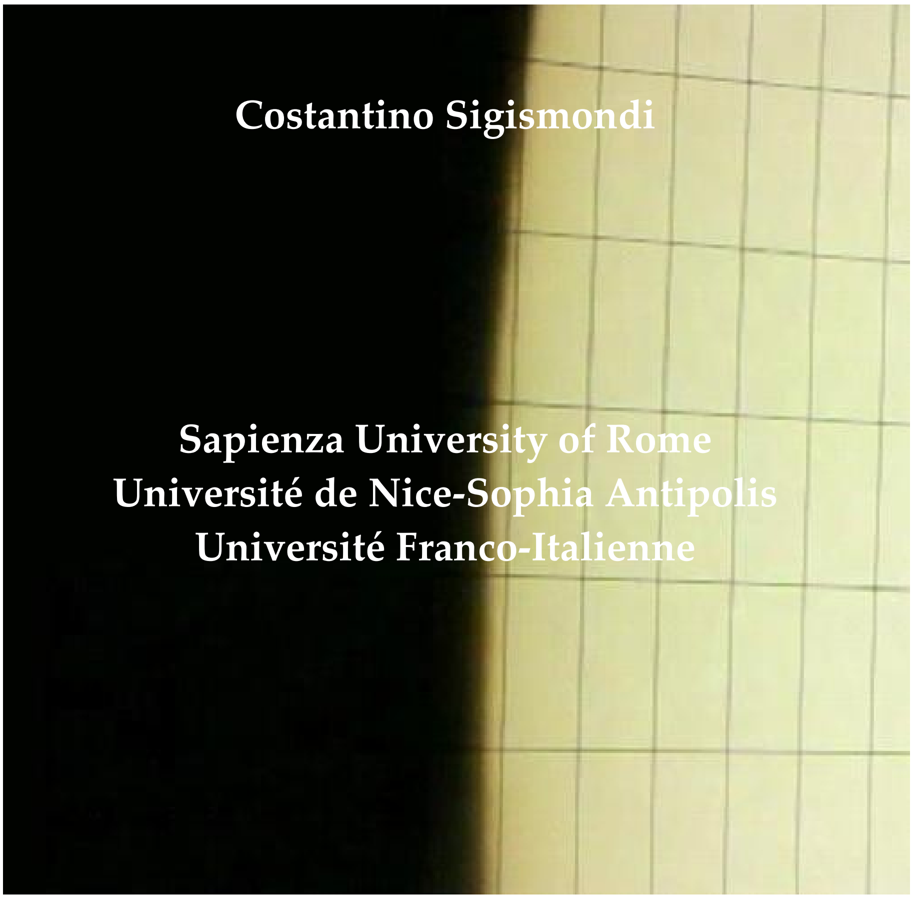
High precision ground-based measurements of solar diameter in support of Picard mission



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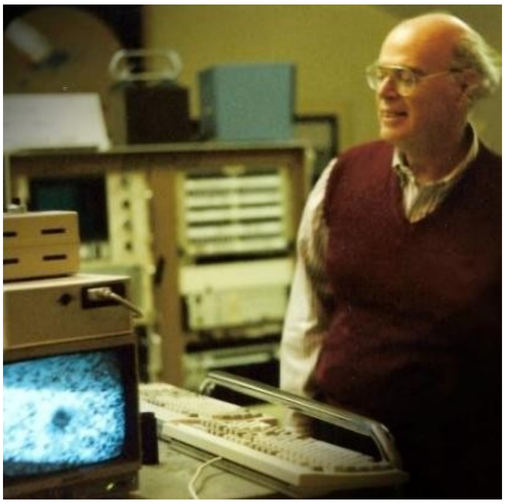
in memory of Jean Arnaud

Jean Arnaud (top left) and myself (bottom right)
during the meeting "Light of the Dark Universe"
held in Taipei in end May 2008.

and Alessandro Cacciani

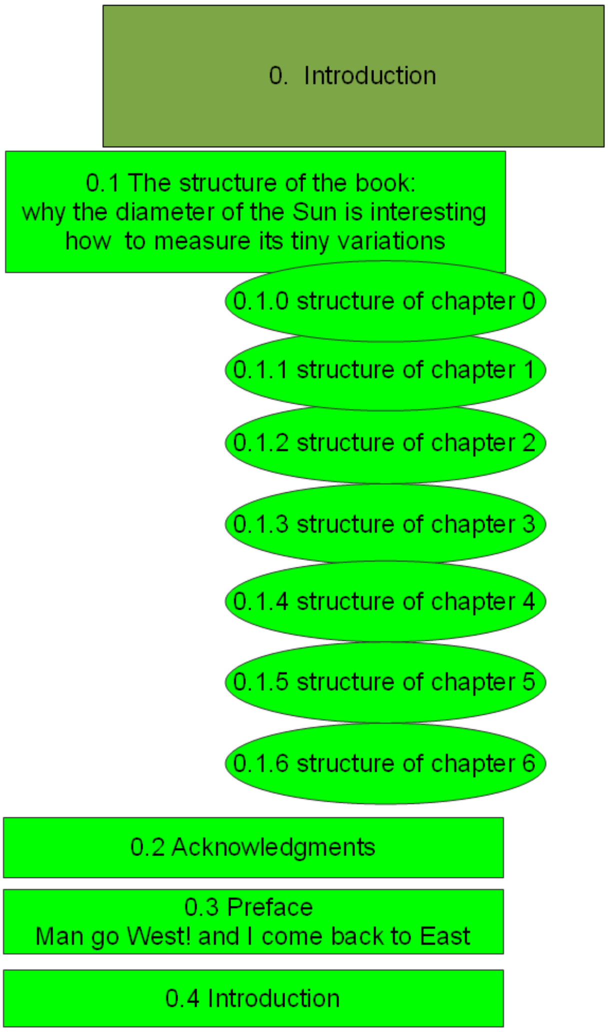


and with the deepest gratitude to my father Camillo

with whom I have seen the better sunsets from the Eternal City
May the Lord welcome them in the eternal life

Chapter 0. Introduction

0.1 Structure of the book



All chapters are presented with their topics, in order to have a conceptual map of the argumentations.

0.1.0 Chapter 0: Introduction

0.1 The structure of the book

The first chapter is devoted to present the conceptual map of the book, divided into seven chapters numbered from 0 to 6, in the paragraphs 0.1.0 to 0.1.6.

0.2 Acknowledgments

The success of a work is due to a network of positive human relationships.

I don't like autistic personalities even if capable of great achievements in science.

0.3 Preface

My roadmap towards solar astrometry lasted more than a decade, and it is drafted in this preface.

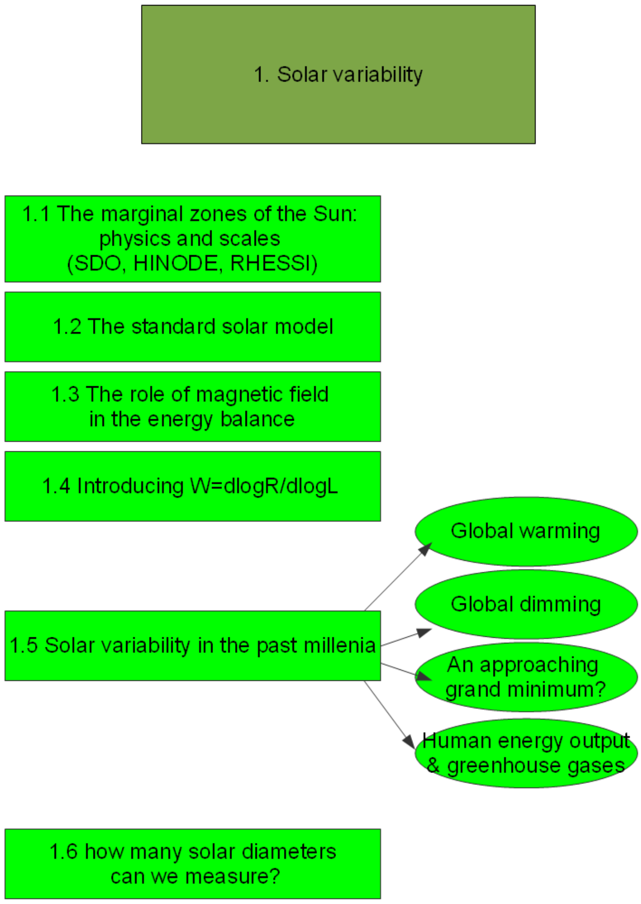
0.4 Introduction "from Picard the abbot, to the satellite"

The theme of the measurement of solar diameter is presented form an historical point of view, driving the focus from the early measurements made by the abbot Jean Picard (1620-1682) to the satellite bearing his

name launched on 15 July 2010.
During the XIX century (see the Nautical Almanac, quoted by Angelo Secchi and Simon Newcomb) the standard value for the angular solar diameter at one astronomical unit has been changed a few times by about 1”. These changes may reflect the use of different methods, instruments as well as a change in the diameter itself. The adopted standard value of solar diameter is 959.63” (Auwers, 1891) with an irradiation correction of -1.55”.

0.1.1 Chapter 1: Solar variability

The title is inspired by “The Sun as a Variable Star” the proceedings of the IAU colloquium n. 143.[1]



The variation of the luminosity L with radius R is described by a parameter W=dlogR/dlogL. Picard mission will measure W accurately, and its value will be used to recover the past values of L_sun from historical measurements of R_sun in order to feed Earth’s climate models.

1.1 The marginal zones of the Sun: physics and scale

This paragraph is dedicated to the marginal zones of the Sun, i.e. the solar surface and the atmosphere nearby when it is seen from a grazing view. Images, scales and physics are here summarized. The solar mesosphere is here defined.

1.2 The standard solar model

The standard solar model has two free parameters: the mixing length scale and the helium abundance, and after 4.52 billion year it should return the present radius of the Sun, its luminosity and the observed metal

[1] The Sun as a Variable Star, Solar and Stellar Irradiance Variations, J. M. Pap, C. Fröhlich, H. S. Hudson & S. K. Solanki, Cambridge University Press 1994.

abundance. During the main sequence phase the solar diameter shrunk of 30%.

1.3 The role of the magnetic field in the energy balance

The energy stored in the magnetic field plays a fundamental role in the energy balance of the Sun, as well as the temperature of the photosphere and the diameter of the Sun.

1.4 Introducing W=dlogR/dlogL

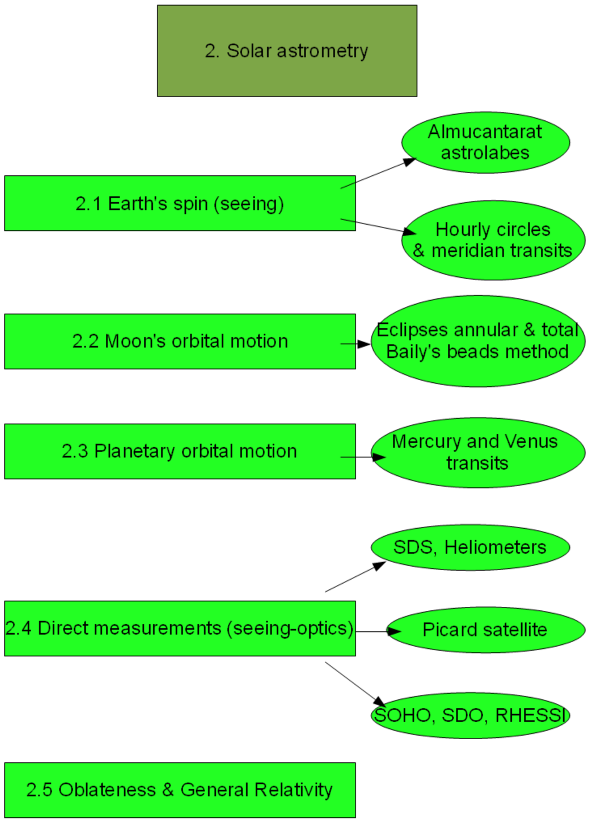
The luminosity and the radius of the Sun are involved in the Stefan-Boltzmann equation, but their logarithmic derivative W is not ½ as for uncorrelated quantities, because of the magnetic field.

1.5 Solar variability in the past millennia

The existence of ice ages either in the last million year and in the pre-cambrian age has been explained also with astronomical causes (e.g. Milankovitch cycles), but the periods of global warming and cooling in the past millennia have indeed a solar origin. Nowadays the global warming seems to be anthropogenic through the greenhouse effect. But this is still an open question with political, economical and social implications. Conversely there are emerging topics as the global dimming and the debate about the approaching new solar grand minimum.

1.6 Several definition of solar radius

There is the seismic radius, there is a different radius for each wavelength, also for radio. How accurate are these values, and how big are their variations?



0.1.2 Chapter 2: Solar astrometry

The measurement of the diameter of the Sun, even if assumed as a perfect sphere, consists into a definite field of the classical spherical astrometry.

The methods for solar diameter measurements are those exploiting Earth rotation (drift-scan; Danjon solar-type astrolabes); those using the Moon, Earth and planetary orbital motion (eclipses and planetary transits) and finally those making direct angular measurements (heliometers of Fraunhofer, heliometers with objective prisms, SDS, Picard SODISM and MISOLFA, the ground-based telescope dedicated to the direct measurement of the solar diameter.) The principal error sources are discussed in this chapter.

2.1 Earth's spin

The rotation of the Earth has an extremely constant rate. In the drift-scan mode the telescope is pointed toward the Sun; the Sun sweeps along the fixed field of view. The time of the drift is proportional to the solar diameter. There are two variants of this method.
The solar astrolabes are used for transits across a circle of constant altitude above the horizon. The last generation of Danjon astrolabes are 10 cm aperture instruments and its data analysis is still controversial. Such instruments have been considered too much influenced by atmospheric turbulences so that measurements made at Calern (OCA) or at Rio de Janeiro were significantly in disagreement.
Other telescopes (not necessarily meridian) are used to observe the transits across the meridian line, or across whatever hourly circle. Because the two limbs and the center of Sun sweep on a fixed field of view, its optical defects act as systematic errors.

2.2 Lunar orbital motion: eclipses and Baily's beads

The Moon along its orbit covers approximately its diameter in one hour. The duration of a total eclipse is depending on the angular diameter of the Moon and of the Sun. The circumstances of an eclipse are depending on the shapes and orbits of celestial bodies involved, and no influence arises from atmospheric seeing. During a solar eclipse the onset of totality was considered as a sudden event, because while the Moon progresses above the solar surface, the light coming from the photosphere drops rapidly to zero. The method of Baily's beads was introduced by D. Dunham in 1973. The strategy consists to observe the maximum number of Baily's beads, visible at the shadow's edge of the eclipse. The beads are videorecorded, timed and associated to the corresponding valleys of the lunar limb which produce the phenomenon. Instead of just using the second and third contacts, many Baily's beads improve the statistical error of the measured solar diameter. Baily's beads occurs both during total and annular eclipses and are observable in the whole shadow's path, with their maximum number visible at the edges. With the exploitation of the Baily's beads the timing of disappearance and reappearance of N beads increases of a factor $\sqrt{N}$ the statistical accuracy of the method.

2.3 Planetary orbital motion

The transits of Mercury (about 13 per century) and of Venus (two each 120 years) have an angular speed which covers the solar diameter (generally a chord) in about 6 hours. If the time of the contacts are defined with an accuracy of one second an optimal precision on solar diameter is attained. It is explained the example of Venus' transit of 8 June 2004.

2.4 Direct angular measurements

The heliometers deal with the whole figure of the Sun, or with the images of the limbs projected through prisms on the focal plane. The optical defects are crucial up to the milliarcsecond level. The Picard astrometric mission is presented here, and its philosophy is compared with SDS balloon-borne telescope and SOHO, SDO and RHESSI.

2.5 Oblateness and General Relativity connection

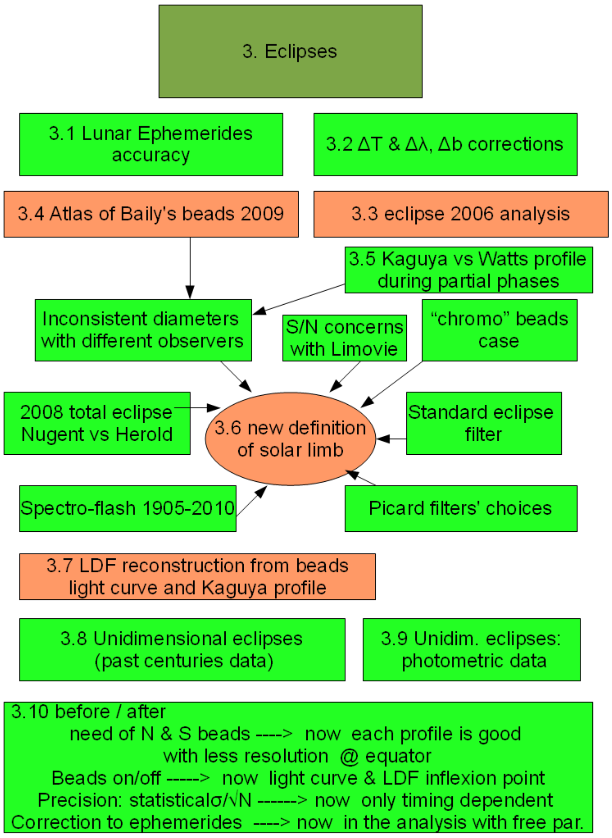
Finally what is the connection between the subject of this thesis and relativistic astrophysics? a slightly oblate Sun was suggested to explain the precession of the perihelion of Mercury. Therefore accurate measurements of solar oblateness were carried out by Dicke (1960-70s), Sofia (SDS 1990s) and now using the RHESSI satellite, to assess classical contributions to this anomalous precession. The required accuracy of these measurements is below one part over 10000, the same order of magnitude of expected solar diameter variability.

0.1.3 Chapter 3: Eclipses

Eclipse data are scattered and rare: about one each year is available; in the past 40 years we have some data useful to measure the solar diameter, mainly based on video tape and digital video.

3.1 Lunar ephemerides accuracy

The method of Baily's beads originally required data from both North and South limits of the shadow. This



was to avoid possible errors on the lunar ephemerides. Here they are described.

3.2 ΔT & Δλ, Δβ corrections

The correction to the lunar ephemerides has been introduced in the data analysis with three free parameters.

3.3 2006 eclipse analysis

The total eclipse of 2006 has been analyzed with this method.

3.4 Atlas of Baily's beads 2005-2008

The data of the observational campaigns of annular and total eclipses of 2005-2008 made by IOTA members have been published in Solar Physics 2009. Later IOTA members have monitored the 15 January 2010 annular eclipse from some successful unclouded stations.

Few data exists on 2010 total eclipse, mainly from photometers (see unidimensional eclipses).

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. Watts in 1962, sometimes locally upgraded with stellar occultation data, was the only one available. The precision of Watts atlas, estimated to 0.20", was considered having random uncertainties. With N beads observed the influence of this uncertainty is reduced by the statistical factor √N. Now the profile obtained by the Laser Altimeter LALT of the Japanese lunar probe KAGUYA is available, 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) 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 (Rocher, 2010).

3.6 New definition of solar limb

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.

Even if the telescopes and the filters have been standardized, the diameters obtained from different observers are inconsistent. The problem of signal to noise ratio is discussed, as well as the (false) case of "chromospheric beads".
The spectro-flash studies of the total eclipses show the evidence of many small emission lines occurring right above the photosphere, and larger telescopes better gather their light, inducing a false perception of a larger photosphere (2008 case). The classic definition of solar limb is the location of the maximum of luminosity profile derivative of the continuum spectrum, already adopted in the oblateness studies. The effect of the blend of tiny emission lines just above the solar limb visible during eclipses is better considered by this definition operative also for eclipses.

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

Limb Darkening Function studies from single Baily beads (with Andrea Raponi) are presented as a possible new method of diameter's measurement.

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.
The history of past diameter is obtained mainly from Mercury's transits. How reliable are these data? 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.

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 eclipse mission of 11 July 2010 in French Polynesia is also dedicated to measure the solar diameter from the ground.

3.10 Before and after this work

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

0.3.4 Chapter 4: Daily Transits

4.1 Seeing and observed position of the solar limb

The influence of the seeing on the observed position of the maximum of the derivative of the luminosity profile of the Sun is here described.

4.2 Instantaneous measurement of the seeing

The different components of the seeing act upon different angular scales. We have images of a 100" scale. From each image of the solar limb obtained during a drift-scan observation we reconstruct a regular arc of a circle from the distorted solar limb. We measure this medium scale effects of the atmospheric turbulence (seeing) by the irregularity of the motion of such arc. Values of the seeing as low as 0.6" have been measured during summer in Locarno. This determination of seeing is strictly related with the measurement of the solar diameter.
The method of parallel transits is presented.

4.3 Transits at the IRSOL 45 cm Gregory-Coudé telescope

The tradition of solar diameter's measurements in Locarno goes back to the late years 1970s with visual observations. Two twin Gregory-Coudé telescopes of 45 cm aperture, designed for solar observations, operated simultaneously in Switzerland and Canary Islands with drift-scan methods between 80's and early 90's. The opening diameter of the telescope is larger than any turbulent atmospheric cell, allowing a better stability in the observed solar diameters.
References: Wittmann and Bianda visual and CCD; Damé private communication.
From 2008 this method has been upgraded in the framework of the Project Clavius, among Italian and Swiss scientific Institutions, for the development of fast detector for physics and astronomy. The drift-scan project at Locarno is being upgraded with fast imaging detectors, exploiting the idea of simultaneous measurement

of the seeing. We started with a commercial CMOS at 60 frames per second, reaching a resolution of 0.25" for a single diameter measurement. We discuss how the number of measurements improve the statistics, since we can obtain much more than 30 consecutives diameters (as in the 1990s) per day using the grid method.
The eventuality to perform such an experiment in Anctartica is outlined.
References: Sigismondi 2006 (multiple transits in st. Maria degli Angeli); Sigismondi 2008 AIPC-CLAVIUS; Caccia 2009 internal notes specifications of CMOS detectors; Koutchmy 2009-10; Damé; Sigismondi 2006 IAUC II-drift-scan on the Moon.

4.4 Transits at the Carte du Ciel 33 cm refracting telescope

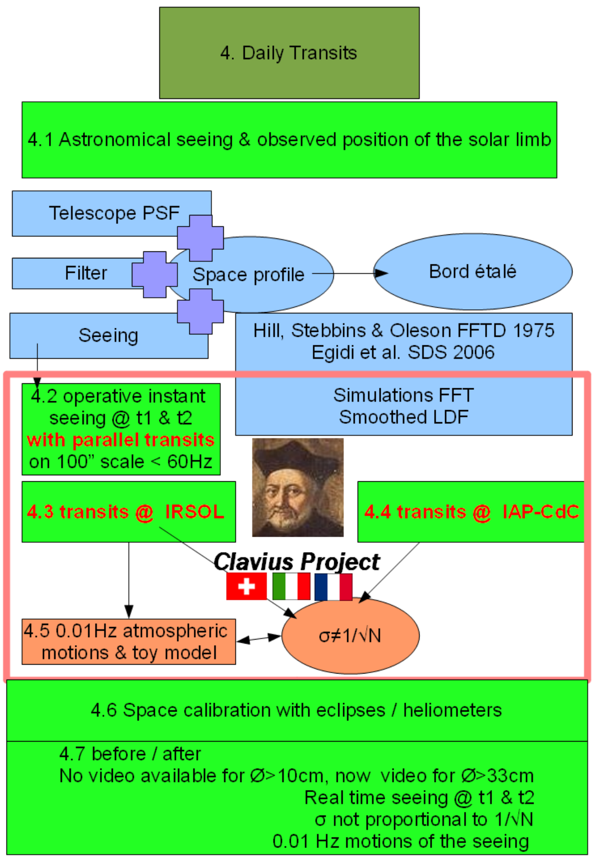
This historical telescope (Institute d'Astrophysique and Observatoire de Paris) used for astrophotography since 1885, has been equipped with a CCD camera Lumenera and screened with a panchromatic filter in astrosolar. The Carte du Ciel 33 cm refracting telescope in Paris, used for our transit measurements, has a PSF particularly clean because of no obstructions in its optics, and a very small scattered light effect.

4.5 Evidence of 1" slow image motion of the whole solar image

The diameters obtained in consecutive measurements are not consistent within all the experimental errors. The first results of the new measurements tests for both telescopes (2008-2010) are discussed: the effect of low frequency waves (0.01 Hz) in the atmosphere could explain the difference in the successive hourly circle transits' measurements. This finding can cast some light also on some ancient puzzling data (Rome - Campidoglio & Greenwich observations).

4.6 Space calibration of transit's measurements

Combined observations space-ground: eclipses and drift-scan. In the occasions of two total eclipses of 1st August 2008 and 22nd July 2009 we have made drift-scan observations at Locarno observatory, and a third session was planned for 11 July 2010 eclipse. A single day of observations made with DORAYSOL on 23 September 2006 can be considered as overlapped with the annular eclipse of 22 September, observed in French Guyana.
The same strategy is planned between SDS and Picard. A new flight of SDS (after the one still unpublished occurred in october 2009), shall be done during the Picard mission to compare the space measurements with



the balloon-borne ones.

4.7 Before and after this work

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

0.3.5 Chapter 5: Didactic outreach

5.1 Required accuracy < 1/10000

The statement on human energy output versus solar input is "1 year of humankind corresponds to 1 hour of Sun". This is the starting discussion of a series of units on solar astrometry, in order to motivate this study in a framework of climate studies.

5.2 Pinhole studies of real time seeing, PSF and ΔUT1

A pinhole is a "lens-less telescope", completely free from spherical aberration and perfectly suitable for astrometric studies of the Sun. It has been exploited since 1475 (Ulugh Begh, 1437, measured only solar declination and not diameter) by Paolo Toscanelli for giant pinhole telescope built in Florence's Cathedral as pinhole camera. With the one in Roma, Santa Maria degli Angeli (the Clementine gnomon of 1702) I have demonstrated its extraordinary accuracy down to one arcsecond for all the range of solar declinations, and the possibility to be used for monitoring the ΔUT1 evolution.

Using an evenly spaced grid at the focal plane in a drift-scan method gives the opportunity to have several diameters in a single transit and it can be used for measuring the seeing in real time. Students already have videocameras, and they are ready to start solar astronomy experiments.

5.3 Pinhole model of Solar Disk Sextant

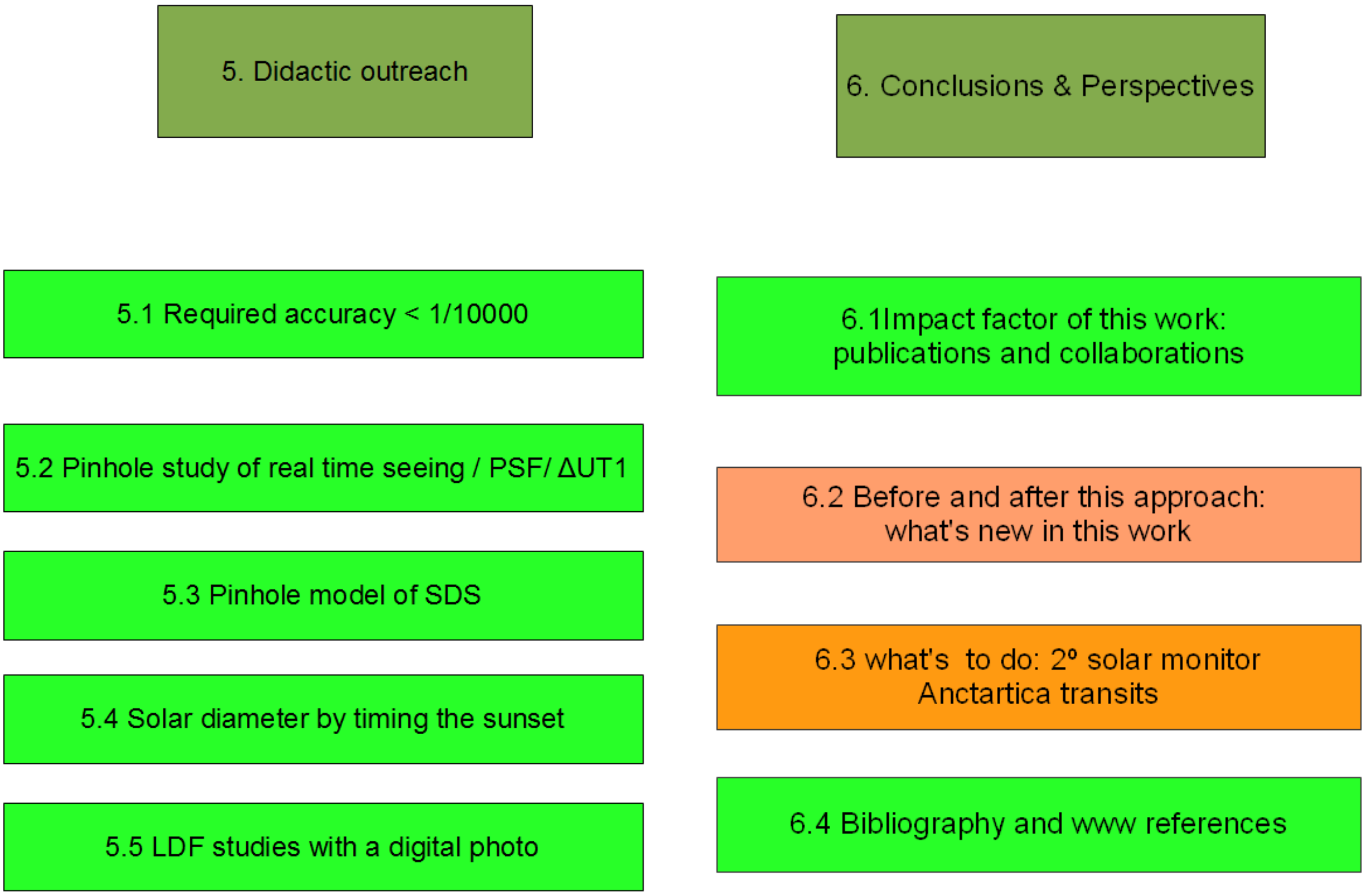
A two-pinholes heliometer can be designed to simulate the situation of having two images at the focal plane. Two scientific museums (Coimbra Museum of Science and Robert Hooke Institute in Nice) have contacted me for implementing this instrument.

5.4 Sunsets and solar diameter

The measurement of the solar diameter is possible also from timing the sunset over the sea horizon. The arcsecond level of accuracy is reached with video.

5.5 LDF studies from a simple projected image of the Sun

Using an ordinary pair of binoculars or a normal telescope, and even a pinhole, it is possible to study the Limb Darkening Function of the Sun by a single digital photo of the image of the Sun projected on a white paper. It is to remember that every commercial videocamera is like a non-linear detector, because it is programmed in order to simulate the eye response.



0.3.6 Chapter 6: Conclusions and Perspectives

This thesis will be discussed when the first data from Picard will be available and when the calibration of MISOLFA will start.

My contribution to this field has been

1. to have shown the need of a more precise definition of solar limb during eclipses, taking into account the phenomena in the flash spectrum region.
2. to have individuated in the low frequency motion of the atmosphere one of the causes of the inconsistency within seeing errorbars of the daily transit's measurements of diameter.

This is a starting point for many relevant scientific issues on the physics of the Sun. The task to bridge together eclipses observations and direct solar astrometry methods has been tempted, but the process to automatize the procedures was still in progress in Locarno and we could only do preliminary tests at the same time of the eclipses of 2008, 2009 and 2010.

Qualified observers belonging to IOTA, International Occultation Timing Association have firstly published, under my guidance, their valuable data of recent eclipses. Historical eclipses have been re-analized with the latest lunar satellite data. The problem of filters adopted in eclipse observations, risen by me, found a partial solution with a standardization of the IOTA filter. The first atlas of Baily's beads has been published.

The measurements of solar diameter using different sets of beads give different results: a new definition of solar limb is crucial, to take into account the solar mesosphere emitting lines.

6.1 Impact factor of this work

The publications and the collaboration activated during this work are here evaluated.

6.2 Before and after this approach: what's new in this work

The original achievements of this work are here drafted. They are the new results in this field, and they bring new understandings and points of view.

6.3 What's to do: 2° solar monitor and Antarctica

The evidence of slow image motions in the atmospheric seeing, involving the whole figure of the Sun, suggests to realize a 2° solar monitor in order to correct the transits' data for this random-like motion.

From Antarctica a very good and steady seeing conditions are expected, and it should be the ideal place of an experience of solar diameter's monitoring with small scale telescopes (10 cm of objective).

6.4 Bibliography and www references

A list of useful books, papers and web links.

0.2 Acknowledgments

I am greatly indebted with many people who helped me to carry on this project. A list of people is necessarily incomplete, also because it is difficult to recognize the contributions of other persons in the formation of the ideas: after their genesis they seem to belong to us since ever. Other persons have sustained me with their example, their intellectual honesty and their enthusiasm. Other persons gave to me spiritual support, helping me to focus on my personal growth, motivations and my responsibility toward the society. It is like a night sky full of stars, many of first magnitude and all of different colors, owing to their different roles: masters, mentors, models, inspirers, colleagues, friends, familiars. They supported me, indeed with some criticism, during all situations.[2] Moreover in the last 10 years I made part of my activity in foreign countries, and I found persons who let me experience warm hospitality and sincere friendship so that "wherever I lay my hat that's my home".[3]

My parents Camillo (+2011) and Erminia, my syster Irene, Lisa and Christopher Hoffer, John Sullivan, Bernard Confer, Sabatino Sofia, Priya Natarajan, William Van Altena, Terry Girard, Linghuai Lee, Federico Spada, Dorrit Hoffleit (+2007), Sue Delong, Ann Giangarra, Laura Artusio, David and Joan Dunham, Martha (+2010) and Wayne Warren, Alan Fiala (+2010), Jean Arnaud (+2010), Pierre Assus, Thierry Corbard, Abdenour Irbah, Wassila Dali-Ali, Marianne Faurobert, Jocelyne Bettini, Valérie Chéron,Yan Fantei-Caujolle, Jean-Luc Beaumont, Richard Beaud, Michel Mathieu, Ting Lee, Marie-Thérèse et Solange, Serge Koutchmy, Cyril Bazin, Patrick Rocher, Barbara Obrist, Michele Bianda, Anna Soldati, Aline Bianda, Renzo Ramelli, Flavio Nuvolone, Massimo Caccia, Carlo Monti, Paolo Zanna, Rossana di Gennaro, Paolo Rossi, Runa Briguglio, Andrea Soddu, Giuseppe Blanda, Renzo Giuliano, Mario Catamo, Massimo Fofi, Paolo Gillet, Alberto Egidi, Remo Ruffini, Alessandro Cacciani (+2007), Giovanni Moreno, Paolo de Bernardis, Simonetta Filippi, Cosimo Palagiano, Raffaele Ciambrone, Daniela Velestino, Flora Parisi, Emanuela Celeste Donna, Rita Fioravanti, Pietro Alessandro Giustini (+2007), Sabina Fiorenzi, Cetta Petrollo, Gabriella d'Amore, Orazio Converso, Laura Paladino, Romano Penna, Gian Matteo Botto, Alberto Orlando, Rafael Pascual, Melchor Sanchez de Toca, Paul Poupard, Gianfranco Ravasi, Sergio Pagano, Benedetto XVI, Davide Troise, Danilo Montagnese, Emilio Sassone Corsi, Sabrina Picchi, Laura Comerci, Veronica d'Angelo, Federica di Berardino, Cristina Adamo, Silvia Latorre, Carles Schnabel, Hans-Joachim Bode, Konrad Guhl, Pawel and Kasia Maxim, Pawel Rudawy, Richard Nugent, Gerhard Dangl, Sven Andersson, Antonino Tata, Lee Hyung Won, Fady Morcos, Ahmed Hady, Cristina Mandrini, Alexandre Humberto Andrei, Jucira Lousada Penna, Sergio Calderari Boscardin, Victor d'Avila, Eugenio Reis, Albert Picciocchi.

I could benefit of a very long "permanent formation", topped with a second PhD being 42 years old. In terms of salaries of teachers, professors and researchers... involved with me[4] during about 39 years of cultural formation, it has been an investment larger than one million of euro, sustained by the Italian State, and by my family.

The cost of "producing a researcher" is probably underestimated, but the order of magnitude is rather

[2] Vanistendael S. et J. Lecomte, Le bonheur est toujours possible, construire la résilience, Paris, Bayard (2000). See the "casita" personality model developed at the BICE/ICCB (Bureau International de L'Enfance di Ginevra/ International Catholic Child Bureau) www.crin.org/docs/Resiliance.doc

[3] Song by Paul Young (1984) lyrics by Marvin Gaye, Norman Whitfield & Barrett Strong.

[4] Salaries divided by the average number of students per teacher.

correct, and it has to be taken into account in the analysis of the "brain drain" phenomenon.
For some sociological reason, the Italian researcher has to develop a special ability to be actually what he became, i. e. to work in the field in which he or she attained the highest specialization remaining in his own country. This further energy threshold tends to reduce the sense of gratitude towards Italy, which is paradoxically capable of generate big scientists and to avoid them to work for Italy itself. This is not a novelty, it is in the genoma of Italians: already Dante reported "Tu proverai come sa di sale lo pane altrui, e com'è duro calle lo scender e 'l salir per l'altrui scale"[5]. Similarly, on a smaller scale, but relevant for Rome there is the "roman area paradox"[6] with the largest concentration of research institutions without any development for the territory. It is necessary to promote the dialogue between institutions, enterprises and research.
But it is also necessary to develop the culture of responsibility, especially in the Italian academic context, because "the product of academy are persons"[7], avoiding to "produce" persons used to survive in human environments with despotic leadership who will reproduce the same victim-villain relationship when they will be in power.
Positive environments are where both rational and emotional intelligence can develop.

[5] Dante, Paradiso, XVII - vv 58-66
[6] See the brochure of Parco Scientifico Romano, University of Rome "Tor Vergata". http://www.parcoscientifico.eu/IMG/pdf/romesciencepark.pdf
[7] William C. Rando, director of the Academy for the Art of Teaching Yale University.

0.3 Preface

Man go West! (and I came back to East)
(quoted to me by Alberto Righini)

At the end of 1990s there was the LEST telescope project for a large international solar telescope based on next-generation technology, to be established on the Canary Islands. 6 European and 3 non-European (Australia, China, USA) countries were participating in this enterprise. A prime objective of LEST was to investigate the subarcsec fine structure of solar magnetic fields. The design of the 2.4m aperture telescope was "polarization-free". Helium-filling and adaptive optics were to be used to achieve 0.1 sec of arc spatial resolution.[8] I attended a presentation of this project by Alberto Righini, during a PhD school in 1998 in Monteporzio Observatory. About solar physics and contemporary trends in science he quoted the American refrain "Man go West"[9] explaining that also in astrophysics there is a West, a unknown territory filled by opportunity, and this field is cosmology. After more than 10 years of this presentation a lot of economical resources have been invested into cosmology, and more and more solar physics loses chairs in the most important universities, without immediate replacement. Righini explained to the audience also that the West of cosmology was a region supportable with some exotic physics based upon data with accuracy yet $\Delta X/X\sim1$ or even larger. Solar physics, on the other hand, was already dealing with much better accuracies $\Delta X/X\sim10^{-3}$ and the field was always generous of new discoveries.

Cosmology is the West, Solar Physics the East... and I decided to quit the West[10,11] after the wondrous spectacle of the eclipse of 1999.

The observation of 1999 solar eclipse, total over central Europe, triggered my interest in solar astrometry, as well as the following visits in the Basilica of St. Maria degli Angeli e dei Martiri in Rome, where the Clementine Gnomon (1702) is located.

The Clementine Gnomon is a giant pinhole telescope, with maximum focal length of 50 m, capable of a few arcsecond accuracy on the determination of the apparent position of the Sun at the meridian transit.

The atmospheric refraction and its differential effect on the superior and inferior limb of the Sun can be compared with computed ephemerides, and also the secular drift of solstices, due to Earth's obliquity change, and phenomenon of UT1-UTC drift are measurable at this lens-less[12] solar instrument.

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[8] Stenflo, J. O.Vistas in Astronomy, **28**, po. 571-576 (1985).
[9] http://en.wikipedia.org/wiki/Go_West,_young_man
[10] Sigismondi, C., Perspectives on the observation of clusters of galaxies in X-ray band with SAX (X-ray Astronomy Satellite), Nuovo Cimento B, Vol. **112**B, p. 501 – 515 (1997).
[11] Sigismondi, C., et al., Damping Time and Stability of Density Fermion Perturbations in the Expanding Universe, Int. J. Mod. Physics D 10, 663-679 (2001).
[12] See http://www.pinholecamera.com/

Fig. 0.1. The eclipse of March 29, 2006 as observed on the meridian line of St. Maria degli Angeli in Rome, at 38.5° from zenith.

The introduction of video-recording, up to 60 frames per second, in order to recover the maximum accuracy on the meridian transit timing, transformed for me and for my fellow students this historical instrument into a scientific laboratory to test our knowledge on solar astrometry.
In parallel, the cold marbles of the Basilica taught us the story of geodesy and technology at the beginning of XVIII century, and so another field of research on history of science was opened.

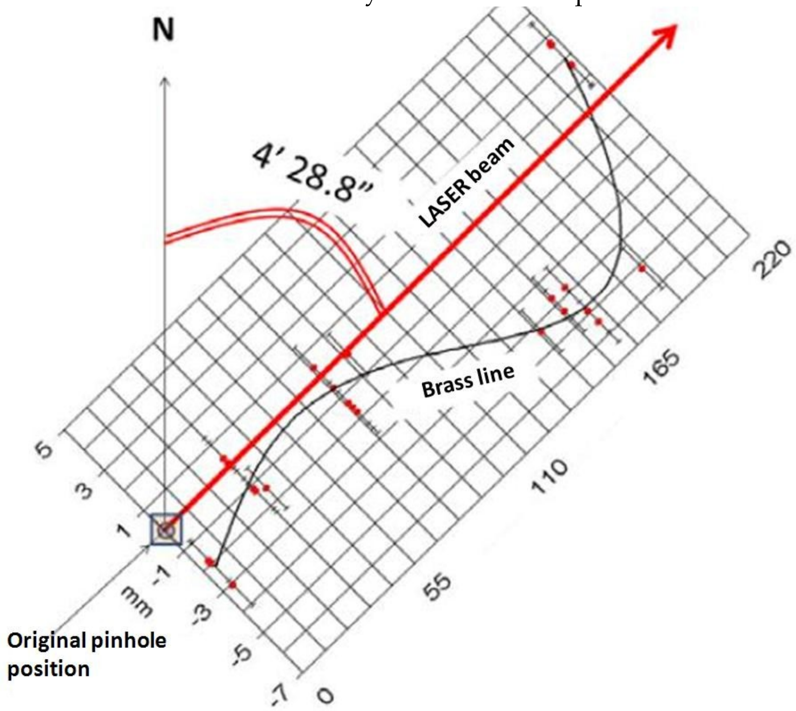

Fig. 0.2 The azimuth of the Clementine gnomon (1702).

In this research, started to understand the small deviation between the meridian line and the geographical North, ephemerides and stellar astrometry, proper motions and diffraction optics led us to know our colleagues of three century ago with their sake of experimental accuracy and their strategies, always much cleverer than our initial belief.
The scholarship at Yale University from 2000 to 2002 allowed me to be in contact with one of the most

important traditions in stellar and solar astrometry.
At the Astronomy department Prof. Sabatino Sofia and Prof. William Van Altena were joining their efforts and their teams to reduce the data of the Solar Disk Sextant (SDS), a balloon borne telescope conceived to measure the solar diameter from stratosphere at 37 km of height, with a residual barometric pressure of 3 millibar.

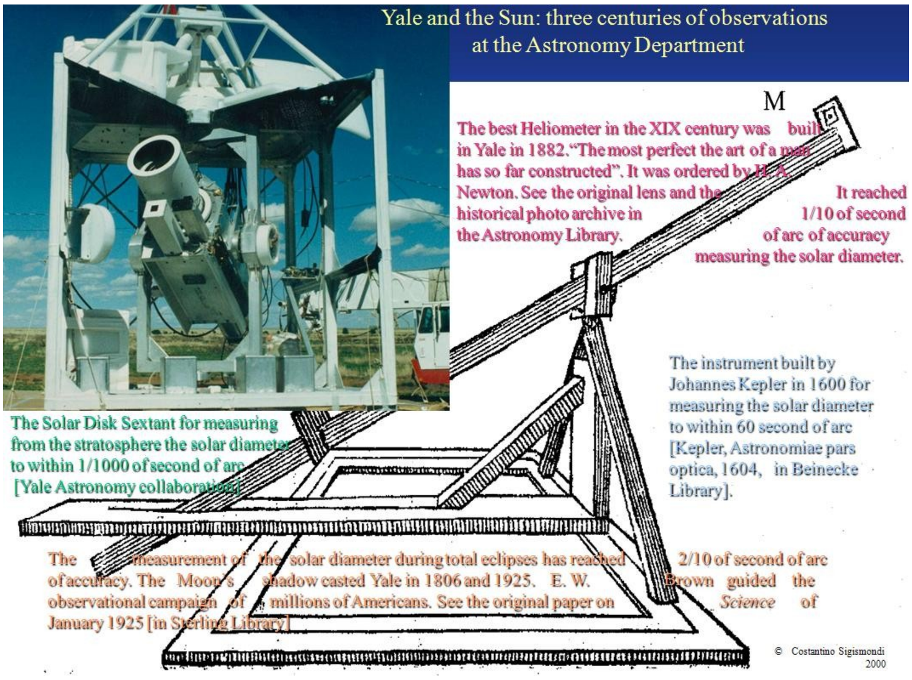

Fig. 0.3 Yale and the Sun, poster realized by me for the tercentennial of the Yale University. The great astrometric tradition is sketched from H. A. Newton and his Heliometer (used in Venus' transit of 1882) to E. W. Brown lunar theory who changed forever the approach to solar eclipses, to SDS with an accuracy to the milliarcsecond level.

Meeting and the collaborating also with the late prof. Dorrit Hoffleit (1907-2007), expert in variable stars and witness of the history of astronomy of XX century in America, made this time in Yale unforgettable.
The following acquisition (2002) of the chair of Physics & Laboratory at the institute in Rome dedicated to Giuseppe Armellini [former director of Rome Astronomical Observatory (1924-1958) in the time of translation from Capitol to Monte Mario hill occurred in 1937] forced to dedicate myself to the art of teaching with all my strengths.
A collaboration, in the spare time, with the late prof. Alessandro Cacciani (1938-2007) started at the Sapienza University in his solar physics laboratory and since 2002 several students interested in solar physics could perform experiments in the framework of Astrophysics Lab course of Prof. Paolo de Bernardis.
The work started at Yale on solar astrometry with eclipses was continued in this contest, until a new eclipse casted its shadow on the European continent. It was the time to get our own data after having examined several video and data from other observers. On October 3rd, 2005 an annular eclipse crossed Spain and with Pietro Oliva and Paolo Colona we organized -at our own expenses- an observing expedition.
The original idea was to go to Santiago de Compostela, where the eclipse was central, and move to Lugo at the antumbral limit of the eclipse, where the Baily's beads were visible.
This program would have been perfect under every point of view, but it come out unrealizable. And after landing in Santander we have chosen to intercept the eclipse path in Leon region, south of Burgos and north of Valladolid.

Fig. 0.4 Poster for the project of eclipse expedition in Galizia.

Later in 2008 while I was participating to Scientific Instrument Committee meeting in Lisboa, I could land in Santiago de Compostela and visit the local observatory who provided me with the images of that eclipse.[13] But since Santiago was in the centerline the duration of Baily's beads was too short to be useful for our measurements of solar diameter.

So we could display our instruments perpendicularly to the calculated eclipse path's limit. It was the first mission with an array of observers over 1 km. Unfortunately the weather changed over the Spanish meseta half hour around the centrality, and we were clouded out.

Fig. 0.5 The annular eclipse of 3 Oct. 2005 at its maximum from Valoria la Buena. No video were possible, for the clouds. Photocomposition.

[13] http://www.fomento.es/MFOM/LANG_CASTELLANO/DIRECCIONES_GENERALES/INSTITUTO_GEOGRAFICO/ Astronomia/ECLIPSE/

This great opportunity to define with a great precision the Northern limit of this eclipse, lost for the clouds, urged us to enter in contact with other observers and Dr. David Dunham, the president of IOTA International Occultation Timing Association, put ourselves in contact with Dr. Carles Schnabel of the Astronomical Association of Sabadell[14] (Catalunya), where several video observations were performed according to the metrological standards used in the solar diameter analyses.
We got several DVD of this eclipse at the Northern limit, and Dr. Wolfgang Strickling provided to us the Southern limit's observation needed to complete the data set to recover the whole antumbral path, independently on the ephemerides.
The first opportunity to observe an eclipse with data occurred in 2006, when on March 29 it was total over the western part of northern Egypt. An international IAU colloquium was organized in Cairo just after the eclipse and the LOC prof. Ahmed Hady sent to us Dr. Abdel Fady Morcos who helped us to get to the Southern limit of the eclipse east of Sidi Barrani at Zawyet al Mahtallah. Three observers were positioned over a line perpendicular to the path, and I was the more external one. The eclipse in my location never attained the totality, while the corona was visible to the naked eye, once the remaining beads were covered with the thumb.

Fig. 0.6 The eclipse at its maximum phase at Zawyet al Mahtallah: the ghost image lower left shows the position of the beads with respect to the whole disk. Photo with Philips KeyRing 008.

The luminosity of the two remaining beads at maximum eclipse was dazzling, even if they were barely visible on the white screen over which the solar image was projected through the 7 cm Meade ETX F/5 refracting telescope.

[14] http://www.astrosabadell.org/

Fig. 0.7 A video taken by Dr. Fady Morcos (250 m inward the umbra) shows the effect of pixel saturation due to the bead's dazzling light. At maximum eclipse its brightness was equivalent to the corona. (Sony miniDV videocamera).

Afterwards, on 22nd September 2006 the whole Draconitic year (354 days) of my directly observed eclipses was completed with the annular eclipse in French Guyana.
At this time I adopted the method learned from Fred Espenak (NASA) the world famous eclipse expert. At Goddard Space Flight Center during my stay in 2001 he presented a talk on the organization of things to do during and near totality in order to maximize the scientific results achievable in such a short time. He registered on a tape in real time the actions to do and he let the tape instructing him during the phenomenon.
I could achieve all the observations thanks to Prof. Albert Picciocchi of the French Ministry of Education who helped me in all logistic needs in French Guyana. So I recorded an audio file, using Occult Baily's beads software for calculating the beads' appearances, with all the operation to do with the videocamera during the phase of annularity.

Fig. 0.8 Annular eclipse of French Guyana at its maximum (92.5%) from Kourou beach. The ghost images up and down (in the water) show the ring of photosphere. (Photo with Philips Keyring 008.)

At the end of that mission 13 beads were identified in the video, but they were very fast since the observations were possible only near the centerline, because the antumbral limits were on the ocean or in the jungle. No other observers worldwide recorded Baily's beads during this eclipse.

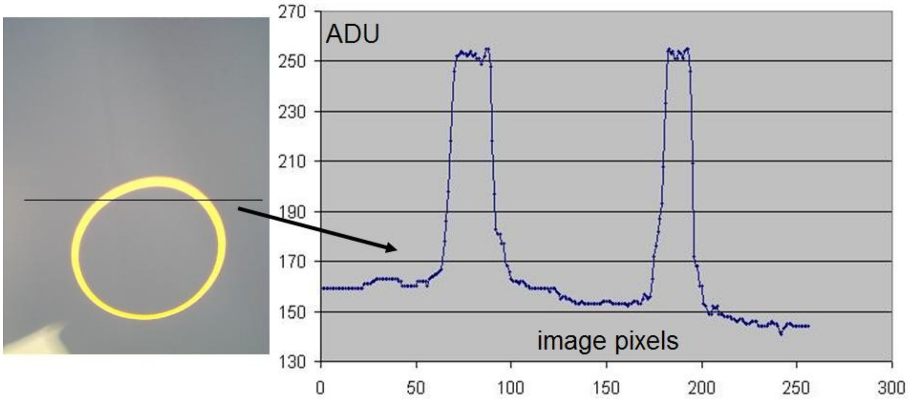

Fig. 0.9 The analysis of background level in the projected image in Arbitrary Digital Units, at maximum eclipse of 22 September 2006. This photo is made with Philips Keyring008 with 255 levels of intensity (8 bits) for each of R,G and B channels.

After Spain, Egypt and French Guyana I had a direct, personal experience of observational conditions during a total and an annular eclipse. For the following eclipses I could rely into the observations made by IOTA (International Occultation Timing Association) members, who were eager to publish their data in view of a research on solar diameter variation.

Planetary transits are also sources of data for measuring the solar diameter: in this decade Mercury crossed the Sun in 2003 and 2006 and Venus in 2004.

While in the 2003 transit I made the largest public observation (about 1000 students during the whole transit) with a Newton telescope and with a pinhole device in Armellini Institute (Rome), for the transit of Venus I organized, also in Rome, a public conference and book's exhibit in the library where the 1761 transit was observed.[15] For 2006 Mercury transit I could contact the observatories of Hawaij through Prof. Jay Pasachoff and Sacramento Peak through Dr. Kevin Reardon. The transit of Mercury was carefully observed in Sac Peak, but not perfectly for our purposes, [16] while it was very windy on Haleakala and the dome could not be opened until about a half hour after first contact.[17] The data of MEES telescope of the Hawaiian solar physics group are published in the web page of November 8 2006 data.[18]

We get very close to a big result in solar diameter determination…

One of the reasons why this was not achieved in the last 3 transits of 2003-2004 and 2006 can be the fame of unreliability of the planetary transits for solar diameter studies, due to the black drop phenomenon. Conversely I had a simple idea to overcome black drop and seeing effects by analyzing a sequence of chrono-dated images near the internal contacts.

A very promising result was obtained with Venus transit in 2004, from 50 photo made each minute with 1 second accuracy, made by Anthony Ayomamitis[19] in Athens with a 160 mm Apochromatic telescope in Alpha line: the instants of the internal contacts were determined by extrapolating to zero the chord draft by the planetary disk and the solar limb with ±8s and ±1 s for different seeing conditions at sunrise and near the local meridian.

With these experiences in mind, and with a paper published on Nuovo Cimento on the oblateness of the Sun[20] in order to put in evidence the links between Celestial Mechanics, General Relativity and Solar Physics, I have participated to the IRAP-PhD competition in 2007, being selected among the winners.

This international PhD program involved also the Université de Nice-Sophia Antipolis, institution

[15] http://www.casanatense.it/index.php/en/gli-eventi-in-biblioteca/le-mostre/159-saros.html

[16] http://www.nso.edu/press/merc_trans06/20061108hl.mpg a Video in 656.28 nm; the web site for all the proceedings is http://www.nso.edu/press/merc_trans06/ "Unfortunately, we did not get good observations of the first contact. We do have observations of the second contact, but the seeing was not very good and the adaptive optics system was not yet locked on resulting in a rather distorted image. I am attaching one of the better images we obtained during second contact, but clearly it is hard to define exactly the time of second contact due to image motion and blurring. Third contact occurred right near sunset and in the minutes leading up to the contact it was hard to even identify Mercury in the highly distorted images." [K. Reardon, Arcetri Astrophysical Observatory, private communication 10 Nov.2006].

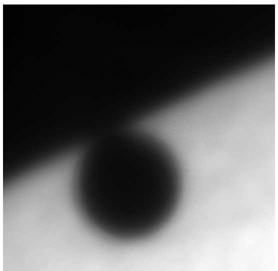

Fig. 0.10 Mercury transit of 2006 second contact.

Observations were carried out at the Dunne Solar Telescope using the Interferometric Bidimensional Spectrometer (IBIS) to observe the exosphere of Mercury, and the Williams College Portable Occultation, Eclipse, and Transit System (POETS) camera system to observe the solar photosphere.

[17] Jay Pasachoff [private communication 9 Nov. 2006]

[18] http://www.solar.ifa.hawaii.edu/cgi-bin/MeesLogSearch?date=20061108

[19] "I just checked my CD backups and I do have both ingress and egress at one-minute intervals. More specifically, I have 08:16:00-08:42:00 UT+3 and 14:00:00-14:27:00 UT+3 and which cover completely both ingress and egress since I included a three-to four-minute window outside the official contact 1-4 times." [A. Ayomamitis, private communication 20 Nov. 2006] I answered "Let me quote Horatius (Epistulae, II, 1.156) *Graecia capta ferum victorem cepit*. [free translation: Once the Greece was kept (from Rome), it prevailed (culturally) on the rude conqueror] Thanks and regards from Rome." Anthony saved his original data with an admirable foreseeing and after some years they were useful to measure the solar diameter in H alpha line, with an accuracy of 8 parts over 20000, i.e. about 0.7".

[20] Sigismondi, C.; Oliva, P., *Solar oblateness from Archimedes to Dicke*, Il Nuovo Cimento B, vol. 120, 1181 (2005).

participating to the satellite mission Picard through the Fizeau department, and in end January 2008 the *cotutèle* between Rome and Nice Universities was stated. The astronomer Jean Arnaud, former director of Themis telescope in Canary Islands, recently arrived in Fizeau department, and prof. Alberto Egidi former director of the physics department of Tor Vergata University (Rome 2) accepted to be my co-directors. After the death of Jean Arnaud in September 2010, Marianne Faurobert has taken his duty in November 2010, for accompanying the last months of this thesis work. In 2008 the VINCI fellowship of the Université Franco-Italienne was granted to this thesis, covering all the local expenses in France and the travels between Italy and France.
During the three years of PhD, according to the current Italian law for public school tenures, I could benefit of the same economical treatment as if I were teaching at school, which was 20% better than the PhD scholarship. Therefore it is important to show also the didactic aspect of this work.
I will try to be clear and simple, rather than verbose and complicate, as it should be for whatever scientific work, in whatever language.
At the time of the "siècle des lumières" Antoine de Rivarol (1753-1801)[21] said "Ce qui n'est pas clair n'est pas Français" and he was proposing the French language as the universal one. This should be the aim of every scientific contribution, in whatever language, and I hope not to be so far from this goal.

0.4. Introduction

The theme of solar diameter is introduced using an historical approach.
This thesis deals with the accuracy of ground-based measurements of solar diameter and their reference values obtained during solar eclipses observations. Thanks to the scientific Institutions which supported this thesis and the observational missions this thesis finalizes a 12 years work on the field of high precision solar astrometry, focusing on methods of measurements, identifying the range of solar diameter variability and rising interest in this subject to young generations. Father Angelo Secchi, who published in 1877 the book "Le Soleil", started the tradition in Rome on solar diameter measurements. Later a 60 years series of measurements on solar diameter made at the Capitol's Observatory become of international interest. The Picard satellite mission will monitor the solar diameter at least in the next 3 years. Daily data from space are expected to be at milliarcsecond level of accuracy. It has been planned that the SODISM data will be exploited to calibrate a ground-based method (SODISM II-MISOLFA now in the Nice/Calern Observatory) for solar diameter measurements to continue monitoring its tiny variations in the years to come.

There are two other methods which can achieve an accuracy comparable with the one of space missions in solar astrometry: they are the eclipses and the transits.

These two methods have been extensively analyzed in this thesis in order to ascertain their accuracies.

[21] http://www.tlfq.ulaval.ca/axl/francophonie/HIST_FR_s7_Lumieres.htm see chapter 5.1.