

Nuovi studi astrometrici sulla meridiana della Madonna degli Angeli in Roma (2018-20) e sull'astronomia del XVIII secolo

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submitted March 11, 2019; accepted September 1, 2020

Abstract The observational campaign started on October 27, 2018 has completed nearly 500 days with more than 125 data points and youtube video. The data analysis was performed along all the 45 m line, to obtain its calibration by comparison of the read positions and timing of the meridian transit with the modern ephemerides calculated for the geographical position of the pinhole. The cylindrical form of the pinhole was included in the data reduction and, for the historical data of Bianchini (1703) was considered the stellar aberration of Sirius. Thirteen points receive new contributions with respect to past studies: 1. the Summer to Winter solstices deviation; 2. the parabolic and linear data fitting of the solstices and equinoxes, and the correction for the apsides; 3. the seasonal refraction of Sirius; 4. the time of solstices and equinoxes in 1703 in view of the stellar aberration of Sirius and the deviation of the line; 5. the penumbra, the weather (Mie scattering) and the signal-to-noise ratio; 6. the cylindrical pinhole; 7. the deviation of the stars of the equator; 8. the six mysterious stars and the almucantar transit; 9. the Summer 1702 solstice markers; 10 the Winter 1702 solstice marker; 11. the days of 220; 12. the zodiacal signs and their entrance timing; 13. the 1702 pinhole and the thermal expansion of the roman walls; 14 the air turbulence and the image.

Introduction

The first calibration after Bianchini's tests (and after his death) was done by Anders Celsius in 1734 (who found the line 2' deviated toward East) and Ruggiero Giuseppe Boscovich in 1750 (who found it 4.5' toward East and with a 'sinus' of 5 mm westward in the southern signs). Most of the new measurements have a positional absolute accuracy of ± 1 mm and a timing accuracy between ± 0.5 and ± 0.2 s depending on the local turbulence at the pinhole's external surface. After a general presentation on the meridian line "manual of instruction" all following items are discussed.

New themes of research put into light during the 2018-2020 campaign

1) A general deviation of $5' 12'' \pm 10''$ Eastward is obtained from Winter to Summer solstices (42" more than Boscovich). With respect to this deviation the Boscovician sinus is evaluated between the equinoxes and the Aquarius/Sagittarius signs (90 to 180 partes centesimae) with a maximum amplitude of 5 ± 1 mm, confirming the measurements made by Boscovich.

This has been necessary to understand the random nature of the original deviation of the meridian line, and the improvement of the quality of the astrometric measurements made along the first half of 18th century.

2) Another verification has been on the possibility to calculate solstices and equinoxes by opportune data fitting of solar transits, because we could not observe the stars as in 1700s, even in daytime, from the meridian line. We obtained as a clear result that Francesco Bianchini calculated always the solar longitude by comparison with Sirius to obtain the beginning of the seasons, showing also the result of the longitude obtained by spherical trigonometry with the measured declination (the only possible to us nowadays) and the known obliquity (measured by himself in 1701 at this "great gnomon"). The resulting difference, tabulated by Bianchini, was not explained, probably considered as a random error instead of systematic as it is. The parabolic and linear data fitting of the solstices and equinoxes, and the correction for the apsides position is presented.

3) The use of Sirius, the brightest star, is documented in his letter "De Nummo et Gnomone Clementino" (Bianchini, 1703) in which he first noticed the seasonal variation of the roman atmospheric refraction index. Bianchini is the first astronomer to notice that in the World, because of the characteristics of this large gnomon, allowing a precision of 0.2 mm using telescopes on the line, on a focal length of nearly 40 m, say 1 arcsecond, while for the observations of the Sun 5 arcseconds are typical, due to the aforementioned turbulence.

4) The solstices and equinoxes published by Bianchini in 1703, when compared with the ephemerides (IMCCE only), show differences which can be explained with the original eastward deviation of the line, including the residual 'sinus' effect at the equinoxes: Sirius passed in advance with respect to the winter Sun and in delay with respect to the other seasons, and by the stellar aberration of Sirius when it passes at the local meridian in daytime. This effect was not considered up to this study, while the aberration of the Polaris was recognized as responsible of the latitude systematic shift of 16

arcseconds ($41^{\circ}54'27''$ instead of $11.2''$ measured with GPS). The stellar aberration was discovered by James Bradley in 1727, almost three decades after these observations. Even though, the accuracy on the tropical year evaluation was obtained by Bianchini within 2 s from the actual value by comparison with 1500s data.

5) A detailed study on the penumbra has been carried on taking into account the seasonal variation of the signal-to-noise ratio in the Basilica, because of the large windows and the solar rays' inclination and also due to the variation of the cylindrical effect of the pinhole itself. The dependance on the weather has been also considered by evaluating the Mie scattering during a clear day, and the corresponding penumbra, and the same thing during a hazy day.

6) From October 27, 2018 the circular pinhole of 25 mm of diameter and 6.11 mm thick, with inclined Sun rays produces a screen reducing the effective aperture either meridional either transversal, both narrower toward the Winter solstice. This reduces the luminosity of the image, which becomes also larger for the projection angle as large as 65° of zenith distance. The reduction of the effective aperture of the pinhole also modifies the diffraction, enlarging its effect up to $8''$ when the pinhole receives light from 12 mm (meridional) times 20 mm (transverse) curved area. Originally the pinhole was obtained in the metal and was thinner as 2 mm, with such effect negligible. From 80 m the pinhole is completely blind allowing a precise evaluation of its thickness, knowing its diameter.

7) The deviation of the equator four-stars line with respect to the real one has also been carefully measured and explained for the first time in fall 2019. These stars are $2'$ deviated from East-West direction showing the solar image approaching the (false) equator faster than $1'/\text{hour}$ (Danti's law for the equinoxes).

8) The six mysterious stars and the almucantar transit, proven on the floor of the Basilica in November-December 2018 and 2019.

9) The Summer solstice markers for 1700 have been identified in 2018 as two half-solar images 15 and 10 minutes before the meridian transit. The second one is no more illuminated after the realization of the decorating arch by Luigi Vanvitelli in 1750; the partial opening made upon the recommendations of Boscovich left "blind" the second marker, far from the meridian line.



Fig. 1 The summer solstice marker

10) The 1700 Winter solstice marker was the black contour of the Capricorn, which was never hit by solar rays coming from the pinhole.

11) The "220 days" are from 19 to 24 December when the Southern solar limb touches the last marker of the meridian line. It will continue up to the XXIII century, when the obliquity and the nutation will move the solstitial image below that marker.

12) The position of the centers of the zodiacal signs corresponded to the beginning of each sign in 1702. Changing the obliquity and diminishing, the meridian line shrunk of 9 cm toward the Equinoxes, 7.5 cm the Winter solstice and 1.5 the Summer one. Recalculating the declination of the entrance of a sign it is possible, by linear interpolation, to calculate the instant of ingress in it with an accuracy comparable to the one for the seasons's beginning.

13) The position of the present pinhole, with respect to the original one, is 4 mm North and 4 mm West, as a result of the fit of more than 125 timing of the transits compared with the ephemerides, and as a result of a pendulum experiment. The thermal expansion of the roman walls modifies also slightly the vertical position of the pinhole.

14) Finally the study to reduce the turbulence of the image with a fan pointed on the external side of the pinhole, did not succeed in short time applications. The realization of a water basin in front (South) of the pinhole could reduce the temperature of the zone (bricks) under the meridian Sun in order to reduce the difference with the air which produces a violent turbulence. The analogous images of Salvador Cuevas' in the entrance dome of the Basilica (Divinity in Light) produced by a 5 cm lens show similar turbulence, produced by the dome heating around the lens.

Conclusions and perspectives

The meridian line or more properly “Clementine gnomon”, which include the pinhole, is the largest solar telescope of its times. The dimension of this gnomon allowed precisions down to 1 arcsec for stellar position and 5 arcsec for solar ones. This instrument allowed to recover the instant position of the Sun in the sky, the beginning of the seasons and, consequently, the form and the orientation of the Earth's orbit and the Earth's obliquity on the orbital plane with a precision of some arcseconds. We have treated, for the first time ever, the gnomon as it would be a modern telescope with 25 mm lensless objective and variable focal length from 21 to 50 m, and with the problems induced by the local turbulence, diffraction & light contrast, due to the penumbra, the weather and the signal-to-noise ratio with ambient light.

Indoor experiments with a catoptric replica of the pinhole, i.e. a mirror which deflects the beam in the most convenient direction, allow in different hours than the meridian passage, and with smaller focus lengths, to study the solar image (geometry and timing, technique of recording and increasing of contrast in a camera obscura).

The procedure of initial alignment of the Boreal and the Austral line has to be investigated in order to understand the technology and the celestial mechanics implemented in 1700-1702.



Fig. 2 L'immagine solare del 26 dicembre 2019, e un modello in scala del foro stenopeico con lo stesso rapporto larghezza-altezza. La linea nera sopra gli zoccoli del Capricorno è il limite invernale del bordo sud dell'immagine solare nel 1702. **Referenze** C. Sigismondi, Gerbertus 7, 1-80 (2014)