Near-coastal surface water velocity field estimation using airborne remote sensing

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ABSTRACT

The study of surface water velocity fields through *in situ* sampling is intrinsically difficult because they are highly variable in time and space. With airborne remote sensing, however, it is possible to determine synoptic changes in velocity fields because spatially and temporally comprehensive data may be obtained. This paper shows how changes in the statistical properties of successive remotely sensed images may be used to estimate velocity vectors associated with chlorophyll-*a* and sea surface temperature (SST). The study area is Kirkcudbright Bay, a small estuary in south-west Scotland. Multi-temporal imagery of the study area were acquired by the NERC Daedalus ADDS-1268 Airborne Thematic Mapper (ATM) and processed to show chlorophyll and thermal indices as substitutes for chlorophyll-*a* and SST. Velocity fields were estimated by the Maximum Cross Correlation technique. Complex patterns were found, confirming that the comprehensive coverage provided by airborne remote sensing is required for their analysis. The chlorophyll-*a* velocity field differed from the SST velocity field, suggesting that these fields are relevant to the water quality parameter in question, and not necessarily the water body itself.

Keywords and phrases: airborne remote sensing, velocity vectors, chlorophyll-a, sea surface temperature, maximum cross correlation, Kirkcudbright Bay

1.0 INTRODUCTION

Coastal zone velocity fields exhibit considerable heterogeneity, manifested in secondary flows of a variety of spatial and temporal scales (Ferrier et al., 1996, Ferrier and Anderson, 1996) which are superimposed on the primary tidal flow (Folkard, 1997). The complexity of these velocity fields means that, for their successful study, comprehensive data (both spatially and temporally) must be obtained. Traditional *in situ* instruments provide ample temporal but poor spatial coverage. Recent developments such as the Ocean Surface Current Radar, can provide this same temporal coverage combined with synoptic spatial coverage, but only at a spatial resolution of typically one square kilometre (Hammond *et al.*, 1987). Although airborne remote sensing cannot provide the temporal coverage required by end-users, it is able to provide spatially comprehensive coverage at a much higher resolution than ground-based instruments. This could then complement the temporally comprehensive but spatially sparse coverage of *in situ* instruments.

Two approaches can be taken towards deducing velocity fields by comparing sequential remotely sensed images. The first views the scalars that determine the radiative or emitted intensity recorded at the instrument - chlorophyll-*a* concentration and sea surface temperature (SST) in the present study – can be assumed to act as passive tracers of water flow. This requires that processes other than horizontal advection of these parameters - for example, atmospheric heat exchange, vertical mixing, and upwelling/downwelling - are either "filtered out" during processing or demonstrated to be insignificant in relation to horizontal advection of the parameters, which is the process assumed implicitly within the Maximum Cross Correlation (MCC) scheme adopted. The alternative approach is to view the velocity field as that of the scalar itself rather than of the waterbody. This is meaningful if the scalar is biological – algal blooms, for example, may spread by means other than advection, and this spreading is of direct environmental and economic relevance. However, for physical scalars such as temperature, the utility of such a velocity field is less clear.

Determination of velocity fields through optical and infra-red remote sensing involves comparisons of similarities or dissimilarities between a sequence of two or more images. A common approach compartmentalises the images into cells, and seeks correlation in pattern between cells from different images. For example, the MCC technique estimates the cross-correlation between small cells within one image and cells in a subsequent image within a given search window. The velocity vector for a cell is then determined from the displacement between a cell's position in the first image and the position of the cell in the second image with which it has a maximum cross-correlation.

Repeating the process for grids throughout the image gives a synoptic velocity field. MCC has been applied as a standard technique to mesoscale oceanic phenomena using coarse spatial resolution satellite images (e.g. Garcia and Robinson, 1989; Emery et al, 1991). The highest resolution imagery to which it has been applied has been 100m per pixel MAMS data for investigating sea surface velocities (Pope and Emery, 1994). The ability to apply this approach to the coastal zone would be of significant advantage, given that complex, though coherent, patterns in either chlorophyll-a or suspended sediment are evident in remotely sensed data (Malthus et al. 1996). However, a limitation to the application of such approaches to finer scale phenomena such as those occurring in coastal waters has been the lack of satellite data obtained at suitable spatial and temporal resolution. Patterns observed in the coastal zone are frequently variable on spatial and temporal scales significantly less than 100 m and one hour, respectively. However, the presence of patterns in both these parameters, as well presumably as in temperature suggests that very accurate velocity maps could be deduced from such multi-spectral imagery of the coastal zone. This paper reports for the first time the application of the MCC technique at spatial resolutions an order of magnitude higher. The use of airborne data in place of the satellite data also allows a much higher temporal resolution, enabling motions at sub-tidal periods to be assessed by this method for the first time.

1.1 Study Area

Kirkcudbright Bay is an estuary on the northern side of the Solway Firth in south-west Scotland (Figure 1). Synoptic velocity fields at the Bay – Firth interface show a semi-diurnal pattern (Hydrographic Office, 1992), which concurs with the general tidal pattern in the Solway Firth. There is a net displacement of water out of Kirkcudbright Bay before low tide (at approximately 12:30 Hours) and a net displacement of water into the bay after high tide. This displacement concurs with a flow of water out of the Solway Firth into the Irish Sea before low tide, and into the Solway Firth after low tide.

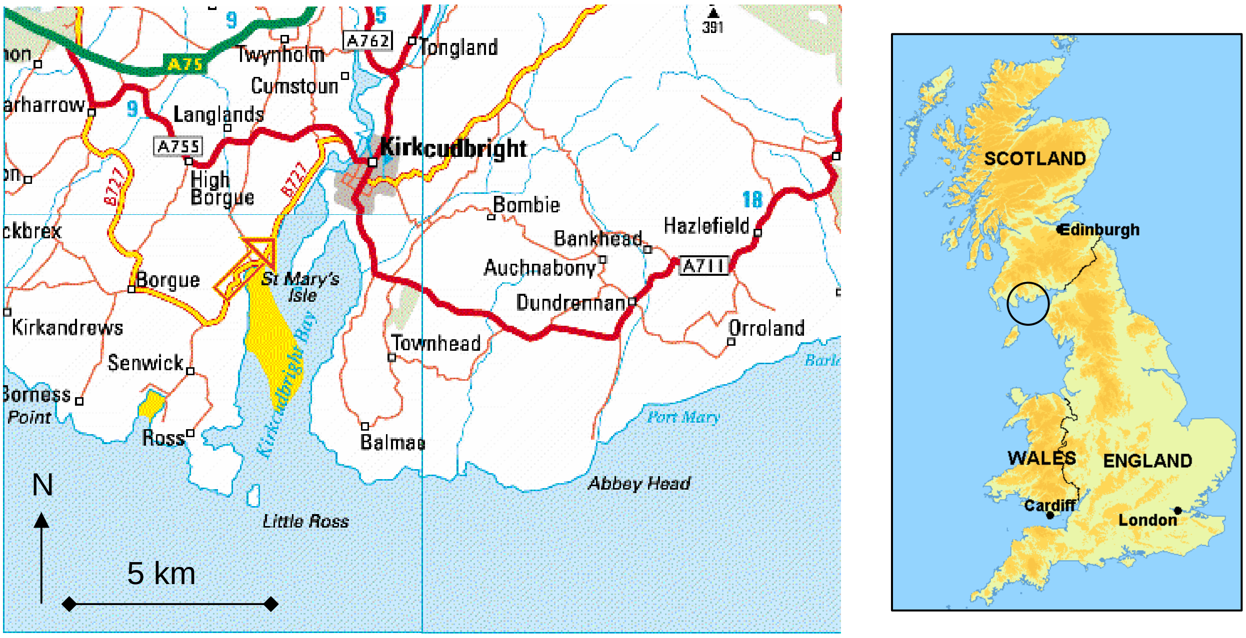

Figure 1. Map of general study area

2.0 METHODS

Repeat overflight images of Kirkcudbright Bay, were acquired by the Natural Environmental Research Council Airborne Thematic Mapper (ATM) at 10:12 and 10:22 Hours on 26 September 1997. The ATM is a multispectral scanner which collects radiance information of the surface in 11 spectral channels in the visible and near, middle and thermal infrared spectral regions. Individual bandwidths range from approximately 30 - 300 nm across the spectral range from 420 to 13,000 nm. Modifications to the NERC ATM instrument have improved the radiometric performance of the instrument from 8 bit to 12 bit digitisation accuracy. Along with the image data, navigation data were also simultaneously acquired by an Ashtech 3-DF GPS position and attitude referencing system, recording GPS positions from four separate antennae fitted in a rigid cruciform shape on the roof of the aircraft. Absolute position of the aircraft was provided by a second GPS receiving station based at CEH, Monks Wood, Cambridgeshire. The estimates of both aircraft attitude and absolute position are used for the subsequent automated geometric rectification of the imagery during post-processing on the ground.

Concurrent with the collection of the airborne data, the positions of three drogues were recorded, showing the mean surface current velocity within Kirkcudbright Bay was approximately 0.3 m s^{-1}, with the direction being towards the south (consistent with the general displacement expected before low tide).

Following initial geometric correction using the navigation data, the images were co-registered and rectified to a ground spatial resolution of 5 m by 5 m, the maximum possible resolution given the ATM Instantaneous Field of View and flying altitude (2000 m). Chlorophyll-*a* concentrations and SST were characterised by chlorophyll and thermal indices. The chlorophyll index used a band ratio of Channel 3 (520-600 nm) over Channel 2 (450–520 nm). This measures the amplitude of the chlorophyll absorption peak, and has been used successfully for estimating chlorophyll-*a* in oligotrophic conditions (Gordon *et al.*, 1983). The thermal index used Channel 11 data. Conversion to absolute values was unnecessary because the MCC technique depends upon gradients in intensity rather than absolute values.

For the purposes of this preliminary investigation, only a small area in the southern part of Kirkudbright Bay was used (Figure 2). Areas towards the northern part of the bay were excluded because of the possibility of bottom reflectance due to shallow water. Processed images were smoothed with a 30 × 30 mean filter, and the first image was compartmentalised into cells of 30 by 30 pixels. The cell size was determined as a compromise between resolving small-scale spatial variation and determining distinctive spatial distributions. The equal size of the smoothing filter to the cell ensured that noise, which might create spurious cross correlations, was removed. The search window size was chosen to encompass the displacement between the times of image acquisition – typically 300 m according to the simultaneous *in situ* drogue measurements. A search window size of 450 m by 450 m (90 pixels by 90 pixels) was chosen.

Cross-correlations were calculated between each cell in the first image and all areas of equivalent size in the second image within the search window. The velocity vector for each cell was derived from the displacement from its centre in the first image to the centre of the cell of maximum cross-correlation in the second image. Estimated velocity fields were smoothed through the use of non-parametric local regression.

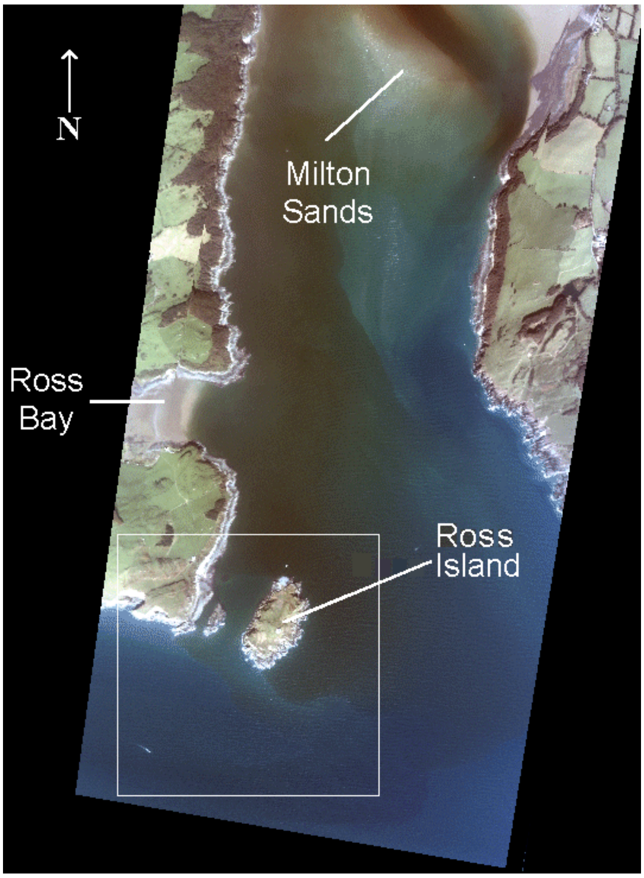

Figure 2. 'True' colour composite of ATM data showing the Kirkcudbright Bay – Solway Firth interface and focused study area (superimposed square).

3.0 RESULTS

Clear north-east to south-west gradients existed in both chlorophyll-*a* (Figures 3a and 3b) and SST (Figures 4a and 4b), marking the change from Bay to Firth waters. The pattern displayed is one of a gradient of nutrient rich and cooler waters of estuarine origin mixing with nutrient poorer and warmer waters of maritime origin. This suggests that, at the time of the acquisition of the first image, the current was in a north-east to south-west direction. Previous measurements of circulation (Hydrographic Office, 1992) support this. However, the estimated displacement from the first to the second image (Figures 3a to 3b, and Figures 4a to 4b) suggests that there is an eastward element to the displacement south of the estuary. For example, the chlorophyll-*a* front in cell ‘g2’ of Figure 3a was displaced to cell ‘g3’ of Figure 2b. It is inferred, therefore, that the high chlorophyll-*a* concentration plume was a residual feature from before the imaging time.

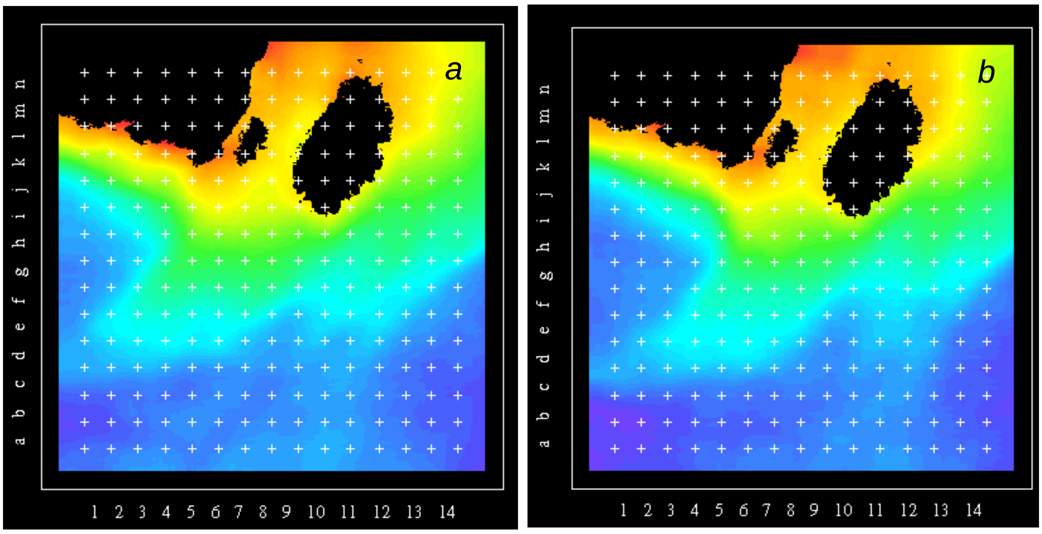

Figure 3. Chlorophyll index of Ross Island area of Kirkcudbright Bay: a) 10:12 hours; b) 10:22 hours

Smoothed MCC estimates of the velocity field concurred with the qualitative interpretation of the images. The velocity field of chlorophyll-*a* (Figure 5a) was similar to that of SST (Figure 5b), both fields showing an overall displacement towards the south and east. However, local differences existed; the chlorophyll-*a* velocity field exhibited more small-scale variation. For example, chlorophyll-*a* velocity vectors from cell ‘e6’ to cell ‘f7’ diverged from the overall displacement, whereas the SST velocity vectors in these cells concurred with the overall displacement.

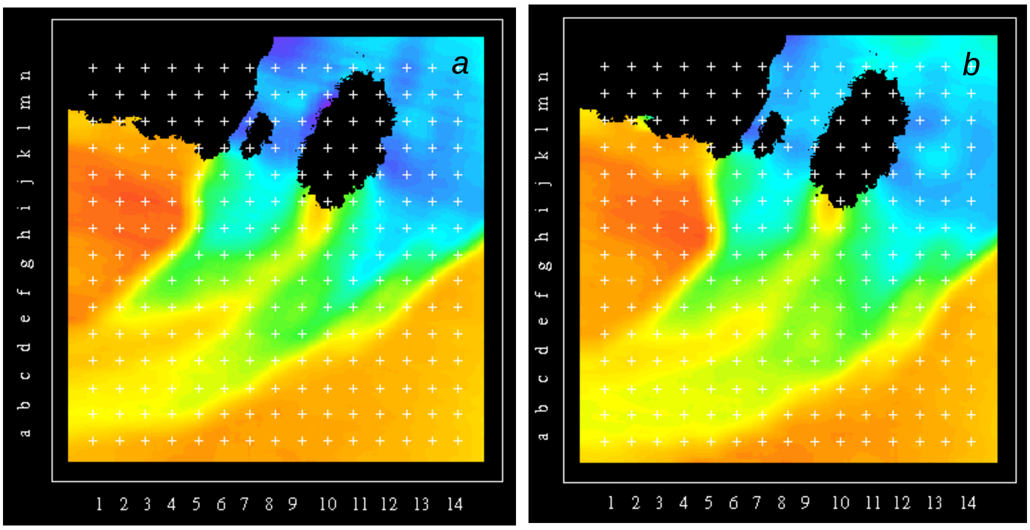

Figure 4. Thermal index of Ross Island area of Kirkcudbright Bay: a) 10:12 hours; b) 10:22 hours.

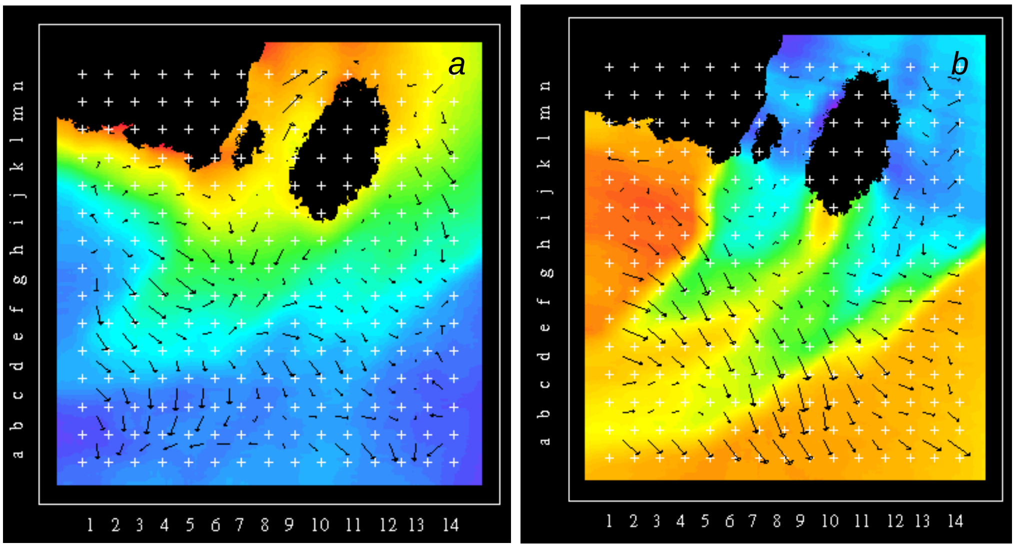

Figure 5. Velocity fields of water around Ross Island area of Kirkcudbright Bay (10:12-10:22 hours): a) chlorophyll index; b) thermal index.

4.0 DISCUSSION

This paper has shown MCC to be an effective technique for determining general chlorophyll-*a* and SST velocity fields in the coastal zone, although the incoherence of the unsmoothed velocity fields illustrates the limitations of MCC's application to a shallow coastal environment. Closer inspection of the individual vectors shows that some concur with a subjectively derived mapping of the earlier image onto the later one, whereas others link two apparently unconnected elements of the pattern. Two reasons are proposed. Firstly, pattern at the search window scale may remain constant even if there is displacement within the scalar field. For example, displacement along (rather than across) a front, or displacement in a homogeneous image, does not change the window's pattern, and produces no MCC vector. Secondly, the pattern within an individual cell may alter between successive images because of non-advective processes. This may be why the velocity vectors to the north-east of Ross Island (m10 in Figure 4a and Figure 4b) did not show a southward displacement of chlorophyll-*a* or SST.

The lack of coherence of the velocity vectors produced, and the extent of smoothing required to approach hydrodynamic continuity of mass also illustrate the limitations of MCC application to a shallow coastal environment. Closer inspection of the individual vectors produced show that some concur with an intuitive interpretation of the velocity field that would map the earlier image pattern onto the later one, whereas others link two apparently unconnected elements of the pattern. This problem may be overcome by using the data produced as input to an inverse hydrodynamic model (e.g. Copeland, 1994), which would force the field to converge to a hydrodynamically realistic solution (i.e. one which obeyed continuity of mass and momentum).

Circulation at the Bay-Firth interface was shown to be complex. Rather than the expected displacement towards the south-west in the Solway Firth (following the path of an ebbing tidal current), there was an eastward displacement. This suggests the existence of a clockwise eddy as the flow exits the bay past Ross Island into the Firth. Such a feature would be expected to arise from separation of flow accelerated through the channel between the coast and the island. This intuitively concurs with the expected acceleration of the flow as it passes by the island, through the narrow channel between the island and the coast. Such an acceleration would tend to enhance the flow separation process.

The velocity field produced from chlorophyll-*a* images was different from that produced via the SST images. This is considered to be because chlorophyll-*a* and SST patterns undergo changes for reasons other than advection, although this is expected to be the dominant mechanism. Additionally, chlorophyll-*a* images were derived from a greater part of the water column than the SST images (the top few metres rather than the top few micrometres) so will have included effects of sub-surface velocities. This is a potentially useful quality for the development of the technique as it may be possible to use it to deduce 3-dimensional flow fields.

5.0 CONCLUSION

MCC analysis of successive remotely sensed images was an effective method for determining velocity fields of chlorophyll-*a* and SST at the interface of Kirkcudbright Bay and the Solway Firth. Limitations of MCC were evident but, in general, synoptic velocity fields consistent with the expected pattern were clearly shown. Velocity fields of chlorophyll-*a* differed from those of SST, suggesting that estimates of water body velocity fields obtained from drogues or radar remote sensing are inadequate for estimating velocity fields of water quality properties. Thus, remotely sensed imagery offers a unique method of investigating estuary and coastal zone water quality dispersion patterns.

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