

## A new approach for the heliometric optics

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**Summary.** — The heliometer of Fraunhofer in Koenigsberg (1824) is a refractor in which the lens is split into two halves to which is applied a linear displacement along the cut. Later in 1890s a variation of the heliometer has been realized in Goettingen using a beam splitting wedge: these methods were both subjected to chromatic and refractive aberrations; the second configuration being much less affected by thermal fluctuations. The reflector version of the heliometer conceived at the Observatorio Nacional of Rio de Janeiro overcome these problems: the two halves of the vitrified ceramic mirror split at a fixed heliometric angle produce the two images of the Sun exempt of chromatisms and distortions. The heliometer of Rio is a telescope which can rotate around its axis, to measure the solar diameter at all heliolatitudes. A further development of that heliometer, now under construction, is the annular heliometer, in which the mirrors are concentric, with symmetrical Point Spread Functions. Moreover the location of the Observatory of Rio de Janeiro allows zenithal observations, with no atmospheric refraction at all heliolatitudes, in December and January.

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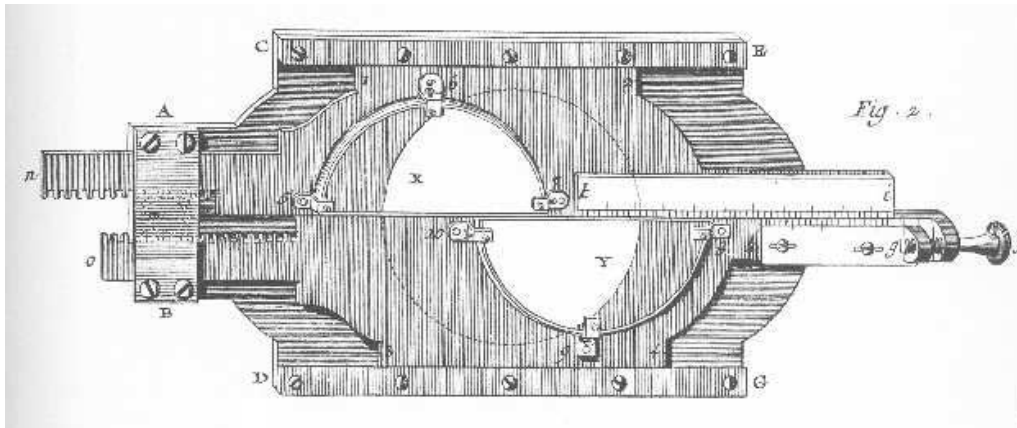


Fig. 1. – The *English Heliometer* in the *Encyclopedia of Diderot et D'Alembert* [1].

## 1. – Introduction

Recent research on global climate changes points to three distinct sources of climate disturbance: anthropogenic; natural changes in the oceans and atmosphere; and irregularities in the solar cycles. One of the most direct way to survey the last origin of climatic variability is through the measurement of variations in the diameter and the shape of the solar disk. The heliometric method is one of the most successful techniques to measure small variations of angles. Its principle has been used for the latest space borne astrometric missions, aiming to milli-arcsecond precision [2]. The success of this method is in the fact that it minimizes the dependence of angular measurements to the thermal and mechanical stability of the instrument. It follows that the classic heliometer is a refractor in which the lens is split into two halves to which is applied a linear displacement along the cut (see fig. 1). However, this classical configuration leaves still room for a residual dependence with the focus, due to non-concentricity of the beams of the two images. An improvement of the Fraunhofer Heliometer (1824) was obtained 70 years later with the Goettingen heliometer [3], reproduced in the optical configuration of the balloon borne telescope SDS [4]. Since solar observations are by nature subject to large temperature variations, the problem was tackled on its basis in the making of the Solar Heliometer of Observatorio Nacional [5]. The mirrors and its niche are made in CCZ, a vitrified ceramic, and the tube on carbon fiber, both materials of negligible thermic coefficients.

Temperature and barometric pressure are determined in real time and associated to each measure.

## 2. – Monitoring solar variability

Stars are kept in place as a product of the balance between the outward radiation pressure produced by atomic fusion in the core and the inward force produced by the sheer weight of the unbound layers of plasma. The surface drawn by such hydrostatic equilibrium defines the stellar boundaries. Thus the volume (or radius) in itself or combined with additional information gives way important information concerning the mass, temperature, age and metallicity of the star. Departures of the surface of hydrostatic

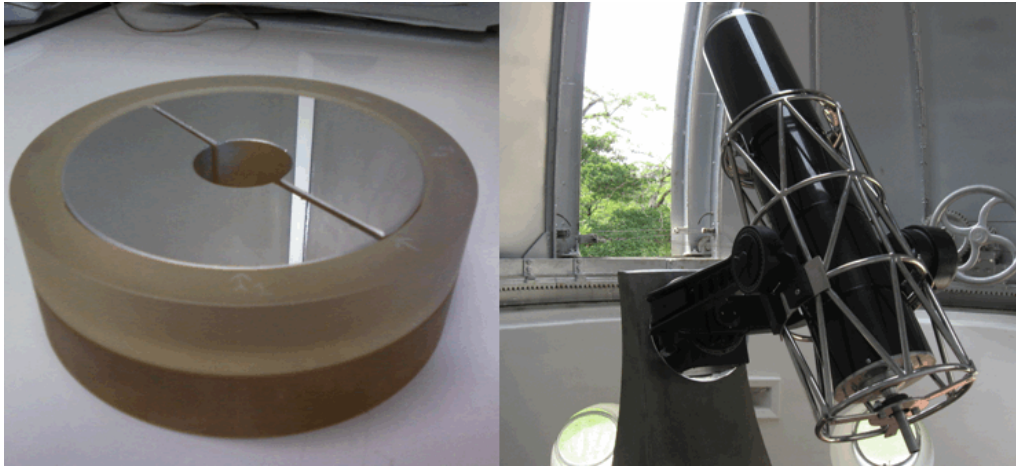


Fig. 2. – The Heliometer now operating in Rio de Janeiro, with its splitted mirror-objective.

equilibrium from a spherical volume tell of stellar magnetic field, activity cycles and sub-surface pulsation modes. In particular the measurement of the solar radius is important when combined to other solar activity, space weather, and long term Earth climate parameters.

Measurements of the Solar diameter have been made from historical times. Among the earlier series the more complete and consistent are those issued from Mercury transits [6] and eclipses [2], and thes from the observatories of Greenwich and Campidoglio (Rome) [7].

From the second half of the last century, the number of measures increased. Yet, the results are still unsure. Variations of the diameter ranging 1 arcsec were reported, but seldom confirmed. Smaller variations at the level of tens of milliarcsecond (up to few hundreds of milliarcsecond over the 11 years cycle) were derived by solar astrolabes, and are compatible also with the extrapolation of solar measurements from space. Nevertheless when comparing with the solar activity, both an in-phase and an out-of-phase signatures befit the data. The semi-diameter is seen to vary in-phase with solar activity for short periods and high bursts, but off- or out-of-phase when long periods regarding the 11 year cycle are considered.

At Brazil's Observatorio Nacional (ON) in Rio de Janeiro regular measurements of variations of the solar diameter started in 1997 with a CCD astrolabe [8]. The series extended till 2009 with a very high density of daily measures (from 10 up to 30). In 2010-11 the instrument is being upgraded and the service is interrupted [9].

From 2008 onwards, and since 2009 with an important subvention of Brazil's science foundation FINEP, an Heliometer started to be developed and build at ON (see fig. 2) [10]. The instrument had its first light in 2009, and entered in routine operation by the end of 2010 after a field test, during the 2010 total solar eclipse at Easter Island.

### 3. – Solar astrolabes and heliometer's concepts in comparison

Solar astrolabes have provided continuous results of the variations of the solar diameter since 1975. It started with the observations of F. Laclare at the Calern Station of the Observatoire de la Cote d'Azur. Immediately followed similar observations at the

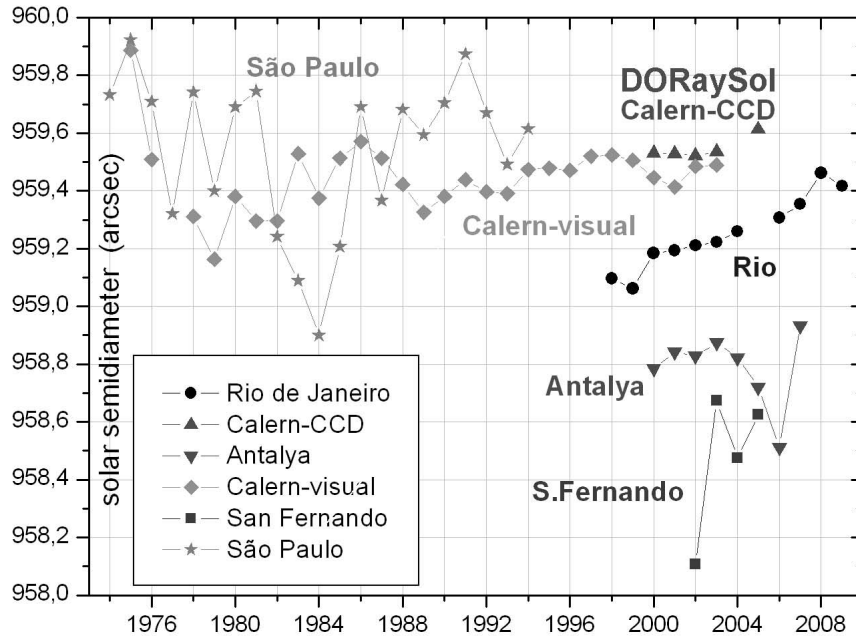


Fig. 3. – Solar semidiameter yearly averages by R2S3 (Réseau de Suivi du Rayon Solaire au Sol) astrolabes series [9].

Instituto Astronomico e Geofisico of the Universidade de Sao Paulo, at the Observatorio de Chile, and at the Real Observatorio de la Armada in San Fernando, Spain. In the later years of the XXth century the Observatorio Nacional also started its observations, immediately followed by the Antalya station of the Akdeniz University, Turkey. Finally, a few years later an improved instrument, based on the astrolabe principles, the DORaySol started operations at the same Calern Observatory [12].

The results from all those settlements show a remarkable coherence, eventhough as previously mentioned several open questions remained. Figure 3 presents the compound series of solar astrolabes highlighting the observed variation of the diameter.

The lengthy success of the solar astrolabes is based on the remarkable metrological qualities of the original Danjon astrolabe. The Danjon astrolabe was originally developed for the field campaigns of International Geophysical Year of 1958 [11]. It was originally used for stellar observations, defining an almucantar and hence the local zenith. Variations of the observed zenith could be translated into variations of the polar axis direction and spinning of the Earth.

Three aspects make the measurements relative, getting rid of instrumental and observational biases.

- The transit through the almucantar was defined by the instant of contact of the mirrored images of the star;
- the time of contact itself was determined from a collection of measures symmetric in height and azimuth; and
- the almucantar itself was defined by a collection of stars of known catalog position. For the solar observations such conditions were naturally improved.

TABLE I. – *Heliometer vs. Astrolabe in Rio de Janeiro National Observatory.*

Period	Number of observations	Standard deviation [arcsec]
Astrolabe 1998-2009	21640	0.590
Heliometer July 2011	54731	0.238
August 2011	21767	0.213
September 2011	31343	0.195
October 2011	54747	0.223
November 2011	32661	0.274
December 2011	44797	0.180
Total Heliometer 6 months	240046	

The observation becomes twice relative since the upper and lower solar limbs are measured in sequence; the number of symmetric points relatively to the almucantar could be increased at will, and placed closer to the point of contact of the mirrored images since the acquisition became digital; the exact placement and homogeneity of the almucantar itself did not matter anymore; the several measurements became fully independent, each one representing a complete determination of the solar diameter; the ancillary quantities of exact coordinates of the station and clock offset did not matter anymore either.

The concept of the heliometer is entirely opposite, and so it is its instrumental assembling. Conceptually it is an absolute measure, in which an angle is confronted against an instrumental standard. Moreover, the angle to be measured is small (the variation of the solar diameter) confronted with the corresponding linear displacement at the focal plane, thus an error on the linear measurement is smaller by orders of magnitude over the angular variation that is being measured. Additionally, if the plate scale cannot be determined, the distance between two given points depends on where lays the image, that is there is a focus dependence. In practice for the solar observations the effect is much further minimized because the plate scale is instantaneously known by timing the solar movement over the detector.

At the Observatorio Nacional, after testing several options [8], the heliometer was built through bisecting mirror. Each half-mirror is tilted of an angle slightly greater than 0.135 degrees in order to displace the images relatively to each other by one solar diameter approximately. In this way we will have opposite limbs of the Sun almost in tangency in the focal plane at the perihelion. The heliometric mirror is all made of CCZ-HS, a ceramic material with very low thermal expansion coefficient ( $0.0 \pm 0.2 \times 10^{-7}/^{\circ}\text{C}$ ). The two half mirrors are immobilized, in relation to each other, by means of an external ring, all resting over an optical plate. Its cell guarantees the mechanical and geometrical stability for the entire set. The mask seen at the top of the cell has been designed to keep the two half-mirrors blocked in place and also assures that entrance pupil has a symmetric shape. The surface quality of the optical plate and the mirrors is better than  $1/12$  and  $1/20\lambda$ , respectively.

As already said, the tube of the telescope is made of carbon fiber. This material is extremely rigid and has very low coefficient of thermal expansion. It is mounted inside a stainless steel truss support and can rotate around its axis. In order to eliminate the secondary mirror the CCD chip was removed apart from the camera electronics and installed directly in the focal plane, on a support also made of carbon fiber. In table I

the number of observations made with the astrolabe is compared with the observations made with the heliometer. In 6 months with the heliometer the number of observations made has been 10 times larger than using the heliometer in 12 years, with a rate 240 times larger, and a lower statistical dispersion.

#### 4. – Forthcoming improvements: the annular heliometer

Simultaneously to the numerous solar observations made nowadays with the Heliometer, an optical system improvement is underway: the new mirror-objective was cut in form of concentric rings. Between them an angular displacement is applied in order to generate two solar images, as the current instrument mirror-objective. With this new instrument, the second generation of the reflector heliometer under construction, it will be possible to achieve the ideal conditions of the heliometric technique, in the sense that, for the first time, angular measurements become totally independent on the instrumental focus stability. By this unique and simple optical characteristic, this telescope is suitable for space missions.

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