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GREGOR: Derotator Manual

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Contents

1 Scope

This document explains the derotator at GREGOR.

2 Overview

The derotator is an optical element consisting of 3 mirrors in a so-called K-configuration, which rotates during the day to keep the image orientation fixed with respect to the Sun. It is located after the exit of the vacuum window, and contains M8-M10. A schematic light path and the Zemax model is shown in Fig. 1. The M8 and M10 mirrors are tilted by 30°, therefore their incidence angles are 60°, while that of M9 is 30°. The mirrors are coated with protected silver (Tafelmaier). The derotator flips one axis of the beam.

Fig. 1: *Left: Derotator as installed at GREGOR with its light path indicated. Right: Zemax model (from D. Soltau).*
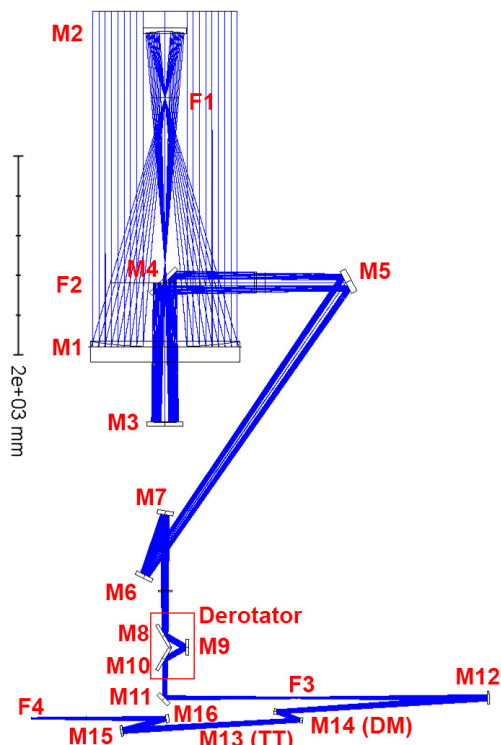

Fig. 2: *In the telescope, the derotator consists of M8, M9 and M10.*

Its location in the overall telescope layout is indicated in Fig. 2.

To describe the image rotation, we use the common astronomical coordinate system shown in Fig. 3. The left image shows the object (the Sun) at X with declination δ. Its azimuth is defined at GREGOR as the angle from south: south being 0°, east -90°, west 90°, and north 180°, which differs from most other astronomical definitions by 180 degrees (in which case the angle PZX would be 360°-azimuth). The elevation is denoted by e [degrees] and the parallactic angle PA is the angle between local zenith Z and the north pole P at the position of the Sun X. H stands for the hour angle, which is zero when the Sun is in the South. The image on the right shows the Sun shortly after sunrise with the direction to Earth's pole indicated by N. Note that this direction does not necessarily have to be identical to solar north, and differs from it by the so-called solar P0-angle. At GREGOR the indicated N-direction corresponds to the telescope's
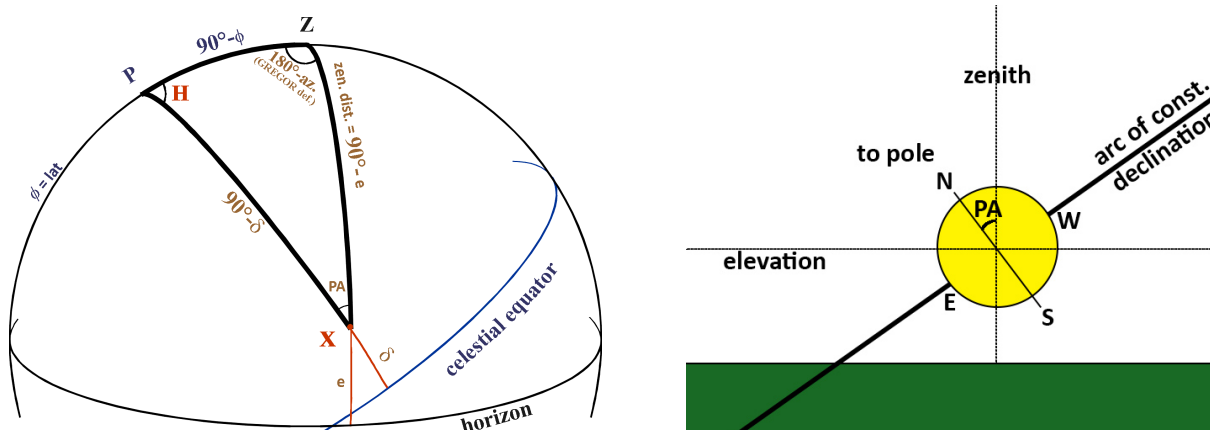
Fig. 3: *Left: astronomical coordinate system adapted from* http://star-www.st-and.ac.uk/~fv/webnotes/chapter7.htm. *Right: Parallactic angle PA shown shortly after sunrise. The directions (N, S, E, W) refer to Earth, not necessarily solar coordinates.*

y-coordinate and its perpendicular axis (along the daily arc) corresponds to the x coordinate. The parallactic angle PA is zero when the Sun is highest in the sky, i.e. crossing the meridian, at which point the positive elevation direction coincides with the direction to the North pole and the telescope's y-coordinates. The solar P0-angle is calculated, but currently not used in GREGOR's ephemeris program and therefore the only way to point in solar coordinates is currently to use the Conductor.

2.1 Image rotation in F1 and F2

For an alt-az mounted telescope, such as GREGOR, the image rotates during the day. The image rotation rate depends on the focus that one is looking at. GREGOR is symmetric until M4, which means that the image orientation and image rotation rate in F1 and F2 is therefore only determined by the variation of the parallactic angle (PA) during the day. PA can be calculated as (see e.g. Smart, Spherical Astronomy, 1971, pg. 50).

$$\sin\left(\mathrm{PA}\right) = \sin(az)\cos(lat)/\cos(\delta) \tag{1}$$

Due to GREGOR's azimuth definition, PA has the opposite sign compared to regular astronomical calculators (e.g. calsky.com). The image rotation rate of the parallactic angle is (Smart, page 55):

$$\mathrm{PA\ rate\ [arcsec/seconds]} = 15 * \cos(lat) * \cos(az)/\cos(elevation) \tag{2}$$

and is shown in Fig. 4. The figure shows rates for given elevations at the latitude of GREGOR. Obviously, the solar elevation is constantly changing during the day, meaning that none of the curves shows the actual solar rate during a given day.

2.2 Image rotation in F3 and subsequent foci

For the other focal planes the rotation becomes more complicated. The image rotation on M5 additionally depends on the elevation of the telescope. M6 induces a rotation of the beam about the azimuth axis. In any Coudé focus the derotator therefore has to compensate for image
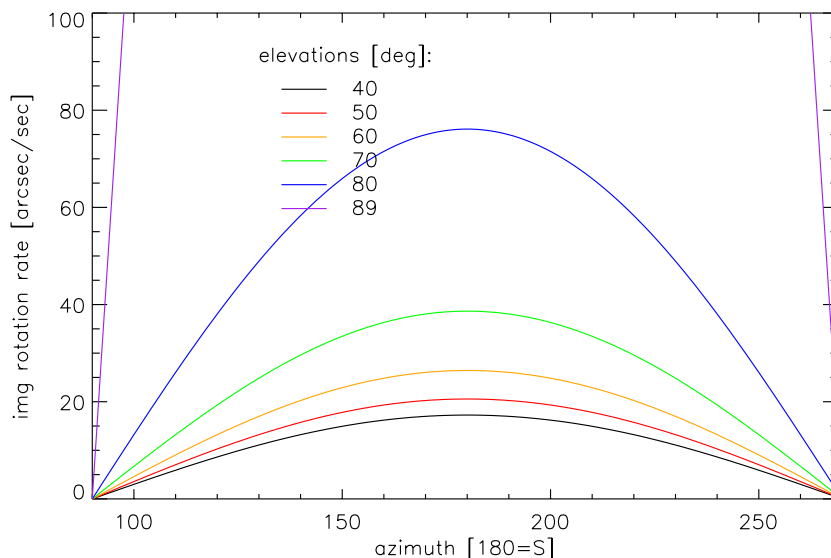
Fig. 4: *Image rotation rates due to changes of the parallactic angle at Izaña. This figure uses the common azimuth system (0=North), unlike GREGOR. At GREGOR these image rotation rates are valid only for F1 and F2.*

rotation due to parallactic angle, elevation, and azimuth changes. The final image rotation in F3 and subsequent foci can be written as

$$\text{image rotation} = \text{parallactic angle} + \text{azimuth - zenith distance} \tag{3}$$

This equation is used for GREGOR. For other telescopes or coordinate systems one may have to modify some signs (see e.g. Solar Instrumentation by O. von der Lühe, 1999). The image rotation rate in a Coudé focus is the derivative of the above equation. The temporal derivative needs to be calculated for each of the 3 terms. $d\text{pa}/dt$ is given by Eq. 2. A more complete derivation of these equations can be found in Smart's book on pages 50/51. The temporal derivatives for the azimuth and zenith distance are

$$d\text{az}/dt = 15. * (\sin(lat) + \cos(lat) * \cos(az)/\tan(\text{zenith dist.})) \tag{4}$$

$$d\text{zd}/dt = 15. * \cos(lat) * \sin(az) \tag{5}$$

These equations are implemented in the ephemeris program of GREGOR (in fov.f), although Eq. 2 is written in a much more complex form, but identical in values. The GREGOR derotator works based on image rotation angle tracks and not based on rotation rates. The base equation for GREGOR's derotator is therefore Eq. 3. Additionally, at GREGOR the derotator has an offset due to the lab orientation, which is defined in fov.f as pzero=0.5d0*π and which is added to Eq. 3, finally resulting in

$$\text{image rotation} = \text{parallactic angle} + \text{azimuth - zenith distance} + \text{pzero.} \tag{6}$$

An example of a daily variation of the image rotation angle is shown in Fig. 5. Due to the reflection in the derotator, the image rotation equals 2*the derotator rotation. This means that the labview derotator program halves this image rotation track and this results in the derotator angle track for a given day. By specifying an offset to this derotator track (a simple addition or
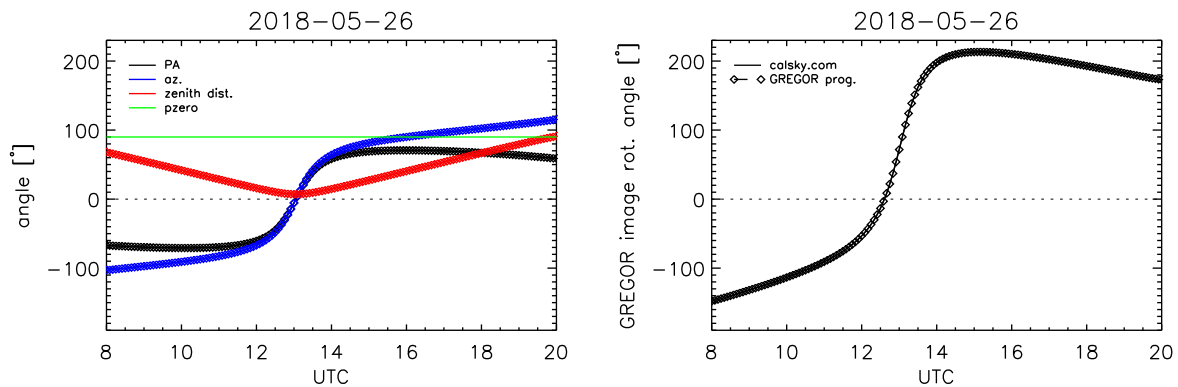
Fig. 5: *Left: The variation of the parallactic angle (black), the azimuth (blue), the zenith distance (red), and the GREGOR lab offset (green) during an example day at GREGOR. The solid lines are values from calsky.com, the symbols were obtained from the GREGOR ephemeris program (they match nearly perfectly). Right: The resulting image rotation angle at GREGOR. The solid lines use az and elev from calsky.com, the diamonds were calculated with the GREGOR ephemeris program.*

subtraction), any desired image orientation can be tracked during the day. The actual rotation rate is interpolated automatically based on the commanded positions in time. An example of all rotation rates is shown in Fig. 6. The image rotation rate varies significantly during the year, mostly due to the varying solar elevation, and it is shown for selected dates calculated with the GREGOR ephemeris program in Fig. 7.

2.3 Orientation of the derotator with respect to solar coordinates

Equation 6 refers to the equatorial coordinate system and not the solar heliocentric system. Because of the varying P0 angle during the year, a given track calculated with equation 6 will not be oriented with any particular solar direction. It will also require a different offset each day to orient the slit for example in E/W direction on the Sun.

To relate the offset of the derotator track with solar coordinates, the P0 angle needs to be taken into account. This can be done by including the line `p = p - p0` at the end of fov.f, where p stands for the image rotation. This gives the equation

$$\text{image rotation} = \text{parallactic angle} + \text{azimuth} - \text{zenith distance} + \text{pzero} - \text{p0}, \tag{7}$$

which describes the image rotation in the heliocentric system. With this equation, a given derotator offset (e.g. 5.1 deg) will always have the same solar orientation (e.g. slit in solar E/W direction). A test GUI (called "start DER LK") has this change implemented and it is foreseen to include it in the main GUI in the future. Be aware that this test GUI does not include the get pos2 command, which makes it incompatible to GRIS and it should only be used for testing purposes.

2.4 Derotator track to keep the pupil stable on the DM

For some testing purposes, it may be useful to keep the spiders in a constant orientation on the deformable mirror. The image rotation of the pupil at GREGOR can be written as

$$\text{image rotation} = \text{azimuth} - \text{zenith distance} + \text{pzero} \tag{8}$$
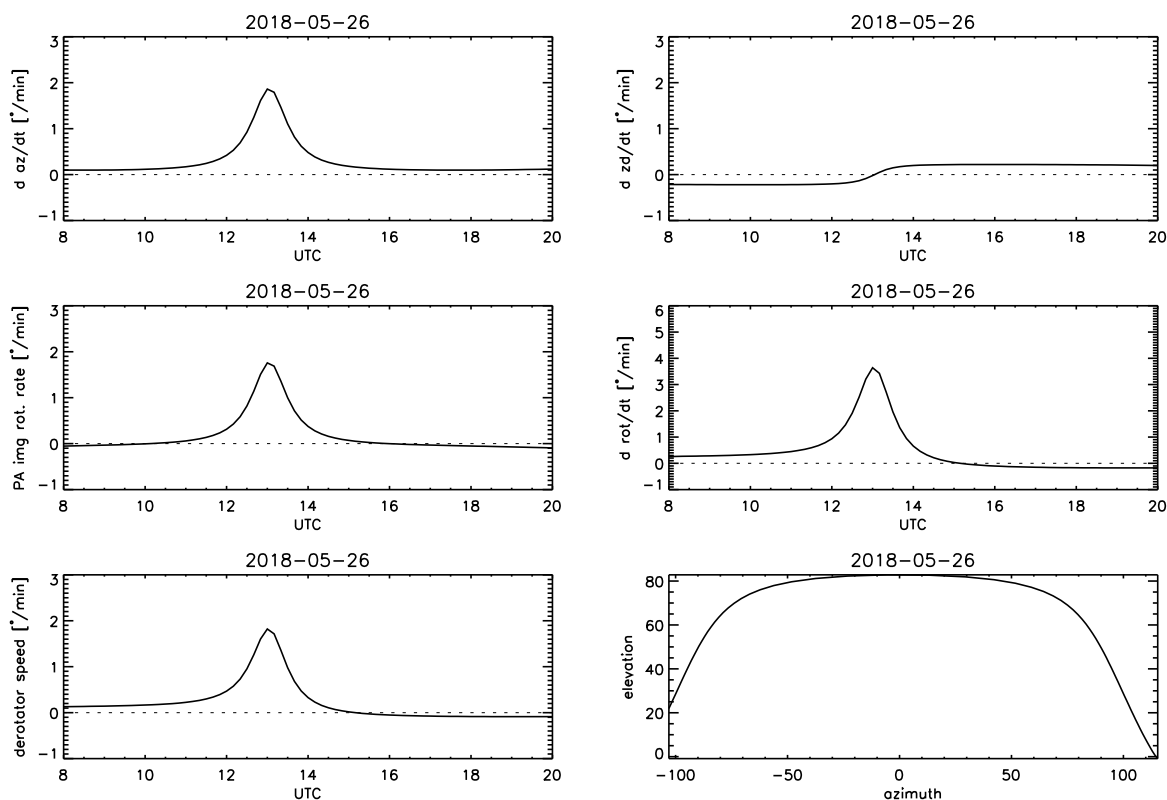
Fig. 6: *Example of image rotation rates for GREGOR for 2018-05-26. From top left to bottom right, the plots show 1) the rate of change of the azimuth, 2) the rate of change of the zenith distance, 3) the rotation rate of the parallactic angle, 4) the rotation rate at the Coudé focus, i.e. the combination of 1-3, 5) the derotator speed, which is a factor of 2 lower than 4), and 6) the solar elevation and azimuth of the day.*
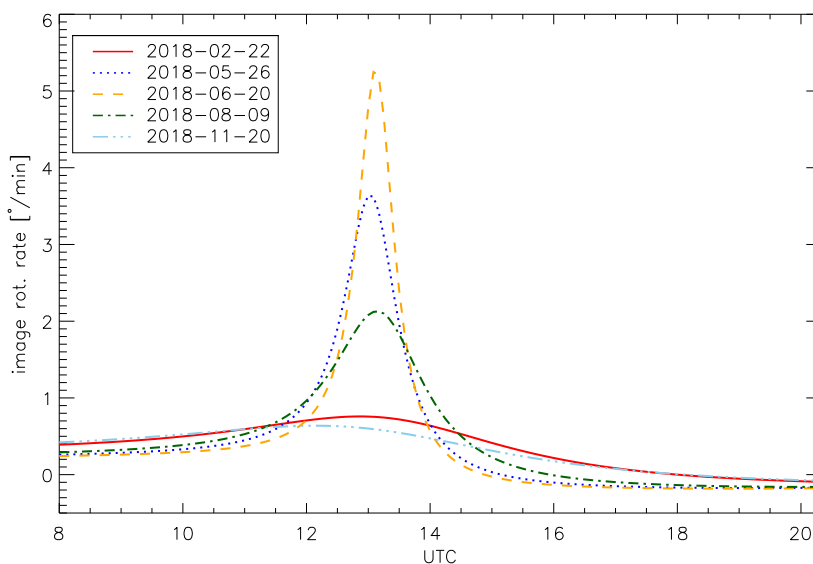

Fig. 7: *Annual variation of the image rotation rate for example dates given in the legend. The derotator speed is half of these values.*
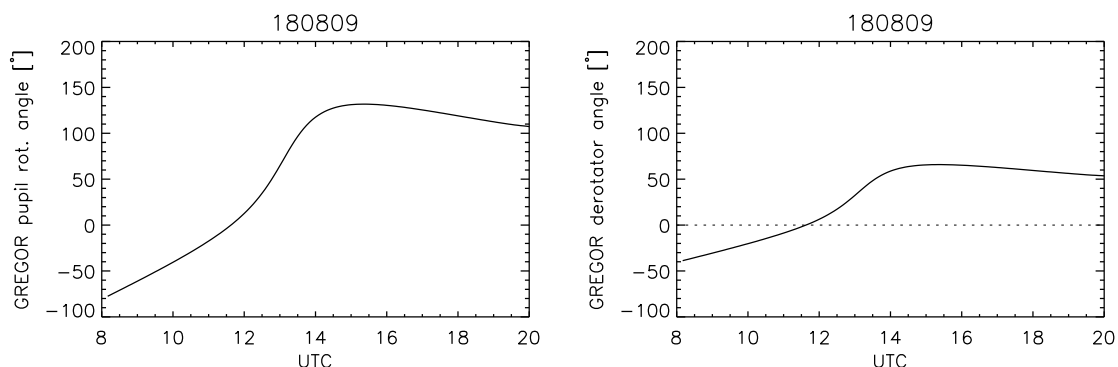
Fig. 8: *Pupil rotation angle at GREGOR for an example date (2018-08-09) and the derotator track to compensate for this rotation. By applying this track, the pupil orientation on the DM remains constant (but the Sun would rotate underneath it).*

and an example is shown in Fig. 8. Another test GUI ("start DER berke") contains the following changes in fov.f: p = az - zd + pzero (PA no longer appears and p0 is also not included), which keeps a constant orientation of the pupil on the DM.

2.5 Differences between north and south

Because the Sun has a non-negligible diameter, its coordinates differ significantly at its poles. The derotator tracks at the poles therefore differ. This difference is most pronounced during the summer solstice when the Sun has its highest elevation in the sky. Figure 9 shows the calculations for 2018-06-21, which were performed for the equatorial coordinates $(x,y) = (0, 940)$" and $(0,-940)$". It is visible that the difference between equatorial N and S may exceed 6 degrees in image rotation, which corresponds to a 3 degree difference in derotator orientation. However, the derotator at GREGOR currently always uses the track for $(x,y)=(0,0)$, independent of the actual telescope pointing. Because one can discern misalignments as small as 0.1 degrees visually, this effect is noticeable. To implement a correction based on the actual pointing is not straightforward because one has to take safety concerns into account (how fast should the derotator rotate when changing the pointing? Should every pointing change lead to a rotation adjustment?), this would require changes in Labview (e.g. a more frequent call of the ephemeris program), plus one needs make sure not to break existing pipelines (e.g. GRIS, which uses disk center for its calibration).
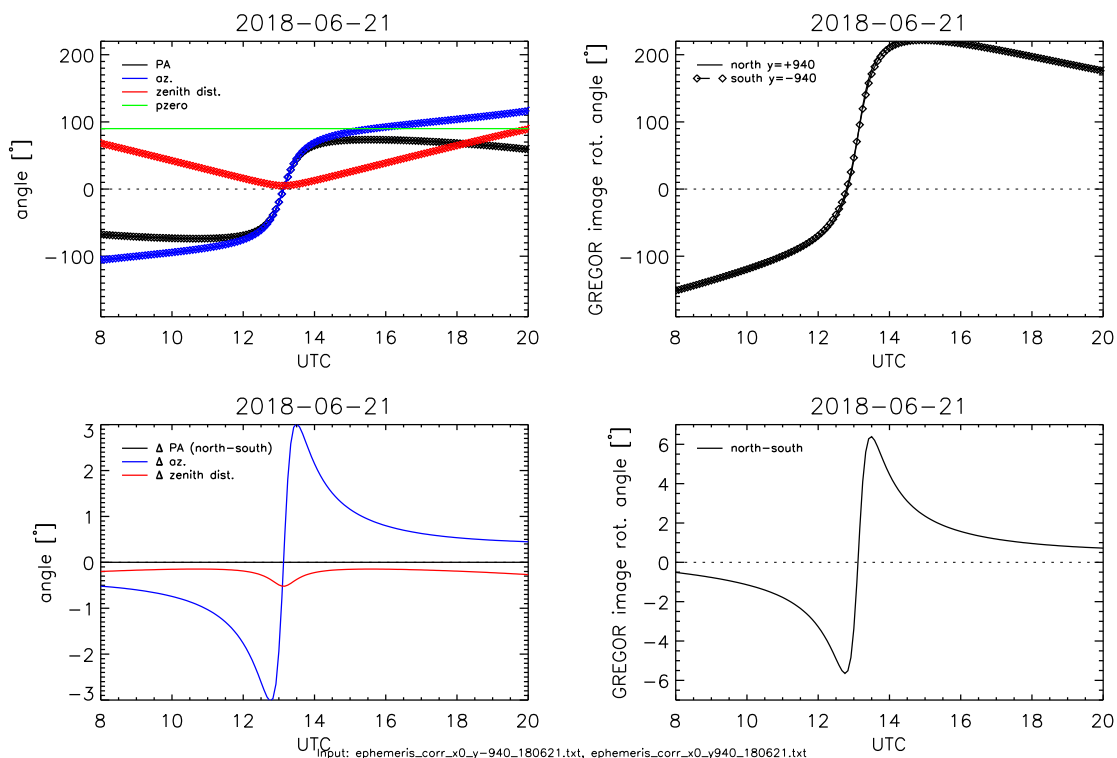
Fig. 9: *Top row: PA, azimuth, zenith distance and image rotation angle for equatorial north and south for 2018-06-21. Bottom row: The differences between north and south can exceed 6 degrees in the image rotation angle.*

3 The GUI

The GUI can be started via the Instrument Control System (-> DER GUI beta2) and is shown in Figure 10. Its left side are controls for the linear axis, the right side for the rotation axis. The rel checkbox generally means "keep relative position" (that is visible on camera). The time offset should not be changed manually, only use rel and set as specified below.

The following sequences of commands are to be used for the most common tasks:

- **Insert derotator into the beam.** Assumption: Parked outside of the beam.

Linear axis → activate

Linear axis → insert

Linear axis → deactivate

Attention: This changes the optical path and the z-position of M3 must be adapted via its GUI according to the values given in the table on the wall or by inserting and focusing the grid in F2.

- **Want to track and adjust slit orientation**. Assumption: Derotator in beam. Slit not in desired orientation.

Main axis → activate

Time offset → checkbox rel activated, click on set

Track → do not check 'rel', click on Track

Position offset → put as desired (by eye, using the arrow buttons or by putting a number in the left position offset box. The value below the arrow buttons is the step size.)

Note: If the offset is put before tracking is started, then the derotator will not move yet.
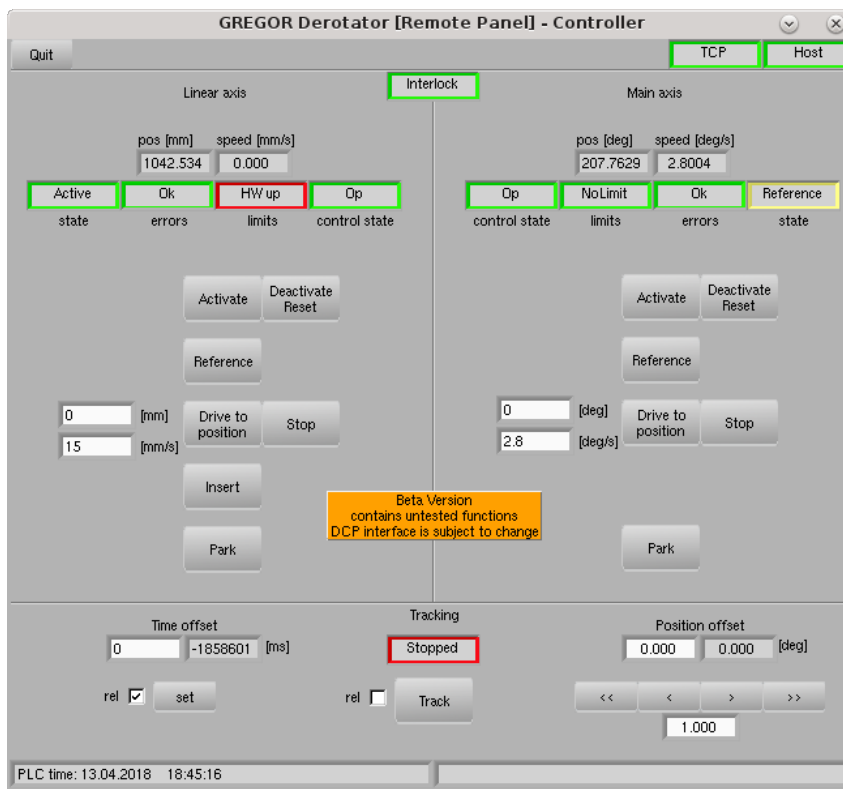
AIP   Doc. No.   GRE-KIS-MAN-0008
KIS   Version: 1
MPS   Date: 14.9.2018

Fig. 10: *The GUI of the derotator.*

- **Want to track with current slit orientation**. Assumption: Derotator in beam. Slit already in desired orientation.

Main axis → activate
Time offset → checkbox rel activated, click on set
Tracking → check 'rel', click on Track

- **Want to stop tracking for a calibration and continue afterwards with the same solar orientation**. Assumption: Derotator in beam. Slit already in desired orientation.

Main axis → stop
Run calibration
Time offset → checkbox rel activated, click on set
Tracking → do not check 'rel', click on Track

- **Parking the derotator**. Attention: Order of axes matters.

Main axis → park, deactivate
Linear axis → activate if necessary, park, deactivate
Attention: This changes the optical path and the z-position of M3 must be adapted via its GUI according to the values given in the table on the wall or by inserting and focusing the grid in F2.

- **If any button on top is red**

Try deactivate, then activate.
Try referencing. First linear axis, then main axis.
In case of interlock red: Check emergency stop. Press Interlock Reset on the cabinet. Deactivate,

activate.

In case of TCP red: Network connection to hardware is missing. Is the cabinet on? Is the SPS on (green PC switch on and TCP in GUI green)? Try restarting the program, otherwise call the assistant.

- **State: axis error upon trying to track**

Try deactivate, then activate.

Try setting the time offset.

Try referencing. First linear axis, then main axis.

Try restarting the derotator according to the defined procedure.

Check if there are overheating issues, potentially leave the cabinet door open.

3.1 Safety features

The derotator has built-in safety features and the GUI will not allow you to crash it. For example, it is not possible to park the linear axis unless the rotational axis has been parked properly. If you try it anyway, the limits and control state boxes of the linear axis turn yellow and say "SafeOp". The derotator will simply not move completely out of the beam if the rotation is not parked. This is schematically shown in Fig. 11.
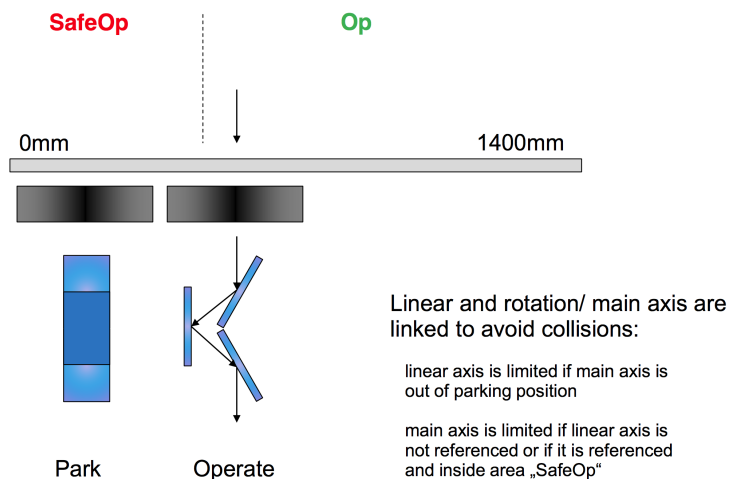

Fig. 11: *Schematic drawing of safe operation (by C. Halbgewachs).*

There are two emergency switches for the derotator in the optics lab. One visible on top of the AO bench, the other in the back of the room on one of the vertical beams as shown in Fig. 12. If they (or one of them) are activated, the red interlock light on the cabinet will be blinking.

As of Aug 8, 2018, the derotator is fully connected to the UPS. If it needs to be reinitialized for any reason, the procedure can be found at the end of this document or on the derotator cabinet. Note that the order of a few steps in the procedure has changed since the derotator was put on UPS.

If the service button is enabled (yellow button at the ceiling near the AO rack, see yellow arrow in Fig. 12), then no external commands can be sent.
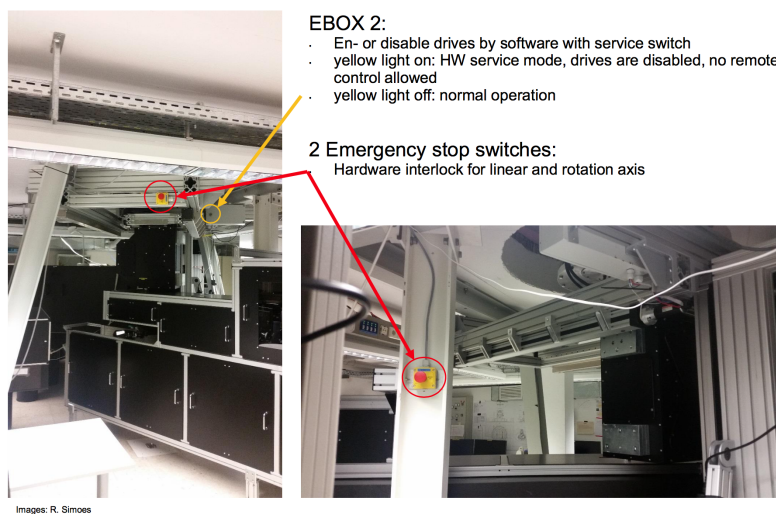
EBOX 2:
- En- or disable drives by software with service switch
- yellow light on: HW service mode, drives are disabled, no remote control allowed
- yellow light off: normal operation

2 Emergency stop switches:
Hardware interlock for linear and rotation axis

Images: R. Simoes

Fig. 12: *Location of emergency stop buttons (copied from Clemens' OTTM presentation).*

If the interlock is blinking, then one cannot reset it. There can be several reasons for the blinking: The emergency stop may be activated, or there is an error with the power supply. Check the 2 emergency stop buttons.

3.1.1 SafeOp

The meaning and limitations of SafeOp are different for the two axes:

When the main (rotation) axis is in the control state SafeOp, this means that
- the axis cannot be activated
- cannot reference
- cannot drive to position
- can only deactivate and reset main axis.

When the linear axis is in the control state SafeOp, this means that
- can activate, deactivate, reference, and drive in positive direction (away from SJ unit).
- cannot move closer to the SJ unit, i.e. cannot park.
- can use insert only if motion would be away from the SJ unit.

4 Calibration of the absolute orientation

To determine the relation of the derotator offset to the absolute orientation of the slit on the Sun, we took slitjaw images of several pores with varying orientations of the derotator on 2018-06-18 around 15:30 UT. The slitjaw images were then aligned to co-temporal HMI images and the slit was fitted with a line. This gave the angle of the slit with respect to solar east-west for a given derotator offset. The different measurements are shown in Figures 13 and 14. The alignment has a maximum error up to a shift of 0.1 arcsec in x and y (larger shifts noticeably decreased the quality of the alignment) and slit rotation of 0.2 degrees.
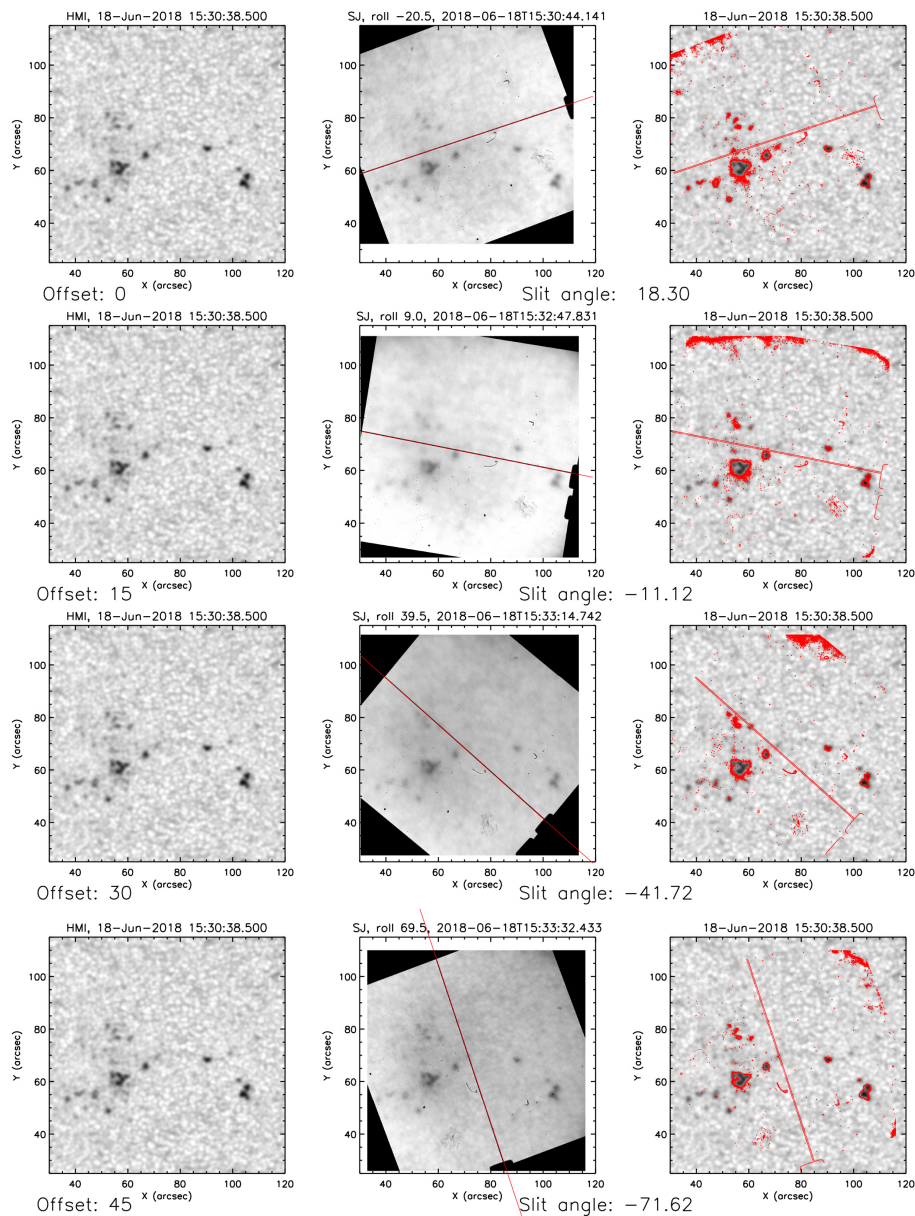

Fig. 13: *Left: Reference HMI image, middle: SJ image at 777 nm rotated to match the HMI image with the slit fit shown as a red line. Right: Contours of the SJ pores overlaid on HMI to show the alignment. The derotator offsets and angles of the slit with respect to solar E-W are given below each set of images.*
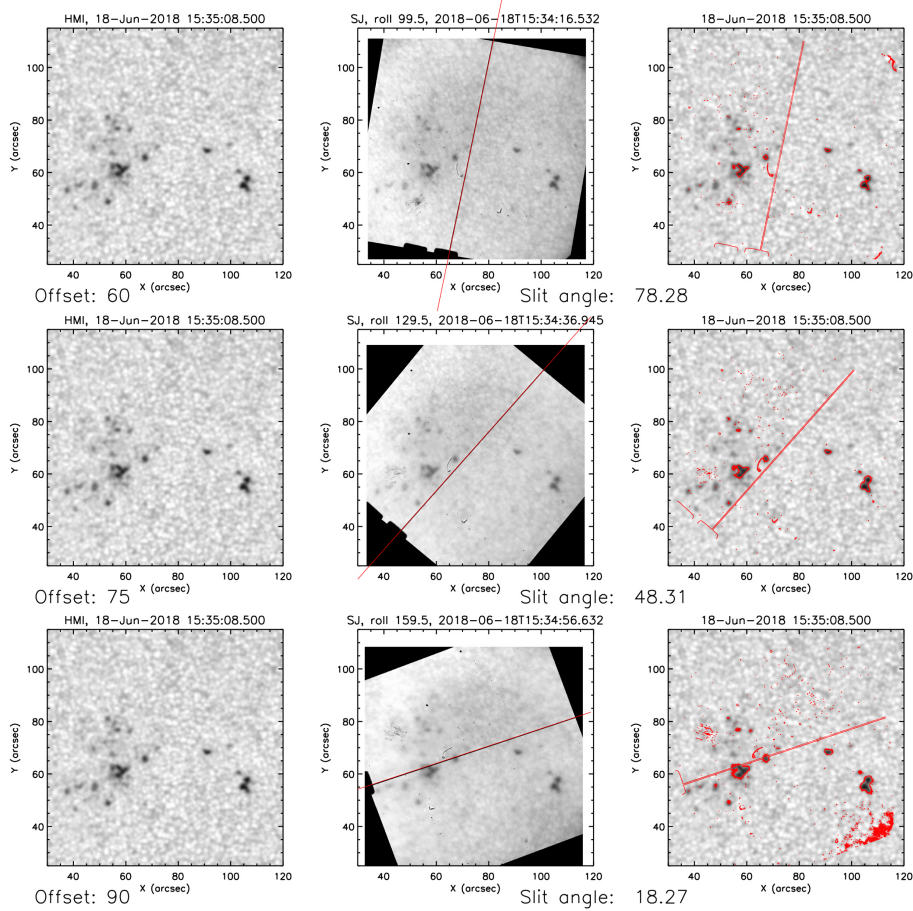
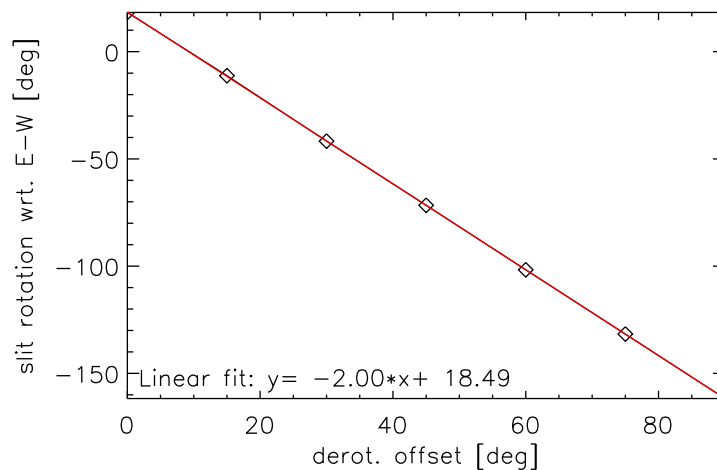**Fig. 14:** *Same as Figure 13 for different derotator offsets.*

Fig. 15: *Calibration of the orientation of the slit versus the derotator offset. The red line shows the linear least-squares fit through the 7 data points.*

The result of the calibration is shown in Figure 15. The sign of the y-axis is arbitrary, obviously a slit orientation of 180, 0 and -180 would be identical and indicate a slit in solar E-W direction. However, the slope is not perfectly 2, but differs from 2 in the third decimal digit, which means

that an uncertainty of 0.1° exists for a slit rotation by 180°. The fit gives a required offset of 9.2±0.1° for the slit E-W and an offset of 54.2±0.1° for the slit N-S. This offset is in heliographic coordinates, valid for 2018-06-18. The p0-angle in degrees on that day was

```
IDL> print,(get_sun('2018-06-18T15:30'))[12]
-8.2578361
```

This means that the slit E-W offset in the equatorial frame, i.e. the one entered in the current derotator GUI at GREGOR, is 9.23+(-8.26/2) = 5.1°. The fitting error combined with the alignment error probably lead to an uncertainty of ±0.2°. **In summary, to orient the slit with the derotator along equatorial E/W use offset=5.1°. To orient it along solar E/W use offset = 5.1-p0/2 °.**

Similarly, for the slit along equatorial N-S, use an offset of 50.1±0.2° and for the slit along solar N-S use an offset of 50.1-p0/2°. These offsets are only valid as long as the slit mask, whose rotation is not fixed, is not touched.

4.1 Alternative method

This method relies on the Sun centering procedure and then uses DCP commands to go to equatorial North and South and putting the slit parallel to the limb. It has the advantage that it does not require pores or sunspots.
The following steps are performed:

- Run the suncenter script in the Conductor.

- Then a DCP command to go to the north limb (e.g. x=0, y=945, in telescope coordinates, not heliographic coordinates with the y-value depending on the apparent solar radius) is used, which takes into account the Sun center position. The slit is oriented parallel to the limb by looking at the SJ camera. This gives a derotator offset for the north limb.

- Afterwards the telescope is pointed to the south limb (e.g. x=0, y=-945) and the slit shall be set parallel to the limb. The required offset will deviate slightly, because x and y are different, which is not taken into account in the derotator. But their average should give the offset angle for sun center.

This test was carried out on 2018-06-18 each hour from 8 to 12 in the morning using ZIMPOL scripts that translated into DCP commands, but could theoretically also be done using the conductor. The agreement was good and the offset yielded 5.125°. After 13 this method failed, possibly because of the high image rotation rate due to the high solar elevation. Additionally, a small error was found in the scaling factor: Going from north to south (2*945"), the telescope went about 8" too far, however this could not be reproduced in August (after a change of the ephemeris program, which may have fixed it). This method was tested on several days and the approximate offset error is ±0.1°, which corresponds to an uncertainty of ±0.2° for the slit rotation. These values are valid for the morning and evening, the errors during midday are significantly larger. This method assumes that the x-y grid is correct. If the x-y grid is rotated by an angle, for example 0.3°, this would give an error of 0.6° in the x-y system. This rotation would give a positioning error of ~10" at the limb, which may be possible, but cannot be much larger because pointing to sunspots at the limb generally works well using the heliographic coordinates and the conductor script.

5 Power On and Power Off Procedures

Please respect the procedures step by step to properly shut down or power on the derotator. In case of a power outage, you may have to ask experienced personnel to restart the cabinet.

5.1 Power UP

- Verify visually that PC green switch light is OFF and button OUT.

- Verify that the Main cabinet switch (yellow/red) is OFF

- Switch ON the Main cabinet switch (yellow/red)

- Switch ON the PC green button. Light appears ON after about 3 seconds and wait for at least 80 seconds for PC to boot. Wait until red interlock button is ON.

- Push the red Interlock button. There is a contact sound inside the cabinet and the red light goes OFF.

The Derotator Motor Control System is now ready.
Restart derotator interface on GCS.

5.2 Power DOWN

- Verify that linear and main axes are deactivated in the derotator user interface (FSG/GCS). If not, deactivate them.

- Exit the derotator interface.

- Verify visually that the PC green switch light is ON and the button pushed ON.

- Push PC green switch and wait until internal PC has shut down.

- The green light must turn OFF after about 15 seconds.

- Turn OFF the main cabinet switch (yellow/red). The PC green switch light is now OFF and button OUT. Power down is successful.