PICARD SOL, a new ground-based facility for long-term solar radius measurements: first results

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Abstract. PICARD SOL is the ground component of the PICARD mission and is operational since March 2011. A set of instruments including the replica of the space instrument and several atmospheric monitors was set up at Calern observatory in order to compare solar radius measured in space and on ground and to better understand and calibrate atmospheric effects on ground based measurements. SODISM II provides full disk images of the chromosphere and photosphere of the Sun in five narrow pass bands ranging from the near ultraviolet to the near infrared. Our preliminary results show a very good instrumental stability. After plate scale calibration using star doublet observations and corrections for atmospheric refraction, first estimates of the mean solar radius at the five wavelengths (393.37, 535.7, 607.1, 782.2, and 1025.0 nm) are deduced from measurements recorded between May 2011 and December 2012.

1. Introduction

The PICARD program [1] owes its name to Jean Picard (1620-1682), considered as a pioneer of precise modern astrometry who measured the solar radius. The project includes not only a space mission but also a ground component set up at the Calern observatory where a solar radius survey was initiated in 1975 with the visual Solar astrolabe [2]. This was later completed by DORAYSOL (Définition et Observation du RAYon SOLaire), an automatized astrolabe using CCD records and a variable prism in order to increase the number of daily measurements [3]. A mean solar radius of 959.48" with a standard deviation (σ) of 0.32" was deduced from 19,169 measurements using DORAYSOL between 2000 and 2006. During the same period, 371 measurements made with the solar astrolabe led to a mean value of 959.55" with σ=0.26". Ground measurements made over two solar cycles at Calern observatory, show a significant variation of about 0.2" peak-to-peak anti-correlated with solar activity [2]. Space measurements have not confirmed this observation but they are covering relatively short periods and were not dedicated to solar metrology. A debate therefore exists to know if this observed variation from ground is of solar origin, purely atmospheric or a combination of both effects. Atmospheric

turbulence has an effect on these measurements and numerical simulations were developed in order to better understand it. The uncertainties and bias introduced by optical turbulence decreases with the seeing but it is also strongly conditioned by turbulence coherence times. It is therefore important to record all the spatio-temporal parameters of optical turbulence at the time of image record. A generalized daytime seeing monitor was built for this goal. Furthermore, general atmospheric conditions (sky brightness, scattering by aerosols, clouds,..) can affect image quality and impact astrometric measurements. This is why a set of complementary monitors was also installed on the site. A continuation of ground-based series represents our best chance to detect possible long-term variations of solar radius. Short-term space missions dedicated to solar metrology can be used for cross calibrating measurements during their lifetime. In the next sections, we present the different instruments of PICARD ground-based facility, and give some preliminary results obtained from the first twenty months of continuous operations.

2. PICARD SOL instruments

2.1. SOlar Diameter Imager and Surface Mapper (SODISM II)

SODISM II is an 11-cm diameter telescope with a charge-coupled device (CCD) at its focal plane [4]. It is a Ritchey-Chrétien telescope with a focal length of 2,626 mm, an aperture of F/23 with a central obscuration of 40% in diameter (F/30 and 50% for the main channel). The field of view is $\sim 36' \times 36'$ and one image is recorded every minute. The CCD array has 2048×2048 square pixels of $13.5\,\mu$m side (~ 1.06" per pixel). The whole SODISM II instrument is in primary vacuum ($\sim$10 mbar), and thermally regulated ($\sim$20°C). The Sun image is stabilized on the detector by the equatorial mount (better than $\pm$0.5" during the exposure time). SODISM main optical path consists essentially of a front window, a primary mirror (M1), a secondary mirror (M2), two filter wheels (FW) with interchangeable interference filters, and a CCD regulated at -10^{o}C ($\pm$0.2^{o}C). SODISM II provides full disk-images of the Sun at five wavelengths: 393.37, 535.7, 607.1, 782.2, and 1025.0 nm with narrow bandwidth of 0.7, 0.5, 0.7, 1.6 and 6.4 nm respectively. Several campaigns of star doublet observations have provided the image plate scale: ~ 1.0611" per pixel with a relative uncertainty of 10^{-4}. This introduces an uncertainty of 0.09" in the determination of the solar radius.

2.2. Moniteur d'Images SOLaires Franco-Algérien (MISOLFA)

MISOLFA is a solar seeing monitor associated with a CCD detector at its focal plane [5]. It is a Cassegrain-coudé telescope with a focal length of 10,000 mm, a main entrance pupil of 252 mm, and an aperture of F/40. The field of view is $\sim 2.1' \times 1.6'$. The CCD array has 640 by 480 square pixels of $9.9\,\mu$m side (~ 0.20" per pixel). An Alt-Azimuth mount supports and rotates MISOLFA and a prismatic entrance window allows to record simultaneously two opposite solar limbs. Thirty-two pairs of opposite solar limbs are recorded every second. The MISOLFA design is based on the statistical analysis of Angle of Arrivals (AA-fluctuations) defined as the slope in each point of the wavefront. Two measurement channels are provided:

- A direct channel in which the Sun's limb images are formed on a CCD camera with suitable magnification. This channel enables the evaluation of the spatial coherence parameters of the wavefront (Fried parameter, outer scale and iso-planatism domain).

- A second channel (pupil channel) that forms the image of the pupil through a diaphragm placed on the solar limb is used to evaluate the wavefront temporal parameters using high cadence photo-electric detectors (photodiodes).

2.3. Additional instrumentation

In addition to a weather station we have set up three instruments in order to provide continuous quality index for atmospheric conditions. The instruments listed below are used:

- A Sun tracking photometer which measures Sun and sky radiance using a combination of seven spectral filters in order to derive total column water vapor, ozone and aerosols properties. The chosen wavelengths are nearly the same as for the SODISM II instrument.

- A pyranometer is used to measure broadband solar irradiance (from 200 to 3600 nm), and is designed to measure the solar radiation flux density from a field of view of 180 degrees.

- A visible wide-field camera monitors weather conditions and cloud coverage. The field of view is slightly greater than 180 degrees in the horizontal direction and the path of the solar disk across the sky is masked.

3. Results

SODISM II images were obtained between May 2011 and December 2012. For this preliminary work, we simply defined the solar radius by the position of the inflection point of solar limb profiles taken at different position angles. The inflection point position is obtained by computing the location of the maximum of the derivative squared of the limb profiles. After computing all contour inflection points, we can find the best circle fit using a least squares method. An evolution of the solar radius estimated this way from SODISM II images is shown on Figure 1 as a function of time for different wavelengths. The corresponding mean solar radii and standard deviations are provided in Table 1. Solar radius measurements at Calern since 1978 are shown on Figure 2. The first important point to notice is that the standard deviation obtain with this new series (around $0.23''$) is of the same order or slightly lower than the one obtained with previous astrolabe measurements. We thus believe that the instrument has been fairly stable during its first twenty months of operations and we do not observe any degradation or systematic effects with time.
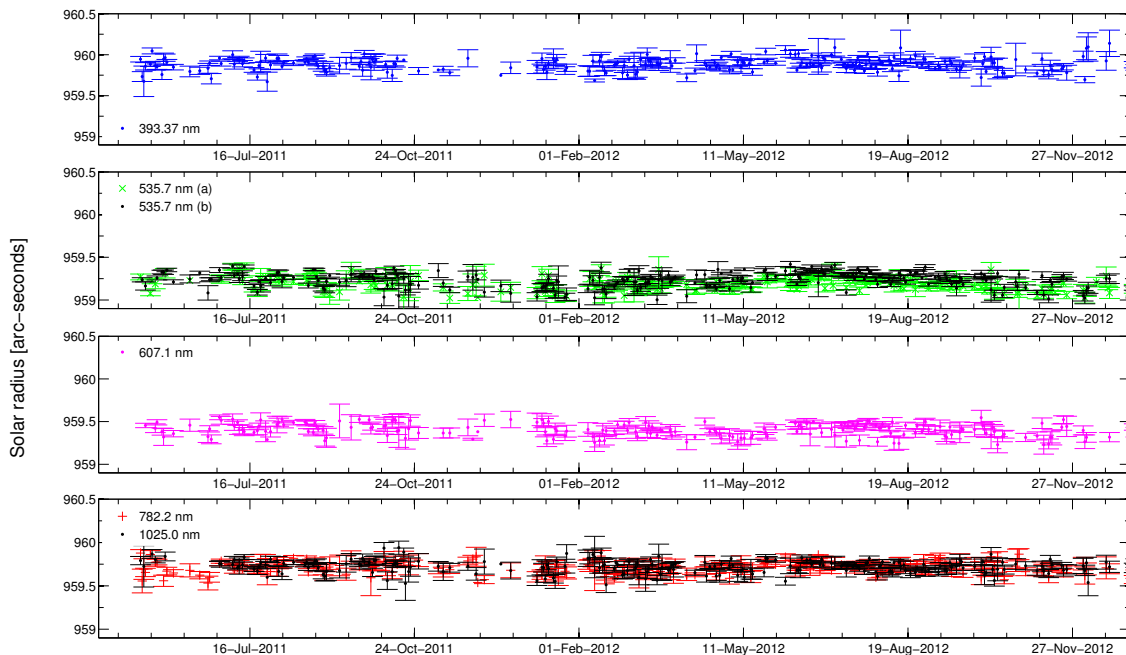

Figure 1. SODISM II solar radius measurements (daily mean) with refraction correction.

Table 1. SODISM II mean solar radii and standard deviation σ for N measurements (corrected for refraction only) - from May 2011 to December 2012.

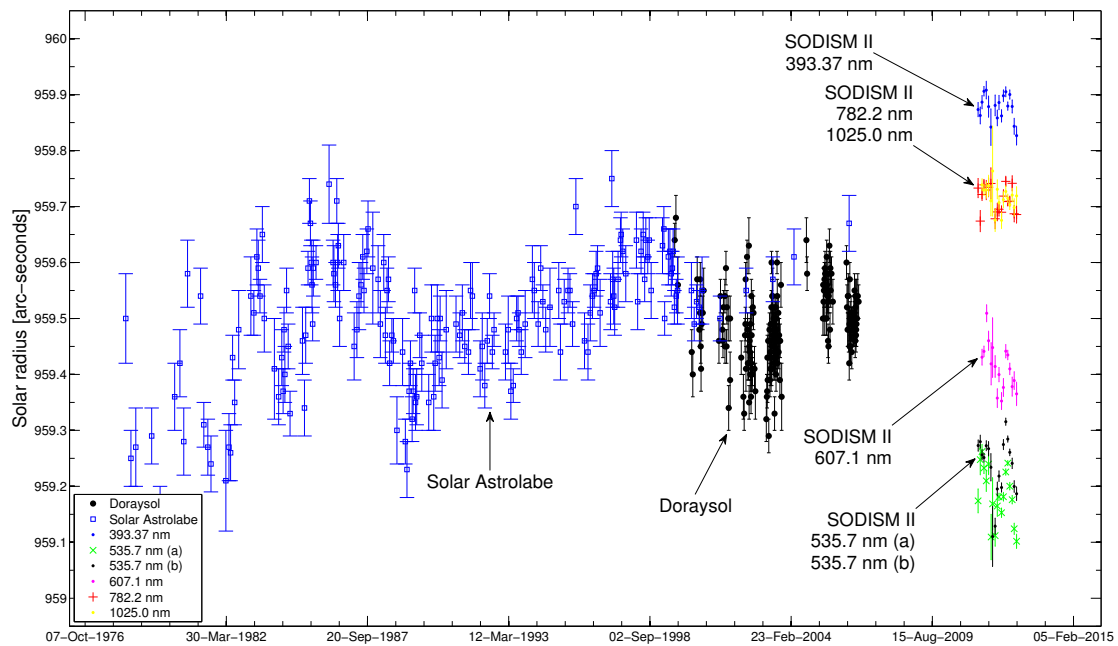| Wavelength λ	Exposure	N	Solar radius	σ	Comparison with instrument(s)
393.37 nm	1.70 s	5,120	959.884"	0.21"	–
535.7 nm (a)	1.30 s	11,813	959.198"	0.25"	Astrolabes at 548 nm (959.51")
535.7 nm (b)	8.90 s	6,032	959.250"	0.18"	Astrolabes at 548 nm (959.51")
607.1 nm	1.28 s	4,904	959.428"	0.26"	SDS [6] at 620 nm (959.53")
782.2 nm	1.43 s	5,657	959.714"	0.24"	SDM [7] at 800 nm (959.68")
1025.0 nm	1.70 s	5,700	959.715"	0.25"	–

Figure 2. Solar radius at Calern site of the Observatoire de la Côte d'Azur since 1978

Another important result is that there is a clear difference between the mean radius values observed at different wavelengths. Images were not de-convolved for diffraction which varies with wavelength. This effect however cannot explain the observed variation with wavelength. The broadening due to larger point spread function (PSF) for larger wavelengths will effectively affect (but by lowering) the inflection point position, but this is compensated by the fact that the continuum limb darkening functions (LDF) themselves become steeper for increasing wavelengths. The overall effect is less than 0.1". The Fried parameter on the other hand varies as $\lambda^{6/5}$ and therefore the bias induced by turbulence on radius estimates will tend to decrease as wavelength increase. This bias being always negative, we therefore expect radius estimates not corrected from turbulence to effectively increase with wavelength as reported here in Table 1. Corrections from the bias induced by turbulence will then decrease this observed wavelength dependence in the continuum but this will be discussed in more details in a future paper. Finally, we note that the CaII line at 393.37 nm is formed higher in the lower chromosphere and the results cannot be directly compared to other observations made in the photospheric continuum. A more detailed study is needed to confront these mean values and their separation as a function

of wavelength to theoretical predictions. The mean values obtained at 607.1 nm and 782.2 nm are consistent with the value found at similar wavelengths by Solar Disk Sextant (SDS) and Solar Diameter Monitor (SDM) respectively (see Table 1). The mean radius value (959.22") obtained at 535.7 nm is however significantly lower than the mean value (959.51") of previous astrolabe series (using a broad bandwidth). Different effects can introduce a bias in solar radius measurements. The most important ones are atmospheric refraction and turbulence. Scattering of the solar light by aerosols plays a non-dominant role. At first order, astrolabe measurements are not affected by refraction as we observe always at the same zenith distance. Solar radius measurements obtained from SODISM II images (Figure 1) were corrected for refraction but not for atmospheric turbulence. Although a more detailed analysis is needed, we can estimate from simulations the mean bias introduced by turbulence for a given Fried parameter r_0 [8]. Monthly Fried parameters obtained with MISOLFA between 2010 and 2012 are shown in Table 2.

Table 2. Fried parameter r_0 measurement performed between June 2010 and May 2012 [8] (monthly median values for this period and standard deviation σ).

Month	r_0 [cm]	σ [cm]	Month	r_0 [cm]	σ [cm]
Jan.	2.82 cm	0.94 cm	Jul.	3.88 cm	1.76 cm
Feb.	3.42 cm	1.26 cm	Aug.	2.50 cm	1.16 cm
Mar.	2.92 cm	1.11 cm	Sep.	3.70 cm	1.24 cm
Apr.	3.71 cm	1.28 cm	Oct.	3.45 cm	1.19 cm
May	4.10 cm	1.32 cm	Nov.	3.50 cm	0.91 cm
Jun.	4.20 cm	1.32 cm	Dec.	2.75 cm	0.50 cm

The broadening due to seeing affect the inflection point position and tend to bias radius estimates toward lower values as the seeing increase. Estimates of this bias with its one sigma uncertainty are given as a function of the Fried parameter by Ikhlef et al. [8]. The average diurnal Fried parameter r_0 for Calern is 3.41 cm from which we can infer that the mean bias on solar radius measurement with SODISM II at 535.7 nm is around 0.55", and that this mean value of the bias can fluctuate within ±0.2" at one σ [8]. This would lead to a fairly good agreement between SODISM II solar radii at 535.7 nm ($\sim$959.75") and the value of Arthur Auwers in 1891 (959.63" with an heliometer) currently used in all ephemeris calculations.

At 607.1 nm, the convolution of the LDF (with SODISM II) and the Earth's atmospheric turbulence cause a shift of the inflection point position. This effect is at the order of 0.4"±0.16" (at one σ) for Fried parameter r_0 equal to $\sim$4.0 cm. With this bias, the mean solar radius at 607.1 nm is found to be equal to $\sim$959.83", whereas the estimated uncertainties of the measures, random plus systematic, are typically less than 0.2". For MDI, at a wavelength of 676.78 nm, the solar radius was 960.12" [9] during Mercury transits (May 7, 2003 and November 8, 2006). SODISM II solar radius at 607.1 nm is consistent with MDI result.

At 782.2 nm, the estimated Fried parameter r_0 is $\sim$5.4 cm from which we can infer that the mean bias on solar radius measurement with SODISM II is 0.16"±0.09" (at one σ). In this case, the mean solar radius at 782.2 nm is found to be equal to $\sim$959.87".

4. CONCLUSION

PICARD SOL is a new ground-based facility for long-term solar radius measurements, which include a multi-wavelengths full disk solar imager stabilized in temperature and a set of atmospheric monitors working simultaneously. It has been operated for 20 months since May 2011 and shows good instrumental stability. First estimates of the mean solar radius observed at five different wavelengths were obtained after plate scale calibration and atmospheric refraction correction. Using the mean value of the Fried parameter given by the turbulence monitor MISOLFA, rough estimates have been made of the bias introduced by optical turbulence on our solar radius measurements. These preliminary results are consistent with previous measurements from ground and give us confidence on our ability to detect possible long-term variation of the solar radius by continuing this series. The complete set of atmospheric monitors has been only very partially used for this preliminary work. The generalized seeing monitor gives us the ability to truly monitor the full spatio-temporal parameters of atmospheric turbulence at the time of each image record and this will be used to correct each measurement individually. Other monitors give us general quality index that will also be included in our future analysis. Finally we note that cross calibrations with space missions such as PICARD, Solar Dynamics Observatory (SDO) or any future dedicated mission are highly desirable in order to validate the corrections that can be made for compensating the bias introduced by optical turbulence.

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