Pinhole Solar Monitor tests in the Basilica of Santa Maria degli Angeli in Rome

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Abstract. 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 tarature 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" variations of solar diameter.

Keywords. Site testing, History of Astronomy, Astrometry, Sun: fundamental parameters

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Introduction

Built in 1702 by the astronomer F. Bianchini upon request of Pope Clement XI, the *Clementine Gnomon* is included in ancient roman walls of Diocletian's baths (IV century a.C., see *La Meridiana* on http://www.santamariadegliangeliroma.it), choosen for their stability: a good reason to test it as PSM. Its brass *Meridian Line* is 44 m long, among white high reflecting marbles, with the *Austral* pinhole at h=20.35 m.

Observations

The horizontal, circular pinhole produces an elliptical moving image on the floor. Its transverse dimensions D_T depend on the altitude angle $a_\odot$ of the Sun at local noon

$D_T = \frac{h \cdot tan(\theta_\odot)}{sin(a_\odot)}$, $\theta_\odot$ being the solar angular diameter.

The duration of a transit is $\tau[s] = \frac{\theta_\odot"}{15 \cdot cos(\delta_\odot) \cdot cos(i)}$, where $\delta_\odot$ the declination of the Sun, and $(90^o - i)$ the inclination of the line to be crossed by the solar image with respect to its direction of motion. τ and D_T are larger in winter near perihelion. Transits have been recorded with SONY DCR-TRV9E camcorder's axis angled at $a_\odot$ to capture solar rays reflected by the marbles/lucid screens. UTC video synchronization of internal clock is obtained filming DIMENSION 4 software's output (thanks to V. Vannini and M. Cosma).

Calibration of the Clementine Line with the Sun and the stars

The *Line* is divided in 220 units *centesimae*, *C*, of 20.35 cm each one. Summer solstice's transit occurs at C=33.3, winter's at C=217.4. The transit of the Sun on the *Line* is in systematic delay with respect to ephemeris. Delays corrected for local deviations from an ideal line (±2.8 mm rms equivalent up to ±2 s in timing) range from 19.1 s at winter solstice to 0.4 s at *C*=36.9 (Moon transit of Feb 5, 2006), corresponding to an average deviation from true North of 5' 47"±2" East.

We also applyed the method described in Monti et. al., 1977, building an auxiliary line external to the church, and timing Polaris transits on it. Thanks to A. Lupi and M. Cola (Rome Architecture MCM Studium), using a total station LEICA TCR703, we transferred this astronomically referenced azimuth into the church finding that a line passing through 220 and 0 (vertical of pinhole) is rotated 4' 49.8"±0.6" Eastward.

Eventually a 190-points survey on the whole line shown that the real line is composed by 4 main branches and only the first keeps the original inclination $i_B = 4' \; 18" \pm 7"$ of the

Boreal line, from C=0∼50. The inclination recovered from daytime observations of Sirius and the Sun made by Bianchini in 1703 around summer solstice is i_{1703} = 3'50"±29" arising from systematic delay of (10.9±1.4) s of Sirius with respect to the Sun. After half century R. Boschovich (see Heilbron, 1999) measured i_{1750} = 4' 30" (± ∼15") by the delays of solstices transits (winter 17 s and summer 5 s). Later restaurators were responsible of *Line*'s misalignments.

Atmospheric seeing

The whole image vibrates with amplitudes ± 10" at frequencies from 2.3 to 8.3 Hz, i.e. the largest oscillations require from 3 to 11 photograms (1/25 s each) to be completed. Closing the pinhole with a 25A red filter eliminates air flux turbulence through it, but vibrations do not vanish. Atmospheric seeing main component is turbulent warm air, rising from the bricks' surface near the pinhole exposed to South at noon, and it is∼4" (see next section). Oscillations frequencies are due to the seeing, their amplitude is modulated by diffraction (∼ 7" for pinhole diameter $\O_P$=1.5 cm). The global oscillation of the image's profile implies a coherence lenght of (seeing) air cells $l_c > \O_P$.

Parallel transits

Following Bianchini the transit's time is the average of preceding and proceding limbs' contacts. A set of 10 lines parallel to the main *Line* was set on white lucid paper. Then the very instant of transit over the *Line* is obtained by averaging 11 transit times, each calculated by two contacts. Each contact is determined with frame per frame video analysis. 11 parallel transits give a timing accuracy $\sigma_\tau \sim \pm 0.3$ s, equivalent to $\sigma_{\theta\odot}$ ∼4". The distance between each line was Δ_l=5 cm, with a contact each 15s (winter)÷35s (summer). At this slow sampling rate, atmospheric seeing is the main responsible of the remaining $\sigma_{\theta\odot}$ ∼4". The quantum limit for a single transit is bypassed using N transits, and statistical uncertainty $\sigma \propto 1/\sqrt{N}$, therefore a grid of 1000 parallel lines would reduce $\sigma_{\theta\odot} \sim$ 0.13", with observations made out of the atmosphere. This level of accuracy corresponds to typical variations of solar diameter identified with eclipses data.

A deviation from true North of meridian line $i \neq 0$, lenghtens $\tau[s]$ and produces spurious extra diameter ϵ_θ ($i = 1^o$ corresponds to ϵ_θ= 0.3"). The misalignments of *Clementine Line* produce effects of ϵ_θ <0.002". For i <12' ϵ_θ <0.01", and for i <36' ϵ_θ <0.1". Then i=36' is the maximum angular width for parallel transits grids.

Penumbra

The systematic penumbral effect, P, is expected to be $P \propto \O_P$. Analyzing data from Dec. 30, 2005 to April, 7, 2006 the penumbra P = (0.85±0.15)·$\O_P$, consistent with theoretical prediction. Uncertainty in this systematic effect is also due to the seeing and diffraction effects and it can be dramatically lowered in space.

Lunar PSM for solar diameter variations measurements

On future lunar bases it will be possible to build a pinhole camera of Santa Maria degli Angeli's size, with 1000 parallel lines separated by Δ_l=0.4 mm. Since the solar transit is 27 times slower on the Moon, the maximum image speed would be 0.13 mm/s with a fair maximum sampling frequency of 0.3 Hz. An array of PSM at different selenographic longitudes would allow a continuos monitor of the micro-variations of solar diameter.

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