ON SOLAR RADIUS VARIATIONS OBSERVED WITH ASTROLABES

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Abstract. Ground-based results on cyclic variations of the apparent solar radius are so far controversial and inconsistent. This is blamed to atmospheric noise which effects can be so severe that even in cases in which the observations are made with similar instruments, the results show strong disagreements (Li *et al.*: 2003, *Astrophys. J.* **591**, 1267). Such claim concerns the results of Danjon astrolabes which during the last decades have been used widely at several sites for solar metrology. The long-term series with thousands of radius measurements made with astrolabe at Calern, France, and at Santiago, Chile, is a case in which the results of radius variations in time are strongly discrepant in spite that the observations were made simultaneously, in quite similar conditions and with almost identical instruments (Noël: 2004, *Astron. Astrophys.* **413**, 725). However, we show here that most of astrolabe discrepancies may be due to data analysis biased by theoretical preconceptions, by empirical results which without scientific arguments are considered as canonical references and by over interpretations of casual agreements between visual and CCD astrolabe results.

1. Introduction

Like sunspot numbers other solar parameters such as UV and total irradiance, radio flux and the entire solar spectrum, show cyclic variabilities of 11 years approximately. According to this evidence one may wonder if the solar size participates also of this variability. However, after 300 years measuring the solar radius and in a strong contrast with those parameters that show clear cyclic variations, the results obtained so far are quite controversial and inconsistent (Ribes *et al.*, 1991). Some of them show marginal radius variations in phase with magnetic activity, other ones are in opposite phase and a third kind do not show significant variations at all. Gilliland (1981) claims that if one is predisposed to desire not detectable change of solar radius, the data sets are marginal enough to allow such a subjective conclusion.

For some authors the solar radius is the global property with the most uncertain determination of the solar cycle-related changes. The disagreement between near simultaneous ground-based measurements at different locations, made even in some cases with similar instruments, suggests that atmospheric contamination is so severe that it prevents any meaningful measurement of solar diameter variations at the expected level from the ground (Li *et al.*, 2003).

Comments on discrepant radius measurements even when they are made with similar instruments are pertinent to the results obtained with solar Danjon astrolabes. This instrument, widely used during the last decades for solar metrology, has produced data sets with thousands of apparent radius values, like those of the astrolabes of Observatoire de la Côte d'Azur at Calern, France, and of Observatorio Astronómico Nacional of Universidad de Chile at Santiago. Covering simultaneous periods of homogeneous observations equivalent to a solar cycle, they give an opportunity to compare long-term series obtained with almost identical instruments working in fairly similar conditions. In such a case, one should expect a reasonable agreement in the results of both series, or at least they could provide the hints to research the origin of eventual discrepancies. However, the astrolabes of Calern and Santiago show such a strong disagreement in the observed variation in time of the solar radius, that it does not seem reasonable to blame it only to atmospheric effects (Noël, 2004). Indeed, we show here that discrepancies of radius measurements with astrolabes are due mainly to mistaken and preconceived criteria in the analysis of some results and not only to severe atmospheric contamination, which according to Li *et al.* (2003) prevent any meaningful ground-based measurement of solar diameter variations. On the contrary, the astrolabes have provided may be for the first time from the ground, significant and consistent results of apparent solar radius measurements as we shall see.

2. The Solar Astrolabe

The Danjon astrolabe (Danjon, 1960) was recognized as an excellent instrument for stellar astrometry (Eichhorn, 1974). Due to its quite simple and compact instrumental system and to the advantages of its observing principle it is free from important systematic errors which affect other astrometric instruments (Fricke, 1972). The observing principle is the method of equal altitudes consisting in timing the transit of the observed object through a small circle of fixed altitude or almucantar (Débarbat and Guinot, 1970). The almucantar is defined by means of a mercury mirror and a transparent prism in front of the objective which produced a reflected image of the observed object. Due to Earth rotation, direct and reflected images are in relative motion and its coincidence marks the transit time through the almucantar. Since this time depends solely on the prism angle that define the almucantar, this is the only instrumental constant which spurious variations could affect the observations accuracy.

With some modifications, the astrolabe can be used for solar astrometry which besides other results gives a value of the apparent radius of the Sun. The modifications consist in installing a solar filter and replacing the original transparent glass prism for observing only at 30° zenith distance with CERVIT reflecting prisms that allow observations at several zenith distances. A CERVIT prism provides a fairly stable reference during the few minutes between both transits of the solar limb. This is a great advantage considering that the most stringent requirement of other techniques of solar metrology is long-term stability of the instrumental system which is difficult to achieve with sufficient precision (Brown *et al.*, 1982).

Moreover, reflecting prisms are free from disturbing effects inherent to transparent prisms (Kovalevski, 1990), and the measuring principle avoid first order effects of spurious refraction (for details see Noël, 1999, 2003).

What is directly measured with the astrolabe is not the solar radius but the time drift of the solar image through the almucantar. Thus, the calibration standard is the Earth rotation which is known with great precision; therefore, the measurements give absolute values of the solar radius.

The first solar observations with modified Danjon astrolabes were made during the 1970s at Calern (Laclare, Demarq, and Chollet, 1980) and during the 1980s at Observatório Abrahão de Moraes, Sao Paulo, Brazil (Leister, 1989). Later on, solar observations with a visual astrolabe started at Santiago, Chile, in 1990 (Noël, 1993), and with CCD astrolabes at San Fernando, Spain, in 1991 (Sanchez *et al.*, 1993), at Rio de Janeiro, Brazil (henceforth Rio), in 1997 (Jilinski *et al.*, 1999) and at Antalya, Turkey, in 1999 (Golbasi *et al.*, 2001).

Presuming that the solar radius could be variable in time, we shall discuss here those astrolabe results obtained simultaneously and during intervals of significant extension.

3. Data Sets of Solar Radius Measurements with Astrolabes

The most extended data set of visual radius measurements with astrolabe is in progress since 1975 at Calern by Dr. Francis Laclare (Delmas and Laclare, 2002). These results have been of great influence for the solar astrolabe community, up to constitute a sort of canonical reference for most of its members. Although one recognizes the pioneer work of Laclare in adapting the Danjon astrolabe to solar metrology, we think that this does not justify without further scientific arguments the excessive credit given by some authors to his results. Obtaining results matching those of Laclare is estimated as a guarantee of good results, and those at issue are considered unquestionably in error (Chollet, 1995; Laclare, 2003). Even it is claimed that the first visual results obtained with other astrolabes were always different to those of Laclare, however, during the course of time they evolved up to finally converge towards Laclare's values (Sinceac *et al.*, 1998; Chollet, 1998). We must stress that we do not know published visual results of other astrolabes that could confirm those claims. At least at Santiago, such sort of evolution was never observed in our visual results. On the contrary, after the first years of observations it was already clear that our results evolved in time, but in phase with solar activity and therefore, diverging from Laclare's results. So was published by Noël (1997, 2001, 2003, 2004) and since 1995 has been privately communicated to several authors. However, later on, those same authors (Sinceac *et al.*, 1998; Laclare, Delmas, and Irbah, 1999a; Andrei *et al.*, 2002), were still affirming that the radius measurements made at several astrolabe stations, including Santiago, confirm the results of Laclare.

Besides the long-term series obtained with the astrolabes of Calern and Santiago, the data set of about 13 500 radius measurements made with the CCD astrolabe of Rio between 1997 and 2000, allows a valid discussion of its results.

The CCD astrolabe of Antalya, Turkey (Golbasi *et al.*, 2001), has produced also radius measurements, but in less quantity and during a shorter interval than those of Rio (see Section 6 and Noël, 2002). Therefore, in this section we shall discuss the variations in time of the apparent solar radius observed with the astrolabes of Calern, Rio and Santiago during 1997–2000.

Figure 1 shows for the interval 1997–2000 second order fits applied to monthly values of sunspot numbers and to daily values of solar radius observed at Rio and Santiago, and a numeric fit applied to the individual radius measurements of Calern. The curves of Calern and Rio show a small decrease of the apparent radius with increasing solar activity, while that of Santiago shows a stronger variation in opposite sense. Thus, the results of Rio would be in agreement with those obtained by Laclare at Calern. However, let us look at the mean daily results of Rio available

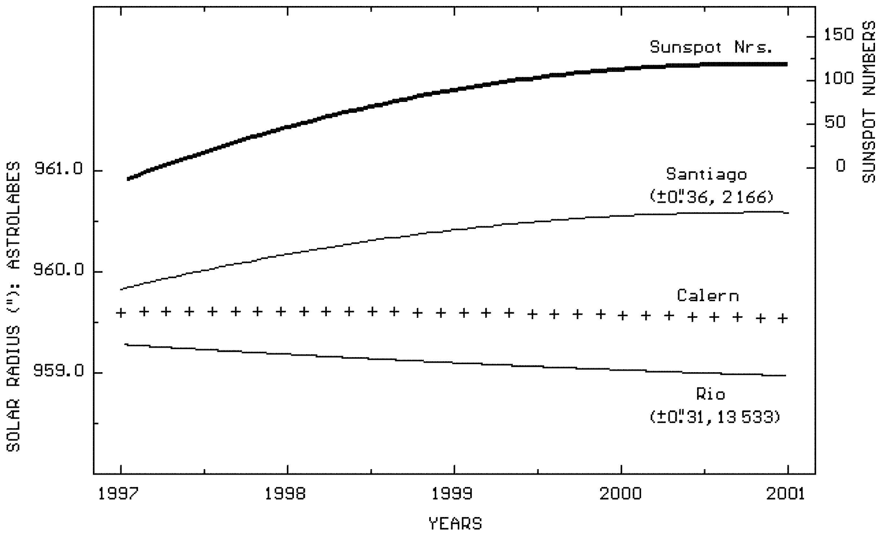

Figure 1. Variations of sunspot number and of the apparent solar radius during 1997–2000. The radius data were obtained with the visual astrolabes of Calern and Santiago, and with the CCD astrolabe of Rio de Janeiro. The curve of sunspot numbers is a least squares second order fit applied to monthly means as given by SIDC. Those for Rio de Janeiro and Santiago are similar fits applied to daily mean values of the observed radius at both the places. The figures in brackets are the standard deviation given by the fits and the total number of individual observations involved in each case. The curve of Calern, adapted from Figure 1 of Delmas and Laclare (2002), is a numerical fit applied to individual radius measurements. The curve of Rio de Janeiro shows a radius variation that would be in agreement with that observed at Calern (see text). It was obtained from individual results of Rio de Janeiro published by Jilinski *et al.* (1999), Puliaev *et al.* (2000) and Penna *et al.* (2002). However, these results that are publicly available at CDS, are affected by strong internal inconsistencies that can be seen in Figure 2 (see also Noël, 2002).

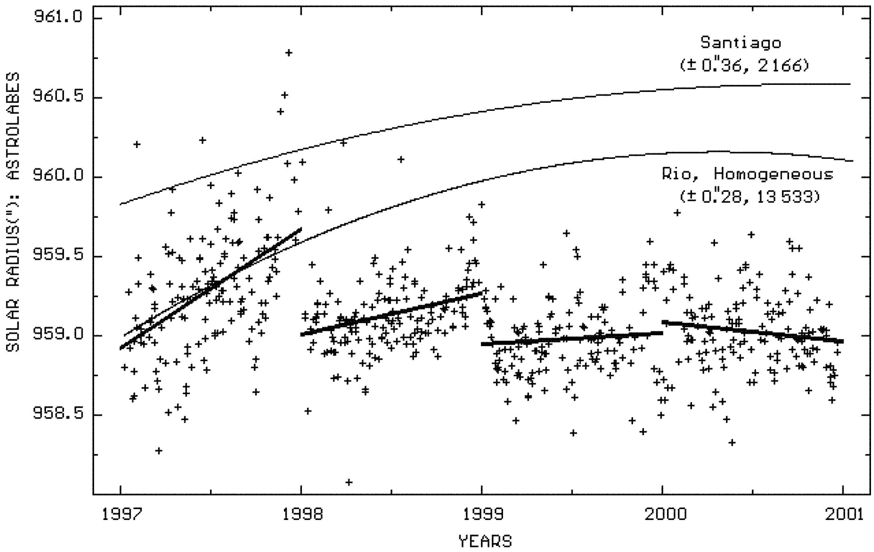

Figure 2. Mean daily values of solar radius measurements (+) made with the CCD Danjon astrolabe of Rio de Janeiro during 1997–2000 (Jilinski *et al.*, 1999; Puliaev *et al.*, 2000; Penna *et al.*, 2002). The observed radius values show large discontinuities around 1998.0 and 1999.0 that are detached by annual least square linear fits. According to the fits parameters they amount to $-0''.660 \pm 0''.136$ and $-0''.323 \pm 0''.089$ for 1998.0 and 1999.0, respectively. The radius jump in 1998.0 can be explained by an instrumental modification related to the CCD, made around the 1st of January, 1998 (Jilinski *et al.*, 1999; Noël, 2002). Although we do not have information on the jump of 1999.0, it may well due to similar, however unpublished instrumental changes (Noël, 2002). Therefore, both discontinuities were removed from the results of Rio de Janeiro to make them homogeneous. The linear fits parameters do not show a significant discontinuity around 2000.0. The curve labeled *Rio, Homogeneous*, is a least square second order fit applied to the daily radius measurements of Rio de Janeiro after removing both radius jumps. It shows an improved internal precision with respect to the original curve in Figure 1, and a radius variation almost identical to that given by the curve of Santiago, which is plotted here for the sake of comparison. The figures in brackets have the same meaning as in Figure 1.

from CDS which are plotted in Figure 2. They show strong discontinuities of the radius values around 1998.0 and 1999.0 which we have detached by least squares annual linear fits (see also Noël, 2002). The radius jumps of 1998.0 and 1999.0 are in the individual results of Rio published by Jilinski *et al.* (1999) and by Puliaev *et al.* (2000), respectively. At least the jump of 1998.0 is visible in Figure 2 of Jilinski *et al.* (1999). However, neither that paper co-authored by Francis Laclare, nor Puliaev *et al.* (2000) give any comment on such radius *jumps* which do not seem imputable to atmospheric effects nor to other sort of observational errors.

We shall see below that the discontinuity of 1998.0 comes from instrumental modifications made in Rio's astrolabe around that epoch, and probably that of 1999.0 has a similar origin (see also Noël, 2002). After evaluating both jumps we have removed them from Rio's data to make them homogeneous and comparable with other results.

The curve of Rio in Figure 2 is a least square second order fit applied to the homogeneous daily radius values. Besides an improved internal accuracy of the homogeneous data of about 10%, it shows a drift of the solar radius almost identical to that observed at Santiago.

We have tried to get from the authors of Rio's results, their own view on the origin of these sudden and strong variations in their radius values. Similar information was kindly requested from Calern considering that both groups work quite closely and that Francis Laclare is co-author of Jilinski *et al.* (1999). Neither from Rio nor from Calern was obtained a reply. However, in a later analysis by Reis Neto *et al.* (2003) of radius variations observed at Rio, the whole set of 2704 radius measurements made during 1997 was discarded. The following reasons are invoked by the authors to discard such a huge amount of empirical data:

- The observations were made with a larger bandpass,
- with an initial version for the program of data acquisition and reduction, and
- for eastward transits only.

However, from these three reasons we could find that only a bandpass modification is mentioned by Jilinski *et al.* (1999). They affirm that around the 1st of January, 1998, *the filter after the image vehicle was swapped by one with a narrower bandpass*. In our view, such constraint on the CCD bandpass explains the large and sudden radius diminution in 1998.0 (Wittmann, 1997; see also Noël, 2002).

Concerning a change in 1998 of the program of data acquisition and reduction, this is not mentioned by Jilinski *et al.* (1999). Furthermore, such change should be at issue with Delmas (2003) who affirms that ... *a Solar astrolabe ... started a series at Rio de Janeiro in January 1997. With the same acquisition and image processing softwares as at the Calern, more than 12 000 measurements were made.*

The third cause invoked by Reis Neto *et al.* (2003) is in contradiction with Table 1 of Jilinski *et al.* (1999). That Table shows that from the 2704 radius values obtained at Rio in 1997, 64% (1730) were based on westward observations made between April and December.

We have kindly requested from the astrolabe staffs of Rio and Calern to clarify these contradictions, but also in this case with negative results. The discard of all the results of Rio obtained during 1997 is even more incomprehensible since Jilinski *et al.* (1999) as Puliaev *et al.* (2000) explain how to obtain their individual results through Internet. This should be considered as a tacit invitation for other authors to use their individual data. The results of Rio discussed here and in our papers of 2001 and 2002 were obtained following such invitation.

From the contradictions that we have seen inside Rio's staff and with some members of Calern, but mainly, from the lack of an explanation from both groups, one must conclude that it is more likely that the homogenized results of Rio discussed in this paper show the real variations in time of the apparent solar radius observed at Rio during 1997–2000.

4. On the Solar Radius Measurements Made at Calern and Santiago

The solar program with the astrolabe of Santiago produced 4383 radius measurements by a single observer between May, 1990 and April, 2003. These results and the thousands of radius values obtained after 1990 with the astrolabe of Calern are the most extended time series of simultaneous ground-based radius measurements. However, they are largely discrepant with respect to long-term variations of the solar radius. That of Calern shows a marginal radius variation in opposite phase with solar activity, while Santiago shows a rather strong variation in phase with the activity cycle. One should expect similar results from almost identical instruments working in fairly similar conditions like these astrolabes, or at least not wholly discrepant as in this case. Therefore, the disagreement between Calern and Santiago is striking, but above all, it is very difficult to explain.

For Laclare (2003) this discrepancy would be only apparent due to the low precision of the results of Santiago. Since our results are of public access at CDS, he gives the following standard deviations for the radius measurements made at both sites:

Calern: $\pm 0''.28$ Santiago: $\pm 0''.50$.

According to this argument the radius variation in time observed at Santiago could be explained by an atmospheric artifact which due to a coincidence shows a drift similar to that of solar activity. Such explanation is difficult to accept considering that the results of Santiago are in agreement with several other obtained during the last years with different observing techniques (Noël, 2004). Moreover, here we have shown that the results of the CCD astrolabe of Rio which with strong internal inconsistencies would be in agreement with Calern, after a quite simple procedure of homogenization are at last in agreement with Santiago.

Concerning the apparently large standard deviation of Santiago we must stress that here no result is eliminated whatever is its dispersion if it was obtained in normal circumstances. One should bear in mind that the Sun is not a solid body and that the eventual presence of plages, sunspots, faculae, etc., can affect the observed position of the solar limb as it is discussed below. This makes difficult to discern how much of the dispersion shown by our visual radius measurements can be blamed on atmospheric noise and how much comes from the Sun. Therefore, the dispersion shown by our results could be not reflecting the true precision of the observations.

In Figure 3 are plotted for the interval 1991–2002 monthly means of sunspot numbers as given by SIDC and results of radius measurements obtained with the astrolabes of Calern, Rio and Santiago. They are compared with results obtained with the Mount Wilson magnetograph (Ulrich and Bertello, 1995) and with the 17 GHz radioheliograph of Nobeyama, Japan (Selhorst, Silva, and Costa, 2004). All these results, except Calern, show similar variations in time of the solar radius. This should be against Laclare's explanation of the discrepancies between Calern

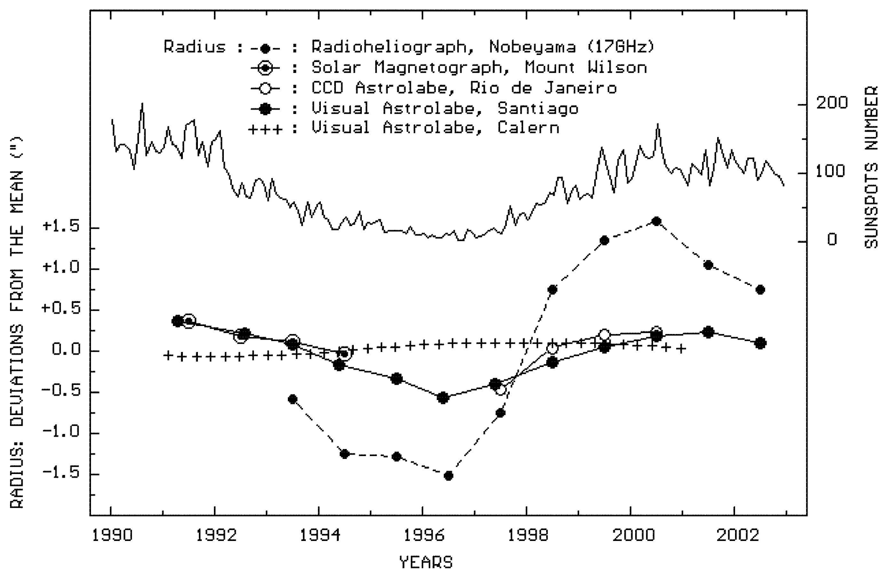

Figure 3. Monthly means of sunspot numbers as given by SIDC and deviations from the mean of the apparent solar radius obtained with several instruments between 1991 and 2002. The values of the astrolabes of Santiago and Rio de Janeiro, the last ones after a procedure of homogenization discussed in the text, are annual means adapted from Figure 5 of Noël (2004). The curve of the astrolabe of Calern was adapted from a numerical fit applied to daily radius measurements as given in Figure 1 of Delmas and Laclare (2002). The values of the 17 GHz radio-heliograph of Nobeyama are annual means computed from a scan of Figure 4a of Selhorst, Silva, and Costa (2004) and those of the magnetograph of Mount Wilson were adapted from Figure 1 of Ulrich and Bertello (1995). The zone of the photosphere observed by the 17 GHz radio-heliograph is quite different to those observed by the astrolabes and by the Mount Wilson magnetograph. However, the radio-heliograph at least confirm the tendency of the other instruments, with the only exception of the astrolabe of Calern. Seventeen Gigahertz observations should be free from atmospheric noise.

and Santiago. However, we shall see that there are even stronger arguments to discard that explanation.

In contrast with the discrepancy between Calern and Santiago seen in Figures 1 and 3, there is an agreement with a correlation coefficient of 0.78 ± 0.14, between these astrolabes on small radius variations along the solar limb as shown in Figure 4 (Noël, 1999, 2004). This agreement means that the precision of both instruments cannot be so different as claimed by Laclare (2003). But moreover, it shows that it is far more difficult and may be impossible, to explain the discrepancy on the larger radius variations in time between both astrolabes. Indeed, if two metrological devices agree in coarse details but disagree in fine details of the measured object, this means simply that one or both devices have insufficient precision. However, how could be explained the opposite case, like that of the astrolabes of Calern and Santiago which agree in small solar radius variation, but not in the larger ones?

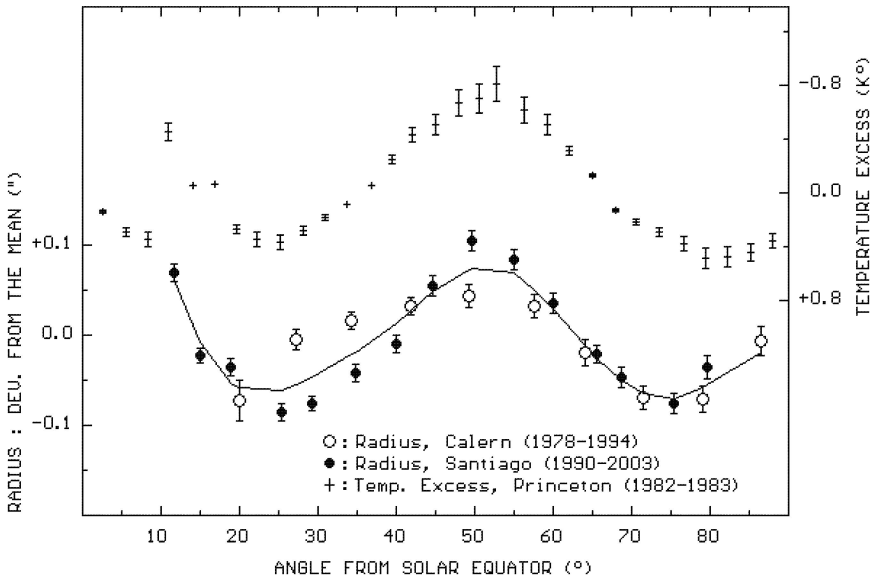

Figure 4. Deviations from the mean of the apparent solar radius and temperature excess of the solar limb as a function of the angle from solar equator or heliographic inclination. For the sake of clarity, the temperature scale is inverted. The apparent radius values are based on observations made with the visual Danjon astrolabes of Calern, France (Vigouroux, 1996) and Santiago, Chile (Noël, 1999). The temperature data, obtained by Kuhn, Librecht, and Dicke (1985) with the Princeton Solar Distortion Telescope, show a puzzling anti-correlation with the apparent radius. From this precise anti-correlation and from the agreement of both astrolabes, one concludes that the observed radius variation along the solar limb should be intrinsic to the Sun and not an atmospheric artifact. This agreement contradicts the claims that atmospheric contamination is so severe that prevent meaningful measurement of solar diameter variations from the ground (Gough, 2001; Li *et al.*, 2003). The smoothing curve is a Vondrak (1969) fit applied to the merged results of Calern and Santiago. For a detailed discussion on similar results see Noël (1999).

We recognize that the rather large radius variations observed with the astrolabe of Santiago and those shown in Figure 3, are at issue in the present frame of solar physics (Antia, 2003). However, this does not mean that these results should be some sort of artifact. Although for theoretical reasons they could not correspond wholly to variations of the true solar radius, such results can be of solar origin anyhow, specially when they seem to depend on solar activity. According to Bruls and Solanki (2004) plage emission near the solar limb associated with magnetic activity variation during a solar cycle, produces apparent radius changes. Those authors show that the radius variations observed at Mount Wilson by Ulrich and Bertello (1995) in the spectral line of neutral iron at 525 nm can be fully explained by a 3% change of the line wing intensities near the limb during a solar cycle. From here and from the almost identical radius variations observed at Santiago and Mount Wilson shown in Figure 3, one should conclude that also the astrolabe observations of Santiago can include effects although not related with radius variations, but of solar origin in some way. A similar conclusion should be valid for the homogenized CCD results of Rio. Therefore, if almost identical instruments should give similar results, we do not see how could be explained the discrepant results of Calern.

Furthermore, if the astrolabes of Calern and Santiago agree in small radius changes along the solar limb (Noël, 1999, 2004; Laclare, Delmas, and Irbah, 1999b) as shown in Figure 4, with far more reasons they should agree also in the larger changes, independently if they are related or not to the true solar radius. Therefore, the disagreement of Calern results with respect to those of Santiago and to the homogeneous results of Rio shown in Figure 3, is striking, fully unexpected, but above all, impossible to explain through atmospheric artifacts or other sort of observational errors.

Solar observations that give large radius variations at issue with solar physics could be considered erroneous by some authors. Obviously, a filtering of such results should have minor effects on small apparent radius variations, but it will mask the larger ones. Something similar occurs comparing the results of Calern and Santiago. They agree in small radius variations along the solar limb, but Calern does not show the larger long-term variations observed at Santiago. There are hints that the analysis of radius measurements at Calern could be biased by preconceptions which consider spurious those results at issue with solar physics as we shall see.

Variations of the apparent solar radius with amplitude of $0''5$ and a cycle of about 900 days were observed by Laclare (1983) at Calern. They were discussed by Ribes *et al.* (1991) and compared with simultaneous results obtained with the astrolabe of Sao Paulo, Brazil, and from meridian timings at Belgrade Observatory. The conclusion of Ribes *et al.* with Laclare as co-author on the agreement of those three results is that *although no theoretical mechanism is known for explaining a 1000-day modulation in visual time series, the similarity in the observed apparent semi-diameter points to a solar cause*. However, later on, in connection with the average solar radius deduced from the long time series of Calern, the possible radius variations were ignored by Laclare, Delmas, and Irbah (1999a) because they *can only be of small amplitude if any*. Moreover, Chollet (1998), co-author of Laclare, Delmas, and Irbah (1999a), claims that variations of the solar radius as large as those observed at Santiago or as those observed in the past at Calern, are in conflict with solar physics and therefore they should be spurious. Nevertheless, radius variations like those reported by Laclare (1983) but with amplitudes up to $0''20$ were found three times at Calern between 1978 and 1986 (Laclare *et al.*, 1996). Its disappearance after 1986 cast doubt to those authors on a possible atmospheric origin of such variations. However, one should wonder if the agreement of the results of Calern, Sao Paulo and Belgrade discussed by Laclare in Ribes *et al.* (1991), could also cast doubt on its possible atmospheric origin?

According to Bruls and Solanki (2004), apparent radius measurements that give results at issue with solar physics like those observed by Laclare (1983) are not necessarily spurious. Nor it would be necessary to explain through exotic atmospheric artifacts the results of Mount Wilson, Rio or Santiago, which give radius variations in phase with magnetic activity but with amplitudes at issue with solar physics. However, the astrolabe of Calern, in spite of being almost identical to those of Rio and Santiago, gives strongly discrepant results on long-term radius variations. But, we have seen that this discrepancy cannot be explained through atmospheric artifacts or other sort of observational errors.

5. On Visual and CCD Observations with Solar Astrolabes

The first CCD observations of the Sun with astrolabe were made at Calern in 1989 (Laclare and Merlin, 1991). Later on, CCD cameras were installed in the solar astrolabes of San Fernando, Spain (Sanchez *et al.*, 1993), Rio (Jilinski *et al.*, 1999) and Antalya, Turkey (Golbasi *et al.*, 2001). However, for the reasons discussed below, the astrolabe of Santiago was kept as a visual instrument throughout our whole program of solar astrometry between 1990 and 2003. Although in 1995 we made some experiments with a CCD camera (Noël, 2001), all our data set of apparent radius measurements is based on visual observations.

Laclare (2003) claims that due to its visual character only, the results of Santiago would be doubtful since they have been not *validated* or *consolidated* through impersonal CCD observations as he did at Calern by means of simultaneous visual and CCD observations of the solar radius. Moreover, Delmas and Laclare (2002) affirm that since 1989 visual and CCD results of Calern match perfectly, providing a *unique qualification* of the whole data set. However, let us look more closely at those claims and at the CCD experiments made at Santiago (Noël, 2001).

In 1995 and with the kind advices and technical support of Dr. Francis Laclare and Dr. Fernand Chollet, we installed a same type of CCD camera as that of Calern in the astrolabe of Santiago. However, our CCD solar images acquired with similar method and software as those of Calern, were contaminated with scattering light that made them useless for metrological purposes. The origin of this problem and the solution that we applied to solved it, is discussed by Noël (2001). Here, in connection with the comments of Laclare (2003) and of Delmas and Laclare (2002) mentioned above, we must point out what follows.

According to Chollet (1995), the CCD solar images at Calern were also affected with scattering light. But the attempts to solve this problem was through an algorithm applied to the acquired solar images imitating the action of a neutral density filter (ibid). However, before 1995 we had not seen in Laclare's papers on CCD observations at Calern, any mention of scattering light problems in his solar images. The classical solution to eliminate scattering light (see Danjon and Couder, 1979) that we applied at Santiago is mentioned for the first time in Calern results by Sinceac (1998). Nevertheless, Laclare was obtaining CCD radius measurements since 1989 with the following mean results for the period 1989–1995 (Laclare, Delmas, and Irbah, 1999a):

CCD: $959''.49 \pm 0''.01$ Visual: $959''.48 \pm 0''.01$

Concerning this agreement between the visual and CCD results of Calern, in no case it should *validate* or *consolidate* the visual results of Calern, nor is a *unique qualification* of its whole data set. One should bear in mind that the human eye and a CCD camera are quite different optical systems. Therefore, if in this case both systems give identical results, this is only a coincidence from which no scientific conclusions can be drawn on the quality of the visual data (see also Sinceac, 1998).

It is pertinent to mention here the long series of visual and CCD radius measurements made during many years by Dr. Axel Wittmann. Using also the drift scan method with two almost identical 45 cm Gregory–Coudé telescopes at Locarno, Switzerland, and at Izaña, Tenerife, he obtained between 1972 and 2002 the following mean values for the solar radius (Wittmann, 2003):

CCD: $959''.89 \pm 0''.12$ Visual: $960''.62 \pm 0''.02$

As one should expect from different optical systems, there is here a significant offset between their results. Dr. Wittmann affirms that the lower precision of the CCD results is due to the fluctuations of the position of the solar limb and image blurring due to the atmosphere which can be monitored with the eye but not with a detector. Moreover, the radius value given by CCD measurements is somewhat dependent on the threshold of the camera which in turn depends on gain, air transparency, etc. This is confirmed in Section 3 of this paper by the large jump in the solar radius observed at Rio after a change in the bandpass of the CCD.

Concerning his results, Wittmann (1997) claims that eight CCD drift scan measurements are required to get the accuracy of one visual drift timing. Comparing the results of the astrolabes of Rio and Santiago, we show elsewhere that the precision of one visual observations at Santiago is attained after six CCD observations at Rio (Noël, 2001).

Following all these arguments we are in full disagreement with the claim of Laclare (2003) that the visual radius measurements of Santiago would be doubtful because they have been not *validated* or *consolidated* by means of CCD observations. This claim comes from an over interpretation of a casual agreement between the visual and CCD results of Calern. However, it contrasts with Laclare, Delmas, and Irbah (1999a) who affirmed that *contrary to what one would expect, the CCD observations do not give significantly better results than those obtained from visual observations*. Indeed, after the scattering light problem was solved at Santiago, our CCD solar images looked still rather poor. This is in agreement with Sinceac (1998) who states that although the visual results of the astrolabe are not affected by eventual imperfections of the instrument's optic, they pose a serious problem for the CCD images which need a *cleaning* to diminish its effects.

From these drawbacks of the CCD solar images and those described above by Wittmann, one concludes that a CCD camera is not a good solution to improve or to make impersonal the results of the solar astrolabe. Therefore, we decided at Santiago to concentrate our efforts in completing at least a solar cycle with the maximum number of homogeneous visual results. We did not have material facilities to keep a parallel program of CCD observations without affecting the visual ones. On the other hand, following what we have seen here on CCD results, such parallel program would have been an effort of dubious justification.

6. Summary and Conclusions

The long history of ground-based attempts for measuring the solar radius is plagued by huge amounts of inconsistent and controversial results blamed to the distorting effects of the Earth's atmosphere (Gough, 2001). Concerning radius variations in time, Li *et al.* (2003) claim that atmospheric noise can be so severe that even in cases when the observations are made with similar instruments the results are still discrepant. Such claim is pertinent to the results obtained with the solar astrolabes of Calern, France, and Santiago, Chile, which are almost identical instruments and work in quite similar conditions. However, their results obtained simultaneously during an interval equivalent to a solar cycle, are strongly discrepant concerning long-term variations of the apparent solar radius (see Figure 3).

Nevertheless, in spite of this discrepancy, the results of Calern, Rio and Santiago, show that the astrolabe has the capacity to disclose small radius variations along the solar limb (Reis Neto *et al.*, 2003). Concerning larger variations in phase with the activity cycle, we have seen here that the visual results of Santiago and the CCD results of Rio after a procedure of homogenization, are almost identical. Thus, the discrepancy of Calern, the only one between these three astrolabes, is very difficult to explain. If it is due to atmospheric noise as suggested by Li *et al.* (2003), with far more reasons that noise should have affected also the results on smaller radius variations. However, we have seen here that concerning such results Calern and Santiago show a remarkable agreement seen in Figure 4 (see also Noël, 1999, 2004; Laclare, Delmas, and Irbah, 1999b).

There are hints that the analysis of radius variations at Calern could be biased by theoretical preconceptions. Indeed, Chollet (1998) and Laclare, Delmas, and Irbah (1999b) claim that variations of the solar radius as observed at Santiago or by Laclare (1983) are erroneous in the present frame of solar physics, or that if radius variations exist they should be small if any (Laclare, Delmas, and Irbah, 1999a). However, theoretical constraints do not concern the apparent radius of the Sun observed with a certain technique. From Bruls and Solanki (2004) one concludes that large variations of the apparent solar radius are not necessarily erroneous or contaminated with atmospheric artifacts. If for theoretical reasons such results could not correspond wholly to eventual variations of the *true* solar radius, they can be anyhow of solar origin.

In a former paper (Noël, 2002) we have shown that the published results of radius measurements made with the CCD astrolabe of Antalya, Turkey, are also in agreement with Santiago. The data set of Antalya (Golbasi *et al.*, 2001) available from CDS covers a shorter interval than that of Rio. However, their 791 radius measurements made between July 26, 1999 and July 16, 2001, show a time drift of the solar radius in agreement with that observed at Santiago during the same interval.

The CCD astrolabes of Calern, Rio and Antalya constitute the *R2S3 Consortium (Réseau de Suivi au Sol du Rayon Solaire)* for a continuous monitoring of the solar radius with CCD astrolabes (Andrei *et al.*, 2004). However, we have seen here that concerning variations in time of the solar radius two astrolabes of that *Consortium* give similar results as those of Santiago and therefore, at issue with the results of Calern.

In spite of the notable disagreement of Calern, tentatively explained above (see also Noël, 2004) the agreement of the astrolabes of Rio and Santiago discussed in this paper and also of the astrolabe of Antalya (Noël, 2002), shows that this instrument can give consistent results on solar radius measurements. This contradicts the claims that due to atmospheric noise ground-based observations are unreliable to disclose long-term variations of the apparent radius of the Sun (Gough, 2001; Li *et al.*, 2003). These achievements of the Danjon astrolabe are due to its reliable instrumental system and to the advantage of its observing principle over other ground-based techniques for solar metrology as described in Section 2.

References

Andrei, A. H., Penna, J. L., Reis Neto, E., Jilinski, E. J., Boscardin, S. C., Delmas, C., Morand, F., and Laclare, F.: 2002, in N. Capitaine and M. Stavinschi (eds.), *Systèmes de Référence Spatio-Temporels*, Journées 2002, Actes, 25–28 September, Astronomical Institute of the Romanian Academy, Bucharest, p. 185.

Andrei, A. H., Boscardin, S. C., Chollet, F., Delmas, C., *et al.*: 2004, *Astron. Astrophys.* **427**, 717.

Antia, H. M.: 2003, *Astrophys. J.* **590**, 567.

Brown, T. M., Elmore, D. F., Lacey, L., and Hull, H.: 1982, *Applied. Opt.* **2**, 3588.

Bruls, J. H. M. J. and Solanki, S. K.: 2004, *Astron. Astrophys.* **427**, 735.

Chollet, F.: 1995, *Personal communication.*

Chollet, F.: 1998, *Personal communication.*

Danjon, A.: 1960, in G. P. Kuiper and B. M. Middlehurst (eds.), *Telescopes*, The University of Chicago Press, Chicago, p. 115.

Danjon, A. and Couder, A.: 1979, in Albert Blanchard (ed.), *Lunettes et Télescopes*, Paris, p. 310.

Débarbat, S. and Guinot, B.: 1970, in Gordon and Breach (eds.), *La méthode des hauteurs égales en astronomie*, Paris.

Delmas, C.: 2003, in J. P. Rozelot (ed.), *Proceedings of the 5th Summer School on Solar Astrophysics*, St. Pierre d'Oléron, France, 22–26 May 2000, *Lectures Notes in Physics*, Springer-Verlag, Berlin Heidelberg **599**, 196.

Delmas, C. and Laclare, F.: 2002, *Solar Phys.* **209**, 391.

Eichhorn, H.: 1974, *Astronomy of Star Positions*, Frederick Ungar Publishing Co., New York, p. 49.
Fricke, W.: 1972, *Ann. Rev. Astron. Astrophys.* **10**, 107.
Gilliland, R. L.: 1981, *Astrophys. J.* **248**, 1144.
Golbasi, O., Chollet, F., Kiliç, H., Sinceac, V., Aslan, Z., and Sozen, E.: 2001, *Astron. Astrophys.* **368**, 1077.
Gough, D.: 2001, *Nature* **410**, 313.
Jilinski, E. G., Puliaev, S., Penna, J. L., Andrei, A. H., and Laclare, F.: 1999, *Astron. Astrophys. Suppl. Ser.* **135**, 227.
Kovalevsky, J.: 1990, *Astrométrie Moderne*, Springer-Verlag, Berlin Heidelberg, p. 181.
Kuhn, J. R., Librecht, K. G., and Dicke, R. H.: 1985, *Astrophys. J.* **290**, 758.
Laclare, F., Demarq, J., and Chollet, F.: 1980, *Academie des Sciences (Paris), Comptes Rendus, Serie B* **291**, 189 (in French).
Laclare, F.: 1983, *Astron. Astrophys.* **125**, 200.
Laclare, F.: 2003, *Communication to F. Noël circulated by the addresser in the solar astrolabe community.*
Laclare, F. and Merlin, G.: 1991, *C.R. Acad. Sci. Paris* **t. 313, Série II**, 323.
Laclare, F., Delmas, C., Coin, J. P., and Irbah, A.: 1996, *Solar Phys.* **166**, 211.
Laclare, F., Delmas, C., and Irbah, A.: 1999a, *C.R. Acad. Sci. Paris* **t. 327, Série IIb**, 645.
Laclare, F., Delmas, C., and Irbah, A.: 1999b, *C.R. Acad. Sci. Paris* **t. 327, Série IIb**, 1107.
Leister, N. V.: 1989, Ph.D. Thesis, Instituto Astronômico e Geofísico, Universidade de São Paulo, Brazil.
Li, L. H., Basu, S., Sofia, S., Robinson, F. J., and Demarque, P.: 2003, *Astrophys. J.* **591**, 1267.
Noël, F.: 1993, *Astron. Astrophys. Suppl. Ser.* **102**, 11.
Noël, F.: 1997, *Astron. Astrophys.* **325**, 825.
Noël, F.: 1999, *Astron. Astrophys.* **343**, 1001.
Noël, F.: 2001, *Astron. Astrophys.* **375**, 614.
Noël, F.: 2002, *Astron. Astrophys.* **396**, 667.
Noël, F.: 2003, in J. P. Rozelot (ed.), *Proceedings of the 5th Summer School on Solar Astrophysics*, St. Pierre d'Oléron, France, 22–26 May 2000, *Lectures Notes in Physics*, Springer-Verlag, Berlin Heidelberg **599**, 181.
Noël, F.: 2004, *Astron. Astrophys.* **413**, 725.
Penna, J. L., Jilinski, E. G., Andrei, A. H., and Reis Neto, E.: 2002, *Astron. Astrophys.* **384**, 650.
Puliaev, S., Penna, J. L., Jilinski, E. G., and Andrei, A. H.: 2000, *Astron. Astrophys. Suppl. Ser.* **143**, 265.
Reis Neto, E., Andrei, A. H., Penna, J. L., Jilinski, E. G., and Puliaev, S. P.: 2003, *Solar Phys.* **212**, 7.
Sanchez, M., Moreno, F., Parra, F., and Soler, M.: 1993, *Astron. Astrophys.* **280**, 333.
Selhorst, C. L., Silva, A. V. R., and Costa, J. E. R.: 2004, *Astron. Astrophys.* **420**, 1117.
Sinceac, V.: 1998, Ph.D. Thesis, Observatoire de Paris, France.
Sinceac, V., Chollet, F., Laclare, F., and Delmas, C.: 1998, *Astron. Astrophys. Suppl. Ser.* **128**, 605.
Ulrich, R. K. and Bertello, L.: 1995, *Nature* **377**, 214.
Vigouroux, A.: 1996, Ph.D. Thesis, Université de Nice-Sophia Antipolis, France.
Vondrak, J.: 1969, *Bull. Astron. Inst. Czech.* **20**, 349.
Wittmann, A. D.: 1997, *Solar Phys.* **171**, 231.
Wittmann, A. D.: 2003, *Astron. Nachr./Astron. Notes 324* **No. 4**, p. 378.