidal analyses with spatially variable phase and amplitude can be carried out on a sufficiently long VM-ADCP survey dataset (Allen, 1995).

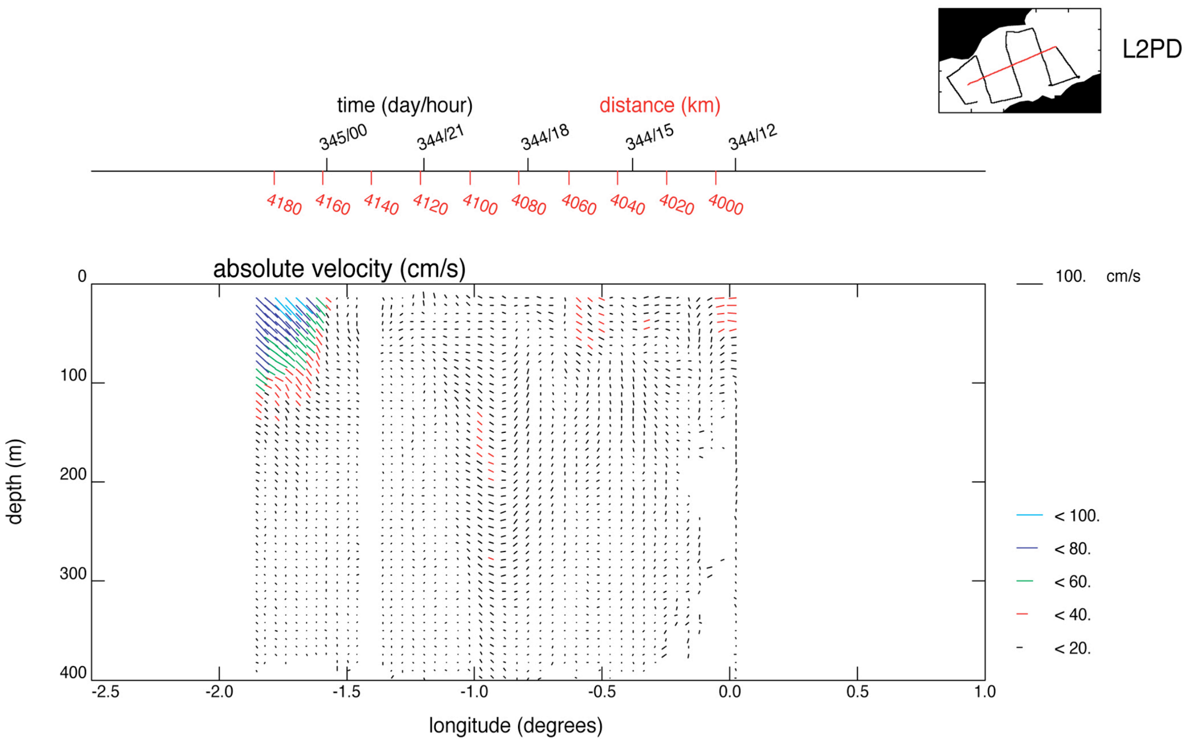

***Figure 15**: An historic example of VM-ADCP velocity vector profiles in a single vertical section. This example was created using Pstar and the data are from the OMEGA2 cruise in December 1996*

9 Near real-time access and dissemination

There is a requirement for the technicians on board R/V SOCIB to send data to the SOCIB Data Centre Facility (DCF) for dissemination on the SOCIB web pages and data repository in near real-time. Here we look at the policy and procedure for doing this in a routine manner. This does not preclude those experimental cruises where VM-ADCP data are central to the research requirements and where on-board highly processed data sets maybe sent to the DCF in real time, but here we consider the minimum analysis and data processing that should be provided during routine scientific work and passage legs.

If the R/V SOCIB technicians follow the Standard Operating Procedures in section 2.4.1 then the outputs that can be sent to the DCF follow:

From **SOP 1:** A cruise related data directory under 'c:OCEANO/RDI' is where the VmDAS software will be pointed to write the collected data files. This can be monitored by the DCF via a remote desktop login to PCLAB02.

From **SOP 2:** The cruise related water track and bottom track initialisation files will be located in the directory 'c:OCEANO/RDI/OS150 Khz Configuration files'. These files should be sent to the DCF with the data files, they provide an important component of the metadata.

From **SOPs 3** and **7:** Bottom track data over long flat < 200 m continental shelves should be used to check misalignment angle and amplitude factor calibrations as discussed in section 4. Ideally these calibrations should be carried out on board and the corrections can be applied through VmDAS. If the technical team are too busy and it becomes apparent that the previous calibrations leave a spurious velocity in the vessel's direction of travel then re-calibration can be applied later at the DCF, but this would significantly delay the dissemination of VM-ADCP data.

From **SOP 5:** A log book should be kept of the VM-ADCP files and the point of file cycling, i.e. where the data collection is started 'go' and 'stop'ped. Section 2.1 gives an example of such a log book. The .STA or .LTA files for each data recording interval should be sent to the DCF as soon as possible or batched up for sending when the preferred wireless communications system (often GSM) is next available. These are then available at the DCF for near real-time processing (section 2.4.2), re-calibration if required, and heading correction to 3D-GPS if required, before archiving and dissemination.

From **SOP 6:** Real-time WinADCP visualisation can be broadcast by the DCF using the remote login to PCLAB02. As standard I would recommend current amplitude and direction relative to bottom track data is displayed if in shallow water (<250 m) and relative to navigation when in deeper water.

References:

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Pollard R. and J. Read (1989) A method for calibrating shipmounted Acoustic Doppler Profilers and the limitations of gyro compasses, J. Atmos. Oceanic Technol., 6, 859-865.