Assignment 1

Derivation of solar differential rotation from measuring sunspot positions

Performance - Tuesday, April 13, 2020

Due to submit a performance report – April 20, 2020

The objective of this assignment is to learn how to derive the angular velocity of solar rotation from following sunspots in white-light solar images obtained in the Kanzelhöhe Observatory in Austria. The Sun is known to show a differential rotation, i.e. the equator rotates faster than poles. Differential rotation is a key process for the solar dynamo, i.e. reprocessing the solar magnetic field in the course of the 11-year solar cycle. In addition, the knowledge of solar rotation allows the prediction of the recurrence of large groups of sunspots on the Earth-facing hemisphere causing space–weather effects on Earth.

This assignment is performed in the class by students as in teams of 2 and the team will submit one document reporting about the performance till April 20, 2020. Within your group, you may discuss all issues openly, and discuss and debate until you reach a consensus.

Here is the recommended procedure:

1. Consult lecture charts
   Topic_1_ Sun as star and solar structure.pdf

2. Task:
   Derive the angular velocity of solar rotation (degrees per day) following sunspots close to the equator and at high latitudes.

3. Data
   In Canvas there are two sets of data provided:
   a) June 10 – 22, 2016 – Sunspot close to equator
   b) December 4 – 15, 2010 - Sunspot at high latitudes
   Data are given in *fits* format (Flexible Image Transport System, format for scientific data)

4. Here is the recommended procedure

   Step 1. Download data

   For Matlab:
   fitsread - Matlab function to read fits file
   fitsinfo - To extract keywords (image information) from fits file
   There is a corresponding command in Python to read in the data.

   Comment:
   In Matlab (and probably in Python) you should additionally flip the image from up to down - *flipud*

   Image keywords:
   Center pixels of the image coincides with the center of Sun
   $X_{cen} = 1024$
   $Y_{cen} = 1024$

Other keywords to extract from fitsinfo

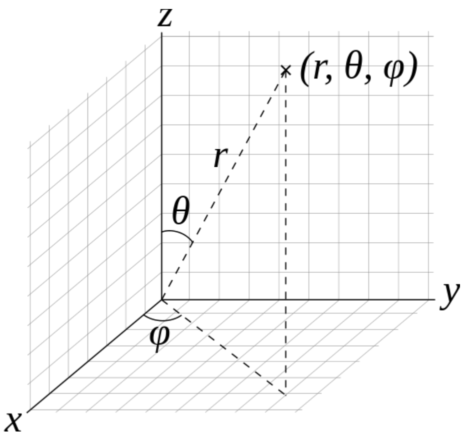
SOLAR_P0 – the deviation of solar rotation axis from the direction to North (in degrees)
You should rotate the image on this angle to put the North up.
imrotate – function in Matlab. When you rotate, the output image should be the same size as the input image.

SOLAR_R – radius of Sun in pixels

DATE-OBS – observation time.

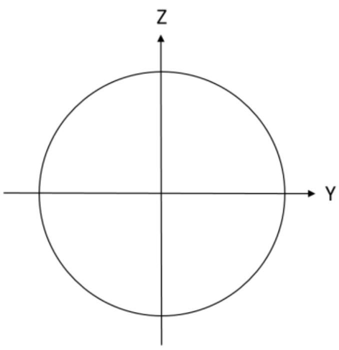
Step 2.
Determine the coordinates (in pixels) of sunspots (center of masses) for every image.
You could do it manually.

Spherical coordinate system



r – radius of Sun
Θ - polar angle (colatitude, heliographic latitude = 90-Θ)
ϕ - azimuthal angle (heliographic longitude)

The Sun is observed in a projection plane ZY



Thus, the pixel coordinates (i, j), i – number of rows, j – number of columns, of center of masses of sunspots correspond to $i = z$ coordinate, $j = y$ coordinate.

The origin of the spherical coordinate system we work with is in the center of Sun. Thus, coordinates z, y should be corrected for the center of Sun coordinates.

$$y_{cor} = y - X_{cen}$$
$$z_{cor} = z - Y_{cen}$$

Note, if you use Matlab where flip from up to down is required, then

$$z_{cor} = Y_{cen} - z$$

Step 3

Determine latitude and longitude of center of masses of every sunspot

Hint:

$$r^2 = x^2 + y_{cor}^2 + z_{cor}^2$$

r, z, y are known
x is unknown

$$\Theta = arcos\left(\frac{z_{cor}}{r}\right)$$
$$Latitude\ B = 90 - \ \Theta$$

Comment: Don't forget to go from radians to degrees

$$Longitude\ \phi = arctg\left(\frac{y_{cor}}{x}\right)$$

Comment: use atan2 function that calculate arctg in the four quadrants.

Plot the obtained latitude and longitude as function of time.
Plot latitude depending on longitude.
Which conclusions can you make from the plots?

Step 4

Determine the angular velocity of solar rotation per day using the obtained longitude and taking into account the time between images.
This will correspond to the synodic angular velocity Ω_{synod}.

You need to obtain the sidereal rotation rate.
For explanations consult the lecture charts.

Step 5

Determine the sidereal rotation rate using the following relations:

Synodic rotation period (i.e. with respect to Earth) in degrees per day:

$$P_{synod} = \frac{360^o}{\Omega_{synod}}$$

Siderial rotation period (i.e. with respect to fixed point in space) can be obtained from

$$\frac{1}{P_{sid}} = \frac{1}{P_{synod}} + \frac{1}{P_{earth}}$$

P_{sid} - siderial rotation period (in days)
$P_{earth} = 365.2564$ days – Earth orbital period around the Sun (1 year)

Siderial rotation rate is given as

$$\Omega_{sid} = \frac{360}{P_{sid}}$$

Step 6
Compare the obtained angular sidereal rotation rate with the functional form of solar differential rotation obtained from statistical studies

$$\Omega_{\text{sid}} = a + b \cdot \sin^2 B$$
$$a = 14.55^{\text{o}}/day$$
$$b = -2.87^{\text{o}}/day$$

B – heliographic latitude.
Think what is the meaning of constants a and b.
Plot the function from $B = -50^o$ to 50^o and overplot the results obtained at step 5.
Make conclusions.

Step 7.
The steps should be repeated for both datasets (2016 with sunspots close to equator and 2010 at high latitudes). Compare the angular velocities for both cases and overplot on the function for solar differential rotation. Make conclusions.

Step 8. Make conclusions to the Assignment.
Conclusions should be done in a form of a learning log. **A learning log** is a journal which evidences your **own learning and skills development.** It is not just a diary or record of **"What you have done"** but a record of **what you have learnt, tried and critically reflected upon.**

1. Prepare performance report and submit to Canvas:
   Performance report should include 2 documents:
   1) A report (PDF) with performance of all the items listed above
   2) Code (PDF)

Notes:
- PDF report should contain the names of team members, number of the assignment
- All questions of the assignment should be addressed
- All figures should have a caption, all axes should have labels, a legend to curves should be given, and short conclusions/discussions/results related to figures should be provided.
- The overall conclusion to the assignment should be provided in a form of a learning log.