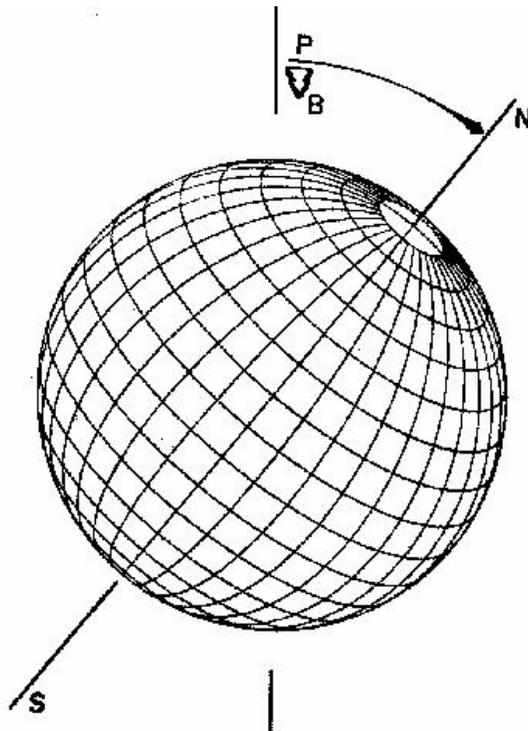


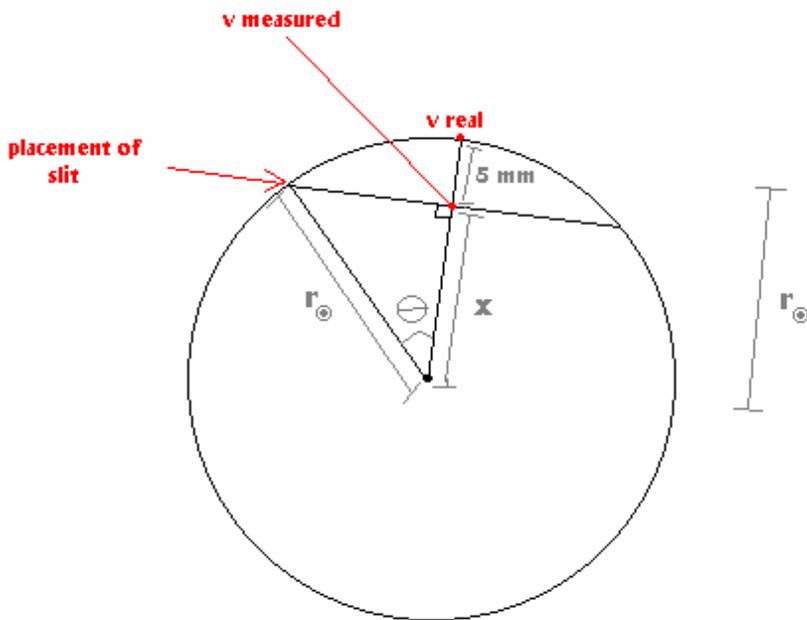
## Solar Spectrum Lab

### Introduction

You are aware of the fact that the sun rotates from studying the motion of sunspots. However, monitoring sunspot rotation period is not the only way to measure the rotational velocity of the sun. At either limb of the sun (the apparent east and west ends of the equator as we see the sun in the sky), you can observe the entire rotational velocity as either towards or away from the earth. As a result, the frequency of the light coming towards us is shifted towards the blue end of the spectrum, and the light receding is shifted towards the red. Using the solar telescope and the attached spectrograph, you can take images of the solar spectrum at either limb, and observe a shift in wavelength between the two, as a result of the difference in velocity. You will also observe spectral lines from the earth's atmosphere, called telluric lines; these of course will not be shifted. You will first find the shift in pixels on your images; you will then need to find the dispersion, in Angstroms per pixel, in order to find the actual wavelength shift. You can then use the equation  $\Delta\lambda/\lambda=v/c$  to determine  $v$  as a function of the wavelength shift. However, you must first take into account some variables in the position of the sun as observed from earth.



As indicated on the diagram, there are two inclination angles of the solar rotation axis that are of primary concern. The angle  $\delta$  is determined by three things. The solar axis of rotation is inclined from the ecliptic by about  $3^\circ$ . Also, the position of the ecliptic in the sky changes according to the time of year (you can see this most easily by paying attention to the orientation of the points of the crescent moon from month to month). These two factors are compensated for by looking up the position angle of the axis in the astronomical almanac. Last, because of the way the solar telescope works, the angle of the image changes throughout the day according to the sun's hour angle, being roughly upright at noon, and inclined at  $90^\circ$  at 6pm. You will compensate for this using the solar image rotator (see diagram 3). The angle  $\Phi$  is the inclination of the sun's polar axis; how much the north pole of the sun is tilted towards or away from us. This is also determined by the time of year, and is available in the almanac. A third correction factor results from experimental error in measuring the limb of the sun. The location of the spectrograph slit is marked on the wall, where the image of the sun will appear, and also where you will focus it. It is difficult to tell if the limb is positioned right on the spectrograph slit, or just to one side; if the latter is true, the velocity will be off by a factor of  $\cos \theta$ , as shown below:



The idea is to be off by a known distance, so that  $\theta$  may be calculated accurately. You will take spectra that are 5mm from the limb on the wall. By measuring the corresponding diameter in mm, you will know the

radius, and  $x$ , and so be able to find  $\theta$ . When you arrive at a numeric result for the rotational velocity, you must divide through by all three correction factors,  $\cos \Phi$ , and  $\cos \theta$ .

### Equipment

- Solar telescope
- CCD camera and software
- Solar almanac for the current date
- White paper and tape for tracing
- Ruler
- Software for analyzing images, and internet access

### Setup

Make sure the **6" objective lens** is on the main track in front of the telescope.



Light passes through this lens and bounces off two mirrors before arriving at the slit. Sometimes there is an additional 2" lens between the second mirror and **the slit**,

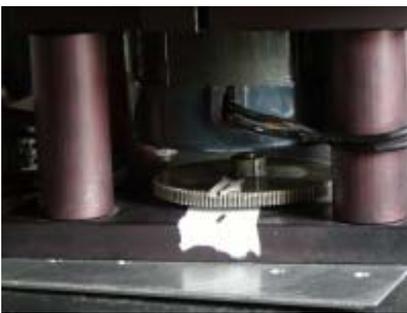


which creates a very small image of the sun;

when this lens is in place, the **solar image rotator** is pushed to the side.



Make sure the 2" lens is not in place, and that the rotator is. The **scanning motor** should be turned off, and the two black lines on it should match, indicating that the image is centered on the slit.



The lever next to the CCD camera should be flipped so that the accompanying mirror deflects light into the camera, i.e. the lever should be parallel to the long axis of the table. The alternate setting (lever 45 degrees to long axis of the table) allows light to pass straight through to the eyepiece which you can use to verify you are in the correct part of the spectrum.

Make sure that the power lead from the camera adapter (the black box the camera cord and the USB cord plug into) is plugged into the AC/DC power adapter (the power adapter's orange LED will be lit when it has power) .

Open MaximDL in the computer. The Camera Control Window is located under View in the Toolbar. Click the Setup tab in the Camera Control Window. Now look to make sure that Starlight Express MX7C USB is chosen as the camera, if not click the Setup button that corresponds to the CCD and choose Starlight Express MX7C USB.

Click the Expose tab to setup your exposure times. Make sure that the Light box is checked. You take a picture by choosing an exposure time and then clicking Expose. To adjust the brightness and contrast of an image to see if there is anything there, go to the View tab in the Toolbar and select Screen Stretch Window. By adjusting the green and red triangles you can set the brightness and contrast to a more appropriate level. Once you have found that you are taking good exposures, save the picture before you adjust anything in the Screen Stretch Window. This will ensure that you don't alter the data. In the Sequence Tab of the Camera Control window you can set MaximDL to take a sequence of exposures. You can also set the base name. This option is useful for distinguishing pictures of the east and west limbs.

## Procedure

Using the wavelength control, find your chosen wavelength. Since the diffraction grating is in second order, this is not as simple as setting the dial to the exact wavelength in angstroms. For second order,

$$(\text{dial \#}) = (5.12367 \times 10^{-5}) \lambda^2 + (2.79344) \lambda - 9325.65$$

For example, if you wanted to look at the two prominent sodium lines at about 5890 angstroms, you would set the dial to  $(5.12367 \times 10^{-5}) 5890^2 + (2.79344) 5890 - 9325.65 = \mathbf{8905.2}$ .

*Set the rotator dial to 44.5° (there are two possible choices for this number; the correct one is marked); this is the value for zero rotation; you will make the corrections starting from this position. The first correction you will make with the rotator is to compensate for the hour angle of the sun (i.e. the telescope). When the sun is on the meridian, no rotation is needed. However, when it is east of the meridian (morning), the dial should be turned counterclockwise as viewed from the slit. To compute the hour angle, find the time of the meridian crossing in the almanac; it will be under the heading "meridian crossing" or "ephemeris transit". Our meridian crossing is approximately 15 minutes before the listed time, since we are east of the center of our time zone (Between March and October it will be 45 minutes later than the almanac listing, due to daylight savings). The current local time minus the time of the local meridian crossing is the hour angle. An hour of rotation corresponds to rotating the prism inside the rotator 15°; however, rotating the dial 1° rotates the image 2°, so for one hour you would turn the rotator dial 7.5°. The next correction is to compensate for the position angle of the*

sun's axis in the sky. This angle is found in the almanac, under the heading "position angle of axis P". *Simply divide the angle in the almanac by 2 to account for the dial's double rotation. A positive value corresponds to a counterclockwise rotation.* So for example, say it is May 13<sup>th</sup> at 10:00am and you want to conduct your observations. You find in the almanac that the official meridian crossing for that day is at 12:15pm, and that the position angle of the sun's axis is listed as +16°. The local meridian crossing will be at 12:15 + 00:45 = 1:00pm. The current hour angle is therefore 10:00am – 1:00pm = -3hours. This corresponds to a counterclockwise rotation of (3hours) x (7.5°/hour) = 22.5°. The second correction will be counterclockwise 16° / 2 = 8°. The total angle of rotation will then be 22.5° counterclockwise + 8° counterclockwise = 30.5° clockwise from the starting position of 44.5°.

Focus the image of the sun on the wall using the focus motor control. You now need to find the correction factor  $\cos \theta$  as discussed above. Tape a piece of white paper over the image and trace the outline. Remove the paper from the wall and measure the diameter of the sun with a ruler. The easiest way is to slide the ruler slowly across the image, looking for the maximum possible value. This is the measurement you will use to find the radius of the sun in mm.

The location of the slit is marked on the wall, on gray paper. 5 mm to either side is the edge of a piece of white paper. Line up the east limb of the sun on one of the edges. You are now ready to take images. Using the computer software, take a test image to determine the proper exposure time. Ideally the maximum value of the image will be about 35-40,000; 80ms usually works well.

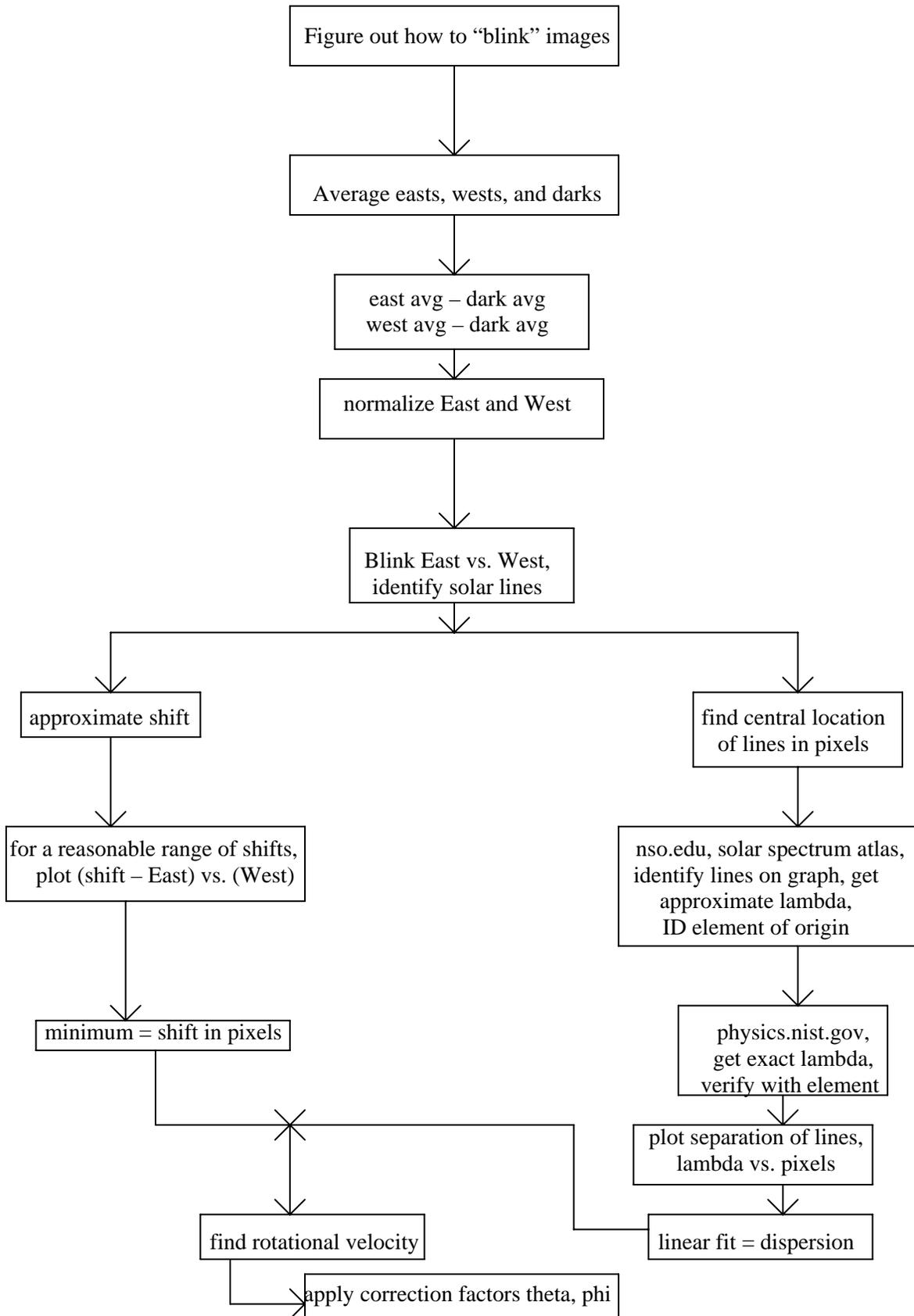
Once you have the correct exposure time, take 5 images of the east limb. Move the image of the sun so the west limb is on the other gray/white edge, and take 5 more. Repeat the process so you have a total of 10 images of each limb. Then take 10 dark exposures. **It is important not to touch the table during the time you are taking the exposures**, as this could introduce an additional shift of the camera, which would show up as a large pixel shift of the spectrum. Make sure to save your images.

Once you are finished taking images for the day, disconnect the camera from Maxim DL under the camera Control window in the Setup tab. Close Maxim DL and logout of the computer. **MAKE SURE TO UNPLUG THE CAMERA ADAPTER WIRE FROM THE AC/DC POWER ADAPTER. LEAVING**

**THE CAMERA ON/PLUGGED IN FOR EXTENDED PERIODS OF TIME WILL DAMAGE THE**

**CHIP.** If you opened the solar telescope, close it when you leave. Also push the **A1 (pause)** button on the hand paddle so the LED is **ON**, this prevents the scope from tracking to the hard stop.

Now you are ready to analyze the images. Following is an outline of the procedure.



Or, in words,

It's necessary to be able to "blink" two images on top of each other successively, which makes it very easy to see any shifting between the two. The Blink window is under the View tab. First, blink two of the east pictures together to verify that there is no shifting due to other reasons than the actual velocity of the sun. Then average all the easts together, then all the wests, then all the darks, to create three main images. Subtract the main dark image from both the main east and the main west, and we have the two final images, hereafter referred to as East and West. Blink East and West, observing the shift in spectral lines (and the lack of shift in telluric lines). Normalize (Screen Stretch) the two images for easy viewing, and select a group of solar lines. For a range of shifts, plot (shift-East) vs. (West); the minimum of this array corresponds with the correct shift. Finally, you need the dispersion. Select as many solar lines as possible, and find their central location in pixels, as accurate as possible (sub-pixel accuracy is desirable). Using the solar spectrum atlas at nso.edu, you can get a good approximation of the wavelength of each line from a recognizable diagram (the selected lines can be recognized as spikes on a graph). You can then take these wavelengths and element names to the list at [physics.nist.gov/cgi-bin/AtData/lines\\_form](http://physics.nist.gov/cgi-bin/AtData/lines_form). Here you can obtain an exact value of the wavelength, after confirming the identification of the line by element of origin. You then have the separation of given lines in both wavelength and pixels; from here it is easy to find the dispersion.

### Analysis

Using the shift in pixels and the dispersion in Angstroms per pixel, find the measured Doppler shift in Angstroms. Using this result, your correction factors, and the formula  $\Delta\lambda/\lambda=v/c$ , find the solar rotational velocity.

### Error

It is reasonable to assume that you can set the position of the solar image rotator to within 1 degree.

This actually translates to a 2 degree rotation of the sun. If you assume an error of +/- 2 degrees in the  $\delta$  position of the sun, what kind of error does this imply in the velocity you arrive at? Is the error on either side of the actual velocity, or just one? Why? How do you think the results would be affected if a telluric line were hidden right on top of one of the selected solar lines? What would happen to the images of the spectral lines on a cloudy or hazy day, or if the mirrors were dirty?