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HF Radar Measurements of Surface Currents in Southern Port Phillip Bay

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EXECUTIVE SUMMARY

This report describes the surface current data set for southern Port Phillip Bay taken using the COSRAD high frequency radar. This work was commissioned as part of the Port Phillip Bay Environmental Study program and undertaken by the Physics Department of James Cook University. Measurements were taken in two phases over a period of about two weeks between 27 April 1994 and 12 May 1994. In the first phase the region north of the Great Sands Region was studied, while in the second phase the region from north of the heads and over the major part of the Great Sands Region was studied.

During the scheduled periods 08:00 30/4/1994 to 08:00 5/5/1994 and 08:00 7/5/1994 to 12:00 12/5/1994 (including the 4 hour extension) the full COSRAD surface current radar system operated for 237 hours giving 97% data recovery. During Phase I the data recovery was 100%. The lost data during Phase II were the result of brown-outs by the Victorian electricity supply and disk write errors. In addition to the scheduled periods, 50 hours of data are available from the non-scheduled periods set aside for testing and diagnosis.

Surface current maps have been produced at hourly intervals for every hour for which COSRAD was operating, including periods outside the scheduled times. There are two main sets of surface current maps, one for each of the two phases.

This report also describes the results of particle tracking and tidal ellipse analysis at selected locations in Port Phillip Bay using the surface current maps produced by COSRAD. This has been undertaken as research and development on the COSRAD system and is provided in addition to the scope of the work specified.

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1. INTRODUCTION

The Physics Department at James Cook University (JCU) has been involved in the study of surface currents using the COSRAD HF radar for many years. This report is a result of an environmental study of Port Phillip Bay being undertaken by CSIRO, on behalf of Melbourne Water, in which JCU Physics was involved as a sub-contractor to study surface currents.

The objective of the larger Port Phillip Bay Environment Study is "to determine the environmental status of Port Phillip Bay in relation to nutrients and toxicants and to provide the basis for long-term management of point-source and diffuse inputs". The COSRAD system is ideal for the continuous monitoring of surface currents over a large area and for providing actual data with which numerical models can be calibrated.

Of the five groups of tasks, P (Physical Processes), N (Nutrients), T (Toxicants), E (Ecology) and G (General), the COSRAD components falls into the physical process Task P1 which covers the collection of meteorological and oceanographic data. We see this as being closely related to the collection and analysis of mixing data (Task P2) and is closely tied to the development of mathematical models (Task P8).

This is summarised in the Consultants Brief for Task P1, as follows:

The main objective is to provide extra essential meteorological and hydrographic data to set up and calibrate the hydrodynamic/dispersion/sediment models to be developed in Task P8. The data will improve understanding of the physical processes which take place in Port Phillip Bay and will ultimately provide statistics on seasonal and long-term events.

Our objectives were to produce hourly maps of surface current vectors for a five day period over the Great Sands Region and a five day period over the area northwards from the Great Sands Region. By monitoring the large scale flow in the south end of Port Phillip Bay we provide validation of the 3D modelling. This deployment was also coordinated with CTD and ADCP transects in Port Phillip Bay conducted by other sub-contractors.

2. THE COSRAD SYSTEM

COSRAD uses high-frequency ocean backscatter radar technology to map ocean surface currents and to infer the sea-state and wind direction. This technology works by determining the Doppler shift of the backscattered radar wave. In COSRAD the radar frequency is 30 Mhz. The incident radar wave is resonantly backscattered from waves whose wave-length is half the radar wavelength - which for COSRAD corresponds to a wavelength of the sea waves of 5 m. This scattering mechanism produces two strong resonance peaks in the Doppler spectrum, called Bragg peaks, as seen in Figure 1.

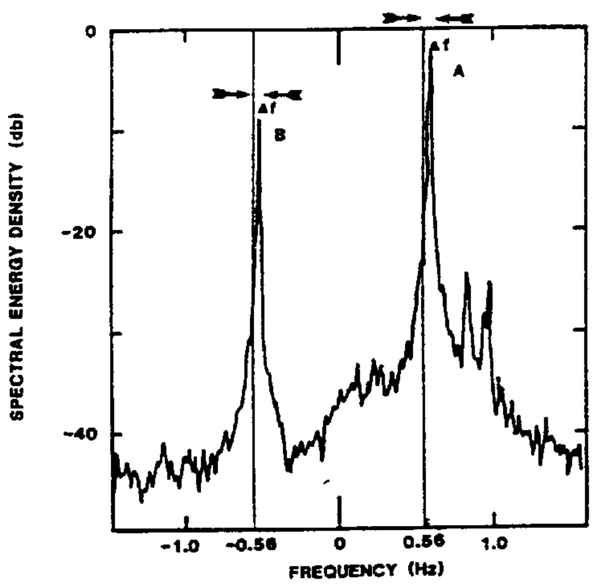

Figure 1. COSRAD Doppler Spectrum showing two Bragg peaks.

The first-order features of this spectrum are explained in terms of wave phase velocity and bulk movement of surface water. The total Doppler shift f_D can be written in terms of a component due to the wave phase velocity f_B of the wave which is resonant with the radar frequency f_O (the Bragg wave), and a component due to bulk movement of the surface water Δf.

$$f_D = f_B + \Delta f$$
$$= \sqrt{\frac{g f_0}{\pi c}} - 2 f_0 \frac{\upsilon}{c}$$

where g is the acceleration due to gravity, c is the speed of light and υ is the magnitude of the surface current component parallel to the direction of the radar beam.

With the 30 MHz radar frequency used by COSRAD the Bragg frequency f_B is 0.56 Hz. This is the frequency at which the spectrum shows strong peaks in the absence of surface currents. The relative amplitudes of these peaks is an indication of the prevailing wind direction.

When there is a bulk movement of surface water these Bragg peaks are shifted by an amount Δf which is proportional to the surface current velocity component parallel to the antenna beam direction. This corresponds to the second term in the above equation and may be rewritten as follows

$$\upsilon = -\frac{\Delta f}{2 f_0} c.$$

In a particular spectrum Δf can be positive or negative, representing frequency shifts to the left or right of the Bragg frequency, as a result of negative or positive values of υ which in turn represent a surface current component moving towards or away from the station. The minus sign in the above expression means that we label surface current components moving away from the station as being positive.

With a second antenna placed so that its beam intersects the beam from the first antenna at about 90 degrees we can reconstruct the true surface current vector at the point of intersection of these beams. It is not strictly necessary to have the two beams at 90 degrees to each other but we eliminate records where the acute angle between the two beams is less than 15 degrees. Considerable effort is made to locate the radars on sites where the beams are approximately orthogonal over the key part of the region to be studied. Physical and social constraints are imposed by the required access to the fore shore.

Electronic steering of the antenna beams allows these antennas to sweep over a 60 degree arc of the sea surface. Coverage of surface current vectors over an area corresponding to the region of intersection of the sweeps for the two antennas is then possible. Each sweep is divided into 17 sectors covering ±30° about the bore-sight (central beam position) of a station.

The radar beam width $\Delta\theta$ depends on the configuration of the antennae - in particular on the number of elements N_A in the antenna structure. COSRAD uses an eight element configuration of $\lambda/4$ whip elements spaced $\lambda/2$ apart, which fixes the azimuthal resolution at about 7.5° (this actually varies slightly with the antenna look direction θ).

$$\Delta\theta \approx 2 \arcsin\ 1/2\, N_A$$

It is only from the common region covered by both radar beams that true surface current vectors can be calculated. Outside the region of intersection only one component of the surface current can be determined and it is then not possible to determine that component of the surface current perpendicular to the radar beam direction.

The amount of time T for which data are collected at each beam position (the sector dwell time) determines the surface current resolution. It takes slightly less than two minutes to accumulate data at each radar beam position, which corresponds to a surface current resolution Δv of 0.05 m/s.

$$|\Delta v| = \frac{|\Delta f|_{\min}}{2 f_0} c$$

$$= \frac{1}{2 T f_0} c$$

An entire sweep of 17 sectors is then covered in 30 minutes and a complete surface current map can be produced every 30 minutes. For this report, time-domain smoothing has been performed with surface current maps presented every hour. Collecting data for a longer time at each beam position improves the surface current resolution but with a corresponding loss of temporal resolution if the same total area is to be covered.

Information on range is obtained by transmitting short radio-frequency pulses and looking in the quiet time for any echoes returned by reflections off the sea surface. The width of this pulse Δt effectively determines the range resolution Δr of the system, which we set at 3 km for this work.

$$\Delta r = \frac{1}{2} c \Delta t$$

The time T_p between successive radar pulses determines the maximum theoretical range $R_{\max} = \Delta r T_p / \Delta t$ of the system. In practice, other factors tend to limit this range. One obvious restriction being the presence of land at distances $r < R_{\max}$, such as occurs for all locations chosen for this study. Clearly, as the range increases the reflected power decreases and the maximum range depends on the sensitivity of the radar receiver.

One COSRAD station will therefore produce data for cells of the ocean surface covering 3 km in range and roughly 7.5° azimuthally. This forms a lower limit on the spatial resolution of the system. However, note that the perpendicular resolution increases closer to the radar since the angular resolution is a constant.

3. SITE SELECTION

In early March a site inspection was made to determine the most suitable sites from which the COSRAD system could be operated. It was desired that the radar coverage over the Great Sands Region and the adjacent area to the north be maximised. Figure 2 shows the region to be studied with the Bellarine, Nepean and Mornington Peninsulas, Mud Islands and the 5 m bathymetric contours indicated.

With approvals from the relevant local authorities and organisations three sites were chosen. The first site was at St. Leonards on the Bellarine Peninsula to the west. This sites was used for both phases, the only adjustment required being a realignment of the antenna from covering the region north of the Great Sands Area during the first phase to covering the Great Sands Area during the second phase.

The second site, located at the Sorrento Sailing Club on the southern end of the Bay, was used only during Phase I. The radar beam was pointing almost due north, the intersection region with the radar beam from the St. Leonards site covering an area north of the Great Sands Region (Figure 3). This arrangement facilitated the monitoring of large-scale flows in the south end of the Bay for validation of the 3D modelling and was coordinated with CTD transects in the Bay.

The third site, located at Safety Beach Boat Hire on the south-eastern end of the Bay, was used only during Phase II. The radar beam was pointing almost due west, the intersection region with the radar beam from the St. Leonards site (now realigned) covering an area over the Great Sands Region (see Figure 5). This arrangement facilitated the monitoring of surface currents flowing across the sand banks and was coordinated with the ADCP current profiler and CTD transects in the Great Sands Region. The combined data will provide an estimate of the flushing rate of Port Phillip Bay.

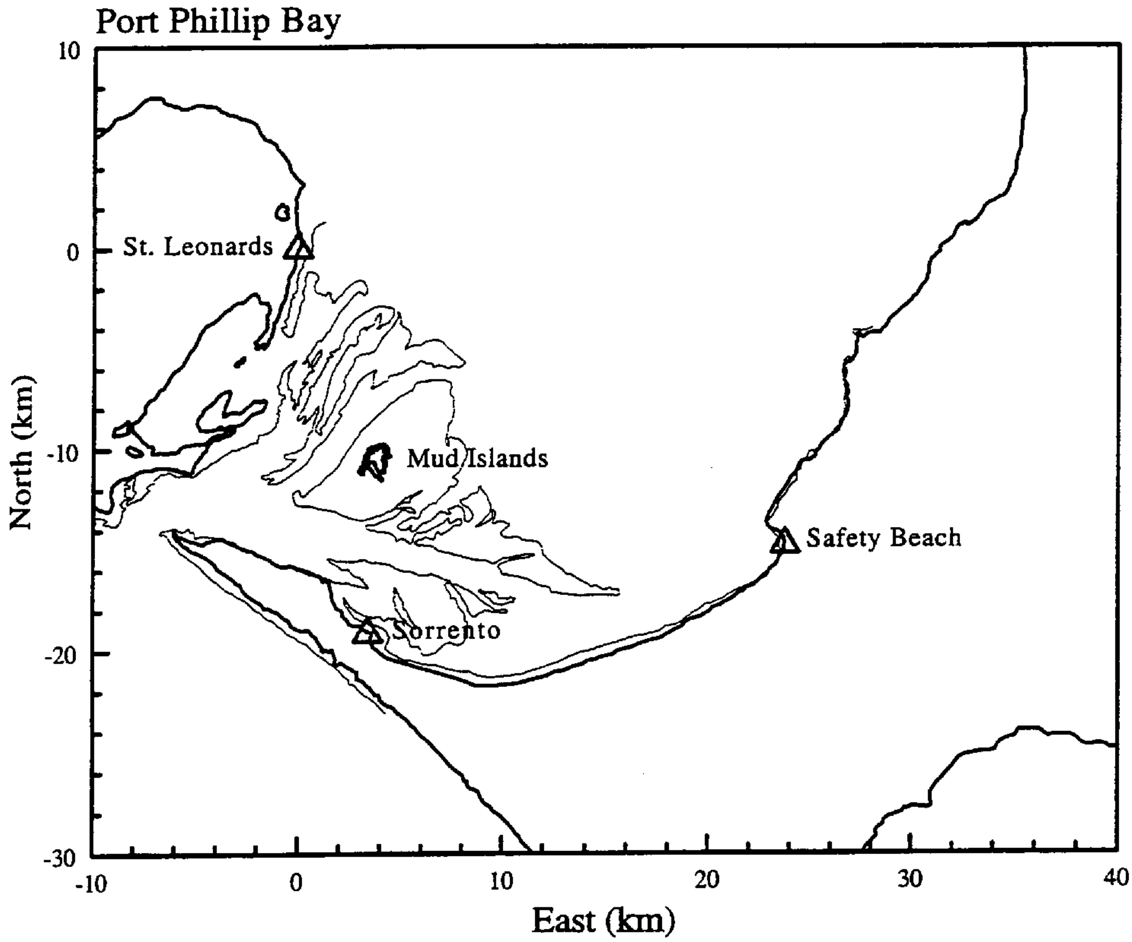

Figure 2. Port Phillip Bay (with 5m depth contours)

4. PHASE I: 20:00 29/4/1994 TO 08:00 5/5/1994

In the first phase of this study the two COSRAD stations were located at St. Leonards (144°43.05'E, 38°10.51'S) on the eastern side of the Bellarine Peninsula and at Sorrento (144°45.41'E, 38°20.83'S) on the southern end of Port Phillip Bay. These sites were chosen to provide coverage of the area adjacent to the north of the Great Sands Region. The purpose of this arrangement was to monitor the large-scale flow in the south end of the Bay for validation of the 3D modelling. This deployment was also coordinated with CTD transects in the Bay.

The bore-sight for the St. Leonards site was set was at 110° E (true). For the Sorrento site the bore-sight was set at 22° E (true). This is illustrated in Figure 3.

In this Figure, and in all subsequent location maps in this report, the values along the *x* and *y* axes are shown as kilometres. The origin of this coordinate system is at the St. Leonards site, which was common to both Phase I and Phase II. The locations of the two stations are indicated by the centres of the shaded open triangles, which also correspond to the vertices of the sweeps. The azimuthal arcs represent the radial extents of each pixel (range cell) while the radial lines represent the azimuthal extents for each sector. Note that it is in the region covered by both radars from which we obtain surface current maps.

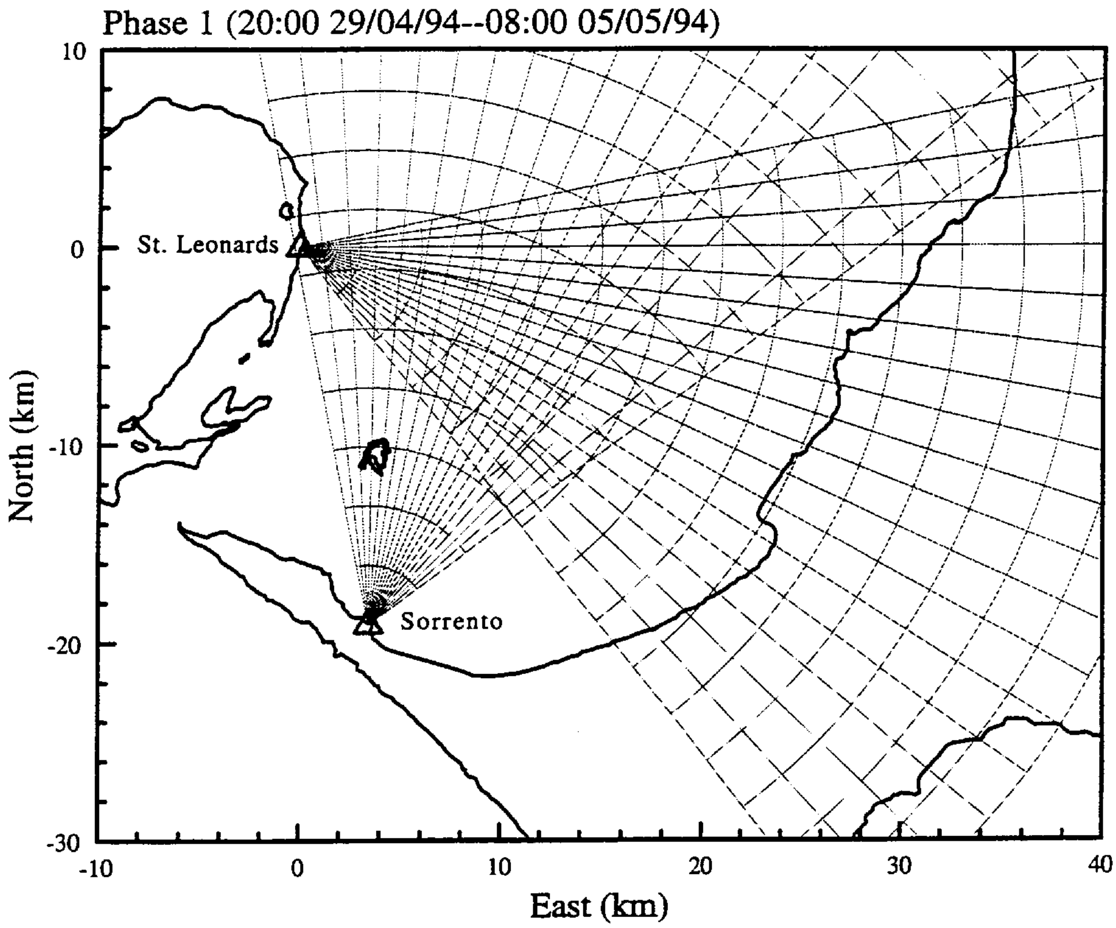

Figure 3. Phase I location diagram (St. Leonards/Sorrento)

4.1 Data availability

There are no breaks in the data set for Phase I. Data are available for 100% of the scheduled times between 08:00 30/4/94 and 08:00 5/5/94. In addition, data are available for 12 hours prior to the scheduled start of Phase I, and for the one half hour beyond the scheduled end of Phase I. This is summarised in Figure 4.

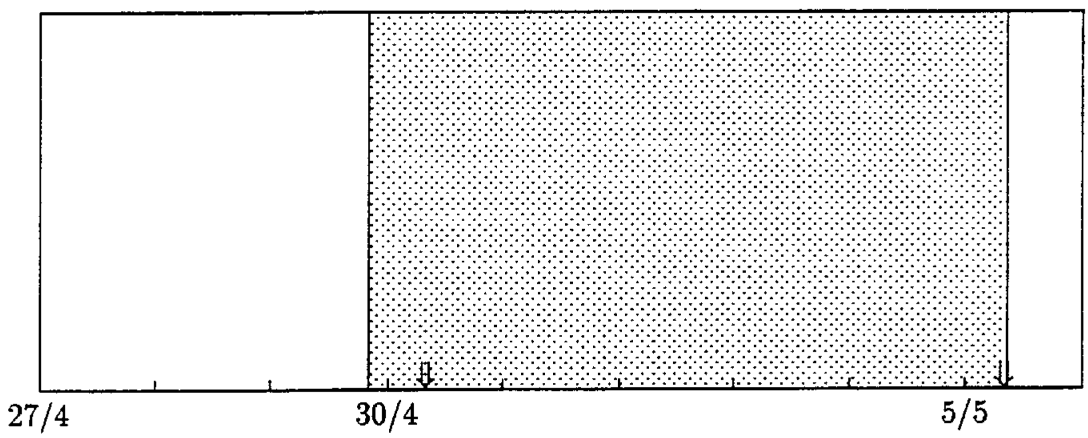

Figure 4. Phase I (St. Leonards/Sorrento) data availability.

Shaded regions in Figure 4 indicate times for which data are available. White regions indicate times for which there are no data but which were used for installation and testing. The scheduled operating times for Phase I are indicated on this graph by the two vertical arrows.

5. PHASE II: 18:00 5/5/1994 to 12:00 12/5/1994

In the second phase the two COSRAD stations were located at St. Leonards (144°43.05'E, 38°10.51'S) on the eastern side of the Bellarine Peninsula and at Safety Beach (144°59.57'E, 38°18.47'S) on the Mornington Peninsula. This deployment covered the Great Sands Region and was designed to provide surface currents along the channels. Further, this arrangement has provided maps of surface currents flowing across the sand banks. This configuration did not map surface currents through The Heads or through the entrance area to the south-west of the Great Sands Region. This deployment was coordinated with the ADCP current profiler and CTD transects in the Great Sands Region, the combined data of which will provide an estimate of the flushing rate of Port Phillip Bay.

For the second phase the station at St. Leonards was not moved laterally but was physically rotated so that its bore-sight was set at 150° E (true). The second station, having been moved to Safety Beach, had its bore-sight set to 283.5° E (true). This is illustrated in Figure 5.

In this Figure, as with Figure 3, the values along the *x* and *y* axes are shown as kilometres and the origin of this coordinate system is at the St. Leonards site. The locations of the two stations are indicated by the centres of the shaded open triangles, which also correspond to the vertices of the sweeps. The azimuthal arcs represent the radial extents of each pixel (range cell) while the radial lines represent the azimuthal extents for each sector. Note that it is in the region covered by both radars from which we obtain surface current maps.

5.1 Inter-station Radar Interference

An aspect of the location diagram shown in Figure 5 is that there could be situations when the radar beam direction from one station points directly at the other station. The receiver of the receiving station may be paralysed by the unattenuated signal (about 100W) arriving from the transmitting station. The receivers are extremely sensitive, being designed to detect very low strength radar signals. This is mitigated by synchronising the two radars so that they never simultaneously point directly at each other. As a result the direct signal is effectively attenuated by going through one of the side lobes of the antenna beam pattern.

However, in such cases there may still be significant interference in the time series of the receiving station. Any interference pulses which appear in the time series will affect the spectrum and consequently can affect the algorithm which identifies the Bragg peaks.

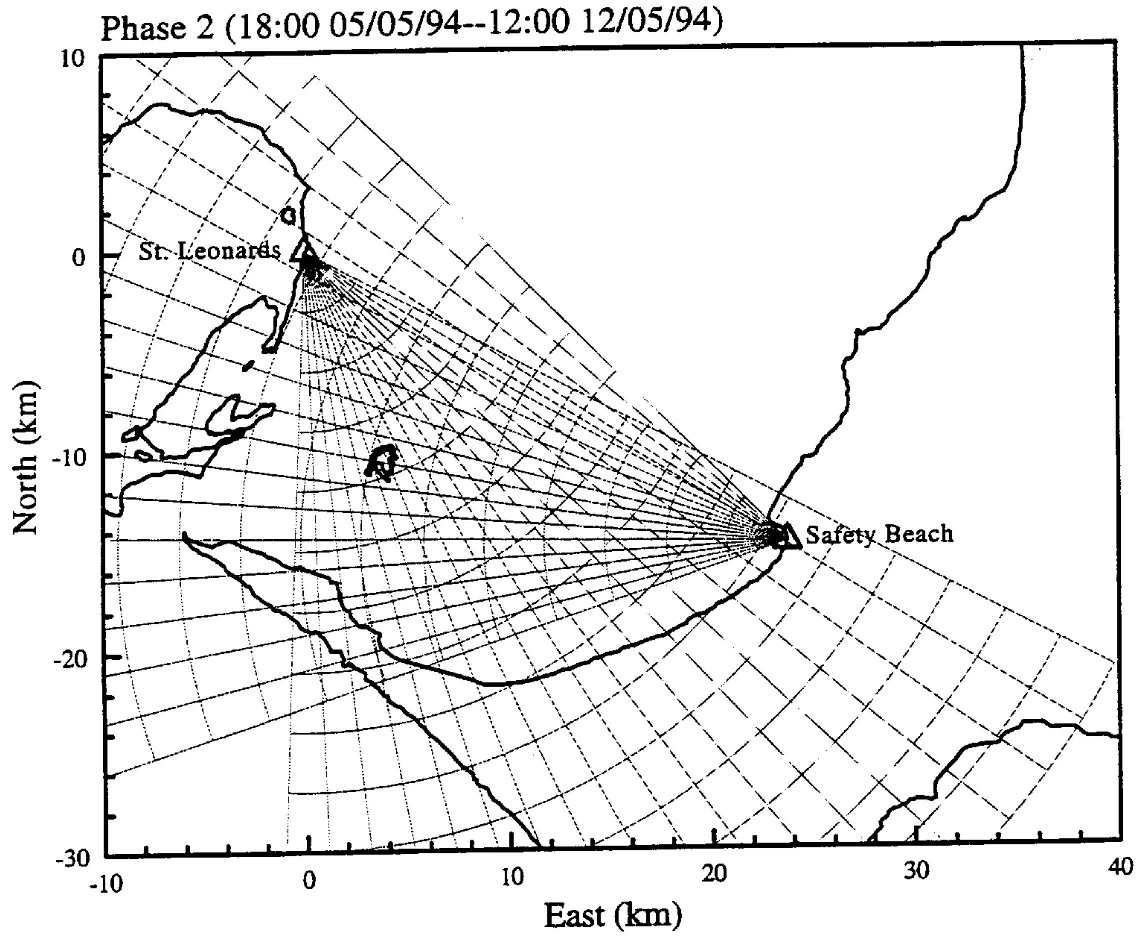

Figure 5. Phase II location diagram (St. Leonards/Safety Beach)

To cope with this situation the interference pulses are first identified and removed from the time series. The short gaps left by removing the radar interference pulses is then 'filled in' using an appropriate interpolation algorithm. Data analysis can then proceed as for the ideal case by calculating the spectrum, identifying the Bragg peaks and determining the surface vector. The COSRAD system is then robust with respect to inter-station interference.

5.2 Colinear Radar Beams

There are situations in Figure 5 when the radar beam directions of the two stations are almost colinear. The effect of this is that the true surface current components perpendicular to that direction become sensitive to small changes in the measured surface current components. These fluctuations can be the result of simple noise in the measurements and analysis or of variations in surface current during a sweep (30 minutes).

To avoid possible large errors in measurements in regions of almost colinear beam directions we do not show true calculated surface vectors at locations that correspond to these beam intersections on the surface current maps. The criterion used is that the acute angle between the radar beam directions has to be greater than 15°. For this reason, surface current maps produced for Phase II will not show surface current vectors for the entire region of overlap of the sweeps of the two stations.

5.3 Data Availability

There are a number of unscheduled breaks in the data set for Phase II, totaling 7 hours for which data are not available. Nonetheless, data are available for 94% of the scheduled times between 08:00 7/5/94 and 12:00 12/5/94. This includes the four hour extension requested by the project supervisor from 08:00 7/5/94 to 12:00 12/5/94. In addition, data are available for 38 hours prior to the scheduled start of Phase II. This is summarised in Figure 6.

Shaded regions in Figure 6 indicate times for which data are available. White regions indicate times for which there are no data but which are also outside the scheduled operating times. The scheduled operating times for Phase II are indicated on this graph by the two vertical arrows. Black regions indicate times for which data are not available. Some data loss was due to brown-outs in the electricity supply to the Safety Beach site. Some data were also corrupted as a result of hard disk write errors.

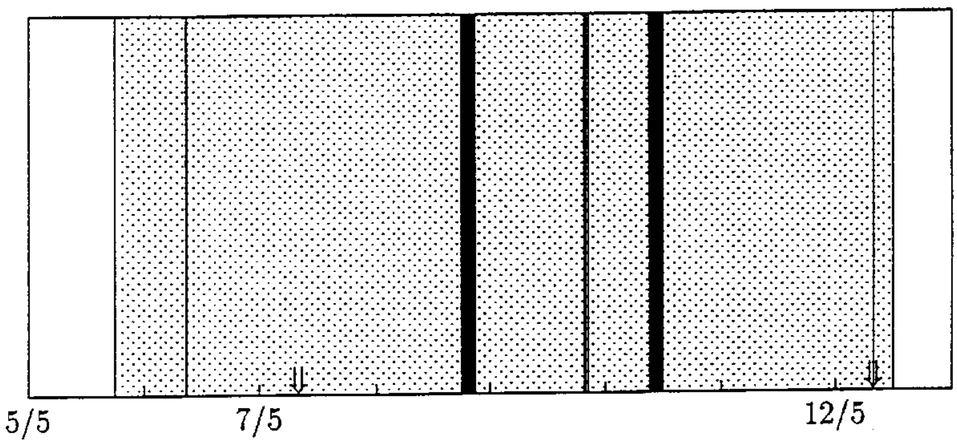

Figure 6. Phase II (St. Leonards/Safety Beach) data availability.

6. PRODUCING SURFACE CURRENT MAPS

In each COSRAD sweep, for each station, there are 17 sectors (±30°) and 15 pixels (45 km range). For each sector and pixel, corresponding to a particular patch of sea, we collect a 1024 point time series. This time series is checked for radar interference pulses resulting from the other station. If any interference pulses are detected they will be removed and the resulting short gaps are interpolated.

With the time series integrity verified the spectrum for each patch can then be calculated. These spectra contain one or two Bragg peaks depending on the prevailing wind direction for that patch. In most cases two Bragg peaks will be observed (see Figure 1). By identifying the positions of these peaks we are then able to estimate the surface current component parallel to the radar beam direction for the sector. Various techniques are employed to ensure that we correctly identify the Bragg peaks. In particular, when a peak is found we also check for the corresponding Bragg peak on the other side of $f = 0$. Both Bragg peaks must be shifted by the same amount.

In this manner we analyse the entire sweep, patch by patch, to build up a surface current component map for each station. Typical examples of these are shown in Figure 7.

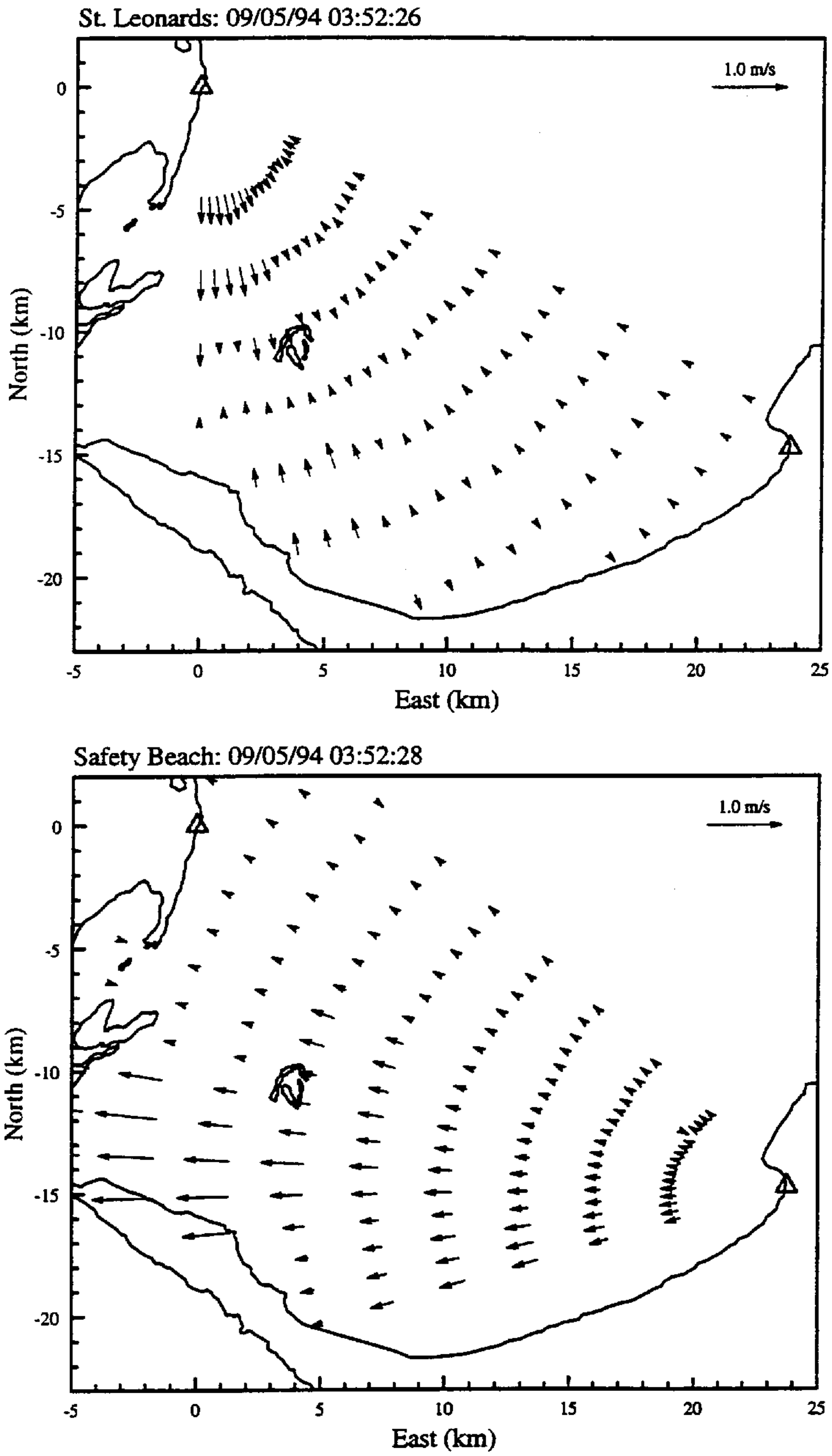

Figure 7. Surface current component maps

A number of pre-processing steps are used to minimise the effect of noise in the data before a pair of sweeps produced at the same time from the two stations can be combined to form the true surface current vector map for that time.

First, a 'despiking' pass is made over each surface current component map to eliminate surface current components at patches that differ by too large an amount from the four immediate neighbours. This tests for large variations in the magnitudes as well as for changes in direction. Of course, in regions of strong directional flow due to channels and rips these variations may be physical. It is for that reason we compare each patch with its four neighbours since actual changes in surface current will then be apparent in at least one or two of the neighbouring patches.

Next, a smoothing pass is made over the surface current component maps for the two stations. The smoothing uses a 1 : 4 : 1 two dimensional smoothing filter that assigns a weight of 4 to the patch being smoothed and a weight of 1 to its four immediate neighbours. This ensures that small features are not masked by too wide a smoothing window but that small random noise fluctuations are still reduced.

At this stage we combine the two surface current component maps into one surface current vector map. All surface current components measured in regions covered by only one of the radars are then eliminated since the true surface current vector cannot be determined from one component alone. Where the radar beams intersect at less than 15° the surface current vectors are also eliminated, for reasons explained earlier.

For the two surface current component vector maps in Figure 7 the resultant surface current vector map is shown in Figure 8.

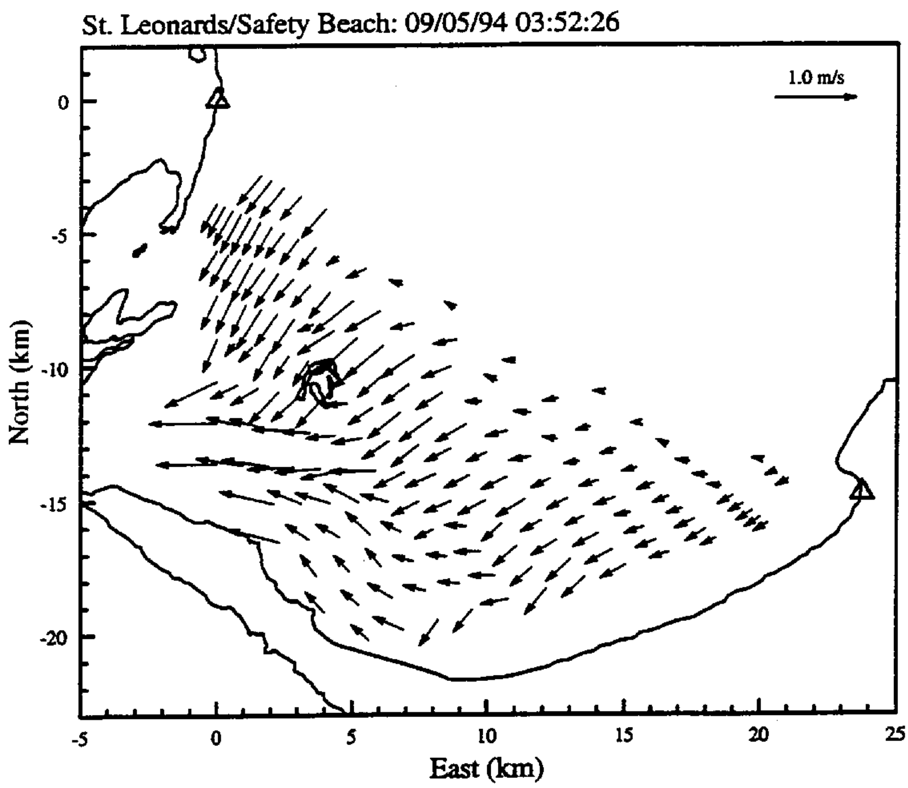

Figure 8. Surface current vector map

Despiking and smoothing is also employed in the time domain. Adjacent surface current maps are compared to determine whether changes in the surface magnitude and direction are too large. Despiking of a particular surface current map compares surface current vectors with the surface current maps measured during the previous and next sweeps. Since surface current maps are produced every half hour the effect of this is to ensure that surface currents over a period of one hour are consistent.

Smoothing in the time domain uses 1 : 2 : 1 smoothing filter that assigns a weight of 2 to the entire surface current map produced at a particular time and a weight of 1 to the surface current maps produced for the previous and next sweeps. Since surface current maps are produced every half hour the effect of this is to perform a one hour smoothing of surface current maps.

Performing this analysis on all sweeps measured for the duration of both Phase I and Phase II forms the basic data set produced for this contract. Surface current maps were generated on the hour for every hour during the scheduled operating times for this contract and also for those periods outside the scheduled times which were set aside for testing and diagnosis during which the equipment was operational. It is due to the ease of installation and reliability of the COSRAD system that these additional surface current maps are available. All surface current map data was transferred to the CSIRO Port Phillip Bay Environmental Study.

It should be noted that even though the surface current maps generated are presented on the hour, the measured surface current maps are not necessarily produced exactly on the hour. To make sure that all surface current maps are given on the hour we interpolated to the appropriate hour using surface current maps on either side of the hour.

7. SURFACE CURRENT RESIDUALS

By calculating the vector average over all sweeps for each Phase and for each position at which we have surface current vectors, we obtain the surface current residuals. These represent the mean surface current vectors experienced at these positions. When the period of time over which the surface current residuals are calculated is short, it is important that one calculates the residuals over an integral number of tidal cycles. This has been done for Figures 9 and 10.

Figure 9 shows the surface current residuals for Phase I, north of the Great Sands Region. In this Figure, and in Figure 10, it must be noted that the current vector scale is a factor of five larger that used in Figure 8 and that used for all surface current maps generated for this study.

In Figure 9 we note that there is a general weak drift towards the south and to the west over the Bay, The magnitude of which is never more than 0.05m/s. Immediately to the north of Mud Islands there is a fairly complex pattern with some counter-flow. Near the Bellarine Peninsula this flow is almost due west. This is map was generated using data from a specific five day period and does not necessarily reflect long-term residuals.

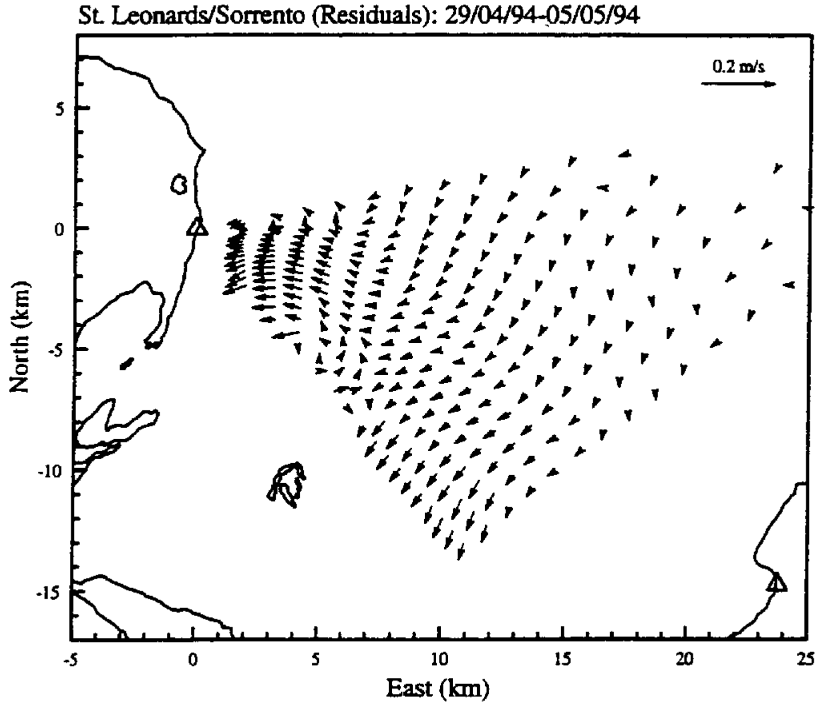

Figure 9. Phase I (St. Leonards/Sorrento) surface current residuals

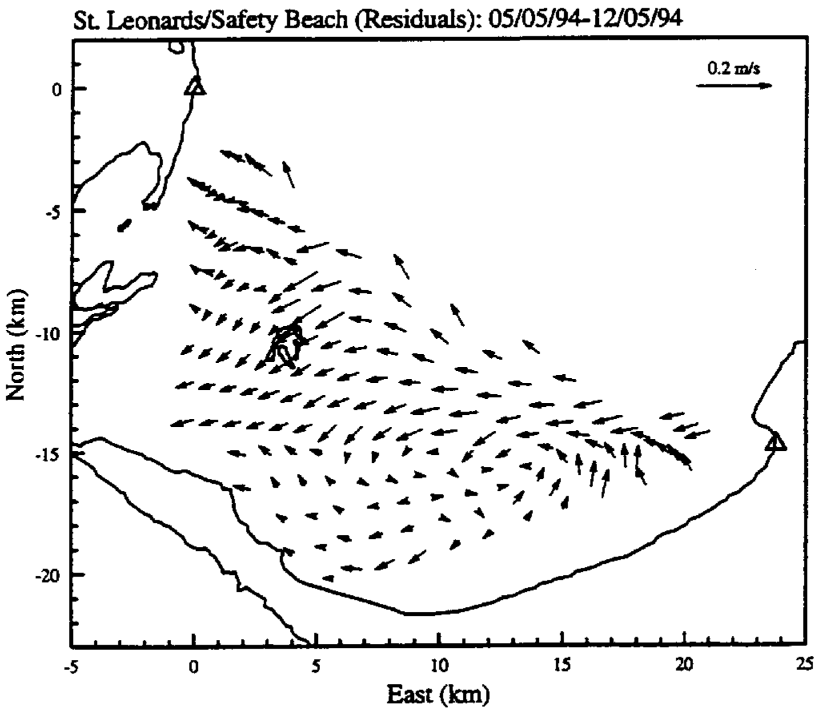

Figure 10. Phase II (St. Leonards/Safety Beach) surface current residuals

Figure 10 shows the surface current residuals for Phase II, over the Great Sands Region. Here there is a general weak drift towards the west, out of the Bay. However, there are regions of rotating flows in the south end of the Bay which suggest that there is some water circulation that tends to trap material in these regions. The residual surface currents over the entire region covered by COSRAD are weak, rarely exceeding 0.05 m/s.

8. PARTICLE TRACKING

While not part of the contract objectives, in this section we show some results of particle tracking that we performed using the surface current maps produced for this study. In this analysis a number of map locations are chosen to be the release points for the particle tracking simulation. Locations can be chosen based on the observed surface current behaviour in a particular region or can be chosen to investigate what happens to particles released randomly throughout the Bay.

To release a particle at a given location on the map we must also specify the time of release, say to coincide with a peak or trough in the tidal cycle. This time of release and the location of the release point may not coincide exactly with a location and time for which a surface current vector is available. In that case the initial surface current vector must be interpolated. We do this by first producing a contour map of surface current vectors for the two sweeps immediately before and after the release times. Three dimensional interpolation is then used to determine the surface current vector at the position and time of release of the particle.

The position of the particle is then projected along a straight line path determined by the surface current velocity at the release point. This projection continues until the next time for which we have another surface current map. This new surface current map is then contoured so that the surface current vector at the *new* position can be determined. Once again, the particle is projected along a straight line path until the following time for which a surface current map is available. This process repeats until a designated stop time is reached or the particle has flowed out of the region for which we have surface current vectors. We then have a true estimate of the actual path material on the surface (such as debris and oil) will take.

In Figures 11 and 12 we show selected particle tracks for Phase I and Phase II. Particle release points are indicated by circles while the end points are indicated by arrows. The direction in which the arrow points indicates the direction of the surface current vector at that point. The solid line connecting a circle and an arrow represents the actual path the particle has taken. When a particle flows out of the region where the surface current vectors are available it can no longer be tracked and we then print, next to the arrow, the number of hours and minutes for which it was tracked. This time is not shown for particles that were tracked through the complete period.

Figure 11 shows current tracks during Phase I for eight release points selected at random, starting at 02:00 02/05/94. The particles were tracked for 37 hours. Two particles were lost, one on the western side of the graph and the other on the eastern side. The particle to the west was lost reasonably quickly suggesting that there is some influence due to the channel between Mud Islands and the Bellarine Peninsula.

Within the Bay proper the particles do not move very far though there is a tendency to drift to the north, further into the Bay. This may, at first, seem to contradict the surface current residuals shown in Figure 9. However, the surface current residuals are indicative of the mean flow during Phase I, a period of five and a half days, while the particle tracks are produced for only a selected 37 hour period during Phase I. It is very likely that these particle tracks are indicative of a south-westerly wind during this time. Note also that the effect of the tides within the Bay appears to be very weak.

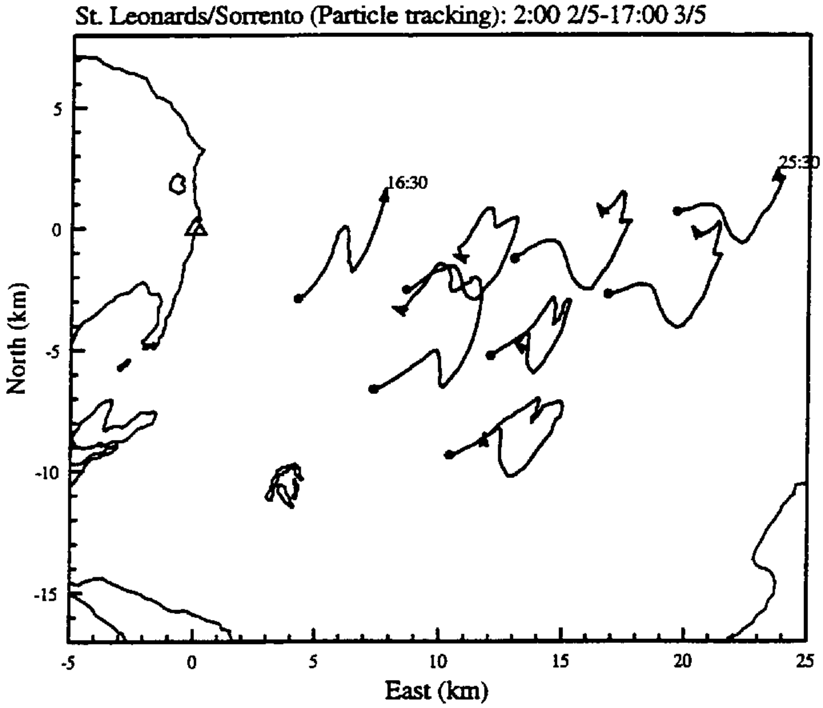

Figure 11. Phase I (St. Leonards/Sorrento) particle tracks

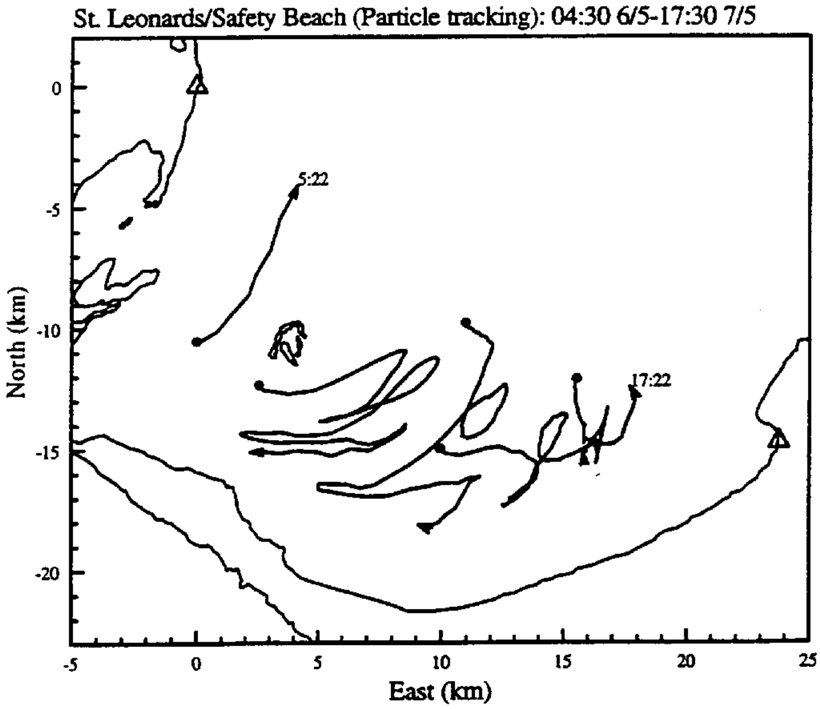

Figure 12. Phase II (St. Leonards/Safety Beach) particle tracks

Figure 12 shows surface tracks during Phase II for five release points selected at random, starting at 04:30 06/05/94. The particles were tracked for 37 hours. Two particles were lost during this simulation, the first in the channel between Mud Islands and the Bellarine Peninsula and the second at the south-eastern end of the Bay. It is clear from this Figure that there is a strong flow in the channel, the particle having been lost in just over four hours. In the basin to the east and south of Mud Islands particles appear to be trapped. The effect of the tidal cycles is evident in the particle motion, though it is interesting to note that they tend to drift to the south.

Surface particle tracking based on COSRAD surface current maps is a powerful technique for estimating the movement and dispersion of pollution. A group of adjacent release points can be tracked to find the displacement as well as the spread of a given patch of surface water.

9. TIDAL ELLIPSE ANALYSIS

While not part of the contract objectives, in this section we show some results of a tidal ellipse analysis performed using the surface current maps produced for this study. In this analysis a number of map locations are chosen for investigation - for this report these locations are chosen to cover the Bay uniformly. In general locations will be chosen based on the observed surface current behaviour to determine the influence of various tidal components.

The positions to be investigated may not coincide exactly with locations for which a surface current vector is available. In that case surface current vectors must be interpolated at the desired locations. We do this by producing contour maps of surface current vectors for each sweep. The time-history of surface current vectors can then be constructed for the entire period that surface current vectors are available during each Phase.

A least squares spectral analysis is then performed on this time series, using a set of known tidal harmonics. From the Australian National Tide Tables we note that the M2, S2, O1 and K1 constituents are dominant in the Port Phillip Bay region. The periods of these constituents are 12:42, 12, 25:82 and 23:93 hours, respectively.

Now, it must be realised that a conventional tidal harmonic analysis requires at least 29 days of continuous data. For this contract we were restricted to less than 7 days of data for each phase, so the results presented in this section are not ideal. However, this is a limitation of the time for which data are available and not a limitation of the COSRAD system. Consequently, the M2, S2, O1, and K1 constituents are the only four components we have included in the tidal ellipse analysis, the results of which are presented here. With a longer data set other minor constituents can be readily included.

The tidal ellipses in Figure 13 show that the M2 component dominates in the middle part of the Bay, with the S2, O1 and K1 components being less by an order of magnitude. Over the Great Sands Region (Figure 14) the K1 and S2 components have a greater impact.

10. COMMENTS ON FLUSHING

Based on the particle tracking presented in Section 8 and the hourly surface current vector maps generated we can make some provisional conclusions regarding the flushing of Port Phillip Bay.

In the West Channel surface currents are sufficiently large that our particle tracking follows a particle from within the Bay, north of the Great Sands Region, to near the Rip, in a tidal cycle. Assuming that the water near the Rip is essentially water from

Bass Strait we conclude that the West Channel is effective in transporting material from the Bay to Bass Strait. This does make the further assumption that the currents within the water column are the same as the surface currents. Data taken by the ADCP will be able to provide information required to make a more accurate estimate.

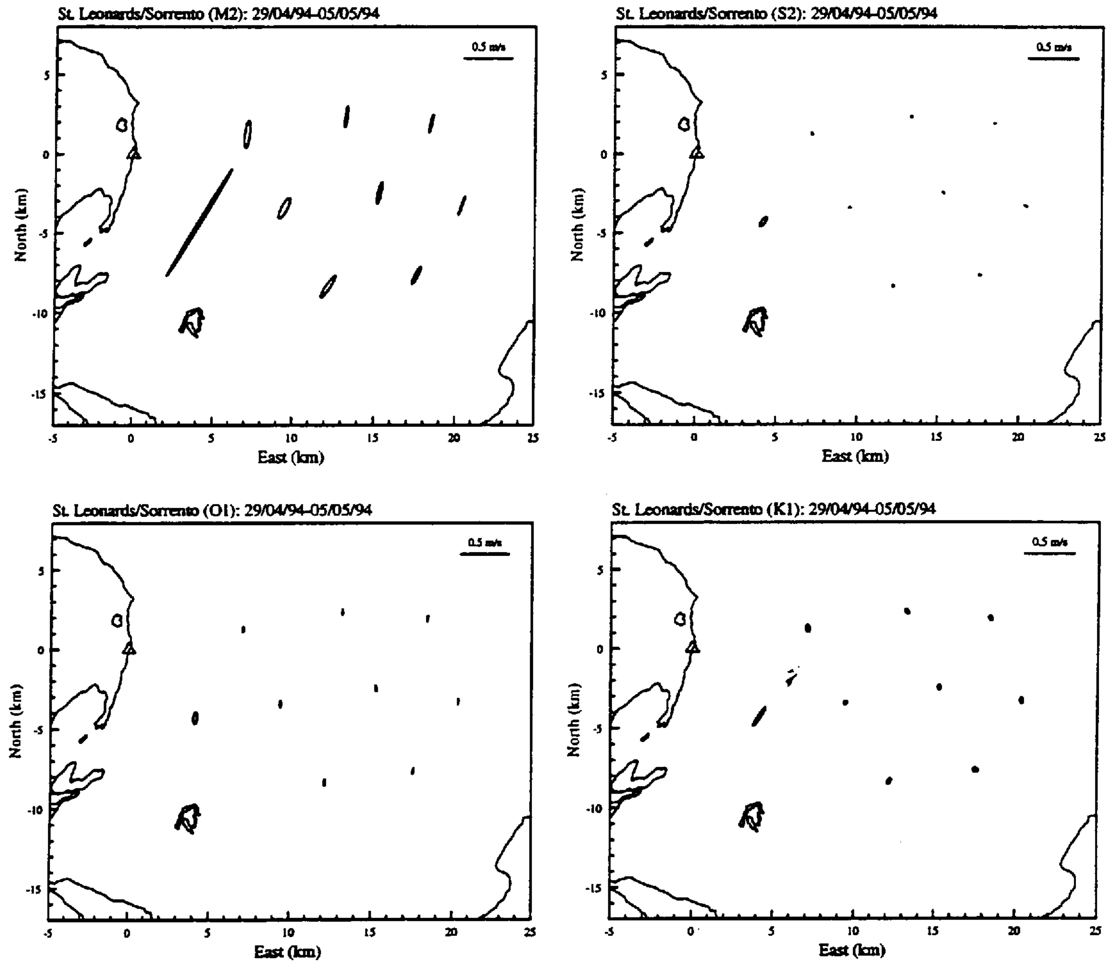

Figure 13. Phase I (St. Leonards/Sorrento) tidal ellipses

Particle tracking indicates that water in the South Channel, though moving quite quickly, does not mix in a tidal cycle with water from Bass Strait. The mechanism for exchange there is then dependent on meteorological conditions and input from rivers such as the Yarra River. This is based on the long-term drift apparent from the surface current residuals shown in Figure 10. Once again, data from the ADCP will indicate the detailed structure of the water column.

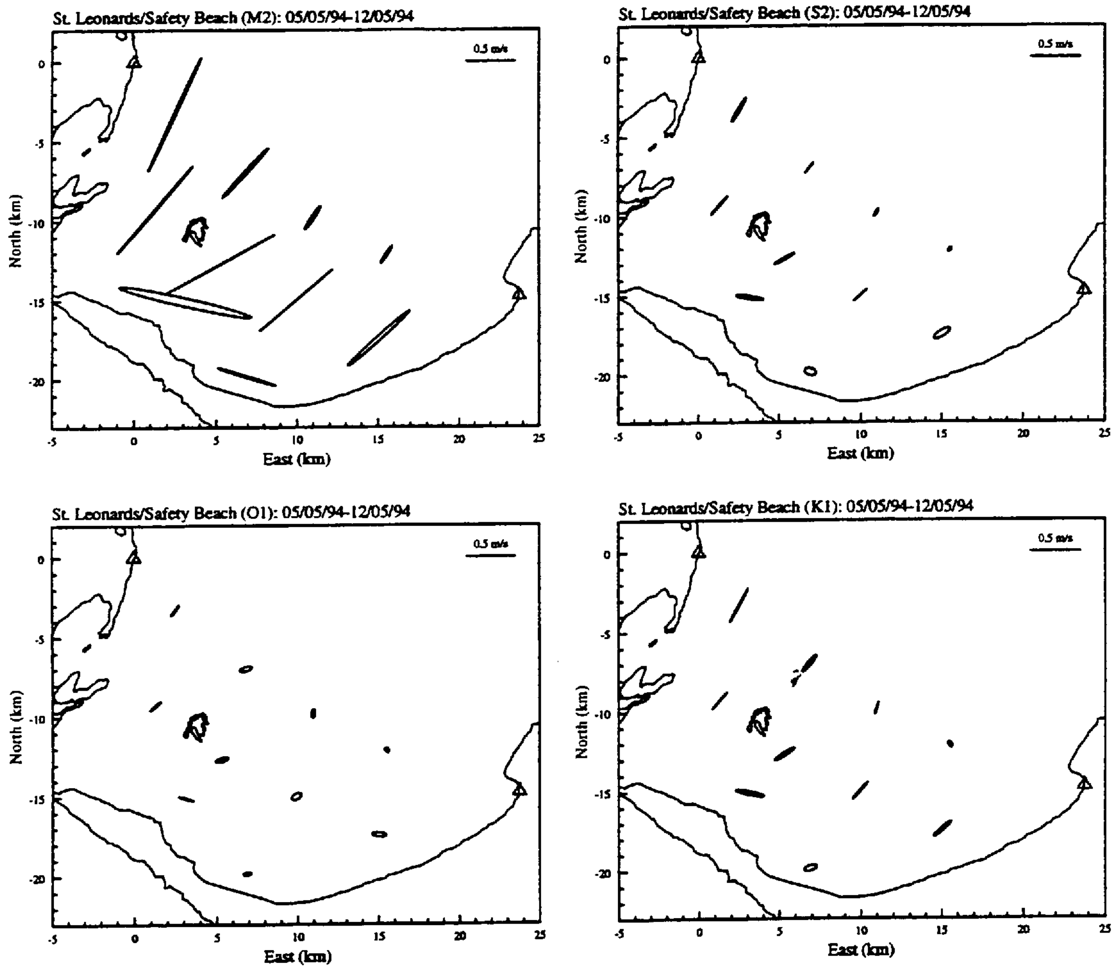

Figure 14. Phase II (St. Leonards/Safety Beach) tidal ellipses

11. ACKNOWLEDGMENTS

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