Retrieval of sea surface velocities using sequential Ocean Colour Monitor (OCM) data

J S Prasad[1,*], A S Rajawat[1], Yaswant Pradhan[1], O S Chauhan[2] and S R Nayak[1]

*Presently at Applied Geophysical Laboratories, Department of Geophysics, University of Houston, Texas 77204, USA

[1]Marine and Water Resources Group, Remote Sensing Applications Area, Space Applications Centre (ISRO), Ahmedabad 380 015, India.

[2]Geological Oceanography Division, National Institute of Oceanography, Dona Paula, Goa 403 004, India.

The Indian remote sensing satellite, IRS-P4 (Oceansat-I) launched on May 26th, 1999 carried two sensors on board, i.e., the Ocean Colour Monitor (OCM) and the Multi-frequency Scanning Microwave Radiometer (MSMR) dedicated for oceanographic research. Sequential data of IRS-P4 OCM has been analysed over parts of both east and west coast of India and a methodology to retrieve sea surface current velocities has been applied. The method is based on matching suspended sediment dispersion patterns, in sequential two time lapsed images. The pattern matching is performed on a pair of atmospherically corrected and geo-referenced sequential images by Maximum Cross-Correlation (MCC) technique. The MCC technique involves computing matrices of cross-correlation coefficients and identifying correlation peaks. The movement of the pattern can be calculated knowing the displacement of windows required to match patterns in successive images. The technique provides actual flow during a specified period by integrating both tidal and wind influences. The current velocities retrieved were compared with synchronous data collected along the east coast during the GSI cruise ST-133 of R.V. Samudra Kaustubh in January 2000. The current data were measured using the ocean current meter supplied by the Environmental Measurement and CONtrol (EMCON), Kochi available with the Geological Survey of India, Marine Wing. This current meter can measure direction and magnitude with an accuracy of $\pm 5^\circ$ and 2% respectively. The measurement accuracies with coefficient of determination (R^2) of 0.99, for both magnitude (cm.s^{-1}) and direction (deg.) were achieved.

1. Introduction

The Indian remote sensing satellite (IRS-P4), also known as the OCEANSAT-1, was launched on May 26th, 1999 by the Indian Space Research Organisation (ISRO). The satellite carried two oceanographic payloads i.e., the Ocean Colour Monitor (OCM) and the Microwave Scanning Multi-frequency Radiometer (MSMR). The first payload of OCM is designed to measure ocean colour, the spectral variation of water leaving radiance that can be related to concentration of phytoplankton pigments, suspended sediments, coloured dissolved organic matter i.e., yellow substance or gelbstoff and aerosols. This paper focuses on retrieving advective vectors using sediments as a tracer from the suspended sediment maps derived from the OCM data. The method is based on matching suspended sediment dispersion patterns, in sequential two-time lapsed images. The pattern matching is performed on a pair of atmospherically corrected and geo-referenced sequential images by Maximum Cross-Correlation (MCC) technique. The work follows the technique developed by many

Keywords. IRS-P4 OCM; suspended sediment concentration; advective velocity; maximum cross-correlation; co-registration.

investigators (La Violette 1984; Vastano and Borders 1984; Emery *et al* 1986; Kelly 1989; Garcia and Robinson 1989; Wu *et al* 1992) and has been applied on IRS-P4 OCM derived suspended sediment maps for the Indian region. The velocities retrieved are time-averaged velocities between the data sets used. This methodology retrieves velocities in terms of rate of transport of sediments. The retrieved velocities were validated using synchronous data collected along the east coast during a cruise (ST-133) onboard R.V. Samudra Kaustubh in January 2000. It is suggested that the use of this technique will find useful applications in providing inputs to hydrodynamic modelling of coastal processes such as computation of alongshore transport, pollutants dispersion rates, siltation, etc.

2. Materials and methods

2.1 *Selection of sequential data*

As part of the IRS-P4 OCM validation programme, synchronous sea truth data with the satellite pass were collected in the northern Bay of Bengal during January 13th – 25th, 2000 onboard R. V. Samudra Kaustubh Cruise No ST-133, a vessel owned by the Geological Survey of India (GSI), Kolkata. IRS-P4 OCM data of the same period were selected for this study. OCM collects data in eight spectral channels (402 – 422, 433 – 453, 480 – 500, 500 – 520, 545 – 565, 660 – 680, 745 – 785, 845 – 885 nm) with spatial resolution of 360 m, every alternate day for the same region at local time around 12 noon with radiometric resolution of 12 bits. Each OCM scene covers 1420 km by 1420 km ground area. Sediment plumes off Mahanadi delta provided persistent features which were useful for implementing the technique.

2.2 *Atmospheric correction*

It is well known that in the case of ocean remote sensing, the total signal received (in VIS-NIR) at the satellite altitude is dominated by radiance contribution through atmospheric scattering processes and only 8 – 10% of the signal corresponds to oceanic reflectance. Therefore, it becomes mandatory to correct for atmospheric effect before retrieving any useful information from space.

The Top of the Atmosphere (TOA) radiance in OCM channel seven (765 nm) and eight (865 nm), mainly corresponds to contributions coming from the atmosphere, since water leaving radiance L_w (765 and 865 nm) can safely be assumed to be zero (Gordon and Clark 1981). An exponential relationship for the spectral behaviour of aerosol optical depth has been used in the atmospheric correction algorithm. A relationship has been obtained for the spectral behaviour of the aerosol optical depth using channels 765 nm and 865 nm of OCM data. The aerosol optical thickness has been extrapolated to visible channels using this exponential relationship. The OCM data were analysed using the atmospheric correction and bio-optical algorithms developed initially for IRS-P3 MOS data (Mohan *et al* 1998) and later modified for IRS-P4 OCM data (Chauhan *et al* 2001).

A sensitivity analysis was carried out on the OCM algorithm to study the changes in the retrieval accuracy of total suspended sediment concentration (SSC) due to errors in the OCM sensor detected radiances, choice of aerosol optical depth model (in the atmospheric correction procedure) and variability in the atmospheric ozone content and differences between the OCM band wavelengths and the wavelengths actually required for the estimation of SSC (SAC Technical Report 2000). This sensitivity analysis shows that for SSC detection with an accuracy of 30%, the tolerable percentage radiance errors in the OCM bands are less than 6.0, 5.0, 6.0, 3.5 and 6.0 in bands 4, 5, 6, 7 and 8, respectively. The percentage error in SSC estimation due to the wrong choice of aerosol optical depth model and differences in the central wavelengths and the band widths are less than 10.0 and 1.0 respectively. Percentage errors in SSC retrieval due to 10, 20 and 30% changes in ozone content are less than 1.0, 1.9 and 3.1 respectively. It is clear from the above discussion that accuracy of atmospheric correction procedures strongly influence retrieval of SSC required for the application of MCC technique. Figure 1 shows IRS-P4 OCM images for January 13th and 15th, 2000 before atmospheric correction as false colour composite (left panels) and after atmospheric correction as suspended sediment concentration (right panels) maps over Dhamra estuary, north Bay of Bengal.

2.3 *Geometric correction*

The implementation of pattern matching technique requires careful geometric correction and co-registration of the successive images within an error limit of one pixel. A rotation between the images reduces the matching coherency and a translation shift reduces the matching accuracy. A two-stage approach was followed. First of all geometric correction was applied separately on individual data sets to remove image distortion and bring them to a standard geographic projection, with modified everest datum (i.e., a local geodetic datum, based on the everest spheroid that

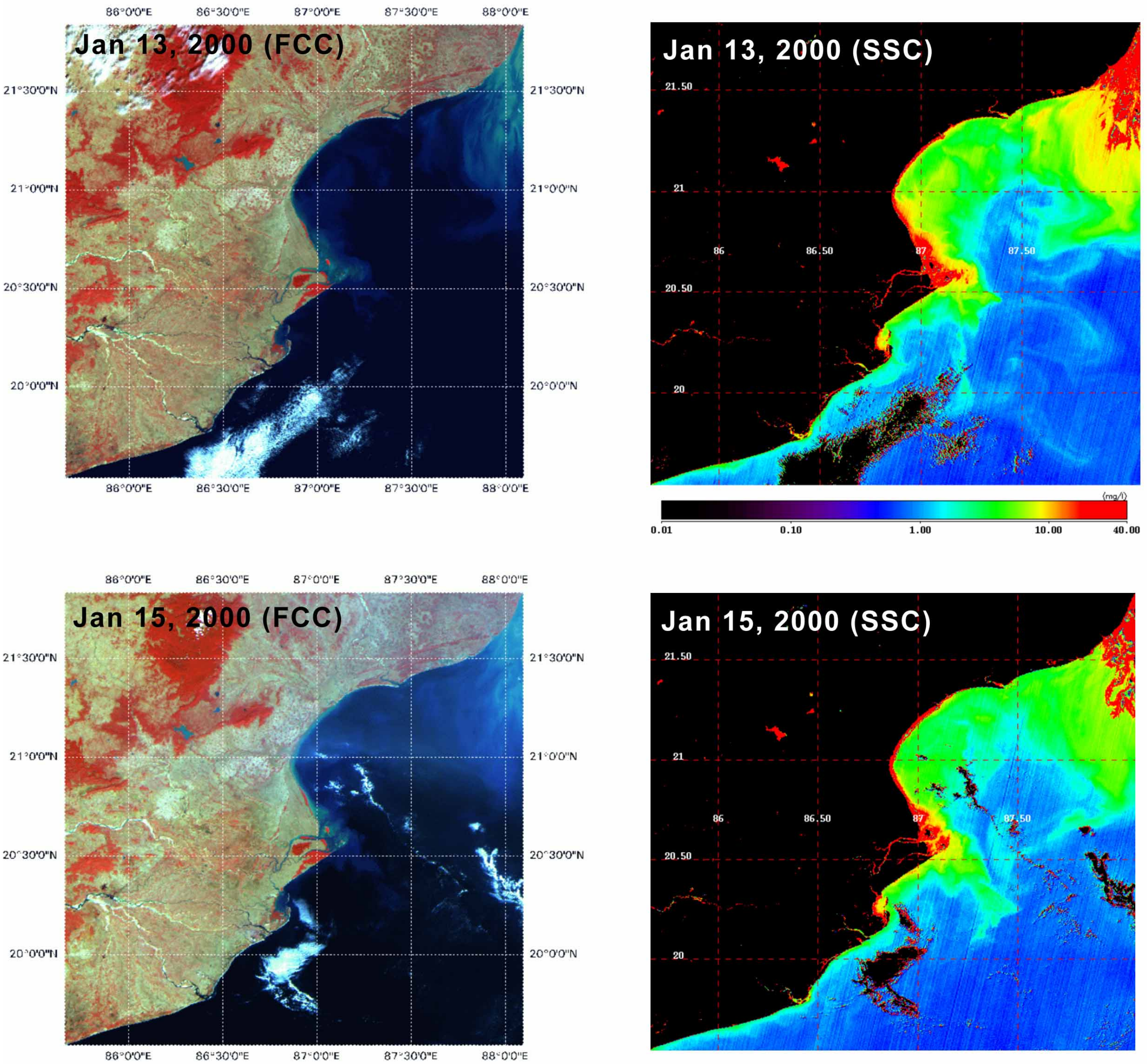

Figure 1. IRS-P4 OCM images for January 13th and 15th, 2000 before atmospheric correction are shown as false colour composite (left panels) and after atmospheric correction are shown as suspended sediment concentration (right panels) maps over Dhamra estuary, north Bay of Bengal. Note the distinct appearance of suspended sediments after atmospheric correction.

best fits the extent of the Indian subcontinent). In the second stage co-registration was done by warping one image to the other using polynomial transformation. The transformation was defined by matching more than 25 pairs (as many as possible) of Ground Control Points (GCP) on the images, selected from identifiable coastline features surrounding the area under study. The resampling at both the stages was performed by cubic convolution interpolation techniques to keep the spatial distortions at a minimum (Legeckis and Pitchard 1976; Emery and Ikeda 1984). The pair of the images could be co-registered within an error limit of one pixel (here 360 meters).

2.4 *Retrieval of suspended sediments*

The suspended sediment concentrations in the coastal areas have been derived using water-leaving radiance in band 490, 555 and 670 nm. The algorithm initially proposed by Tassan (1994) has been used to compute suspended sediments from OCM data. It has the following mathematical form:

$$\log S = 1.83 + 1.26(\log X_s) \text{ for } 0.0 \leq S \leq 40.0 \quad (1)$$

where S is suspended sediment concentration in mg/l and X_s is the variable defined as

$$X_s = [\text{Rrs}(555) + \text{Rrs}(670)] \times \left[\frac{\text{Rrs}(490)}{\text{Rrs}(555)}\right]^{-0.5} \quad (2)$$

where Rrs(λ) is the spectral remote sensing reflectance in respective wavelengths. The retrieval accuracy of SSC from OCM data is within 15% (Chauhan 2002).

2.5 *Implementation of the Maximum Cross-Correlation (MCC) pattern matching technique*

The Maximum Cross Correlation (MCC) pattern matching method is based on calculating cross-correlation coefficients (Emery *et al* 1986; Kamachi 1989; Gao and Lythe 1998). Statistically cross-correlation is a measure of the linear relation of two random variables. The cross-correlation coefficient is given by Kreyszig (1970)

$$\rho = \frac{\text{cov}(x, y)}{\sqrt{\text{var}(x)\text{var}(y)}} \quad (3)$$

where x and y represent random variables from a two-dimensional population, and var, cov are the variance and covariance of the random variables. By definition $-1 \leq \rho \leq 1$.

The computation method for deriving sea surface advective velocities consists essentially of identifying the maximum cross-correlation in a lagged matrix between two sub areas of a pair of sequential scenes. The first image is divided into continuous sub areas called template window. The size of this window is taken as 64×64 pixels. For the template, a large search window was identified in the second image, having the template as its centre. In the Cartesian coordinate system $f(x, y)$ and $g(x+p, y+q)$ denote a possible pair of similar patterns in two time lapsed images. The vector (p, q) represents a possible spatial displacement of the original pattern between the two images. The cross-correlation matrix is formed as (Wu *et al* 1992):

$$\rho(p, q) = \frac{\text{cov}\{f(x, y), g(x + p, y + q)\}}{\sqrt{\{\text{var}[f(x, y)]\text{var}[g(x + p, y + q)]\}}}. \quad (4)$$

Since the computation of the cross-correlation matrix is time consuming, a significant reduction of computational effort can be achieved by working in the frequency domain using the Fast Fourier Transform (FFT) techniques. Use of the FFT has its limitations. It restricts one to square regions or at least rectangular regions. It is fast but requires integral length of the data series thus avoiding any irregularities due to cloud cover, coastline etc.

Using the procedure given by Leese *et al* (1971) and Ninnis *et al* (1986) for FFT, cross-correlation coefficients, between the template and searching kernels are calculated. For 128×128 search window and 64×64 template window, a matrix of 65×65 cross-correlation coefficients are calculated. From this matrix, maximum cross-correlation coefficient and corresponding $x$lag ($p\,$max), $y$lag ($q\,$max) are found. Figure 2 shows the schematic of feature tracking using the above approach.

The MCC method indicates the actual flow during a specific period (average of two-time lapsed images), i.e., integrating tidal and wind influences.

The maximum cross-correlation in the relative displacement (p, q) between the template and the search windows of the sequential scenes determines the advective velocity vector; the magnitude of which is given by Garcia and Robinson (1989) as:

$$C = \frac{\sqrt{(p\max\Delta x)^2 + (q\max\Delta y)^2}}{\Delta t}, \quad (5)$$

and the direction of motion, θ, can be calculated as

$$\theta = \arctan\left[\frac{q\max\Delta y}{p\max\Delta x}\right]. \quad (6)$$

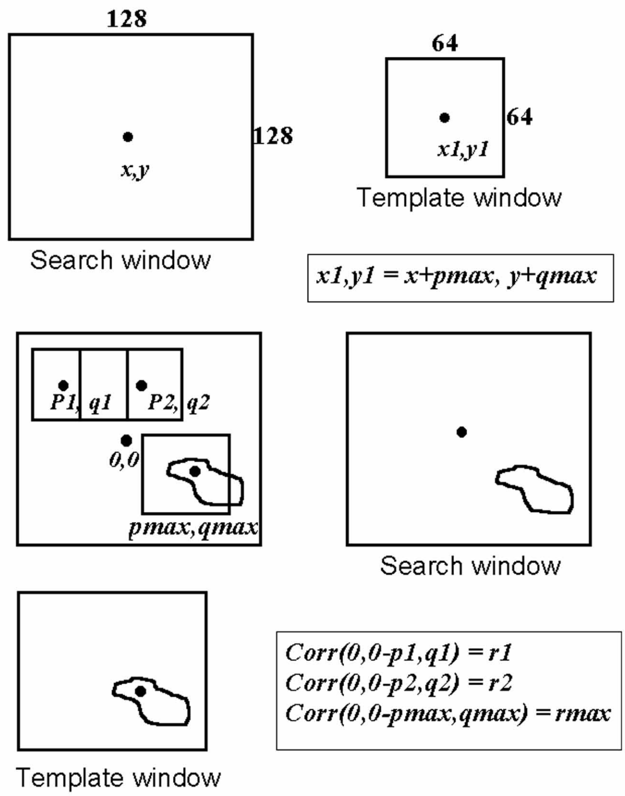

Figure 2. A schematic of the use of maximum cross-correlation technique for pattern matching.

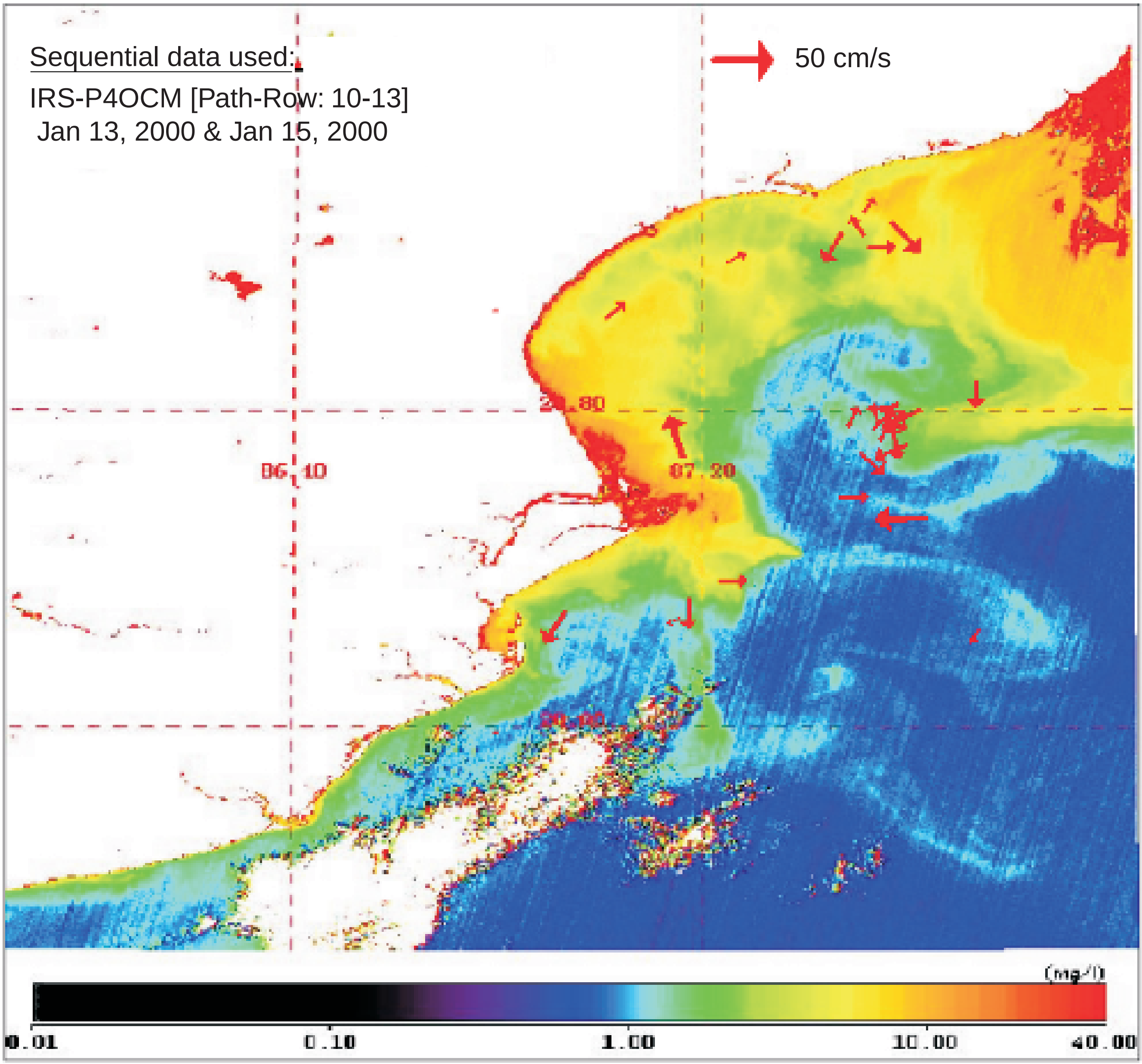

Figure 3. Advective sea surface velocities derived from sequential IRS-P4 OCM suspended sediment imageries (January 13th and 15th, 2000) over Dhamra estuary, north Bay of Bengal.

3. Results and discussions

The patterns of ocean colour on sequential images are used as tracers to measure displacements of surface waters. The velocity derived, as a measure of this transport is known as the advective velocity. The spatial resolution was one of the major constraints for achieving the desired accuracy (Garcia and Robinson 1989; Wu *et al* 1992). IRS-P4 OCM data has improved spatial resolution and distinct signatures of suspended sediments acting as tracer and hence they were analysed to derive the advective velocities. Figure 3 shows the velocity vectors overlaid on suspended sediment concentration map derived from IRS-P4 OCM data of January 13th, 2000. The current velocities retrieved were compared with simultaneous data collected along the east coast of India. The current data were measured using ocean current meter supplied by the Environmental Measurement and CONtrol (EMCON), Kochi; available with the Geological Survey of India, Marine Wing. This current meter can measure direction and magnitude with an accuracy of ±5° and 2% respectively. The resultant magnitude and direction were calculated by averaging 10 and 50 readings respec-

Table 1. *Comparison of in situ current vectors and advective velocity vectors derived by maximum cross-correlation pattern matching method applied on sequential (January 13th and 15th, 2000) IRS-P4 OCM data covering north Bay of Bengal.*

Sr. No.	Latitude (°N)	Longitude (°E)	*In situ* magnitude ($cm.s^{-1}$)	Derived magnitude ($cm.s^{-1}$)	*In situ* direction (°)	Derived direction (°)
1.	19.05	85.47	6	9.5	195	210
2.	20.97	87.16	12	10.0	312	288
3.	20.02	87.21	10	12.0	71	84
4.	21.07	87.16	15	13.5	185	172
5.	20.83	87.21	15	13.6	60	65
6.	20.97	87.26	16	15.9	73	75
7.	21.07	87.26	16	17.5	217	216
8.	20.91	87.26	20	18.6	253	278
9.	20.97	87.31	23	21.9	45	45
10.	20.71	87.31	26	23.9	255	280
11.	20.91	87.31	22	23.9	330	338
12.	21.08	87.21	24	25.0	193	188
13.	20.96	87.21	28	28.2	50	47
14.	19.12	85.60	35	29.4	260	270
15.	20.66	87.28	29	32.6	200	205
16.	20.97	87.36	41	39.8	216	208
17.	20.02	87.36	46	48	178	181

tively up to 5 m depth during the IRS-P4 OCM pass time (around 12 noon) for each location

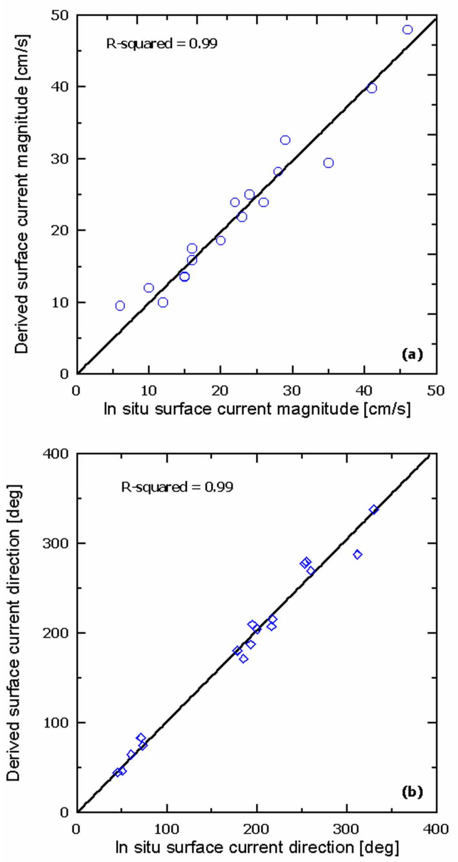

Figure 4. A plot of *in situ* surface current magnitudes vs the derived current magnitudes **(a)** and a plot of *in situ* surface current directions vs the derived surface current directions **(b)**.

used in this study. The Global Positioning System (GPS) of the ship was used for the geographical location measurements, whose accuracy is within meters far within the threshold location accuracy of around 1 km for OCM standard data products. The pair of the images could be co-registered within an error limit of one pixel (here 360 meters). Table 1 shows the *in situ* current vectors (13th and 15th January, 2000 off Dhamra estuary, north Bay of Bengal) and the advective velocity vectors derived by maximum cross-correlation pattern matching method applied on sequential (January 13th and 15th, 2000) IRS-P4 OCM data. The coefficient of determination, R-squared is 0.99 for both magnitude (in cm s^{-1}) and direction (in deg.) (figure 4).

This study demonstrates the feasibility of applying the maximum cross-correlation method to sequential IRS-P4 OCM data in order to generate vector fields representing the transport velocity of optically visible near-surface tracers.

Acknowledgements

The authors express their sincere gratitude to Dr. A K S Gopalan, Director SAC and Dr. R R Navalgund, presently, Director, NRSA, Hyderabad and earlier Deputy Director, RESA, SAC for their guidance and valuable suggestions during the course of this study. They are also thankful to Dr. N Sengupta, the then Deputy Director General, Marine Wing, Geological Survey of India for providing the opportunity to collect sea truth data during R.V. Samudra Kaustubh Cruise

ST-133. Thanks are also due to the two anonymous reviewers for their constructive comments which have greatly improved the presentation of this work.

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