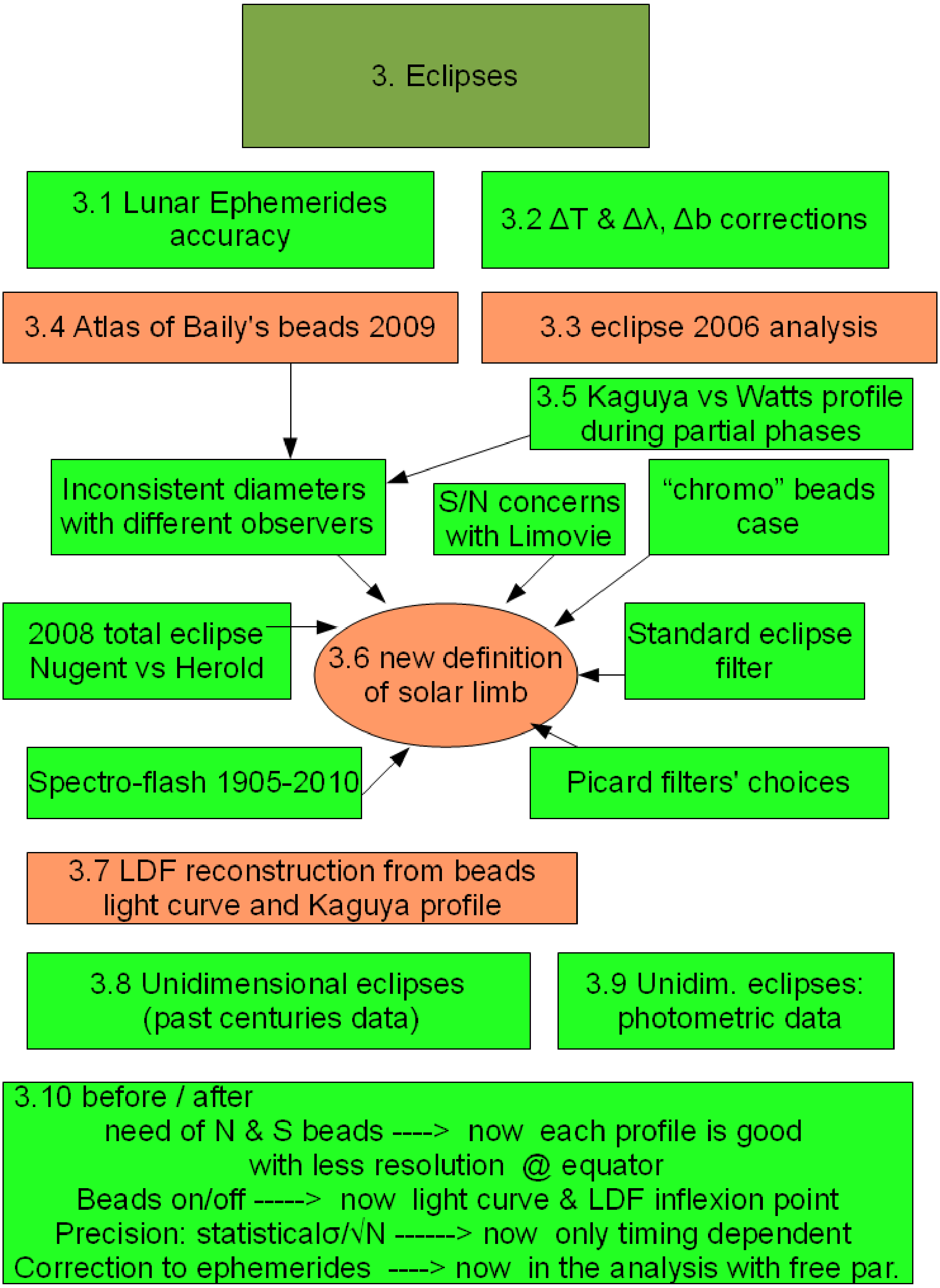
Chapter 3: Eclipses



The method of measurement the solar diameter with the total eclipses is based on the fact that the last

glimpse of photospheric light changes sudden the aspect of the sky, the darkness appear and some stars are visibile. The transition between partial and total phase occurs rather instantaneously.
Several eclipses have been studied, historical and recent, both with naked eye and electronic detectors and the information of the light during the transition before totality becomes crucial to achieve resolutions down to 0.01 arcsec in the solar diameter measurement.
The eclipse data are scattered and rare, about one each year is visible; I have inspected the past 40 years of eclipses in video tape and digital video.

3.1 Lunar ephemerides accuracy

The ephemerides of the Sun are much better known with respect to the lunar ones. This is since the times of Tycho Brahe, who gathered several observations of the Sun and produced the first accurate ephemerides of his time. Later Giandomenico Cassini, using the great meridian line of Bologna, recovered further precision, such that he was able to distinguish between Ptolemaic ephemeris and Keplerian, in the famous problem of Bissection of eccentricity.[1]
The two body problem of the Sun – Earth has much less perturbations from the other planets, than the three body one including the Moon. Newton produced a “theory” of the lunar motion with several parameters in 1702.[2] Later the “theory” of the Moon was constantly studied, because the method of the lunar distances was promising for the solution of longitude’s problem in the sea.
E. W. Brown[3] at Yale after studying the works of G. W. Hill (the one of the restricted three body problem) completed the lunar theory entirely based upon gravitation, publishing tables with precision up to 0.001 arcsec. Later a discrepancy of 10.71 arcsec and the secular acceleration of the Moon, already discovered by Halley studying the occultations published in the Almagest of Ptolemy, drove Brown to attribute to the Earth’s rotation variations the cause.
This is to understand why the “lunar theory” is much more complicated than the solar one. Nowadays more than 400 terms are used to compute the polynomials for the numerical lunar theories (of JPL and of IMCCE, the former Bureau de Longitudes) which have names like DE200 (DE are ephemerides numerically integrated) or Chapront (the French astronomers prefer to use series of analytical polynomials, usually of Chebitchev type).

The inclusion of laser-ranging data allows getting very high precisions in the lunar ephemerides.
Nevertheless the method of Baily's beads for measuring the solar diameter, originally, required data from both North and South limits of the shadow. This was to avoid possible errors on the lunar ephemerides.
Nowadays the problem of the position of the center of the Moon, which is the issue of a lunar theory, has two main problems: the difference between center of mass and center of figure, and the radius of the Moon.
For the first problem there is a maximum distance between the center of mass and the center of the figure of 0.5 arcsec in longitude and 0.24 in latitude. This space vector rotates in the space with the Moon, such that there is an instantaneous value each time.[4] Generally the ephemerides are referred to the center of mass, because they are calculated with the gravity laws.
The second problem appeared when the lunar profile changed from Watts to Kaguya (see chapter 3.5). The Japanese team of the Kaguya lunar probe, calculated the altimetry of the Moon with respect to a sphere, centered on the center of mass. The radius of this reference sphere is different from the one

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[1] Heilbron, J. L., The Sun in the Church, Harvard University Press, Boston (1999).
Kollerstrom, N., Newton's Forgotten Lunar Theory: His Contribution to the Quest for Longitude, Green Lion Press, Santa Fe,(2000).
[2] Cohen, B., Isaac Newton, Theory of the Moon's Motion (1702). With a bibliographical and historical introduction, Dawson, London (1975).
[3] Brown, E.W. Tables of the Motion of the Moon. Yale University Press, New Haven CT, (1919).
[4] Sigismondi, C., Relativistic Corrections to Lunar Occultations, Journal of the Korean Physical Society, **56**, 1694 (2010).

used in the classical Watts profiles published in 1963 and tested with more than 60000 occultations. The Watts profile has fewer points than Kaguya, and therefore less resolution, but the Kaguya profile still lacks of the test of occultations.

Source	Lunar radius
Van Flandern[5] (1970)	1738,11 ± 0,03 km
Morrison[6] (1979)	1738,23 ± 0,02 km
Morrison & Appleby[7] (1981)	1738,05 ± 0,02 km
Rosseló & Jordi[8] (1982)	1738,07 ± 0,02 km
Newhall et al.[9] (1983)	1738,09 km
Sôma[10] (1985)	1738,107 ± 0,004 km
Rosseló & Jordi[11] (1991)	1738,103 ± 0,002 km
Kaguya[12] (2009)	1737,400 km

Table 3.1 Different lunar radii for the Watts profile, in the last row the Kaguya radius.[13] As it is evident, the Moon of Kaguya is smaller than the others.

Accurate tests have still to be done in view of clarifying the compatibility between the figure of the Moon of Kaguya and the Watts profile. The Watts profile was adjusted by occultations, while Kaguya is produced by the LALT Laster ALTimeter of that Japanese lunar probe.
There are several cases which demonstrate that the profile of Kaguya is more accurate, but the times of contacts suffer of systematic differences due to the different radius and the position of the center of the figure different from the center of mass.
At the moment, as an example, the duration of totality in 2010 July 11 eclipse, in the Hao atoll, French Polynesia, has been calculated with two programs based on the two profiles Watts and Kaguya, and the result is rather different.

Phenomenon	Watts (Occult4)	Watts IMCCE	Kaguya Occult4	Kaguya IMCCE Optical center	Kaguya IMCCE Center of mass
Second contact	18h 37m 43,8s	18h 37m 43,8s	18h 37m 41,6s	18h37m 41.459s	18h 37m 43.367s
Troisième contact	18h 38m 8,6 s	18h 38m 8,6 s	18h 38m 12,2s	18h 38m 8.279s	18h 38m 11.349s
Durée phase totale	24,8s	24.780s	30,6s	26,82s	27,98s

Table 3.2 Different prediction for the duration of the totality of July 11, 2010 at Hao atoll.[14]

The reason of these discrepancies is not yet clear. Nevertheless the calculation with Kaguya profile

[5] Van Flandern, T., Astron. J. **75**, 744 (1970)
[6] Morrison, L. V., An analysis of lunar occultations in the years 1943-1974 for corrections to the constants in Brown's theory, the right ascension system of the FK4, and Watts' lunar-profile datum , Monthly Notices of the Royal Astronomical Society, **187**, 41 (1979).
[7] Morrison, L. V. and G. M. Appleby, Monthly Notices of the Royal Astronomical Society, **196**, 1013 (1981).
[8] Rosseló, G. and C. Jordi, The Moon and the Planets **27**, 131 (1982).
[9] Newhall, X. X., E. M. Standish, J. G. Williams, DE 102 - A numerically integrated ephemeris of the moon and planets spanning forty-four centuries, Astron. Astrophys. **125**, 150 (1983).
[10] Sôma, M., Celes. Mech. **35**, 45 (1985).
[11] Rosseló, G. , C. Jordi and A. Salazar, Astrophysics and Space Science **177**, 331 (1991).
[12] Araki, H., et al., Lunar global shape and polar topography derived from KAGUYA-LALT laser altimetry, Science **323** 897 (2009).
[13] This table has been compiled by Patrick Rocher of IMCCE (Paris), to whom I am particularly indebted for the fruitful discussions and for the research material he provided to me.
[14] Also this table has been computed by Patrick Rocher.

made with the center of mass is to be preferred.

Source	Ellipticity correction
Morrison (1979)	–(0,09" ± 0,01") cos(2p – 146°±1°)
Morrison & Appleby (1981)	–(0,09" ± 0,01") cos(2p – 146°±1°)
Rosseló & Jordi (1982)	–(0,087" ± 0,007") cos(2p – 146°±4°)
Sôma (1985)	–(0,128" ± 0,003") cos(2p – 135°±1°)
Rosseló & Jordi (1991)	–(0,091" ± 0,003") cos(2p – 145°±4°)

Table 3.3 Different ellipticity corrections to the Watts lunar profile.[15]

Moreover the North pole of the Watts profiles (WA=Watts Angle) is displaced from the real North pole (AA=Axis Angle) of 0.241°. The formula WA=AA + 0.241° is valid for conversions.[16]
The profile of Kaguya is not corrected as happened with the Watts profile. It is centered on the center of Mass of the Moon, while Watts was centered on the figure's center in continuous rotation around the center of mass.

3.2 ΔT & Δλ, Δβ corrections

Despite of the claimed accuracy of the ephemerides, dealing with hundredths of arcsecond, there are differences between analytical and numerical ephemerides.
In the analysis of the total eclipse of 2006 I have assumed that the profiles of Watts (the only one available before November 2009) with and without corrections of Morrison and Appleby, were the better approximations of the real lunar limbs, or the lunar figure.
The rigid figure of the Moon has been left free to move around the first solution for Baily's beads timing with a modified solar diameter, in order to minimize the residuals.
In other words the differences between Observed and Calculated timings $\Sigma(O\text{-}C)^2$ for each bead event has been minimized first with respect to a ΔR for the solar radius; after, starting from this solution, other minimizations have been calculated numerically with respect to

- ΔT which changes slightly the phase of the Earth rotation; it is the ΔUT1 parameter which is available daily from the IERS[17] service "International Earth Rotation System". The accuracy of the published values ΔUT1 is better than 0.001 s, but its use here is like a freedom parameter to include all possible uncertainties on ephemerides and their implementation in the softwares.[18]
- Δλ moves the Moon in longitude, along its orbit, leaving the Earth rotation fixed. The effect is similar to the previous correction, but there are small differences.
- Δβ is a change in lunar latitude (zero corresponds to the Moon's center of mass exactly on its orbit). This correction was originally[19] computed by arithmetical average between the solar radius correction calculated using the beads observed at the Southern edge of the eclipse, and the solution coming from the Northern ones.

Variations due to the librations	Motion of the origine of	Visibility

[15] Also this table has been computed by Patrick Rocher.
[16] Sôma, M., Celes. Mech. **35**, 45 (1985).
[17] www.iers.org
[18] The software utilized by me for the analysis of the eclipses is Occult 4. Since the year 2000, when I started these analyses many versions of the software have been modified by D. Herald. I never get access to the code. That's why I assume as fairly good the software, but I always concern with a possible small error. The same consideration stands valid for other ephemerides softwares.
[19] The method of the Baily's beads during total eclipses has been developped since 1973.The prescription to cover both Southern and Northern edges of the umbral shadow was made for being able to correct for the Δβ.

	selenographic coordinates	
$\beta > 0$	The center of the Moon is moved down	The North of the Moon is more visible
$\beta < 0$	The center of the Moon is moved up	The Sud is more visible
$\lambda > 0$	The center of the Moon is moved toward geocentric East	The East is more visible at the geocentric West
$\lambda < 0$	The center of the Moon is moved toward geocentric West	The West is more visible at the geocentric East

Table 3.4 The variations of the appearances of the Moon when β and λ change.[20]

According to the table 3.4 there is a small change also in the profile of the lunar limb, if β and λ change. These variations are of the second order, and I neglected them in my analysis, leaving the profile unperturbed.

The complete procedure has been described by me in 2009,[21] and applied to the analysis of 2006 eclipse.[22]

The advantage of this method is to reduce the errors of the ephemerides or of the software which implement them. The disadvantage is that, if the figure of the Moon departs significantly from the real one, this method converges on a solution affected by this systematic error. But this would occur even with correct ephemerides and wrong profile.

The case of Kaguya profile is still under examination: this profile is much detailed than Watts, but the radius of the "lunoid" is 0.7 km smaller, which may introduce significant systematic errors, if the altimetry of the Moon made with Kaguya does not include automatically all past corrections made upon more than 60.000 occultations. More tests have still to be done on this respect.

3.3 2006 eclipse analysis

The total eclipse of 2006 has been analyzed following the method described above in paragraph 3.2.

According to this analysis the correction to the diameter of the Sun on March, 29 2006 was $\Delta R=-0.41 \pm 0.04$ arcsec.

The event of appearance or disappearance of a Baily's bead has been inspected on the video, visually and using the LIMOVIE software.[23] The first or the last glimpse of light has been considered as the first or the last appearance of the photosphere.

3.4 Atlas of Baily's beads 2005-2008 and 2010 eclipses

The data of the observational campaigns of annular and total eclipses of 2005-2008 made by IOTA members have been published in Solar Physics in 2009.[24] Later IOTA members[25] have monitored the 15 January 2010 annular eclipse, and also other colleagues in Sri Lanka.[26]

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[20] Also this table has been computed by Patrick Rocher.

[21] Sigismondi, C., Guidelines for measuring solar radius with Baily beads analysis, Science in China, **52 G**,1773 (2009).

[22] Kilcik, A., C. Sigismondi, J. P. Rozelot and K. Guhl, Solar Phys. **257**, 237 (2009).

[23] http://www005.upp.so-net.ne.jp/k_miyash/occ02/limovie_en.html

[24] Sigismondi, C., et al., Solar Phys. **258**, 191 (2009).

[25] Raponi, A., C. Sigismondi, K. Guhl, R. Nugent, A. Tegtmeier, The Measurement of Solar Diameter and Limb Darkening Function with the Eclipse Observations, submitted to Solar Physics arXiv:1109.3559 (2011).

[26] Adassuriya, J., S. Gunasekera, N. Samarasinha, Determination of the Solar Radius based on the Annular Solar Eclipse of 15 January 2010, submitted to Sun&Geosphere (2011).

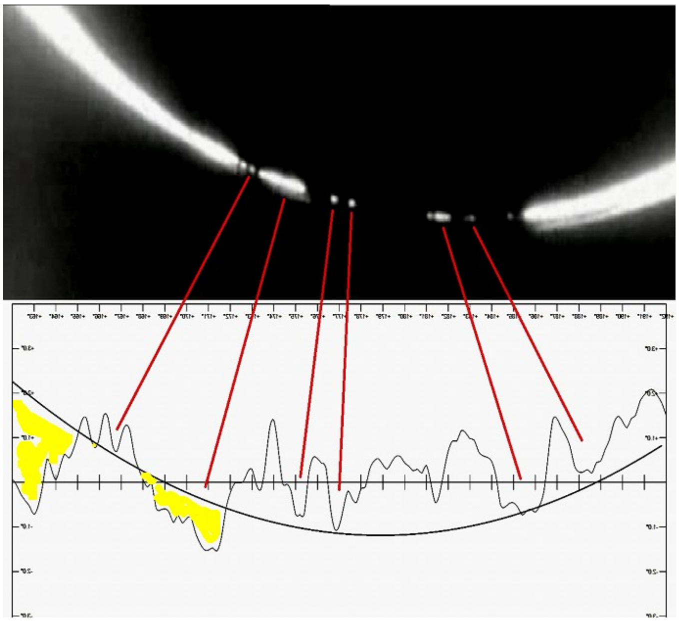

Fig. 3.1 Baily's beads from the annular eclipse of January 15, 2010.[27]

The total eclipse of 2010 on the Easter Island is being used at the Observatorio Nacional of Rio de Janeiro to calibrate the new heliometer, and the mission of CNRS in French Polynesia with 12 photometers is also under analysis.
We gather all the observations of Baily's beads on a single paper, and therefore we create a reference atlas.
The following analyses of these beads on these data did not drive us to clear conclusions: the diameter found by the various observers at different locations did not match together.
We looked for a reason, and this fact proved the need of changing the solar edge definition.
No more the ON/OFF treatment of considering the limb darkening function as a "step function", but the search of the inflexion point of the same function. This was needed because a different combination of telescope + filter + detector has different limiting magnitude for the beads, and so the outer part of the limb darkening function can or cannot be detected. In the "step function" view the limiting function of the instrument determines the position of the observed limb, yielding to inconsistencies between the diameters determined by different instruments.
The following figures explain better this concept.

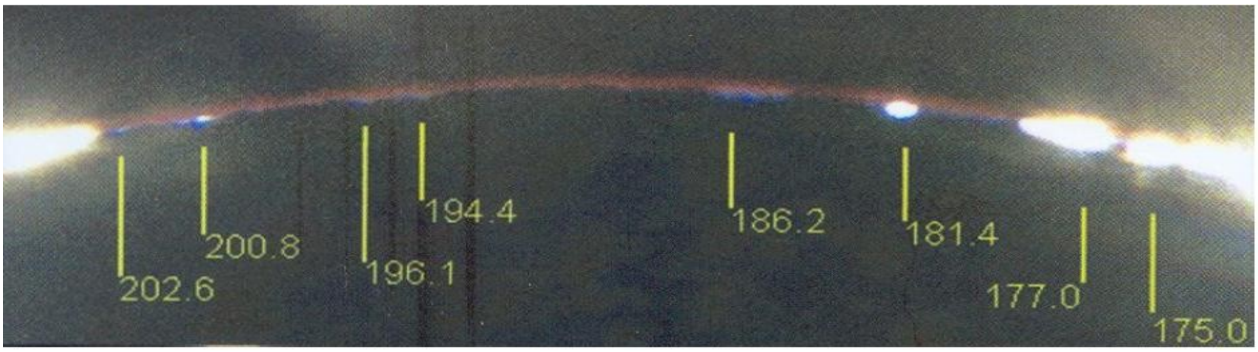

Fig. 3.2 Baily's beads and light from the solar mesosphere, as observed in the annular eclipse of October 3rd, 2005.[28]
The thin light has firstly been interpreted as chromospheric light, observable during total eclipse even

[27] Raponi, A., C. Sigismondi, K. Guhl, R. Nugent, A. Tegtmeier, The Measurement of Solar Diameter and Limb Darkening Function with the Eclipse Observations, submitted to Solar Physics arXiv:1109.3559 (2011).
[28] Schnabel, C., in Trabajos de investigacion II (Agrupacion Astronomica de Sabadell) p. 46 (2009).

with filters at density 4 to 5. After the presence of chromatism suggested that it was white light. Later it become clear that it was the light from the region of emitting lines which is above the solar photosphere and presented in the chapter 1.1 as solar mesosphere.

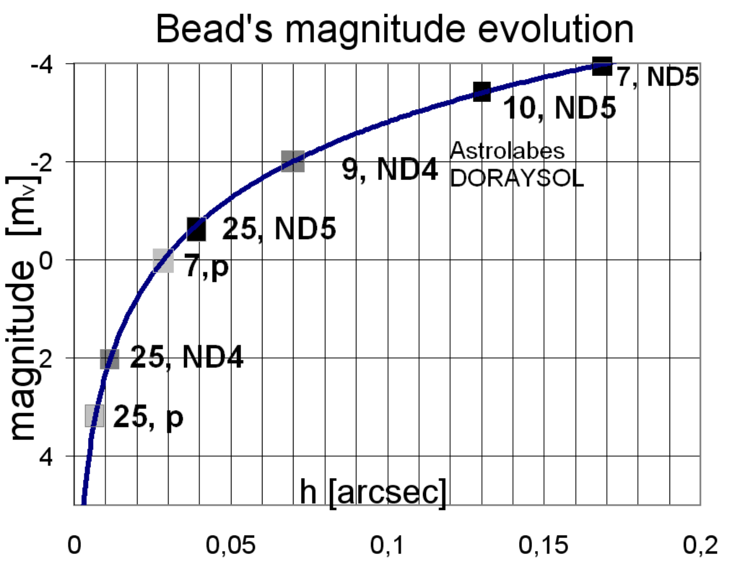

Fig 3.3 Bead´s magnitude evolution: the height of the solar limb above the valley is on the abscissa. The various square dots represent different type of telescopes. [25, p] means 25 cm opening with projection of the image. [25, ND4] the 25 cm telescope with a filter of Neutral Density of transmittance 1/10000; ND5 stands for 1/100000. **For this reason IOTA/ES decided in 2009 to standardize the filters and the telescopes for the eclipse missions**.

The visibility of the light from the solar mesosphere, which is usually difficult to be seen when observing the full disk for background reasons, and the limiting magnitude of a bead which depends on the telescope+filter+detector show that considering as a step function the true Limb Darkening Function (LDF) drives to estimate different photospheric diameters, as it is sketched in the following figure.

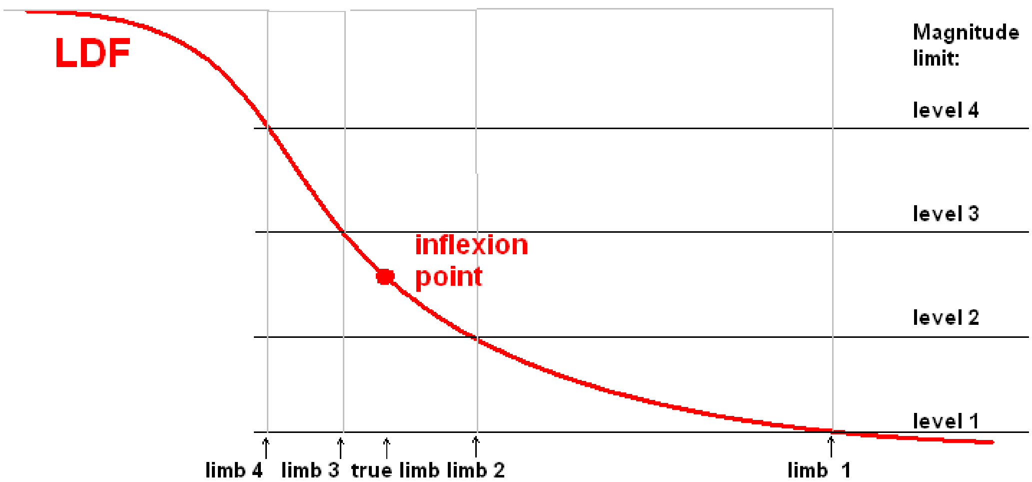

Fig. 3.4 Variation of the estimated limb with different limiting magnitudes.

The choice of Picard satellite filters has been done in order to select either regions of the spectrum with emission lines and without (see paragraph 2.4.4).

3.5 Kaguya vs Watts profile

To process the data concerning eclipse Baily's beads it is crucial to know the lunar limb profile. Until November 2009 the profile published by C. B. Watts in 1963,[29] sometimes locally upgraded with stellar occultation data, was the only one available. The precision of Watts atlas has been estimated to 0.20 arcsec.
With N beads observed the influence of this uncertainty is reduced by the statistical factor √N.
During the occultation of Pleiades occurred on August 7-8, 2007 with a Schmidt Cassegrain telescope of 20 cm I recorded 9 stars occulted, spread over 90° of axis angles.
A correction of 0.7±0.8 arcsec was required to the lunar longitude, to minimize the residuals (O-C).[30]
The occultations of Venus (June 18) and Saturn (May 22, 2007) were also used to control the lunar longitude correction to the Occult 3 software.
After that correction a residual of 0.093 arcsec represented the departure of Watts profile from the real one in the case of Venus, the better measured.

Now the profile obtained by the Laser Altimeter LALT of the Japanese lunar probe KAGUYA is available,[31] with a sampling each 1.5 Km (about 1 arcsecond at the lunar distance) and an height's accuracy of ±1 m. Kaguya data are expected to be error-free.
In the partial eclipse of 4 Jan 2011 we attempted the imaging of the lunar profile (data from Bialkow coronograph)[32] with the purpose to compare it with the profile calculated by Kaguya. Moreover the fit of "Kaguya lunoid" with the observed limb is still to be fully verified.

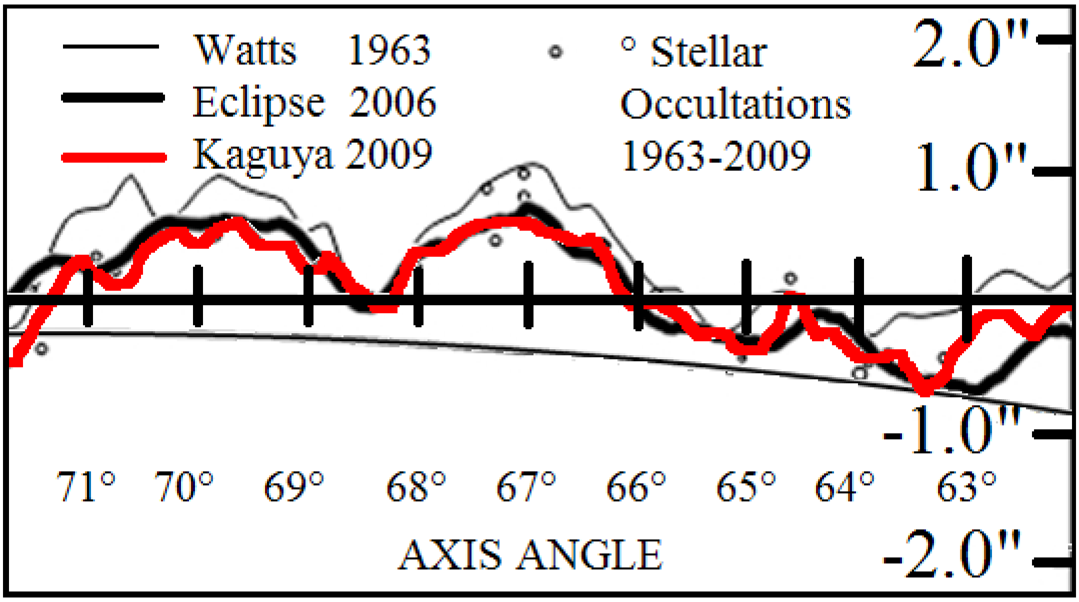

Fig 3.5 The Watts and Kaguya profiles versus the real lunar profile.

This image has been obtained superposing to the Watts profile the lunar profile as obtained with an edge finding algorithm applied to the total eclipse of 2006 observed from centerline with a 20 cm Schmidt-Cassegrain telescope near Antalya, Turkey. The small dots are data from the archive of stellar occultations occurred near the same Watts angle (in abscissa) and near the same libration.

[29] Watts, C. B., The Marginal Zone of the Moon, Astronomical Papers prepared for the use of the American Ephemeris and Nautical Almanac, Vol. XVII (U. S. Government Printing Office, Washington, 1963).
[30] Sigismondi, C., Relativistic Corrections to Lunar Occultations, J. of Korean Physical Society **56** , 1694 (2010).
[31] Araki, H., et al., Lunar global shape and polar topography derived from KAGUYA-LALT laser altimetry, Science **323** 897 (2009).
[32] presented firstly in the first chapter of this thesis, and used to measure the height of the spiculae.

The thick (eclipse) line is the real profile, obtained with the algorithm to find the edge.[33]
The thin line is the Watts profile and red thick one the Kaguya profile. Departure as big as 0.4 arcsec occur between Watts and real.
A similar situation occurs when comparing Watts and Kaguya.
The great sampling of the Laser Altimeter of the Japanese probe Kaguya (Selene) gives a point each 1.5 km all over the Moon, with an accuracy of 4 m in height.

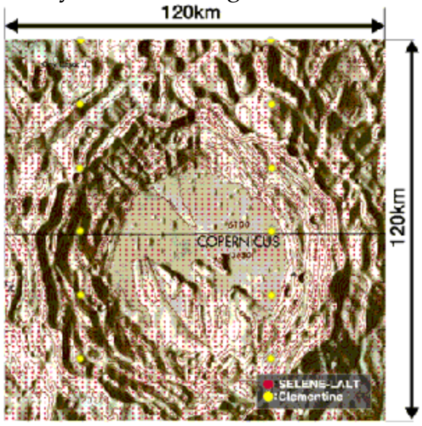

Fig 3.6 The sampling rate of Kaguya in red dots, compared with Clementine (yellow).

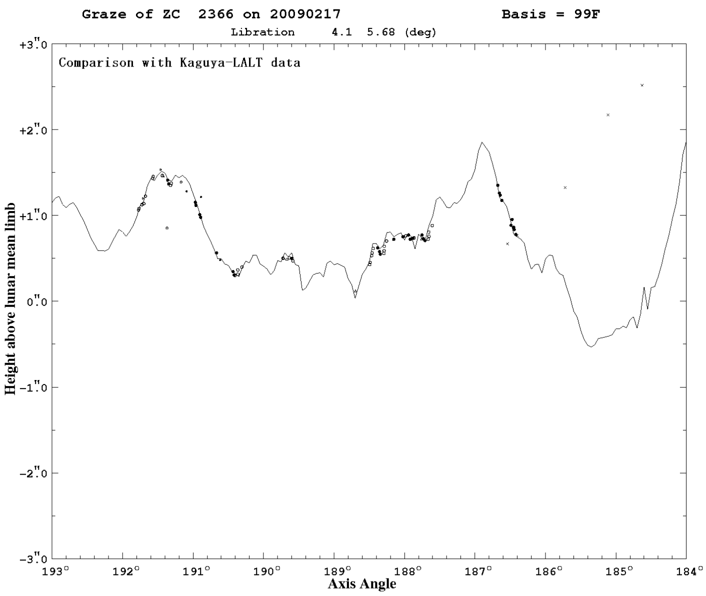

Fig 3.7 The comparison between Kaguya and a grazing occultation of the star ZC2366 of February 17, 2009, observed by IOTA/ES.

From the previous figure the agreement seems to be perfect, but there are other positions in which the departure is significant.

33 Canny, J., A computational approach to edge detection, IEEE Trans. Pattern Analysis and Machine Intelligence, vol. 8, pages 679-714 (1986).

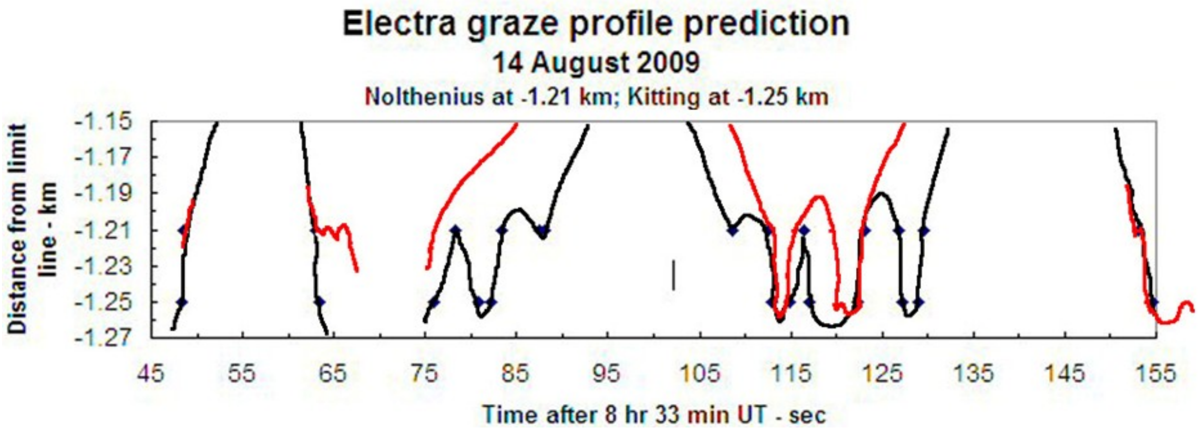

Fig 3.8 The predictions (red) vs observations (black with dots) of the grazing occultation of Electra (Pleiades) on August 14, 2009. There is a discrepancy of 0.8 arcsec, due probably to the different radius of Kaguya's lunoid.[34]

The tests on the Kaguya profile are still ongoing, the "lunoid" used by Kaguya with its smaller radius has to be checked again, before using directly the Kaguya profile.

3.6 New definition of solar limb

Different extension of the solar photosphere are measured at different wavelengths.
The classic definition of solar limb is the location of the maximum of luminosity profile derivative of the continuum spectrum,[35] already adopted in the oblateness studies. The effect of the blend of tiny emission lines just above the solar limb[36] visible during eclipses is better considered by this definition operative also for eclipses.
Otherwise the observations of Baily's beads with different level of signal to noise show clearly the effect of the emission lines, which extends the measured solar photosphere depending on the instrumental parameters.
With the use of the inflexion point in the eclipses observations we adopt for the first time the same approach as the observations at full disk.

3.7 LDF reconstruction from Baily's beads light curve and Kaguya profile

The studies on the Limb Darkening Function made with Baily's beads of the annular eclipse of 2010 is presented in the annexed paper, submitted to Solar Physics.[37]
The inflexion point position is reconstructed from the luminosity profile of a bead and from the geometrical form of the lunar valley at the limb, available from Kaguya data.
The light curve of two beads have been determined and the Limb Darkening Function deconvoluted by a numerical procedure including the area of photospheric light through these Baily's beads varying with the time.

[34] Bredner, E., Moon Limb after Kaguya, XXVIII ESOP meeting, Niepolomice, Poland 29 August – 3 September 2009.
[35] Hill, H. A., R. T. Stebbins and J. R. Oleson, Astrophys. J. **200** 484 (1975).
[36] Flash spectrum is related to spectroscopy: a better definition is the one of solar mesosphere give in chapter 1.1
[37] Raponi, A., C. Sigismondi, K. Guhl, R. Nugent, A. Tegtmeier, The Measurement of Solar Diameter and Limb Darkening Function with the Eclipse Observations, submitted to Solar Physics arXiv:1109.3559 (2011).

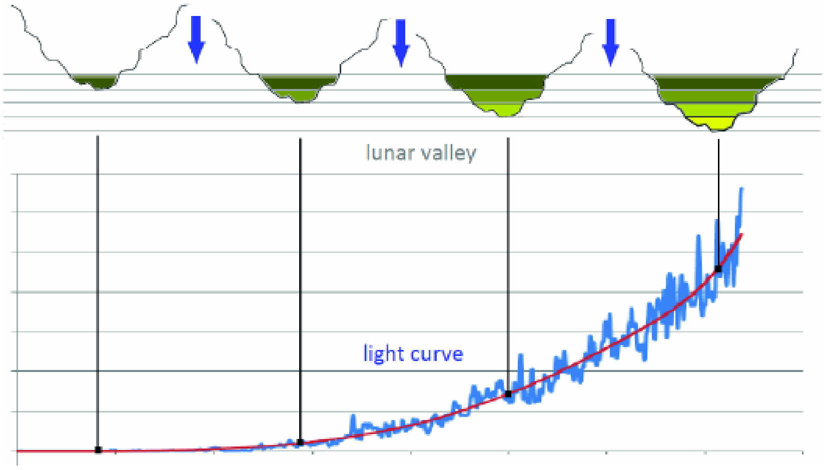

Fig 3.9 The light curve of a bead is the product of the LDF by the exposed area.

In this figure the variation of the LDF is represented by layers of different colors, which covers gradually the different strips of the lunar valley. The area of the strips is computed on the Kaguya profile, the light curve is observed and the LDF is obtained with the inverse operation described in the caption. More details of the algorithm adopted are in the annexed paper.

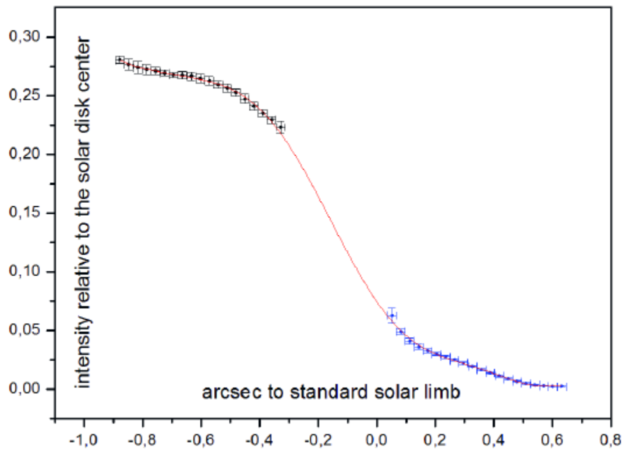

Fig 3.10 A Limb darkening profile obtained by the inversion technique here described. The left and right parts of the curve are obtained with two different 8-bits CCDs, the lower right saturated before the inflexion point, the upper left had a limiting magnitude brighter than the inflexion point. 12-bits CCD are recommendable.

The luminosity profile is normalized to the center of the solar disk according to Rogerson (1959)[38] for the inner parts, and in arbitrary way for the outer parts. The zero of the abscissa is the position of the standard solar limb with a radius of 959.63 arcsec at 1 AU. The error bars on y axis are the 90% confidence level. The error bars on x axis are the thickness (h) of the lunar layers. The solid line is an interpolation between the profiles and gives a possible scenario on the position of the inflection point.

The results shows light at least 0.85 arcsec beyond the inflection point, and this suggests to reconsider the evaluations of the historical eclipses made with naked eye.

From the two beads examined it is impossible to infer an exact location of the inflection point, but it is possible to deduce an upper and lower limit corresponding to the points that better constrain it:

-0.190 arcsec $< \Delta R < +0.050$ arcsec, for the eclipse of January 15, 2010.

[38] Rogerson, J.B., The Solar Limb Intensity Profile, Astrophys. J. **130**, 985 (1959).

3.8 "Unidimensional" eclipses: solar diameter in the past centuries

Reliable past values of the solar radius are believed to be obtained from the durations of ancient total eclipes.

The values of solar diameter calculated from historical (1567 on), and recent (1966 on) eclipses (and planetary transits) using the Watts' lunar profile are discussed and compared with the solar activity.

Before 1966 there are only edge data for eclipses of 1567, 1715, 1869 and 1925. The precision on the solar diameter with these naked eye data is discussed.

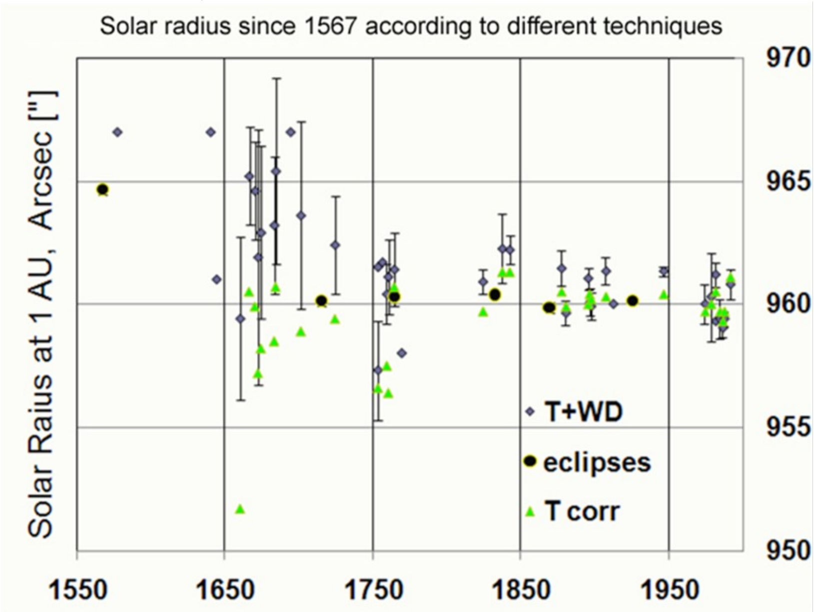

Fig. 3.11 All historical data available on the solar diameter. T stands for Toulmonde,[39] WD for Wittmann and Débarbat.[40] The eclipses are much stable and with narrower errors, excepted the eclipse of Clavius.

The history of past diameter is obtained mainly from Mercury's transits. How reliable are these data? I already discussed this topic in the paragraph 2.3 about the transit of 1832.

Once we will know the W parameter the past eclipses would give us the luminosity of the Sun in these times, especially right after the Maunder minimum in 1715, in order to understand the role of our star in the little ice age.

The studies for the following historical eclipses show a solar radius significantly larger than the standard one, but they must be reconsidered in the light of the results obtained in the previous section: determination with the "classical approach" can be misleading.

3.8.1 Clavius, 1567, Rome

Stephenson, Jones, and Morrison[41] studied the observation of an annular eclipse made by the Jesuit astronomer Christopher Clavius in April on 9, 1567 in Rome, they derived limits to the Earths spin rate back to that time. They attributed the appearance as a ring of the annular eclipse to the effect of

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[39] Toulmonde, M., The diameter of the Sun over the past three centuries, Astronomy and Astrophysics, **325**, 1174 (1997).

[40] Wittmann, A. D. and S. Debarbat, The solar diameter and its variability, Sterne und Weltraum **29**, 420 (1990). In German.

[41] Stephenson, F. R., J. E Jones, L. V. Morrison, The solar eclipse observed by Clavius in A.D. 1567. Astronomy and Astrophysics, **322**, 347 (1997).

the ”inner corona” of the Sun. If the ring of that annular eclipse was instead a solar layer inner to the inflection point position, the average angular radius of the Sun would have been some arcsec larger than its standard value of 959.63 arcsec.

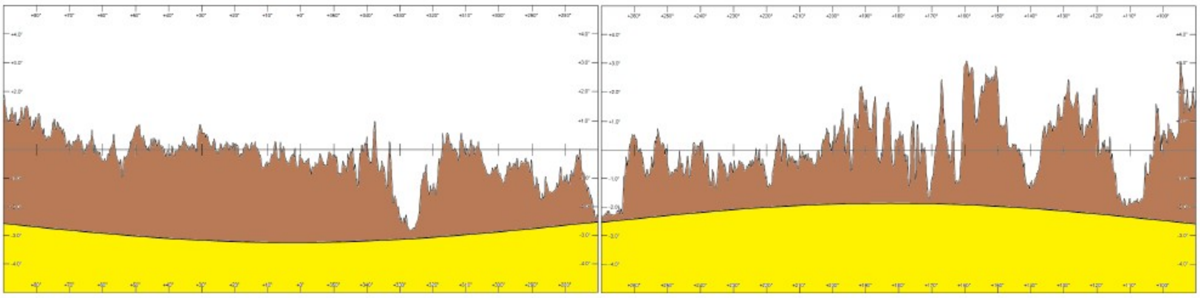

Fig. 3.12 The lunar limb during the eclipse of Clavius. The solar limb would have been 4.5 arcsec below the standard value.

The figure 3.12 shows the eclipse of April 9, 1567 simulated with Occult 4.0 software. View from Collegio Romano (lat = 41.90◦ N, long = 12.48◦ E) where probably he made his observation. The lunar limb's mountains are plotted in function of the Axis Angles (the angle around the limb of the Moon, measured Eastward from the Moon's North pole). 1◦ in the Axis Angle (abscissa) corresponds to 16 arcsec at the mean lunar distance. The solid line under the mountains is the standard solar limb. The figures are the Northern (left) and the Southern (right) semicircle.
To have the solar limb higher than all the mountains of that lunar limb it should be $\Delta R \geq +4.5$ arcsec.

According to the formula of Rayleigh for the angular resolution $\varrho=1.22\lambda/D$, and taking into account a pupil diameter D=2 mm (day vision), one gets $\varrho=50$ arcsec.
Details smaller than 50 arcsec are not visible on the Moon profile.
This means that the ring of the annular eclipse could have not been complete but divided by mountains no more than 50 arcsec, that is about 3◦ in Axis Angle. For explain the observation of a complete ring with naked eye, for this eclipse, is thus sufficient $\Delta R = +2.5$ arcsec, that still remains a great value.
According to this proof of a larger solar diameter Eddy et al. (1980)[42] assumed a secular shrinking of the Sun from the 17th century to the present. The observation of Clavius was the subject of several studies and publications: even Kepler asked Clavius to confirm it was a solar ring, rather than diffuse appearance, that he would attribute to the lunar atmosphere, but Clavius always confirmed what he already wrote (Clavius, 1581).[43] The interpretation for an annular eclipse is still debated in scientific publications.
Because this observation was made with naked eyes, a more careful study on this eclipse has to take in account the angular resolution of an eye pupil.

3.8.2 Halley, 1715, England

Edmund Halley attempted to measure the size of the umbral shadow by observing the total eclipse of 1715 in England. Halley as secretary of the Royal Astronomical Society collected the numerous reports of this observation (Halley, 1717).[44]
His idea was to associate the duration of the eclipse with the position for each observer, in order to

[42] Eddy, J.; Boornazian, A. A.; Clavius, C.; Shapiro, I. I.; Morrison, L. V.; So_a, S.: Shrinking Sun. Sky and Telescope 60, P. 10 (1980).
[43] Clavius, C., Commentarius in Sphaeram Iohannis de Sacrobosco, Venezia, (1581).
[44] Halley, E.: 1717, Observations of the Late Total Eclipse of the Sun on the 22d of April Last Past, Made before the Royal Society at Their House in Crane-Court in Fleet-Street, London. By Dr. Edmund Halley, Reg. Soc. Secr. with an Account of What Has Been Communicated from Abroad concerning the Same. *Philosophical Transactions (1683-1775)* **29**, 245 – 262.

assess the size of the shadow of the Moon on the Earth.
But from these observations we can obtain also interesting informations about the solar diameter.
In the present work, thanks to the Occult 4 software and the new data on lunar profile we are able to reanalyze the 1715 eclipse data. In particular we consider the observations on the Southern and Northern path of totality, where timings are not required to deduce the diameter of the Sun. We simply require to know where the observers were and if they saw a total or a grazing eclipse to infer an upper or a lower limit of ΔR from each eyewitness.
Table 3.5 shows the observations we consider. The first is located in the Northern limit of the shadow, the second and the third in the Southern one. According to Occult 4 we have from the observers in the Southern limit: +0.85 arcsec $<\Delta R<$ +0.94 arcsec. The error, due to the uncertainties on the observation's coordinates is 0.2 arcsec.

Location of observation	Position coordinates	How appeared the Sun in the instant of maximum occultation	Lunar - Solar limb position by Occult 4
Darrington	53°, 39', 50.4" N 358°, 44', 09.6" E	"Point like Mars"	+ 0.34 arcsec
Bocton Kent	51°, 17', 16.8" N 0°, 56', 16.8" E	"Point like Star"	+ 0.85 arcsec
Cranbrook Kent	51°, 06', 03.6" N 0°, 31', 44.4" E	"Duration instant"	+ 0.94 arcsec

Table 3.5 The Eclipse in 1715, England. Observation in the Northern (Darrington) and Southern (Bocton Kent and Cranbrook Kent) limit of the umbra shadow. Position coordinates by Dunham *et al.* (1980).

Because of the uncertainties on ephemeris, the center of the solar disk could have been in a different position with respect to the simulated standard Sun.
Thanks to the observation in the Northern limit, an eventual error on ephemeris could be bypassed, obtaining a larger gap: +0.59 arcsec $<\Delta R<$ +1.28 arcsec.
The lower and upper limit are obtained moving the center of the solar disk in the North-South direction till the positions where the eyewitnesses are still valid.
Both the evaluations of the historical eclipses are made without any reference to the inflection point, and considering the LDF as a step function. This can enlarge the measured ΔR. It is the main concern with naked eye observations.

3.8.3 Recent eclipses

Here the plot of the analysis of the recent eclipses published and discussed in the annexed paper.[45]

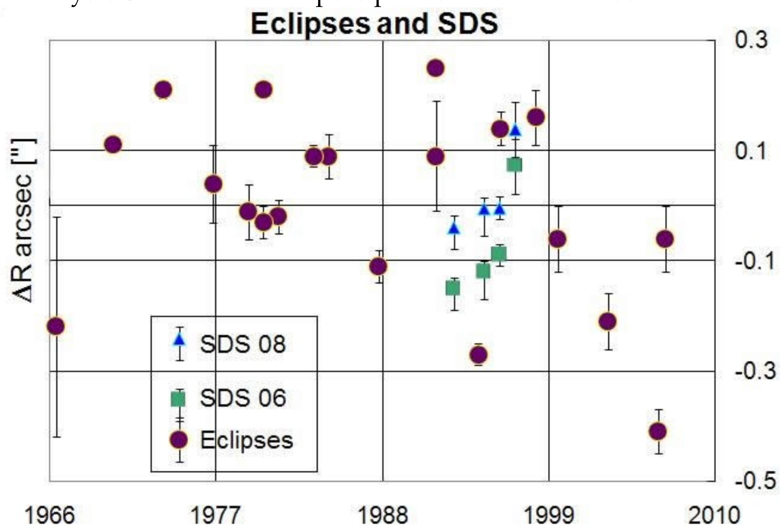

Fig. 3.13 The eclipses in the last 45 years. The four eclipses without errorbars are the photometric data of Y. Kubo. The data of SDS are superimposed.

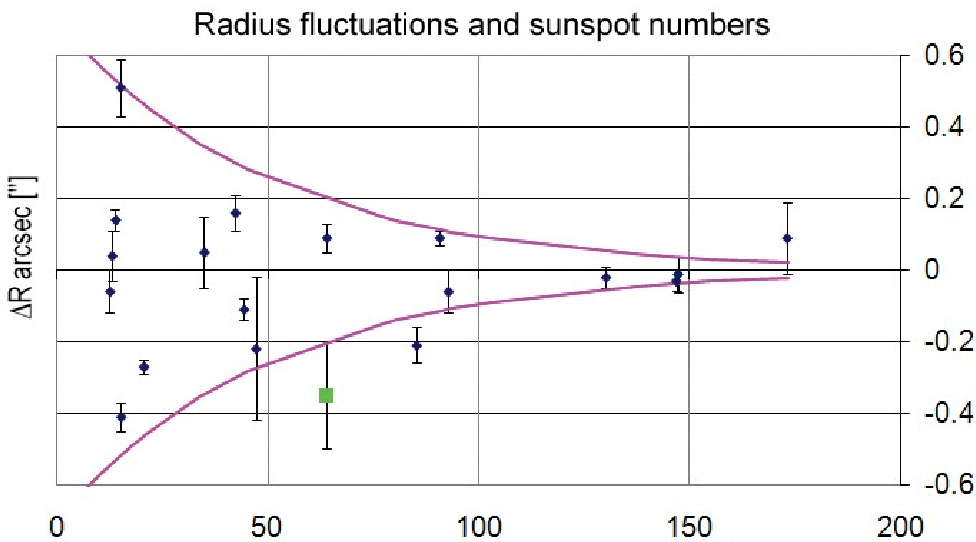

Fig. 3.14 The eclipses data redrawn as function of the solar activity, with the sunspot number in abscissa. The green square is the transit of Mercury of 2003 used by SOHO for a calibration of the MDI.

3.9 Unidimensional eclipses: photometric data

Eclipse data from photometers have very high time accuracy and almost no spatial information. Their utility in accurate diameter's measurements is discussed.
The first attempts of this kind of measurement have been done by Kubo in 1973.[46]
The eclipse mission of 11 July 2010 in French Polynesia is also dedicated to measure the solar diameter from the ground.
The difference between Baily's beads and photometer's concepts is in the "memory" of the detectors. The pixels of CCD used in the video for eclipses can have a memory up to 1s after their illumination.

[45] Kilcik, A., C. Sigismondi, J. P. Rozelot and K. Guhl, Solar Phys. **257**, 237 (2009).
[46] Kubo, Y., Publications of the Astronomical Society of Japan, **45**, 819 (1993).

And this occurs also with CMOS detectors, as verified during the occultation of Venus by the Moon of December 1, 2008,[47] where another glimpse of light appeared 1s after the complete decrease of the fitted curve.

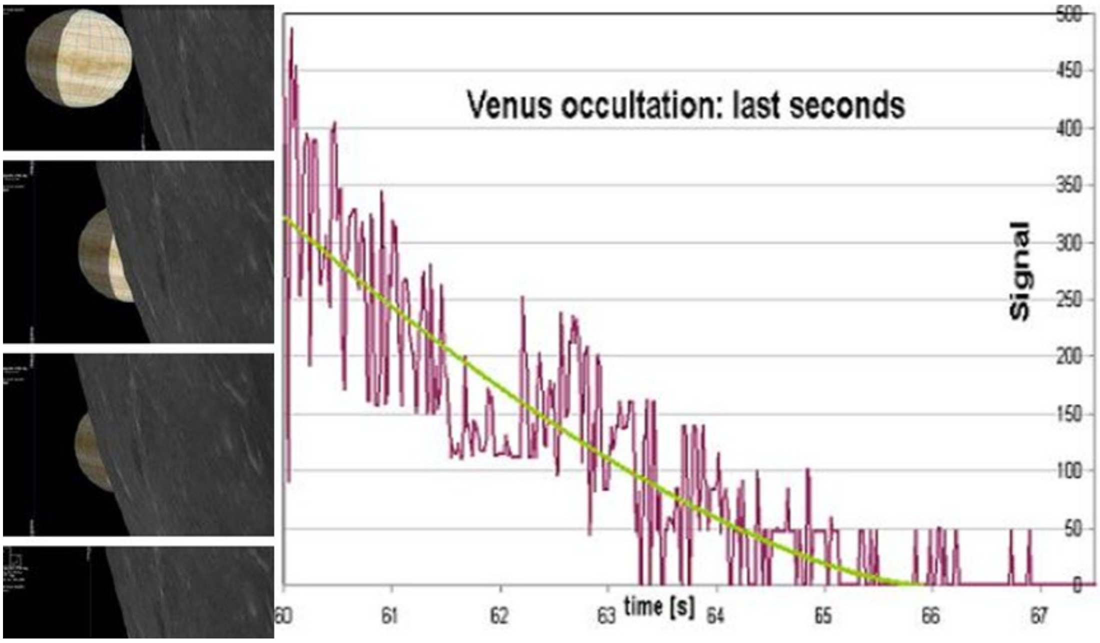

Fig. 3.15 Venus occultation of December 1st, 2008 observed from Rome. See the two signals 1 s after the zero of the fit.[48]

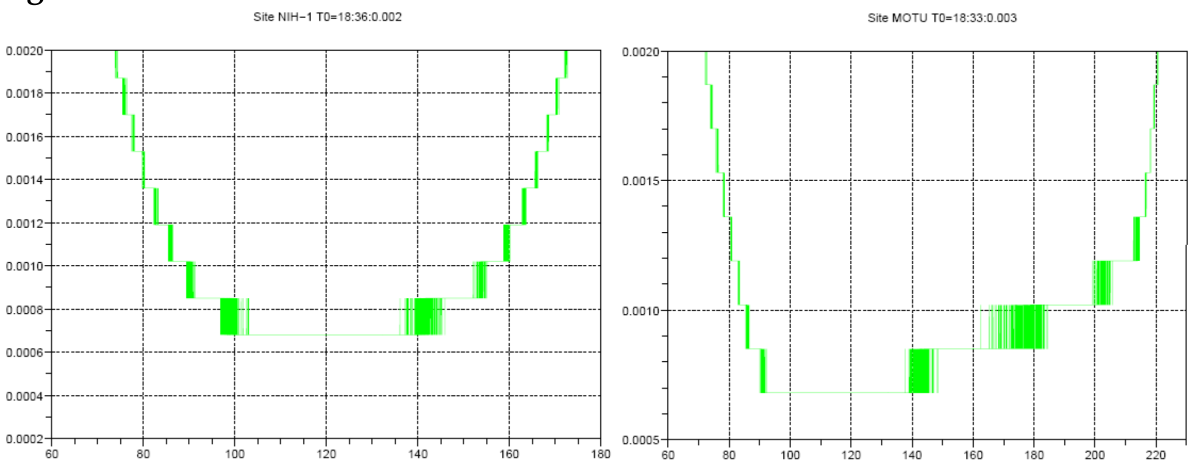

Fig. 3.16 Signals from two photometers at different sites in the CNRS mission in French Polynesia (2010).[49]

The observable is the duration of totality (the lower horizontal line in the figure). With respect to Baily's beads observations here we have the information without spatial resolution.
One chord for each observing station can be recovered on the solar disk, i.e. only one diameter at time.
The passage of clouds can also affect the last stages before totality.
The use of a network of 12 photometers displaced on the ground at several km each from the other, compensates the unidimensionality of each measure.

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[47] Sigismondi, C., R. Nugent, G. Dangl, Measuring solar disk shape up to relativistic accuracy: the role of scintillation in ancient naked eye data, Proceedings of the 3rd Stueckleberg Workshop on Relativistic field Theories, Pescara, Italy, 8-14 July 2008. edited by N. Carlevaro, R. Ruffini and G. V. Vereshchagin, Cambridge Scientific Publishers, p. 303 (2011). arXiv:1106.2451
[48] Figure from Sigismondi, C. R. Nugent and G. Dangl, arXiv:1106.2451(2011).
[49] Courtesy of Jean-Yves Prado, CNES.

The same strategy will be exploited in Australia, near Cairns, for the November 13, 2012 eclipse. [50]
The oscillation of the signal before totality can also be attributed to the electronic noise and to scintillation.[51]
The photometers are 2.4x2.4 mm without collecting optics, for these reason the scintillation can have important effect.
A formula[52] for estimating scintillation without taking altitude into consideration is:
$\Delta mscint = (0.09 \cdot A^{7/4}) / (D^{2/3} \cdot \sqrt{(2 \cdot t)})$
where A is the airmass, D is the aperture in cm and t is the integration time in seconds.
For A=1.89, because the Sun altitude was h=32° and A=1/sin(h), D=0.24 cm and t=0.01 s, Δmscint = 5 magnitudes, or a factor of 100 in intensity, which is beyond of what observed.
Nevertheless in the case of the eclipsing Sun, the poissonian approach is more correct.
With N photons detected, a temporal variation within $\pm\sqrt{N}$ is expected, and this can be responsible of the noise near the beginning of the totality.
The scintillation of the last crescent of Sun, moreover, produces the flying shadows, observed for the first time during total eclipse of 1870 in Sicily.

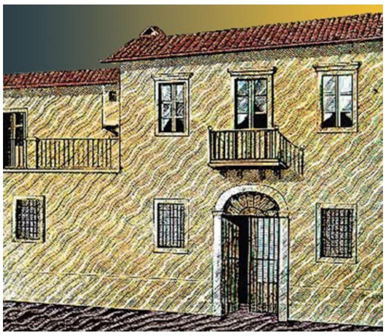

Fig. 3.17 Flying Shadows in Sicily during 1870 eclipse. Image of the epoch.

For the experiment of Australia with the network of photometers, I strongly recommend to put a "mighty mini"[53] device near to each photometer, in order to have also spatially resolved information.
The mighty mini devices have been developed in IOTA, for asteroidal occultations, with spectacular results obtained by a single observer controlling several stations.
The cost of the mission would not increase significantly.

[50] Espenak, F., http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2012Nov13Tgoogle.html
[51] Sigismondi, C., R. Nugent, G. Dangl, Measuring solar disk shape up to relativistic accuracy: the role of scintillation in ancient naked eye data, Proceedings of the 3rd Stueckleberg Workshop on Relativistic field Theories, Pescara, Italy, 8-14 July 2008. edited by N. Carlevaro, R. Ruffini and G. V. Vereshchagin, Cambridge Scientific Publishers, p. 303 (2011). arXiv:1106.245
[52] This formula is adapted by Radu Corlan from a series of papers by Dravins et al. that begin with "Atmospheric Intensity Scintillation of Stars, I. Statistical Distributions and Temporal Properties" PASP 109, 173 (1997) and published in The AAVSO CCD Observing Manual, AAVSO, Cambridge MA (2009).
[53] Degenhardt, S., http://scottysmightymini.com/ (2011).

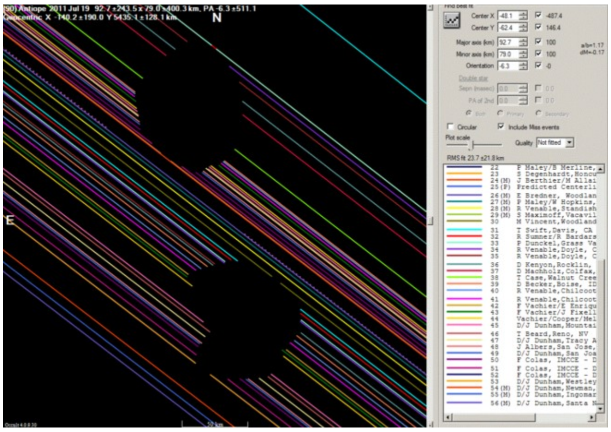

Fig. 3.18 The asteroidal occultation of the double asteroid 90 Antiope (July 19, 2011) observed with an array of mighty mini devices coordinated by IOTA/US section.

3.10 Before and after this work

The situation of this field of research before and after this work is described, putting into evidence our new contributions.

The unification of the methods to find the solar edge between the full disk observations and the eclipse observations has been the achievement of this work.

This was possible only after gathering all observations of Baily's beads by the European Section of the IOTA members since the year 2005.

The coordination of this activity has permitted to exploit the observational competences of these amateurs and their economical effort (about 30 travels all around the World, i.e. 100-150 K€ of budget) to converge on a more accurate and general procedure for the evaluation of the solar diameter with eclipses.

Now the different limiting magnitudes of the instruments, or the different saturation levels of the detectors are no longer affecting the estimate of the solar diameter.

As in the new procedure adopted with the annular eclipse of 2010, it is possible to see if the CCD are saturated before or after the inflexion point by the inclination of the recovered LDF curve.

CCD at 12 bits are recommended for the next eclipse mission, in order to avoid this saturation problem which prevents to locate correctly the inflexion point of LDF.