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Representation of Solar Features in 3D for Creating Visual Solar Catalogues

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Abstract

In this study a method for 3D representation of active regions and sunspots that are detected from Solar and Heliospheric Observatory / Michelson Doppler Imager magnetogram and continuum images is provided. This is our first attempt to create a visual solar catalogue. Because of the difficulty of providing a full description of data in text based catalogues, it can be more accurate and effective for scientist to search 3D solar feature models and descriptions at the same time in such a visual solar catalogue. This catalogue would improve interpretation of solar images, since it would allow us to extract data embedded in various solar images and visualize it at the same time. In this work, active regions that are detected from magnetogram images and sunspots that are detected from continuum images are represented in 3D coordinates. Also their properties extracted from text based catalogues are represented at the same time in 3D environment. This is the first step for creating a 3D solar feature catalogue where automatically detected solar features will be presented visually together with their properties.

1. Introduction

Solar images, along with other observational data, are very important for solar physicists and space weather researchers aiming to understand the way the Sun works and affects Earth. Much of the data available in solar images are catalogued in terms of solar features and solar activities by different organizations around the world in order to provide researchers with historical changes of the Sun to facilitate research. Almost all of these catalogues are text based and once a researcher decides to investigate a certain activity he or she has to search all the feature catalogues and solar images available during the time of activity to acquire all the relevant data of changes on the Sun. For example if we want to investigate coronal mass ejections (CMEs) on date A , we can go to a CME catalogue or SOHO/ LASCO image and try to determine the source regions. After identifying a source region, we may go to an EIT, continuum or magnetogram image, etc. to investigate the changes in the region, we may go to a sunspot catalogue and examine the properties of the region causing the CME or we may make comparisons with solar flares occurring on or around date A. These examples will change according to the type of research that is being conducted and the problem will become more complicated if we extend the time frame.

Currently, although the variety of solar images in different wavelengths produced everyday by different observatories (i.e. BBSO, Meudon, Mt Wilson, etc.) and satellites (e.g. SOHO,STEREO, etc.) increase the opportunities for understanding solar phenomena and help researchers to discover new secrets of the Sun, the increasing cadence of the data is making the job of researchers harder in terms of time spent investigating. With the availability of vast new sources of solar data (e.g. SDO will be launched shortly), it will be almost impossible for researchers to manually investigate all the available data and images and compare them against each other to get an idea of the real "full picture" of the Sun.

There is a growing need for automated data analysis and knowledge extraction techniques. One attractive approach is to create automated systems to analyze solar images and extract features that would be used to create corresponding 3D models. These 3D models would provide physical and visual descriptions for the features of interest, which would be more complete than the current text-based descriptions and model specification would require less storage than 2D image segmentation. Such a system would improve interpretation of solar images, since it would enable advanced 3D processing and manipulation to be applied to the modeled solar features. Also such a system would allow us to extract data embedded in various solar images and visualize it at the same time.

Many good results have been achieved by researchers on automated feature extraction in recent years, especially in the extraction of active regions, sunspots, and filaments. Although the results of these researches are promising they don't go further than facilitating and computerizing the creation of text based catalogues created and maintained by observatories. Because of the difficulty of providing a full description of data in text form, it can be more accurate and effective for scientist to search images visually and look for specific features they want related to the events they are working on. Therefore it would be much easier for scientists to investigate events if the data embedded in text based catalogues were backed up with visual descriptions or models. This would reduce the need for searching different sources of data such as catalogues and images concurrently. Also creating these visual descriptions as 3D models would allow researchers to more easily understand and track the changes in solar features and their effects. This study is our first step towards creating a 3D visual solar feature library. This library will allow researchers to investigate and visualize solar features at a given time without having need to store, search and compare all solar images. Figure 1 shows a general view of the stages required to create such a library.

In this paper we present a system that extracts active regions from SOHO/MDI Magnetogram images and sunspots from SOHO/MDI Continuum images (Figure 2) and creates 3D representations of these solar features. The MDI instrument on SOHO provides almost continuous observations of the Sun in the white light continuum and also provides line of sight magnetogram images. White light pictures show how the Sun appears to the naked eye and the MDI continuum images are primarily used for sunspot observations. MDI magnetogram images are captured to measure the magnetic field strengths on the Sun's photosphere, with black and white areas indicating opposite magnetic polarities of the active regions. Data that are extracted from the National Geophysical Data Center (NGDC) [1] sunspot catalogues are also used to aid the representation of 3D solar features.

This paper is organized as follows: in Section 2, previous work on automated feature extraction is summarized. In section 3 we introduced a method for converting solar images to Carrington heliographic coordinates and an algorithm for enhancing the quality of heliographic images. In Section 4, algorithms for the detection of solar features in Carrington heliographic coordinates are described. Techniques to represent these solar features in three dimensions and some sample results are presented in Section 5. Finally, conclusions and suggestions for future work are provided in Section 6.

[1] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/, last access: 2009

2. Previous Work on Automated Feature Extraction from Solar Images

Because of the increase in available data, automated feature extraction has been a very popular solar research activity in recent years and many good results have been achieved by researchers in this field, especially in the extraction of active regions, sunspots, and filaments from solar images as summarized below.

In Gao, Wang et al. (2002), local thresholding and region-growing methods were used to detect filament disappearances. In Benkhalil, Zharkova et al. (2003), active regions were detected using region growing techniques. Filaments were detected in H-alpha images in Shih and Kowalski (2003) using morphological closing operations with multi-directional linear structuring elements to extract elongated shapes. The Singular Spectrum Analysis of signals was used to detect active regions on solar disk, in Lefebvre and Rozelot (2004). Examples of machine learning approaches include Neural Networks used in Zharkova and Schetinin (2003) for filament recognition in solar images and in Borda, Mininni et al. (2002) for flare detection. Qu, Shih et al. (2003) experimented and compared Multi-Layer Perceptron (MLP), Radial Basis Function (RBF), and Support Vector Machine (SVM) classifiers for solar flare detection on the solar H-alpha images obtained from the Big Bear Solar Observatory (BBSO). Morphological image processing algorithms and neural networks were used together in Qahwaji and Colak (2006) and Qahwaji and Colak (2006) for detection of filaments and active regions.

Previous attempts at the detection of sunspots are reported in Curto, Blanca et al. (2003) Zharkov, Zharkova et al. (2004), and Nguyen, Nguyen et al. (2005). In Zharkov, Zharkova et al. (2004) an automated system for the detection of sunspots on the Ca II K_1 and SOHO/MDI white light images was presented. Nguyen, Nguyen et al. (2005) used image processing, and clustering methods on SOHO/MDI white light images for the recognition and classification of sunspots according to the modified Zurich class of the McIntosh system. Also, Curto, Blanca et al. (2003) used full disk white light images to automatically detect and cluster sunspots into groups. Sunspots were detected using morphological image processing techniques and neural networks were used to classify them. Colak and Qahwaji (2008) used SOHO/MDI continuum and magnetogram images together for detection of sunspot groups and active regions and combined these data to classify sunspot groups.

3. Heliographic Coordinate Transformation of Solar Images

In order to convert the coordinates of the solar images from 2D to 3D, the first step is to calculate their heliographic coordinates. This is a spherical coordinate system that shows the spherical "surface" of the solar photosphere and expresses the latitude (*B*) and longitude (*L*) of a feature or region on the solar surface. In this study, heliographic coordinate transformations of solar images are conducted using the equations described in Smart (1977).

It is worth mentioning here that there are two basic variations of heliographic coordinate system; Stonyhurst and Carrington heliographic. They differ in the definition of longitude. The Stonyhurst heliographic coordinate system is fixed with respect to earth, while the Sun rotates underneath it. The Carrington heliographic coordinate system rotates at an approximation to the mean solar rotational rate, as originally used by Carrington (Thompson, 2006).

In order to calculate the location of a specific point on the solar disk on a solar image, Carrington longitude of the centre of the solar disk (*Lo*), latitude of the center of the solar disk (*Bo*) and the tilt of rotation axis (*P*) have to be calculated. This data is available in FITs formatted solar images but for GIF images they have to be calculated. In this work it is sufficient to use the low accuracy equations from Meeus (1998) for these calculations. When an accuracy of 0.01 degree is acceptable, the geocentric position of the Sun may be calculated by assuming a purely elliptical motion of the Earth; that is, the perturbations by the Moon and planets may be neglected Meeus (1998). Higher accuracy calculations can be achieved by using VSOP87 (Variations Seculaires des Orbites Planetires, 1987) theory (Bretagnon and Francou, 1988). Although solar images used in this research are from the SOHO satellite and it is in orbit between the Earth and the Sun around the Lagrange point (*L1*) Lagrange (1873), the Carrington heliographic coordinates are calculated for the Earth view. This will not affect the outcomes of this research since the *L1* is located approximately 0.99 astronomical units (AU) from the Sun and 0.01 AU from the Earth.

3.1 Creating Images for Storing Data in Carrington Heliographic Coordinates

The Carrington heliographic coordinate system expresses the latitude (*B*) and longitude (*L*) of a point on the solar surface and the Carrington heliographic coordinates of a point on a solar disk can be calculated using the following equations, where *Bo*, and *Lo* are the latitude and longitude of the centre of the solar disk respectively, P is the tilt of rotation axis, θ is the position angle of the point on the solar disk, and ρ is the angle between the position of the point on the solar surface, the Earth and the centre of the disk (Smart 1977) .

$$B = arcsin[(\sin(B_o) \times \cos(p)) + (\cos(B_o) \times \sin(p) \times \cos(P - \theta))] \quad (1)$$

$$L = arcsin\left[\frac{\sin(p) \times \sin(P-\theta)}{\cos(B_o)}\right] + L_o \quad (2)$$

Using Eq. (1) and Eq.(2) Carrington heliographic coordinates of any pixel on the solar disk can be calculated but in order to avoid information loss caused by truncation, the size of the image that is going to be used for storing the pixel values in Carrington heliographic coordinates must be chosen very carefully. The Carrington heliographic latitude values change between -90 and 90 degrees and longitude values change between 0 and 360 degrees. If we store the converted data on a 180 by 360 image that means each degree will be represented with one pixel on the new image. When we use Eq. (1) and Eq. (2) for calculating the Carrington heliographic coordinates of a pixel on a solar image the resulting Carrington heliographic coordinates will be floating numbers and depending on the size of the solar image there will be more than one pixel which have latitude and longitude values separated by less than one degree. In this case all the values of the pixels separated from each other with less than one degree will be stored to the same pixel in the 180 by 360 heliographic images and this will cause information loss. To avoid this situation, the resolution (pixels per degree) of the image that is used for storing the data in Carrington heliographic coordinates is calculated as explained below.

The radius of the solar disk on a 1024 by 1024 MDI image is approximately 490 pixels which corresponds to 90 degrees in Carrington heliographic coordinates. However the distribution of pixels in degrees is not uniform due to the spherical shape of the Sun. Towards the limb of the Sun on the two dimensional solar image each degree will be represented by fewer pixels. If r_o is the radius of the solar disk on the solar image in pixels and α is the number of longitudinal or latitudinal degrees from the center of the solar disk then the visible pixels (V_p) representing these degrees can be calculated using:

$$V_p = ro.\sin \propto \quad (3)$$

Using Eq.(3) it can be calculated that one longitudinal degree at the centre of the solar disk on an 1024 by 1024 MDI image with a radius of 490 pixels is represented with approximately ~8.55 pixels. For the same image the region between 59° and 60° degrees will be represented with approximately ~4.41 pixels. In this study in order to prevent truncation we represented each degree on the heliographic image with 10 pixels which is a little higher than the minimal requirement of ~8.55.

On heliographic images the vertical axis corresponds to change in latitude values and horizontal axis corresponds to change in longitude values. If we represented each degree with one pixel, the heliographic image would be 180 by 360 pixels in size, but because each degree is represented by ten pixels in this study, the image used for storing the data on the heliographic coordinates is 1800 by 3600 in size.

3.2 Enhancement of image in Carrington Heliographic coordinates

One of the novel aspects of this work, which distinguishes it from other heliographic conversion algorithms, is that each pixel on the Continuum or Magnetogram images are treated as separated points rather than covering a certain spatial extent on the Sun. In this manner, the assignment of certain pixel intensity to more than one pixel on the heliographic image in the way it is done in classic heliographic conversion algorithms is prevented. Instead, after assigning the intensity of every original pixel to just one pixel on the heliographic image, an image enhancement algorithm is applied to determine the missing pixels on the newly created heliographic image. This new method presented here reduces the deformation and projection affects that increases towards the solar limb and is explained in the following paragraphs.

In a new empty heliographic image that is 1800 by 3600, each pixel corresponds to an area defined by 0.1 longitudinal and 0.1 latitudinal degrees. Each pixel representing solar disk on MDI images are detected and their corresponding coordinates on the newly created heliographic image are calculated using Eq. (1) and Eq. (2), multiplying the resulting latitude and longitude values by 10 and converting the final values to nearest integer. For example, if the calculated latitude and longitude of a detected pixel (Using Eq. (1) and Eq. (2)) are 15.73 and 130.46 respectively, after multiplying these values by 10 (157.3 and 1304.6) and converting to nearest integer the corresponding coordinates of this pixel on the heliographic image will be 157 and

1305. On Carrington heliographic image, the horizontal axis represents the longitude and the vertical axis represents the latitude values. If the calculated latitude and longitude of next detected pixel are 15.74 and 130.83 respectively then the corresponding coordinates of this pixel on the 1800 by 3600 heliographic image will be 157 and 1308. The pixels between 1305 and 1308 on horizontal axis while vertical axis value is 157 will be left empty on the new heliographic image. Once the corresponding coordinates of each pixel on the heliographic coordinate image are calculated, the intensity value of the detected pixels in the Continuum image (Figure 3-A) and Magnetogram image (Figure 3-B) are assigned to the newly created heliographic images using these coordinates. As can be seen from Figure 3, data that has been converted from solar images is just enough to construct half of the heliographic images because on solar images just one side of the solar disk is visible. The area corresponding to the non visible side of the solar disk is filled with grey pixel values and the converted data is shifted to the centre for a consistent view. Also because ten pixels represent each degree on heliographic image, there are gaps in the converted data that represents the visible area of the solar disk. These gaps increase in area nearer the solar limb because each degree is represented by fewer pixels towards the limb as explained before. These gaps could be reduced by decreasing the pixel per degree ratio on heliographic images but this would cause truncation of the data near the centre of the disc.

To overcome the problem of missing data in the heliographic images illustrated by Figure 3, an algorithm was designed to enhance the newly created heliographic images by estimating the pixel values of missing data.

In this algorithm every pixel is examined and when a pixel without any information (marked with pixel value zero) is found, its neighboring pixels are searched using variable size windows. First a window sized 3× 3 is centered on the empty pixel and the values of the neighboring pixels within this window are added if they have information (if the pixel value is non-zero). If no valid pixels are found within the initial window, the size of the window is increased by one and the process continued until at least one pixel with information is available within the window. Then the average value of the valid pixels found (The total value will be divided with the number of non-zero pixels) within the final window is assigned to the empty pixel. The algorithm continues until all the pixels have been processed.

After all the data gaps have been filled, a smoothing algorithm that is using 3×3 linear uniform filter is applied to all images. In this algorithm, all the pixels within the 3× 3 rectangular window are added and normalized by 9 while assigning the resulting pixel value to center pixel. The images resulting from enhancing those in Figure 3 are shown in Figure 4. The enhancement process is computationally expensive and time consuming because of the size of the heliographic image. Although in Figure 4, the resulting image is enhanced to full extend (± 90 longitude and latitude degrees from the centre), in time critical applications or in the absence of solar features on upper and lower latitudes, limiting the enhancement process to certain latitudes can significantly improve the execution time of the algorithm.

3.3 Analyzing the results of heliographic conversion process

In order to evaluate the performance of the heliographic conversion algorithm, we compared the results of the new algorithm (Space Weather Research Team (SWRT)) with classical heliographic conversion algorithm, both visually and quantitatively. In classical conversion method, each pixel on the image covers a certain spatial extent on the Sun; after the heliographic coordinate of a pixel is calculated, the intensity value of that pixel will be assigned to all the nearest missing pixels in the heliographic image.

In order to compare the results of conversion visually, we converted MDI continuum image taken on 28th March 2001 at_06:24 to Carrington heliographic coordinates by using both SWRT and classical algorithms. This image is chosen because there are various sunspot groups scattered on the solar disk. Figure 5 and 6 shows the results of these conversions. On Figure 5 comparisons of all the regions on the images are provided. The cropped images SWRT heliographic images are marked with letter ‘N’. Although in this scale the results look similar for the regions in the central part of the solar disk, the cropped regions towards the limbs are clearer for the SWRT heliographic images and don’t suffer from effects that look like pixilation in classical heliographic images. The difference is also visible for the regions that are close to the centre of the disk when the cropped images are zoomed into like in Figure 6 where active region 9393 is visible. In this figure the errors (difference from the original image) on the classical heliographic image is marked with small arrows. SWRT heliographic image looks quite similar to original image.

For the quantitative comparison of the classical and new conversion algorithms we used a test method that tracks any given region on heliographic images within a time frame. 44 continuum images available between 2^{nd} and 14^{th} January 2007 and they were converted to Carrington heliographic coordinates using both of the algorithms and a fixed window is defined on each heliographic image to track active region 10935. This is a stable single spot region that is visible from the eastern part of the limb on 1^{st} January 2007 and the Carrington heliographic longitude and latitude of its centre doesn't change more than a few degrees whilst it is on the visible side of the Sun. The graph on Figure 7 shows the results of area calculations for region 10935 by using Carrington heliographic images created by SWRT algorithm and classical algorithm. In this graph also the difference in area calculations by using two algorithms and area calculations provided by the Space Environment Center (SEC) are plotted. The area calculation difference between the two algorithms is found by subtracting classical algorithm results from SWRT results. The area calculated by using classical algorithm is always higher than new algorithm and the difference between them increases towards to limbs and this can be seen from the black coloured trend line drawn using difference values. Area calculation results of region 10935 using SWRT algorithm is on average ~5% lower closer to the limbs (after ±75 degrees from the disk centre) and ~1.75% closer to centre (between -5 to 5 degrees from the disk centre) when compared to classical algorithm. This shows that the classical algorithm suffers more from projection effects towards the limbs. SEC provides one area calculation result per day for each active region and that is why same area value is plotted against the areas calculated from several images available in a day. The average area calculation difference between SEC and SWRT algorithm is 28.08 millionths of hemisphere per image while the difference between SEC and classic algorithm is 31.24 millionths of hemisphere. The area calculations involving SWRT algorithm produces closer results to those provided by SEC.

In general it can be concluded that projection effects are minimized and area calculations suffer less from this effect using the new Heliographic conversion method described here. Also visual results show us that heliographic conversions using the methods provided in this paper can be reliable up to ±80 degrees from the centre of the solar disk.

4. Detecting Solar Features in Carrington Heliographic Coordinates

Before calculating the 3D coordinates of solar features they first have to be detected in the heliographic images. Detection of sunspots from continuum heliographic images and active regions from magnetogram heliographic images is carried out using image enhancement and segmentation algorithms, in a manner similar to Colak and Qahwaji (2008). One of the common algorithms used for both types of images is intensity filtering, which depends on using different threshold values for the detection of both features. In this research the intensity filtering threshold value T_f for each image is found automatically using:

$$\mathrm{T_f} = \mu \pm (\sigma \times \alpha) \tag{4}$$

Where, μ is the mean, σ represents the standard deviation, and α is a constant that is determined empirically based on the type of the features to be detected and the images. To find the optimum value of α intensive experiments were carried out by applying the detection algorithm, with different α values, on many continuum and magnetogram images. The performance of the algorithm was subjectively analyzed for each image. Detected sunspots and active regions are shown on Figure 8 and the detection process is explained in more detail in the following subsections.

4.1 Detection of sunspots

In order to detect sunspots from heliographic continuum images, histogram stretching is applied to enhance the contrast followed by Gaussian blurring to the resulting image to reduce noise and the level of detail. In the continuum images, the pixels darker than the background represent sunspots. After enhancing the images, sunspots are detected using intensity filtering where the threshold value is calculated using Eq. (4) using the minus (-) sign and setting α to 2.5. If the value of the processed pixel is less than the calculated threshold value, the pixel under consideration is marked as a sunspot. Although, the optimized value of α was determined as 2.7 in Colak and Qahwaji (2008) for sunspot detection from the images in heliocentric images, in this study we found empirically that setting α to 2.5 give better sunspot detection results due to changes in image data after heliographic conversion and enhancement processes. As a result of conversion process, σ and μ value is higher for images in heliographic coordinates than heliocentric coordinates due to addition of new pixels with high intensity values (There are more light pixels in continuum images than dark pixels representing sunspots). The increase in σ affects the threshold value more than increase in μ due to multiplication with α and reducing α compensates this effect.

This detection process has direct effects on sunspot area calculations since a decrease in threshold value T_f could lead to miss detection of pixels that are part of a sunspot which will reduce the calculated area. An increase in T_f could increase the calculated area due to wrong detection of pixels that are not part of a sunspot.

In continuum images, large sunspots have a dark central umbra surrounded by the brighter penumbra. In order to separate the umbra and the penumbra parts of the detected sunspots, the mean (μ), standard deviation (σ) of the detected sunspots on the original image is found and a threshold value (T_p) is calculated using Eq. (5).

$$T_p = \mu - \sigma \tag{5}$$

The detected sunspot pixel values are compared with this threshold value. If the sunspot pixel value is smaller than T_p, it is considered to be part of the umbra; otherwise it is considered to be part of the penumbra (Colak and Qahwaji, 2008). In Figure 8 the penumbra and umbra of the detected sunspots are marked with grey and dark pixels, respectively.

4.2 Detection of active regions

In order to detect active regions from magnetogram images, smoothing and intensity filtering is applied. The smoothing algorithm is applied to reduce the noise in magnetogram images. In this algorithm the intensity value of each pixel in the smoothed image is set equal to the average of itself and the pixels surrounding. In magnetogram images, the dark areas represent the part of the active regions with the South magnetic polarity and the light areas represent the part of the active regions with the North magnetic polarity. Both areas have to be segmented separately which means that two different threshold values have to be determined. The first threshold is used for detecting regions with the North magnetic polarity and the second is used for detecting regions with the South magnetic polarity.

The value of the first threshold is determined using Eq. (4) with the plus (+) sign and setting α to 2. All pixels that have intensity values larger than this threshold are marked as active regions with *north* polarity. In the same manner, the second threshold is determined using Eq. (4) with the minus (-) sign and setting α to 2. Any pixel with an intensity value less than this threshold is marked as active regions with *south* polarity. In Figure 8 detected regions with south and north polarities are marked with grey and white pixels, respectively.

5. Representation of Solar Data in 3D

After sunspots and active regions have been detected from heliographic images, the detected data is converted to 3D Cartesian coordinates. Also sunspot group data extracted from the NGDC sunspot catalogue are also represented in the 3D environment and displayed together with detected solar features that are converted to 3D.

5.1 Conversion of Solar Feature Data from Carrington Heliographic to 3D Cartesian Coordinates

Detected features in Heliographic coordinates can be used to calculate the 3D Cartesian coordinates of the same features using the following equations:

$$
\begin{aligned}
x &= r \sin(B) \cos(L) \\
y &= r \sin(B) \sin(L) \qquad (6) \\
z &= r \cos(B)
\end{aligned}
$$

Where, *B* is the latitude and *L* is the longitude of the detected solar data on the Carrington heliographic image and *r* is equal to the radius of the solar disk that the new data is mapped to.

In this study, and for converting solar feature data to 3D coordinates, we start by searching the previously detected pixels in the Carrington heliographic image. When a pixel that is part of a solar feature is found its coordinates are stored. As explained on Section 2.1, in heliographic images the horizontal axis represents the longitude and the vertical axis represents the latitude of the solar data. But as we assigned 10 pixels for each degree on the heliographic images, the horizontal and vertical axis coordinates of the detected solar features must be divided by 10 in order to calculate their latitude value B and the longitude value L. After the latitude and longitude values are calculated, their 3D Cartesian values can be calculated using Eq. (6). By changing the radius value *r*, the detected solar feature data can be mapped onto any spherical surface in 3D. It is suggested to choose *r* value closer to radius value of the original solar image. If the selected r value is too much smaller or larger than the radius value of the original solar image there can be visual problems on the 3D model.

5.2 Representing NGDC Catalogue Data in 3D

In this work, we have used data from the publicly available sunspot group catalogues that are provided by NGDC in order to aid visual solar feature data we detected from MDI images. NGDC keeps record of data from several observatories around the world and holds one of the most comprehensive publicly available databases for solar features and activities.

The NGDC sunspot catalogue holds records of many solar observatories around the world that have been tracking sunspot regions and supplying their date, time, location, NOAA number, physical properties, and classification. The sunspot catalogue is analyzed by a C++ computer program that we have created, in order to extract these data and map them to 3D together with solar feature data using their timing and location information.

The location data provided by catalogues are in Stonyhurst heliographic coordinates and they needed to be converted to Carrington heliographic coordinates before mapping the rest of the data to 3D. In order to convert Stonyhurst coordinates to Carrington coordinates, *Lo* (Longitude of the centre of the solar disk in heliographic coordinate) has to be added to the extracted longitude without changing the extracted latitude in Stonyhurst heliographic coordinates. As mentioned in section 2, *Lo* can be calculated with the help of the date and time information extracted from the rest of the data using low accuracy equations from Meeus (1998) or in higher accuracy using VSOP87 theory (Bretagnon and Francou, 1988).

Once the conversion of location data to Carrington heliographic coordinates is completed, the rest of the extracted information can be mapped to any spherical surface in 3D by using Eq. (6) as described in the previous section. In this study we extracted the NOAA number, McIntosh classification and area of sunspot groups from the catalogue and displayed this information in 3D.

5.3 Results

Using the algorithms described in the previous sections, a program called *3DFeature* was created using the C++ programming language. *3DFeature* can read MDI magnetogram and continuum images and the NGDC sunspot catalogue and then creates a 3D solar catalogues. *3DFeature* creates a data file in text format which includes the 3D coordinate data for sunspots and active regions and their properties extracted from sunspot catalogues. For visualizing the data created by *3DFeature* another program named *3DSolarView* was created using C++ and OPENGL (OPEN Graphics Library) programming languages. A snapshot of this tool is shown in Figure 9.

3DSolarView tool allows us to visualize different solar features detected from various solar images at the same time. Also these models can be rotated and magnified. This allows us to display changes in solar features with respect to time, as it allows us to study the solar features regardless of rotation effects.

The algorithms presented in this work were tested on the MDI continuum and magnetogram images available between 1st April 2001 and 6th April 2001. In this period there are 20 continuum and 75 magnetogram images available and *3DFeature* tool can process each image in 2 to 6 seconds depending on its complexity.

Some of the results from this period are presented in Figure 10. In this figure cropped images from the original continuum and magnetogram images and from the output of *3DFeature* tool are shown. In Figure 9, in sections A, B, and C cropped images for active region 9393 from 1st April 2001 at 00:00, 2nd April 2001 at 00:00, and 3rd April 2001 at 00:00 are presented, respectively. It can be seen 3D representations allow us to see the changes in this active region better by reducing the effects of rotation and solar limb. Also the information provided for a region allows us to see the NOAA number, and track the changes in McIntosh classification and area of the sunspot group.

The remainder of the results for this tested period can be inspected by downloading and running *3DSolarView* tool from http://spaceweather.inf.brad.ac.uk/3DSolarView.html which is available for Windows based systems.

6. Conclusions and Future Work

In this paper algorithms for representing solar features such as active regions and sunspots in 3D are presented. The system presented in this paper works efficiently as a solar data visualization tool. We believe this is the first step towards creating a fully functional 3D visual solar feature and activity catalogue. A visual catalogue can significantly improve our understanding of the Sun and ease the job of researchers and scientists having to deal with the dramatically increasing amount of solar data.

Although only sunspots and active regions are processed in this paper, these algorithms can also be used for other solar features such as filaments. Filaments that are detected from h-alpha images can also be converted to 3D representations, while assuming they are not extending to solar corona. The effects of the algorithms on elongated features such as filaments have to be investigated further, especially when such features are extending towards the limb there creating a possible information loss. As shown in Figures 9 and 10, these algorithms can also be used to visualize different solar features detected from various solar images and wavelengths at the same time, which provides a more complete picture of activities on the solar disk. Moreover the 3D models also allow us to rotate, magnify and display changes in solar features without missing any of the important information embedded on ordinary solar catalogues.

The Heliographic transformation method described in Section 3 reduces the projection effects of up to ±80 degrees from the centre of the solar disk of the original heliocentric images and is more reliable than classical heliographic transformation methods. Using this method, solar features can be tracked in real time without the need for additional algorithms, just by comparing with the coordinates of the previously detected features. Feature tracking can improve the near real time solar flare predictions tools such as Automated Solar Activity Prediction (ASAP) (Colak and Qahwaji 2009).

The 3D transformations of data on magnetogram images as decribed here can also be used to model magnetic field lines and magnetic connectivity energy in 3D, as shown in Figure 11. Active regions shown in magnetogram images represent the magnetic footprints of magnetic field lines. By using the 3D coordinates of these regions as described in this paper, magnetic field lines can be modelled in 3D in near real time. These models can also be used for identifying source regions of solar activities such as solar flares and CMEs and futhermore used to calculate and visualize magnetic connectivity energy on Sun in 3D which also leads to predicting the intensity of such activities. Our research on these aspects of the 3D modeling is still going on and the images on Figure 11 are our initial results

In the near future, we would like to improve the presentation of solar features, while reducing the amount of required 3D data. Sunspot data detected from a continuum image and active region data detected from a magnetogram image need approximately 200KB and 800KB of data for storage respectively. In this paper the detected solar features are presented in *x*, *y* and *z* coordinates in a 3D environment and presenting these solar features in minimum polynomial form can significantly reduce the space needed for storing the data. This would also allow us to create an online version of the *3DSolarView* tool where the visual database can be used around the world.

We will also combine these algorithms with ASAP tool. In this way sunspot group data and solar flare predictions provided by ASAP can be improved and also outputs of ASAP can be visually represented in 3D.

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FIGURES

Figure 1: Stages in creating a 3D solar feature catalogue.

Figure 2: Greyscale SOHO/MDI continuum (left) and magnetogram (right) images from 3rd April 2001 at 00:00 UT.

Figure 3: The resulting image after converting MDI continuum (A) and magnetogram (B) images to Carrington heliographic coordinates. The original image data are shifted to centres of the Carrington heliographic images. These images are created using SOHO/MDI images from 3rd April 2001 at 00:00 UT.

Figure 4: The images shown in Figure 3 after enhancement to fill gaps (A) MDI continuum heliographic image and (B) magnetogram heliographic image. These images are created using SOHO/MDI images from 3rd April 2001 at 00:00 UT.

Figure 5: Visual comparison of Carrington heliographic image conversions. Image in the middle is MDI continuum image taken on 28th March 2001 at_06:24. Cropped images tagged with ‘N’

are from heliographic images created using SWRT algorithm, the other images created using classical conversion algorithm.

Figure 6: Active region 9393. O: Cropped from original MDI Continuum image taken on 28th March 2001 at_06:24. G: Greyscale version of Image O. C: Cropped from the heliographic image created using classical conversion algorithm. N: Cropped from the heliographic image created using SWRT conversion algorithm.

Figure 7: Comparison of area calculations for active region 10935 between 2nd and 14th January 2007 using classical and SWRT comparison algorithms. X–axis represents the angular separation of active region centre from the centre of solar disk. Area calculations from Space Environment Center (SEC) are also provided.

Figure 8: Detected sunspot and active region data from Heliographic continuum (top) and magnetogram (bottom) images respectively. These images are created using SOHO/MDI images from 3rd April 2001 at 00:00 UT.

Figure 9: MDI continuum and magnetogram images from 1st April 2001 together with NGDC sunspot catalogue are processed with 3*DFeature* tool, and created 3D model is displayed using *3DSolarView* tool.

Figure 10: Cropped continuum and magnetogram images and the output of *3DFeature* tool for active region 9393 from 1st April 2001 at 00:00 (A), 2nd April 2001 at 00:00 (B), and 3rd April 2001 at 00:00(C).

Figure 11: 3D modeled magnetic field lines (on left) and 3D magnetic connectivity energy maps (on right).