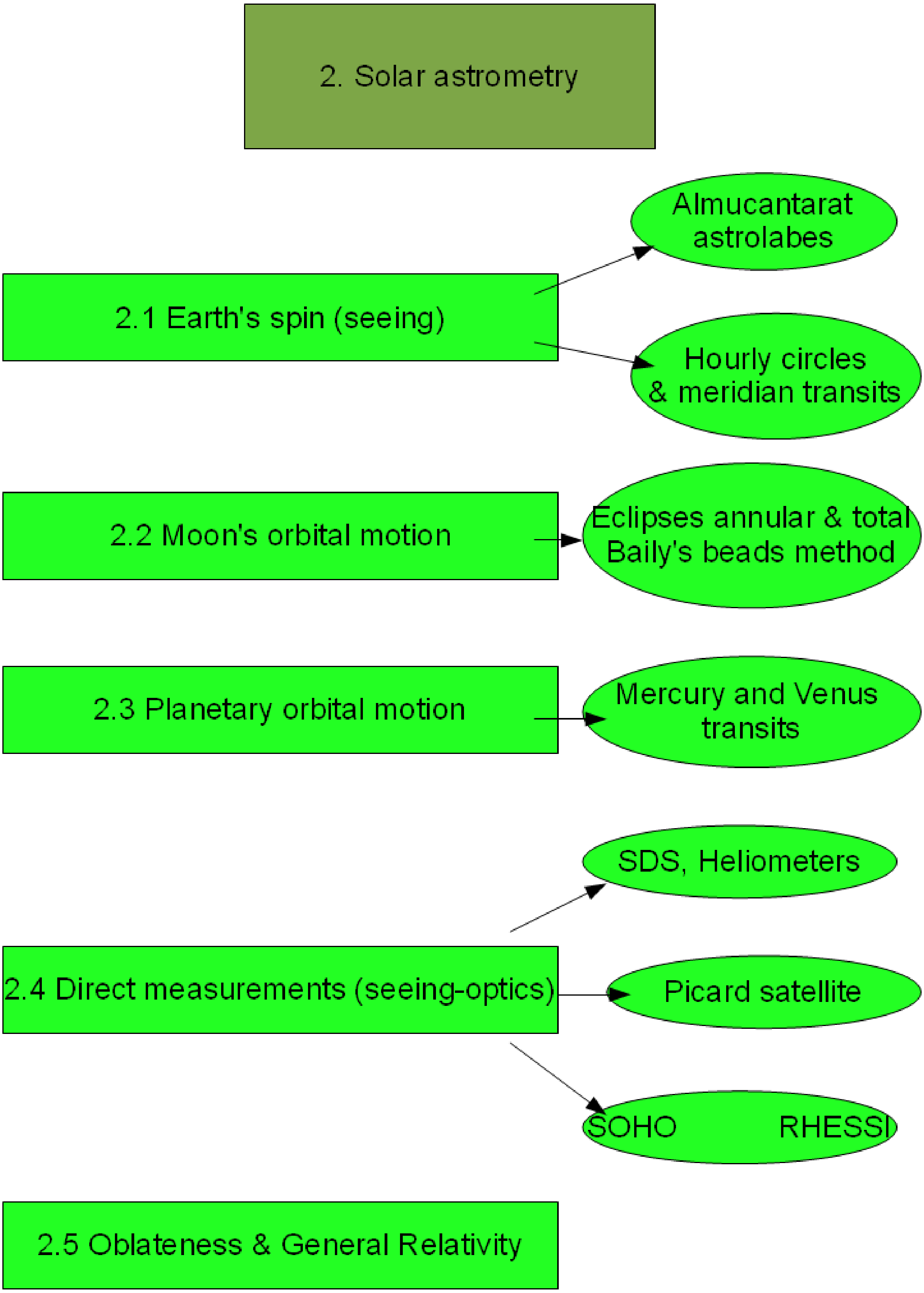
Chapter 2: Solar astrometry



The word "astrometry" is usually related to very accurate (down to the milliarcsecond level) measurement of the positions of the stars. By adding "solar" it is to show that the milliarcsecond level is also a goal for the measurement of the variations of the solar diameter. Solar astrometry is a field of classical astrometry.
The measurement of the diameter of the Sun was firstly started quantitatively by Archimedes before 212 b.C. he published his method in the "Arenarius", the *Sand reckoner*.[1]
Afterwards several methods have been developed, and here I have classified them. We start with the method using a fixed telescope and measuring the drift time of the Sun, due to the diurnal motion, i.e. the rotation of the Earth.

2.1 Earth's spin and seeing problems

These methods exploit Earth's rotation (drift-scan over meridian circles; Danjon solar-type astrolabes).

2.1.1 The solar astrolabes

André Danjon, former director of the Observatoire de Paris, invented an istrument which was called astrolabe,[2] and become later the "impersonal astrolabe". These instruments measure the transits of stars over an almucantarat, an arabic name standing for equal height circle.
The history of the astrolabes and solar diameter has is craddle in France, at the Calern Observatory, where since 1978 Francis Laclare and his colleagues did work with them to measure the solar diameter.
Originally the astrolabe was conceived to recover the position of the stars, the exact timing when a star reached a given altitude.[3] Laclare started in Calern a long series of observations with impersonal astrolabes, and later in 1999, a new type of astrolabe, the "DORaySol", was created.[4] Also in Brasil, at the Observatorio Nacional, in 1983 the astrolabes started to be used for measuring the solar diameter, after their classical use to correct the reference systems.[5]
Due to the inclination of the daily orbit of the Sun, the duration of these transits range from the minimum 1887/15=125.8 s at the equator during equinoxes, to infinty near the time of the meridian transit.
Operational durations of such transits range only up to 6 minutes.
While the standard astrolabes were limited to a few measurements in the morning and in the afternoon, because of the number N of prisms available, DORaySol using a prism movable with springs, had a continuous range of measurements potentially available. DORaySol operated from 1999 to 2006, with the last documented observation in 2008.[6]
At the Observatorio Nacional in Rio de Janeiro, an astrolabe was modified with a "continuous prism" of the same type of DORaySol, and it is still performing measurements according to the project in which there is DORaySol: the R3S2 Réseau de Suivi au Sol du Rayon Solaire, ground-based network of solar radius monitoring.
DORaySol, which is an acronym standing for Definition et Observation du RAYon SOLaire, made up to 2006 about 20000 observations. A similar number, 21640, was attained at the Rio astrolabe from 1998 to 2009.[7]

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1 Sigismondi, C., and P. Oliva, Solar oblateness from Archimedes to Dicke, Il Nuovo Cimento **B 120**, 1181 (2005).
2 Danjon, A., Astronomie Générale, J. & R. Sennac, Paris (1952) ; seconde édition, revue et corrigée, 1959.
3 Débarbat, S., Sur l'extension des applications de l'astrolabe de Danjon, Thèse, Université de Paris (1969).
4 Morand, F., Ch. Delmas, T. Corbard, B. Chauvineau , A. Irbah, M. Fodil and F. Laclare, Comptes Rendus Physique **11** 660 (2010).
5 Penna, J. L., private communication.
6 The observation of october 14 to which I could assist. The experiment was interrupted because of lack of personnel, engaged with priority on Picard-sol set up (Morand, et al, Comptes R. Phys. **11** 660 2010).
7 Boscardin, S. C., UM CICLO DE MEDIDAS DO SEMIDIÂMETRO SOLAR COM ASTROLÁBIO, Ph. D. Thesis, Observatorio Nacional, Rio de Janeiro (2011).

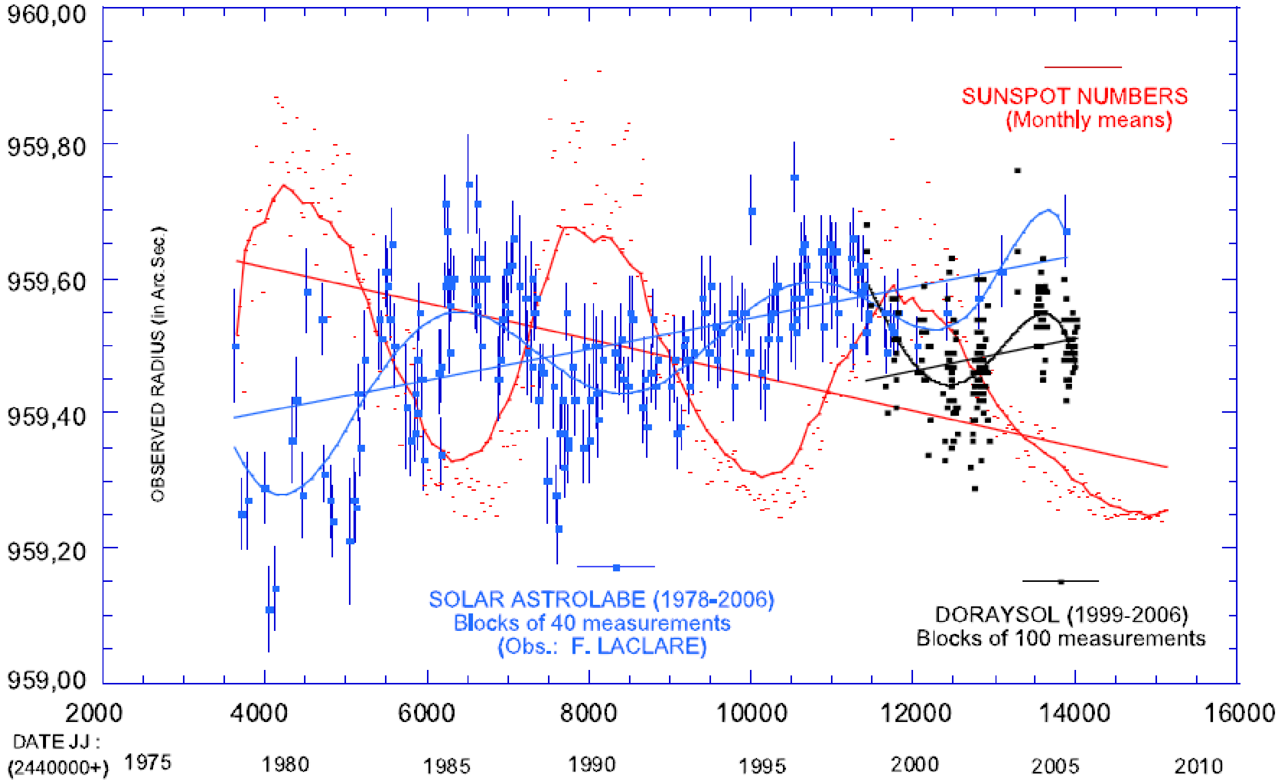

Fig. 2.1 Solar Radius at Calern and magnetic activity (1978-2006) from Morand, et al (2010).

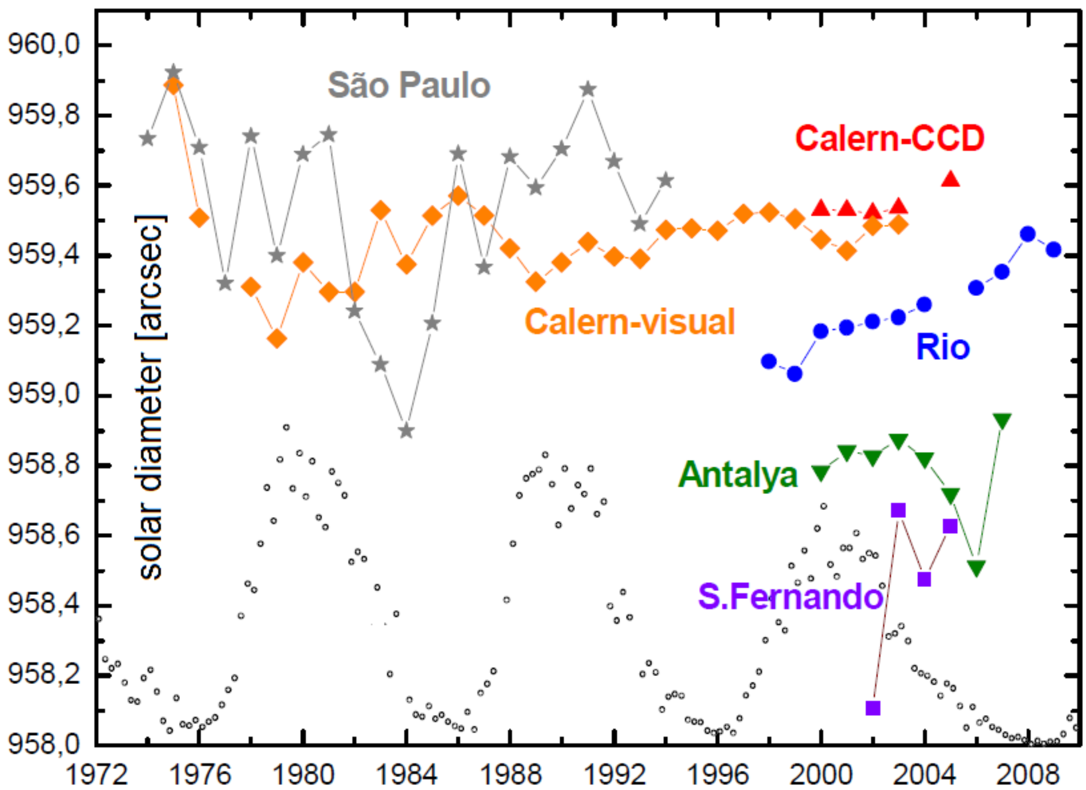

Fig. 2.2 Solar Radius changes as from the R3S2 network. CERGA CCD stands for Calern CCD "impersonal astrolabe", from S. Boscardin (2011).

The difference between the various instruments of the R3S2 network is due essentially to a difference between the filters adopted. The trend in anticorrelation with the solar activity of the variation of the diameter is confirmed.

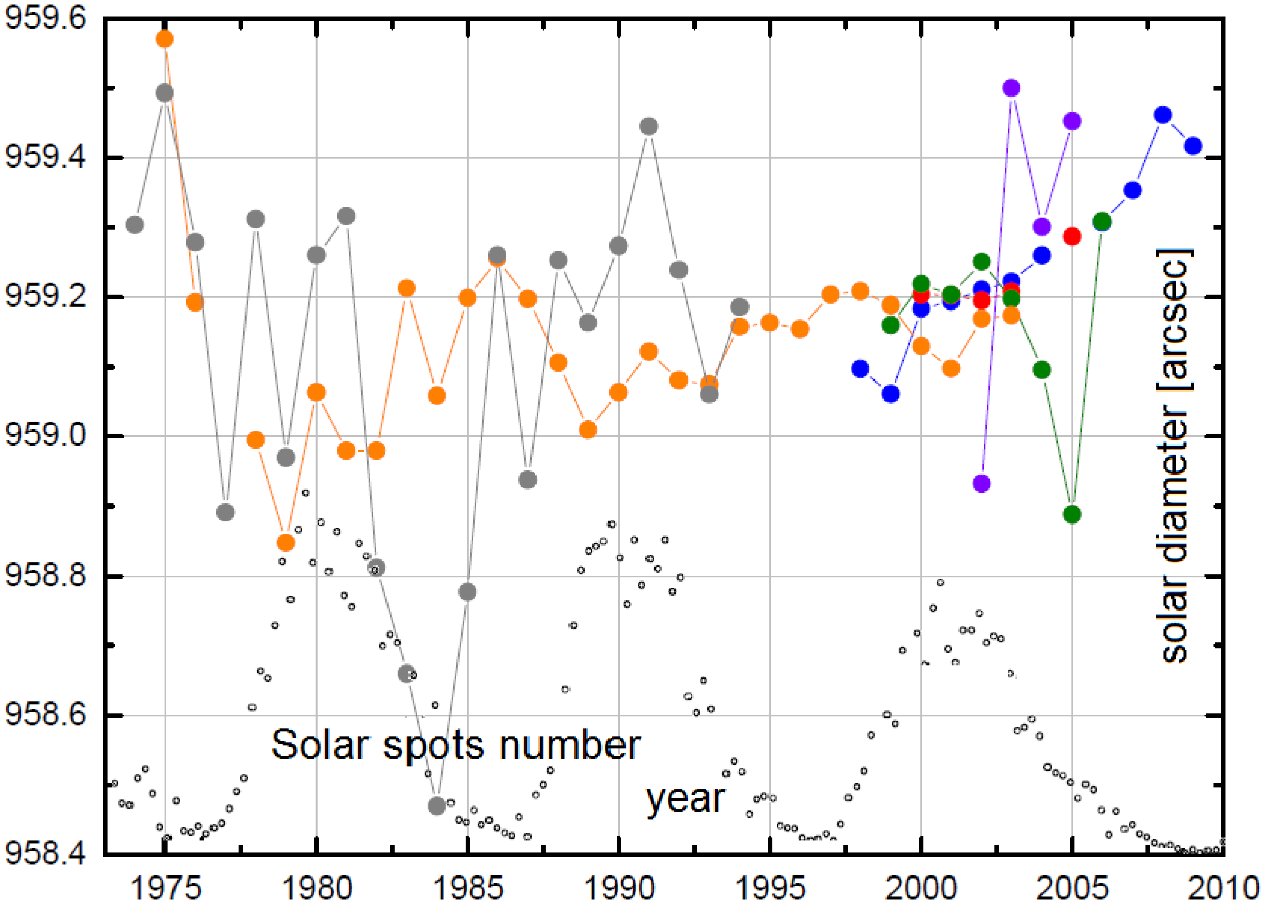

Fig. 2.3 Solar Radius changes of fig 2.2 traslated to the same reference of Rio de Janeiro, from S. Boscardin (2011).

The optical and mechanical scheme of DORaySol is shown in the following figure.[8] The main issue about this instrument is the diameter of the telescope, 11 cm, but since half of the objective is used at time, its point spread function is aymmetric, with the vertical axis more affected than the horizontal one.
The average Fried parameter for DORaySol[9] has been measured as r_0=4 cm, and therefore the instrument aperture is fully exploited with respect to the seeing.
Nevertheless the choice to use big solar telescope, with lenses larger than 33 cm, gives another perspective to these measurements. That happened in the Clavius project, that we will examine later in chapter 4.

[8] – A Cassegrain reflector (110 mm diameter; 3450 mm focal length) is horizontally disposed on a rotating plate, in order to ensure azimuth pointing;
– A varying prism, whose edge has to remain horizontal and perpendicular to the optical axis, ensures the altitude pointing. Associated with the mercury surface materializing the horizon, it allows to image in the focal plane of the telescope the two symmetric components of the Solar edge;
– A CCD camera and its acquisition system reconstruct the Solar edge; they also time its transit through the parallel of altitude. A spectral filter limits the wavelength range at a bandwidth of 60 nm around a central wavelength of 548 nm. A rotating shutter, in front of the telescope, alternately triggers the acquisition of the direct and reflected images of the solar edge;
– A 4.5 density filter and a shield (not sketched here) protect the whole instrument;
– Five computer-driven motors pilot the instrument: rotating plate (azimuth), angle of the prism (altitude) and inclination of the density filter. Accurate controls of the horizontality of the edge of the prism and of the optical axis are achieved.

[9] Fried, D. L. Optical resolution through a randomly inhomogeneous medium for very long an very short exposures, J. Opt. Soc. Am. **56** (1966) 1372–1379. See also: Irbah, A., F. Laclare, J. Borgnino, G. Merlin, Solar diameter measurements with CALERN Observatory Astrolabe and atmospheric turbulence, Solar Phys. **149** (1994) 213–230.

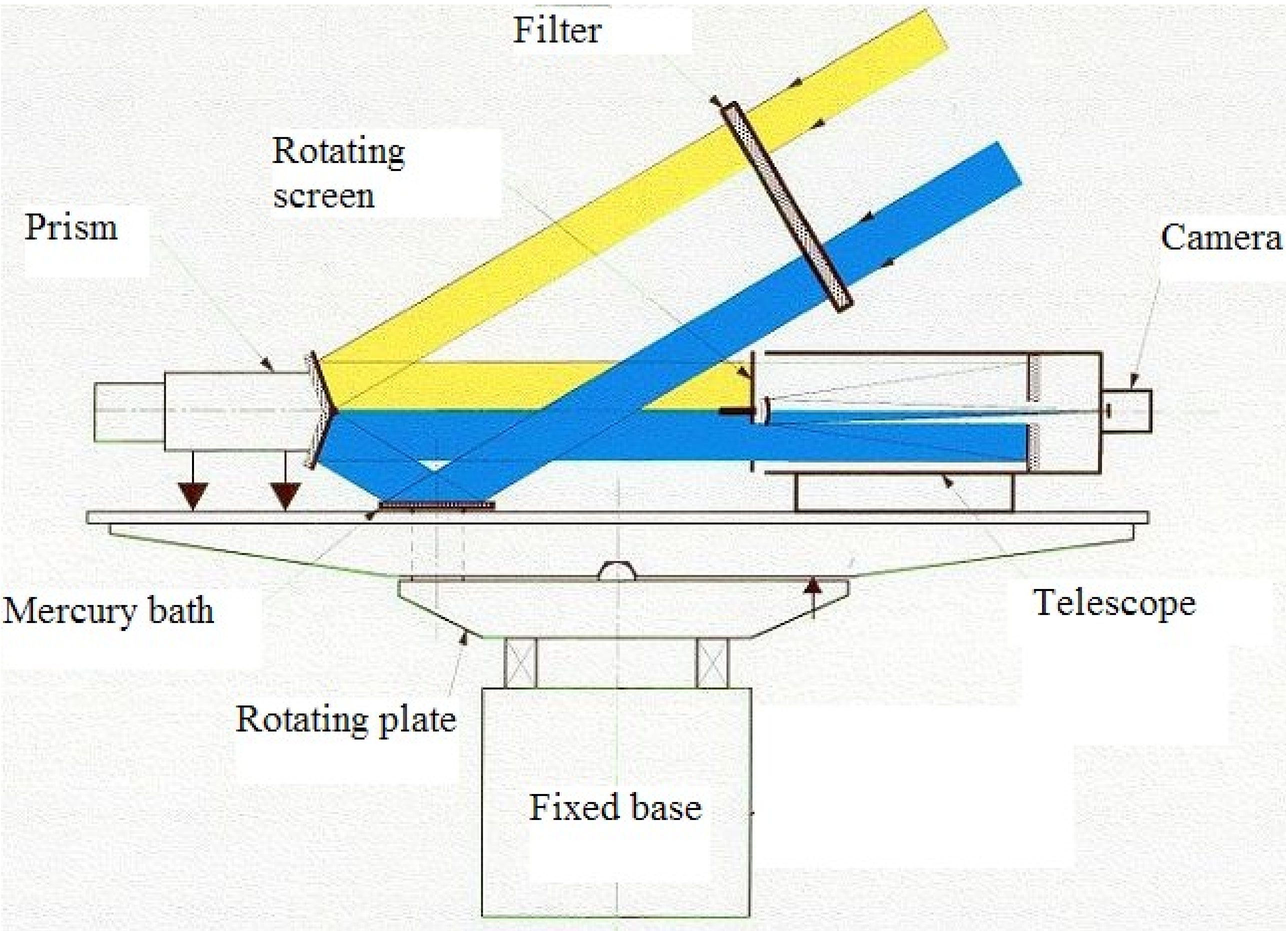

Fig. 2.4 DORaySol optical scheme. The yellow ray is direct the blue one reflected.[10]

The measure of the solar diameter, on different heliolatitudes, made with the astrolabes is not an instantaneous measurement. Up to the first order the refraction at the same altitude is the same, but some density waves in the atmosphere can modify the relative position of the two observed limbs of the Sun. Another advantage of having fixed optics is that the optical defects act like systematic effects, the same for the first and the second limb (admitting that the paths are symmetrical).
A single measurement made with the astrolabe is not significant, only statistical errors can be associated to a series of measurements. Thermal effects and seeing play a crucial role in the interpretation of the data, if the accuracy required is better than one part over 10.000.

The influence of the solar spots on the measurements made at the astrolabe has been debated.
A statistical study shows that the presence of a solar spot at limb may have affected 4.13% of the observations made at the astrolabe of Rio de Janeiro. The influence of a solar spot in the measurement of the solar diameter has been evaluated, with simulations of the software of analysis, less than 0.002 arcsec, even if the probability to have a spot on the solar limb is relevant. [11]
While the effect of the faculae is not relevant, for other scholars[12] the solar spots at the limb can have a significant effect, therefore this aspect requires more attention in the future research.

10 Source: http://www.oca.eu/gemini/equipes/ams/doraysol/index.html
11 Boscardin, S. C., UM CICLO DE MEDIDAS DO SEMIDIÂMETRO SOLAR COM ASTROLÁBIO, Ph. D. Thesis, Observatorio Nacional, Rio de Janeiro (2011), chapter 6.
12 Courcol, B. et S. Koutchmy, Mesures et variations du diamètre solaire, IAP, Paris (2011).

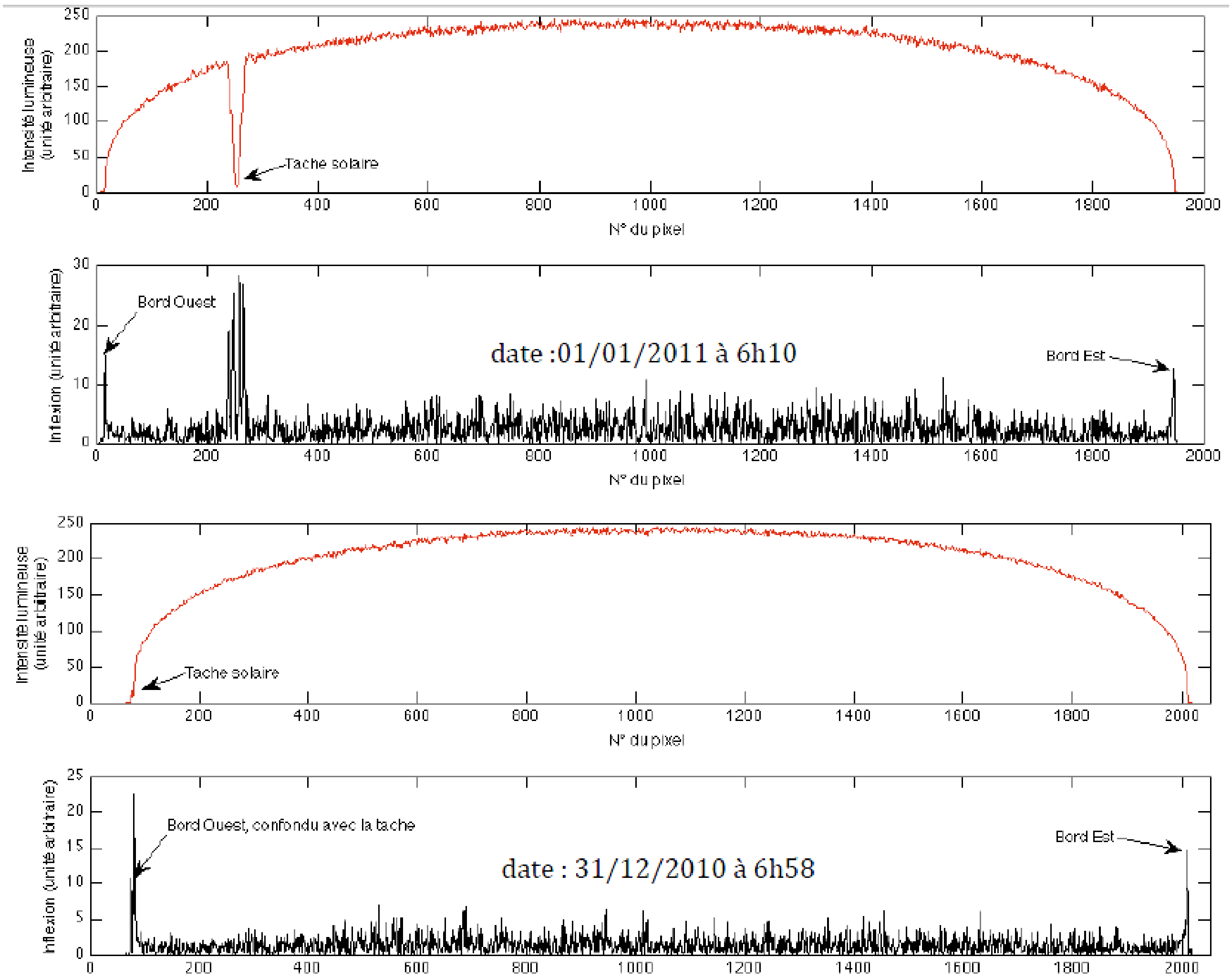

Fig. 2.5 The algorithm of edge finiding in the case of a big spot on the limb between December 31, 2010 and January 1st 2011, gave a difference of 25 arcsec, i. e. 1.7% of variation on the diameter's evaluation.[13] Original images from SDO–HMI[14] experiment.

[13] Courcol, B. et S. Koutchmy, Mesures et variations du diamètre solaire, IAP, Paris (2011). Figure 2 and 3.

[14] http://hmi.stanford.edu/

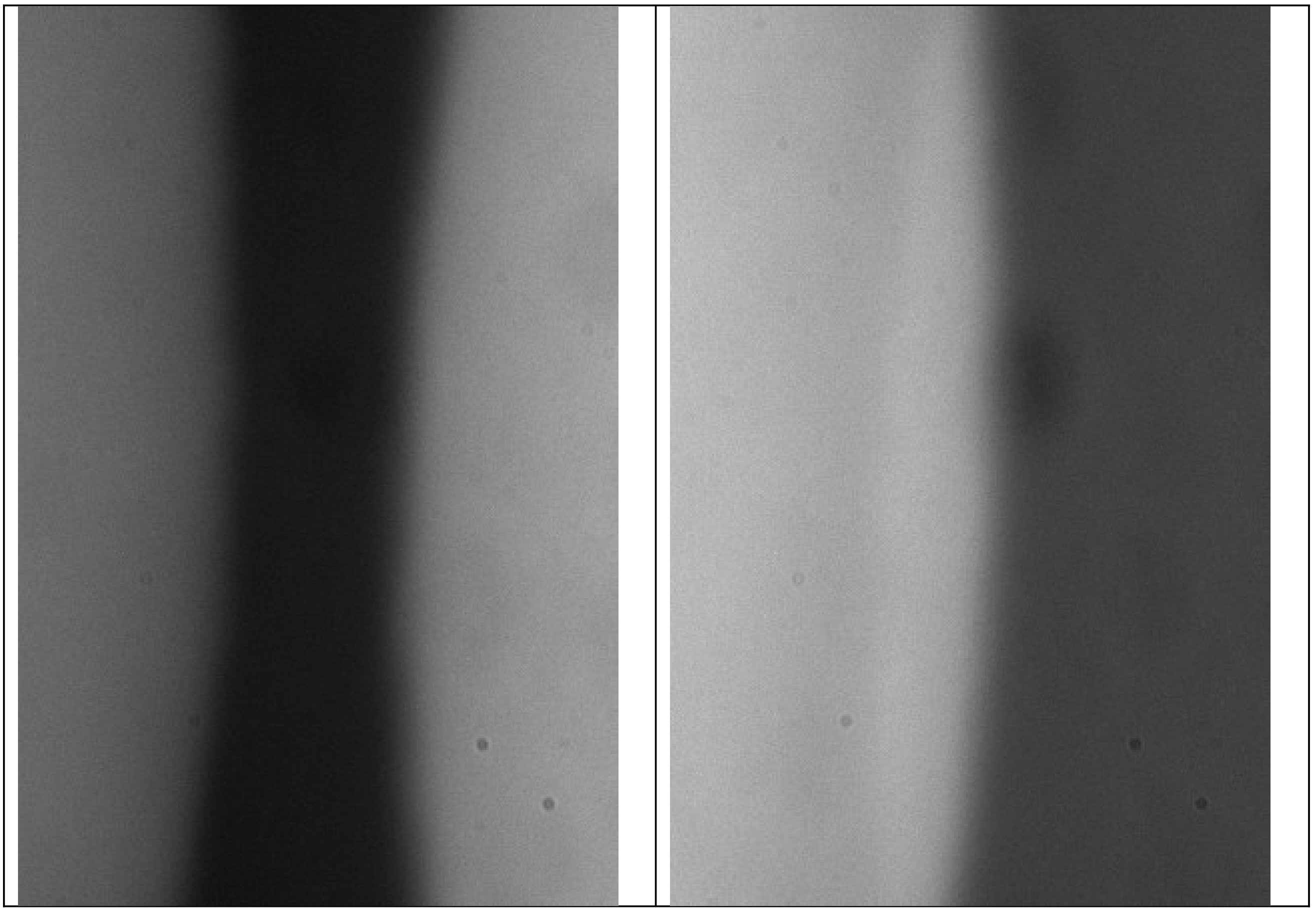

Fig. 2.6 The two images of the solar limb at the Astrolabe of Rio de Janeiro. Observations of March 18, 2011. The image reflected by the bain of mercury is on the left. While in DORaySol there is a shutter which shows alternatively the direct and the reflected image, in Rio the two images superpose, like in this right side image.

Presently only the Astrolabe of Rio is working, and its acquisition system is being renovated, thanks also to my contribution (see paragraph 2.4 on the Heliometer of Rio). It is important that the activity of this instrument could be prolonged during the Picard mission, in order to overlap its data with the space ones, and also with the new heliometers and the eclipses. In this way all the four decades of solar diameters recovered with astrolabes can be used in understanding better the relationship solar radius-activity.

2.1.2 Meridian and hourly circle transits

The measurement of the diameter of the Sun using meridian transits, and later the hourly circles transits, is the method used since the invention of the telescope. The french abbot Jean Picard measured the solar diameter before 1680 with this method. The duration of a transit is typically about 2 minutes.
The largest angular diameter of the Sun is 1952 arcsec on Jan 4, corresponding with the largest declination 23°26′, therefore the maximum duration is about $1952/(15\cdot\cos(\pm 23°26'))= 141.8$ s.
Chapter 4 will be dedicated to this topic more wider, when presenting the CLAVIUS project.

2.2 Lunar orbital motion: eclipses and Baily's beads

The Moon along its orbit covers approximately its diameter in one hour. The duration of a total eclipse is depending on the difference between the angular diameters of the Moon and of the Sun. By timing the totality near the centerline an error of ±1 s corresponds approximately to ±0.5 arcsec in the uncertainty of solar diameter. If the timing is made near both the edges of the umbral path a greater accuracy can be achieved. A variation of Δt=1 in the duration of the totality phase corresponds to a few meters on the ground, and the dimension of the umbra, and then of the solar diameter, can be measured better than one part over 10.000.[15] More details concerning the Baily's beads method are explained in the chapter 3, on the eclipses.

2.3 Planetary orbital motion

The transits of Mercury (about 13 per century) and of Venus (two each 120 years) have an angular speed which covers the solar diameter (generally a chord) in about 6 hours. If the times of the contacts are defined with an accuracy of one second an optimal precision on solar diameter is attained.

Shapiro[16] in 1980 used the historical data on Mercury transit to check the hypothesis of variations of the solar diameter claimed by Eddy and Boornazian[17] and Dunham, et al.[18]

Other works reconsidered the question of the transits of Mercury.[19],[20]

The problem of the ancient data is due to the difference between the instruments utilized. I have presented the comparison between the observations of the transit of Mercury of 1832 made by Bessel and Gambart respectively in Königsberg with the Fraunhofer heliometers of 16 cm and in Marseille with a 7 cm refractor.[21]

The younger and skilled observer Gambart, under perfect meteorological conditions, observed a transit shorter (and therefore a shorter solar diameter) than Bessel. This occurred because the instrument of Gambart was smaller and its point spread function poured many photons into the disk of Mercury. The measurement of the diameter of Mercury, also published by the two observers on the Astronomische Nachricthen in 1833, showed clearly this effect. Gambart measured the diameter of Mercury one arcsecond less than Bessel (6.91", very close to the ephemerides value).

In this direction is also the modern explanation of the famous black drop effect: an interplay between the solar limb darkening function, rapidly varying near the limb, and the point spread function of the telescope.[22]

The method of chords has been applied by me already in 2006, to the data of the Venus' transit of 8 June 2004.[23] The influence of the seeing on the determination of the internal contacts of Venus with the solar photosphere (observed in Halpha by Anthony Ayomamitis in Athens) was evidenced. An uncertainty of ±7 s arose from the morning measurements with the Sun still low in the sky, while it decreased to ±1 s with the Sun at the local noon. The solar diameter calculated from this observation was consistent with Halpha diameter.

The errorbar of 7 seconds could have been reduced if the number of photo would be larger. Ayomamitis made a photo each minute, and only 25 photo per contact were available. Nevertheless this is the only observation of Venus' transit of metrological quality I have found after many years of research on the internet and in various solar observatories in Europe and worldwide. This is rather unbelievable!

I tried to coordinate some observatories (Big bear and Mauna Kea) for the transit of Mercury in 2006, but the meteo and the geometry prevented the measurements of both internal contacts.

Let's see what will happen in 2012 with the next Venus transit.

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15 Sigismondi, C., Measures of Solar Diameter with Eclipses: Data Analysis, Problems and Perspectives, AIPC **1059**, 183 (2008).

16 Shapiro, I. I., Science, **208**, 51 (1980).

17 Eddy, J. A. and Boornazian, A.A., Bulletin of the American Astronomical Society, **12**, 437 (1979).

18 Dunham, D. W., S. Sofia, A. D. Fiala, P. M. Muller and D. Herald, Science **210,** 1243 (1980).

19 Gilliland, R. L., Astrophysical Journal, **248**, 1144 (1981).

20 Parkinson, J. H., L.V. Morrison and F. R. Stephenson, Nature **288**, 548 (1980).

21 Sigismondi, C., AIPC **1059**, 183 (2008).

22 Pasachoff, J. M., G. Schneider, L. Golub, The black-drop effect explained, in Transits of Venus: New Views of the Solar System and Galaxy, Proceedings of IAU Colloquium #196, held 7-11 June, 2004 in Preston, U.K.. Edited by D.W. Kurtz. Cambridge: Cambridge University Press, 242-253 (2004).

23 Sigismondi, C. and P. Oliva, Astronomia UAI, **3**, 14 (2006).

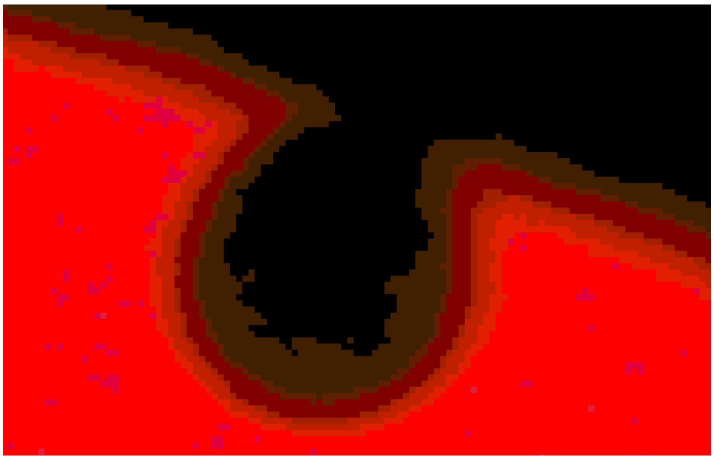

Fig. 2.7 Venus' transit of 2004 in Hα (A. Ayomamitis, 15 cm refractor ingress phase at 7:37:00 Athen's time). The solar radius in Hα was measured as $\Delta R=0.38\pm0.64$ arcsec.

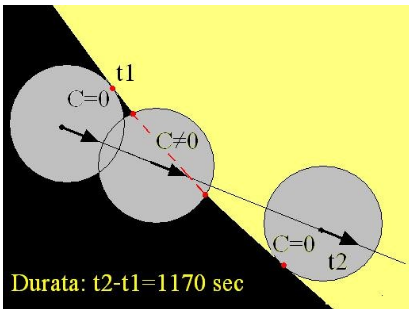

Fig. 2.8 The sketch of chord's method, original figure of G. Di Giovanni.[24]

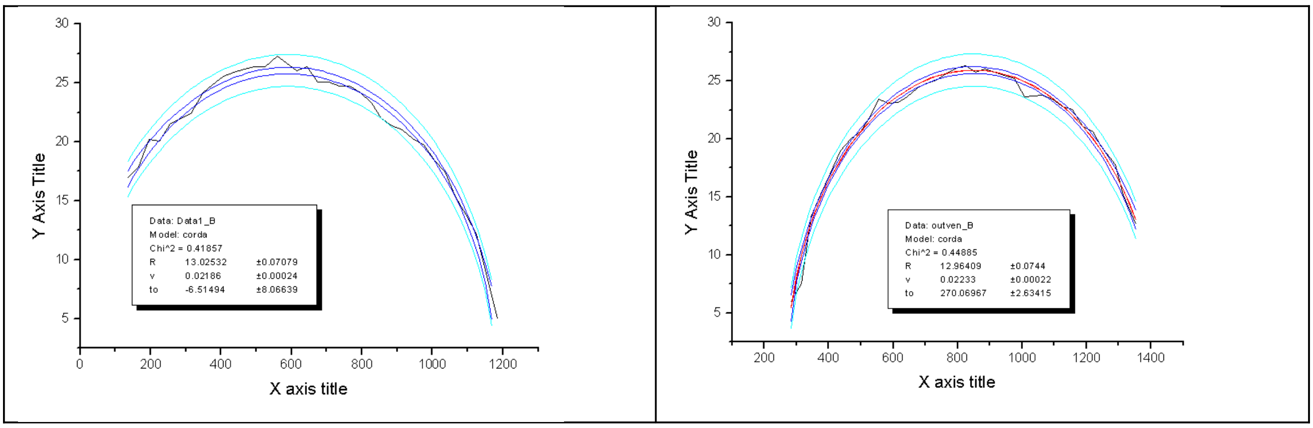

Fig. 2.9 A parabolic fit applied to the length of the chords vs time, is required to find t1 and t2. The ingress is on the left (±8 s of uncertainty because of the seeing), the egress on the right (±2.6 s). The angular velocity of Venus above the Sun was about 0.08 arcsec/s; this corresponds to 0.64 arcsec of uncertainty in the ingress and 0.20 arcsec at the egress.

[24] Di Giovanni, G., Astronomia UAI, **2**, 15 (2005).

2.4 Direct angular measurements

The heliometers deal with the whole figure of the Sun, or with the images of the limbs projected through prisms on the focal plane. The optical defects are crucial up to the milliarcsecond level.

The advantage of these measurements is that they are instantaneous.

At the same time the two opposite limb of the Sun are observed one in front of the other, and from the distance between them the diameter is recovered.

The first application of the divided object-glass and the employment of double images in astronomical measures is due to Servington Savary from Exeter in 1743. Pierre Bouguer, in 1748, originated the true conception of measurement by double image without the auxiliary aid of a filar micrometer, that is by changing the distance between two object-glasses of equal focus. John Dollond, in 1754, combined Savary's idea of the divided object-glass with Bouguer's method of measurement, resulting in the construction of the first really practical heliometers. As far as we can ascertain, Joseph von Fraunhofer, some time not long before 1820, constructed the first heliometer with an achromatic divided object-glass, i.e. the first heliometer of the modern type.[25]

2.4.1 Heliometers

There are various type of heliometers, starting from the lenses splitted in two halves, the classical one, to the Göttingen's type (1890s) with a prism in front of the objective used also in the balloon-borne solar telescope SDS Solar Disk Sextant, to the mirror heliometer and to its recent variant called annular heliometer both invented by V. d'Ávila and developed at the Observatorio Nacional in Rio de Janeiro (2011).

The last two instruments being based on reflecting splitted mirrors have the advantage of no chromatic aberrations, as well as of no optical aberrations.

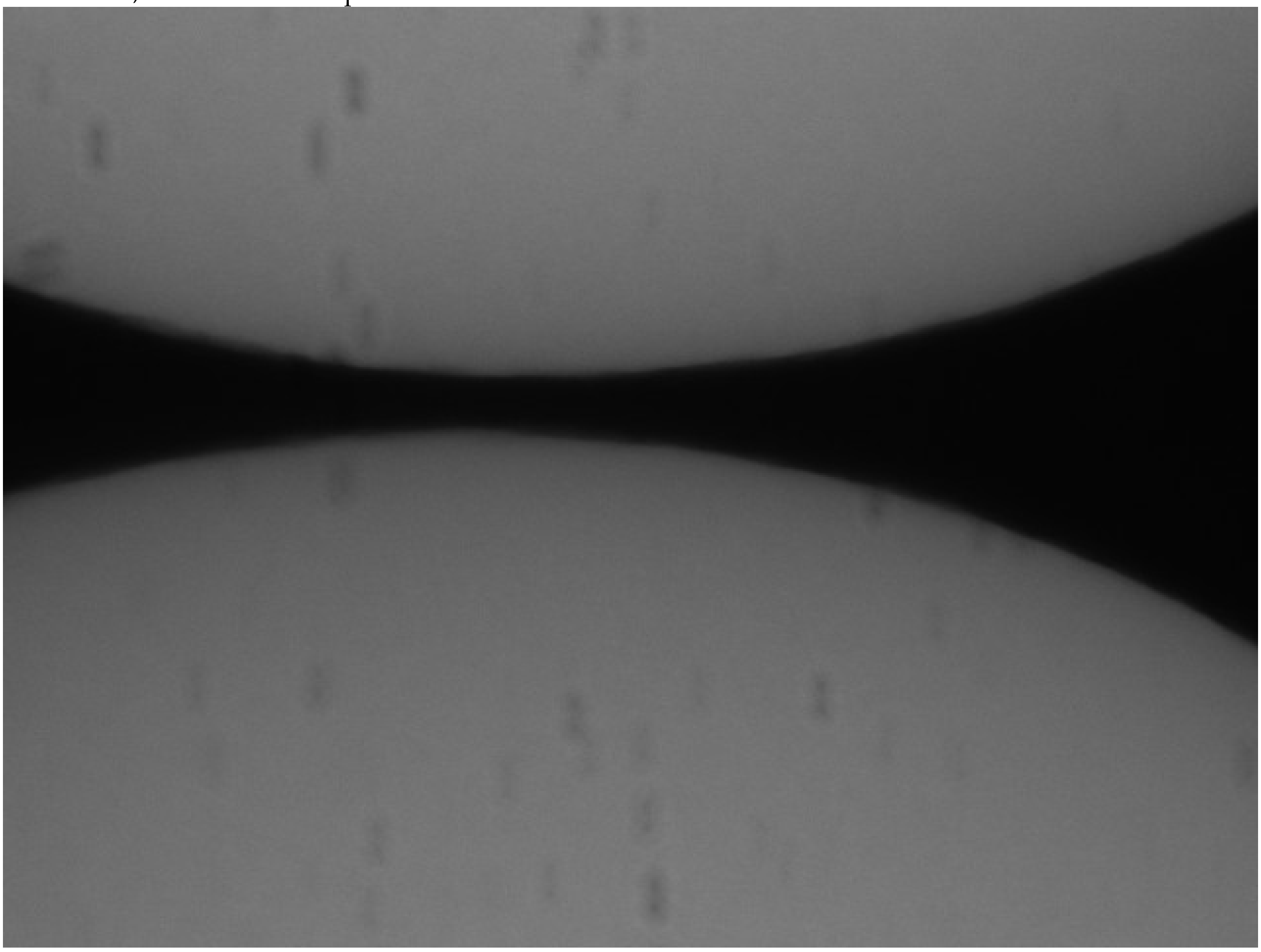

Fig. 2.10 The two limbs of the Sun at the Heliometer of Rio de Janeiro on March 28, 2011.

[25] Chisholm, Hugh, ed. (1911). Encyclopædia Britannica (11th ed.). Cambridge University Press. Volume 13, pp. 224-230.

The heliometer of Rio de Janeiro now performs a series of 100 measures each minute, this increase the number of measurements of solar diameter well beyond the DORaySol-type instruments.
The heliometer of Rio de Janeiro is being calibrated also with the results of diameter's measurements from eclipses. For this purpose it has been transported to the Easter's Island in occasion of the total eclipse of July 11, 2010, and it will observe also the eclipse of May 20, 2012 in southern China.
The software and camera used for the heliometer recognizes the two limbs of the Sun, and calculates the position of the centers, and the radii. The distance d between the two limbs depends on the focal length F of the telescope, on the angle θ between the mirrors and on the angular solar diameter ds". $d=F\cdot \theta - F\cdot ds''$.
F and θ are constant (the temperature is under control in order to keep F constant) and therefore the angular diameter of the Sun is $ds''=d/F-\theta$.
The same software has been adapted to the astrolabe, where the point of contact of the two limbs is crucial.
Therefore the measure of d, and its extrapolation to zero, is the strategy of the new acquisition system of the the Rio Astrolabe. The possibility is offered by the fact that the Rio Astrolabe yields both images, reflected and direct, at the time. I implemented this idea during my stay in the Observatorio Nacional in Rio de Janeiro from February to April and June 2011. In this way the astrolabe will work together with the heliometer during the Picard mission.

2.4.2 MISOLFA

On the same principle, but with the purpose of measuring the parameters of the atmosphere, is the solar monitor MISOLFA[26] (*Moniteur d'Images SOLaires Franco-Algerien*). It is placed in the same dome of SODISM II is devoted to measure the caracteristics of the atmospheric turbulence during the measurements of SODISM II, made in parallel with SODISM instrument onboard of Picard. At the end of the space mission a procedure of accurate measurement from ground with SODISM II and MISOLFA will work routinely.

[26] Irbah, A., M. Meftah , T. Corbard, R. Ikhlef, F. Morand, P. Assus, M. Fodil, M. Lin, E. Ducourt, P. Lesueur, G. Poiet, C. Renaud and M. Rouze, Ground-based solar astrometric measurements during the PICARD mission, submitted to SPIE (2011).

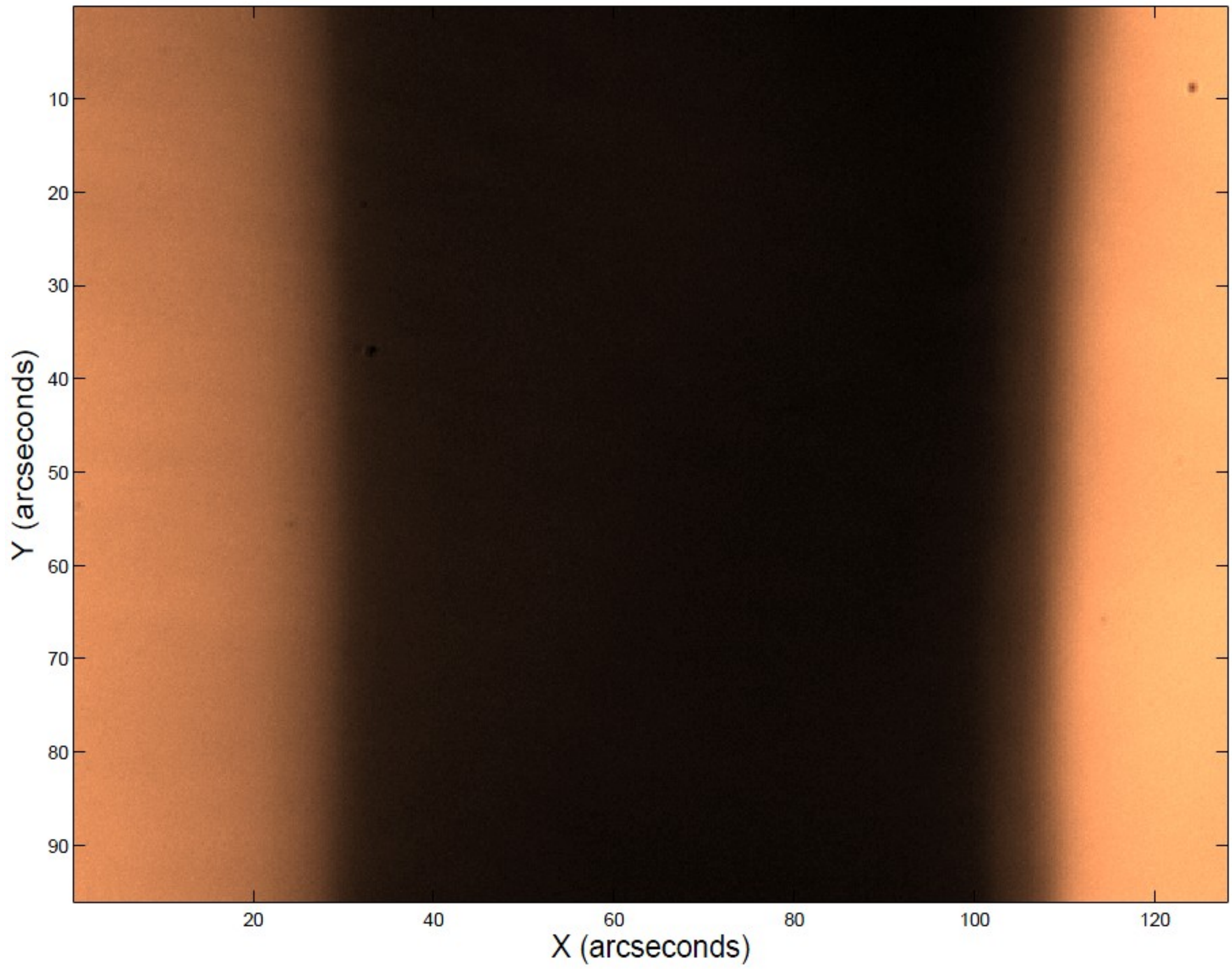

Fig. 2.11 The two limbs of the Sun observed with MISOLFA on August 11, 2011.

2.4.3 SDS, the Solar Disk Sextant

The third instrument of this type, and the first to produce results, has been SDS. The two images of the Sun are projected on the focal plane, where are 7 linear CCDs. These CCDs detect the luminosity profile, and an algorithm individuates the inflexion point.

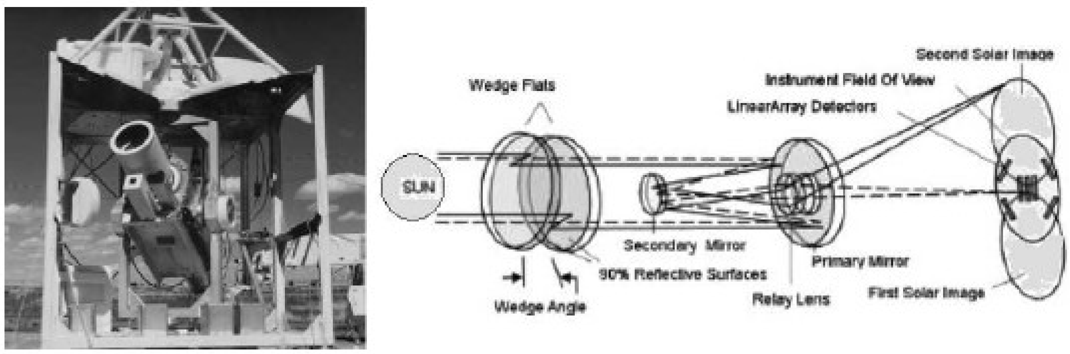

Fig. 2.12 SDS: focal plane scheme.[27]

SDS has made 5 useful flights, 4 of them have been published, with two different analyses,[28] leading to

[27] Chiu, H.Y., Maier, E.,0 Schatten, K. H., Sofia, S. Solar disk sextant optical configuration, Applied Optics, **23**, 1230 (1984).

[28] Egidi, A., B. Caccin, S. Sofia, W. Heaps, W. Hoegy, L. Twigg, High-Precision Measurements of the Solar Diameter

similar trends with a systematic difference between them. The solar diameter increased since 1992, inversely to the magnetic activity. This result is in agreement with the result of the astrolabes.

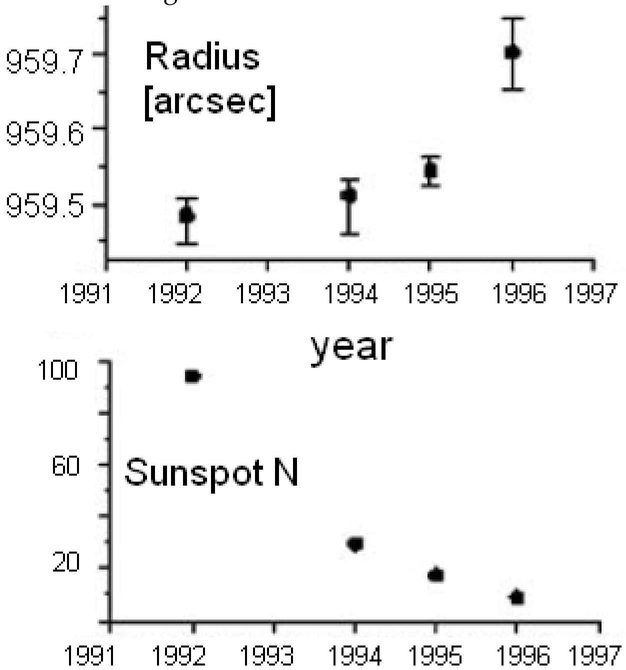

Fig. 2.13 SDS: measurements of solar diameter, from Egidi et al. (2006).

2.4.4 Picard satellite

Picard is a satellite dedicated to the simultaneous measurement of the solar diameter, the solar shape, the solar irradiance and the solar interior. The Picard payload consists in absolute radiometers and photometers measuring the total solar irradiance and in the SODISM instrument which is an imaging telescope developed to determine the diameter, the limb shape and the asphericity of the Sun. The Picard mission has also a ground segment consisting of several instruments based at the Calern observatory. The ground segment is composed with the qualification model of the space instrument, MISOLFA the solar seeing monitor and some others ground-based instruments giving useful data such as the solar irradiance, air temperatures, the wind velocity and directions, the nebulosity etc. The Picard ground-based instruments are installed at the Calern observatory.[29]
SODISM (Solar Diameter Imager and Surface Mapper) is an 11-cm diameter Cassegrain telescope associated with a 2048x2048 pixels CCD detector where the whole SUN is formed. Wavelengths are selected by mean of interference filters placed on 2 wheels. Wavelength domains have been chosen free of Fraunhofer lines (535.7, 607.1 and 782.2 nm). Active regions are detected in the 215 nm domain and the CaII (393.37 nm) line. Helioseismologic observations are performed at 535.7 nm. The satellite platform is stabilized within 36 arcseconds field. The telescope primary mirror stabilizes then the Sun image within 0.2 arc-second using piezoelectric actuators. An internal calibration system composed with 4 prisms, allows to follow scale factor variations induced by instrument deformations resulting from temperature fluctuations in orbit or others causes.[30] This is obtained by processing the 4 corner images formed at 535 nm by the prisms. The diameter measurements are referred to star angular distances by rotating the spacecraft towards some doublet stars several times per year. The instrument stability is assured by use of stable materials (Zerodur for mirrors, Carbon-Carbon and Invar for structure). The whole instrument is temperature stabilized within 1°C. The

and Oblateness by the Solar Disk Sextant (SDS) Experiment, Sol. Phys. 235, 407 (2006).
Djafer, D., G. Thuillier, S. Sofia, A. Egidi, Processing Method Effects on Solar Diameter Measurements: Use of Data Gathered by the Solar Disk Sextant , Sol. Phys. 247, 225 (2008).

[29] Sigismondi, C.,Picard satellite for solar astrometry, Proc. 2nd Galileo-Xu Guangqi Meeting, Ventimiglia - Villa Hanbury, Italy, 11-16 July 2010, also on arXiv:1106.2198 (2011).

[30] Assus, P., A. Irbah, P. Bourget, T. Corbard and the PICARD team, *Astron. Nachr.*, 329, No. 5, 517 - 520, 2008.

CCD is also temperature stabilized around -7°C within 0.2°C. In order to limit the solar energy, a window is set at the telescope entrance limiting the input to 5% of the total solar irradiance. No significant ageing has been measured in laboratory for all the duration of the mission.[31]
Picard satellite has been launched on June 15, 2010. The analysis of the first data is still ongoing at October 1st, 2011.

2.4.5 SOHO

SOHO MDI has been used for determining the solar diameter,[32] even if its configuration is not optimized for this purpose. The value of the solar diameter has been constant within 0.05 arcsec according to the last analysis, around the standard value of 959.63 arcsec,[33] but the calibration of the instrument was made using the Mercury transit of 2003,[34] and the solar diameter was consistent, 959.25 arcsec[35] (ΔR=-0.38 arcsec) with the one measured during 2006 total eclipse where ΔR=-0.41 arcsec.[36] Since the first publication[37] the authors claim to have fully under control the systematic errors as ageing processes of the detector and temperature forcing, but the accuracy of their result (0.01 arcsec) is two order of magnitude below the systematic errors. For this reason and for their calibration made with the Mercury transit (which disconfirm the thesis of Sun radius close to the standard one) I take these conclusions with care.

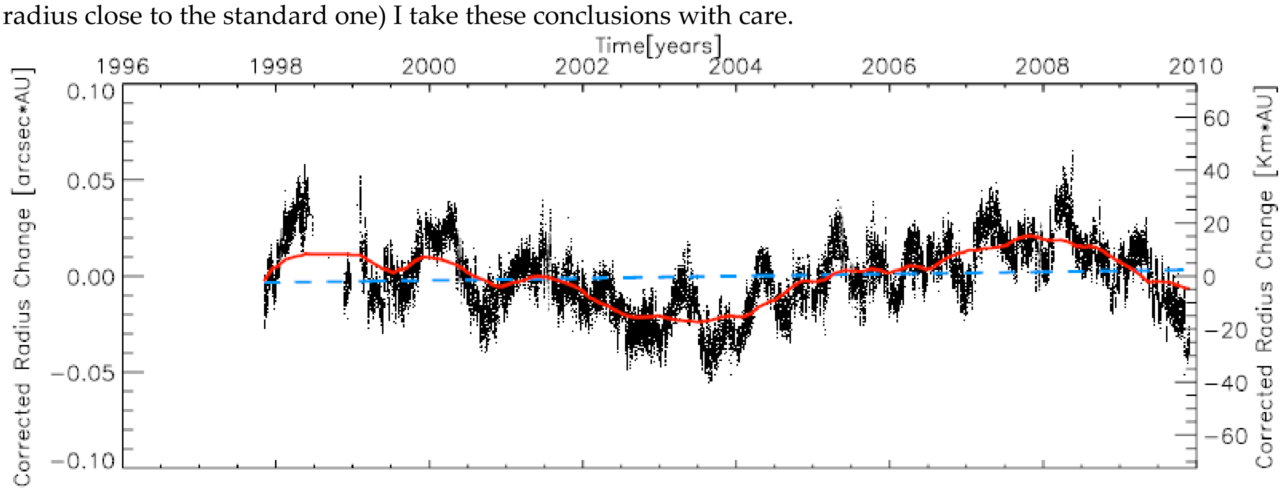

Fig. 2.14 SOHO MDI measurements of solar diameter (version 2010). Here the anticorrelation seen with the astrolabes between solar spots and radius would disappear.

2.4.6 RHESSI

RHESSI is a satellite devoted to the study of solar flares. RHESSI is a solar X-ray/γ-ray observatory, and the astrometric data come serendipitously from the Solar Aspect Sensor. The RHESSI measurement essentially follows Dicke's[38] method of using a rapidly rotating telescope to control systematic errors. The Solar Aspect Sensor consists of three independent optical systems, each with a simple lens (4 cm diameter) mounted on the front tray of the RHESSI modulation collimators, and a linear CCD sensor mounted on the rear tray at a separation of 1.55 m. The 2048-element CCD pixels are 1.73 inches square, and the observing wavelength is a 12-nm bandpass at 670 nm wavelength. The telemetry provides frequent samples (16/s) of each of the six

[31] Irbah, A., et al., Ground-based solar astrometric measurements during the PICARD mission, submitted to SPIE (2011).
[32] Bush, R. I., M. Emilio and J. R. Kuhn, On the Constancy of the Solar Radius. III, Astrophys. J., **716**, 1381 (2010).
[33] Auwers, A.: Der Sonnendurchmesser und der Venusdurchmesser nach den Beobachtungen an den Heliometern der deutschen Venus-Expeditionen. Astronomische Nachrichten, **128**, 361 (1891).
[34] Kuhn, J. R., R. I Bush, M. Emilio, and P. H. Scherrer, On the Constancy of the Solar Radius. II Astrophys. J., **613**, 1241 (2004).
[35] i.e. ΔR=-0.38 arcsec with respect to the standard angular solar radius at 1 AU 959.63 arcsec.
[36] Kilcik, A., C. Sigismondi, J. P. Rozelot and K. Guhl, Solar Phys. **257**, 237 (2009).
[37] Kuhn, J. R., R. I Bush, M. Emilio, and P. H. Scherrer, On the Constancy of the Solar Radius. Astrophys. J., **543**, 1007 (2000).
[38] Dicke, R. H. and M. Goldenberg, Phys. Rev. Lett. **18**, 313 (1967).

limb intercepts in nominal pointing conditions, plus full CCD images at a slower cadence (1/min).
The solar oblateness (equator-pole radius difference) are determined from the axisymmetric quadrupole term of the Fourier components of the limb position given by the RHESSI data. The radius measurements are numerous, telemetered at about 100 samples/s, and are distributed approximately uniformly in azimuth around the limb.
Sunspots (negative excursions) and active-region faculae (positive excursions) produce obvious effects.

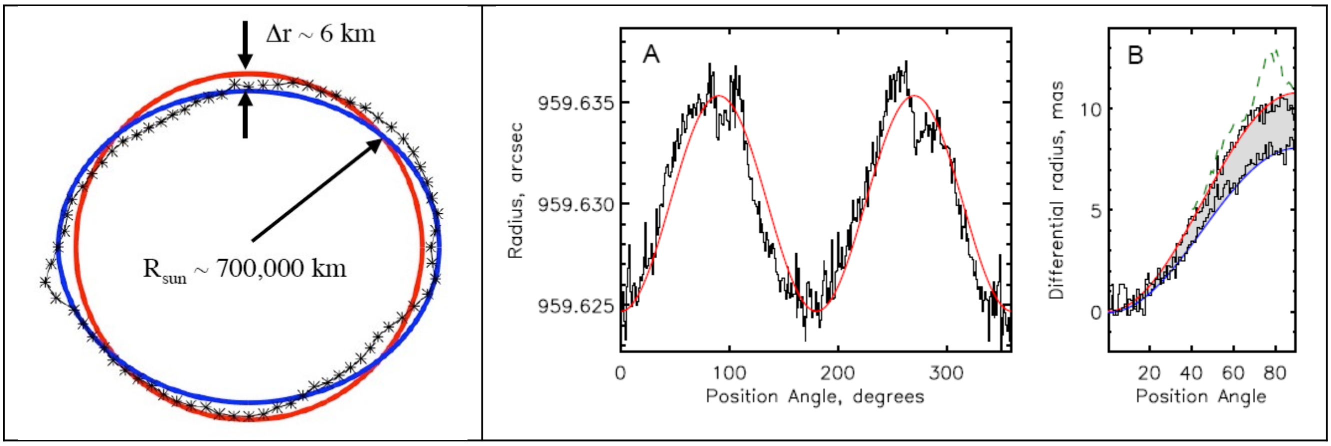

Fig. 2.15 RHESSI measurement of the solar figure: the normalization has been done with respect to the standard solar radius. From 2002 to 2007 the oblateness of the Sun is slightly larger (10.74 ± 0.44 mas) than the one (8.7 mas) due to the rotation of the Sun, because of magnetic activity.[39]

2.5 Oblateness and General Relativity connection

A slightly oblate Sun was suggested to explain the precession of the perihelion of Mercury. Therefore accurate measurements of solar oblateness were carried out by Dicke (1960-70s), Sofia (SDS 1990s) and now using the RHESSI satellite, to assess classical contributions to this anomalous precession. The required accuracy of these measurements is below one part over 10000, the same order of magnitude of expected solar diameter variability.
To this topic I have published two papers[40], [41].

[39] Fivian, M. D., H. S. Hudson, R. P. Lin, H. J. Zahid, Science **322**, 560 (2008).
[40] Sigismondi, C., Il Nuovo Cimento B, **120**, 1169 (2005).
[41] Sigismondi, C., Relativistic Implications of Solar Astrometry, http://arxiv.org/abs/1106.2202v1 (2011).