ROYAL OBSERVATORY
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Long-term evolution of large scale magnetic structures on USET images

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1. Summary

The global dynamics and evolution of large-scale magnetic structures such as sunspots in the photosphere and bright plages in the chromosphere is one of the primary topics of contemporary solar physics. This can provide unique insight in sub-photospheric processes leading to the production and decay of solar magnetic fields. It can also improve our understanding of the evolution of the global solar irradiance. Moreover, the detailed information obtained from solar images can be used to decipher the similar mechanisms acting in other magnetically active stars.

2. Objectives

This PhD project aims at a better understanding of the long-term evolution of large-scale magnetic structures seen in the photosphere (such as sunspots) and in the chromosphere (such as bright plages). The study is based on the scientific exploitation of the long-term archive of synoptic images taken on-site at the Royal Observatory of Belgium (ROB) with the Uccle Solar Equatorial Table (USET). Those images give a simultaneous view of the photosphere and the chromosphere.

First we plan to study the long-term brightness variation of the chromosphere in the Ca II K line taking into account the contribution of the different magnetic structures: plages, chromospheric network, filaments, sunspots. As we will decompose the disk-integrated brightness variation into its different spatially resolved chromospheric structures and as chromospheric proxies based on the Ca II K emission are commonly used as a tracer of stellar activity [Wright 2004], we can compare our solar images in the Ca II K line with the integrated spectral measurements available for distant stars and thus study the Sun seen as a star.

A second part of our project will use the images of the photosphere to study the proper motion of sunspots inside a group.

3. Timeline

I started my PhD project in October 2020, i.e. 9 months ago. **Figure 1** shows a schematic timeline of my PhD project. Complementary to the literature research, I already started the practical part of my project: the construction of synoptic maps and the segmentation of the different chromospheric structures.

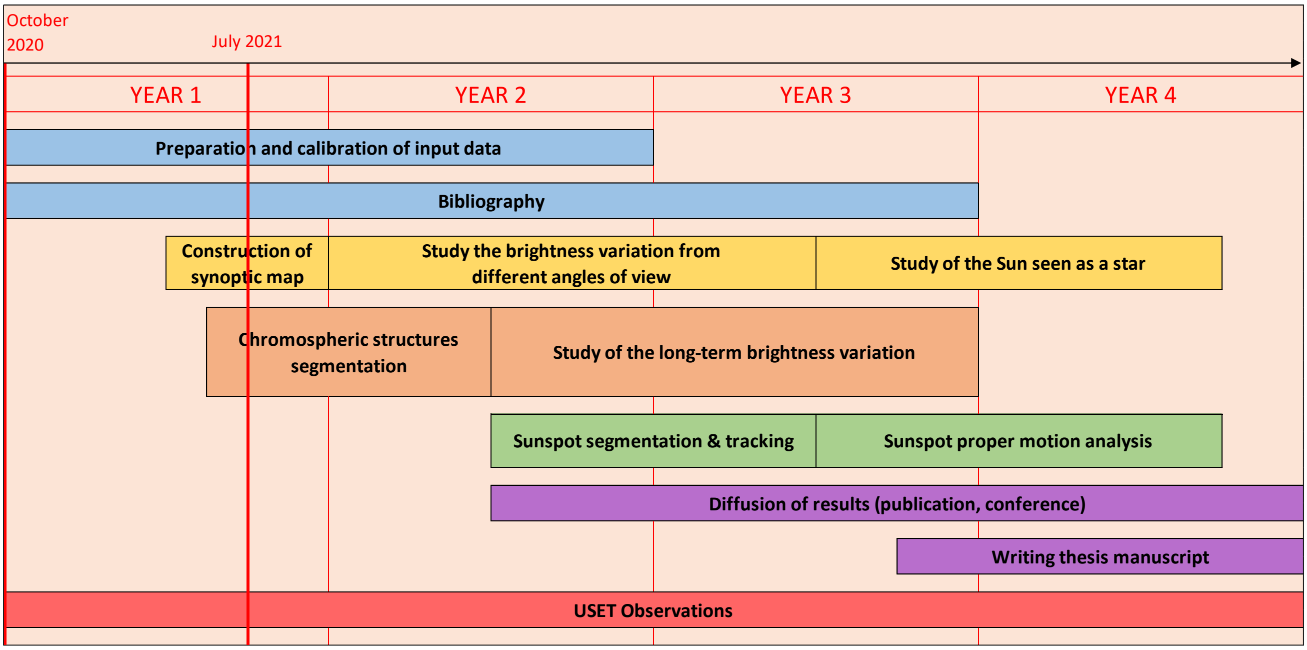

***Figure 1**. Timeline of my PhD project*

4. Progress and results

1) Construction of synoptic maps

As the topic aims at a better understanding of the evolution of large-scale magnetic structures, an important tool to study this evolution over the long-term is the construction of synoptic maps from series of successive images over full solar rotations, in order to map the entire solar surface. Based on USET images, we must first produce a plane projection of the solar sphere and then precisely assemble successive images. The production of synoptic maps allowed me to have a more accurate view on the distribution and proportion of the magnetic structures on complete solar rotations. This activity represents the most important part of my work so far.

a) Solar projection

To map the solar surface, we must apply a projection of the solar sphere. 3 projections were considered: Mercator (MER), Plate carrée (CAR) and Cylindrical equal area (CEA). After implementing the 3 projections, shown in **Figure 2**, we can see that the MER projection (top image) shows a flattening of plages. The surface of plages were better reproduced with the CAR and CEA projection (middle and bottom images). The only difference between them is that for CEA, the structures at the Poles are more flattened. But since there is no plage at these latitudes, the 2 projections are similar. So we chose the plate carrée projection for the simplicity of the equal space in degrees of the latitude and longitude values [Thompson 2006, Calabretta 2018].

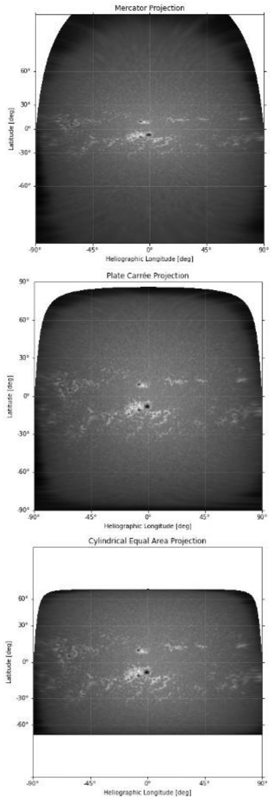

Figure 2. *Example of the 3 projections: MER (top), CAR (middle) and CEA (bottom).*

b) Image assembling

The best way to construct a synoptic map of the Sun is to select a same specific slice on each image during a solar rotation and to assemble those slices to cover the entire solar surface. Once the slices are selected for each image, we can assemble all successive images by juxtaposing them and create the synoptic map.

c) Normalization

Each image has a different intensity level because of multiple parameters: the exposure time, air transparency, etc… Hence to produce a map without artificial contrast between the slices, one must normalize the pixel intensity of the images. My first idea was to use the pixels at the edge of each slice for this purpose. I assumed that the right edge of the slice 1 is the same as the left edge of the slice 2, shown in **Figure 3**. So I calculated the average intensity of all pixels for the right edge of slice 1 and all pixels for the left edge of slice 2 and I divided those intensities to obtain a factor that I use to multiply all the pixels for slice 2. I performed those steps for all successive slices. The resulting synoptic map is shown in **Figure 4**.

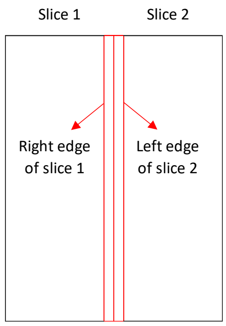

Figure 3*. Schematic way to normalize the images.*

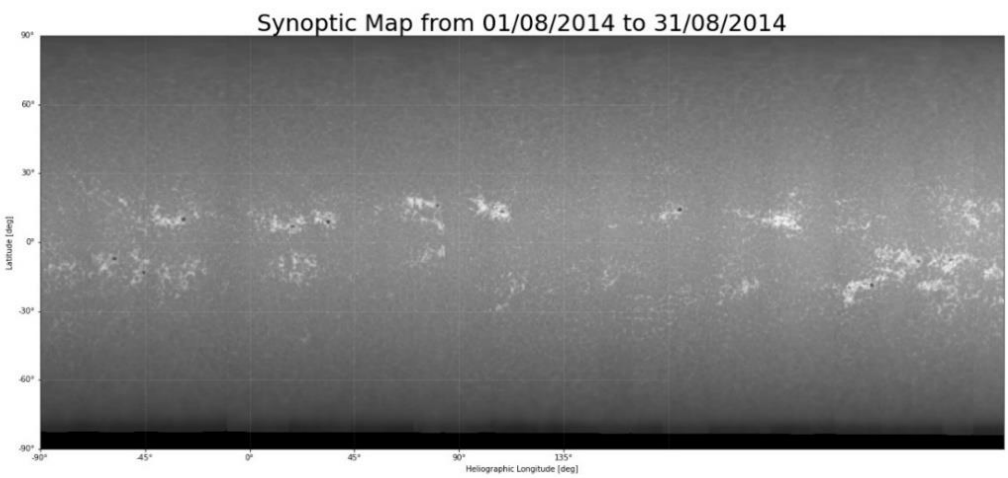

Figure 4*. Example of a synoptic map from 01/08/2014 to 31/08/2014 constructed with the method of normalization by using the pixel intensities of the slice's edges.*

At first glance, the normalization worked and we can see clearly the distribution of the active regions at the solar surface. But after in-depth consideration, the method I used for the normalization has several drawbacks:

- Due to the differential rotation, the assumption I used (**Figure 3.**) is right for some latitudes. For those where the rotation period is longer or shorter than the mean rotation period used, this assumption is wrong. I used this value as a first step but differential rotation must be accounted for in the next steps.
- Due to the dependence of optical depth on viewing angle, there is a centre-to-limb variation (CLV) in intensity. We can see that it is darker at the top and bottom of the map, corresponding to the North and South Pole of the Sun. So using the same normalization factor for all latitudes is not appropriate.
- It is not accurate to use only one column of pixel intensity to normalize the whole slice. It will be more precise to use the whole image to normalize, so before the selection of the slice.

Therefore, I am now testing another way to do the normalization.

<u>2) Chromospheric structures segmentation</u>

We plan to study the long-term brightness variations of the chromosphere in the Ca II K images taking into account the contribution of the different magnetic structures that are the main contributors to the variability of solar irradiance [Domingo 2009]. Our goal is to reach a better understanding of the different contributions of those structures. In order to do that, we are performing the steps as followed.

a) <u>Correction of the centre-to-limb variation (CLV)</u>

As it was explained before, there is a CLV in intensity present on the images. To detect the different structures based on an intensity threshold of a fixed value, it is essential to correct the images from this variation. After the CLV correction (**Figure 5.**), we can see that the limb is now brighter. This artefact is different for all images and the cause of this is not yet understood. I am working on it for the moment to solve this problem. As a first step, in order to remove the effect of any possible artefacts close to the limb, I considered pixels within $0.98R$, where R is the solar disc radius [Chatzistergos 2019, Chatzistergos 2020].

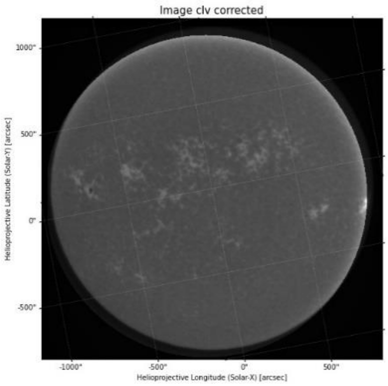

Figure 5*. Example of a USET Ca II K image after CLV correction.*

b) <u>Threshold determination</u>

Chromospheric plages are bright extended regions. In order to segment those structures, we need to determine an intensity threshold below which the intensity doesn't correspond to plages. As a first step, I tested 4 different thresholds. I consider all the pixels within $0.98R$, and I calculate the mean, the 90th percentile, the 95th percentile and the 98th percentile of all pixel intensities. All pixels with an intensity below this threshold are set to 0. **Figure 6** shows the results for each threshold. We can see that with the mean and the 90th percentile (1^{st} et 2^{nd} images), too many pixels have been kept and with the 98th percentile (4^{th} image), some pixels may have been forgotten. That is why I chose to use the 95th percentile (3^{rd} image).

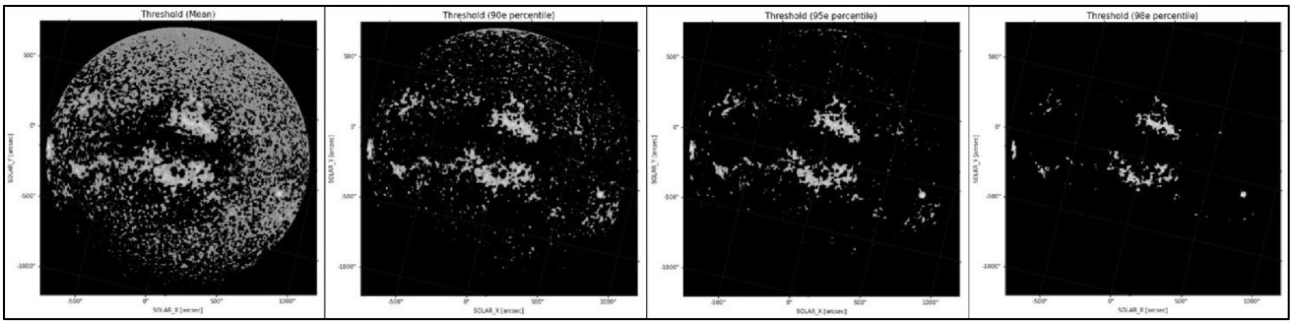

Figure 6*. USET image after applying the different intensity thresholds. The first picture is with the mean intensity, the second with the 90th percentile, the third with the 95th percentile and the last picture with the 98th percentile.*

c) Plages vs chromospheric network

Once the threshold applied, we can see that there are still some "single" pixels that didn't correspond to plages. They form the chromospheric network. Sometimes, the pixel intensity of the chromospheric network can be as bright as the plages but we can identify them because they don't correspond to extended structures. In order to remove those pixels, I used the size of the supergranulation, visible at the solar surface as a cellular pattern and it manifests itself indirectly in the chromospheric network [Hirzberger 2008, Hagenaar 1997]. Hirzberger 2008 found that the supergranular cells have a mean diameter of $27100\ km$. Hence for all pixels after applying the threshold, I looked up the value of 8 pixels around it at a distance of the supergranular radius R_{sg}, as shown in **Figure 7**. If at least one pixel of 8 is not 0, I keep the pixel, otherwise I remove it. Results after this method are shown in **Figure 8**. This first method is not really accurate and still needs to be improved.

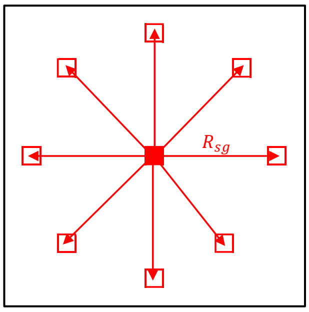

***Figure 7**. Illustration of the way to remove the pixels corresponding to the chromospheric network. R_{sg} represents the radius of a supergranulation cell.*

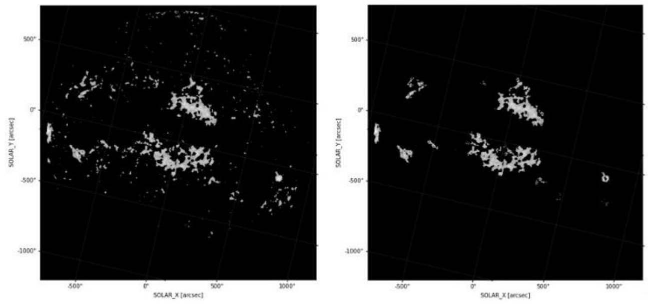

***Figure 8**. Results of the segmentation method. Left image corresponds to the image after applying the threshold and right image represents the image after removing the "single" pixels.*

5. Next steps

1) Synoptic map and the Sun seen as a star

Once we have the synoptic map completely finalized, we will study the brightness variation as seen from any viewing angle relative to the polar axis of the Sun. The measurements of Ca II K emission are suspected to be affected not only by the stellar intrinsic properties but also by the inclination angle of the stellar rotation axis. Until now such an inclination effect on this observed Ca II K emission has remained largely unexplored. A recent study, Sowmya et al. 2021, has already worked on this effect but they essentially used numerical simulations.

2) Chromospheric structures segmentation

We want to study the contribution of the chromospheric structures to the long-term brightness variations. The next steps after the segmentation is to run my algorithm for all images during a solar cycle and extract the intensity and the area of the segmented structures. Then I will plot the intensity variations of the plages, chromospheric network and sunspots as a function of time and I will compare it with the solar irradiance variation to study their contributions. I also plan to study the specific contribution of the plages in order to understand if it is primarily due to their area and spatial distribution or to overall changes in their brightness. For that, I will use the extraction of the area of plages to see if there is a correlation with the intensity variation.

6. Other activities

- At the beginning of my PhD, I applied for a FRIA grant. This required a written project proposal as well as an online oral presentation. Unfortunately, my final grading was A- and my application was not funded due to the strong competition.

- Since October last year, I have also participated in several formations. These include tutorials on the Sunpy library given by a solar physicist, trainings as part of my doctoral formation and internal ROB seminars.

- USET images and drawings are acquired 7 days a week on-site at the ROB by a team of observers. After several weeks of training, since the beginning of 2021, I am part of the team of professional observers that perform the daily observations. This activity requires a lot of attention, precision and patience and gives me a better understanding of solar activity and the different parameters to be taken into consideration in the acquisition of solar images.

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