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Sunspots Areas and Heliographic Positions on the Drawings Made by Galileo Galilei in 1612

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Abstract. In 1612, Galileo Galilei made very accurate drawings of the solar disk. Currently, 47 of them are in the open access: 9 in May 3 – 11, 35 in June and July, and 3 in late August. Unfortunately, reports have not provided the clock time, which results in uncertainty of sunspots heliographic coordinates. In the present study, we determine the exact time of the drawings by comparing the positions of the same spots from day to day. The time of the observations, which varies from 12 to 16 UT, gives us the direction of the solar rotation axis and the position of the helioequator. Unlike the spots drawn by Christopher Scheiner in 1611 – 1612, none of the analyzed spots lies within the helioequator. This confirms the quality of the Galileo's drawings.

Keywords. Sun: activity, (Sun:) sunspots

1. Introduction

Historical sunspot observations are highly potential data source on the long-term behavior of the solar activity. One of the long-standing problem is the reconstruction of homogeneous time-series of the solar indexes in the past. Detailed revision of historical astronomical reports should help to resolve whether the Sun is a star with a regular periodicity or there are periods without the Schwabe cycle.

One of the first telescopic monitoring of sunspots was carried out in 1612 by Galileo Galilei. His pupil, a monk of Cassino named Benedetto Castelli, invented the projection technique to observe sunspots and draw sunspot positions on the solar disk in details. Continuous observations from June 2 to July 8 and August 19, 20, and 21 were published in the book by Galilei (1613, *Istoria e dimostrazioni intorno alle macchie solari e loro accidenti comprese in 3 lettere*). Note that these observations are highly accurate in comparison with sunspot drawings of other observers in the beginning of the seventeen century (Zolotova & Ponyavin 2016). Thin structure of a spot, umbra and penumbra, were depicted. Every day, a new image of the solar disk was made.

June and July drawings were processed by Casas *et al.* (2006). To define the differential rotation speed, they provided positions of sunspots which appear on the next day, besides spots near the limb were also excluded from analysis. Casas *et al.* (2006) roughly suggested that Galilei observed at local noon.

In this paper, we present the reconstruction of the heliographic coordinates of all sunspot groups, observed by Galilei in June – July 1612, their area and number. Basing on our technique which minimizes the discrepancy between the sunspots latitudes from day to day, we find out that sunspots were drawn after the solar noon.

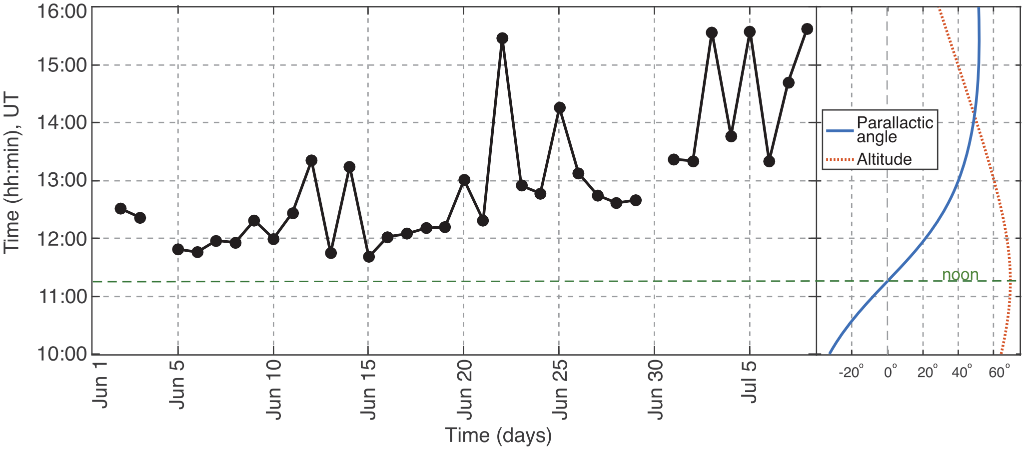

Figure 1. Black points joined by black line shows the time when spots were drawn. On the left, blue denotes the parallactic angle and red the solar altitude for mid-June. Horizontal dashed green line marks the solar noon in Villa delle Selve.

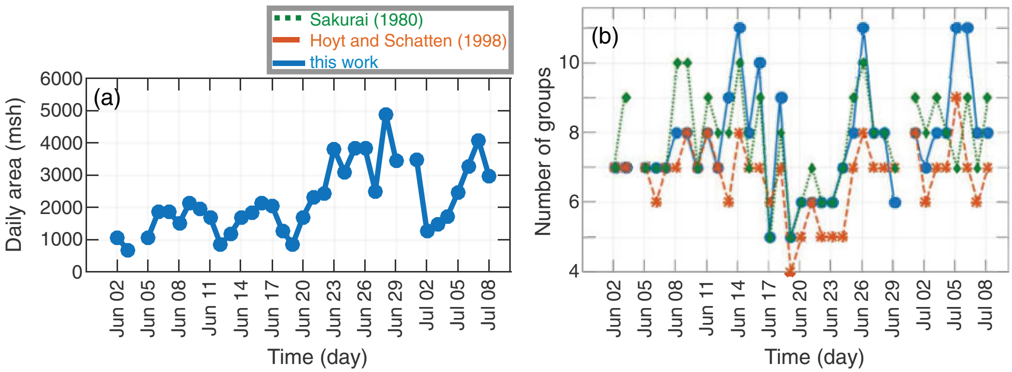

Figure 2. (a) Daily sunspot area. (b) Green denotes the number of groups according to Sakurai (1980), red, those by Hoyt & Schatten (1998), and blue, this work.

2. Results

Time on clock and geo-location are required to define the heliographic sunspot coordinates. Unfortunately, sunspot drawings by Galilei (1613) do not provide time of observations that results in uncertainty of ephemeris of the Sun. To deduce time of observation, we developed the iterative method which minimizes the difference between the latitudes of sunspot groups or subgroups in a given day and average latitudes of these groups over the range of preceding or successive days. Although, the uncertainty of the spots position increases with distance from the center of the disk, we find out that the near limb spots are valuable for adjustment of the heliographic grid.

Figure 1 shows time of observation in UT. Green dashed line defines the local solar noon, when altitude of the Sun is maximal, but parallactic angle equals zero. The farther from noon the observations were made, the greater an error in determination of time of observation.

One may see that sunspots were drawn after the noon. Here, we can speculate that the upper culmination could be engaged for astrometric measurements. The other reason of not fixed time of drawing could be clouds.

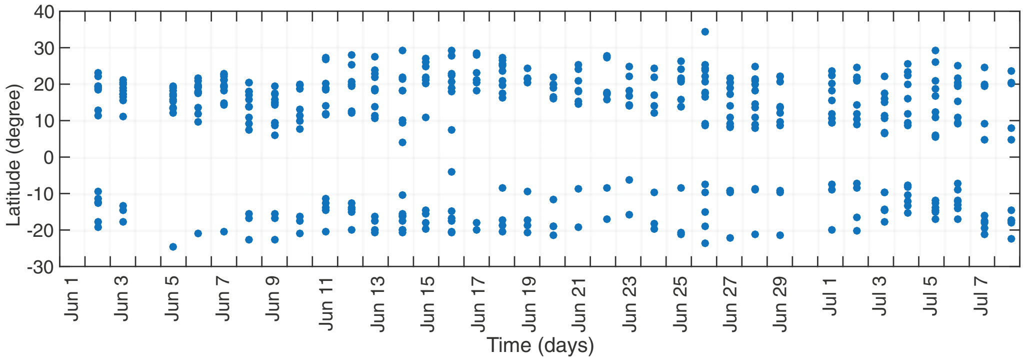

Figure 3. Time-latitude distribution of sunspots in June – July 1612.

Figure 2a depicts the total daily sunspot area in the millions of the solar hemisphere. Figure 2b compares number of sunspot groups defined by Sakurai (1980) shown by green dotted line, by Hoyt & Schatten (1998), red dashed line, and by us, blue solid line. Note that group counts defined by Sakurai (1980) and by us systematically exceed those by Hoyt & Schatten (1998).

Figure 3 shows the butterfly diagram. Sunspots sit on high- and mid-latitudes, that corresponds to the ascending phase or maximum of a solar cycle. Note that the near-equator region is spotless. On the contrary, according to early observations by Scheiner (Arlt *et al.* 2016) spots in 1612 emerged on the equator. The fact is that Scheiner had not been interested in accurate sunspot mapping, but demonstrated that spots are not an optical artifact.

3. Conclusions

We analyzed continuous set of drawings of sunspots on the solar disk published by Galilei (1613). For June – July 1612, we provide the heliographic coordinates of sunspot groups, their areas and number. We define the time of observations by minimizing the discrepancy between the latitudes of sunspot groups (or subgroups) in a given day and average latitudes of these groups over the range of preceding and successive days. In the further work, we will process observations by Galilei of May 3 – 11 and August 19 – 21 1612.

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