Snake-based Technique for Plasmapause Tracking

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Abstract

A new approach to tracking the boundary of the plasmasphere (i.e., the plasmapause) in a time-series of satellite images of the Earth is described. The approach is based on the active contour models (snakes) and exploits prior knowledge of the plasmasphere to automatically initialize and refine the snake’s position in each image. It then uses a greedy minimization scheme to drive the snake toward the plasmapause in each image. A Voronoi diagram is used to restrict the snake evolution to ensure that the snake does not loop over itself. Correspondences between successive images are established using a radial alignment process. The approach aids in quantifying plasmasphere changes, which are key indicators of the impact of solar events on the Earth’s magnetosphere.

1 Introduction

The plasmasphere is the region about the Earth that contains cold plasma that rotates with the Earth [1]. The plasmasphere is significantly affected by solar storms and other natural phenomena. Identifying and tracking its boundary (i.e., the plasmapause) can be quite useful in analysis of the impact of natural phenomena (such as solar storms) on the plasmasphere. The hallmark of the boundary is a steep decrease in the concentration of plasma.

The recent NASA IMAGE satellite mission has allowed acquisition of the first global, external images of the terrestrial plasmasphere. One of the imagers on IMAGE is the Extreme Ultra Violet (EUV) sensor, which collects intensity images that are 3D-to-2D projections of the terrestrial plasmasphere’s plasma density. The EUV sensor produces one image of size 140 × 150 pixels about every ten minutes. Hence a large amount of data is available to the researchers for investigation. One of the primary tasks performed on EUV images is localization of the plasmapause, typically by manual tracing—which is tedious, especially if a long time-series of images needs to be studied. Hence it is advantageous to have an automated way to identify the plasmapause in the EUV images. Challenges to automated segmentation include presence of noise, presence of some bright structures (such as the auroral arc) and some dim regions (i.e., Earth’s shadow) within the plasmasphere. Also, there is very low contrast between some segments of the plasmapause and the background.

In this paper we propose a new method, based on active contour models (snakes) [2], to track the plasmapause in a sequence of EUV images. The method exploits knowledge of the plasmasphere to aid snake initialization and uses a greedy minimization scheme constrained by a Voronoi diagram to drive the snake. The correspondences between successive EUV images are then determined by a radial alignment approach.

The paper is organised as follows. Section 2 describes related work. In Section 3, the new approach and preprocessing are described. Results are presented in Section 4.

2 Related Work

Two basic approaches for image segmentation are intensity-based thresholding and edge detection. Such approaches can exhibit under- and over-segmentation due to dependence on image intensity. They can also poorly segment indistinct portions of boundaries. Higher level processing techniques, such as the active contour models (i.e., snakes) are often useful for reliable detection of the boundaries in an image.

Kass et al. [2] have described a snake as a parametric contour $S$ of unit arc length with each point $v(t)$ in the snake represented by $v(t) = ((x(t), y(t)))$, where $(x, y)$ is a geometric location in the image domain. The snake is adjusted to minimize an expression of energies, namely the sum of the internal energies ($E_{int}$) at each point of the snake plus the external energy forces ($E_{ext}$) acting on the snake, and is described as

$$E(S) = \int E_{int}(v(t)) + E_{ext}(v(t)) dt, \quad (1)$$

where $E_{ext}(v(t)) = E_{img}(v(t)) + E_{con}(v(t)), \quad (2)$

where $E_{img}$ is an image force and $E_{con}$ is an external constraint force. The external forces, namely image forces
such as image intensity and gradients and the external constraint forces, such as springs—which attach the snake to specific points in the image—tend to deform the snake while the internal energy forces resist deformation. The snake has to be initialized appropriately near the germane image features for the snake to be attracted by those features and thus reach an acceptable final solution.

Snakes have been used in many application areas, including tissue segmentation in medical images (e.g., [8], [9]), roadway analysis in satellite images (e.g., [11]), and object tracking in time-series of images (e.g., [12]). Many snake-based object tracking applications have used prior knowledge of shape to limit the object’s motion and deformation between images. One complication to use of prior knowledge in snake-based tracking of the plasmapause is that its shape at any instance in time cannot be well-known due to the dynamic nature of the physical forces affecting the plasmasphere.

3 Snake-based Plasmapause Tracking

A typical EUV image is shown in Fig. 1(a). The Earth is near the center of this image. The image, like most of the EUV images, also contains the auroral arc, which is a somewhat bright central oval atop the Earth. The Earth is surrounded on most sides by a very bright region, which is known as the airglow. The EUV image in Fig. 1(a) is typical in that it is noisy and has a plasmasphere boundary of non-uniform contrast. In fact, in this image, the plasmasphere is hard to see. A histogram-equalized version of the EUV image of Fig. 1(a) is shown in Fig. 1(b). The plasmasphere is more visible in Fig. 1(b); it is the whitish blob with an arm-like extension in the image center. The relatively low contrast of the plasmapause “arm” at the right of the image highlights the segmentation challenge. In this section, we describe a new snake-based technique that addresses this challenge and allows tracking over time. Our approach is a two step approach in which the energy terms and search directions are varied.

Use of the snake formulation requires definition of $E_{img}$ forces based on image properties such as pixel intensity and gradient. Since the plasmasphere in EUV images is not always charaterized by a well-defined gradient and since the noise in the EUV images generates spurious gradients, prior to application of our snake-based method, we filter the histogram-equalized images with a Gaussian filter and then apply a morphological opening operator to remove some of the noise. Fig. 1(c) shows the result of applying these preprocessing steps to the EUV image of Fig. 1(a).

3.1 Snake Initialization

Our approach’s first step is snake initialization. It has two components: a coarse initialization followed by an energy-minimizing refinement. The process of snake energy minimization is influenced by the initial position of the snake. Thus in our approach, the snake is automatically initialized near the boundary of the plasmapause. The initialization’s coarse component involves finding a reference point on the image. This point is found by template-matching against a representative sub-image (of a raw EUV image) that contains only the Earth and the airglow. Although the plasmapause boundary varies considerably from image to image, the earth and airglow’s appearance is less variable. The template-matching essentially allows the center of the Earth to be located, and a closed circular loop centered at that landmark is then overlaid on the image, as shown in Fig. 1(d). This loop is then deformed outward. This outward deformation refines the initial position by following a snake-like approach. The refinement involves a search, at each loop point, for maximal gradient magnitudes. Each search proceeds in the direction of the outward normal at the loop point. The maximal image gradient found for each search serves as the external force for the refinement. Such a behavior is similar to the balloon force described by Cohen [5].

As the snake balloons out, the distance between the loop’s original points usually increases and, hence, the snake is reparameterized (as suggested by [11]) after every iteration. A new point $v_i$ is added between existing points $v_i$ and $v_{i+1}$ if the distance between $v_i$ and $v_{i+1}$ becomes too large. A point $v_j$ is removed if the distance between
The second step in our approach drives the snake toward the plasmapause. The snake is driven through energy minimization, which can be achieved by directly solving the snake energy formulation’s equations. An alternate, popular solution is to use dynamic programming, as proposed by Amini et al. [4]. However, our method adopts the greedy approach of Williams and Shah [3] since it is simple and converges to the solution very quickly. In addition, in the greedy approach, the coefficients to the energy terms can be determined an energy minimized snake [3]. In our approach, we evaluate the energy terms at each of the points describing the snake, however we restrict the neighborhood search to the inward normal direction at each point.

The energy terms used in our energy formulation are

\[ E_{\text{int}}(v_i) = \alpha \left| \frac{\tilde{u}_{i-1,i} \cdot \tilde{u}_{i,i+1}}{\|\tilde{u}_{i-1,i}\| \|\tilde{u}_{i,i+1}\|} \right|, \]

\[ E_{\text{img}}(v_i) = \beta I(x,y) + \gamma \|\nabla I(x,y)\|^2, \]

where \(\tilde{u}_{i,j}\) is the vector from point \(v_i\) to point \(v_j\) and \(I\) is the intensity of the image and \(\nabla I\) is the gradient of the image at location \((x,y)\). \(\alpha, \beta\) and \(\gamma\) are the coefficients that control the influence of each of the terms on the evolution of the snake. The \(E_{\text{int}}(v_i)\) is an estimate of the local curvature of the snake at the point \(v_i\) and is invariant to rotation [3]. The values of \(\alpha, \beta\) and \(\gamma\) have been determined empirically as \(\alpha = 0.125, \beta = -1.0\) and \(\gamma = -1.0\). The low value of \(\alpha\) permits the snake to bend into concave regions and the negative values of \(\beta\) and \(\gamma\) attract the snake towards regions of high intensity and high gradient.

Our approach restricts the snake’s evolution to prevent formation of local loops in the snake. This restriction is achieved by limiting the neighborhood search about each point to a region of influence about the point that is determined from a Voronoi tessellation [7] of space. It is important to restrict the snake’s evolution since when the snake enters any very sharp concave regions, non-consecutive points are not restricted by the curvature term in the energy formulation which can lead to loops. Ghanei and Soltanian-Zadeh [10] have avoided this problem by first exhaustively searching for crossing segments of the snake. Their method then inserts a new point at each crossing and deletes the points in the loops. Our approach is simpler: we compute and exploit a Voronoi tessellation of space about the snake. Each pixel in the image is assigned the same label \(i\) as the nearest snake point \(v_i\). During energy minimization, the Voronoi diagram constrains movement; a snake point \(v_i\) can be moved to a new location only if the new location also has the label \(i\). Fig 2(b) shows a Voronoi diagram for a sample snake. Since a point’s evolution is now restricted to the region within the Voronoi polygon defined by that point, the problem of the snake forming loops is eliminated.

A reparameterization process (the one described in Section 3) is performed after every iteration to ensure that the snake points are uniformly spaced. The snake’s evolution terminates when the number of snake points that change location in an iteration is small. The result of application of the constrained evolution process on the initialized snake of Fig. 1(f) is shown in Fig. 2(a).

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**Figure 2.** (a) Snake after constrained evolution. (b) Voronoi diagram for a snake. (c–f) Snake on a time-series sequence of EUV images, (c) 20th frame, (d) 25th frame, (e) 30th frame, (f) 35th frame.
3.3 Tracking in Image Sequence

In order to find the correspondence mapping between two snakes, A and B, obtained from consecutive images, we take advantage of the available domain knowledge such as the position of the Sun in the images. The position of the sun is determined by template matching that locates the airglow, which is on the sunward side of the Earth. Then the snake in each image is split into two parts: one part on the sun side and the other on the shadow side. Salient features, such as a sudden change in curvature which occurs at the tip and pit of the plasmapause “arm”, are used to further divide the snake into sections. Correspondence mapping of the tip and pit of the plasmapause “arm”, are used to further

ture mapping of the snakes is achieved by mapping each section from snake A to its corresponding section in snake B.

We have used a method similar to the multi-radial correspondence approach described by Newman and Yi [6] to find the point matches of the contour sections. Rays are cast along the normal at each point in snake A. The closest intersection of each ray with snake B is taken as the location of the point in snake B that corresponds to the point in snake A. This process is performed on a sequence of snakes obtained from a time-series of EUV images.

4 Experimental Results

Our method has been applied on a sequence of 20 EUV images. These images have been preprocessed as described in Section 3. Fig. 1(d) shows the initialization of the snake inside the plasmasphere in one EUV image in the sequence. The pre-processing step’s results for this image are illustrated in Fig. 1(b) and Fig. 1(c). Fig. 2(c)–2(f) show the boundaries detected in some of the images obtained from a time-series sequence of EUV images. The boundaries are superimposed on their corresponding histogram-equalized images.

We have compared the contours obtained by our method with contours that have been traced by a human operator on the same 20 image sequence. The amount of deviation is measured at each point in the human traced contour. Let a be a point in the human traced contour. Then the deviation at a is the distance from a to a point b, which is the intersection of the normal at a and the contour generated by our method. The average amount of deviation for each contour was found to be 1.05 pixels.

5 Conclusion

In this paper we have introduced a new algorithm for tracking the boundary of the plasmasphere automatically. The new method is based on the active contour models (snakes) and fully automates detection of the boundary of the plasmasphere by space scientists.

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References