ASTROMETRY AND NUMERICAL METHODS FOR THE SOLAR HELIOMETER AT OBSERVATÓRIO NACIONAL IN BRASIL

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ABSTRACT

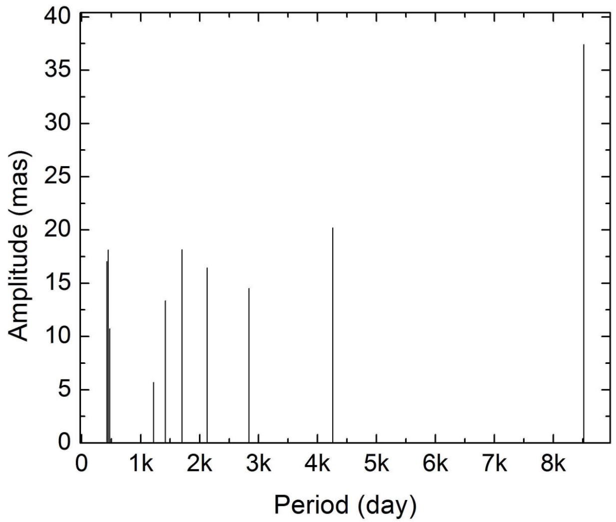
Started its regular, daily operational phase in 2011, the results so far obtained show that the Heliometer from Observatorio Nacional fulfilled its planed performance of single measurement to the level of few tens of mas, freely pivoting around the heliolatitudes without systematic deviations or error enhancement. Such fruition led to evaluate high order terms that are commonly neglected in other solar astrometric observations. Before and foremost is the constancy of the basic heliometric angle, against which the measurements are made. This is monitored by the timing of the solar transit over the CCD with the instrument halted (see Sigismondi et al., this meeting). Next the usual terms of observational origin are studied, namely dependence to meteorological and pointing conditions. These are shown of no effect, due to the cares used in the making and use of the instrument. The second order terms for diurnal aberration and parallax are then discussed. The effects are found negligible on themselves, and also on the building up of spurious yearly trends. On the contrary, for the accounting of the Earth´s ellipticity of the orbit the standard astrometric procedures had to be upgraded to make room for the full description of daily variations, instead of the usual approximation to the mean observational day. Finally, a thorough model for the second order atmospheric refraction has had to be developed to match the systematics left on the observations by using the geometrical second order description. We present and discuss these astrometric additions that are seldom required on ground base astronomic programs.

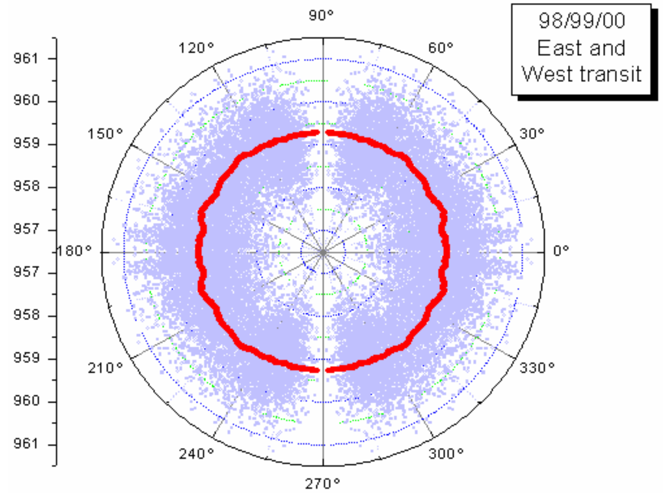
1 – Motivation

- Pressure, Temperature, and Volume define the state of an isolated gaseous body. Of these, only the radius is directly measurable for the Sun (in special in the optical window and for ground base measures).
- Measurements of the Solar diameter have been made from historical times.
- From the second half of the last century, the number of measures increased. Yet, the results are still unsure. Variations at the level of tens of milliarcsecond (up to few hundreds of milliarcsecond over the 11 years cycle) were derived by solar astrolabes and are compatible also with the extrapolation of solar measurements from space.
- Nevertheless when comparing with the solar activity, both an in-phase and na out-of-phase signatures befit the data. The semi-diameter is seen to vary in-phase with solar activity for short periods and high bursts, but off- or out-of-phase when long periods regarding the 11 year cycle are considered.
- At Brazil’s Observatorio Nacional (ON) in Rio de Janeiro regular measurements of variations of the solar diameter started in 1997 with a CCD astrolabe. The series extended till 2009 with a very high density of daily measures (from 10 up to 30).
- In 2010-11 a new instrument was developed (FINEP) and is now in current use The Solar Heliometer.

2- The Early Results – The Solar Astrolabe (1997-2009)

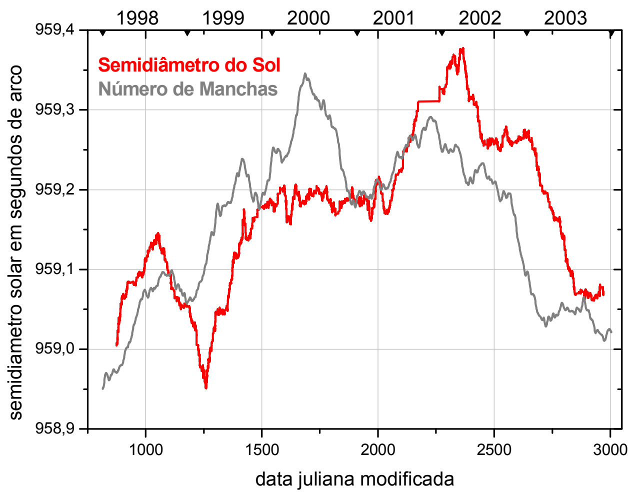
- 11y period, plus harmonic and sub-harmonic. And flattening plus heliolatitude modulation.

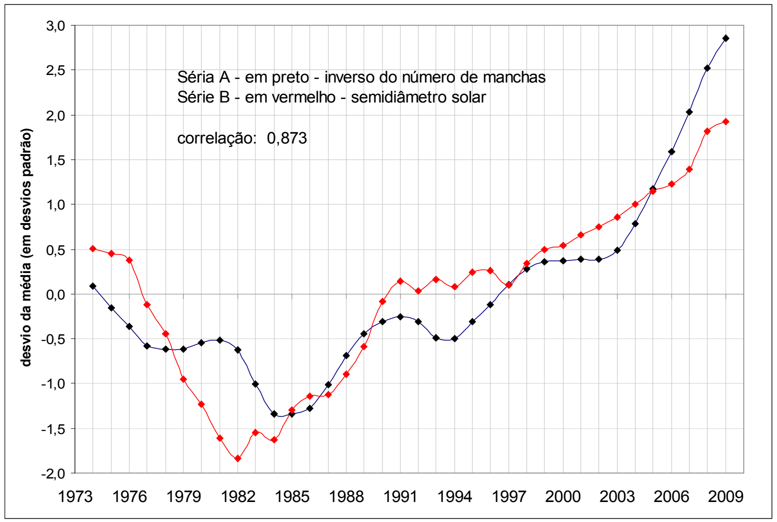




- Two modes of relationship to the solar activity. In-phase on cycle-length time lapses, whereas off-phase on the secular run.

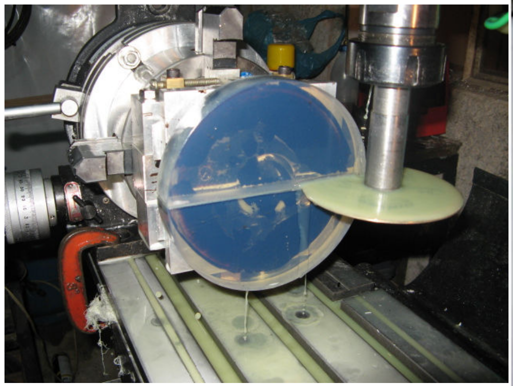
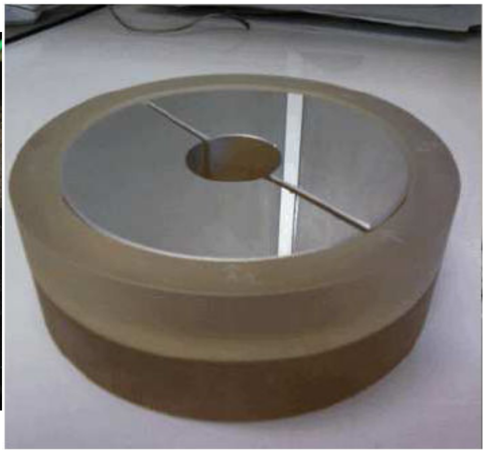
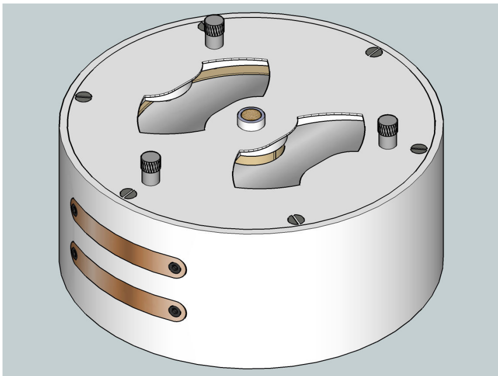
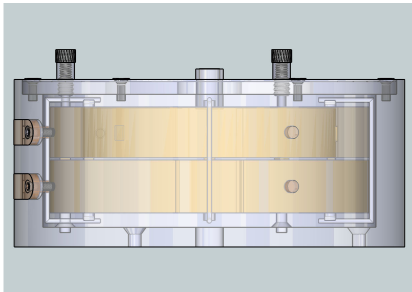
Figura 7.3 - Semidiâmetro do Sol e número de manchas.





3 – The Concept of the Solar Heliometer

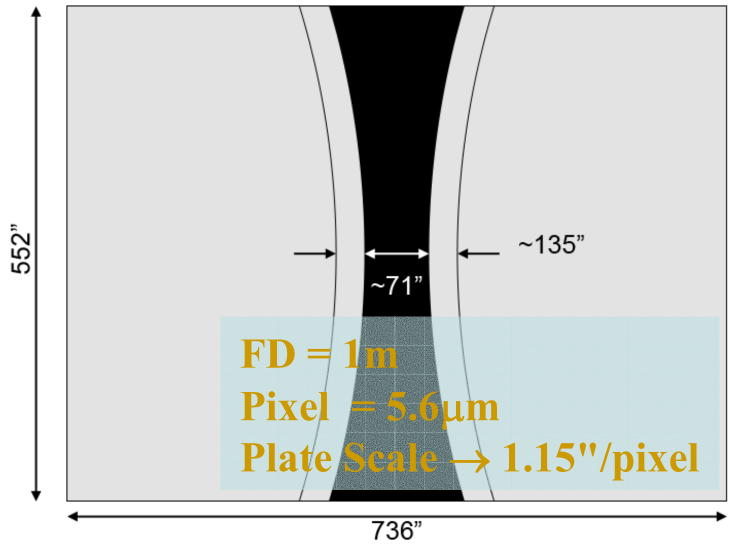
- The heliometric method is one of the most successful techniques to measure small variations of angles. Its principle has been used for the latest space borne astrometric missions, aiming to milli-arcsecond precision.
- The angle to be measured is small (the variation of the solar diameter) confronted with the corresponding linear displacement at the focal plane, thus an error on the linear measurement is smaller by orders of magnitude over the angular variation that is being measured.
- The plate scale can be instantaneously known by timing the solar movement over the detector, removing the out-of-focus dependence for the linear distance between two points.
- At Observatorio Nacional a primary parabolic mirror was bissected to form an angular heliometer. The displacement of the images is produced by rotating the two half-mirrors along a line perpendicular to the line of cut.

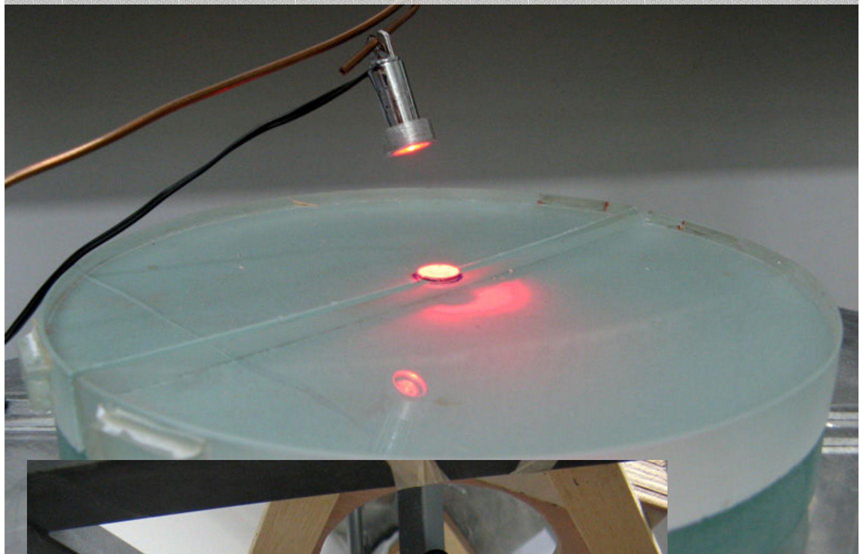
4 – Development of the Heliometer

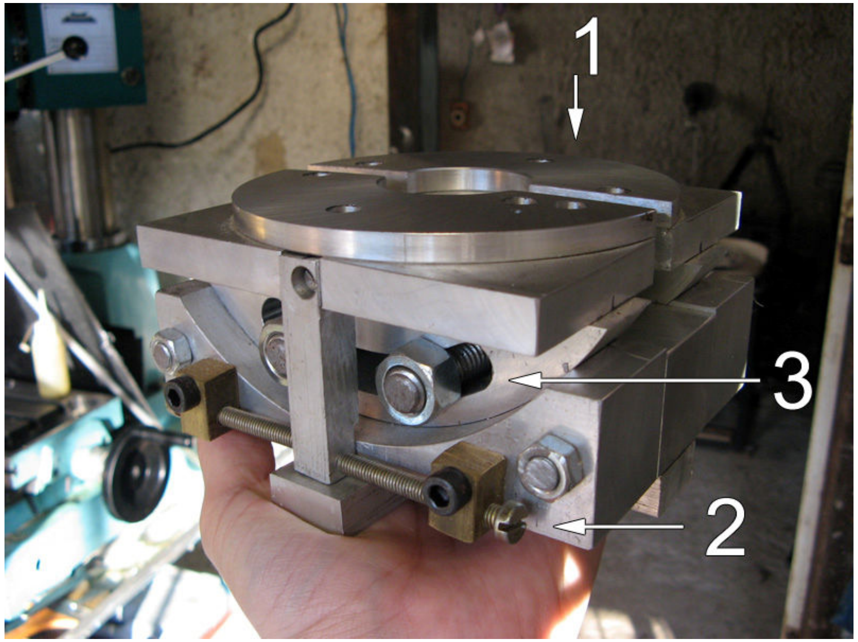
- The heliometric mirror is all made of CCZ-HS, a ceramic material with very low thermal expansion coefficient (0.0 ± 0.2 × 10−7/◦81 C).
- The two half mirrors are immobilized, in relation to each other, by means of a external ring, all resting over an optical plate. Its cell guarantees the mechanical and geometrical stability for the entire set. This niche is also in CCZ.
- The surface quality of the optical plate and the mirrors is better than $\lambda/12$ and $\lambda/20$, respectively.
- A mask at the top of the cell has been designed to keep the two half mirrors blocked in place and also to assure that the entrance pupil has a symmetric shape, regularizing the PSF.
- The tube of the telescope is made of carbon fiber. This material, as well as extremely rigid, has very low coefficient of thermal expansion. It is mounted inside a stainless steel truss support and can rotate around its axis.

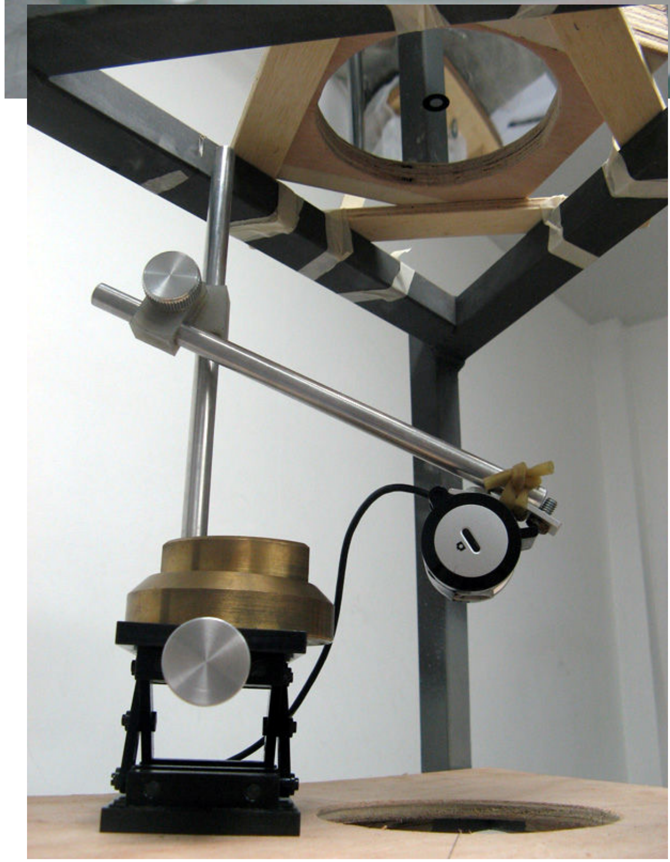
- In order to eliminate the secondary mirror the CCD chip was removed apart from the camera electronics and installed directly in the focal plane.
- Each half-mirror is tilted of an angle slightly greater than 0.135 degrees in order to displace the images relatively to each other by one solar diameter approximately. In this way we will have the opposite limbs of the Sun almost in tangency in the focal plane at the perihelion.

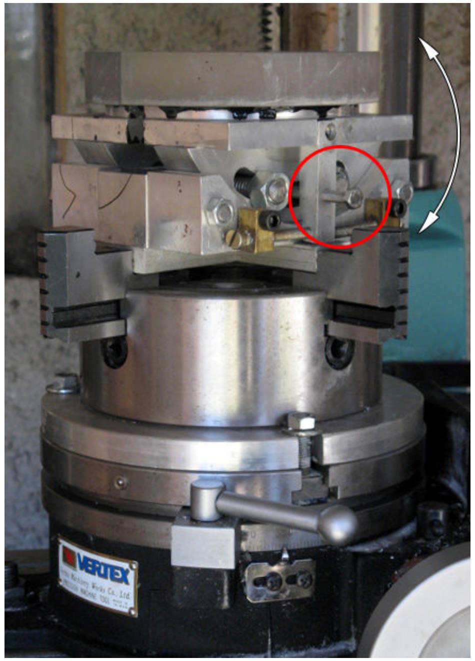


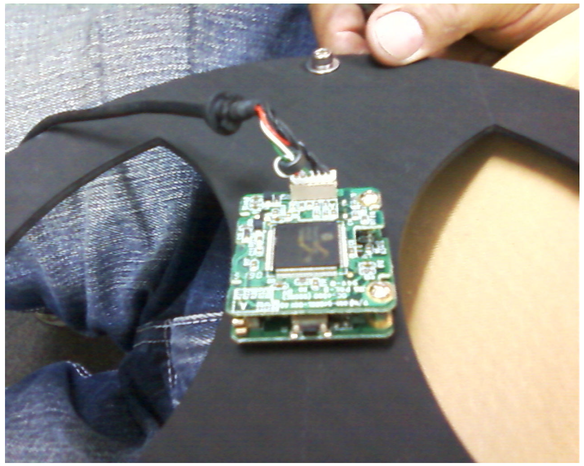
5– The Making of the Heliometer



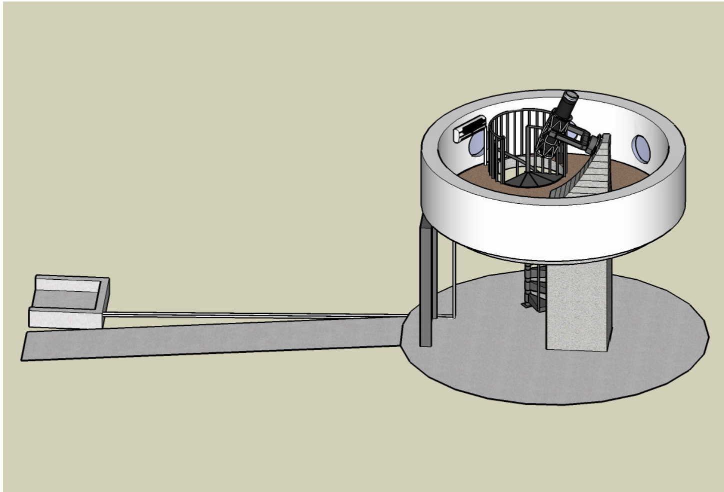


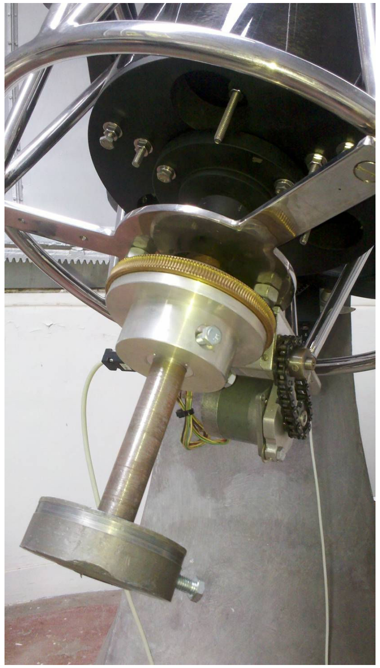




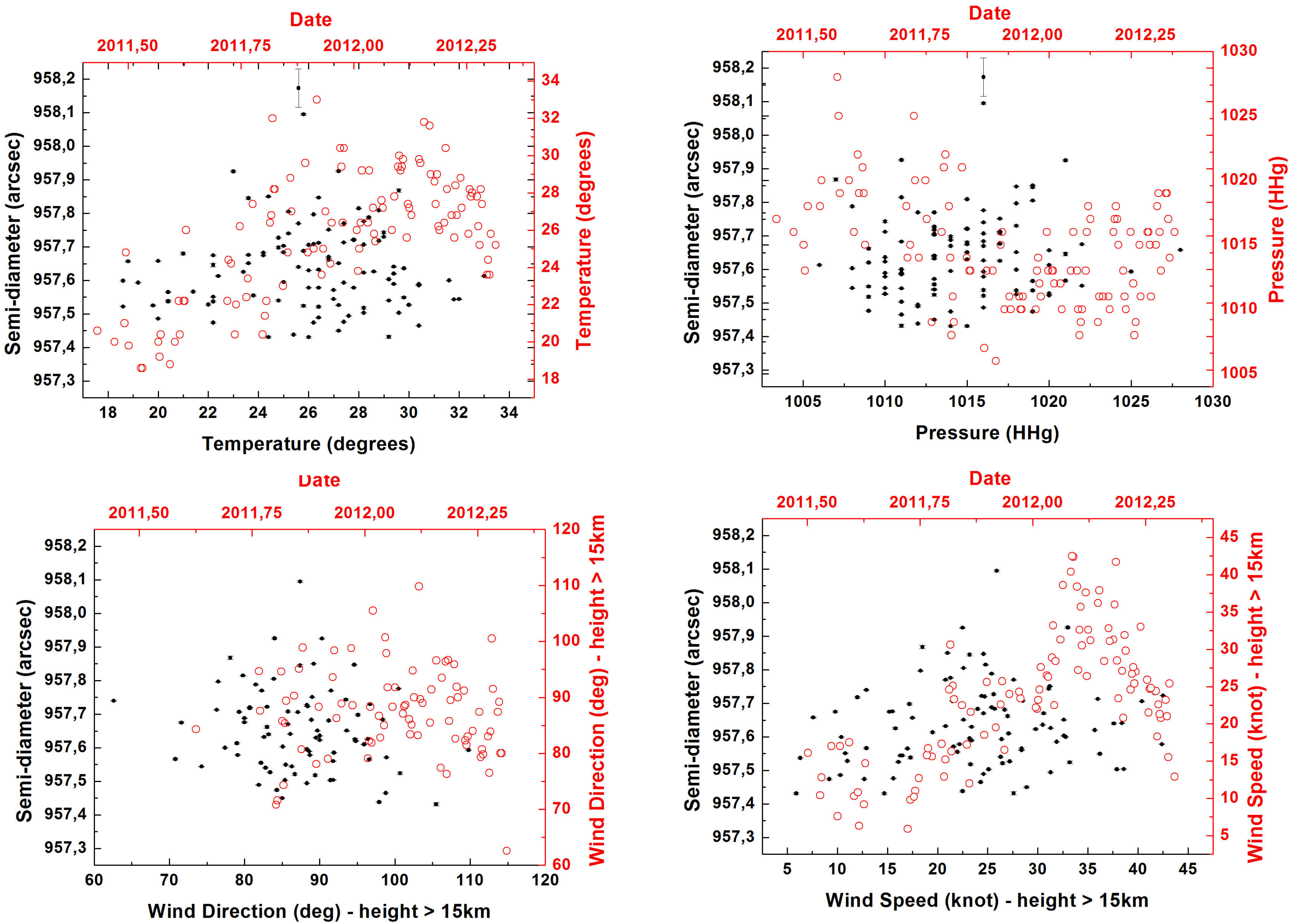


6 – Setting up the Heliometer





7 – No dependence found to meteorological conditions. Nor on response to upper atmosphere/stratosphere conditions



8 – Astrometric Corrections

♣ The usual corrections for Refraction and Annual Parallax follow what is usually done for precision astrometry. And in particular for the treatment of the Solar Astrolabe observations. Their effects are large (~arcsec) but taken care of.

♣ However there are smaller terms which are usually discarded. But that had to be considered for the ~0.01 arcsec Heliometer precision.

♦ **Aberration** – Annual and diurnal effects are opposite for Solar observations. The net effect owes more to the translation velocity. It is given by the difference of two opposite points on the equatorial limb, that is 30arcmin. The maximum correction is **0.04arcsec**.

♦ **Diurnal Parallax** – Maximum effect is when for the Sun in perihelion and observed at lowest (in our case z=50deg). The difference between the geometric and observing distance amounts to a correction of **0.02arcsec**.

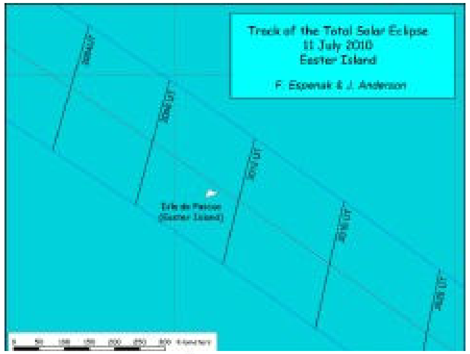
♦ **Diurnal Parallax Hourly Variation** – The variation of the Solar diameter between aphelion and perihelion is of 16.01arcsec, with a quasi-sinusoidal modulation. It hence translates to a maximum hourly correction of **0.05arcsec/hour**.

♦ **Refraction second order terms** – Taking into account the third order terms in the *tan* expansion of the refraction series, and deriving the maximum difference, which refers to a vertical diameter, the correction attains to **0.02arcsec**.

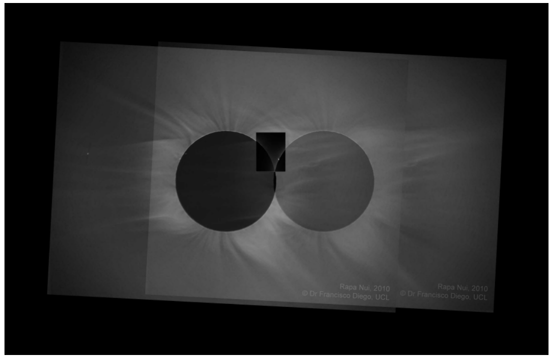
♥ **All these corrections are fully implemented in the program of treatment of the Heliometer mean results.**

9 – A traveling Heliometer

- **Total solar eclipse of 2010 July 11th. Observed from Easter Island.**
- Heliometric and Timing (classical) observation of the diameter, using a modified, transportable heliometer.



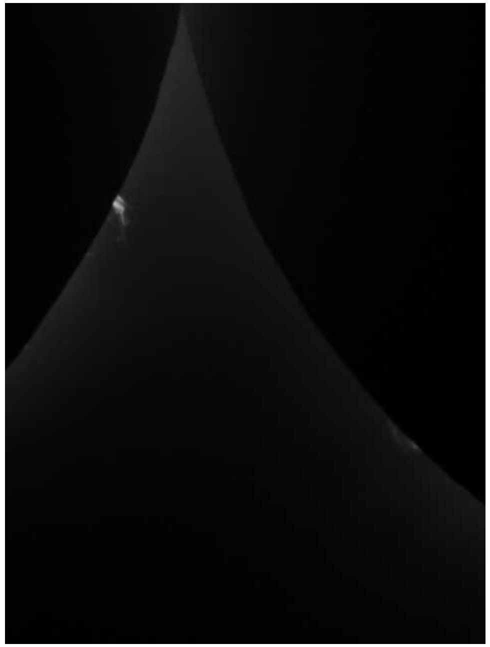
Circumstance	Num. Measurements
July 10th	1,800 pol + 1,200 eqat
before event	2,800 pol + 2,800 eqat
1st contact	360
Intercontact	2,080 pol
2nd contact	360
3rd contact	360
Intercontact	2,080 pol
4th contact	360
after event	2,080 pol + 2,080 eqat
July 12th	360 pol + 360 eqat



seing ~ 2 arcsec

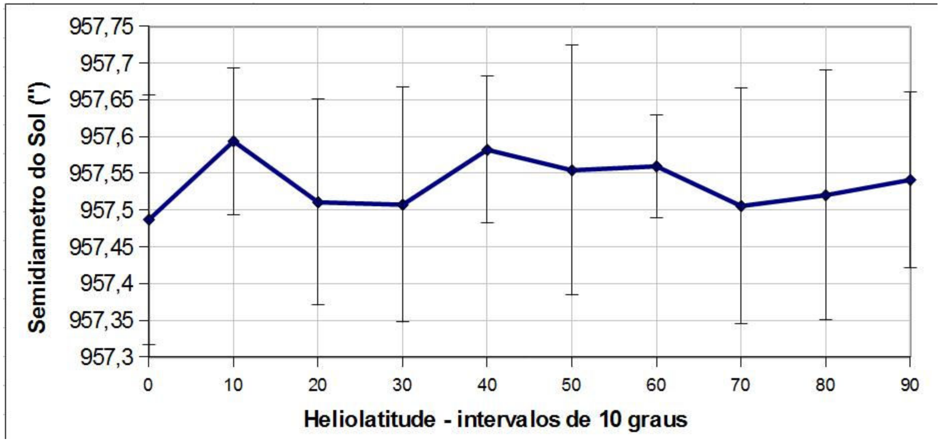
timing = 0.1 msec

precision ~ 13 milli arcsec

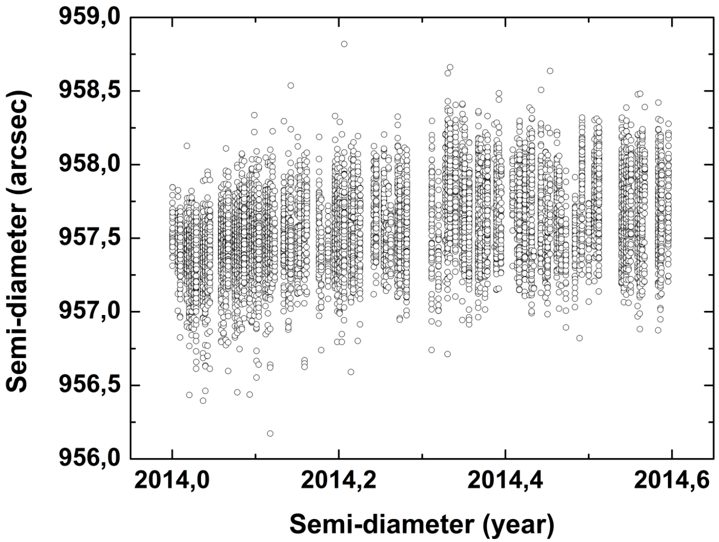


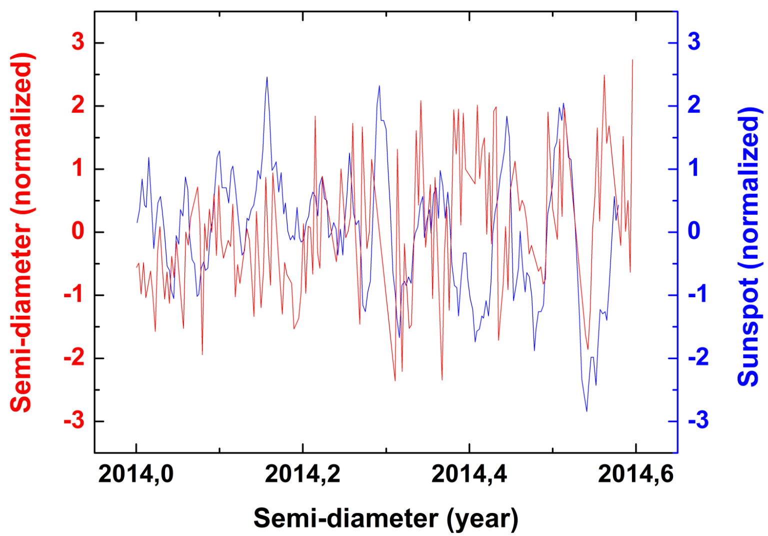
10 – Results from the Heliometer

In the period of zenith transit observations were made at steps of 6° of heliolatitude, to a total of 198 sessions, of 50 measurements each, on 14 days.



Current series and comparison to the sunspot number





YEAR	Semi-diameter (")	Err (")	Num. Obs.
2011 (from July)	957.581	0.004	4.141
2012	957.927	0.004	11.120
2013	958.816	0.005	8.892
2014 (up August)	957.569	0.007	9.883
07/2011 - 07/2014	958.001	0.004	34.036

A double peak for cycle 24 ?