

European Projects of Solar Diameter Monitoring

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Abstract. Three projects dealing with solar diameter evolution are presently in development. Historical and contemporary eclipses and planetary transits data collection and analysis, to cover potentially the last 5 centuries with an accuracy of few hundreds of arcsecond on diameter's measurements. The French space mission PICARD with a few milliarcseconds accuracy. With PICARD-SOL instruments located at the plateau of Calern the role of the atmosphere in ground-based measurements will be clarified. CLAVIUS is a Swiss-Italian project based on drift-scan method, free from optical distortions, where hourly circles transits will be monitored with fast CMOS sensors in different wavebands. The will run at IRSOL Gregory-Coudé telescope.

Keywords: Solar Instruments; Space-based Optical Telescopes; Eclipses; Ephemerides; Astrometry; Solar Physics; Diameter; Photosphere; Solar Variability.

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INTRODUCTION

The observations of eclipses and transits help to understand better the historical sources on which the past history of solar diameter is based. In this respect European IOTA/ES eclipses expedition at shadows limits are providing us data and video of eclipses which will help to recover the solar diameter's history of the last three decades.

We present here new results on solar diameter in 1832 and 1869, calculated using the observations of Mercury transit by Bessel (radius correction $\Delta R=+0.75''$), and of 1869 total eclipse seen from shadow's limits ($\Delta R=+0.23''$).

A discussion on Clavius eclipse of 1567 and the first analysis of 2008 total eclipse with a solar radius correction of $\Delta R=-0.10''$ are also presented. In the incoming international year of Astronomy, 2009, two projects dedicated to solar diameter monitoring will start to produce scientific data: the space mission PICARD and the ground based project CLAVIUS.

PICARD is a French microsatellite capable of milliarcsecond accuracy on solar diameter measurements from space. A replica of the space telescope will perform observations from the Plateau of Calern (site of the Observatoire of the Côte d'Azur) in order to assess the influence of the atmospheric turbulence on ground-based observations, with the aim of following solar diameter's variations beyond the lifetime of the

satellite (3 years). PICARD follows a three decades tradition of metrological accuracy on solar diameter measurements obtained with ASTROSOL, a Danjon astrolabe with fixed prisms, and DORAYSOL with a variable prism.

CLAVIUS is a Swiss-Italian project at the vacuum Gregory-Coudé telescope of Institute of Solar Research of Locarno (IRSOL) with the Universities of Como and Roma and SUPSI. A fast CMOS detector will monitor the solar diameter in different wavebands, through the method of drift scan: solar transits on a sequence of parallel hourly circles with an angular extension of two arcminutes. The fast acquisition rate of CMOS detector will allow to freeze the atmospheric seeing to obtain a very good statistical uncertainty for each series of measurements. The errorbar will be reduced improving the statistics.

HISTORICAL ECLIPSES AND SOLAR VARIABILITY

The question of solar secular variability remains still controversial after more than three decades of debate: the paper of Eddy and Boornazian in 1979 put into evidence that with current ephemerides the hybrid (annular-total) eclipse of April 9, 1567 observed as annular by the Jesuit astronomer Christopher Clavius (1581) in Rome would imply a

solar angular diameter at unit distance rather larger than the IAU1976 standard value. In the year 1571 a prominent maximum of solar activity was recorded in European and Islamic chronicles of aurorae (Schove, 1983, Schroeder, 2000 and Basurah, 2006). Therefore in 1567 the phase of activity was rising.

The first eclipse used to assess a secular variability is therefore the 1715 one, observed by the fellow of Royal Society under the coordination of Edmund Halley. After eclipses data, a shrinking of mean solar radius of $0.50''$ from 1715 and 1925 up to now is generally accepted not without criticism (Thuillier, Sofia, Haberleiter 2005; Parkinson, Morrison and Stephenson 1988). The question of solar variability, even grounded on serious data (Wittman and Débarbat, 1990) remains unsolved.

Clavius in his *Commentarius in Sphaera* (ed. 1581) mentioned the eclipse of 1567, April 9 as annular. According to Ptolemy the lunar diameter would always exceed the solar one, and such an eclipse was impossible. Twice Kepler, convinced on the existence of a lunar atmosphere, asked Clavius about this eclipse through his correspondents. To Johannes Remus Clavius draw the circumstance of that eclipse: it was a ring, while they were looking for totality (as seen in 1561).

Stephenson et al. 1997 attributed the vision of a ring made by Clavius to the inner corona, but the inner corona is not circularly shaped (Pasachoff et al. 2006; Sigismondi, 2008). They used this eclipse, and the value of lunar acceleration $dn/dt = -26 \text{ arcsec/cy}^2$, to recover $\Delta T = UT1 - UT$. This is the value of the Earth rotation delay with respect to orbital motions due to non uniform rotation rate. The (ant)umbral cone of the Moon, as shown in figure 1, could be pointed over Rome at Collegio Romano only with $145 \text{ s} < \Delta T < 165 \text{ s}$.

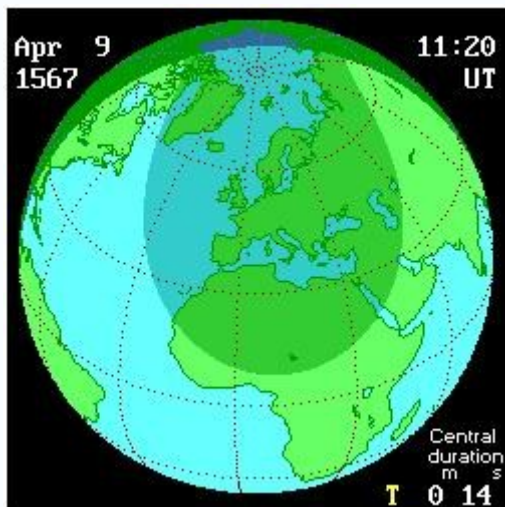


FIGURE 1. Eclipse of April 9, 1567. The hybrid nature of this eclipse determined a very narrow (ant)umbral zone of 10 km of width; here it is represented by a small dot over Rome. Clavius was probably exactly on the centerline because he does not mention the rotation of the cusps, anevident phenomenon a few km apart.

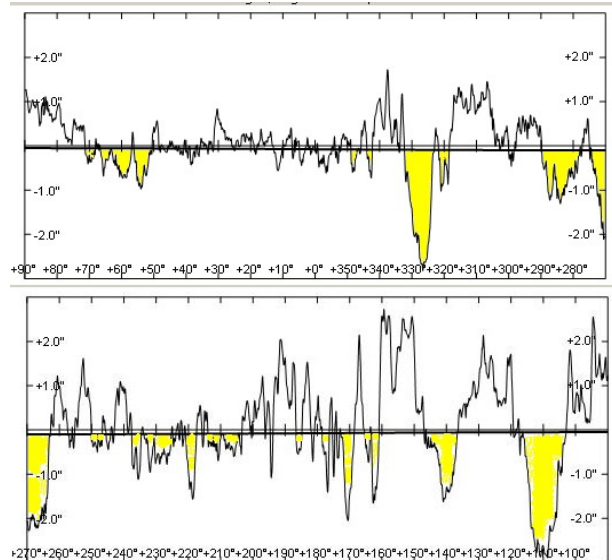


FIGURE 2. Eclipse of April 9, 1567 simulated with Winocult4.0 software. The lunar limb's mountains are plotted for all position angles. The upper figure is the northern semicircle containing lunar North pole and the lower one represents the southern. The shadowed regions are illuminated by the solar photosphere already increased by $\Delta R = 2.5''$ over the standard value. Without this correction the eclipse would have been total. To have a complete ring as Clavius reported, the radius of the Sun should be increased by further $2.5''$ above the lunar mean limb, so the correction to standard radius would be $\Delta = +5''$. Such ΔR value is very large, but it is comparable with Jean Picard's results of one century later.

MERIDIAN TRANSITS

In Paris Jean Picard from 1666 to his death in 1682 and Philippe de la Hire up the end of Maunder minimum measured solar radius (Ribes, 1990). The Sun mean radius at unit distance appeared to have been $964'' - 965''$, more than $4''$ larger than present standard value and slower in its rotation during Maunder minimum. A decelerated Sun rotation with larger diameter are quite consistent with a real pulsating phenomenon (dilation and contraction of convective layers) over a timescale of centuries (Ribes et al. 1987). Picard's data also showed more sunspots in the southern hemisphere than in the northern one during Maunder minimum.

Nevertheless the timing method allowed an accuracy of ± 0.5 s and $\pm 7''$ in diameter's determination. At Greenwich from 1852 to 1953 (Gething, 1955) and in Rome, at Campidoglio from 1876 to 1936 (Gialanella, 1952; Cimino, 1953) long series of daily transits showed variations in the semi-diameter, with possible periodicities and ranging around mean values larger than current mean value of $959.63''$ corresponding to conventional 696.000 km of solar radius at 1AU (IAU 1976).

Meridian transits have similar problems to partial eclipses (see below), at Greenwich, for example, they observed through the $6''$ meridian circle, with filter, while at Campidoglio Observatory in Rome they observed the projected image of the Sun crossing 7 wires, and from there they recovered the timing of both solar edges at the meridian.

The method of parallel transits, introduced to increase the time resolution of the great meridian line of Santa Maria degli Angeli in Rome (Sigismondi, 2006), is a new edition of the method adopted in Campidoglio observatory to monitor the solar diameter: projection of 1 m solar image crossing 7 wires, and the observers timed those passage with $1/4$ s accuracy; averaging the measurements they could reach $1/10$ s of precision corresponding to $1.5''$ for each measurement.

Moreover, in the data analysis, the standard solar radii adopted by the Nautical Almanac changed (Giannuzzi, 1955): $960.90''$ for the period 1851-1852; $961.82''$ for 1853-1895 and $961.18''$ for 1896-1937.

Major criticisms to those data, and to those even older of Picard, dealt with irradiation correction, already mentioned by Bessel in 1833 and extensively presented by Cullen at Greenwich in 1926, personality equations (Gething, 1955), seeing conditions and limb shifting when FFT or other algorithms are used to determine its position (Lakhal et al., 1999; Irbah et al. 1999).

Irradiation is due to optical dispersion and appears to be a function of solar altitude (Cullen, 1926).

Even with impersonal micrometers the measurements may be influenced by atmosphere conditions, like the onset of westerlies and easterlies stratospheric winds (Ribes, 1990).

In order to take into account of all such contributing errors to each measurement of solar diameter a theoretical and numerical approach is not enough. New measurements with solar transit technique and modern imaging and image reconstruction procedures can help in the goal of reconstruction of the past solar history.

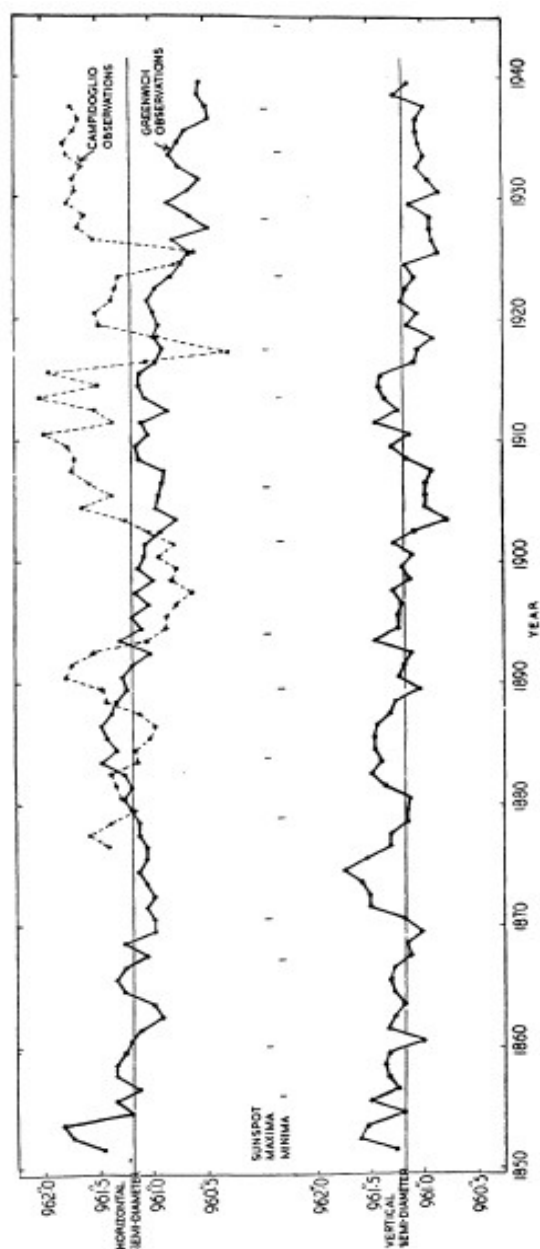


FIGURE 3. Horizontal (left) and vertical (right) diameters of the Sun measured at Greenwich with Airy's meridian circle. Campidoglio observations are superimposed at left. (Gething, 1955). Straight lines correspond to a radius of $961.2''$.

PLANETARY TRANSITS

A long debate in the 1980s ended without definitive statements on past solar variability. Large collections of data of different observers, instruments and methods were often averaged obtaining no secular variations, nor periodicities (Parkinson et al. 1988). As example the transits of

Mercury of 1832 has been carefully observed at Marseille (Gambart, 1832) with a 67 mm telescope, and at Königsberg (Bessel, 1832) with the celebrated great heliometer of 158 mm. Gambart has measured a total duration between the internal contacts larger than Bessel, and, consistently, he also measured Mercury diameters of 5.18", smaller than Bessel's 6.70". The smaller is the diameter of the telescope the larger is the amount of solar light shifted inside the dark planetary disk. This effect ceases almost completely with large instruments. Schneider, Pasachoff and Golub (2004) have deeply analyzed this effect comparing space (TRACE and SOHO) and ground based measurements of 1999, 2003 Mercury and 2004 Venus transits.

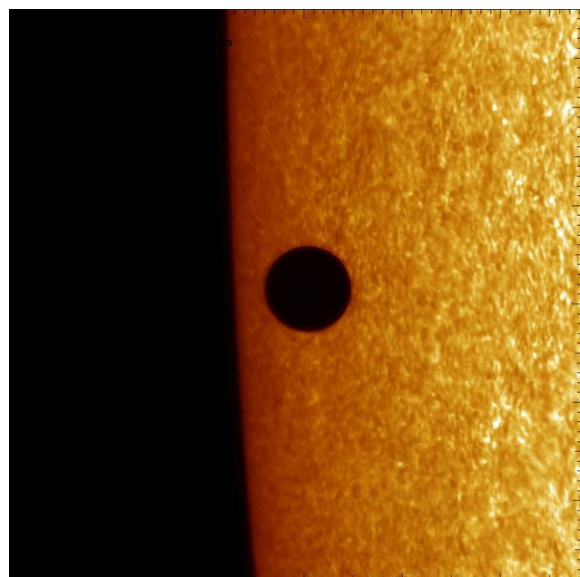


FIGURE 4. Transit of Mercury of 2003 observed with Swedish Vacuum Solar Telescope, diameter 47.5 cm.

From the data of Bessel, the time interval between internal contacts is 24179.26 s while using conventional solar radius at unit distance calsky.com gives 24160.3 s and Winocult4.0 yields 24159 s; this corresponds to a radius correction of 0.75"-0.80" in excess with respect to 959.63".

TOTAL ECLIPSES CAMPAIGNS AT SHADOW'S LIMITS

Total solar eclipses have been used to measure the solar diameter evolution considering data from 1567 (Clavius, annular-total eclipse in Rome) to August 1, 2008.

US Naval Observatory (Newcomb, see USNO 1869) and Yale Astrometry school (Brown, see e.g. Lewis,

1946) carried out a collection work of eclipse data in the last two centuries, and also Mercury and Venus transits were taken into account (See, 1901).

The total eclipse of August, 7 1869 crossed United States and the U.S. Naval Observatory (Newcomb, 1870) organized an observational campaign and a collection of observations made near shadows limb by amateurs.

People located a quarter of mile SW of the Oakland station, near Bowling Green, KY watched a totality of 2 s (Southern limit of the eclipse); for Northern limit at the courthouse of Franklin, IN others watched 37 s of darkness and at Geneseo, IL 33 ¼ s. Those data, fully reported in the table, imply a solar radius correction of +0.23"±0.02".

Oakland st. KY	-91°11'42.7"	39°20' 24.2"	2s
Franklin, IN	-86°02'45.4"	39°28'40.8"	37s
Geneseo, IL	-90°09'29.9"	41°27'10.8"	33¼s

The positions of the observers has been recovered on the basis of their description and Google maps. The presence of data from both limits assure that there are not shifts in lunar latitude to be considered. The simulations have been done with Winocult4.0.

The total eclipse of August 1, 2008 has been observed at both limits. At this moment I have data of Richard Nugent and Chuck Herold (IOTA, International Occultation Timing Association / United States section) at Southern limit near Hami, China, and a report of Frank Edison who watched the eclipse at Alert, Nunavut (Northern limit and northernmost human community; the coordinates have been estimated with Google maps because Alert is a Canadian military base). A first analysis based only on the duration of the totality yields a correction to standard radius of -0.10". The complete analysis with all Baily beads also at Northern limit recorded by a IOTA/ European Section team will improve better this estimation.

R. Nugent	93°35'13.6"	42°52' 54.6"	16.5 s
C. Herold	93°36'19.4"	42°53' 38.8"	23 s
F. Edison	-62°56'26.4"	82°26'13.9"	43 s

PROBLEMS WITH PARTIAL ECLIPSES

The observations of Father Angelo Secchi at the Cauchoix refractor of 169 mm at Collegio Romano Observatory (Roma) of the eclipse of July 28, 1851 yield a diameter 2.14" smaller than standard value (7234.5 s observed instead of 7250.7 s calculated including the effects of lunar limbs). In his paper

Secchi (1851) is the first to mention the influence of lunar mountains on the total duration of the eclipses. The influence of the blue filter used to look at the Sun can explain the large negative correction to solar radius, but not completely. The limb darkening function (Rogerson, 1959) at the limb is 16.2 % of the value at the center of the disk, while 2.14'' inside it is 31.4%, the difference is 0.72 magnitudes.

Therefore the density of the filter used or its use at the eyepiece or at the objective are crucial parameters for partial eclipse studies.

For the 1851 partial eclipse no definitive conclusion can be issued without inspecting the filter used. In the case of Mercury transit observed by Bessel there is the data on the planet's diameter which validate the diameter's measure.

In the case of Robert Treat Paine observation of 1869 August, 7 total eclipse in Boonesboro we have an observed duration of 178.2 s of totality and (182.1 s calculated with Winocult4.0 considering lunar mountains). He was near the centerline, where 3.9 s of difference correspond to a radius correction of +2.14'', but considering the duration of the whole eclipse of 7363.4 s with respect to the calculated value of 7359.9 s and the correction is +0.46''. Probably the uncertainty on his position affects our calculation of the totality.

From the report of Maria Mitchell's (1890) of the annular eclipse observed in Nantucket in 1831, the phase of annularity lasted 1 m 42 s, 4 s more than the calculated duration with standard solar radius. Maria Mitchell measured a total duration of the annular eclipse of 10648 s versus a calculation of 10670.1 s which implies evidently a solar radius smaller than standard value. In this case the conclusions on solar radius corrections obtained from annularity phase duration and from the whole eclipse with partial phases are in internal contradiction. A dense filter for allowing the direct view at the telescope can explain the shorter duration of the whole eclipse, like in the case of Father Angelo Secchi, while a small diameter of the telescope can explain with its point spread function a longer duration of the light between lunar and solar limbs at internal contacts.

Therefore partial eclipses and planetary transits have to be treated very carefully, in order to know filtering and diffraction systematic effects, emphasized right in the case of convolution with rapidly changing solar limb darkening function.

An experiment to exploit the eclipse of August 1, 2008, partial at 8% from Locarno, has been set up at IRSOL, to observe the difference in entrance time of the Moon over the solar disk at two wavelengths: 446nm, with 44 nm FWHM and 700 nm with 22 nm FWHM, and consequently to see the difference of

solar diameters in two wavelength during this quiet Sun period at beginning of cycle 24.

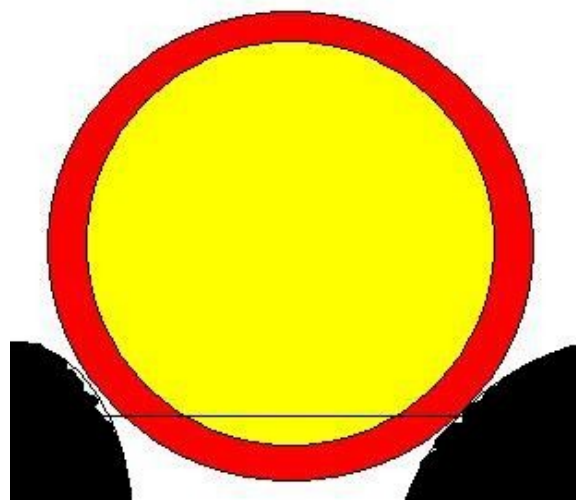


FIGURE 5. Geometry of partial eclipse of August 1, 2008; the Moon's limb enters not perpendicularly to the solar limb, scanning its outer regions at a 0.23'' per second for 46.5°N 9°E. The difference in ingress timing of the same lunar feature in the blue and red channel give the difference of diameters.

The average deviations of the measured radii with respect to the standard value ranged from -0.5'' at $\lambda=311$ nm to -0.1'' at $\lambda=445$ nm, and scattered between -0.07'' and +0.02'' at longer wavelengths, however, due to the inclusion of chromospheric radiation at the extreme limb regions, the CN channel (near $\lambda=385$ nm) yielded radii $\sim 0.5''$ larger than standard value (Neckel and Labs, 1994).

With rather bad weather conditions, because of the clouds the contrast between Sun and sky was really poor, we obtained from video $\Delta_{\text{red-Blue}}=4.8\pm 1.4$ s, corresponding to a difference of $1.1''\pm 0.3''$ between the two wavebands, much larger than 0.12'' expected. This effect can be also instrumental, as the focus was impossible to be adjusted with clouds, but the intent of this measurement was mainly demonstrative. This experience made at the 45 cm telescope of IRSOL has shown clearly the difficulty to follow the profile of the Sun in the very beginning of the eclipse and also at the end. The seeing leave uncertain the determination of the extreme instants. Nevertheless using video to fit the solar limb and to extrapolate the lunar limb motion it has been possible to infer those instants with a reasonable accuracy.

PICARD SATELLITE AND PICARD- SOL

The PICARD satellite is named after Jean Picard, it is a mission dedicated to the study of the Earth's climate and Sun variability relationship: a better understanding of the climate changes through a better knowledge of the Sun.

PICARD will be launched in June 2009 from Baikonour with a DNEPR launcher. It consists in three instruments: SOVAP (Solar VARIability Picard) which measures the total solar irradiance, PREMOS (PREcise Monitor for OSCillations) to measure the spectral irradiance in four spectral domains as well as the total solar irradiance, and SODISM, Solar Diameter Imager and Surface Mapper.

SODISM is conceived to measure the solar diameter and the limb shape at three wavelength in the photospheric continuum all around the Sun. The chosen wavelengths are 535, 607, 782 nm in the spectral domains without Fraunhofer lines. It will detect the active regions (faculae and sunspots) that might corrupt the diameter measurements. The chosen wavelength is the CaII emission at 393 nm which will furthermore be used to measure the differential rotation. It studies in relation with PREMOS the effects of the solar activity on the spectral irradiance and the Sun radiance image at 215 nm. It studies the influence of the active regions on the diameter.

In this way it will achieve a deep sounding of the Sun.

The instruments will be operated by on-board electronics contained in a box named PGCU (PICARD Gestion Charge Utile), which includes all functions necessary to operate the three instruments: formatting of telemetry, receipt of commands, thermal regulation system, image compression, measurements sequencing, power supply, safety management.

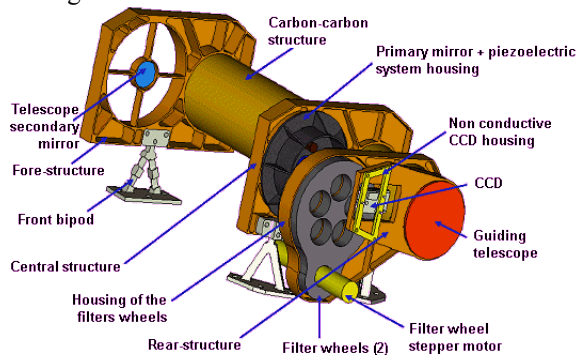


FIGURE 6. SODISM/PICARD telescope: the dimensions are 35 cm between the primary and secondary mirror and 15 cm between the primary and the CCD plane. There are 3 INVAR plates linked together by a 55 cm carbon-carbon

tube of diameter 10 cm. The primary mirror is mounted on 3 piezoelectrics driven by guiding telescope itself placed inside the C-C tube. The CCD cooled to $-40\text{ }^{\circ}\text{C}$ is uncoupled of the INVAR plate by a Cordierite support.

SODISM is an 11 cm diameter telescope with a 2048x2048 usable pixels CCD. The relative accuracy of the measurements to reach the scientific goals is a 3 milliarcseconds per image. The uncertainty is essentially due to the pixellisation of the observed limb. Its effect will be decreased by integration (by orbit, by day...) due to the time constant as expected from the development of the solar activity, enabling to reach our objective of one milliarcsecond. The expected accuracy of the measurements is based on very good dimensional stability, which is ensured by use of stable materials (Invar and carbon-carbon for the structure, Zerodur for the mirrors) and an accurate thermal regulation (within 1°C) of the whole instrument. The detector will also be thermally regulated (within 0.1°C) to keep constant the size of the pixels. Nevertheless, to alleviate any evolutions of the metric characteristics of the instrument, an angular reference has been included in the instrument, and referenced stars have been chosen for astrometric calibration. Four prisms are used to generate four auxiliary images placed in each corner of the CCD. The distance between a point of the limb of the central solar image and the corresponding point of the auxiliary image only depends on the angle of the prism and of the temperature which will be measured with the appropriate accuracy. These measurements enable to check the relationship between the angular distance of two points on the Sun and the distance of their images on the CCD (see optical diagram). The solar diameter will be referenced to the angular distances of doublets of stars so that the measurements which will be achieved in the next decades referenced to the same doublets, enable to evaluate the long term evolution of our Sun. These doublets have been identified in the Hipparcos catalog. Their positions will be corrected with their own proper movement by the use of future astrometric missions.

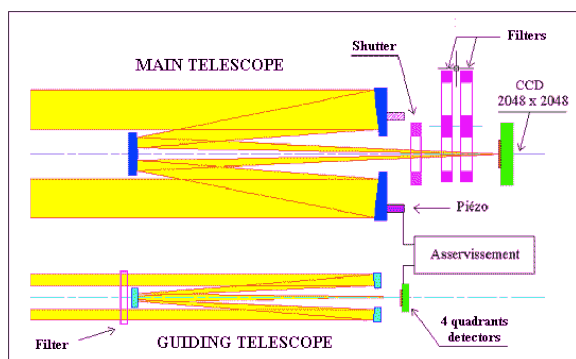


FIGURE 7. SODISM/PICARD schematic optical setup.

In parallel with SODISM there will be ground-based measurements instruments: SODISM II, which is a replica of SODISM and MISOLFA, Moniteur d'Images SOLaires Franco-Algérien, which will operate during and after the PICARD mission. A radiation transfer model through the atmosphere will be validated by comparison between simultaneous measurements in orbit and from the ground.

The ground measurements will be achieved by the following instruments placed on the Plateau de Calern (South of France) which is the observing site of the Observatoire de la Côte d'Azur (OCA):

Those two instruments replace the Danjon astrolabe, DORAYSOL (Définition et Observation du RAYon Solaire) for the measurement of the solar diameter (Sigismondi, 2008b).

This set of instruments named PICARD-SOL will enable understanding the modification of the solar limb shape induced by the solar photons traveling through the atmosphere, by comparing the limb shape and diameter measured in orbit with the ground based measurements. It will enable after the end of PICARD mission to continue the measurements from the ground with the possibility to interpret them, in principle without ambiguity.

CLAVIUS: MULTITRANSITS AND FAST CMOS IMAGING

CLAVIUS, named in honour of the great astronomer, witness of the puzzling hybrid eclipse of 1567, is a common project involving the University of Insubria in Como, the University of Applied Sciences of Southern Switzerland-SUPSI, Istituto Ricerche Solari Locarno-IRSOL and the University of Rome La Sapienza. It is devoted to drift measurements of the solar diameter. The goals are to measure: differences in the diameter in different colors, the diameter itself, and to take advantage of the PICARD mission to compare ground with space

data, in order to guarantee an easy technique available also without a running space mission.

The wave bands of observations will also include those used by PICARD satellite.

A collaboration with RHESSI satellite (Fivian et al., 2002; Fivian et al., 2007; Zahid et al., 2007) will consider the calibration of diameter's measures not on the solar equator, due to the rotational oblateness.

A CMOS camera used by University of Insubria for high energy experiments can be used also for electromagnetic waves in the visible. The advantage using a non commercial camera is related to the possibility to understand in a very deep way how the photons are converted in a digital number and at which time. This allows to precisely study the limb affected by seeing effects (image motion and blurring) and by instrumental effects induced by the telescope.

The instrument will consist in an optical device dividing a solar portion (about 100" x 200") in two images filtered by different interference filters. The two images are projected on the CMOS sensor of the camera, and are digitalized with a high cadence (frequencies higher than the typical seeing frequencies of few hundreds Hertz).

The instrument will be tested and used at IRSOL, because the 45 cm aperture Gregory Coudé is an excellent instrument for these observations, indeed the instrumental scattered light is very low.

Once the technique will be mature and convincing results will appear, the instrument can be easily transported for campaigns at telescopes offering excellent seeing conditions.

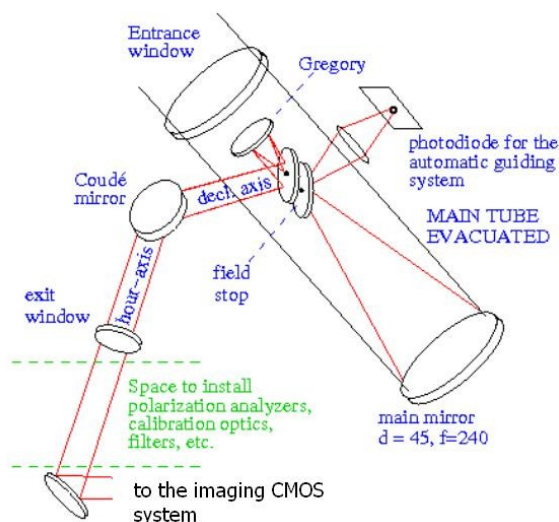


FIGURE 8. Scheme of 45 cm Gregory-Coudé evacuated solar telescope at IRSOL. The field stop allows to avoid

99% of diffuse light, without loosing in angular resolution. The field of view is 220". The total focal length is 25 m.

In the drift scan method the telescope aims at a fixed direction and the Sun edges and the center pass through the field of view of the telescope.

The advantage of drift scan method is that it is not affected by optical defects and aberrations, because both edges are observed aiming in the same direction, moreover with parallel transits we can gather N observations, at rather homogeneous seeing conditions, during the time of a single one of past measurements (Wittmann, Alge and Bianda, 1993; 2000).

The seeing conditions will be monitored by real time numerical reconstruction of solar profiles, and will be used to correct the measured value.

Preliminary studies with 1/60s CMOS commercial camera (SANYIO CG9) have shown internal coherence of different series of N measurements, with statistical errors already at the level of 0.15" (N=20, sigma of each measure=0.04 s). A grid of parallel lines has been oriented parallel to the western and eastern limbs in order to measure N transits (Sigismondi, 2006) in about 2.5 minutes.

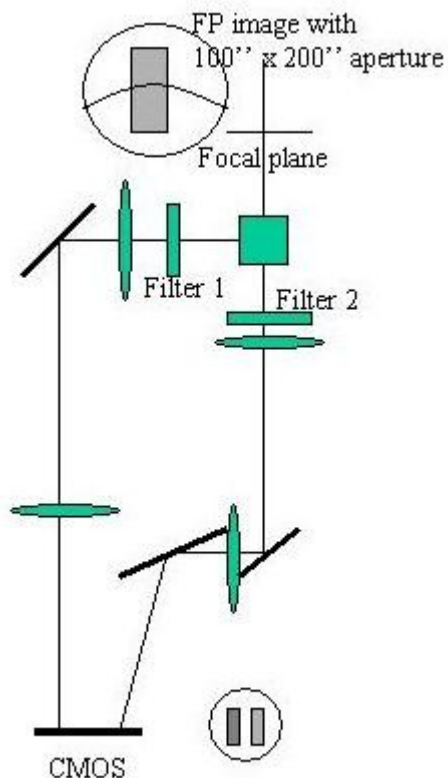


FIGURE 9. Draft of the optical parts of CLAVIUS experiment. A 100"x200" slit on the focal plane is imaged twice on the CMOS sensor, in two different colours.

Acknowledgments: Thanks to Paul D. Maley, R. Nugent and C. Herold for sharing IOTA/US eclipse data of August 1, 2008.

APPENDIX: CHRISTOPHER CLAVIUS

Christopher Clavius, (March 25, 1538 – February 12, 1612) was a German Jesuit mathematician and astronomer who was the main architect of the modern Gregorian calendar. In his last years he was probably the most respected astronomer in Europe and his textbooks were used for astronomical education for over fifty years in Europe and even in more remote lands (on account of being used by missionaries).

Clavius joined the Jesuit order in 1555. He attended the University of Coimbra in Portugal, where it is possible that he had some kind of contact with the famous mathematician Pedro Nunes.

There in 1561 Clavius observed the total eclipse of August, 21, reporting its duration equivalent to a "Miserere" (the Psalm 50). Following this he went to Italy and studied theology at the Jesuit Collegio Romano in Rome, where he taught Mathematics. He was considered as "the second Euclid" by all European scholars.

In 1579 he was assigned to compute the basis for a reformed calendar that would stop the slow process in which the Church's holidays were drifting relative to the seasons of the year. Made with Egnazio Danti and Luigi Giglio this calendar reform was adopted in 1582 in Catholic countries by order of Pope Gregory XIII and it is now the Gregorian calendar used worldwide.

As an astronomer Clavius held strictly to the geocentric model of the solar system, in which all the heavens rotate about the Earth. Though he opposed the heliocentric model of Copernicus, he recognized problems with the Ptolemaic model. He was treated with great respect by Galileo, who visited him in 1611 and discussed the new observations being made with the telescope; Clavius had by that time accepted the new discoveries as genuine, though he retained doubts about the reality of the mountains on the Moon. Later, a large crater on the moon was named in his honour, by Giovanni Battista Riccioli.

Among his large scientific production there is the great *Commentarius in Sphaera*, a treatise of astronomy, in several editions. Based upon the simple text of John Holywood (Sacrobosco, 1256) it is a 500 pages volume with detailed geometrical demonstrations of spherical astronomy.



FIGURE 10. Christopher Clavius.

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