INTI
Processing guide : How to compute a solar magnetogram

1. Introduction

Magnetic field measurement is a highly advanced feature of the Sol'Ex instrument. The data required to achieve this result can be processed using INTI software. This software greatly automates operations and hides their complexities.

To find out more about how to observe the solar magnetic field, we recommend watching this film: https://www.youtube.com/watch?v=ux1rgkgdauY&t=2999s

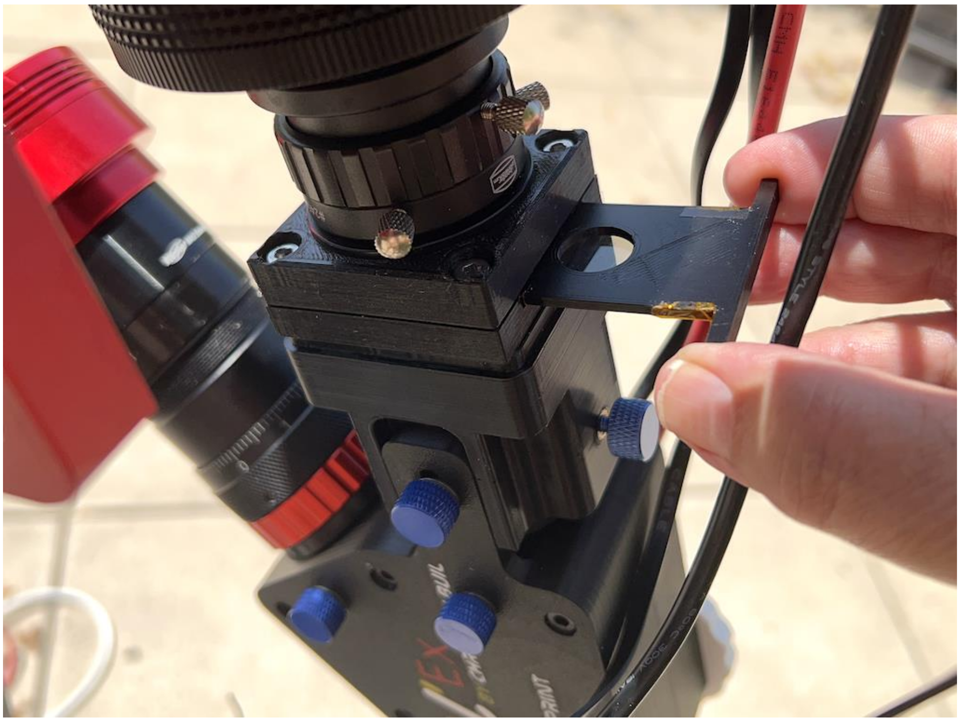
To put it simply, magnetic field measurement is the indirect result of an effect known as the Zeeman effect. In the presence of a magnetic field from where the light is emitted, the spectral lines split. This is the Zeeman effect. Its amplitude is directly proportional to the strength of the magnetic field, enabling measurement. We can even detect the polarity of this field. Here, we can observe the vertical component of the magnetic field's lines of force.

This Zeeman splitting is very small, and its observation is at the limit of Sol'Ex's capabilities, but it's a great physics experiment to perform. What's more, the results obtained, compared with professional instruments, sometimes on-board satellites, are ultimately very convincing.

2. Data acquisition

In practical terms, to facilitate the measurement of line splitting, we need to carry out two series of scans of the solar disk, placing special filters in front of the slit to isolate the left and right circular polarizations in the light (see video above). These filters are very easy to obtain from the glasses you collect at the end of a 3D movie projection in your favorite theater.

A minimum of two SER files therefore needs to be made on the telescope while pointing at the Sun: one by placing a filter in front of the slit to isolate the right-hand circular polarization, the other the left-hand circular polarization. This photograph shows the device for inserting a filter in front of the slit (a kind of slit, acting as a filter drawer):

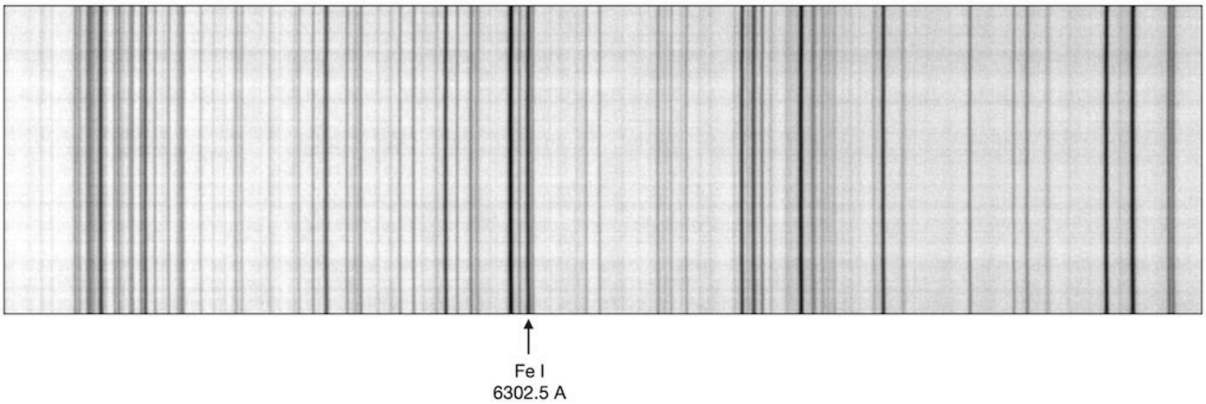


For the rest, observations are made in the traditional way, scanning the solar disk to obtain a well-rounded image. A word of caution: the polarizing filters used are sensitive to temperature rise. It is therefore important to use a fairly strong neutral density at the front of the telescope, in our case a ND16 HOYA density, which offers every guarantee. As a further precaution, we add a classic 1 ¼ inch UV/IR cut filter, screwed to the Sol'Ex interface. Note that Herschel helioscopes are unsuitable for measuring the Zeeman effect.

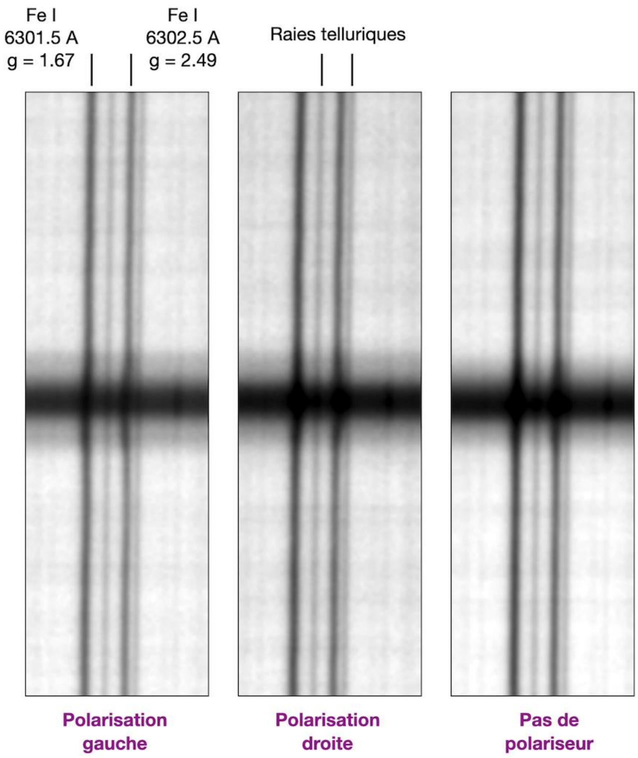
The Doppler effect induced by the Sun's rotation causes the lines to shift, impairing the quality of the magnetic field observation when scanning along the right ascension axis. The version of INTI (V5.0) discussed here does not feature dynamic correction of the line shift between the eastern and western edges of the Sun. For this reason, and even if it's not prohibitive, it's advisable to scan along the axis of equatorial declination.

Not all spectral lines are equally sensitive to magnetic fields. This sensitivity is determined by the line's Lande factor. If the factor is 0, the line is not sensitive; if it is 2.5, sensitivity is maximum. For optimum quality in the final result, we need to choose a line that both reacts well to the magnetic field and has good depth and contrast.

A classic choice, even among professionals, for constructing a magnetogram, i.e. an image of the longitudinal magnetic field of the solar surface, is an iron line located at the 6302.5 A wavelength. It is indicated by an arrow in the following spectrum extract:



The following document shows a detail of this region of the solar spectrum:



The presence of a spot, a place where the magnetic field is high, shows how the iron line at 6302.5 A (but also its neighbor at 6301.5 A) deforms according to the direction of circular polarization selected by changing the filter (right or left rotation). This information is used to determine the magnetic field value. The disadvantage of choosing the 6302 A line is the presence of telluric lines, produced by the Earth's atmosphere, which vary over time and are a source of spurious signals.

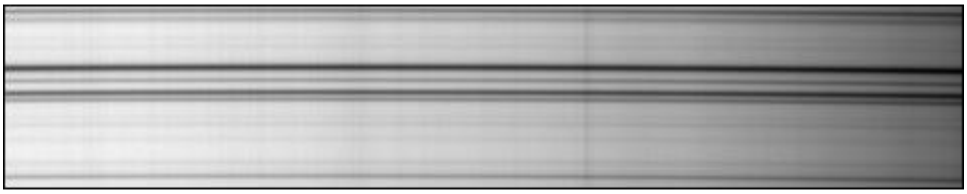
Since line distortions are discrete, especially when the magnetic field is weak, we recommend that you use 1x1 binning with your acquisition camera (although the author has also obtained good results with 2x2 binning, so there is no hard and fast rule).

3. Processing with INTI

Let's assume we have a set of two SER files, one associated with right-hand polarization, named "07_12_26.ser", the other with left-hand polarization, named "07_24_04.ser".

We'll deal with the right-hand polarization first.

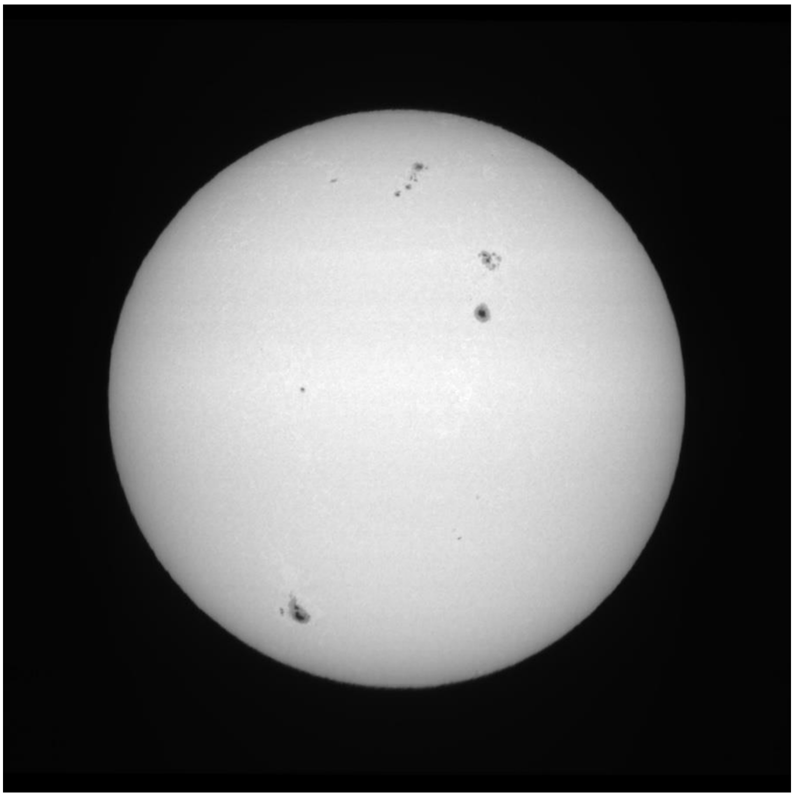
Here's an extract from one of the frames making up file 07_12_26.ser :



You can see our two iron lines, close to the center. The acquisition was made with an ASI462MM camera (2.9 microns pixels, 1x1 binning).

In INTI, go to the "General" tab, select file 07_12_26.ser, then Ok:

In this situation, INTI will extract an image of the Sun based on the deepest line it finds in our SER film, in this case the line at wavelength 6301.5 A (not our target line, mind you). Here, for example, is the content of file 07_12_26_recon.fits (an Askar FRA300 refractor was used here):



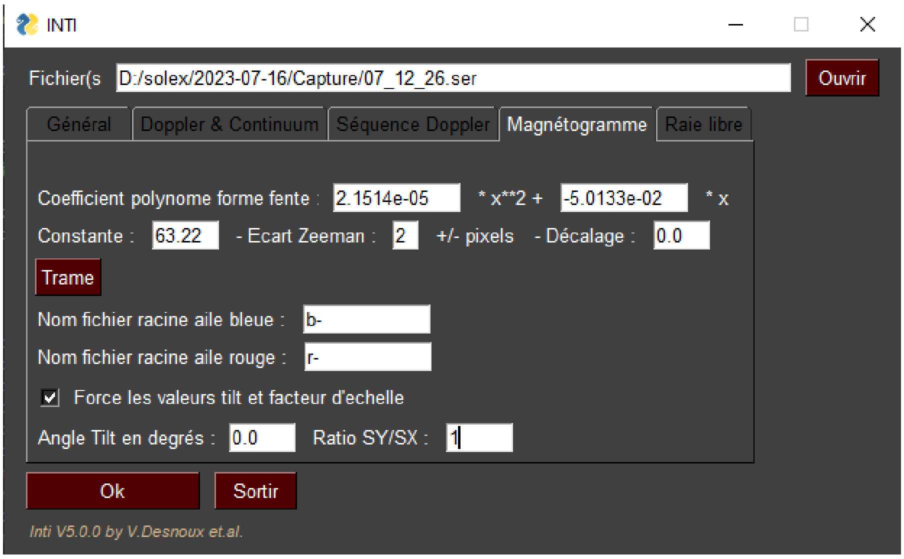
At this point, record in the output terminal (or in file 07_12_26 _log.txt) the distortion coefficients of the spectral line used:

```
SER date local :"2023-07-16T07:12:26.9540997"
Mean Image - Vertical limits y1,y2 : 222 1690
Coef a*x2,b*x,c :2.1514e-05 -5.0133e-02 63.22
Noise reduction option
```

Note the values:

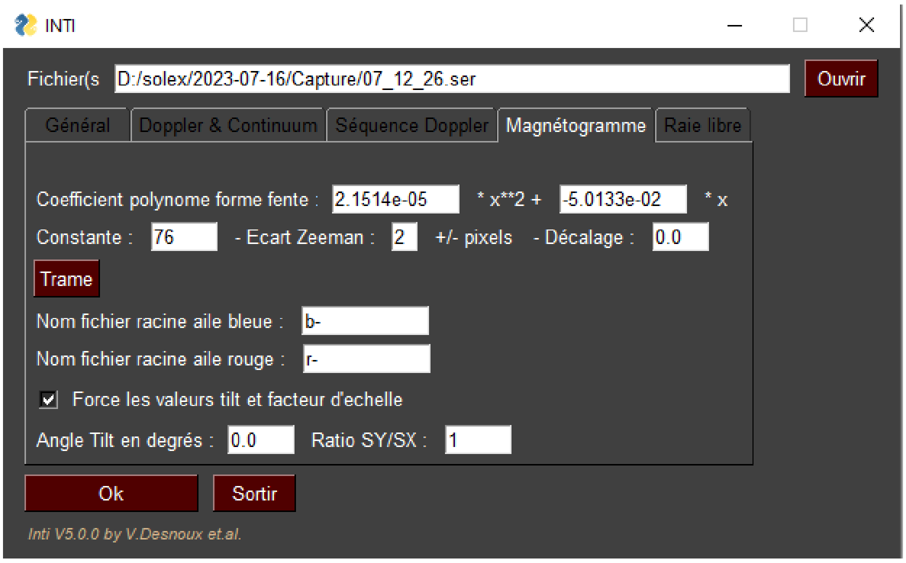
2.1514E-5 * X2 - 5.0133. E-2 * X + 63.22

Open the "Magnetogram" tab and enter the values of the polynomial we've just calculated, giving:

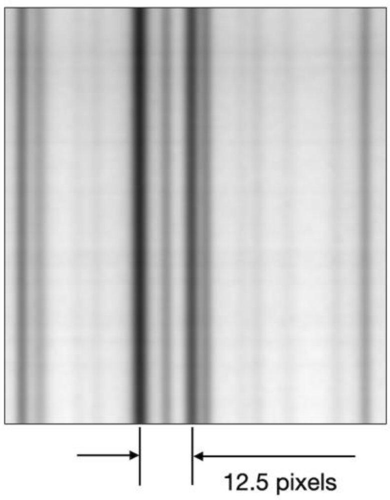


But here, the constant c = 63.22 defines the position of the Fe I 6301.5 A line, not that of the 6302.5 A line. We therefore need to make a correction to this constant, equal to the difference in pixels between these two lines. This is the sensitive part of the processing. There are several ways to find this shift and correct the constant to point to the correct line.

A quick way is to click on the "Frame" button. Then select file 07_12_26_mean.fits from the list. Remember that the content of this file is the average of all the frames in the SER file processed from the "General" tab. In addition, INTI performs a geometric correction of the lines using the coefficients of the polynomial we've just provided, so that they appear straight (hint: if they're not straight, you've made a mistake in transcribing the numerical values - it's a check). Click with the mouse somewhere on the iron line at 6302.5 A, and we find, for example, x = 76 (the value is displayed at the top of the image). When you close the image, the value of 76 pixels is automatically copied into the constant field:

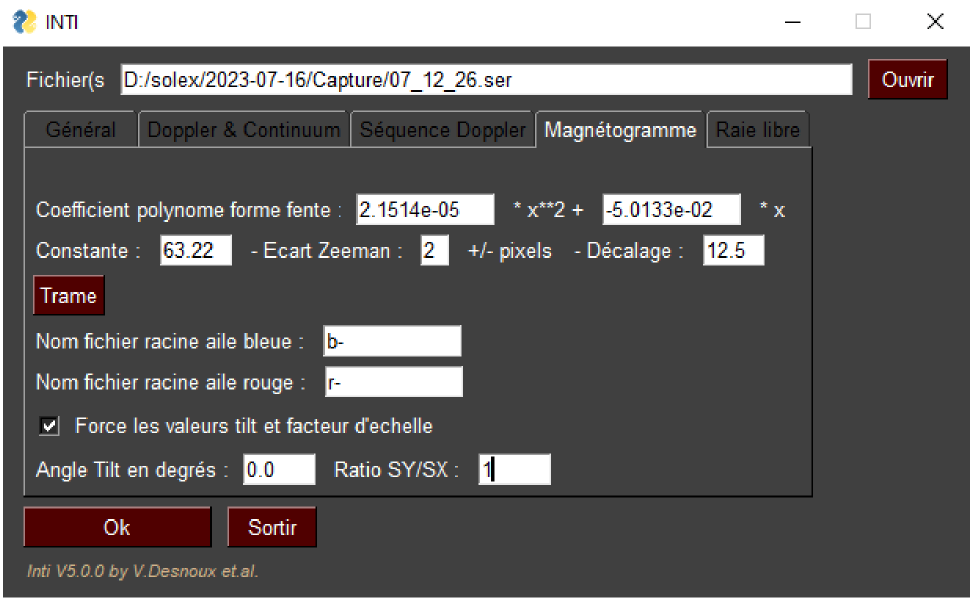


However, our work on measuring the Zeeman effect requires such precision that we can't be satisfied with evaluating the position of the line of interest to within a pixel. We need to be more precise and work to a fraction of a pixel. You can do this, for example, using image processing software capable of zooming in for a precise reading (ISIS, for example). Here's what we find for our example:



Since the value of the constant for the line at 6301.5 A is c = 63.22, the value to adopt for the line at 6302.5 A is c = 63.22 + 12.5 = 75.72.

You can also keep the initial value of the constant, but apply an offset of 12.5 pixels in the "Magnetogram" tab, which is often easier to read, and gives:



In fact, there's another way to find this 12.5-pixel value, without leaving INTI, which is both powerful and rigorous. We take advantage of the fact that the center of a line is the place where light energy is minimal. This is also where the reconstructed image of the solar disk will be the least intense, relative to what will be found in the wings of the line.

This intensity of the disk (averaged over the center) is systematically returned by INTI at the end of each processing run. It is the "Average Intensity" value that is displayed in the console. It's therefore easy to iteratively find the "minimum" of the line by testing several offset values: 12.4, 12.5, 15.6... You're bound to end up with a minimum value, with the offset value you're looking for.

Note: each time you test a new offset value, you can also examine the xxxx_recon.fits image, generated with the current value. For example, note its appearance and overall intensity.

The hard part is done: we've found the precise value in pixels separating the reference line (the darkest) and the line of interest. Note that this parameter is a constant on your instrument. The next time you make a magnetic field observation, you don't have to repeat these operations. Just remember the offset value and things will go very quickly.

Your observations are ready to use. We'll start with right-hand polarization by making:

What does INTI do?

The software first loads your SER file, then extracts the image from disk using the polynomial parameters supplied, and possibly adding an offset (in this case 12.5 pixels). At the very bottom of the dialog box, we force the image's geometric parameters (tilt is form factor), even if they're not quite exact in value, so that processing a SER file sequence is always identical.

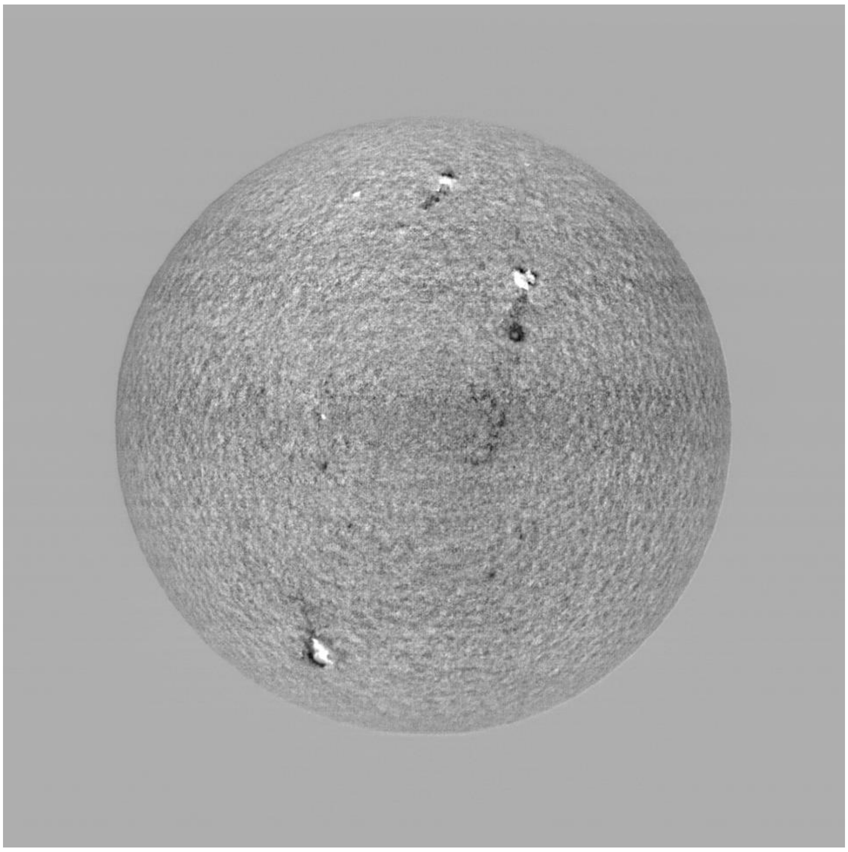
INTI then outputs two images of the solar disk, positioned at a certain distance on either side of the target wavelength (in this case, the core of our iron line). In the example, INTI generates one image by shifting the wavelength blue by 1 pixel (b), and a second image by shifting the wavelength red by 1 pixel. These are very small deviations, so we're still in the flanks of our iron line, but it's the subtle variations in these line wings that will give us information about the magnetic field, via the Zeeman effect. Normally, the Zeeman deviation is +/- 1 pixel (which requires very good images), or +/- 2 pixels, with a better tolerance for defects in the data, but also a lower sensitivity to the magnetic field.

We decide that the image of the Sun extracted from the blue flank of the Fe line at 6302 , written in the SER files folder, will be called "droite_b-1.fits", while for the blue flank it will be called "droite_r-1.fits".

Understand these designations and the constitution of the root name: (b) or (r) identifies the line flank (blue or red), while (right) identifies the polarization direction isolated by the circular polarizing filter.

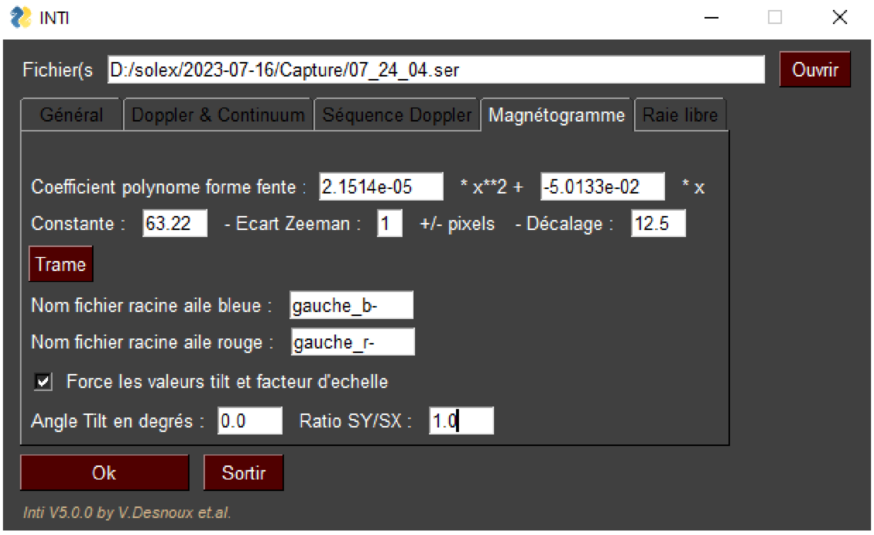
You can, of course, process several files simultaneously by selecting them in advance. The result is a sequence of images, such as droite_b-1.fit, droite_b-2.fit, droite_b-3.fit...

It's instructive at this stage to examine the difference between the images associated with the blue and red wings of our ray. INTI does this for you. The corresponding image file is "07_12_26_diff.fits". Here it is:

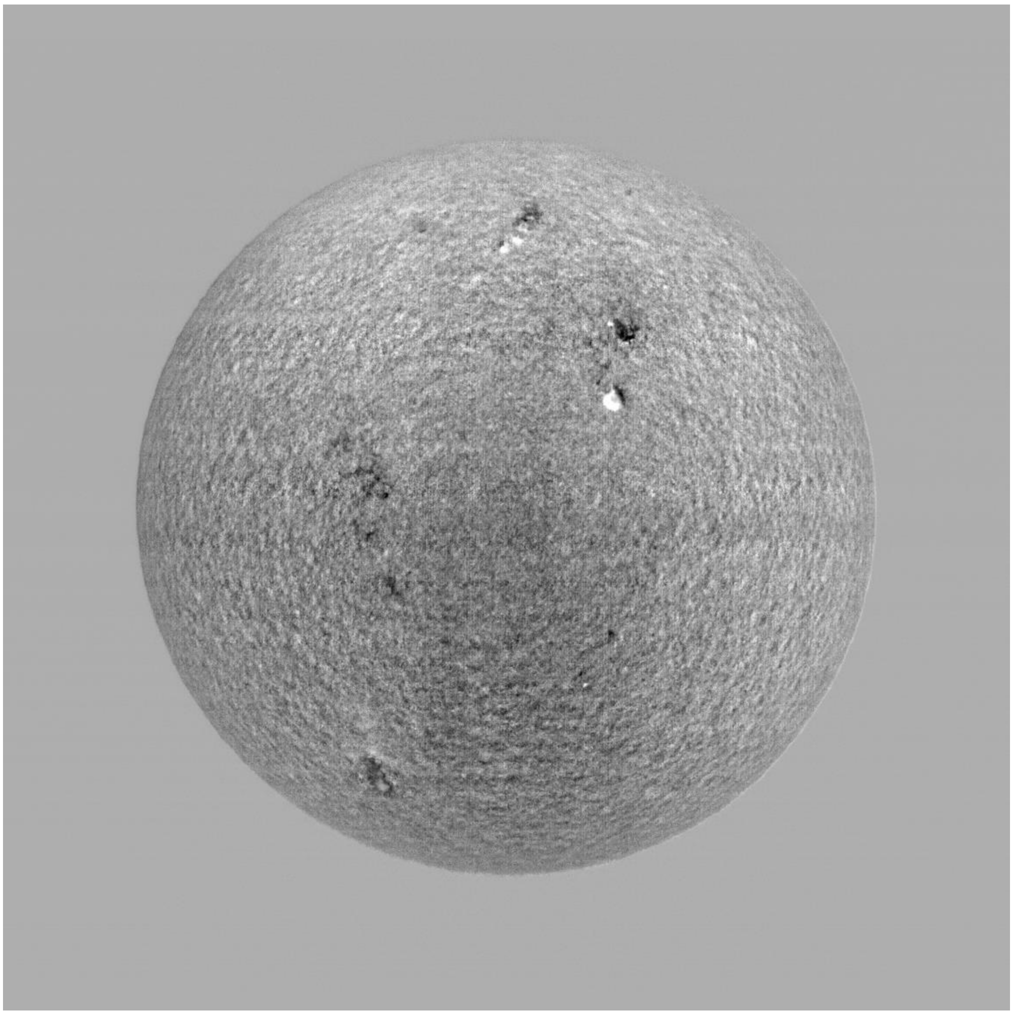


The image is unusual. It already contains information about the solar magnetic field. In particular, it shows the bipolarity of this field, coded in black or white.

Let's proceed in the same way with the SER file associated with the shot isolating the left-hand circular polarization:



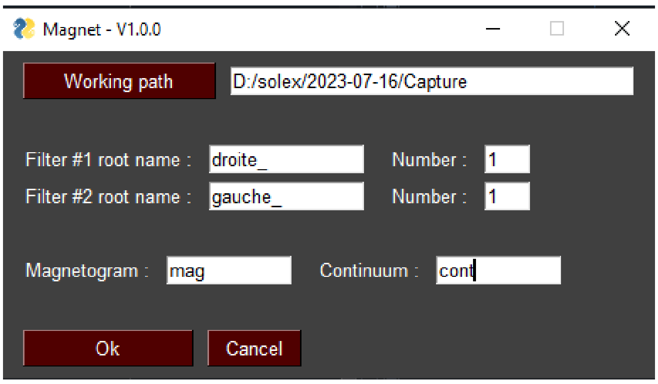
And here's the related image difference:



It looks different, in particular, the sign of the polarities changes.

INTI's work is now complete. We have on our disk the images: right_b-1, right_r-1, left_b-1, left_r-1. We now need to combine them to extract the true solar magnetic field.

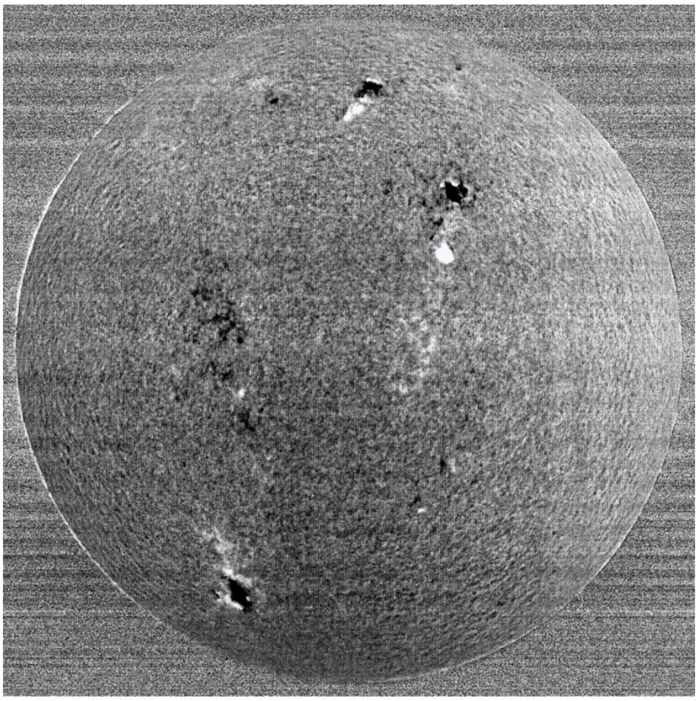
To do this, we're using a little utility you'll find in the INTI distribution: magnet.exe. Launch the application and fill in the fields as follows:



Note that we haven't indicated (b) and (r) in the root names, so the utility will add them for you when it needs them. Here we only have one set of images, but we could have many more, in which case Magnet calculates an average (INTI formats data intelligently, providing images of the same size and systematically centering the solar disk, so operations are easy).

Click on Ok.

In a fraction of a second, you have the magnetic field image (mag.fits) and the solar continuum image for verification (cont.fits). You can of course choose other names here. Here's how the mag.fits image looks from a single pair of SER files:



And the result using 10 pairs of scans performed in succession (10 scans with right-hand circular polarization, followed immediately by 10 scans with left-hand circular polarization). We compare our result with an HMI image after correctly orienting the disk image (vertical pole axis)