

Pinhole giant meridian lines: a review on ancient data retrieval and modern observations (IGEA-ZIA campaign)

Costantino Sigismondi

sigismondi@icra.it

(ICRA/Sapienza Università di Roma e ITIS G. Ferraris, Roma)

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Abstract The study of the position of the Sun through pinhole meridian lines flourished between XV and the end of XVIII century, especially after the invention of the telescope. The results obtained with pinhole astronomy allowed to know the Earth's orbit with great accuracy. The possibility to recover solar diameter measurements before and after the Maunder minimum from historical data is discussed by performing new observations. The inflexion points of the meridian Limb Darkening Function of the solar image are used to obtain the solar diameter within an arcsecond of accuracy. The observational campaign IGEA-ZIA 2018-2022 is available on youtube.

Sommario Lo studio della posizione del Sole, e quindi della forma dell'orbita terrestre, è stato fatto con grande precisione tra il XV secolo e la fine del XVIII secolo, proprio con meridiane a foro stenopeico, sia prima, ma soprattutto dopo l'invenzione del telescopio. La possibilità di ottenere dati precisi anche sul diametro solare da dati storici è analizzata, anche realizzando nuove osservazioni con metodi di analisi moderni (punti di flesso della Limb Darkening Function meridiana, che è l'andamento dell'intensità luminosa dell'immagine solare lungo l'asse meridiano).

La campagna di osservazioni IGEA-ZIA 2018-2022 è archiviata su youtube.

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Introduction: pinhole heliometers

The age of the meridian lines in the churches starts in 1475 when Paolo Toscanelli realized a pinhole in the Brunelleschi dome of St. Maria del Fiore in Florence. Before him Ulugh Begh realized his meridian observatory in Samarcand (1429) used for the stars, and for the Sun as well.

Egnazio Danti realized pinhole meridian lines in Santa Maria Novella in Florence, in the basilica of Saint Petronio in Bologna

(1577) and in the Tower of Winds in Vatican (1580). He contributed to the 1582 Gregorian Reformation of the calendar. Giandomenico Cassini re-traced the meridian line of Saint Petronio in 1655, the heliometer, obtaining the atmospheric refraction law with the zenithal angle z : $r=60''\tan(z)$ by comparing the apparent positions of the Sun with respect to the ones calculated through its ecliptic longitudes. The angular extent of the solar diameter was also consistent with the bisection of the Ptolemaic eccentricity: a consequence of the Keplerian ellipse for Earth's orbit.

Eustachio Manfredi and Giandomenico Cassini in 1695 controlled the heliometer to assess its absolute and relative accuracy. Francesco Bianchini in 1700 started the works at Santa Maria degli Angeli in Rome, to exploit a potentially unmovable pinhole, located on roman large and steady wall.

Bianchini realized a meridian line which is also a giant level.

These instruments verified the length of the tropical year and the amount of obliquity variations; they gave the local time until meridian circles telescopes working in XIX century.

Positional Astronomy after the Gregorian reformation

Copernicus was not in the advice, around 1510, to proceed to a reformation of the Calendar before having new and more accurate measurements of the tropical year. By the end of the same century the reformation was promulgated with stronger observational basis, always encompassing several centuries.

When Francesco Bianchini in 1703 published the first results obtained at Santa Maria degli Angeli meridian line, he compared his measurements (1703) with Bernard Whalter's ones of 1500. The uncertainty of 5 minutes on the single Equinoxes, was reduced to a two seconds dividing 203 tropical years by 203 times.

The lensless Heliometer after the invention of the Telescope

The position of the Sun and the obliquity of Earth's axis

The orbit of the Earth is subjected to the gravity pull of the Moon and of the other planets, beyond the solar one, so it changes continuously. At the dawn of Newtonian gravitation and since a millenium before it was clear that the obliquity of Earth's axis was changing, as the arabic astronomers started to verify. Also the apsides line (apogee-perigee, now aphelion-perihelion) was rotating, and they noticed it, even with large relative uncertainties.

Bianchini when proposing the new meridian line to the Cardinal Gianfrancesco Albani, who financed that, had in mind to minimize all observational uncertainties related to the solar position, in order to recover with the best quality all Earth's orbital parameters, and to assess the parameters adopted in the 1582 calendar reformation.

The Easter problem, the eccentricity and the tropical year

The solemnity of the Easter's Sunday is the central feast of Christianity, it is related to the first spring full Moon (XIV Moon day and Jewish Easter), but it has to depart from it not being the fourteenth lunar day and always on Sunday.

The ecclesiastic equinox was conventionally fixed at March 21, in Nicea Council (325). The algorithm to find the date of full Moon occurring after March 21 each year, had to deal with three "missing" leap years each four centuries, as the Gregorian reformation stated. We can say that the ecclesiastic mean Moon was basically independent on new astronomical observations, being the mean lunar cycles determined by ancient and well observed lunar eclipses.

A check on the tropical year and on the synodic month was indeed worth when Bianchini built that meridian line, and the year 1703 had three lunar eclipses, all observed at Santa Maria degli Angeli.

The solution of Cassini, and its model of atmosphere

The zenithal distance of the Sun, or its altitude above the horizon, change from 19° to 65° in Rome, and from 24° to 68° in Bologna. The meridian observations include the transit's instant which can be compared with a stellar transit time, to find, the difference in Right Ascension and in Ecliptic Longitude. By using spherical trigonometry it is possible to obtain the Ecliptic latitude and the Declination, once known the longitude and the obliquity of the Ecliptic with respect to the Celestial Equator.

An increasing difference between the calculated declination and the observed one was found when the zenital angle increased. Cassini found that difference $\Delta z = 60'' \cdot \tan(z)$.

This is called Cassini refraction and it is still used by several modern ephemerides softwares. It is fully valid until 15° above the horizon, or $z=75^\circ$. Cassini was aware to have dominated the "horses of the (chariot of the) Sun" using a mythological similitude. Cassini to re-trace the Danti's meridian line measured accurately the latitude by sighting at the Polar star from the same line, through a window in the façade of the Basilica.

The upgrade of Bianchini: a meridian line also for the stars

Bianchini in Santa Maria degli Angeli made possible the observation of all stars, by creating a window with a crossing wire, which materialized the meridian line, over the pinhole.

Even if on the meridian line are reported 22 stars, for sure Bianchini observed Sirius in all seasons of the year, in order to recover the ecliptic longitude of the Sun. The time was guaranteed by a pendulum craft by Thuret in Paris, the best of his epoch. The accuracy of that pendulum was better to a second, and it was synchronized by the meridian transits of Sirius.

Seasonal effects due to stellar Sirius' aberrations (2021)

The position of Sirius was measured in centesimal parts of the height of the pinhole, and it was found slightly moving. Bianchini thought it was a seasonal effect of the atmosphere, and reported the phenomenon in his publication.

In 2021 we found that these positions are compatible with stellar aberration applied to Sirius' declination.

Also the observed ecliptic longitude of Sirius was affected by the stellar aberration yielding slightly different times of crossing the meridian line, which determined errors in the estimate of the equinoxes and solstices. The errors are dependant on the season, as the aberration is. These errors convolve with the N-S deviation of the meridian line, which was discovered by Celsius in 1734 and precisely measured by Boscovich in 1750.

Sirius on May 3rd 2022 passes at the meridian at 17:10:24.5.

Latitude systematic error due to Polaris' aberration (2006)

The stellar aberration of the Polaris between 1 and 8th of January 1701, is the responsible of the difference between the true pinhole latitude $41^{\circ} 54' 11.2''$ and the one measured by Bianchini $41^{\circ} 54' 27''$ rounded to $30''$ on the floor of the Basilica. Before 2006 this difference was simply attributed to the ancient instruments, while it is perfectly explained by the aberration, and a single arcsecond angular accuracy.

The three summer solstice markers (2018-2021)

The two twin markers located before the meridian line near the Cancer sign, were identified as solstice markers in 2018 (Sigismondi and Pietroni, 2018). Later in 2021 the third marker, on the white marble, was recognized as belonging to the same solar path of the summer solstice of 1721.

Previous studies (Heilbron 1999, Catamo and Lucarini 2002/12) The Clementine Gnomon has been deeply studied by Celsius in 1734 for a whole semester, and by Boscovich in 1750 for the same length of time at least. Later several publications appeared on that meridian line, always for local distribution.

John Heilbron published in 1999 a book entitled “The Sun in the Church” with Harvard University Press, and these astronomical instruments become worldwide famous.

Mario Catamo and Cesare Lucarini in 2002 for the third century anniversary published a book “Il Sole in Basilica” (The Sun in the Basilica) with an update in 2012, in Italian, whose distribution remained local. Lo “Gnomone Clementino”, issued in 2009 and reprinted in Gerbertus 7 (2014) along with a report on the Tower of Winds, potentially got a wider audience being online. The language was Italian, with an English resume available only in press.

The scientific modern results about the Clementine Gnomon have been published online by Costantino Sigismondi and can be retrieved by the NASA/ADS archive.

Solar diameter before and during the Maunder Minimum (1978-2021) The correlation between solar diameter and great minima has been proposed in 1978 by Eddy and Boornazian, upon the observation of Clavius on may 9th 1567 of a annular eclipse in Rome.

The observation took place, very reliably, on the Salviati palace,¹ East of the present Piazza del Collegio Romano, in the former site of the Jesuit University, before the Collegio

¹ « Nel 1557 il Collegio passò nell'abitazione più vasta di Giov. Battista Salviati, unita ai giardini del duca di Urbino e posta di fronte all'arco di Camillo, il numero dei gesuiti fu di 145, gli esterni superavano il numero degli anni precedenti. »
https://it.cathopedia.org/wiki/Collegio_Romano

Romano. To have an annular eclipse there, given the hybrid nature of the 1567 total-annular eclipse, the Sun had to 4" larger than the standard value. This thesis rose a great debate on the variability of the solar diameter, up to present days.

Tovar et al. (2021) used Cassini and Manfredi observations in Saint Petronio meridian line, to verify if the solar diameter was larger than the 1919.26", during the Maunder minimum, as the measurement obtained with the Halley eclipse (1715 may 3rd, Gregorian style) suggested.

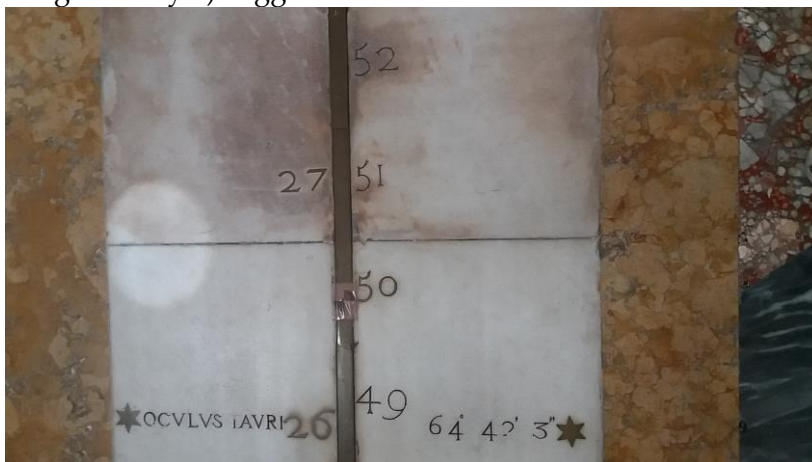


Fig. 1 The solar image on May 1st 2022 (St. Maria degli Angeli)
The authors concluded that seasonal effects on the pinhole data may affect their result.

In effect they analyzed 4400 data eliminating 400 outliers and concluding that the averages in Cassini times 1655 and in Manfredi times 1695-1736 did not change statistically.

Nevertheless there is a strong correlation between thin clouds and outliers, as it is evident in the original data (Sole Languidissimo in Latin and Italian means "very faint Sun" because of thin clouds, frequent in late spring and fall). The following measurements conducted at Santa Maria degli

Angeli meridian line (the only one still fully operating) demonstrate quantitatively the spread of the diameter's measures and its correlation to sky transparency.

IGEA Informatized Geometric Ephemerides for Astrometry calibration campaign (2018-2021) with ZIA Zenithal Imaging Analysis (2022) This special observational campaign was aimed to calibrate all the meridian line. The multiple of 5 of the centesimal parts are original, while the other centesimal part have been replaced in 2000 with the last restauration.

For this reason a new calibration of all the points of the meridian line was needed, in order to verify its actual resolution. The theorem of Hill, Stebbins and Oleson (1975) applied to the solar limb as seen through turbulent atmosphere suggested to use as limb's definition the stable inflexion point of the radia limb darkening function. For the first time (2022) this theorem has been applied to the meridian images, and they were taken from zenithal view.

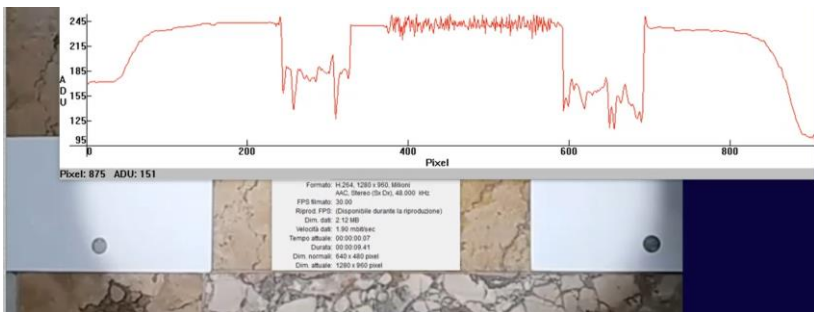


Fig. 2 The inflexion points of the limb darkening function in the pinhole image of Santa Maria degli Angeli.

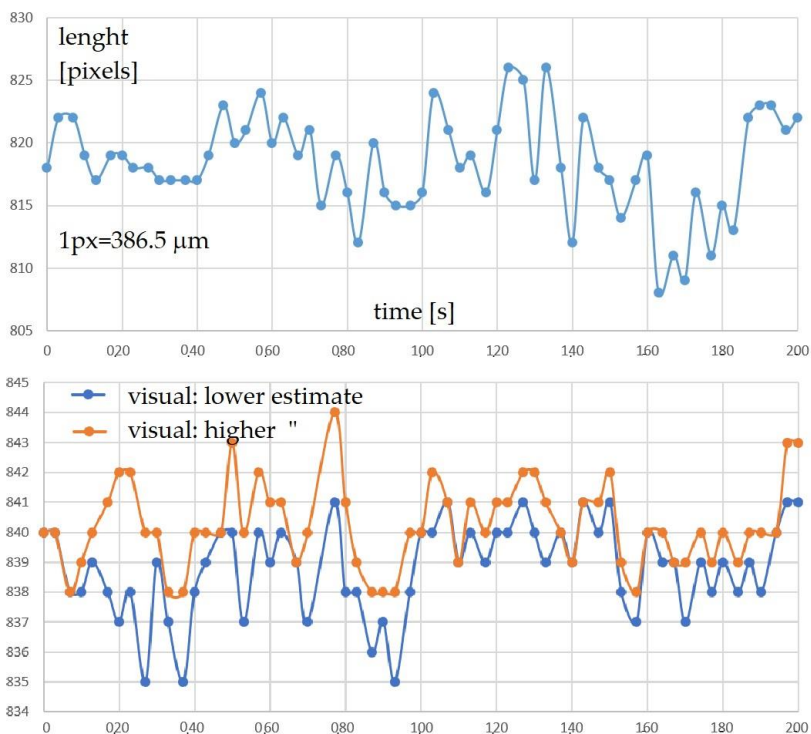


Fig. 3 The inflexion points (up) and the visual limbs (low) as from the pinhole solar image of Santa Maria degli Angeli.

We could verify that the haze conditions are responsible for the outliers, yielding a larger solar diameter, while with clear sky the value of the Solar diameter is more stable.

That problem was named “penumbra problem” at the time of Manfredi in debate with Bianchini, and they were disputating if the penumbra was 1 or even 2 pinholes more than the geometrical image. Manfredi in Bologna sustained 2 when Bianchini in Rome 1, having –evidently– more clear sky than Manfredi.

Conclusions

The geometrical principle upon which is based the pinhole giant camera, when the pinhole is very steady as in the roman walls of Diocletian, is verified up to 1'' of accuracy. It allows to recover the position of the Sun and the parameters of the Earth's orbit to an high degree of accuracy, enough to detect the stellar aberration for Polaris and Sirius, affecting the latitude and the equinoxes/solstices results of 1701-1703, re analyzed in 2006 and 2021. The present review includes the Proceedings to the MGXVI meeting of General Relativity of 2021, now in press. The online database on youtube of IGEA-ZIA campaign allows to re-analyze the single transits.



References Fig. 4 Beginnign of daily eclipse on Palm Sunday '22.

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