Tracking Sunspot Waves Across the Solar Disk Using IRIS

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A Senior Thesis submitted to the faculty of Brigham Young University - Idaho in partial fulfillment of the requirements for the degree of Bachelor of Science in the Department of Physics at Brigham Young University - Idaho.

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Department Approval

of a Senior Thesis submitted by

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Abstract

Tracking Sunspot Waves Across the Solar Disk Using IRIS
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Waves can be observed in the transition region and upper chromosphere of sunspots. Two particular phenomena, running waves and umbral flashes, can be seen in the 1400 Å and 2796 Å passband, respectively, on Slit-Jaw images from the Interface Region Imaging Spectrograph (IRIS). The trans-sunspot theory provides the explanation of these waves moving across the sunspot just as they appear visually. However, it is likely this development is fake, due to changes in period of the waves. The upward propagating theory exhibits these waves are tied to the magnetic field lines and are therefore slow magnetoacoustic waves. After applying global wavelet analysis to high-pass filtered Slit-Jaw images, we were able to find the dominate periods of both phenomena, and then apply them to a period map. This period increases from 180 seconds to 240 seconds when moving away from the sunspot center through the umbra and penumbra, lending credence to the upward propagating theory. To ensure angle viewing bias from a central image was not a factor, images from the Sun’s center toward the limb were run through this process as well. We then compared the period maps to photospheric Helioseismic and Magnetic Imager (HMI) magnetic field line inclinations to display the correlation between distance from sunspot center and period. These waves could provide a mechanism for transporting local seismic energy from the photosphere to the corona.
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Left: Period map of 2796 Å passband. Only a sliver of the sunspot is left to be seen here, and it is obvious the 2796 Å is nearly impossible to see a period at all. Right: Period map of 1400 Å passband. Due to the optically thick plasma, only part of the sunspot is available for analysis. From the sliver of the sunspot that is analyzed, it is still apparent there is a period increase and the HMI contours are related to that period increase.

First image of AR 12546 in 2796 Å passband. Located near the center of the disk of the Sun. The black vertical lines that seem to make up the background are from the rastered images having the slit move across them. The period increase that was seen in AR 11836 are very similar to what is seen here, with 145 s near the center of the sunspot, and an increase to ~ 225 s. Past that, the period seems to get mixed with the plage. The y-axis is solar Y coordinates, but the title was cut off during processing.

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Images 1-5 of AR 12546 in 2796 Å passband.

Images 6-10 of AR 12546 in 2796 Å passband.

Images 1-5 of AR 12546 in 1400 Å passband.

Images 6-10 of AR 12546 in 1400 Å passband.
1 Introduction

The Harvard - Smithsonian Center for Astrophysics, located in Cambridge, MA uses space telescope data to study waves, jets, coronal mass ejections, and many other phenomena from the surface to the upper atmospheres of the Sun. For this thesis, the images were obtained from the Interface Region Imaging Spectrograph (IRIS) in slit-jaw image cubes which prevent sunspot waves in the 2796 Å passband in the upper chromosphere and 1400 Å passband of the transition region in the solar atmosphere. The first sunspot observed for this project occurred in September 2013 [Active Region (AR) 11836], and a second was viewed in July 2014 [Active Region (AR) 12456]. Interactive Data Language (IDL) was mostly used for the programming of this project because of its ease of use for studying imaging data.

1.1 Formation and Anatomy of a Sunspot

A sunspot is a polarized region of magnetic field lines that occurs due to the differential rotation of the sun. Most sunspots have a similar diameter to that of Earth, but can range from 1,500 km to 50,000 km. The number of sunspots observed on the Sun follows an 11-year cycle. Active Regions are aptly named because they are relatively small regions of the Sun that are changing rapidly. Sunspots are visual indicators of active regions.

![Approx. size of Earth](image)

Figure 1: “NASA’s SDO Sees Giant January Sunspots” Image of AR 1944 as seen in early January 2014 with an Earth for comparison.

These active regions are formed from what is called “Differential Rotation,” in which parts of the Sun rotate at different speeds. The poles take about 35 days to make a full rotation, but the center takes only 25 days. At solar maximum the differential rotation has dragged the field enough at the rotational equator to produce an unwanted high-energy, high-tension magnetic state. In an attempt to resolve this on small scales, the field will buoyantly rise to the surface where it heats the local plasma and forms an active region. The energetic plasma phenomena associated with the active region drains magnetic energy, allowing the local field to relax into a lower energy state. The North and South poles flip at solar maximum which resets the polarity in equal and opposite directions. This flip decreases the number of visible active regions since they are tied to the behavior of the magnetic field lines. At solar minimum, the magnetic field is roughly a dipole in its least energetic state. Sunspots form from strong, vertically oriented magnetic fields that have disrupted the convection of hot plasma from below to the surface.
Figure 2: Diagram of the Sun’s differential rotation as time passes. The poles are oriented with north at the top and south at the bottom. The equator is rotating more rapidly than the poles which causes a twist to the magnetic field lines. As these magnetic field lines become very polarized in certain regions (just above and below the equator), they buoyantly rise above the surface of the Sun, heating the local plasma and creating active regions. Sunspots form in these active regions as seen in the diagram on the right.

When looking directly at a sunspot in the 2832 Å passband, the anatomy becomes very clear. The outer granular looking surface is called the “plage” and is very noisy - the plage is defined as any extended area of bright plasma. The middle part of a sunspot is called the “penumbra” and is where most of the waves are observed very clearly. The innermost and darkest area is the “umbra”, and the waves are seen to permeate through the sunspot starting here.

Figure 3: IRIS 2832 Å passband image taken 27 July 2014 20:04 - showcasing the plage, penumbra, and umbra. The “slit”, where spectra is captured, can be seen running vertically through the image.
1.2 Instruments Used

This research project used data received from the Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO), and the Interface Region Imaging Spectrograph (IRIS). IRIS acted as the primary source of imaging data for the sunspot waves while HMI provided context of the underlying photospheric magnetic field inclination.

IRIS is a NASA Small Explorer Mission that takes high resolution images of the chromosphere and transition region of the Sun. The goal of IRIS is to better understand the phenomena that occur between the cool photosphere of about 6,000 K and the hot corona of about 1 million K. IRIS produces slit-jaw images, meaning the center of the images will have a “slit” down the middle which allows light to enter the spectrograph while the surrounding image is redirected to a separate detector. In this thesis, images of the 1400 Å and 2796 Å passband are analyzed.

HMI is an instrument located on SDO, and provides high resolution photospheric full vector magnetic field images. In particular, this means that we are able to tell how the magnetic field lines on the solar surface (photosphere) are inclined in sunspots.

1.3 Regions in Solar Atmosphere

This study concerns two regions of the solar atmosphere. The lower region is the upper chromosphere, a layer of plasma observed in the 2796 Å passband of IRIS which primarily detects radiation from Mg II formed at 16,000 K. The more elevated region is the transition region, which has a temperature much higher than that of the upper chromosphere as seen in 1400 Å passband of IRIS which primarily detects radiation emitted from Si IV formed at 80,000 K. The chromosphere is located in the Sun’s atmosphere 400 km above the Sun’s surface and extends to about 2080 km above the surface. The transition region is a very thin layer between the chromosphere and the corona where temperature changes rapidly. The sunspot wave phenomena seen in these regions are called “umbral flashes” in the upper chromosphere, and “running waves” in the transition region.
1.4 Wave Candidates and Theories

The Sun is like a giant ringing bell. When it “vibrates,” helioseismic “sun-quakes” occur, much like the earthquakes we experience on Earth from the shifting of tectonic plates, however unlike earthquakes, the Sun is continuously vibrating instead of releasing seismic energy in bursts. The dominant seismic wave on the Sun is the five minute p-mode oscillation, which is similar to the period of the running waves and umbral flashes observed in the solar chromosphere and transition region. The wave candidates are fast and slow magnetoacoustic waves because they are both compressional and are observed in the solar atmosphere. A third wave type, the Alfvén wave is the only transverse wave in the magnetohydrodynamics regime and can only brighten plasma by dissipating currents into it. They are not likely seen here due to the low resistivity throughout the chromosphere and would not be bright enough to produce the observational signatures we see with the running waves and umbral flashes. This leaves the compressional modes - fast and slow magnetoacoustic waves - as the only other candidates.

The trans-sunspot theory says that if the waves are fast magnetoacoustic waves, then the RWs are excited by UFs in the chromosphere. This further suggests a nearly constant period throughout the sunspot. Fast magnetoacoustic waves are not tied to magnetic field lines.[1]

The upward-propagating theory implies that if the waves are slow magnetoacoustic waves, then RWs are affected by the emerging magnetic field inclinations, and there would be a change in period from the center of the sunspot outward. Slow magnetoacoustic waves are unique in that they are tied to the magnetic field lines, unlike the fast magnetoacoustic waves. In a sunspot, field lines are vertically oriented suggesting slow magnetoacoustic modes can only propagate vertically. The cutoff period varies inversely with the cosine of the magnetic inclination angle from the normal. If we assume the field lines become more inclined the further we look from the sunspot center, longer period waves will be expected further out. [1]

An important note about these theories is that these are simply monikers adopted for this text, not official term names.

2 Methodology

The data analyzed in this research was put through three computational processes, the first was a “High Pass” filter, then a Wavelet Transform, and last was overlayed with the HMI inclination data. Once the three processes were complete, it was a simple addition to apply them to new images of the same or different sunspots that are in different positions across the disk of the Sun. This is important to find if there is an angle viewing bias and if similar results can be found as sunspots move away from the center of disk, or are a different sunspot altogether.

2.1 High Pass Filter

The high-pass filter serves to draw out the running waves and umbral flashes from the complex, nonuniform background of the sunspot. A high pass filter is a computational method of removing static or slowly evolving phenomena and leveling the nonuniform background noise from the images, leaving only the rapidly changing phenomena. This was done using a running centered mean subtraction method which mathematically, looks like this.

$$\tilde{P}_M(i,j) = P_M(i,j) - (2R + 1)^{-1} \left\{ \begin{array}{ll} \sum_{k=0}^{2R} P_k(i,j) & \text{if } M > R \\ \sum_{k=M-R}^{M+R} P_k(i,j) & \text{if } R \leq M \leq N - R - 1 \\ \sum_{k=N-2R-1}^{N-1} P_k(i,j) & \text{if } M > N - R - 1 \end{array} \right.$$

(1)

Where:
- $M \equiv$ Location of center image
- $(i, j) \equiv$ Horizontal and vertical coordinates of pixel
- $P_k(i,j) \equiv$ Intensity value of pixel located at $(i, j)$ in image $k$
- $P_M(i,j) \equiv$ Intensity value of pixel located at $(i, j)$ in center image $M$
- $\tilde{P}_M \equiv$ Filtered value of pixel located at $(i, j)$ for center image $M$
- $R \equiv$ # of images on either side of $M$ included in mean; coder chosen value

The running centered mean subtraction method is a way to filter averaged pixel values taken from these images. When using this process, a center image, $M$, averages the intensity values of a number of images before and after
it which then creates new images from these calculated averages subtracted from the original value. To apply this method to each image means to first pick a value of R - the number of images on each side of the image to use for averaging. For AR 11836, 25 was used, this is because with the 12 second time step between sequential images and the expected p-mode oscillation period of 5 minutes. For AR 12546, 8 was used, for the change of \( \sim 37 \) seconds between sequential images. At the ends of the data sets which are the first and last R images (R = 25 images for AR 11836 and R = 8 images for AR 12546), we will settle for a truncated edge mean meaning since these first and last images do not have enough images on both side of the centered image, only the side of the center image with R+ images will be incorporated in the averaging.

I will describe this process assuming AR 11836 is the image cube in processing. First, we needed to take the first 25 images, calculate the average of each of the pixel intensity values, and subtract it from the actual value on that particular image. Once the 25th image was reached, then the 25 previous and 25 sequential images were used in calculating this mean which was then subtracted from the image in calculation. Once the center image was less than 25 images from the end of the image cube, then the previous 25 images were used for the mean calculation. This means we settled for a truncated edge mean on the images close to the edges.

Figure 5 and Figure 6 provide a visual of the running centered mean. Figure 5 is a colorized 1400 Å passband image before the running centered mean subtraction has been applied, and Figure 6 is after it has been applied.

![Figure 5: Colorized 1400 Å passband image before high-pass filter applied.](image1)

![Figure 6: Colorized 1400 Å passband high-pass filtered image using running-mean subtraction method.](image2)

2.2 Wavelet Transform Application

Once the high-pass filter is applied, the pixel intensities on the images can be run through what is called a “Wavelet Transform” which takes one pixel over time (through all the images) and breaks down the intensity signal into its wave components, very similar to a Fourier Transform. The goal of a wavelet transform is to find the dominant period which is done through first forming a power spectrum of the pixel intensities, and then summing it over time to find the period of maximum global power above 95% confidence threshold. A power spectrum gives the plot of a signal’s power (energy per unit time) per given frequency bins [8]. The most common way of generating a power spectrum is by discrete Fourier Transform. Only wave periods above a 95% confidence threshold were accepted in this analysis.
Figure 7: Power spectrum calculated from wavelet analysis. The top graph is the pixel intensity throughout the images, the colored graph is the resulting power spectrum showing the dominant wavelength components of the pixel intensity as a function of time. The “dominant period” is then summed and shown on the graph on the right. This particular pixel had a dominant period around 200 s. This process was done to each pixel in the image cubes.

Figure 8: Non-colorized dominant period map of AR 11836 in the 1400 Å passband. The result of the wavelet analysis is a map of dominant wave periods throughout the sunspot.
2.3 Helioseismic and Magnetic Imager Contour Overlay

After calculating the dominant period and creating a map of how it varies spatially, the final step is to see how the inclination of the magnetic field lines relate to this change in period. The Helioseismic and Magnetic Imager (HMI) takes full-vector magnetic field images that can be contoured and overlayed onto these dominant period maps. After many calibrations and transforms have been applied to the HMI data, the images look like Figure 9. This image represents the cosine of the inclination angle of the full-vector magnetic field in the photosphere. The white and black portions of the image mean the solar magnetic field lines are mostly vertical and thus have small inclination angles, pointing directly perpendicular to the surface of the Sun. The gray covering most of the surface indicates the magnetic field lines that are far more inclined, or more parallel with the surface. Once the contours have been found, they can be easily overlayed.

![Figure 9: HMI cosine of the full-vector field image with AR 11836 located near the center of the disk as a mottled patch of white and black surrounding the sunspot and identified by the red box.](image)

3 Observations and Results - Angle Bias Testing

The previous sections feature work that is similar to what was analyzed in [1]. That work analyzed only one instance of a sunspot near disk center. However, it did not assess the potential for measurement biases due to changes in viewing angle as the sunspot crosses the solar disk. To check for this, images of the sunspots as they moved away from the disk center toward the limb were analyzed through the high-pass filter and wavelet transform, then overlayed with their respective HMI contours. We analyzed sunspots from two different active regions: AR 11836 and AR 12546. Black pixels were rejected for not meeting the 95% confidence threshold during the wavelet analysis, the purple pixels represent the upper saturation point (305 seconds) - any pixels with dominant periods above this were turned purple.

3.1 Active Region 11836 - September 2013

The first image in each set of 3 images is the location on the disk of the sun, emphasized by the blue square. The second image is the 2796 Å passband image, and the third is the 1400 Å passband. Descriptions of each image will be found below them.
Figure 10: Left: Period map of 2796 Å passband. Near the center of the sunspot, you can see that the dominant period of the waves starts around 145 s and increases to 171 s. The relation of the HMI contour inclination and the period change is very visible. Right: Period map of 1400 Å passband. The period here increases from the 145 s that was also visible in the 2796 Å passband, but much more of the outer parts of the sunspot were within the 95% confidence interval.

Figure 11: Left: Period map of 2796 Å passband. The original image here cut off the bottom half of the sunspot, meaning observations of the top half were all that were available. The very top noisy parts of the images were also removed to cut down computational run time. The period is 145 s near the center of the sunspot and much noisier, but it is still obvious there is an increase in period to 300 s moving outward. At this angle, the increase is still visibly related to the inclination of the HMI contours. Right: Period map of 1400 Å passband. Because of the cut-off of the original images, there is only about half of the sunspot available for analyzing. This image is still consistent with the results previously seen. The period near the center of the sunspot is around 145-170 s, and increasing outward.
Figure 12: Left: Period map of 2796 Å passband. This observation was not very clear and caused the results to be inconsistent with the other results. The majority of the sunspot here has a period between 200 and 225 s, which is not consistent with the other results. Right: Period map of 1400 Å passband. A bit more consistent than the 2796 Å results, the HMI inclination is starting to appear to the left of the sunspot. This is because the observations are looking through very optically thick plasma, and we are only able to see a part of the sunspot. The HMI inclinations are becoming more squished horizontally because of the angle of viewing.

Figure 13: Left: Period map of 2796 Å passband. The sunspot is becoming more distorted in shape, but the period results are still clear. There is less correlation between the inclination of the HMI contours and the period increase, but there is still a relation that can be seen. Right: Period map of 1400 Å passband. This result produced a very visible increase in period outwardly, even being so close to the limb of the sun.
Figure 14: Left: Period map of 2796 Å passband. This image looks like a vertically stretched sunspot, but this is because the plasma is very optically thick and only the side closest to the telescope is visible. There is evidence of the dominant period increase here, but not as easy to see because of the limited view. Right: Period map of 1400 Å passband. Parts of the sunspot are no longer visible here, but the increase in period is still apparent. Near the center a 145 s dominant period is seen, and again outward there are parts showing the 300 s period.

Figure 15: Left: Period map of 2796 Å passband. Only a sliver of the sunspot is left to be seen here, and it is obvious the 2796 Å is nearly impossible to see a period at all. Right: Period map of 1400 Å passband. Due to the optically thick plasma, only part of the sunspot is available for analysis. From the sliver of the sunspot that is analyzed, it is still apparent there is a period increase and the HMI contours are related to that period increase.
For the most part, the results from the research of AR 11836 were very consistent. Periods are seen from 145 s to the 300 s range, which is what we expect if the source of these waves are the p-mode oscillations that occur at the surface of the Sun. The correlation between outward period increase and the outward inclination increase lend credence to the upward propagating theory. The third 2796 Å image had some external issue causing the results to be inconsistent from all the other observations, but overall the results were consistent.

### 3.2 Active Region 12546 - July 2014

This Active Region 12546 was seen in rastered images, meaning the slit from the “Slit-Jaw” is seen moving through the image, which rendered some of the results much less clear than those of AR 11836. However, the results are mostly consistent and there is a relation between the HMI contour inclination and Dominant Period increase. Only the first and seventh images of AR 12546 were overlayed with their HMI contours due to time constraints, but the rest of the AR 12546 images can be seen without their HMI contours. Because of the age of IRIS at this point, the sensitivity and time between images is much longer at \( \sim 37 \) s, when AR 11836 had a time between images of \( \sim 12 \) s. To account for this cadence change, instead of the 25 images \((R)\) used on each side of the center image from AR 11836, only 8 images were used for this active region.

![Figure 16: First image of AR 12546 in 2796 Å passband.](image16)

Located near the center of the disk of the Sun. The black vertical lines that seem to make up the background are from the rastered images having the slit move across them. The period increase that was seen in AR 11836 are very similar to what is seen here, with 145 s near the center of the sunspot, and an increase to \( \sim 225 \) s. Past that, the period seems to get mixed with the plage. The y-axis is solar Y coordinates, but the title was cut off during processing.

![Figure 17: First image of AR 12546 in 1400 Å passband.](image17)

Located near the center of the disk of the Sun. The slit is not as prevalent in this image, but the reduction in spatial resolution from the raster and IRIS’s loss of sensitivity are why the results of the sunspot looks so dark and without any real clear period in the image. The y-axis is solar Y coordinates, but the title was cut off during processing.
Figure 18: The seventh image of AR 12546 in the 2796 Å passband. The period near the center of sunspot is still visible, but there is very optically thick plasma covering the far side of the sunspot, making the results difficult to see - although still there. The y-axis is solar Y coordinates, but the title was cut off during processing. Remnants of the slit can be seen throughout this image.

Figure 19: The seventh image of AR 12546 in the 1400 Å passband. This image came out very unclear as to what the period was, once again, more likely to be the worse spatial resolution that comes with rastering and the depreciated sensitivity of the detector. The period is still somewhat visible, but only a small sliver of the sunspot can be seen from this angle.

Figure 20: Images 1-5 of AR 12546 in 2796 Å passband
Figure 21: Images 6-10 of AR 12546 in 2796 Å passband

Figure 22: Images 1-5 of AR 12546 in 1400 Å passband

Figure 23: Images 6-10 of AR 12546 in 1400 Å passband
4 Conclusion

From these results, a few conclusions can be made. A viewing angle bias is not present, because from all viewing angles similar results have been observed. The sunspots, both AR 11836 and AR 12546, saw a 145 s period near their centers, and an outward increase to ~300 s near the outer part of the penumbra where observable. The relation between the HMI contours and the period suggests the upward propagation theory. The upward propagating theory entails that the umbral flashes and running waves are slow magnetoacoustic waves tied to the magnetic field lines that become more inclined outward, leading to the apparent motion we see in the IRIS images. The theory also suggests that both umbral flashes and running waves are the same phenomena, viewed at different altitudes with both originating from p-mode oscillations. The consistency in the results is clear when looking at the period distribution of a single sunspot at different viewing angles. However, consistency is not clear between different sunspots due to the limitations present in AR 12546. Further work is needed to make claims about the consistency between sunspots. Another data set similar to AR 11836 with less limitations (no rastered images, taken early in IRIS mission with better sensitivity, highest possible spatial and temporal resolutions) would be preferable.

This work is ultimately important for two reasons: coronal heating and magnetohydrodynamic (MHD) seismology. In coronal heating, this research could characterizes a potential mechanism for transporting seismic energy in the photosphere to the hot corona. In MHD seismology, understanding these waves may allow us to probe the properties of the plasma and magnetic field in the chromosphere and transition region, two notoriously difficult regions to observe directly. This is similar to seismology on the Earth.

5 Potential Future Work

Measuring phase velocities of the waves across the solar disk to further support the conclusions of this work. This means to take a cut of pixels throughout the sunspot and analyzing the speeds of these waves close to the sunspot center and further away. The phase velocities should be seen as c-shaped structures, and have a changing velocity moving away from the sunspot center.

Look for extensions of these waves higher up in the corona. IRIS and other instruments allow for looking in different passbands and therefore different altitudes. Using the image analysis methods described in this thesis to see if the changing period higher up in the atmosphere would provide more conclusions to these results.

Model how much seismic energy can be carried by these waves and place constraints on their potential to heat the corona. Using computational methods to create a model of how these waves are transporting the local energy to the solar corona would be an addition to generate an idea of why the corona is so high in temperature and where that energy is coming from.
References

High Pass Filter

```plaintext
PRO Task5

fname = '/home/hsager/Downloads/REU_2016/REU_2016/Data/iris_12_1720130902_163935_400256147_SJI_1400_t000.fits'
mydata = IRIS_SJI(fname)
myimages = mydata->getvar()
n_images = n_elements(myimages[12:362, 28:385, *])
myimagesarray = myimages[12:362, 28:385, *]
allimages_sorted = myimagesarray[SORT(myimagesarray)]
n_allimages = n_elements(where(finite(allimages_sorted)))
solarx = mydata-> xscale()
solary = mydata-> yscale()
pixresx = mydata-> getresx()
pixresy = mydata-> getresy()
myimagesarrayshifted1400 = SHIFT(myimagesarray, -15, -4, 0)
nx = n_elements(myimagesarrayshifted1400[*,0,0])
ny = n_elements(myimagesarrayshifted1400[0,*,0])
fname1400 = '/home/hsager/Downloads/save files/shifted.sav'
restore, fname1400
aspr = (double(ny)*pixresy)/(double(nx)*pixresx)
xprime = 0.05
yprime = (xprime)/((aspr*(1.0-(2*xprime)))+(2.0*xprime))
dx = (1.0-(2.0*xprime))
dy = (1.0-(2.0*yprime))
R = 12 ; number of images on either side of M included in mean.
N = 399 ; total number of observed images

filterarray = dblarr(nx, ny, 400)
window, 0,xs = 1000, ys = 1000*aspr, retain = 2
loadct, 3
n_images_smooth = smooth(myimagesarray, 3, /edge_truncate)
for M = 0, N do begin
  ti = systime(/seconds)
  if (M LT R) then begin
    for i = 0, nx-1 do begin
      for j = 0, ny-1 do begin
        filterarray[i, j, M] = myimagesarrayshifted1400[i, j, M] - mean(myimagesarrayshifted1400[i, j, 0:(2*R)])
      endfor
    endfor
  endif
  if (M GE R) and (M LE (N-R-1)) then begin
    for i = 0, nx-1 do begin
      for j = 0, ny-1 do begin
        filterarray[i, j, M] = myimagesarrayshifted1400[i, j, M] - mean(myimagesarrayshifted1400[i, j, (M-R):(M+R)])
      endfor
    endfor
  endif
  if (M GT (N-R-1)) then begin
    for i = 0, nx-1 do begin
      for j = 0, ny-1 do begin
        filterarray[i, j, M] = myimagesarrayshifted1400[i, j, M] - mean(myimagesarrayshifted1400[i, j, (N-2*R-1):(N-1)])
      endfor
    endfor
  endif
endfor
```
plot_image, filterarray[0:336,0:334,M], min = allimages_sorted[n_allimages*0.00001], max = allimages_sorted[n_allimages*0.5], origin = [solarx[0], solary[0]], scale = [pixresx, pixresy], xtitle = 'solar X [Arcsec]', ytitle = 'solar Y [Arcsec]', /noerase, POSITION = [(0.75*xprime), (yprime*0.75), dx, dy+(yprime*1.5)]
colorbar, RANGE = [allimages_sorted[n_allimages*0.03], allimages_sorted[n_allimages*0.98]], /vertical, /right, title = '1400 Angstrom SJI Intensity [Arbitrary Units]', position = [(xprime/2)+dx, (yprime*0.75), dx+(1.2*xprime), (1.5*yprime)+dy]
�名 = '/home/hsager/Downloads/MoviesFiltered1400/' + STRCOMPRESS(STRING(M), /REMOVE_ALL) + '_frame.png'
scrncap = TVRD(TRUE=1)
write_png, wfname, scrncap
tf = systime(/seconds)
dt = tf-ti
trem = dt * double(n-1-M)
trem_h = LONG(trem/3600D)
trem_m = LONG((trem/60D)-(DOUBLE(trem_h)*60D))
trem_s = ROUND(trem-(DOUBLE(trem_m)*60D)-(DOUBLE(trem_h)*3600D))
PRINT, STRCOMPRESS(STRING(trem_h), /REMOVE_ALL)+':'+ STRCOMPRESS(STRING(trem_m), /REMOVE_ALL)+':'+ STRCOMPRESS(STRING(trem_s), /REMOVE_ALL)+' remaining'
writefits, '/home/hsager/Downloads/save files/filtered1400.fits', filterarray
END
6.2 IDL Wavelet Analysis - Calculating Dominant Period

PRO task6
rfname = '/home/hsager/Downloads/save files/High Pass Filter2796'
restore, rfname
;filterarray2 = filterarray
y = filterarray2
dt = 12
timearr = dt*DINDGEN(400)
dfreq = 0.00125
nx = n_elements(filterarray2[*,0,0])
ny = n_elements(filterarray2[0,*,0])
newimage2796 = DBLARR(nx,ny)

;help, periodarray
;plot_image, abs(wavedata)^2, SCALE=[12,dfreq],POSITION=[0.05,0.4,0.95,0.6]

LOADCT,39
Ni = nx
Nj = ny
N = Ni*Nj
M = -1
for i = 0, Ni-1 do begin
for k = 0, Nj-1 do begin

; window, 0, retain = 2

wavedata = WAVELET(y[i,k,*], dt, PERIOD=periodarray,DJ=dfreq,s0=2*dt,j=4690,MOTHER='morlet',
SIGNIF=sigarray, SCALE=scalearray)

; PRINT, MAX(scalearray)
; PRINT, MAX(periodarray)
;HELP, scalearray
;PRINT, MAX(WHERE(periodarray LE 1000D))
;PLOT, periodarray,PSYM=3;,deriv(periodarray,dindgen(N_elements(periodarray)))

wavepower = abs(wavedata)^2
; help, wavepower
;PLOT_IMAGE,wavepower,/NOERASE,ORIGIN=[timearr[0],periodarray[0]],SCALE=[12,(MAX(periodarray)-MIN(periodarray))/DOUBLE(N_ELEMENTS(periodarray))],YTITLE='Period [s]',TITLE='Power Spectrum at x='+STRCOMPRESS(STRING(i),/REMOVE_ALL)+' y='+STRCOMPRESS(STRING(k),/REMOVE_ALL)

;CONTOUR,wavepower,timearr,periodarray,POSITION=[0.1,0.25,0.75,0.75],/NOERASE,XSTYLE=1,YSTYLE=1,NLEVELS=15,C_COLORS=[0,15,30,45,60,90,120,150,175,180,195,210,125,240,255],/FILL,XTITLE='Time [s]',YTITLE='Period [s]',TITLE='Power Spectrum at x='+STRCOMPRESS(STRING(i),/REMOVE_ALL)+' y='+STRCOMPRESS(STRING(k),/REMOVE_ALL)

sum = total(wavepower,1) ;takes sum in the time direction of wavepower
HELP, sum
maximum = max(sum) ;returns maximum of the summed wavepower
; PLOT, sum, periodarray,/NOERASE, POSITION=[0.8,0.25,0.98,0.75],XSTYLE=1,YSTYLE=1,XTITLE='Global Spectral Power',YTITLE='Period [s]' ; OPLOT,sigarray,periodarray, LINETYLE=1

dominantpindex = MAX(where(sum EQ maximum)) ;tells where the dominant period is - location
if sigarray[dominantpindex] GT sum[dominantpindex] then begin ;if significance at location of dominant period is LT 0.95, don't use
dominantperiod = 0
else

if sigarray[dominantpindex] LT 0.95 then dominantperiod = 0
else

dominantperiod = periodarray[dominantpindex] ;value of the dominant period

print, dominantperiod
newimage2796[i,k] = dominantperiod; puts dominant period into new image cube at pixel each location

; print, newimage2796[i,k]

; wfname = '/home/hsager/Downloads/waveletpixels/' + STRCOMPRESS(STRING(i), /REMOVE_ALL) + '_' + STRCOMPRESS(STRING(k), /REMOVE_ALL) + '_frame.png'

; scrncap = TVRD(TRUE=1)

; write_png, wfname, scrncap

tf = systime(/seconds)
dt = tf-ti

M++
trem = dt * double(N-1-M)
trem_h = LONG(trem/36000D)
trem_m = LONG((trem/60D)-(DOUBLE(trem_h)*60D))
trem_s = ROUND(trem-(DOUBLE(trem_m)*60D)-(DOUBLE(trem_h)*3600D))

PRINT, STRCOMPRESS(STRING(trem_h),/REMOVE_ALL)+':'+ STRCOMPRESS(STRING(trem_m),/REMOVE_ALL)+':'+ STRCOMPRESS(STRING(trem_s),/REMOVE_ALL)+' remaining'

endfor

endfor

dominantfile = '/home/hsager/Downloads/save files/2796Version2.sav'
save, newimage2796, FILENAME = dominantfile

plot_image, newimage2796

;help, filterarray
;HELP, wavedata

PRINT, 'I, this program, have completed computing'

END
6.3 IDL Dominant Period Map Code

```idl
PRO waveletimage

;loads in the files, sorts the data and takes each number of elements
dominantfilerestore = '/home/hsager/Downloads/save files/2796Version2.sav'
restore, dominantfilerestore,/VERBOSE
sfshifted = '/home/hsager/Downloads/save files/shifted.sav'
restore, sfshifted
newimage = newimage2796
newimagesorted = newimage[SORT(newimage)]
n_newimage = N_ELEMENTS(WHERE(FINITE(newimagesorted)));
print, newimage[203, 181]

;to open new window each time rerun
window, 0, xs = 1000, ys = 1100, retain = 2
loadct, 4, /silent

tvlct,r_vect,g_vect,b_vect,/get
tvlct,reverse(r_vect),reverse(g_vect),reverse(b_vect)
r_vect[0:150] = 0
g_vect[0:150] = 0
b_vect[0:150] = 0

tvlct,r_vect,g_vect,b_vect
;minimum/maximum saturation values
minimum = 0
maximum = 150

;plots the image and the colorbar
plot_image, newimage, min = newimagesorted[n_newimage*0.01], max = newimagesorted[n_newimage*0.65],
    position = [0.05, 0.035, 0.98, 0.98], xstyle = 1, ystyle = 5, xtitle = 'solar X [arcsec]', scale =
    pixresx, pixresy, origin = [solarx(0), solary(0)]
colorbar, /reverse, /vertical, range = [min(newimage), max(newimage)], position = [0.025, 0.035, 0.035, 0.98]

;prints values and saves the image as a .png
print, max(newimage), min(newimage), mean(newimage), median(newimage)
print, n_elements(where(newimage LE 0))
waveletimage = '/home/hsager/Downloads/dominantperiod2796version2.png'
scrncap = tvrd(true=1)
write_png, waveletimage, scrncap
writefits, '/home/hsager/Downloads/save files/newimage2796version2.fits', newimage

print, newimage[203,181]
print, "completed running"
END
```