→ ESAC SOHO SCIENCE ARCHIVE TUTORIAL

DETERMINING THE SOLAR DIFFERENTIAL ROTATION

esa

Tutorial created by Luis Sánchez, ESAC SOHO Archive scientist,
adapted from the 'Tracking Sunspots' SOHO classroom exercise:
http://soho.esac.esa.ubt/classroom/docs/Spotexerweb.pdf
and modified for use with the SOHO Science Archive and Aladin
by Deborah Baines and Pedro Osuna.

This tutorial can be found online at:
http://www.sciops.esa.int/SD/ESAVO/docs/SSA_SolarDiffRotation_Tutorial.pdf

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http://archives.esac.esa.int

We would also like to thank the developers of the Aladin
interactive sky atlas tool at CDS, Strasbourg.

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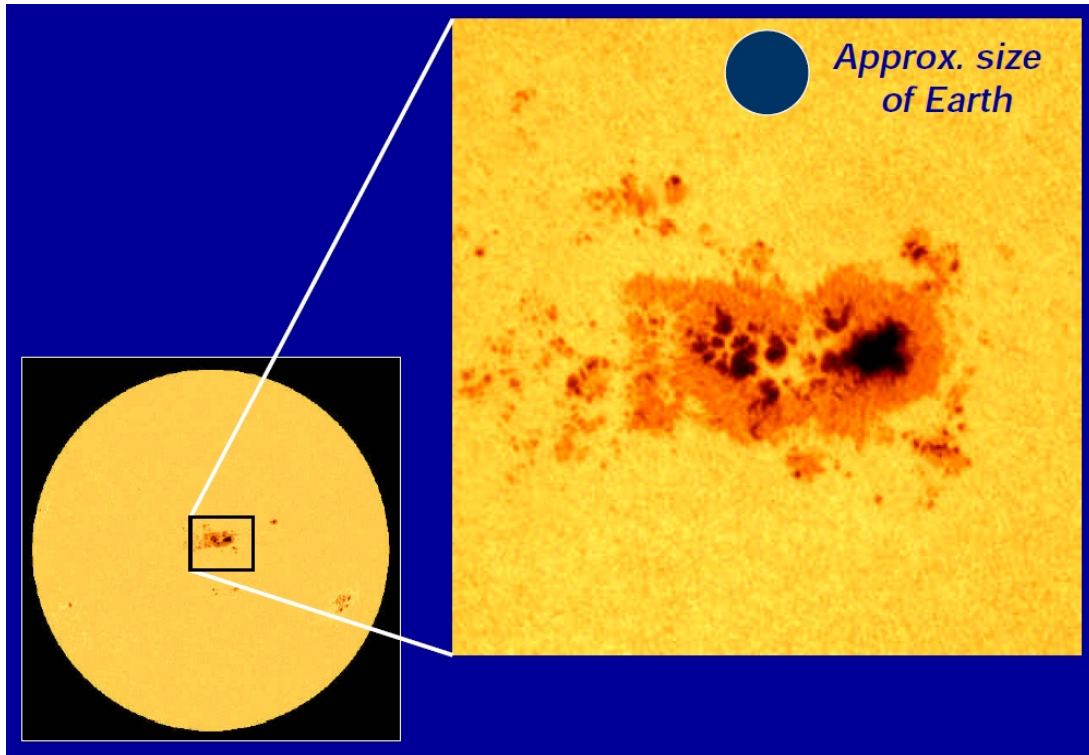
ESAC Science Archives and Virtual Observatory Team

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THE SUN,
SOHO SPACECRAFT
AND
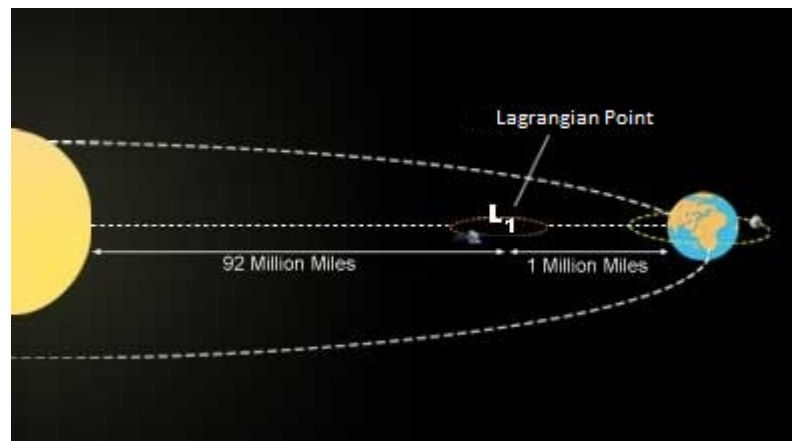# INSTRUMENTS

1   BACKGROUND

1.1   SUNSPOTS

- Sunspots are dark, cooler areas on the Sun's surface that indicate areas of strong magnetic activity.
- They appear dark only because they are not as hot or bright as the area surrounding them (4,000 degrees Celsius versus 6,000 degrees Celsius).
- Sunspots extend down into the Sun as well as above where loops of magnetic field lines carry charged particles.
- They can last from just hours to several months.
- Sunspots, which usually appear in groups, can grow to many times the size of Earth.

1.2   SOHO AND MDI

- SOHO, the Solar & Heliospheric Observatory, is a project of international collaboration between the European Space Agency and NASA to study the Sun from its deep core to the outer corona and the solar wind.

- SOHO was designed to answer the following three fundamental scientific questions about the Sun:

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- What is the structure and dynamics of the solar interior?
- Why does the solar corona exist and how is it heated to the extremely high temperature of about 1 000 000°C?
- Where is the solar wind produced and how is it accelerated?

- SOHO maintains an orbit around the Sun at 1.5 million km (1 million miles) from the Earth. It orbits around the Lagrangian point (L1), and is always pointing towards the Sun:

http://soho.esac.esa.int/gallery/Movies/orbit/orbit.mov

- SOHO consists of 12 complementary instruments, developed by 15 countries.

- The Michelson Doppler Imager (MDI) is one of the instruments on board SOHO.
  - It measures velocity and magnetic fields in the solar photosphere to learn about the convection zone which forms the outer layer of the interior of the sun and about the magnetic fields which control the structure of the solar corona.
  - MDI measures line-of-sight motion (Dopplergrams), magnetic field (magnetograms), and brightness images in full disk at several resolutions (4 arc-second to very low resolution) and a fixed selected region in higher resolution (1.2 arc-second).

- See below for information on SOHO and its instruments:
  http://soho.esac.esa.int/about/docs/SOHO_Fact_Sheet.pdf
  http://soho.esac.esa.int/about/about.html
  http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=33379

## 1.3 HISTORICAL DETERMINATION OF DIFFERENTIAL SOLAR ROTATION

- The first telescope was made in Europe in 1608. Galileo, who first performed scientific observations in the early 1613, concluded that the Sun did indeed have spots. If, as others suggested, these spots are planets passing in front of

the Sun, they'd be the same in the centre as near the edges. He noted changes in size and shape. Other scientists came to similar conclusions.

- The first historical determination of differential solar rotation was in 1630 by Scheiner, and then again in 1843 by Schwabe. This is an example of how scientific advances can sometimes be lost to tradition, and are re-discovered much later.

1.4   SOHO SCIENCE ARCHIVE

- The SOHO Science Archive is hosted at the European Space Astronomy Centre (ESAC), ESA, Madrid, and also at NASA, and contains all the data from the SOHO spacecraft.
- The SOHO Science Archive is designed, developed, maintained and operated by the Science Archives Team at ESAC.
- The archive can be accessed by using the SOHO Science Archive tool at ESAC: http://soho.esac.esa.int/data/archive/index_ssa.html
  or through a traditional web interface: http://soho.esac.esa.int/data/archive/index_gsfc.html (note that this version will not be used in the following tutorial).
- Using the SSA it is possible to easily search for data, as well as make time animations from images of the Sun.
- See also: http://archives.esac.esa.int .
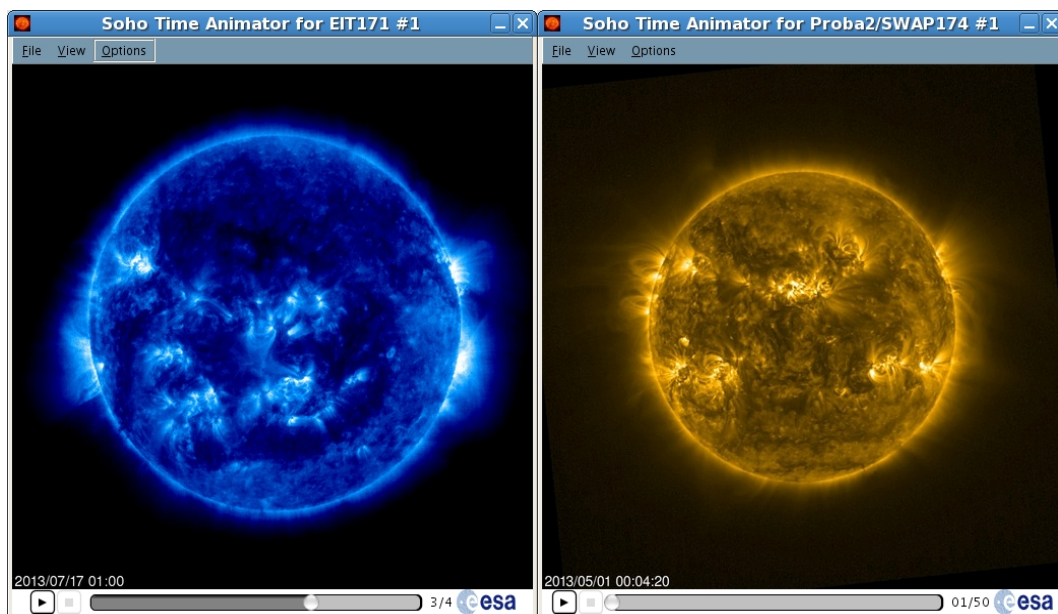
THE TUTORIAL

→ THE AIM

The aim of this tutorial is to explore SOHO images of the sun (downloaded from the SOHO Science Archive), watch the evolution of sunspots, and finally to determine the differential rotation of the Sun at different latitudes.

2 DETERMINING THE SOLAR DIFFERENTIAL ROTATION

This tutorial can be found online at:
http://www.sciops.esa.int/SD/ESAVO/docs/SSA_SolarDiffRotation_Tutorial.pdf

TOOLS USED:

The SOHO Science Archive: the SOHO Science Archive (SSA) contains all the data from the SOHO spacecraft. Using the SSA it is possible to easily search for data, as well as make time animations from images of the Sun.

Aladin: Aladin is a Virtual Observatory interactive sky atlas tool for interactive image and catalogue visualisation.

1. Open the SOHO Science Archive:
   http://ssa.esac.esa.int/ssa/ssa.jnlp
   And open Aladin:
   http://aladin.u-strasbg.fr/java/nph-aladin.pl?frame=downloading
   (either download the version for your computer operating system, or open the Web Start: http://aladin.u-strasbg.fr/java/nph-aladin.pl?frame=get&id=aladin.jnlp)
2. Using the SOHO Science Archive (SSA), we are able to download images of the Sun taken by the SOHO satellite, and to build movies, with just a few clicks of the button!
3. Firstly, we are going to take a look the sunspots by building a movie. In the main menu of the SOHO Science Archive, select Windows -> Time Animator:
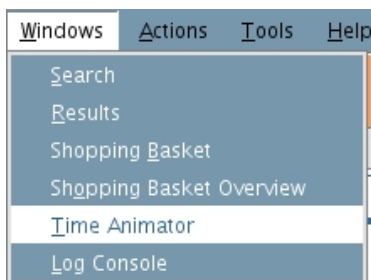
4. The Time Animator window now opens. In the Instrument/Filter box select MDI Continuum, change the Resolution to 1024 and change the 'Max Number of Evenly Spaced Images' to 300:
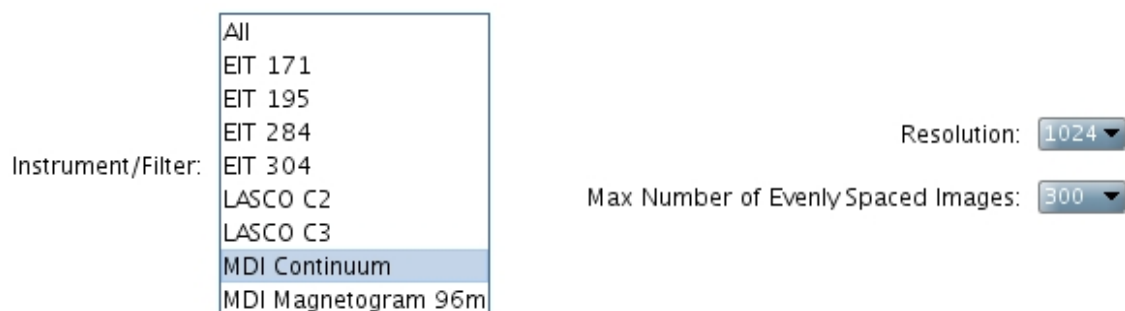
5. In the Date Range fields choose from 01/01/2005 to 01/02/2005:

6. Click the 'Search' button

7. Once the search is finished, the results are shown below the Time Animator Filters in the Time Animator Result panel:

8. Click on the 'Play Movie'.
9. The Soho Time Animator window opens and immediately starts playing the movie, which is actually just a time sequence of MDI Continuum images taken between the date ranges, 1st January 2005 and 1st February 2005.
10. This movie can be paused, reset, and played using the icons and bar at the bottom of the window (and also by using the View and Options menus).

11. Do you notice how sunspots appear, evolve and then disappear?

12. **Optional**: Try building movies for other instruments by selecting 'All' in the Instrument/Filter field and click select (be patient as this may take some time to load).
    The instruments available are:
    o EIT (Extreme Ultraviolet Imaging Telescope): high resolution images of the solar corona in 4 filters in the ultraviolet (17.1nm, 19.5nm, 28.4nm and 30.4nm, which correspond to temperatures of 80,000 K to >2 million K).
    o LASCO (Large Angle and Spectrometric Coronagraph): visible images of the solar corona which mask out the sun in the centre of the image. The LASCO C2 field of view is from 2 to 6 solar radii, and LASCO C3 from 3.7 to 32 solar radii.
    o MDI (Michelson Doppler Imager): visible images (called MDI Continuum) and magnetic field images (called MDI Magnetogram 96m) of the solar photosphere.
    o Proba2/SWAP: Proba2 is actually another ESA satellite. The Proba (Project OnBoard Autonomy) satellites are small satellites being used to test new spacecraft technologies. Proba2 is the second of these types of satellites and contains an extreme ultraviolet imaging telescope called SWAP (Sun Watcher using ASP detectors and image processing). The SWAP images are high resolution extreme ultraviolet images (at a slightly better resolution that the SOHO EIT images) of the solar corona, at 17.5 nm.

13. **CALCULATING THE SOLAR DIFFERENTIAL ROTATION:** To calculate the solar differential rotation we are going to measure a sunspot when it becomes visible in the sun and then when it has travelled across the sun after a number of days. We're going to do this for two sunspots:

one close to the solar equator, visible between:

09/01/2005 06:24 and **17/01/2005 16:00**

the other further away from the solar equator, and visible between:

27/12/2009 06:24 and **02/01/2010 18:42**

14. To do this we will be loading some SOHO images into Aladin. So, go back to the SOHO Science Archive window and select the Search tab.

15. This window is divided into three panels: the Results Display, the Main Query Panel and the Instruments Panel. Keep the Results Panel as it is, with 'Observations' selected, Sort Criteria as 'Begin Date' and 'Ascending':

16. In the Main Query Panel open the Begin Date Range and select 09/01/2005. In the Instrument section, scroll down and choose MDI:

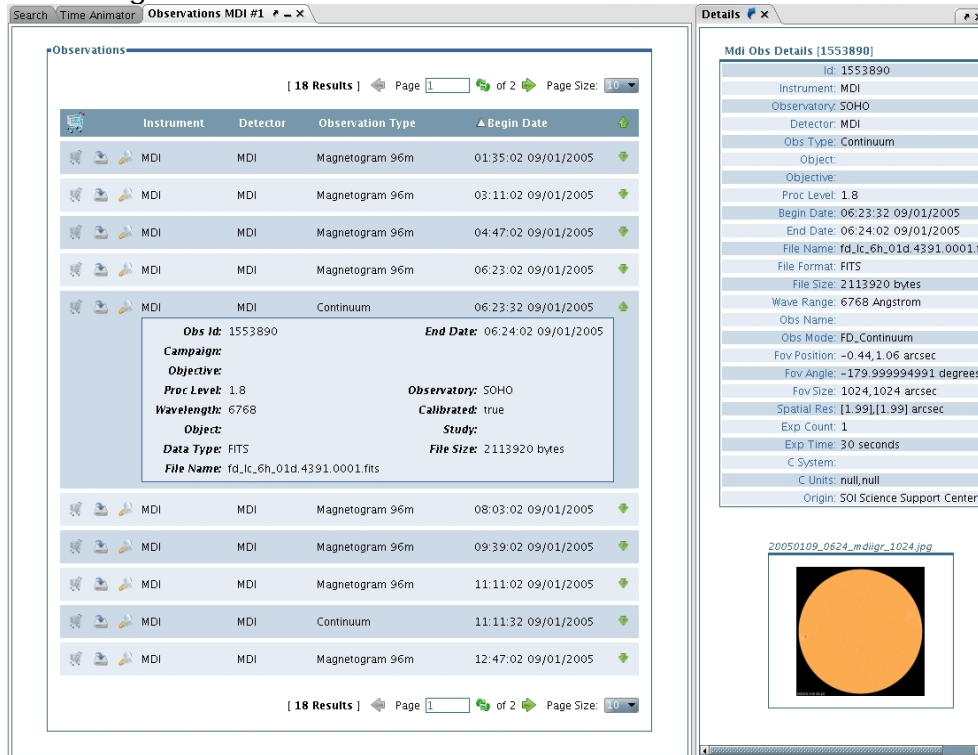17. Then click the 'Query' button in the bottom right corner.

18. A new window opens showing the results. We are going to download the first MDI Continuum image in the list. Click the green arrow on the right for this observation and open up the overview details:
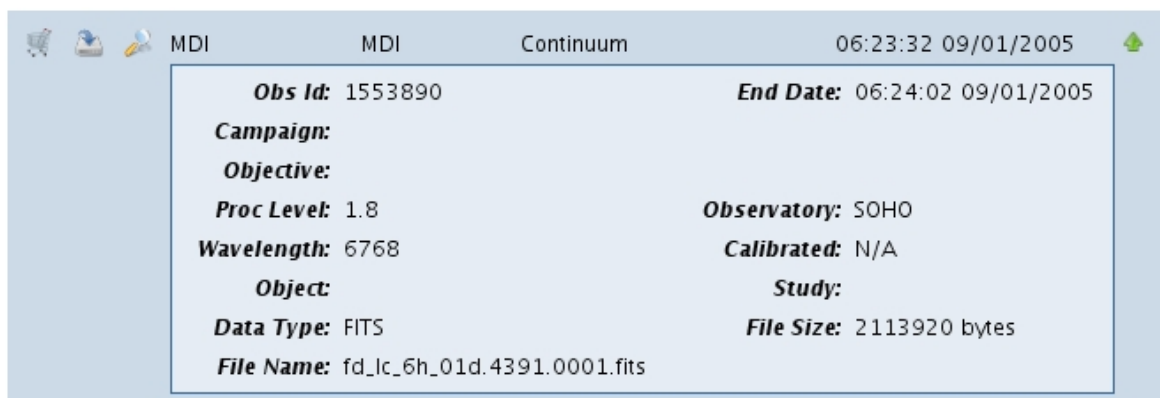
19. On the top left of this observation, click on the magnifying glass icon (show observation details).

20. A second panel opens to the right which gives a table of observation details and a thumbnail image of the observation at the bottom:
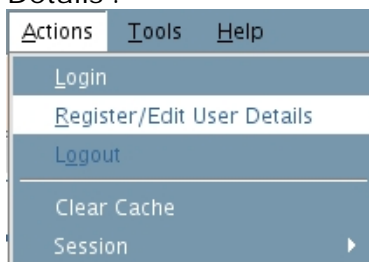

If you left click on the image it will pop out into a resizable postcard window.

21. Before we can send the image to Aladin we first need to register or login to the SOHO Science Archive. Go to 'Actions' in the main menu and either select 'Login', if you already have a username and password, otherwise select 'Register/Edit User Details'.

22. The Registration window opens in the SOHO Science Archive. Fill in your details (boxes highlighted in red are compulsory), and click Register.
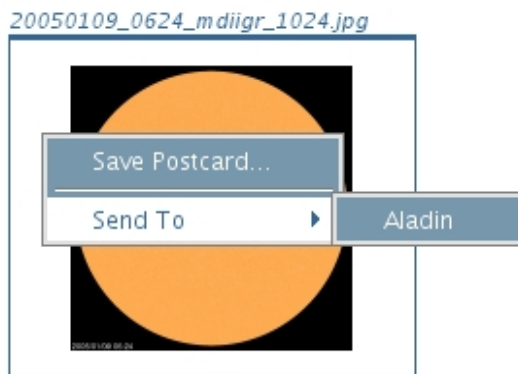

23. A second window will appear to say you have successfully registered.

24. Click the 'OK' button and go back to the Observation details on the right-hand panel.

25. Right click on the thumbnail image of the sun and select 'Send To -> Aladin':


26. Go to the Aladin tool and the image of the Sun should be loaded.

   Did this work? If yes, go straight to step 27. If no, try the **troubleshooting tips** in section 2.2, at the end of the tutorial.
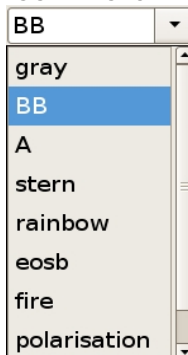27. What two things do you notice about the image displayed in Aladin?
28. The image is very dark isn't it? To change this, click on the pixel icon, located on the panel to the right of the main Aladin display of the Sun.

29. A new window opens called Pixel mapping. Click on the 'Reverse' button (towards the centre).
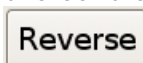
30. Your image of the sun is reversed, so the sun now appears a light gray. To make it look more like the sun, select the 'Color map' option and change from 'gray' to 'BB':

31. Your sun should now look a nice yellow colour with a black background.
32. What else do you notice about the image (compare it to the thumbnail image in the SOHO Science Archive)?
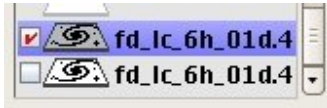
33. Do you notice the position of the sun spot in both images?
34. The image in Aladin has been rotated 180 degrees!
35. Select from the main menu 'Image -> Symmetry' and click Top/Bottom once and Right/Left once. Your image of the sun should now be the same as in the SOHO Science Archive:
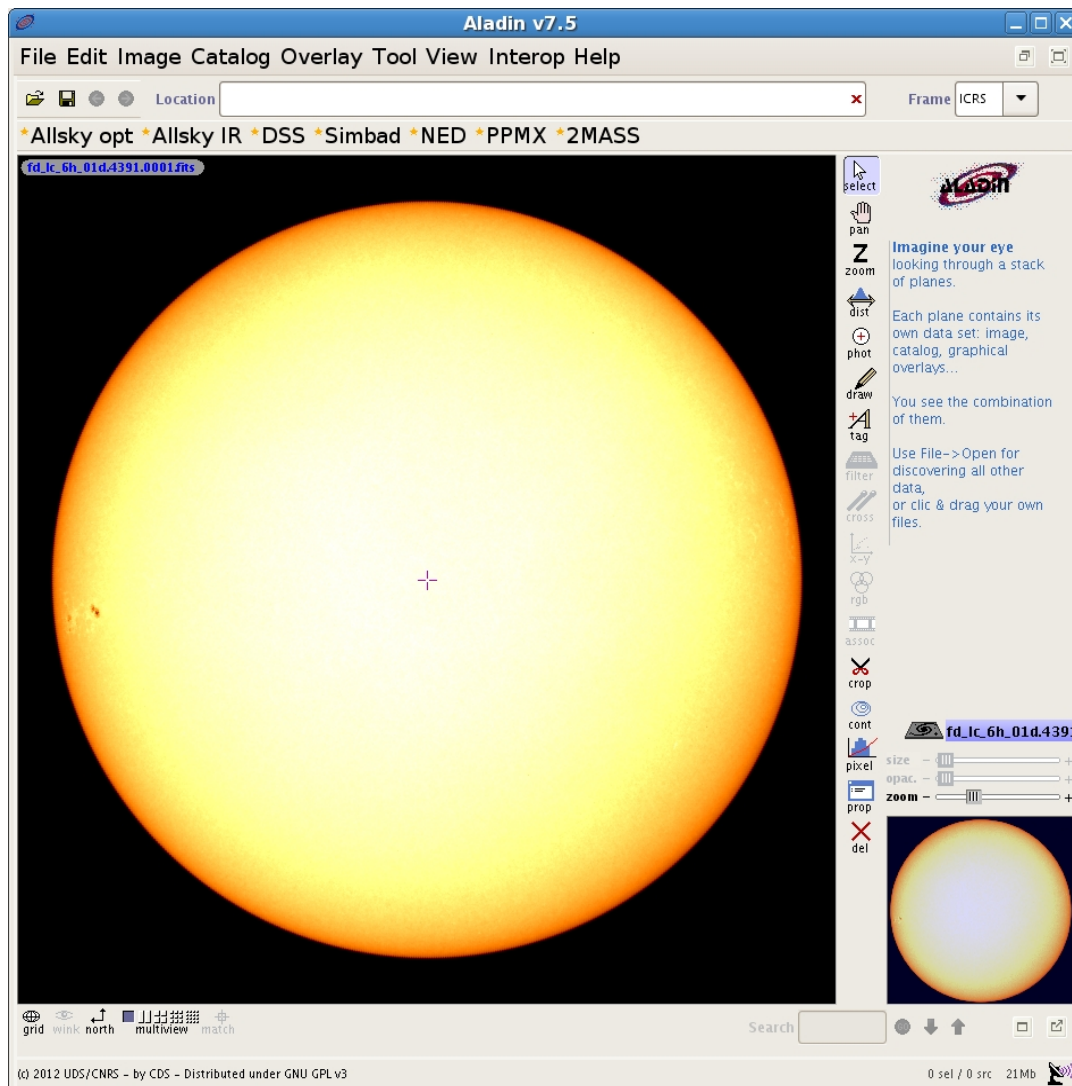
36. Go back to the SOHO Science Archive and send the MDI continuum image taken on 17/01/2005 at 16:00 to Aladin, by doing the following: Select the Search window by clicking the 'Search' tab in the main SSA window.
37. Change the Date Range to Begin on 17/01/2005 and end on 18/01/2005.
38. Make sure have selected just the MDI Instrument and then click the 'Query' button.

39. Another window opens with the results. Go to the second page, or change the Page Size to '25'.
40. Click on the magnifying glass icon (show observation details) for the last MDI Continuum observation (taken at 15:59:32 on 17/01/2005).

41. The observation details for this observation, and the thumbnail image is shown in the right-hand panel.
42. Again, right click on the thumbnail image and select 'Send To -> Aladin'.
43. Go back to Aladin and your second image should be loaded. This will appear as a second 'plane' in the panel on the right. To change from one image to the other, tick the box to the left of the plane:


44. Change again the display by selecting the pixel icon in Aladin.

45. A new window opens called Pixel mapping. Click on the 'Reverse' button, towards the centre of the Pixel mapping window and change the 'Color map' from 'gray' to 'BB'.
46. Select from the main menu 'Image -> Symmetry' and click Top/Bottom once and Right/Left once. Your image of the sun should now be the same as in the SOHO Science Archive.
47. To calculate the differential rotation, firstly let's determine the position of the sunspot for the first and last image of the series. Take a look at the movie you made with the SSA and make a note what is the same sunspot in each image (see below, marked with red circles):
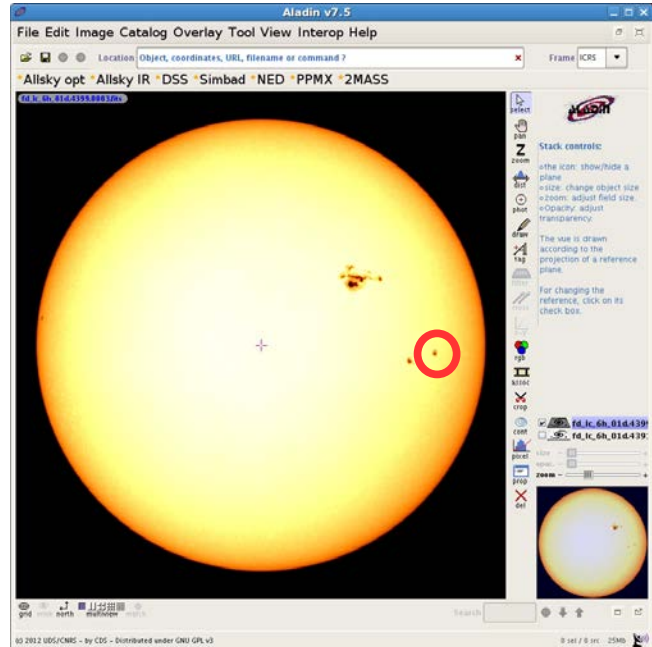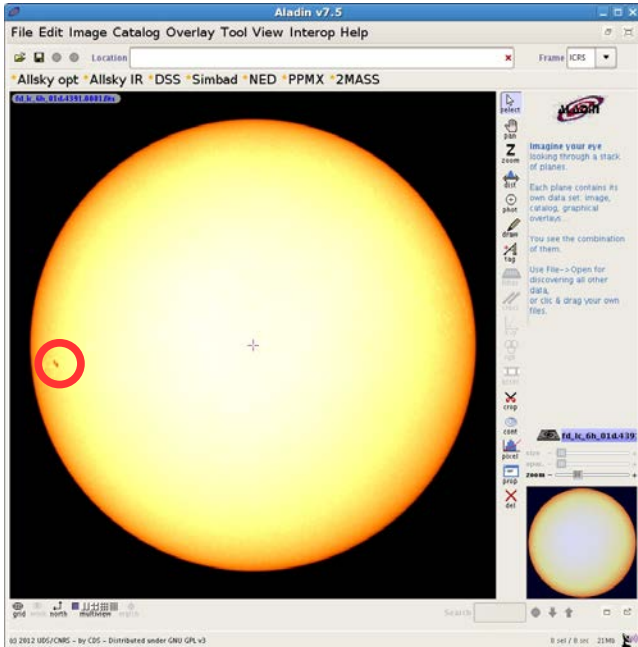
48. In Aladin, locate the 'Frame' box (located in the top right corner) and change it from 'ICRS' to 'XY Fits':
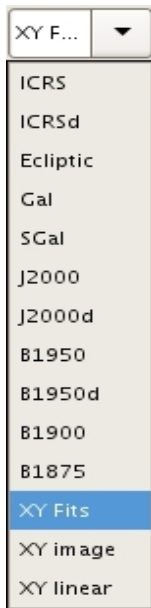
49. Now if you move your mouse across the image of the sun, you'll see the coordinates changing in the Location field, at the top of the window:

Location `950.6098  557.7536`

50. These are the x and y pixel coordinates of the image.
51. Make a note of the x and y pixel coordinates for the centre of the sunspot in the first and last images:

   09/01/2005 06:24 Sunspot (x, y) =
   17/01/2005 16:00 Sunspot (x, y) =

52. It may help to zoom into the image. To do this select the 'zoom' icon and click on the sunspot:

53. Or change the zoom in the zoom scroll bar (to the right of the main Aladin window, below the planes) and then pan to the sunspot by clicking on the 'pan' icon, and scrolling with your mouse on the image:
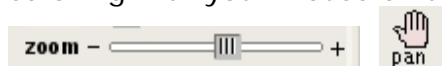
54. Or zoom in with the central wheel of your mouse.
55. Next, find the centre coordinates for the Sun (in pixels) and the Radius of the Sun (in pixels). These can all be found within the information in the image. Click on the properties icon in Aladin (located just below the pixel icon):

56. A properties window now opens. Select the 'Get original header' button.
57. Another window opens called FITS header. FITS is the type of format the images are

saved in, these formats also contain header information, which is all the observational information on the image.

58. The value giving the x centre coordinate for the Sun is called CENTER_X. The value for the Y centre coordinate is called CENTER_Y and the value for the radius of the Sun is called R_SUN. All of these values are given in pixels.

59. Make a note of these and add them to the Sunspot values you found earlier:

09/01/2005 06:24   Sunspot (*x*, *y*) =
                        Centre (*CENTER_X*, *CENTER_Y*) =
                        Radius (*R_SUN*) =

17/01/2005 16:00   Sunspot (*x*, *y*) =
                        Centre (*CENTER_X*, *CENTER_Y*) =
                        Radius (*R_SUN*) =

60. We are going to use trigonometry to calculate the longitude and latitude of the sunspots.

61. Calculate the latitude and longitude for the sunspots in each image, using the following formula:
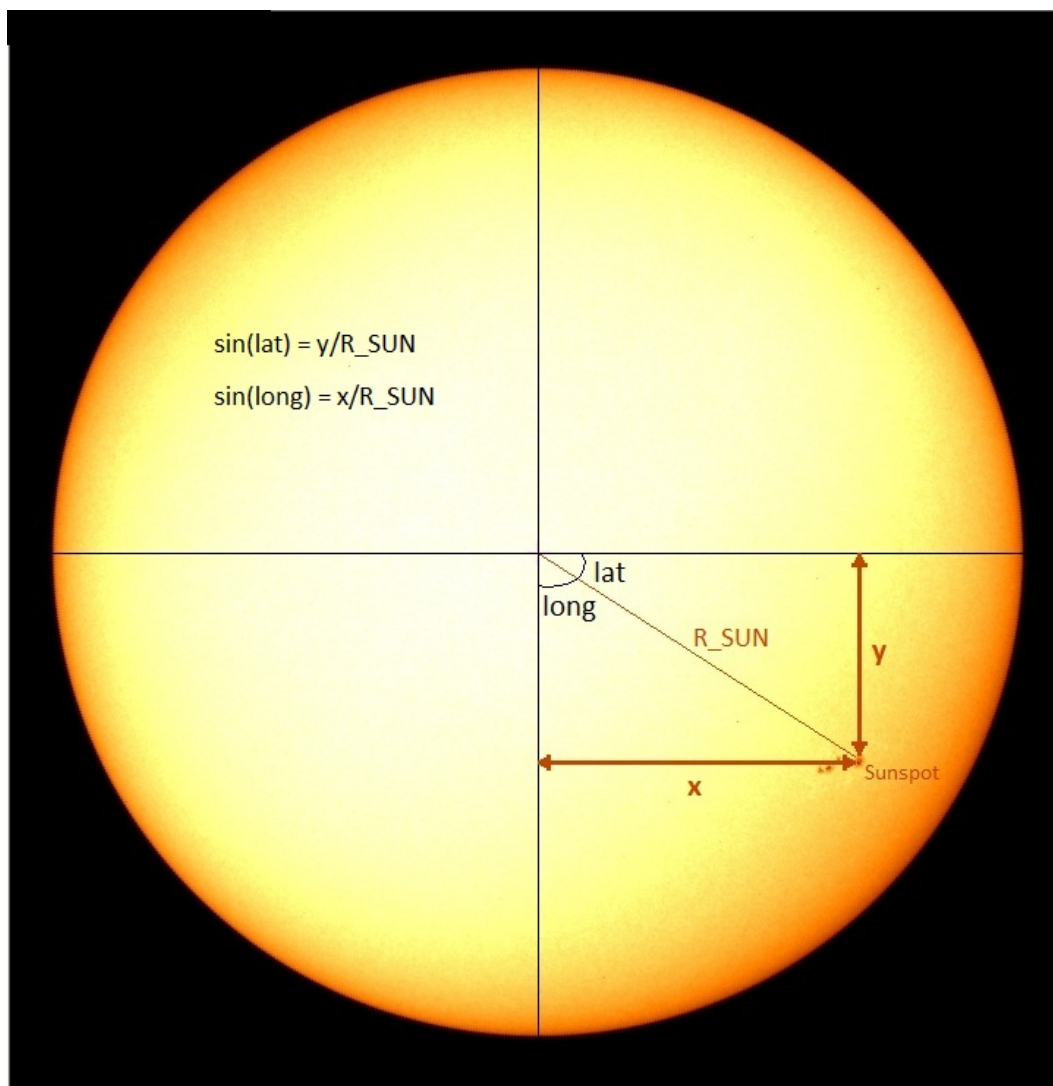
Rearrange the formula to find the latitude:

$$Latitude = \sin^{-1}\left(\frac{\left(y - CENTER\_Y\right)}{R\_Sun}\right)$$

And the longitude:

$$Longitude = \sin^{-1}\left(\frac{\left(x - CENTER\_X\right)}{R\_Sun}\right)$$

Note: The formulae are approximated and more or less valid for small latitudes. However, we are actually calculating the longitude and latitude of points on a sphere (see images below). It would therefore be better to use spherical trigonometry, which, to calculate the longitude, approximates to: multiply x with the cosine of the latitude to find a new X, and then compute the longitude applying the formula above, substituting x for X.
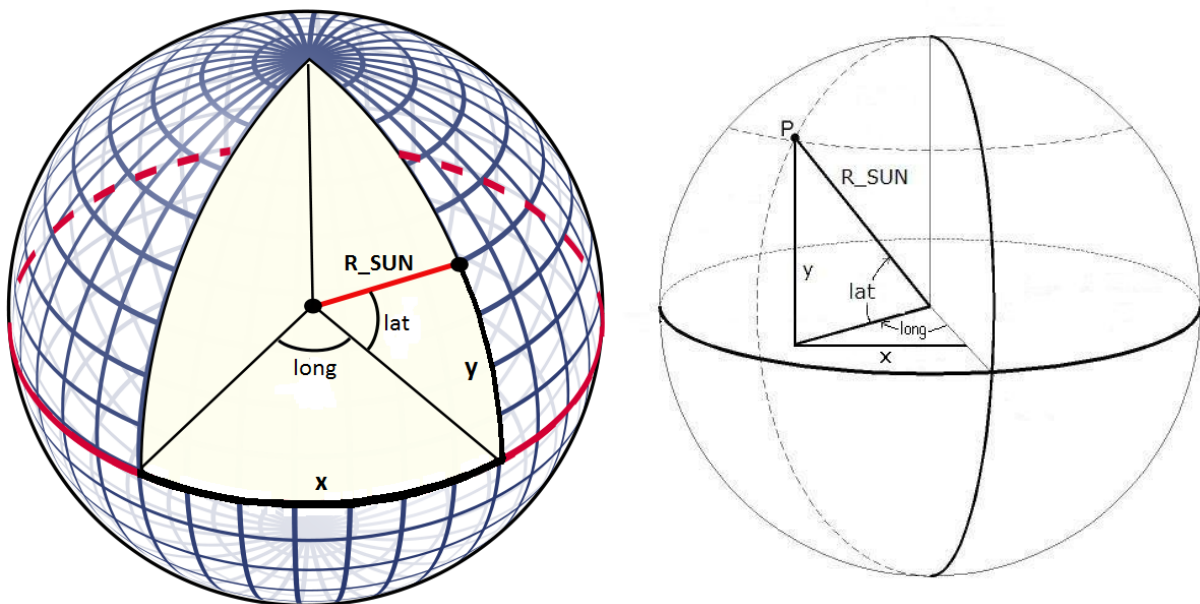
62. Record your values with the other values:

    09/01/2005 06:24   Sunspot (x, y) =
                                        Centre (*CENTER_X*, *CENTER_Y*) =
                                        Radius (*R_SUN*) =
                                        Latitude =
                                        Longitude =

    17/01/2005 16:00   Sunspot (*x*, y) =
                                          Centre (*CENTER_X*, *CENTER_Y*) =
                                        Radius (*R_SUN*) =
                                        Latitude =
                                        Longitude =

63. Now calculate the difference in the longitude, remember that 0 degrees is in the centre of the image, negative to the left and positive to the right. How many degrees in longitude did the sunspot travel between the first and last images?
ANSWER ~112.2 degrees.

64. Calculate the difference in time between the first image and the last image (in days). ANSWER ~8.4 days.

65. Calculate the Rotation in degrees per day, where Rotation = Difference in longitude/ Difference in days. ANSWER ~13.36 degrees/day.

66. And finally, calculate how long it seems to take the Sun to make a full rotation of 360 degrees: Solar Rotation = 360 degrees/ Rotation.
ANSWER ~27.0 days for one rotation.

67. Now we are going to repeat the same steps for another sunspot, this time at a higher latitude, and between the dates: **27/12/2009 06:24** and **02/01/2010 18:42**.
68. Firstly, we'll take a look at the sunspots by building another movie. In the main menu of the SOHO Science Archive, select Windows -> Time Animator.
69. The Time Animator window now opens. In the Instrument/Filter box select MDI Continuum, change the Resolution to 1024 and change the Max Number of Evenly Spaced Images to 300:
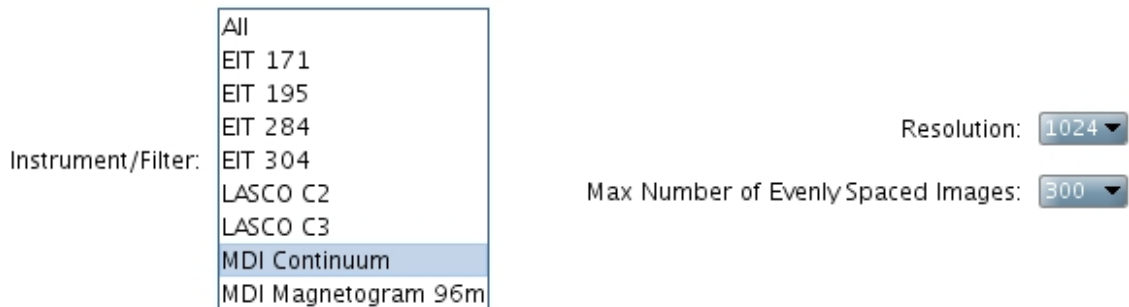
70. In the Date Range fields choose from 27/12/2009 to 02/01/2010.
71. Click the 'Search' button
72. Once the movie has been built click on the 'Play Movie'. Choose one of the sunspots and then download the images by doing the following:
73. Go back to the SOHO Science Archive window and select the Search tab.
74. In the Main Query Panel open the Begin Date Range and select 27/12/2009 and in the End Date Range select 03/01/2010. In the Instrument section, scroll down and choose MDI.
75. Then click the 'Query' button in the bottom right corner.

76. We are going to download the first MDI Continuum image in the list and the last MDI Continuum image taken on the 02/01/2010:

77. On the left of each observation click on the magnifying glass icon (show observation details):

78. Right click on each thumbnail image and send both of them to Aladin.
79. In Aladin, change the display of each image by selecting the pixel icon:

80. Click on the 'Reverse' button, towards the centre of the Pixel mapping window and change the 'Color map' from 'gray' to 'BB'.

81. Select from the main menu 'Image -> Symmetry' and click Top/Bottom once and Right/Left once. Your image of the sun should now be the same as in the SOHO Science Archive: To calculate the differential rotation, first determine the position of the sunspot for the first and last image of this particular series. Take a look at the movie you made with the SSA and make a note of where the same sunspot appears in each image (see below, marked with red circles):
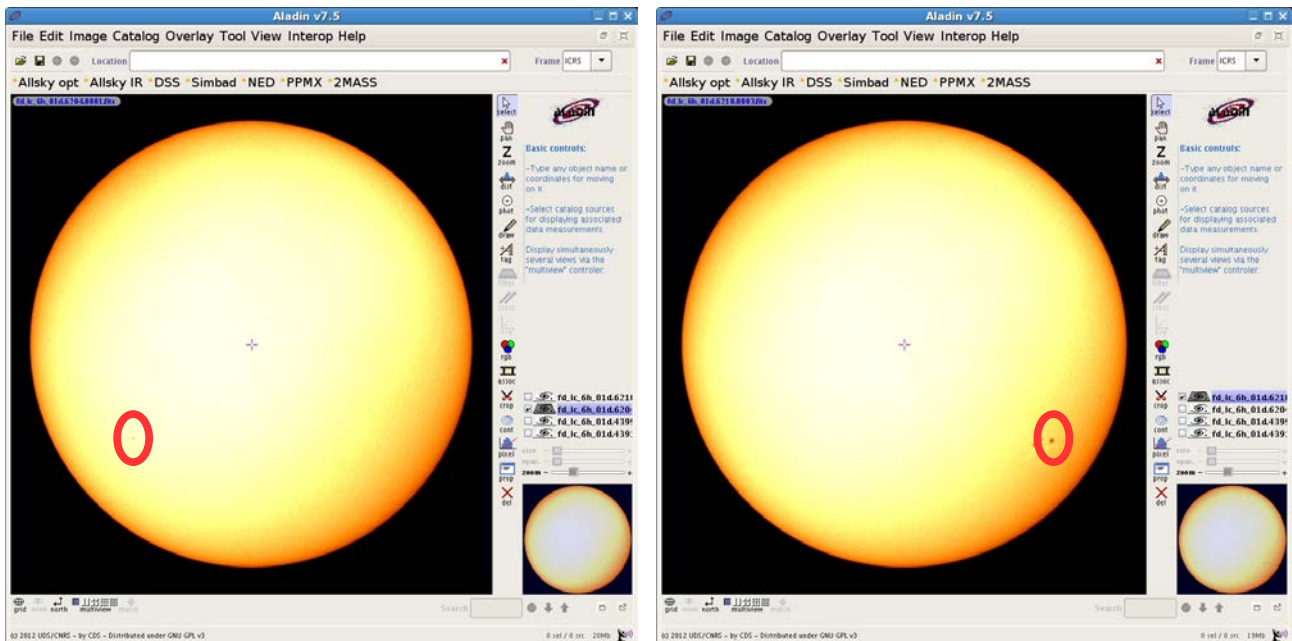
82. Make a note of the x and y pixel coordinates for the centre of the sunspot in the first and last images:

27/12/2009 06:24 Sunspot (x, y) =
02/01/2010 18:42 Sunspot (x, y) =

83. Again, find the centre coordinates for the Sun (in pixels) and the Radius of the Sun (in pixels) by clicking on the properties icon.

84. A properties window now opens. Select the 'Get original header' button.
85. Another window opens called FITS header. The value giving the x centre coordinate for the Sun is called CENTER_X. The value for the Y centre coordinate is called CENTER_Y and the value for the radius of the Sun is called R_SUN. All of these values are given in pixels.
86. Make a note of these and add them to the Sunspot values you found earlier:

27/12/2009 06:24   Sunspot (x, y) =
                                Centre (*CENTER_X*, *CENTER_Y*) =
                                Radius (*R_SUN*) =
02/01/2010 18:42   Sunspot (x, y) =
                                Centre (*CENTER_X*, *CENTER_Y*) =
                                Radius (*R_SUN*) =

87. Calculate the latitude and longitude for the sunspots in each image, using the following trigonometric formula:

$$Latitude = \sin^{-1}\left(\frac{(y - CENTER\_Y)}{R\_Sun}\right)$$

$$Longitude = \sin^{-1}\left(\frac{(x - CENTER\_X)}{R\_Sun}\right)$$

88. Record your values with the other values:

27/12/2009 06:24
Sunspot (x, y) =
Centre (*CENTER_X, CENTER_Y*) =
Radius (*R_SUN*) =
Latitude =
Longitude =

02/01/2010 18:42
Sunspot (x, y) =
Centre (*CENTER_X, CENTER_Y*) =
Radius (*R_SUN*) =
Latitude =
Longitude =

89. Now calculate the difference in the longitude, remember that 0 degrees is in the centre of the image, negative to the left and positive to the right. How many degrees in longitude did the sunspot travel between the first and last images?
ANSWER ~73.5 degrees.

90. Calculate the difference in time between the first image and the last image (in days).
ANSWER ~6.51 days.

91. Calculate the Rotation in degrees per day, where Rotation = Difference in longitude/Difference in days.
ANSWER ~11.3 degrees/day.

92. And finally, calculate how long it seems to take the Sun to make a full rotation of 360 degrees: Solar Rotation = 360 degrees/ Rotation.
ANSWER ~31.9 days for one rotation.

93. **SYNODIC ROTATION:** Remember, the Earth is moving around the Sun in the same direction at about 1 degree per day (almost 365 days to circle the Sun in a year). Therefore, the rotation we have calculated will be larger than the actual solar rotation (we can assume that the SOHO satellite is at approximately the same distance from the Sun as the Earth). This is called synodic rotation.

94. **RESULTS:**
    2005 dataset: Period is 26.9 days (synodic) at 5 degrees latitude.
    2009 dataset: Period is 31.8 days (synodic) at 25 degrees latitude.

95. **IN CONCLUSION:** The surface of the Sun (called the solar photosphere) rotates faster close to the equator than at higher latitudes.

    The synodic rotation of the sun at its equator is approximately 27 days, and near the poles approximately 35 days.

96. Optional: Calculate the sidereal differential rotation speeds by adding one degree per day to the apparent movement of the sunspots.

2.1 VERSION FOR YOUNGER STUDENTS

Follow the tutorial up to and including point 47, then instead of calculating the longitude and latitude using trigonometry, use the following images. These are the same as those loaded into Aladin with an additional grid placed on top (the sunspots to use are marked with a red arrow):
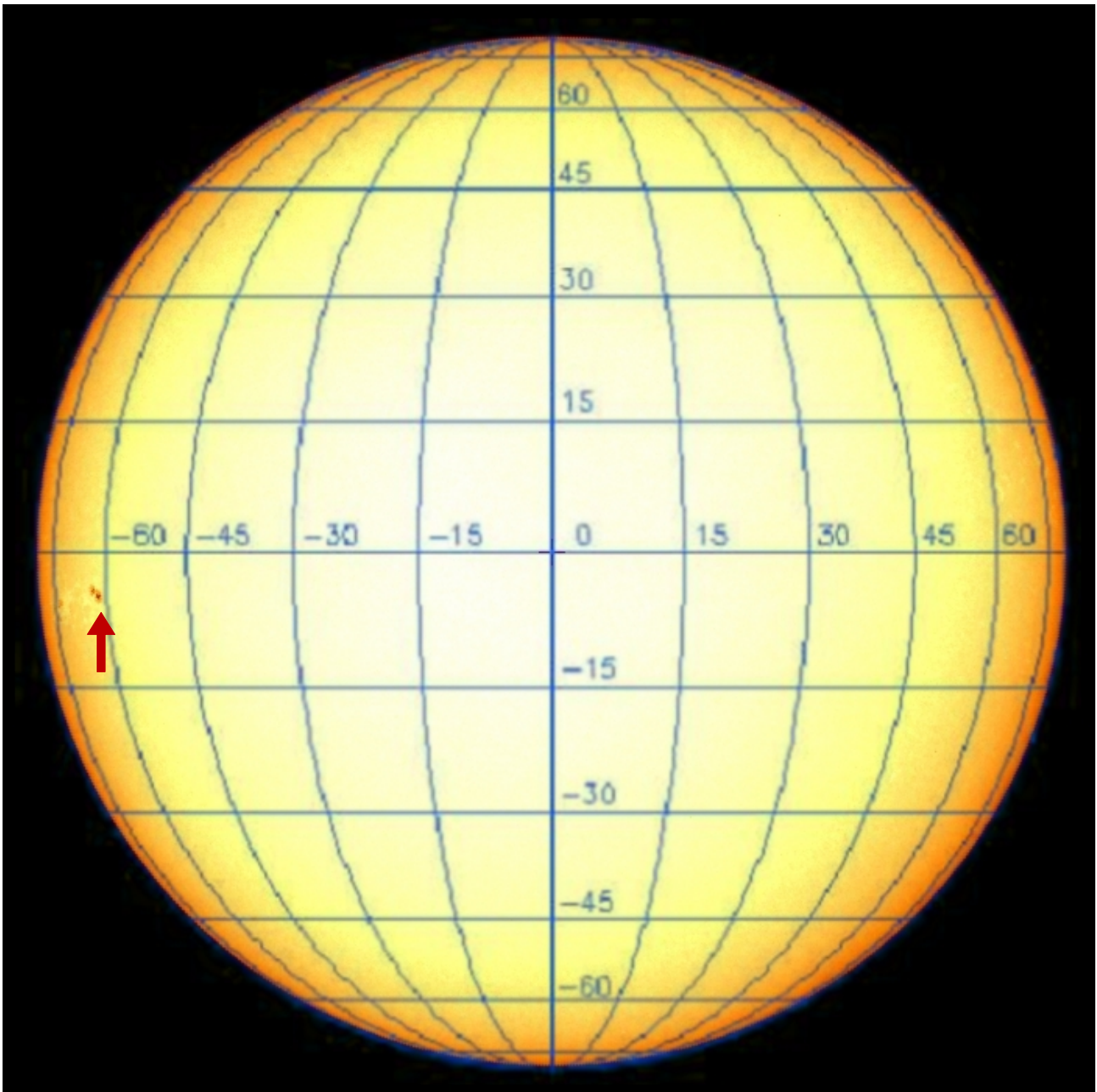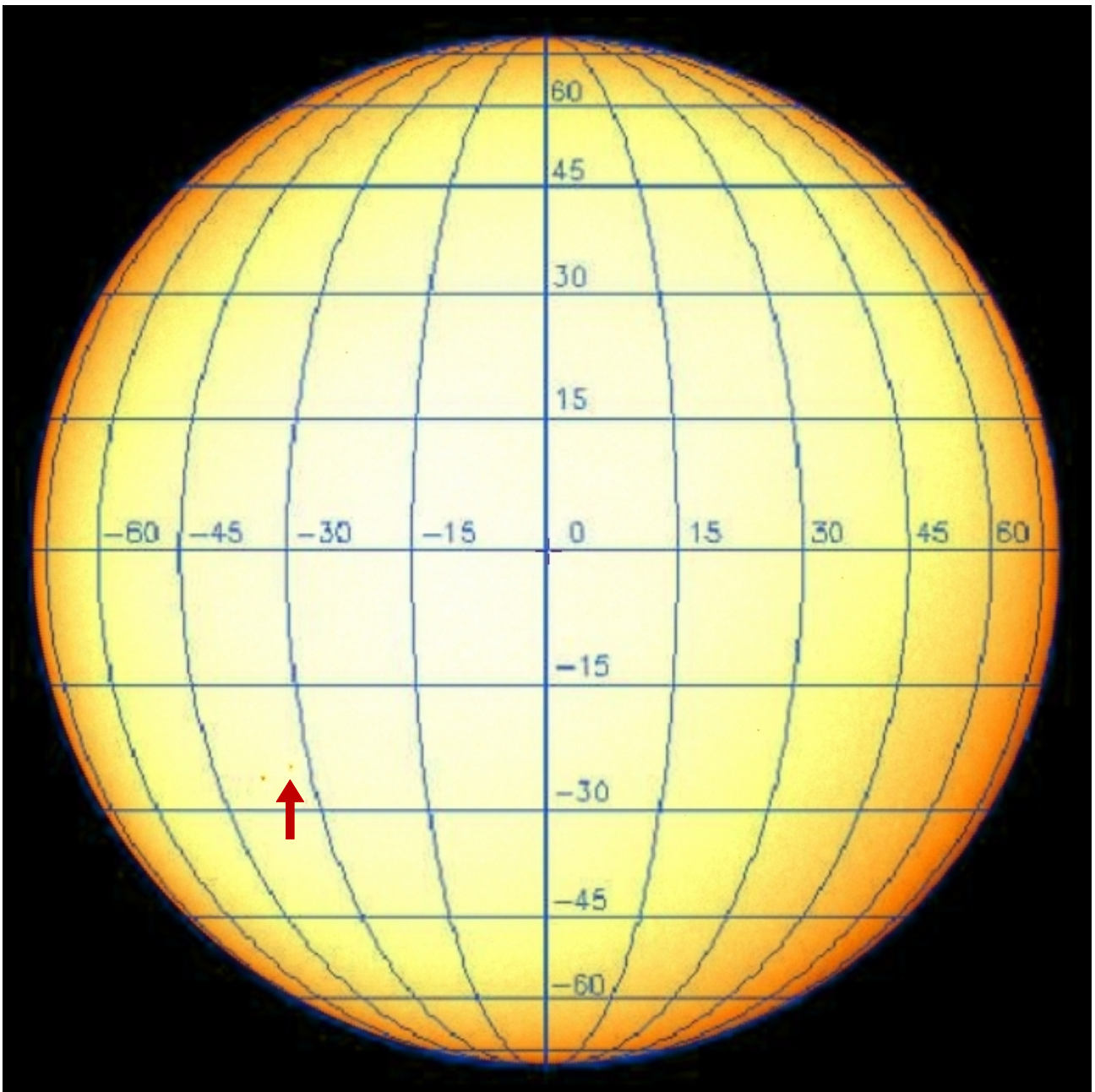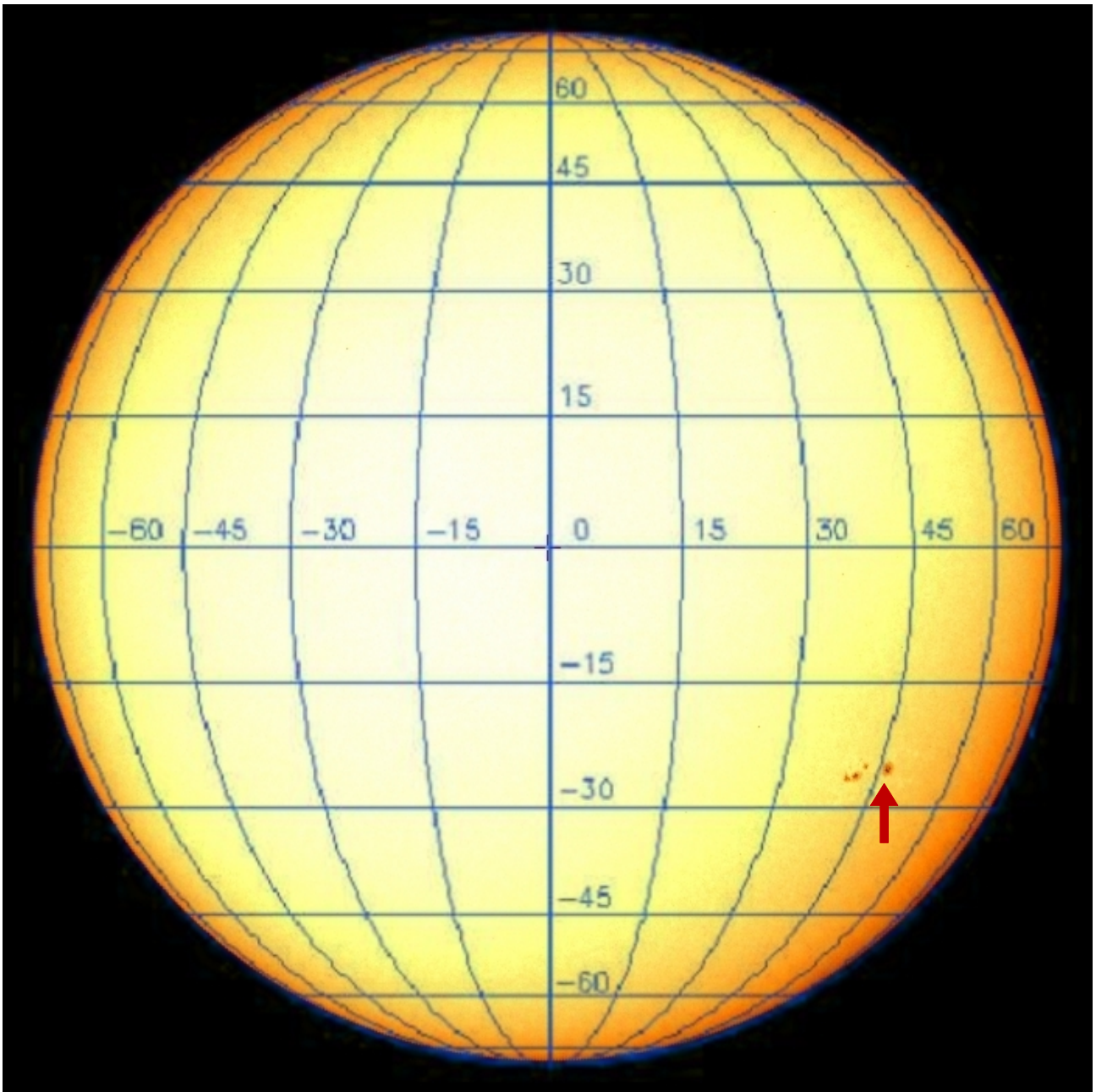

2005/01/09 06:24
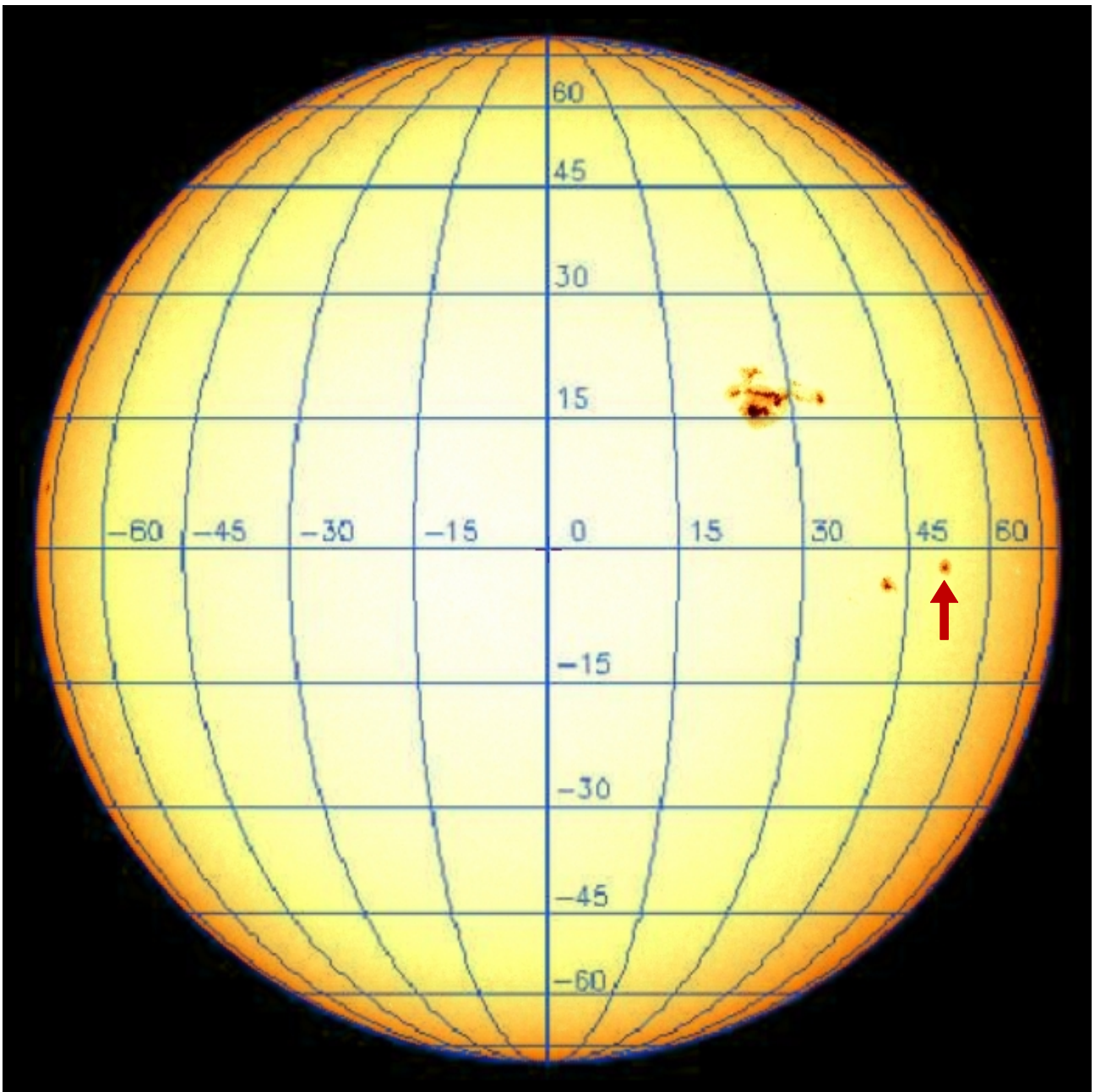
2005/01/17 16:00

Use the grids to estimate the longitude and latitude of each sunspot, then carry on following the above tutorial from point 63.

Once you reach point 82, use the following two images to estimate the longitude and latitude of the sunspots:

2009/12/27 06:24

2010/01/02 18:42

Then carry on following the tutorial from point 89 to the end.

This tutorial will be similar to the 'Tracking Sunspots' tutorial from the SOHO classroom exercises:

http://soho.esac.esa.int/classroom/docs/Spotexerweb.pdf

TROUBLESHOOTING TIPS

3 TROUBLESHOOTING TIPS

Here we list some of the most common factors that may affect the proper functioning of any of the tools used in this tutorial:

Problems opening the SOHO Science Archive and/or Aladin?
Both the SOHO Science Archive and Aladin need a Java virtual machine installed on your computer before they can work. Sometimes this is available in your computer by default, other times you need to install it and keep it up to date yourself. Try installing the latest version from this website:
http://java.com/en/download/index.jsp

Problems sending an image from the SOHO Science Archive to Aladin?
Try the following:
- Go to Tools in the main Archive menu -> Interoperability -> Register with Hub. Click 'Yes' if you are told 'There is no Hub running. Would you like to start one?'.
- Go to Tools in the main Archive menu -> Interoperability -> Interoperability Status. This opens the Interoperability Monitor window. In the left section, under Clients, you should see a Hub and SSA. Do you also see Aladin? If you do, try sending the SOHO image again by right clicking on the thumbnail image of the sun and selecting 'Send To -> Aladin'. If you do not see Aladin in the Clients list, try the following in the Aladin tool:
- Go to Interop in the main Aladin menu. If the first two options are 'Connect with PLASTIC' and 'Disconnect from PLASTIC', close the Aladin tool and reopen it.
- Repeat the above, go to the Interop menu in Aladin. It should now say 'Connect with SAMP' and 'Disconnect from SAMP'. Select the 'Connect with SAMP' option. You should now see Aladin in the SSA Interoperability Monitor window. You should also

  see this icon in the bottom right corner of Aladin:
  Try sending the SOHO image again from the SSA by right clicking on the thumbnail image of the sun and selecting 'Send To -> Aladin'.

For more troubleshooting tips see:
http://soho.esac.esa.int/data/archive/ssa_troubleshooting.html

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