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Observations of the Evolution of the Solar Diameter and Solar Constant with CubSat 3U Satellites

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***Abstract*— The article presents a CubeSat project with a 3U form factor designed for simultaneous measurements of the solar diameter, its differential rotation, and the solar constant. The optimal mission duration is discussed – up to a maximum of 2 years – in order to investigate the nature of variability of these parameters and their interrelationships. The satellite will have a mass of up to 3 kg and a payload of 2 kg, consisting of three optical instruments that will enable measurements of the solar diameter and shape, as well as the total solar irradiance and ultraviolet (UV) radiation. It is planned that the satellite will be placed in low Earth orbit and will have an operational lifetime of approximately one and a half years, after which it will be replaced by an identical satellite in the same low Earth orbit. This approach allows for long-term mission continuity due to the low cost of the satellite and launch expenses. The mission will provide valuable data on the Sun's diameter, rotation, and radiation, and will include ground-based observations for validation of measurements from space. The main scientific objectives to be achieved by the satellite mission include:**

- Confirmation of variations in the solar diameter (and validation of ground-based measurements and their accuracy);

- Establishment of the relationship between solar diameter, total irradiance, and differential rotation;

- Measurement of the Sun's oblateness and shape to a high order of precision.

Keywords*— diameter of the Sun, differential rotation, shape of the solar disk, solar astrometry.

I. Introduction

From 1666 to 1719, Jean Picard and his student Philippe de La Hire measured the solar diameter by observing sunspots and determining the Sun's rotation rate. These measurements cover the Maunder Minimum and the period following it. The data were re-examined by Ribes et al. in 1987 [1], who, after removing seasonal variations of the solar diameter, derived annual mean values at a distance of 1 astronomical unit (AU). These values, averaged over the Maunder Minimum and post-minimum period, indicate a recovery of solar activity as well as a clear difference in angular diameter of about 0.5 to 1 arcsecond, corresponding to a larger solar diameter during the Maunder Minimum. A smaller number of sunspots was also observed. In addition, Picard's data show a slowdown in the solar equatorial rotation rate and a significantly higher number of sunspots in the southern hemisphere of the Sun compared to the northern hemisphere.

It was not until the 21st century that the PICARD microsatellite mission provided simultaneous measurements of the solar diameter, differential rotation, and the solar constant from near-Earth space, and investigated the nature of their interrelationships and variability [2]. The satellite, with a mass of 110 kg, carried a payload of 42 kg and hosted three instruments on board:

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SODISM, which provided precise determination (4 milliarcseconds) of the solar diameter and shape; SOVAP, which measured the total solar irradiance; and PREMOS, which measured the light flux in the visible and UV ranges. The main scientific objectives of the mission, in addition to measurements of the solar diameter and solar constant, were related to the study of heliospheric influence on Earth's climate and space weather, as well as helioseismology.

These and other studies show that a number of interconnected solar characteristics undergo both monotonic and cyclic changes with different periodicities. In general, the Sun appears to have a complex pulsating shape that varies depending on the phase of solar activity. This is the result of a quasi-periodic reorganization of its internal layers, especially the photosphere and the overlying envelopes [3]. Variations in the solar radius lead to a restructuring of the envelopes starting from the convective zone, which is particularly sensitive to small disturbances. The dynamics of the magnetic field characteristics in these layers and their interaction with convective flows influence the efficiency of convective energy transport. This makes the precise measurement of short- and long-term changes in the shape and radius of the Sun one of the key approaches for studying the structure and dynamics of its internal layers. The study of variations in these parameters over the entire solar activity cycle thus represents an important problem in solar physics in general.

The Sun's photosphere is the visible surface of the star, emitting most of its optical radiation. The thickness of this layer ranges from 100 to 400 km, while its temperature varies from about 6600 K (in the inner region) to 4400 K (at the outer layer). The size of the Sun is defined precisely by the photosphere. The gas in this region is relatively rarefied, and its rotation rate varies depending on the heliographic latitude of the emitting area. In the equatorial region, one rotation takes about 24 days, while near the poles it takes about 30 days.

Systematic astrometric measurements of the angular radius of the Sun using various optical instruments and methods have been carried out for more than 360 years. The presence of systematic errors associated with determining the exact position of the solar limb in the image makes most of the data unsuitable for processing. At the same time, the question of what should be considered the edge of the solar limb image remains open to this day. Therefore, measurement errors, particularly those related to the precise determination of the photometric position of the limb edge in solar images, impose certain limitations on the accuracy and reliability of solar radius measurements. More recently, the photometric position of the limb edge in solar disk images has begun to be defined more reliably [4]. Under these conditions, all observers can obtain comparable observational material, the processing of which may reveal real variations in the solar disk radius. It should be noted that the most reliable and high-precision measurements of the solar shape and radius can only be obtained from space using a specialized instrument (a so-called solar limbograph), which allows full elimination of the effects of the Earth's atmosphere. In such a space-based observational setup, the problem of automatic determination of the solar disk image radius becomes particularly relevant [5].

The Sun is a star currently undergoing the main-sequence phase of its evolution and is therefore expected to remain stable over extremely long timescales. A reference evolutionary model for a solar-mass star was computed by L. Siess (1999) and published on the website of the University of Liège. The standard solar model is commonly employed as a benchmark case for stellar evolution calculations because the luminosity, radius, age, and chemical composition of the Sun are well constrained. Nevertheless, it has been observed that certain solar properties vary throughout the solar sunspot cycle. At the same time, it is understood that an enormous amount of energy would be required to alter the global structure of the Sun, particularly the extent of the convective envelope. Consequently, small variations within the surface layers, occurring under conditions of approximate energy balance, are of considerable interest.

Daily mean values of solar irradiance exhibit variations ranging from a minimum of approximately 1362 W/m² to a maximum of approximately 1368 W/m². The irradiance is influenced by the appearance of individual sunspots on the solar disk. When a 100-day running average is considered, the peak-to-peak luminosity amplitudes are found to be approximately $\Delta L/L \sim 0.001$. Furthermore, variations in the effective surface temperature are constrained to 1.5 ± 0.2 K and are observed to be in phase with other indicators of the solar cycle. By applying these constraints to the Stefan–Boltzmann equation for a radiating sphere, an upper limit for variations in the solar radius can be derived:

$$\Delta L/L = 2\Delta R/R + 4\Delta T/T$$

Thus, with $\Delta L/L = 0.001$ and $4\Delta T/T = 0.001$, where T = 5777 K for the photosphere and L = 1365 W/m², and assuming that luminosity and temperature variations are in phase, the amplitude of the term $2\Delta R/R$ becomes much smaller than 0.0001, implying $\Delta R \ll \pm 0.1''$. If luminosity and temperature are assumed to be in antiphase, then $\Delta R \sim 0.1''$, while the maximum permissible variation in the solar radius is $\Delta R \pm 1''$, where the mean solar radius is $R = 959.63''$ at an average distance of 1 AU. In the literature, the parameter $W = d\log R/d\log L$ has been introduced to describe the relationship between luminosity and radius. For an isothermal Sun, W = 0.5. Within the widely accepted standard model, W varies between approximately 0.2 and 0.6 during the main-sequence evolution of a solar-type star. However, it is anticipated that this parameter will be determined observationally with unprecedented precision by future space missions.

A more accurate estimate of W has been obtained using solar diameters measured with SDS, while the solar irradiance was determined by instruments aboard the ACRIM II satellite, yielding: $W = -0{,}3 \pm 0{,}1$. This value of W is affected by luminosity variations associated with the emergence of sunspots on the solar disk. The mechanism responsible for variations in luminosity and solar radius on the 11-year timescale differs from the mechanism governing solar evolution on nuclear timescales (i.e., the standard solar model), since the corresponding values of W appear to differ significantly. The parameter W characterizes fluctuations in the solar diameter during the present evolutionary stage of the Sun, particularly over the 11- or 22-year cycles associated with the Hale magnetic cycle. When diameter measurements are available, the parameter W enables reconstruction of the solar luminosity over past centuries. These reconstructions may subsequently be employed as inputs for appropriate climate models. Historical measurements of the solar diameter (from the years 1567, 1715, 1869, and 1925) were obtained through timing observations of total solar eclipses.

II. Materials and methods

As already mentioned, during the period from 2010 to 2014, the instruments on board the PICARD microsatellite enabled the acquisition of extremely precise data on the Sun's radius, rotation rate, polar oblateness, and radiated power. This made it possible to gain deeper insight into the internal structure of our Sun and its impact on Earth's climate. The problem with the PICARD microsatellite mission lies in its short operational lifetime, whereas observations of solar parameters require a long series of measurements, spanning at least several solar cycles.

The paper presents a project for a 3U CubeSat designed for simultaneous measurements of the Sun's diameter, its differential rotation, and the solar constant. Within the optimal mission duration – up to a maximum of 2 years – it becomes possible, through several consecutive flights of identical CubeSats, to investigate the nature of the variability of these parameters and their interrelations over the course of solar activity evolution. The report proposes a solution to the observational task that requires the development of a method for automatic measurement of the solar disk radius from its digital image. The term "edge of the image" of the solar disk should be understood as the location of the maximum gradient in the radial brightness distribution – the boundary curve obtained for the corresponding radius/segment of the disk. When a rectangular coordinate grid is superimposed on the sampling grid of the solar limb image, the distances between the center of the disk image and the grid cells take on a set of values that are not integer multiples of the sampling step. Therefore, after averaging the signal along the solar limb, it is possible to obtain a radial signal distribution at the limb edge with an accuracy significantly exceeding the defined sampling interval.

Let us consider an image of a uniformly illuminated disk with a well-defined edge, projected onto the photometric structure of a CCD matrix consisting of vertical columns and horizontal rows of square pixels. We assume that the disk radius is much larger than the sampling step, and that the signal from a given pixel is proportional to the fraction of its area covered by the image (i.e., the sensitivity is uniformly distributed over the entire area of the image sampling pixels). Let the center of the disk lie at the center of one of the sampling pixels, and let the photometric boundary pass through the center of one of the pixels located directly above the center.

If we assume that the signal from a pixel completely covered by the disk image is equal to one, and from a completely uncovered pixel is zero, then the signal from this pixel will be equal to 1/2 and will correspond to a radial distance

$$r_1 = k \cdot \Delta \qquad (1)$$

where Δ is the sampling step and k is the number of readings. During the readout of the next row through which the boundary passes, the first pixel will give a signal 1/2 − δ, where δ is a small value, corresponding to the distance

$$r2 = \Delta \cdot \sqrt{(k+1)} \qquad (2)$$

and the distance from the center of the disk to the j-th pixel in the row is given by the general expression:

$$rj = \Delta \cdot \sqrt{(k+j)} \qquad (3)$$

Clearly, as the pixels along the line extending from the center of the disk to the limb are removed, their distance from the disk center increases, while at the same time the overlap area with the next pixel decreases toward the edge of the disk. On the next row, the pixels will be almost fully covered as we further shift the readout along the line toward the disk limb. The process of reading individual discrete elements through which the disk edge may pass can be compared to scanning a line of discrete samples along the boundary of a half-plane with a non-uniform step. By assigning the readings from the pixels through which the image edge passes according to their distances from the center, we obtain the curvature of the contour at the chosen sampling resolution. Transitioning to a real image of the Sun obtained from a ground-based optical heliograph and projected onto a CCD matrix, it will be somewhat blurred due to the optical system and atmospheric effects. Despite these limitations, we obtain the boundary curve of the solar disk and its image, averaged over viewing orientations and projection points. By separating these effects using specialized software, we can derive the point spread function along individual radial lines. It should be noted that the resulting digital image is associated with distances from the disk center; therefore, by determining the coordinate of maximum curvature, we obtain the radius of the disk image, averaged over the considered regions of the solar limb.

III. Results and discussion

The process of determining the radius of the solar image can be divided into seven stages. The first step is to determine the center of the solar disk image. The center of mass is estimated over segments of the limb edge according to a chosen brightness level. At this stage, a preliminary estimate of the disk radius is also made. For this purpose, along one of the selected central lines of the image (any line), the coordinates of the gradient maxima along the image edge are determined on the left and right sides. In addition, knowing the preliminary position of the solar image center, two rough estimates of the radius can be obtained simply as the hypotenuses of the corresponding triangles. In the second stage, a direction along the solar limb (with a corresponding heliolatitude) is selected, and the signal is averaged within a fixed segment (for example, 45°) along the limb in order to obtain the corresponding boundary curve. It is derived by averaging signal values (image brightness) within the defined radial sampling step from the center of the solar disk in the chosen segment and direction. The boundary curve is determined relative to the preliminary position of the limb edge within an interval of ±10 pixels, i.e. within the selected segment angle over which averaging is performed. In testing the method on real solar images with a resolution of 1024×1024 pixels over a 45-degree segment, a resolution of 1/50 of a pixel step was achieved, corresponding to approximately 8 points on average from the original image of the boundary line. For the application of this method, it is necessary to ensure the stability of the obtained photometric estimates over time across different solar images.

At the third stage, differentiation of the corresponding boundary curve is performed. Typically, the resulting measurement data contain a significant amount of noise. This requires a subsequent smoothing procedure to be applied to the obtained curve. The smoothing procedure represents the fourth stage of processing and is carried out through spatial-frequency filtering.

In processing specific solar images, a result was obtained that was superior to the classical window-averaging method (where the signal-to-noise ratio proved to be rather low). In this case, all useful information in the spectrum is concentrated within the interval up to the 15th pixel readout, while the spectral components located at higher spatial frequencies are purely noise. Accordingly, a notch filtering approach is applied, i.e. part of the spectrum above the 15th sample is set to zero and an inverse Fourier transform is performed, which corresponds to the fifth stage of processing. The result of such smoothing, overlaid on the original noisy curve, is very good. In addition, the cutoff frequency (the starting point of the zeroing) of the notch filter is automatically determined from the position of the first minimum of the spectral curve.

It should be noted that the low-frequency part of the curve can be interpreted as an estimate of the modulation transfer function of the optoelectronic imaging system. The position of the curve maximum corresponds to a fairly accurate estimate of the solar disk radius. However, this estimate corresponds to the mean value over the 45-degree heliolatitude range. Based on the previously obtained radius estimate from the smoothed point spread function of the solar image boundary, a simplified model of the solar disk limb is constructed. By processing it with the smoothed point spread function of the solar image boundary, we obtain the theoretical model of the solar disk limb (sixth stage of processing).

In the seventh and final stage, the root mean square deviation between the theoretical curve and the segmental values obtained for a given angle is calculated. By varying the radius value in this model, the final estimate of the desired solar disk image radius is determined as the value corresponding to the minimum standard deviation.

The method was tested on two ground-based digital images of the Sun obtained at intervals of approximately 10 minutes. The resulting mean estimates of the radius over the entire limb are quite close in value: R1 = 496.20 pixels and R2 = 496.25 pixels. The obtained estimates were averaged for radii corresponding to a mean heliographic latitude of 45°.The orientation and ordering of the segments are counted from the solar north pole in a clockwise direction. In addition, the mean value of the solar disk radius was measured along the diagonal, vertical, and horizontal lines, respectively.

IV. Conclusion

The described version of the method can be used for automated determination of the mean radius over the entire area of a digital solar image and its segments at different heliolatitudes. The term "edge of the image" of the solar disk refers to the location of the maximum of the brightness distribution obtained for the corresponding segment of the solar limb. The described method was tested on two real digital images of the Sun. The accuracy of the method largely depends on the amount of averaged data. We initially planned to estimate the accuracy of the method through the difference between the radii obtained from the two images, since they were taken with a time difference of 10 minutes; however, for the second image, the radius estimate obtained consistently in a series of measurements shows a stable difference of approximately 0.06 pixels. These data were further tested and confirmed by correlation analysis. The correlation coefficients of the limb segments of the two images are comparable to the correlation maxima for opposite regions of the limb. The overall difference between the radii of the first and second solar images is relatively small ($\Delta R_{12} \approx 0.06$ pixels), obtained from images taken almost simultaneously under conventional ground-based heliograph conditions. This can be explained both by the uncertainty of the method itself, by atmospheric instability during the observations, and by instrumental characteristics of the heliograph (e.g. fluctuations in the focal length of the optical system, variations in the angles of incidence of light rays, etc.).

The assessment of the impact of atmospheric instability on the difference between the radii of the first and second solar images is rather difficult to quantify. In our study, we are therefore compelled to attribute the observed difference to errors inherent in the applied method. In this case, the obtained difference ($\Delta R_{12} \approx 0.06$ pixels) in the determination of the radius from two consecutive solar images likely represents the error limit of the method itself when used with the given optical instruments and under the prevailing astroclimatic conditions.

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