Tongue of Ionisation Motion Estimation from Polar TEC Sequences

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***Abstract*—A new approach to tracking the ionospheric storm enhancements known as tongues of ionisation is presented. In contrast to conventional model-based methods, the technique works by applying block-based motion estimation methods directly to ionospheric total electron content image sequences. Solutions to the particular problems posed by the low image resolution and the non-rigid motion of the tongue of ionisation are proposed. Experimental results for an image sequence covering the 2003 "Halloween storm" establish that the approach produces estimated motion fields that show a good correspondence with the observable motion when the inter-frame differences are not extreme.**

I. INTRODUCTION

During geomagnetic storms, characteristically shaped enhancements can form in the ionosphere and be carried across the poles by convection. These enhancements are known as tongues of ionisation (TOI) and their motion is of interest to engineers trying to quantify their effect on communication systems and to scientists studying atmospheric dynamics [1], [2].

Previous approaches to analysing the behaviour of the TOI during storms can broadly be categorised into two classes. The first of these uses convection patterns to provide information on the plasma motion, where the motion of interest is the that of the TOI itself. This has traditionally been performed using models, e.g. [3] or $\mathbf{E} \times \mathbf{B}/B^2$ velocity vectors provided by electric and magnetic field models and measurements. While modelled data are very useful for providing large-scale overviews of expected behaviour and increasing physical understanding, the benefits of their use to study ionospheric storm-time behaviour are less clear as storms, by their nature, represent large deviations from normal conditions. Alternatively, radar observations of ion velocities can be used to provide direct motion estimates and hence information about the plasma convection patterns. However, the vectors provided by sources such as SuperDARN [4] and the EISCAT radar are typically sparse and can also have large uncertainties, making them unsuitable for the analysis of some storm events [5]. Furthermore, approaches based on observed or modelled vectors are unable to provide any information about plasma density.

The second class of techniques for studying the TOI are those based on tomographic imaging [6], [7]. Tomographic imaging systems perform inversions on electron data enabling three-dimensional, time-varying total electron content (TEC) images of the polar ionosphere to be routinely produced. In contrast with convection-based approaches, tomographic imaging produces TEC image sequences in which regions of enhanced electron density such as TOI can clearly be identified. However, they do not give any quantitative information about the motion of such enhancements. Consequently, previous motion analysis of TOI based on tomographic imaging has employed qualitative description rather than quantitative measurements. For example, Spencer and Mitchell presented data from TEC visualisations of the October 2003 storm and suggested that there was visible convection of uplifted plasma around the polar cap [7]. Middleton et al. examined a storm which occurred during November 2001 and found that a tongue of photoionisation was drawn antisunward by the convection pattern [6].

This paper aims to provide a fuller picture of the evolution of TOI by augmenting the visualisations of the TEC amplitude provided by tomographic imaging with quantitative motion vectors. In particular, it investigates the feasibility of applying image motion estimation techniques directly to the TEC sequences to derive full field estimates of the TOI motion. This approach is similar in spirit to that of Bust and Crowley, who have combined the three-dimensional maps of ionospheric structure with two-dimensional trajectories obtained from an inversion-based assimilation algorithm [8]. However, it differs in that the motion vector fields are derived directly from the TEC sequences using template-based motion estimation algorithms, as opposed to being trajectories based on calculated convection patterns. In addition, the techniques presented here are computationally simple and can be run in small fractions of a second on commodity hardware.

Template matching using the maximum cross-correlation (MCC) method has been widely used to estimate motion in many geoscience applications, for example deriving cloud motion vectors [9] and estimating sea surface currents [10]. To successfully apply MCC-based motion estimation techniques to ionospheric TEC images two main problems must first be overcome: (1) the non-rigid motion of the TOI and (2) the low-resolution of the TEC images.

As the TOI are non-rigid features, their motion is hard to track using the MCC method alone. Previously, this problem has been addressed by the application of an additional smoothness constraint to the initial motion estimates, in the form of a relaxation-labelling stage [11]. This approach has been successfully applied to ocean currents, glacier surface motion [12] and cloud tracking [13]. This letter investigates the suitability and performance of the combined correlation-relaxation labelling approach when applied to ionospheric TEC images.

The second problem is the low-resolution of the TEC images. This is a direct consequence of the limited number

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of global positioning system (GPS) receivers in the northern polar region, through which TOI flow. Direct application of block-based template matching to these low-resolution images results in a motion vector field that is both spatially sparse and consists of vectors of limited resolution. In this letter we seek to address these issues by using overlapping blocks to give denser motion vectors and sub-pixel motion estimation to provide higher resolution vectors. Finally, the use of a further smoothing stage consisting of a vector median filter (VMF) [14] is investigated.

The format of this letter is as follows. Section II describes the TEC data used in this study. Section III briefly explains the template matching method of estimating motion and the use of overlapping blocks and sub-pixel estimation. The relaxation labelling and post-filtering steps are also described. In Section IV, the results of applying the motion estimation techniques to the data described in Section II are presented. Finally, Section V presents conclusions and discusses the ramifications of these results for TOI motion estimation.

II. POLAR IONOSPHERIC TEC MAPS

TOI are convective patterns consisting of regions of enhanced electron density, for example see [1], [2], [7]. The TOI typically appear at lower latitudes before moving into the northern polar region. The data used for this study consisted of a sequence of TEC images covering the peak of the well known "Halloween storm", from 20:00 to 23:00 UTC on 30th October 2003, with a temporal resolution of five minutes. The TEC sequence was produced using the MIDAS software from the University of Bath [7], [15]. MIDAS performs tomographic inversions using path measurements of electron content between GPS receivers and satellites. It has previously been demonstrated that this technique is accurate during this storm event by comparisons with data from EISCAT [7].

The maximum resolution of an output field from any given inversion algorithm is heavily dependent on the number of available path measurements. Thus the number of GPS receivers is an important factor in determining output resolution. There is a strong correspondence between population density and the number of GPS receivers in a given area, such that the achievable resolution of the TEC images varies with geographic location. For example, over North America, there are over 500 GPS receivers operated by the International Global Navigation Satellite System Service, whilst in the northern polar region through which TOI convects the number of receivers is considerably lower. In practice this means that the TEC images of TOI produced by MIDAS are characterised by low resolution.

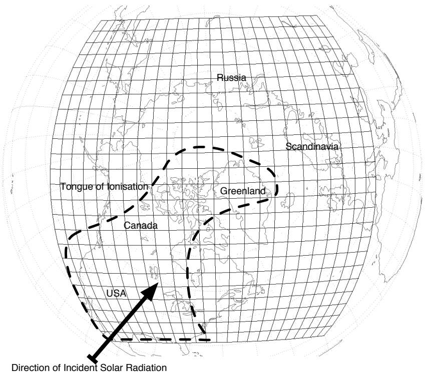


Fig. 1: Correspondence between the 25 × 25 TEC pixel grid and the Earth's surface. The position of the TOI from 2a is indicated with a dashed line. The direction of incident solar radiation is also shown and will precess as the Earth rotates during the 3 hour storm period.

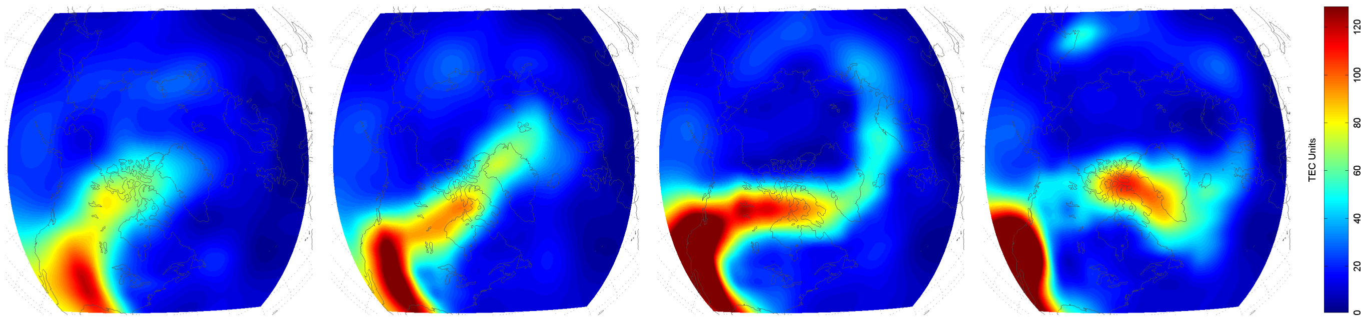
Each frame of the sequence was formed by inverting GPS path measurements on to a thin shell at an altitude of 400 km to produce a 25×25 pixels image corresponding to a grid covering a 100° square region centred on the north pole. The relationship between the pixel grid and the Earth's surface, and the direction of incident solar radiation are shown in Fig. 1. To produce the inputs for the motion estimation algorithms, each frame was upsampled by a factor of two, resulting in a sequence of 36, 50×50 pixels TEC images covering the 3 hour storm period.

Fig. 2 shows visualisations of four frames from the sequence, each separated by 50 minutes. These frames are typical of those used in TEC imaging of TOI and were formed by upsampling each 25×25 pixels image by a factor ≈ 10 and then displayed using a false-colour contour plot. Fig. 2a–2c clearly show a growing region of enhancement which then splits off in Fig. 2d. In the full sequence animation provided, it is possible to track the TOI by eye as it migrates northwards. However, when the enhancement separates from the main body during the latter stages of the sequence it is hard to determine the underlying motion. In particular, the direction of the apparent motion is reversed as the TOI appears to retreat due to electron recombination. This should be borne in mind when trying to automatically identify the motion of the TOI; what is hard for humans is likely to be very challenging for computer vision.

This study investigates the suitability of block-based template matching techniques for estimating the inter-frame motions directly from the TEC image sequence, with the overall aim of tracking TOI through the storm period. For template-based motion estimation techniques, the challenges to be overcome are those posed by the motion of the non-rigid TOI and the low resolution of the images. These are addressed in the following section.

III. TEMPLATE-BASED TOI MOTION ESTIMATION

Template matching is a motion estimation methodology based on matching small image patches between temporally adjacent frames. Typically, this is performed by splitting the input image into a number of tiles and then matching each tile with overlapping areas within a predefined search area in the second image. The goodness of the matches are assessed using similarity or dissimilarity measures, the most popular of which is the cross-correlation coefficient (CCC). The result of the matching stage is a correlation surface which gives the CCC for all displacements in the search area. Selecting the position with the highest CCC gives rise to the well known MCC method of motion estimation [10].



(a) 20:00 UTC (b) 20:50 UTC (c) 21:40 UTC (d) 22:30 UTC (e)

Fig. 2: Example false-colour frames from the TEC images sequence for the Halloween storm on 30th October 2003, each separated by 50 minutes. The colour scale is shown in (e).

Although the MCC motion estimation method is widely used in remote sensing, for example to derive cloud motion vectors from infrared imagery [9], its underlying assumption of rigid-body motion does not always hold for objects such as clouds, ocean currents and TOI. In these cases, the correlation surfaces are typically both multi-modal and noisy, making the simple MCC strategy ineffective. For example, Dransfeld *et al.* recently applied MCC-based motion estimation to high resolution thermal imagery and found that it was unable to provide locally consistent fields which were representative of small-scale ocean currents [10]. One way to overcome this problem is to use relaxation labelling to impose an additional smoothness constraint on vectors from the correlation surface.

Correlation-relaxation labelling was first proposed by Wu [11] and provides a probabilistic framework for regularising vector fields using a local smoothness constraint. Unlike the MCC method, which only selects a single match position for each template, correlation-relaxation labelling considers a set of candidate vectors, typically consisting of the N highest CCC positions. If $\mathcal{C}_J$ is the set of candidate vectors for template J, the initial probability that the template has a vector j is denoted $P^{(0)}(J \to j)$ and found by normalising the CCC for the N vectors $j \in \mathcal{C}_J$.

The initial match probabilities are then iteratively refined according to their compatibilities with the candidate vectors belonging to templates within a local neighbourhood using a non-linear relaxation formula [12],

$$P^{(n+1)}(J \to j) = \frac{P^{(n)}(J \to j)Q(J \to j)}{\sum\limits_{\lambda \in \mathcal{C}_J} P^{(n)}(J \to \lambda)Q(J \to \lambda)} \qquad (1)$$

$Q(\cdot)$ is the support function that assesses how compatible the proposed vector labelling $J \to j$ is with those in the local neighbourhood G_J,

$$Q(J \to j) = \prod_{I \in G_j} \sum_{i \in \mathcal{C}_J} P^{(n)}(I \to i) R(J \to j, I \to i) \qquad (2)$$

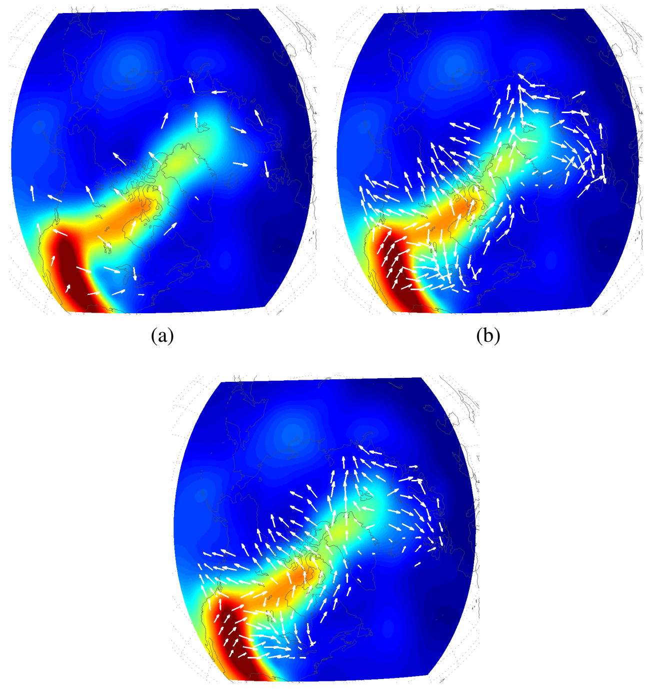
where the mutual information measure $R(J \to j, I \to i)$ gauges the compatibility between the vectors $J \to j$ and $I \to i$. Here, a simplified form of $R(J \to j, I \to i)$ is used, that only considers candidate vectors for neighbouring templates [13]. The overall number of iterations used can be set manually or by using a pre-determined stopping criterion.

By imposing local consistency on the motion vectors, the relaxation labelling technique can be used to reliably estimate the motion of non-rigid objects in situations where the MCC motion fields are noisy and inconsistent. This has previous been demonstrated for a number of remote sensing applications, see for example [11]–[13]. Here, the ability of this approach to estimate the non-rigid TOI motion is investigated.

The second problem is the low spatial resolution of the TEC image sequence. This leads to several small issues, each of which must be addressed. Firstly, an appropriate block size must be selected. In general, smaller blocks provide vectors that are well localised but noisy, while larger blocks provide less localised vectors but with better noise immunity. When using low resolution images, the problem of selecting a block size to satisfy these two conflicting requirements is exacerbated. Using overlapping blocks is a suitable compromise, as it produces vector fields that are both smooth and dense, albeit at the expense of increased computational cost.

The low resolution of the TEC images results in estimated motion vectors with correspondingly low resolution. This issue has been addressed in part by upsampling the original images by a factor or two. Whilst not adding any new information, this procedure also allows the use of larger block sizes in the template matching stage. To further mitigate the problem, motion vectors with sub-pixel accuracy can be found by upsampling the second image before the correlation-matching process is carried out.

Finally, the low resolution TEC images are characterised by limited textural content. This is a problem which manifests in smooth images which lack the high frequency information that is requisite for successful template matching. Limited texture results in correlation surfaces that are smooth and contain many high CCC values. These problems mean that accurately discriminating between the true motion and anomalous matches is very difficult. Although the relaxation labelling process can overcome this to some degree, when the quality of the input vectors is low it can only select the “least bad” vector from the candidate set. To fully overcome this problem, we propose applying a VMF [14] to the relaxed motion field.



(a) (b)

(c)

Fig. 3: Motion vectors for the frame from 20:50 UTC (see Fig. 2b) using 5×5 blocks. (a) MCC with non-overlapping blocks, (b) MCC with overlapping blocks and (c) overlapping blocks with relaxation labelling. For clarity, the vectors in (b) and (c) are subsampled before displaying.

IV. EXPERIMENTAL RESULTS

The effectiveness of the various motion estimation methods was evaluated using the TEC image sequence described in Section II. All experiments used 5×5 blocks and a search radius 5 pixels. Motion vectors were found to a half-pixel accuracy which gives rise to a spatial resolution of $1°$. As we are only interested in TOI motion, templates in the image background were not considered for matching. In practice, this was achieved by thresholding the variance of the templates, such that $\sigma^2 > 16$. Finally, for display purposes, the vector fields were all down-sampled by a factor of three, allowing easier comparisons to be made throughout and between the images in the sequences.

Fig. 3a shows the motion fields produced using the MCC method with non-overlapping blocks for the 50×50 pixels TEC image from 20:50 UTC whose visualisation is shown in Fig. 2b. Results for the entire sequence for this and subsequent Figs. are included with this submission. The vectors produced by this method are sparse and show some local inconsistencies. The sparsity of the output can be reduced by applying the MCC method to overlapping blocks, see Fig. 3b. However, whilst this improves the visualisation of the motion of the TOI, there are still many instances of locally inconsistent vectors, for example where adjacent vectors have very disparate directions, which show a flow that is not consistent with the underlying physical models. This clearly demonstrates that the MCC method alone is unable to accommodate the non-rigid motion of the TOI.

Applying relaxation labelling to the motion fields produces smoothed fields such as that shown in Fig. 3c. The candidate vector sets required for the relaxation labelling were generated by thresholding the CCC at 0.2. This contrasts with previous studies (e.g. [13]) which used higher threshold values, as the smaller templates used here yield fewer high-quality matches. Ten iterations of the relaxation labelling algorithm were applied. The relaxed results are clearly an improvement on those produced by the MCC method, particularly in the earlier part of the sequence. This can be seen by comparing the rightmost group of vectors in Figs. 3b and 3c, where the latter are more locally consistent, and in the full sequences provided. Despite the improved smoothness relative to Fig. 3b, problems with large changes in direction are still prevalent towards the end of the sequence, where the TOI extends and then splits into two regions of enhanced density.

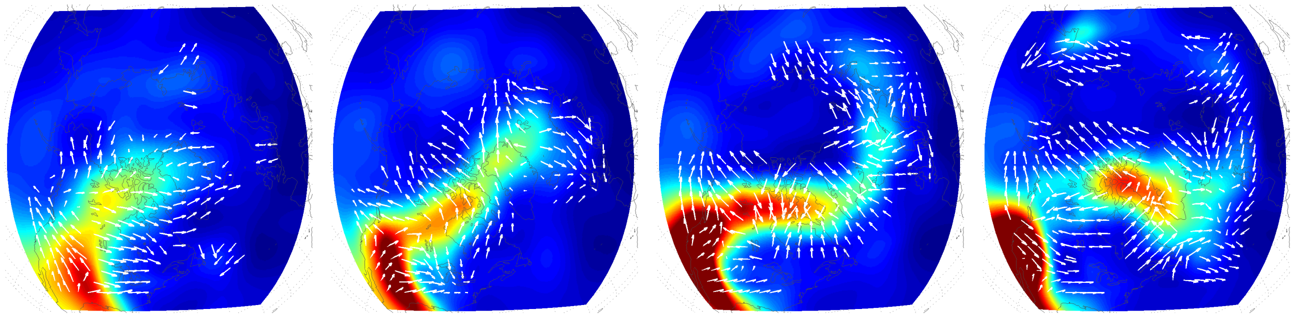
The motion fields produced by relaxation labelling can be further smoothed by the application of a VMF, as proposed in Section III. Fig. 4 presents results created by applying a VMF using a 3×3 window to the relaxed vectors produced for the 50×50 pixels frames visualised in Fig. 2. Comparing these vectors with the observable motion (in the sequence) shows good agreement in the earlier frames. The results from approximately 21:40 UTC onwards prove problematic, especially along the ridge towards the top-right. Nevertheless, they show a substantial improvement in vector quality, especially when compared with the MCC results, for example those of Fig. 3a and 3b.

In addition to comparing the motion fields with the observable motion in the TEC sequences, an indication of the expected, underlying motion fields can be obtained by running the implementation of the $\mathbf{E} \times \mathbf{B}$ model provided as part of the MIDAS software package [15] for the storm event. Comparing Fig. 4 with the modelled vectors shown in Fig. 5 shows some common features. For example, the early frames in both sequences capture the TOI moving through the centre of the two-celled convection pattern and the latter frames show a reversal in the motion direction around the edges of the TOI. Despite these similarities, there are also some clear differences between the Figs. However, as discussed in the introduction, the behaviour of storms is not necessarily well described by models and this is borne out by comparison with the observable TOI motion in the TEC sequence.

V. DISCUSSION AND CONCLUSIONS

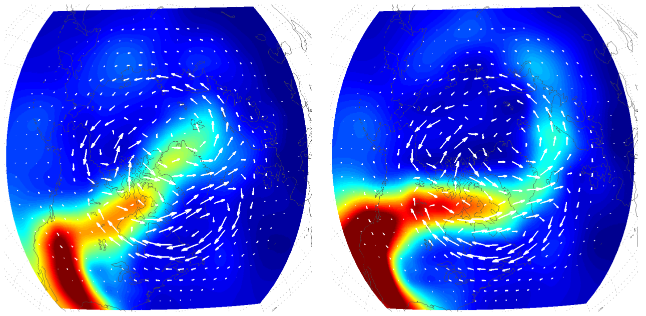
A new approach to estimating the motion of ionospheric storm enhancements has been presented. Instead of using vectors derived from a model, the direct application of block-based motion estimation techniques to polar ionospheric TEC sequences has been investigated. The particular problems associated with the low resolution of the images and non-rigid motion of the TOI have largely been overcome through the application of overlapping blocks and relaxation labelling, respectively.

Results show that standard MCC motion estimation does not produce locally smooth motion fields that are consistent



(a) 20:00 UTC (b) 20:50 UTC (c) 21:40 UTC (d) 22:30 UTC

Fig. 4: Motion vectors field after applying a VMF to the vectors produced by the relaxation labelling stage, such as from Fig. 3c. For clarity, the vectors are subsampled before displaying.



(a) 20:50 UTC (b) 21:40 UTC

Fig. 5: $\mathbf{E} \times \mathbf{B}$ model vectors for two TEC images from Fig. 2.

with the observable motion. However, relaxation labelling gave improved, more consistent motion fields, particularly in the early part of the sequence. The application of a vector median post-filter further improves the quality of the output fields. These methods all produce output fields that provide estimates of TOI motion directly from observed data. As such, the results suggest that the proposed method is a viable alternative to the model-based approach for TOI tracking during storm times.

Towards the end of the sequence the motion fields are still hard to interpret. However, this is not unexpected as it difficult for human observers to track the TOI through these frames when, due to a combination of electron recombination and large changes in morphology, the inter-frame correspondences are very hard to discern. Despite this, the motion sequences presented here are clearly able to corroborate the qualitative findings given by [6], [7], supporting the hypothesis that TEC image-derived motion estimates are a useful tool for the analysis of TOI during ionospheric storms. The presented comparison with model vectors was largely qualitative and also limited by the fact that the model does not represent ground truth. To accurately assess the vector fields a quantitative comparison with real data should ideally be performed. However, this is problematic as only sparse convection measurements are available. One way to overcome this problem is the use of an assimilation algorithm such as Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure [8] and performing such a comparison is an area of further work.

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