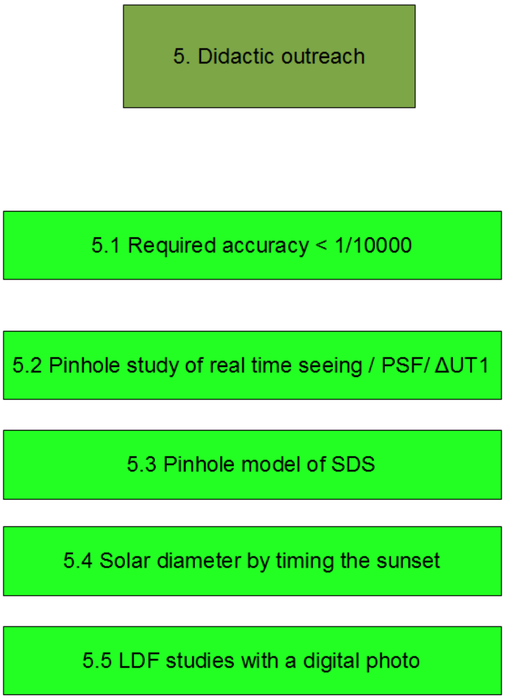
5 Didactic Outreach



5.1 Required accuracy < 1/10000

The statement on human energy output versus solar input is "1 year of humankind energuy production corresponds to 1 hour of Sun". This is the starting discussion of a series of units on solar astrometry, in order to motivate this study in a framework of climate studies.

Knowing the evolution of our star, and therefore of its diameter, up to 1 part over 10.000 is necessary if we want to understand really the problems of global warming and climate changes.

The first thing on which to reflect is the intrinsic difficulty to obtain such a precision even in measuring a rod of 1 meter. The accuracy required is 0.1 mm, already out of the possibility of the unaided eye.

5.2 Pinhole studies of real time seeing, PSF and ΔUT1

A pinhole is a "lens-less telescope", completely free from spherical aberration and perfectly suitable for astrometric studies of the Sun. It has been exploited since 1475 (Ulugh Begh, 1437, measured only solar declination and not diameter) by Paolo Toscanelli for giant pinhole telescope built in Florence's Cathedral as pinhole camera. With the one in Roma, Santa Maria degli Angeli (the Clementine gnomon of 1702) I have demonstrated its extraordinary accuracy down to one arcsecond for all the range of solar declinations, and the possibility to be used for monitoring the ΔUT1 evolution.

The observation of the Sun with a pinhole in order to check the first and the second Kepler's law has been realized for high school students. The settling of the experiment in order to minimize the errors of measure has permitted to verify the Rayleigh formula for obtaining sharpest images given the diameter of the pinhole.[1]

Pope Clement XI (1700-1721) ordered Francesco Bianchini (1662-1729) to build a Meridian Line. Bianchini was the Secretary of the Commission for the Calendar. He chose the Basilica of Santa Maria because of the stability over centuries of the ancient walls where the pinhole is located is a requirement for making high precision astrometry, such as the measurement of the inclination of the Earth axis over its orbit plan. In the 18th century it was possible to open the window holding the southern pinhole, and, even in daylight, stellar transits were recorded and precisely timed with pendulum mechanical clocks. The accuracy of such clocks was better than 1 s per day, and the observations of stellar transits allowed their synchronization with sidereal time. This "hybrid feature" of the Clementine Gnomon to measure solar and stellar transits allowed Bianchini to accomplish in 1703 the whole measurement of the duration of the tropical year, which was usually made by comparing observations very widely spread in time. The small deviation of the Line from true North of ~ 4'28.8 arcsec Eastwards[2] has been measured comparing the delays of transits at both solstices with respect to the ephemerides.[3]

The Clementine Gnomon is basically a solar meridian telescope dedicated to solar astrometry operating as a giant pinhole dark camera, being the basilica of Santa Maria degli Angeli the dark room. The solar images produced on the floor of the Basilica are free from distortions, excepted atmospheric refraction, because the pinhole is opticsless.

Similar historical instruments are in Florence (Duomo, by Toscanelli and Ximenes), Bologna (San Petronio, by Cassini), Milan (Duomo, by De Cesaris) and Palermo (Cathedral, by Piazzi). The azimut of the Clementine Gnomon has been recently referenced with respect to the celestial North pole, and it is 4' 28.8±0.6 arcsec, a comparison with similar coeval instruments is presented. Also the local deviations from a perfect line are known with an accuracy better than 0.5 mm. With these calibration data we used the Gnomon to measure the delay of the solar meridian transit with respect to the time calculated by the ephemerides (ΔUT1). The growth of this astronomical parameter is compensated by the insertion of a leap second ad the end of the year in order to keep the Universal Time close to astronomical phenomena within less than a whole second. On December 31, 2008 at 23:59:59 there is one of those leap seconds leading to 23:59:60 before the new year's midnight 00:00:00, being ΔUT1~0.7 s at that date. ΔUT1 has been measured with an accuracy of ±0.3 s.[4]

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[1] Sigismondi, C., Introduction to pinhole astronomy, Proc. of "Einstein 120" conference, Bishkek, Kyrgyzsthan, 12 September 1999, V. Gurovich ed., Kyrgyz State University, Bishkek (2000) also on arXiv:1107.0820v1 (2011).
Sigismondi, C. and L. Cesario, Solar Astrometry with Pinholes, Effective Teaching and Learning of Astronomy, 25th meeting of the IAU, Special Session 4, 24-25 July, 2003 in Sydney, Australia, meeting abstract (2003).
[2] see figure 0.2 in Chapter 0.
[3] Sigismondi, C., Astronomy in the Church: the Clementine Sundial in Santa Maria degli Angeli, Rome, Il Cigno GG Editor, Roma - Italy (2009), also on arXiv:1106.2976v1 (2011).
Sigismondi, C., Lo Gnomone Clementino: Astronomia Meridiana in Chiesa dal '700 ad oggi, Astronomia UAI **3** 56 (2011) also on arXiv:1106.2498 (2011).
Subjects: Instrumentation and Methods for Astrophysics (astro-ph.IM); History and Philosophy of Physics (physics.hist-ph)
[4] Sigismondi, C., Misura del ritardo accumulato dalla rotazione terrestre, DUT1, alla meridiana clementina della Basilica di Santa Maria degli Angeli in Roma,in "Mensura Caeli" Territorio, citta', architetture, strumenti, a cura di M. Incerti, p. 240-248, UnifePress, Ferrara, (2010).
Cite as: arXiv:1109.3558v1

Using an evenly spaced grid at the focal plane in a drift-scan method gives the opportunity to have several diameters in a single transit[5] and it can be used for measuring the seeing in real time.[6]
A pinhole camera has the advantage of undistorted field of view. Its imaging capability is limited by random (diffraction and atmospheric seeing) and systematic (penumbra) effects. The Pinhole Solar Monitor, PSM, measures the solar angular diameter by timing meridian transits. Meridian transits have been videorecorded with UTC synchronization at the pinhole gnomon of Santa Maria degli Angeli church in Rome. The taratures of this Clementine Gnomon is outlined with its accuracy as PSM. On the Moon an array of such PSM equipped with 1000 lines for parallel transits can monitor 0.1 arcsec variations of solar diameter.
This apparatus was called Pinhole Solar Monitor.[7] Students already have videocameras, and they are ready to start solar astronomy experiments.

5.3 Pinhole model of the Solar Disk Sextant

A flat mirror projects sunlight onto a framed pinhole. The pinhole produces the solar disk's image of diameter Di on a screen parallel to the frame posed at focal distance f better in a room. For an ideal point-like pinhole the angular solar diameter is tan(D)=Di/f and can be measured:

1. like Kepler comparing the disk with pre-drawn disks of known diameter;
2. measuring Di on the image (possible errors: identifying the true diameter among chords; problems due to the motion of the image; limb darkening);
3. timing the passage of the disk perpendicularly to a profile posed before the screen (error sources: not perpendicular path; uncertainty on the limb's contact times).
4. Using two equal pinholes built on the same frame at distance d between centers measuring the focal fc where the disks are in contact; tan(D)=d/fc (main error source: fc uncertainty).

All methods have to deal with systematic errors due to diffraction and to the finite opening of the pinhole.
They are experiments with easy to find and low cost material good to make indoor demonstrations offering to students different levels of complexity in setup strategies and data analysis.

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[5] Sigismondi, C., Pinhole Solar Monitor tests in the Basilica of Santa Maria degli Angeli in Rome, Solar Activity and its Magnetic Origin, Proceedings of the 233rd Symposium of the International Astronomical Union held in Cairo, Egypt, March 31 - April 4, 2006, Edited by Volker Bothmer; Ahmed Abdel Hady. Cambridge: Cambridge University Press, pp.521-522 (2006).
[6] Sigismondi, C., Daytime Seeing and Solar Limb Positions, IAGA-II Proceedings, Cairo University Press Luc Damé and Ahmed Hady (eds.) p. 207-212 (2010), also on arXiv:1106.2539
Sigismondi, C., Misure quantitative del seeing atmosferico, Proceedings of the 42nd UAI congress, Padova - Italy, 24-27 September 2009, to appear in Astronomia UAI, also on arXiv:1106.2520
[7] Sigismondi, C. and C. Contento, Pinhole Solar Monitor to Detect 0.01"RADIUS Variations, Solar and Solar-Like Oscillations: Insights and Challenges for the Sun and Stars, 25th meeting of the IAU, Joint Discussion 12, 18 July 2003, Sydney, Australia (2003).

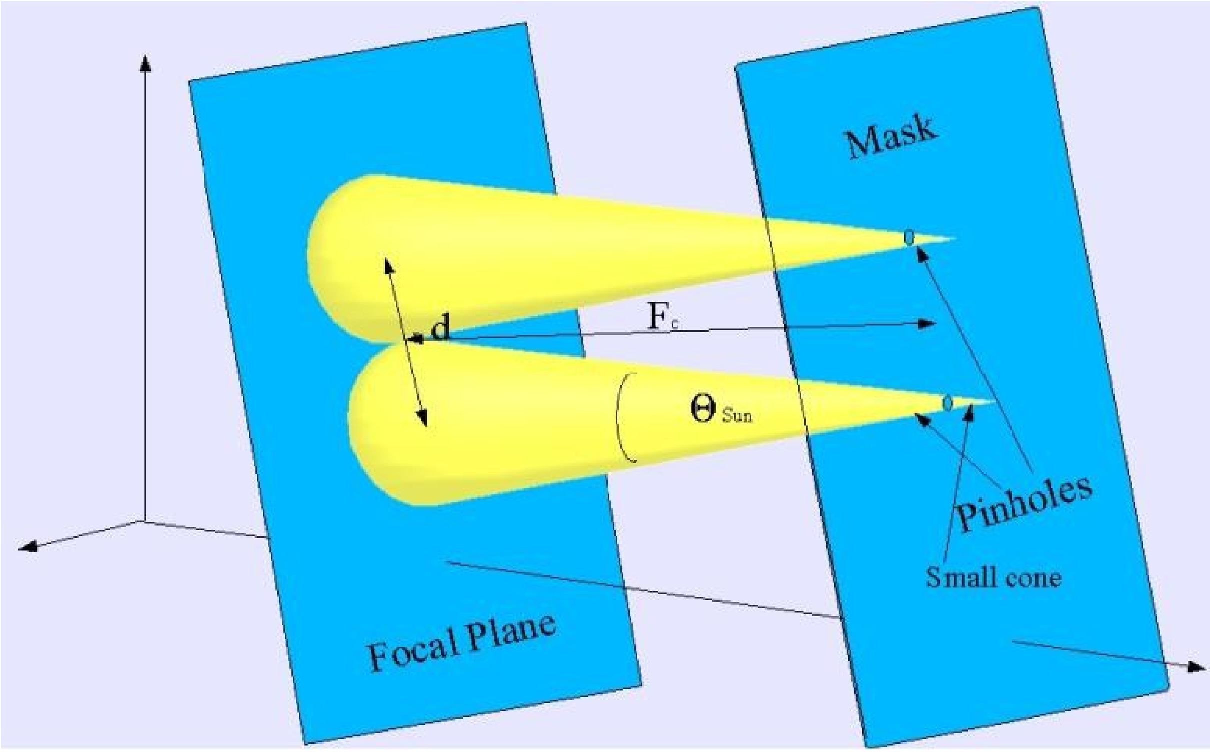

Fig. 5.1 The two-pinholes heliometer, a simple device to measure the annual angular variations, ±1.67% i.e. ±32 arcsec, of the solar diameter, due to the eccentricity of Earth's orbit.

A two-pinholes heliometer[8] can be designed to simulate the situation of having two images at the focal plane. Two scientific museums (Coimbra Museum of Science in Portugal and Robert Hooke Institute in Nice, France) have contacted me for implementing this instrument after the publication on the American Journal of Physics, annexed to this thesis.

At the turn of the sixteenth century Tycho Brahe and Johannes Kepler made single pinhole measurements of the solar diameter. Their accuracy was limited by diffraction (unknown to them) and the motion of the image on the screen. We discuss how two pinholes built on the same mask can be used to bypass all the problems inherent in the single pinhole approach. The distance at which the two images of the Sun are in contact is the only measurement needed, and the experimental accuracy is much better than measuring the diameter of a single moving image. We obtained 0.5% accuracy, sufficient to follow the angular variations of the solar diameter due to the motion of the Earth in its orbit.

5.4 Sunsets over the sea horizon and solar diameter

The measurement of the solar diameter is possible also from timing the sunset over the sea horizon.[9] The arcsecond level of accuracy is reached with video.[10]

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[8] Sigismondi, C., Measuring the angular solar diameter using two pinholes, American Journal of Physics, **70**,1157-1159 (2002).
[9] Sigismondi, C., Misura del diametro solare ad almucantarat zero, Proceedings of the 42nd UAI congress, Padova - Italy, 24-27 September 2009 ; to appear in Astronomia UAI, also on arXiv:1106.2514 (2011).
[10] Sigismondi, C., Sunsets and solar diameter measurement, Proc. of 2nd Galileo-Xu Guangqi Meeting, Ventimiglia - Villa Hanbury, Italy, 11-16 July 2010, also on arXiv:1106.2201 (2011).

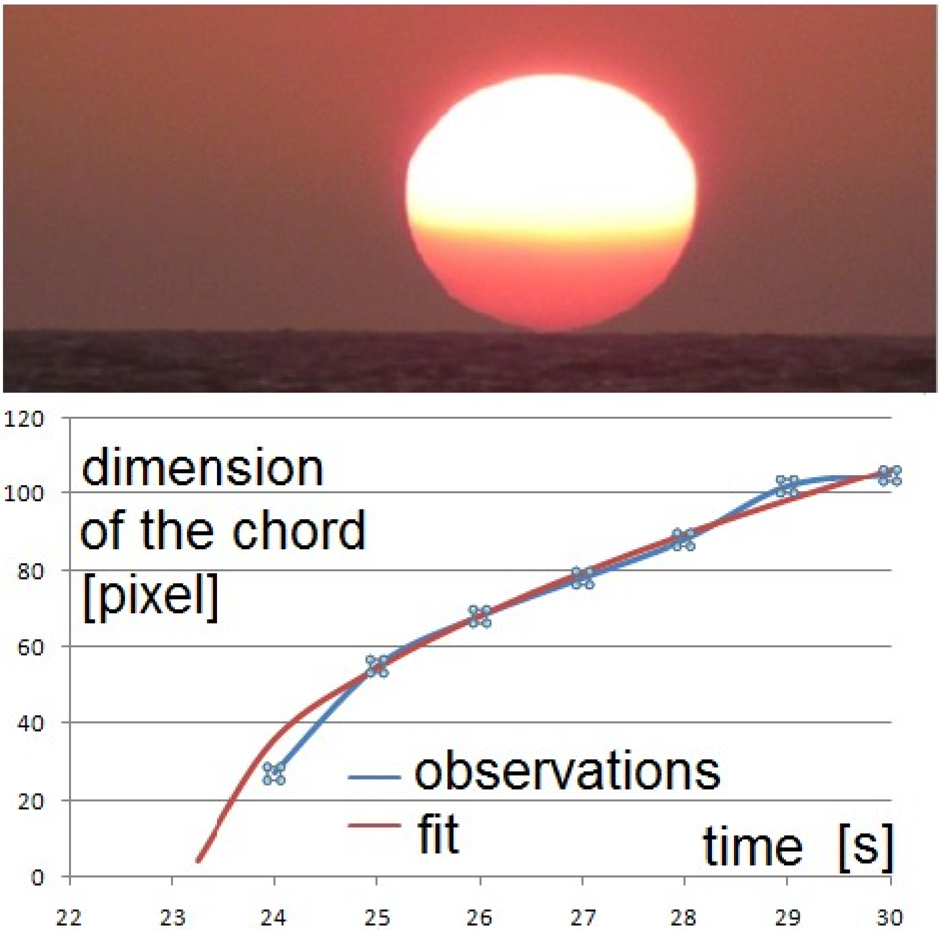


Fig. 5.2 The method of chords applied to the intersection between the solar disk and the sea horizon. An accuracy better than 1 arcsec in the diameter's measurement has been achieved.

Fig. 5.3 The contact between the solar disk with its reflected image occurs with connecting lights. This is a "black drop" phenomenon, which could affect the measurement of the solar diameter if it is not bypassed with the chords' fit.

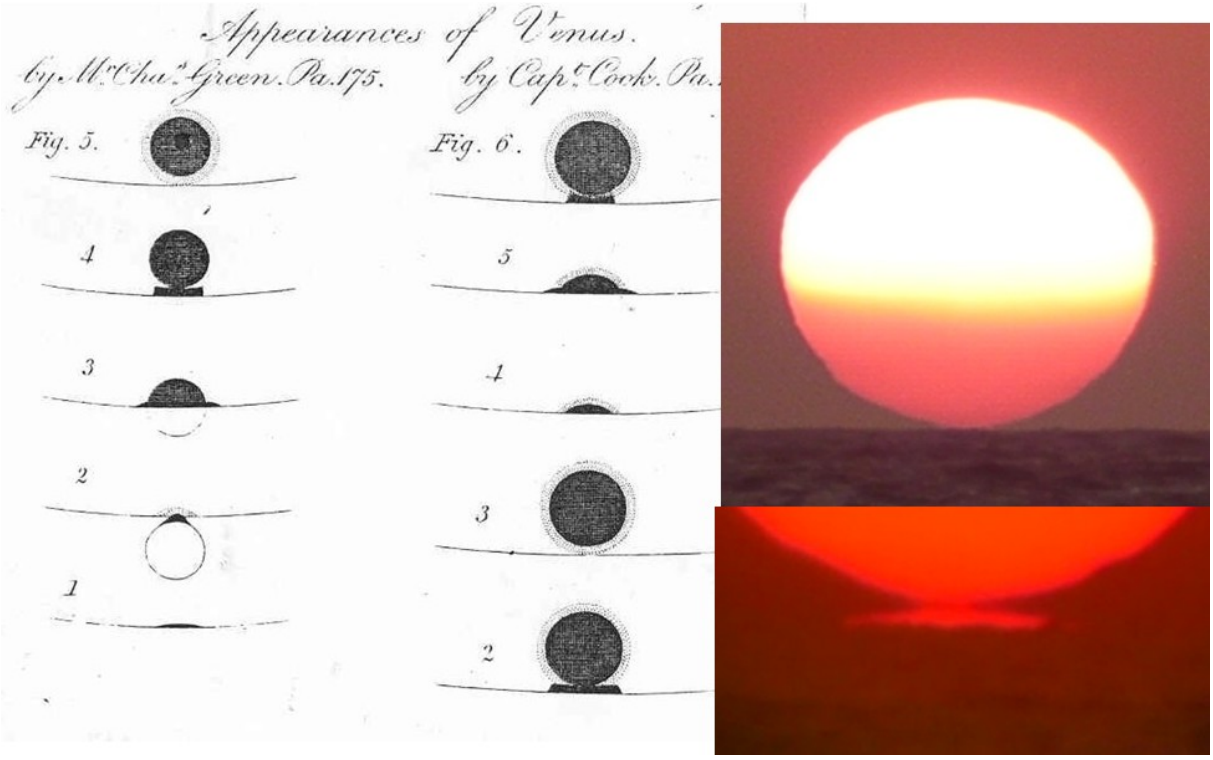


Fig. 5.4 Black drop phenomena: the transit of Venus of 1761 and a sunset.

5.5 LDF studies from a simple projected image of the Sun

Using an ordinary pair of binoculars or a normal telescope, and even a pinhole, it is possible to study the Limb Darkening Function of the Sun by a single digital photo of the image of the Sun projected on a white paper. It is to remember that every commercial videocamera is like a non-linear detector, because it is programmed in order to simulate the eye response.

Fig. 5.5 An image of the Sun projected by a binocular 7x50 onto a white screen (photo made at Yale University on November 3rd, 2010, during a demonstration).

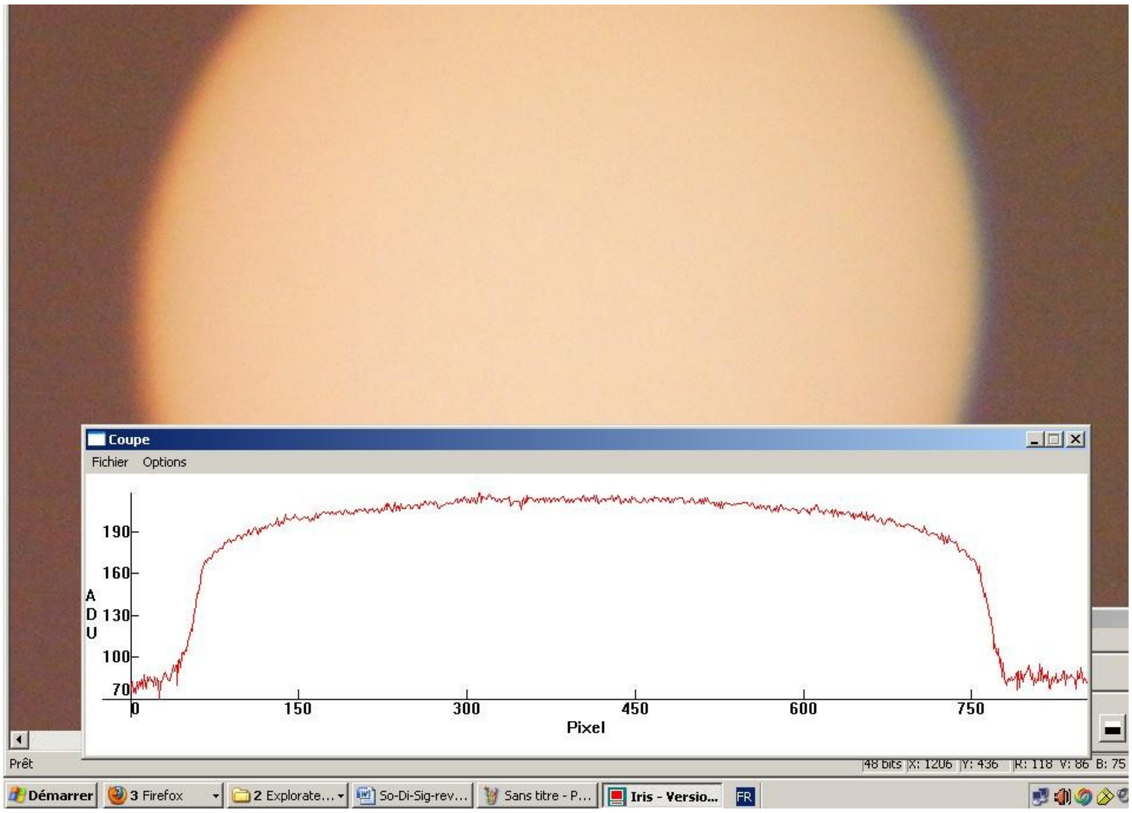
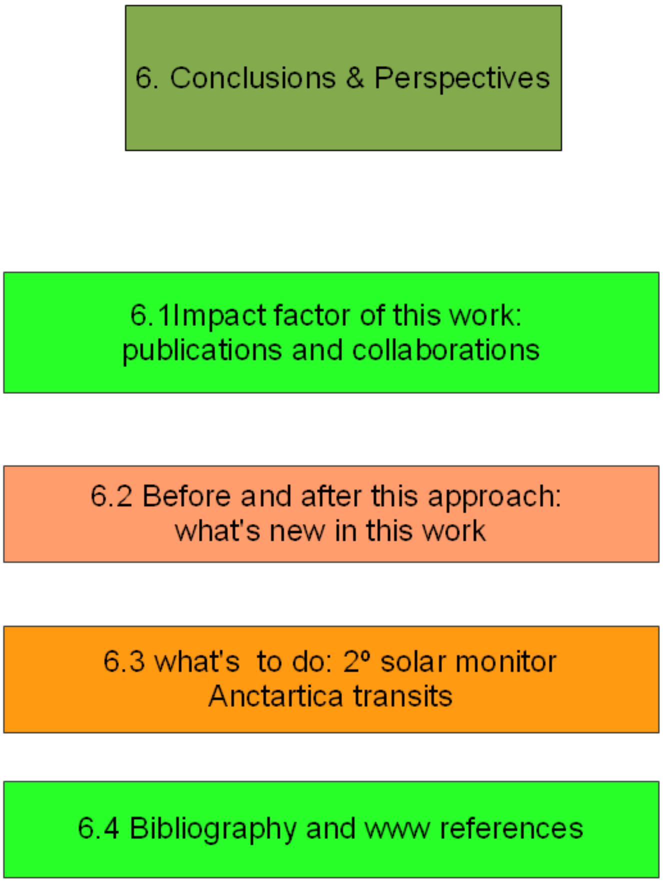


Fig. 5.6 the Limb Darkening Function obtained on the same digital photo of fig. 5.4 in jpg, with IRIS software[11] analysis.

[11] Buil, Christian, http://www.astrosurf.com/buil/us/iris/iris.htm (2010). Iris is a copyrighted freeware.

Chapter 6: Conclusions and Perspectives



This thesis is written when the first data from Picard are still under examination and whit the calibration of MISOLFA already started.

My contribution to the measurement of solar diameter with high accuracy and from ground has been

1. to have shown the need of a more precise definition of solar limb during eclipses, taking into account the phenomena of tiny emission lines in the solar mesosphere.

2. to have individuated in the low frequency motion of the atmosphere as one of the causes of the inconsistency within seeing errorbars of the daily transit's measurements of diameter.

This is a starting point for many relevant scientific issues on the physics of the Sun. The task to bridge together eclipses observations and direct solar astrometry methods has been started, and the procedures of automatization of transits measurements are is still in progress in Locarno and we could only do preliminary tests at the same time of the eclipses of 2008, 2009 and 2010.

3. Qualified observers belonging to IOTA, International Occultation Timing Association have contributed to the publication of their data of recent eclipses. The problem of filters adopted in eclipse observations, risen by me, found a partial solution with a standardization of the IOTA filter. The first atlas of Baily's beads has been published.

4. Historical eclipses have been re-analized with the latest lunar satellite data. The measurements of solar diameter using different sets of beads give different results: a new definition of solar limb is crucial, to better take into account the effects in the solar mesosphere.

6.1 Impact factor of this work

The field of the measurement of solar diameter using eclipses had an outburst of activity in the early years 1980s with a series of paper dealing with ancient observations also of Mercury's transits.
In 1994 the paper of Dunham, Sofia and Fiala posed a standard in this domain of research.
Only Dunham, through the direction of IOTA, International Occultation Timing Association, continued the series of measurements, no more funded by the US government, and presented in a COSPAR meeting of 2005 a new approach to the data. The polar beads were considered more stable with respect to the equatorial ones, because these region were better covered by the grazing stellar occultations, and because libration effects are reduced.
No new publications on this subject appeared on major journal until our two papers appeared in Solar Physics in 2009.
From that time on, we continued to rise the interest on this subject, which is now considered as a solid alternative to the satellite, and a valid reference for the solar diameter.
Our last achievement on the Limb Darkening Function recovered from Baily's beads light curve analysis is already matching in perfect timing, the organization of CNES (Centre National des Études Spatials, France) mission to Cairns, Australia, for the next total eclipse, to be observed with a network of photometers.
In term of quotations in other works our number is still low, but this is due mainly to the fact that the field of eclipses and solar diameter has a restricted number of experts, and that to have new data it is necessary to wait for new unclouded eclipses.[12]

The discovery of the slow fluctuations of the atmosphere which make inconsistent two following measurement of the solar diameter made with hourly circle transit in drift-scan mode is another great achievement in this field.
This fact suggests to put in parallel with the main telescope another wider field telescope, in order to evaluate the motion of the whole figure of the Sun during the transit.
In this case the impact factor acts on several ancient publications, which presented large statistical errors on the determination of solar diameter. This effect explains, at least at the first order, the reason of such fluctuations.
The authors of such works, published about 60 years ago, cannot react, but I am sure they would appreciate that discovery, that has been done in the observatory of Locarno, which participated to the project on solar diameter measurements since 30 years.
Finally on the field of didactic outreach, the high school's teachers are not prolific in scientific publications, due to their load of daily work with students.
I have found some quotations of my works in various educational websites,[13] and also on refereed journals.[14]
The experiences I have suggested do not are suitable for a further original publication, unless one says "yes it works".
The number of collaborations activated during my thesis is the real index of the impact factor of this work.
Stable contacts in France at IAP, Institute d'Astrophysique de Paris, in Switzerland at Locarno IRSOL facility, in Brasil at the Observatorio Nacional in Rio de Janeiro are started independently one from

[12] I have observed 4 eclipses, 2 of them I was clouded out.

[13] As an example I present http://faraday.physics.uiowa.edu/optics/6J10.80.htm
[14] Susman, K. and M. Čepič, Physics Education, **45**, 469 (2010).

another from congresses and directly from the publications. In these institutions I have spent several periods of research, of about 8 months in total, producing about 30 publications, most of them in NADA ADS Catalogue.

6.2 Before and after this approach: what's new in this work

The original achievements of this work are here drafted. They are the new results in this field, and they bring new understandings and points of view.

All the methods of measuring the solar diameter have been reviewed, compared and classified according to a logical order. The following table, presented at the Friedmann Seminar held in Rio de Janeiro on May 30-June 3, 2001, is summarizing also using different colors the concepts developed in this thesis.

Ground-based			**Above the atmosphere**	
Drift-scan	**Heliometer**	**Astrolabe R3S2 d~9cm**	**Balloon borne**	**Satellite**
CLAVIUS project: IRSOL d= 45 cm (CH)	Koenigsberg Fraunhofer, Bessel 1824 d=15cm	**Rio de Janeiro (1999 - now)**	SDS (1992-2009) Diameter and Oblateness d = 20 cm	SOHO MDI (1999-2010) Diameter and oblateness
CLAVIUS project: Carte du Ciel d=33 cm (IAP Paris)	Goettingen (1895)	**São Paulo (1975-1990)**	**Eclipses & Planetary Transits**	RHESSI (2008) oblateness
Greenwich d=15 cm (1850-1955)	**Rio de Janeiro (2009-now)**	Calern (FR) (1975 - 2008)	Baily's beads (1973 – 2010) **Easter Island ON mission**	SDO Diameter, magnetic field
Rome–Capitol d=11cm (1877-1937)	Antalya (TK) Santiago (Chile) 1975-1995	San Fernando (ES)	Mercury transits (1832 -2006) Venus transits (2004-2012)	Picard (2010-2013) Diameter, oblateness, irradiance

Table 6.1 Different techniques of solar diameter measurements. Heliometers, balloon borne and satellite made instantaneous measurements, but are subject to optics errors. The others suffer from atmospheric variations during the measure.

Some problems in the four centennial activity of solar diameter measurements have been recognized and the solution has been approached.

The following scheme helps us to understand our main achievements presented in this thesis, with respect to some of the open problems still present in solar astrometry.

Phenomenon	Interpretation
Long historical series (Rome and Greenwich, 70-100 years) show big annual fluctuations $\Delta R_\odot/R_\odot > 0.1\%$ From Stefan-Boltzmann eq. $\Delta L_\odot/L_\odot \sim 2\Delta R_\odot/R_\odot$; $\Delta L_\odot/L_\odot < 0.1\%$ (COSPAR data), so $\Delta R_\odot/R_\odot < 0.05\%$.	Aging process in the eyes of the observers (data acquisition). Cloudy days in different amount from year to year in the same season (data analysis problem). Irradiance effect on small telescopes (Rome d=11 cm, Greenwich d=15 cm).
Different values in consecutive drift-scan measurements at IRSOL (d= 45 cm) and IAP Carte du Ciel (d= 33 cm).	Atmospheric fluctuations at 0.01 Hz (firstly measured by us in 2010 in CLAVIUS project), 10000 slower than usual seeing timescales.
Eclipses data of the same eclipse produce different results from different telescopes	Signal-to-noise ratio and the thin layer of emitting lines under the chromosphere: the solar mesosphere. **Lack of inflection point detection.**
Different diameters obtained with Mercury transits (Gambart d= 7 cm & Bessel d= 15 cm 1832)	Irradiation (diffraction) which reduces the perceived diameter of the planet with the smaller telescope

Table 6.2 Phenomena and their interpretation. New solutions are in the second and third row: the detection of 0.01 Hz atmospheric variation, and the use of Limb Darkening Function also during eclipse observations.

This thesis ends with a didactic application of many of these principles developed in the most advanced solar laboratories around the world. The request of high accuracy in the quest of solar variability can be transmitted to the young generations through simple but thoughtful experiments here presented.

6.3 What's to do: 2° solar monitor, Antarctica, space and the Moon

The evidence of slow image motions in the atmospheric seeing, involving the whole figure of the Sun, suggests realizing a 2° solar monitor in order to correct the transits' data for this random-like motion.
This second full-disk monitor, during the drift-scan, could verify the motions of the whole disk.
The other solution, without that, should be to make a great statistics and analyze as many transits as possible in order to get an average value.
But this solution is not easy and not converging, since the data are not distributed as a Gaussian.

From Antarctica, at Dome C, there are very good and steady seeing conditions as good as 0.36 arcsec,[15] and it should be the ideal place of an experience of solar diameter's monitoring with small scale telescopes (10 cm of objective) and also with bigger ones.
A 10 cm class instrument would be easily transportable, even on top of a tower to avoid the ground level turbulence.
Moreover it can be robotized, as it happened for the IRAIT funded by the Italian Progetto Antartide.
IRAIT (International Robotic Antarctic Infrared Telescope) is a telescope with an 80 cm aperture, installed at Dome C. Equipped with AMICA (Antarctic Multiband Infrared CAmera), the main focal plane instrument, it observes in near (1.5 μm) and mid infrared regions (5.28 μm), benefiting from the exceptional site characteristics.[16] The small IRAIT has been tested by Runa Briguglio, who developed his project in astrophysics laboratory with prof. Alessandro Cacciani and myself at the Sapienza University of Rome in 2003,[17] during the Antarctic night in 2008.[18]

[15] Gredel, R., Site Characterization at Dome C – The ARENA Work, 3rd ARENA Conference: An Astronomical Observatory at CONCORDIA (Dome C, Antarctica) L. Spinoglio and N. Epchtein (eds) EAS Publications Series, **40**,11-20 (2010).

[16] di Varano, I., et al., EAS Publications Series, **33**, 279 (2008).
[17] http://www.icra.it/solar/lab2002/fotoastro.html
[18] http://astro.fisica.unipg.it/dome_c_news.htm site with photos of the small IRAIT

The Pinhole Solar Monitor (PSM)[19] is a small space-device with two pinholes projecting two identical images on the focal plane. It has the advantage to be an astigmatic heliometer, without optics, compact, without need of accurate pointing and costless. On the payload of a satellite PSM exploits the side facing the Sun and monitors the secular variations of the angular solar diameter D.
Two pinholes of equal radius r are built on the same rigid platform at distance d between the centers; they project two images on the focal plane a flat screen parallel to the platform at distance f. When those images are in contact tan(D)=d/f.

The contact between the two solar limbs is simulated with a raytracer and studied numerically.

The focal length of contact about 1 meter can be measured with a system of encoder-actuators within 10 micron of precision. Although d and r are measurable within a micron of accuracy they introduce errors in the calculation of D which are systematic due to thermal stability in the space.

With such a compact device an accuracy of 0.01 arcseconds is expected evaluating the variations of the mean angular solar radius D/2~959.63 arcseconds.

The same kind of apparatus could be used one the Moon, where the drift-scan method would profit of an angular velocity 1/27 smaller than on the Earth.[20]

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[19] Sigismondi, C. and C. Contento, Pinhole Solar Monitor to Detect 0.01"RADIUS Variations, Solar and Solar-Like Oscillations: Insights and Challenges for the Sun and Stars, 25th meeting of the IAU, Joint Discussion 12, 18 July 2003, Sydney, Australia (2003).
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CV of Costantino Sigismondi with all the publications made, updated to 2011. Hosted by the Brazilian National Council of Reseach CNPq. http://lattes.cnpq.br/5502043303695823