



Sunspot Positions and Areas from Observations

by Thomas Harriot

Mikhail Vokhmyanin¹ · Rainer Arlt² ·
Nadezhda Zolotova¹

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Abstract The reconstruction of sunspot parameters in the early era of telescopic observations extends our knowledge on visual sunspot activity up to 400 years into the past. 200 digital solar images from 18 December 1610 to 28 January 1613 by the English astronomer Thomas Harriot were analyzed to yield sunspot counts, areas and positions. Harriot generally observed in the early morning when the Sun was near the horizon, and he specified the local time of observation, date, place, number of spots, zenith and ecliptic lines, and other information. We assigned 753 sunspots into 293 groups and defined their areas. We developed two approaches to reconstructing the heliographic coordinates of the sunspots. Method I makes use of the time of observation noted by Harriot, and Method II minimizes the day-to-day variability of sunspot latitudes independently of Harriot's notes. The results of the two methods are discussed.

Keywords Sunspots · Solar cycle · Observations

1. Introduction

Reanalysis and recalibration of sunspot data resulted in an open discussion on the magnitude of the secular cycle during the past 400 years (Muñoz-Jaramillo and Vaquero, 2019). To clarify the variability of sunspot activity, records of all the observers are valuable, even if

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✉ M. Vokhmyanin
m.vokhmyanin@spbu.ru

R. Arlt
rarlt@aip.de

N. Zolotova
ned@geo.phys.spbu.ru

¹ St. Petersburg State University, Universitetskaya nab. 7/9, 198504 St. Petersburg, Russia

² Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

they are short and sparse. Overlap of records of different observers helps reduce the error of sunspot locations and improve the sunspot indices. This, in turn, will become the basis for evaluating Joy's law and the differential rotation profile in the past. Adding the sunspot areas might help determine solar activity more accurately. In comparison with the group number, such evaluation is less sensitive to small sunspot groups being missed.

Digitization and exploration of historical records piece by piece close the gaps in sunspot observations in the past; see e.g. recently Arlt *et al.* (2016), Hayakawa *et al.* (2017), Svalgaard (2017), Arlt (2018), Carrasco *et al.* (2018), Hayakawa *et al.* (2018), Neuhäuser, Arlt, and Richter (2018), Tlatova *et al.* (2018), Carrasco *et al.* (2019b,a), Karoff *et al.* (2019).

The present paper yields sunspot data from observations of the English astronomer, optician, and mathematician Thomas Harriot (1560–1621). His manuscripts are stored at Petworth House Archives, West Sussex, UK, while a digital version is provided by ECHO – Cultural Heritage Online. At Syon House (just west of London) and in London, Harriot made 200 (plus two repeated) drawings of the solar disc and its spots. Images are accompanied by Julian calendar dates, observing conditions, local time, magnifying power of the Galilean type refractors (8/1, 10/1, 20/1, 30/1, and 50/1), number of sunspots, and other information. Harriot observed through clouds or misty air, and once on 23 December 1611 (here and further we give the calendar dates on the Gregorian calendar) he mentioned: “I observed through the thick layer & also through my colored glasses”. Harriot commonly exploited the 10/1 and 20/1 instruments; the field of view of the 10/1 instrument was smaller than the solar disc. On 26 July 1612, he noted: “With 20/1 I see a little more the 1/3 of the diameter of the sonne. That is 11' or 12'”. Magnification 8 is mentioned only once on 13 December 1611, and that of 50 once on 10 February 1612. There are a few days when Harriot stated that he observed, but did not see spots.

The method with which Harriot made drawings is not known, but apparently he did not take advantage of the projection apparatus (Bradley, Harriot, and Rigaud, 1833; Chapman, 1995, for more details and on the quality of observations, telescope device and eyepieces). Typical images contain a circle of the solar disc with dashed lines likely denoting the zenith and the ecliptic which are not drawn from 12 July to 12 September 1612.

In spite of the fact that Harriot's observations were processed to estimate the solar differential rotation (Herr, 1978), sunspot positions and areas were not published. In this paper, we fill this gap providing sunspot parameters from 18 December 1610 to 28 January 1613. Section 2 is devoted to areas and numbers of sunspot groups. In Section 3, we address the latitude–time diagram reconstructed by means of two methods. Section 4 is devoted to a comparison of the results of these methods. A summary is given in Section 5. An [Electronic Supplementary Material](#) file provides the sunspot data.

2. Areas and Numbers of Groups

Similarly to Vokhmyanin and Zolotova (2018a), we focus on the assignment and classification of sunspot groups by McIntosh (1990) and presume that the linear size of a sunspot group is on average limited to 7° of latitude and 15° of longitude. In complex cases, groups were assigned arbitrarily. We sorted 753 spots into 293 groups. Compared to Hoyt and Schatten (1998), we systematically assign more sunspot groups (Figure 1). Cumulatively, there were assigned 12% more sunspot groups.

To estimate sunspot areas in millions of the visible solar hemisphere (microhemispheres, msh), we rescale each solar disc to a diameter of 1400 pxl and define the heliocentric angular distance (α in the supplementary files) on the surface of the Sun from the center of the disc

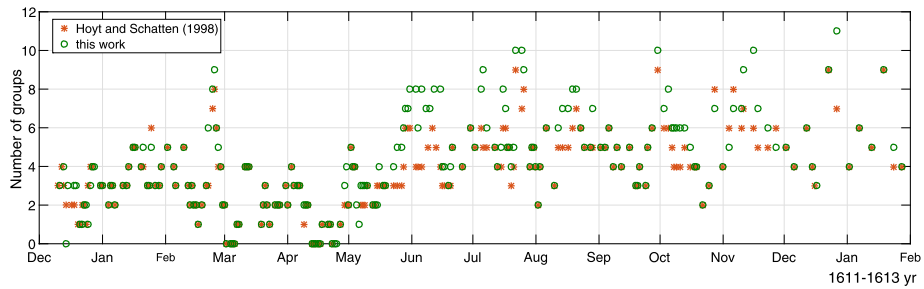


Figure 1 Red stars denote the daily number of groups from Harriot's observations according to Hoyt and Schatten (1998), and green circles show the group numbers derived in this work.

to the intensity-weighted x - y coordinates of a spot (Vokhmyanin and Zolotova, 2018a, for details).

Notice that early drawings are poorly detailed, apparently the result of a hurried manner of looking at the Sun (Mitchell, 1916). Drawings were made with a pen and ink. Harriot did not divide sunspots into umbra and penumbra. There are repeating defects (small black spots) on the sheets from May to August 1612. Accordingly, if these defects fell on the solar disc, they were not recognized by us as sunspots.

On a few days in 1612, Harriot stated that he observed but did not see sunspots. In the supplementary materials, on these days we assigned the sunspot area as NaN (Not-a-Number), because the size of the spots on drawings on previous or next to these days drawings suggests to us that these spots should not have disappeared the next day or have already present on the previous one. Most likely these spots could have been smaller. For a similar statement by Harriot in 1611, we also assigned the area as NaN. Here, because earlier drawings are quite schematic, hence Harriot might not have recognized small structures.

The smallest sunspot was registered by Harriot on 17 August 1612 (9 msh), and the largest one (1918 msh) on 11 December 1611. The smallest sunspot group was registered on 22 July 1612 (20 msh), and the largest one (4088 msh) on 3 May 1612 (Figure 2a and b). In more detailed observations by Galilei in May–August 1612 by means of the projection apparatus, the same sunspot group on 3 May is also the largest with area 3898 msh.

Like Vokhmyanin and Zolotova (2018b), we compared historical drawings and the RGO/USAF/NOAA database. Figure 2c shows the distributions of sunspot group area by Harriot with blue bars and modern observations in magenta, orange, and green.

The majority of Harriot's drawings cover a 14-month period from December 1611 to January 1613. From the modern observations, we chose three periods of the same length with the largest medians of the sunspot group area distribution (May 1874–June 1875, April 1946–May 1947, and April 1957–May 1958). Namely, we compare historical observations with those periods of Greenwich observations, when the highest percentage of large groups of sunspots was recorded. We use the distribution of areas divided by the total number of groups since there are less sunspot groups in the 14-month interval of Harriot's observations than in the Greenwich catalogue on the corresponding time interval.

Interestingly, the beginning of the Greenwich catalogue is the one closest to Harriot and is the poorest period in the RGO coincidentally. Also, Figure 2c demonstrates that Harriot's reports have a lack of small sunspot groups with an area less than 60 msh which in turn make up 45% of all groups in the Greenwich catalogue.

In order to evaluate the accuracy of sunspot area drawing, we compared sunspot areas from repeated drawings made by Harriot on 22 February and 21 August 1612. Area differ-

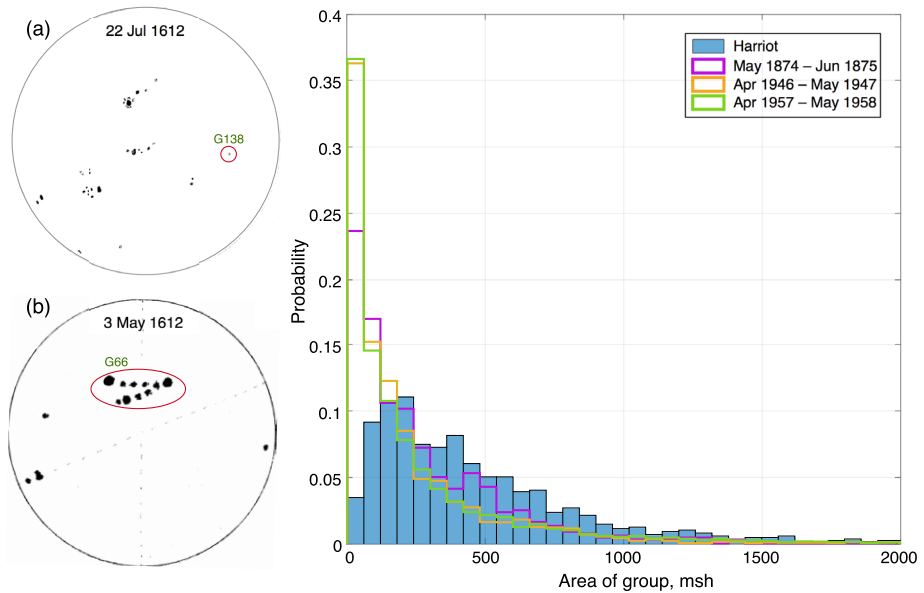


Figure 2 (a) and (b) are examples of Harriot's drawings. *Red ovals* mark the smallest and largest sunspot groups G138 and G66 correspondingly; (c) shows the probability density functions of the sunspot group area from Harriot's drawings (*blue*) and three 14-month periods of the Greenwich catalogue.

ences vary significantly, especially for small spots. The average uncertainty is about 30%. A more accurate estimate of the area error might be given after comparing the drawings made by different observers.

3. Sunspot Positions

On 29 January 1611, 2, 4, 5, and 6 March 1612, 13–17 and 23–25 April 1612, Harriot reported that he did not see spots. On 14 December 1611, weather conditions did not permit to make a drawing. For these days, in the supplementary files, columns with the drawing number, sunspot group, coordinates, area and other values are filled with NaN.

To define sunspot positions, we applied two methods. Both of them only optimize latitudes of solar objects omitting their longitudinal displacement. The first one (Method I) exploits the time of observation provided by Harriot himself. Each solar image, except for the first one, is accompanied by one to three local time entries. We provide this information in the supplementary files in the last columns as *time_1*, *time_2*, and *time_3* in decimal hours, i.e. 8.75 means a quarter to nine. We also assume that Harriot's records of time should not be wrong by more than 0.5 hours. The first of Harriot's observing times, *time_1*, is arbitrarily assigned by us to be the time when the drawing was made.

To compensate for possible inaccuracies in the time measurement in the 17th century, we introduced a window of one hour (± 0.5 hour around *time_1*; we also add sunrise–sunset limits) inside which we minimize the difference between a sunspot latitude on a given day and the average latitude of this object over the preceding drawings (first run) and over subsequent drawings (second run). After several iterations and calculation of a weighted mean of these two runs, we determine the rotation angle (Rot) of each image. Precisely (Meeus,

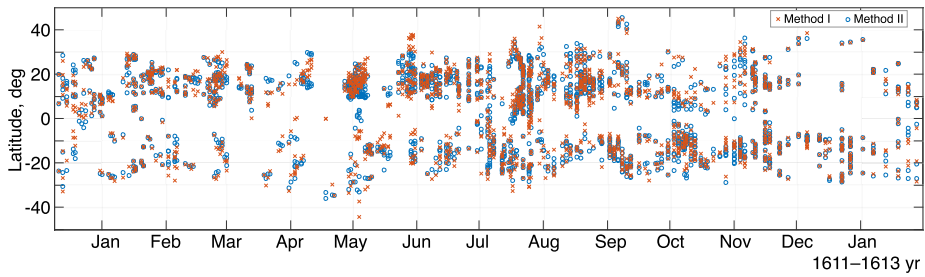


Figure 3 Latitude–time diagram from December 1611 to January 1613 reconstructed by two methods.

1991, for details), we find the orientation of the solar axis (the angle between solar axis and zenith direction) which is $\text{Rot} = P - q$, where P is the position angle (the angle between the celestial and solar north), q is the parallactic angle (the angle between the celestial north and zenith). Finally, these parameters imply the local time (HH and MI) of the observation and other ephemeris, which in turn define the heliographic coordinates of the sunspots. According to the formulas in Meeus (1991), we use the equation of time with coefficients determined for J2000 astronomical epoch. These coefficients were slightly different during Harriot’s observations leading to a time error of about several tens of seconds. For example, a one-minute difference in time definition causes $0.1 - 0.2^\circ$ difference in sunspot latitudes and longitudes.

Another method (Method II) to extract sunspot positions does not take into account time of observation specified by the observer. Basically, this approach is identical to Method I, but here we removed all the limits on the rotation angle of an image. Here, our goal is to minimize the cumulative latitude dispersion of sunspots (Vokhmyanin and Zolotova, 2018a, for details). The procedure is as follows: after sorting sunspots by groups, we rotated the images from -180° to 180° (in increments of 0.2°) looking for the image rotation angle at which the difference between latitudes of spots on the current and previous drawings becomes the smallest (first run) and the difference between latitudes of spots on the current and subsequent drawings also reaches a minimum (second run). After several iterations, the resulting rotation angle (Rot) is a weighted mean of these two runs. Finally, this angle provides us with a set of ephemeris, the time of observation and the heliographic coordinates of the sunspots.

In this approach, there were several cases when the cumulative latitude dispersion taken over all spots in a given day has two similar minimal values. Here, we choose the angle which is closer to the Method I approach.

Also, on some days (62 of 200) the rotation angle of an image does not fall into a range of $P - q$ value for the Sun above the horizon. Therefore, we were not able to determine the local time, position and parallactic angles, heliographic latitude and longitude of the apparent disc center (B_0 and L_0), altitude and azimuth (Alt and Azm). On these days, these values are NaN (see the corresponding supplementary file). The mismatch of the rotation angle Rot with the daily range of $P - q$ possible during daytime might be due to uncertainties in the observation or drawing or due to several observing attempts during a day combined in one drawing. On these 62 days, the longitude of sunspots was assigned for L_0 at 9 a.m.

Figure 3 shows the latitude–time diagram from December 1611 to January 1613 reconstructed by means of Method I (red crosses) and Method II (blue circles). Ideally, sunspot position and other parameters have to be close in these two methods. However, differences

in sunspot latitudes occasionally exceed 10°. We also would like to emphasize that the near-equator region is usually spotless, while observations by Scheiner from October 1611 to January 1612 demonstrate equator occupancy. The latter are likely due to the poor quality of Scheiner’s early drawings (Arlt *et al.*, 2016).

The total uncertainty of sunspot latitude (longitude) with ≈ 95% confidence level is found from:

$$\Delta B_{\text{total}} = \sqrt{\Delta B_{\pm 15 \text{ min}}^2 + \Delta B_{\text{drawing}}^2}, \tag{1}$$

where $\Delta B_{\pm 15 \text{ min}}$ is the error caused by the inaccurate definition of the drawing time and $\Delta B_{\text{drawing}}$ is the uncertainty caused by the rough drawing quality.

Harriot mentioned times of observations in 15-minutes step, although the majority of the observations were made at minutes 0 or 30. Note also the painting of the sunspots takes time and the accuracy of the time counting is questionable. We suggest the ±15 minutes interval is a fair evaluation for the accuracy of the time found within a one-hour interval around the time noted by Harriot. The corresponding uncertainty in the solar ephemeris (P , B_0 , L_0 , etc.) and coordinates of the spots ($\Delta B_{\pm 15 \text{ min}}$ and $\Delta L_{\pm 15 \text{ min}}$) are found as maximum and minimum values within ±15-minutes of the mentioned time. These errors rarely exceed 1°, which is much less than the uncertainty caused by drawing quality.

Even in the Method II which minimizes the day-to-day variability of the sunspot latitudes, the uncertainty coming from inaccuracy of the drawings ($\Delta B_{\text{drawing}}$) may exceed several degrees. Considering that this uncertainty has a normal distribution, it is found for each sunspot according to the following formula (with 70% confidence interval):

$$\Delta B_{\text{drawing}} = t_{N,70\%} \cdot \sqrt{\frac{\Sigma(B - \bar{B})^2}{N(N - 1)}}, \tag{2}$$

where \bar{B} is the average sunspot latitude, N is the number of observations of the analyzed sunspot, $t_{N,70\%}$ is the Student coefficient. For a solitary observation $\Delta B_{\text{drawing}}$ is presumed to be about 10°.

For the longitude we get

$$\Delta L_{\text{drawing}} = t_{N,70\%} \cdot \sqrt{\frac{\Sigma(L_t - [\bar{L} + (\omega_B - \frac{360^\circ}{25.38d})(t - \bar{t}]])^2}{N(N - 1)}}, \tag{3}$$

where t is the time of the observation (in days, 0 for the first observation) and \bar{t} is the mean time (in days) of the observations, ω_B is the differential rotation rate at the latitude B in °/d. For a solitary observation $\Delta L_{\text{drawing}}$ is presumed to be about 15°. For Method II, $\Delta L_{\text{drawing}} = 15^\circ$ is assigned for 62 days when the rotation angle of an image does not fall into the range of position angles when the Sun is above the horizon.

4. Comparison of Methods

Figure 4 compares results of two methods. In Figure 4a, the rotation angle or the angle between solar axis and zenith direction is shown. Light blue lines mark daily limits of $P - q$ angle. 62 blue circles, which corresponds to Method II, are located out of these limits. The largest deviation occurred in the second half of May 1612 and amounts to 24°.

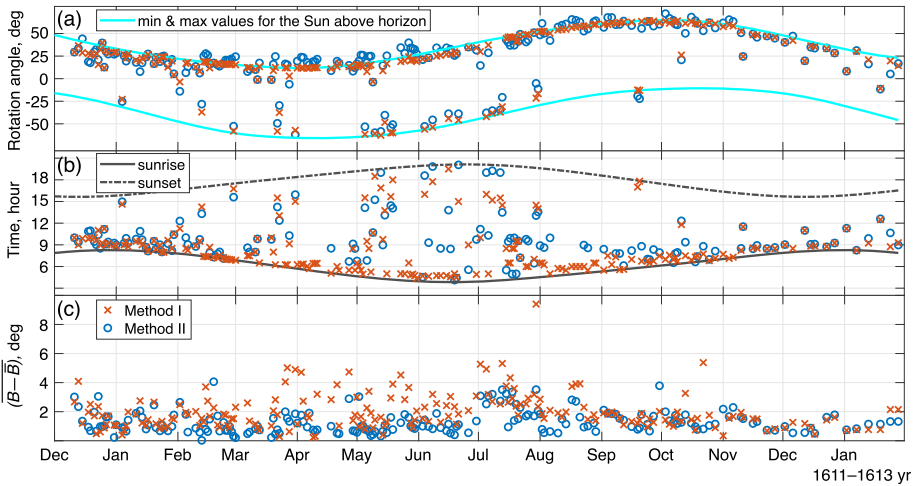


Figure 4 Red crosses and blue circles define the rotation angle of an image (a), the observation time (b), the average dispersion of all sunspots on a drawing from their average latitudes (c), all calculated by Methods I and II, correspondingly. Light blue curves mark $P - q$ limits when the Sun is above horizon. Black curves denote time of sunrise and sunset.

Figure 4b shows the local time of the observations obtained by the two methods. Black curves mark the times of sunrise and sunset. Harriot usually observed in the morning hours. The differences in time of the two methods increases in warm months. Here, there are 62 circles fewer (Method II) than crosses (Method I), because the rotation angle does not match with the Sun being above the horizon. Here, we would like to emphasize that Method II itself is not aimed to precisely define the time of observation, but gives the best image rotation in order to define an average picture of spot positions.

Figure 4c depicts the daily average dispersion of sunspots from their average latitudes. Since spots observed on only one day gave zero dispersion, we excluded them from the figure. In the cold months, the scatter of both methods usually does not exceeds $2 - 3^\circ$. In the warm season, the average dispersion according to Method I varies up to 6° , and only on 30 July 1612 jumps to almost 10° . The latitude scatter of Method II rises to 4° , but generally does not exceed 2° . The latter seems less than the actual plotting accuracy by Harriot, and hence Method II may be overfitting because of too much freedom in the parameters. Moreover, in Method I we do not throw away useful information (time of observation reported by Harriot). Therefore, sunspot positions defined by means of Method I could be preferable, but Method II may correct for errors Harriot made, e.g. wrong time or wrong orientation of the disk.

Figure 5 shows the sunspot trajectories (thin black curves) restored according to Methods I and II on 30 July 1612, when the average dispersion of sunspots from their average latitudes jumps to almost 10° in Method I (Figure 4c). Apparently, on this day, the observation time is incorrect. Fortunately, this is the only case.

Figure 6 shows a superposition of rotated drawings of the second half of May 1612, when the rotation angle in Method II deviates most of the daily limits of $P - q$ angle (Figure 4a). Results of the two methods are compared in Figures 6a and b. The imposed heliographic grids correspond to the middle day within the observation series. Dashed gray lines are zenith and ecliptic lines plotted by Harriot. The colored curves schematically mark the trajectories of several sunspots. During this time period, in Method I sunspots tend to

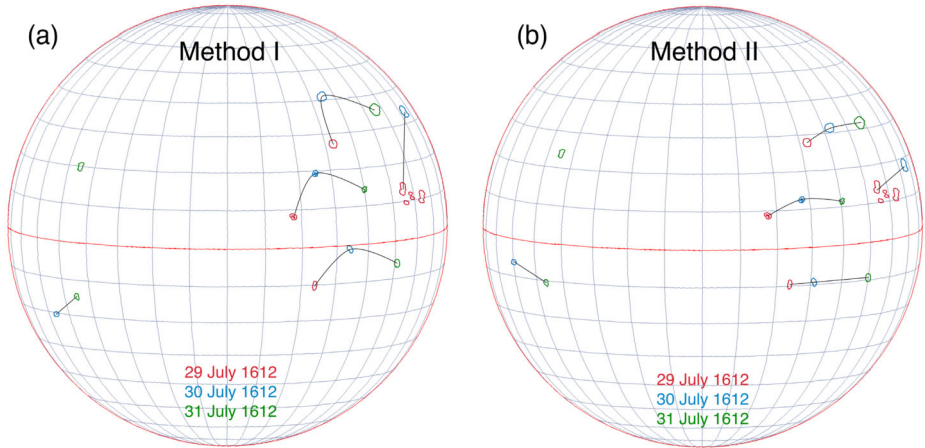


Figure 5 Superposition of schematic colored images of Harriot’s observations on 29–31 July 1612. Images were derotated according to Method I (a) and Method II (b). The *thin black curves* schematically mark the trajectories of sunspots, the heliographic grid on 30 July is underlaid.

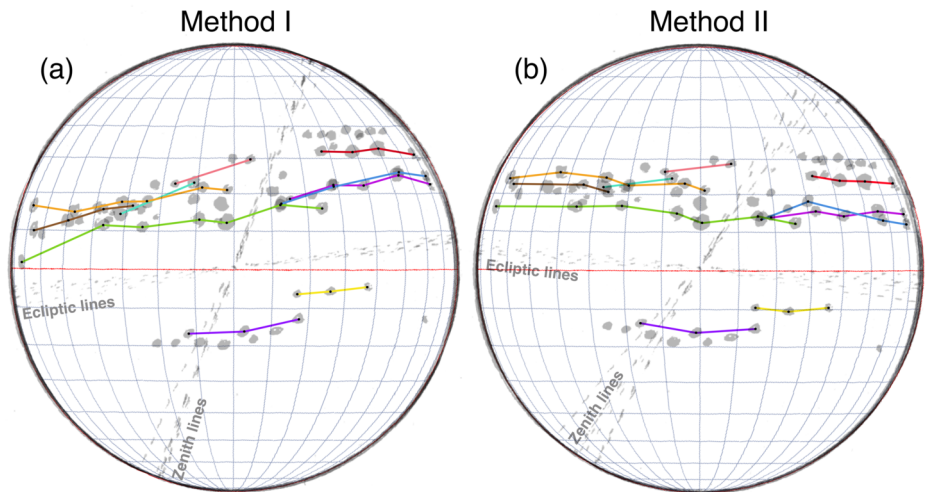


Figure 6 Superposition of drawings of 23, 25, 27, 28, 29, 30, and 31 May 1612. Solar images of individual days were derotated by Method I (a) and Method II (b). The heliographic grids correspond to the middle day within the observation series. The *colored curves* schematically mark the trajectories of several sunspots. Dashed grey lines are zenith and ecliptic lines plotted by Harriot.

move upwards on the grid. Sunspot trajectories obtained in Method II (Figure 4b) evidently demonstrate minimal variation in latitude, while zenith lines worse match each other, and ecliptic lines are wrongly tilted.

Eventually, there are periods, when both methods significantly suffer from uncertainties. As an example, Figure 7 shows three days of August 1612. Black curves schematically trace the sunspot trajectories. Fortunately, similar cases of large deviations in latitude are rare. We would suggest that this latitudinal spreading of the sunspot runs is due to the rapid

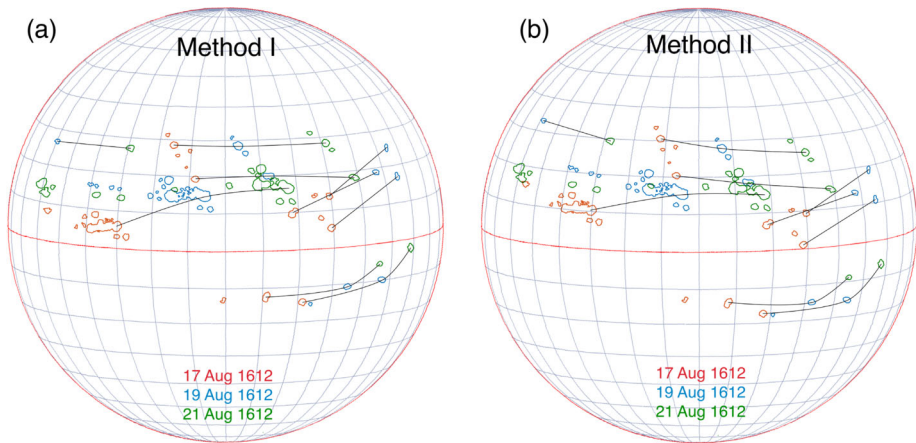


Figure 7 Superposition of schematic colored images of Harriot's observations on 17, 19, and 21 August 1612. Images were derotated according to Method I (a) and Method II (b). The thin black curves schematically mark trajectories of sunspots, the heliographic grid on 19 August is underlaid.

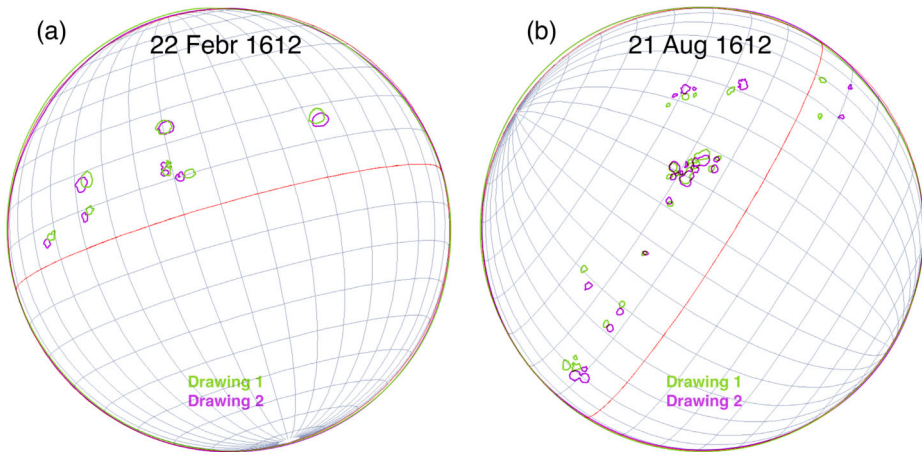


Figure 8 Superposition of repeated drawings by Harriot on 22 February 1612 (a) and 21 August 1612 (b). The heliographic grid according to Harriot's time of observation is underlaid.

change of the parallactic angle q at the time of drawing, but according to Harriot's report these observations were carried out near sunrise when the slope of the solar axis is slowly changing. Hence, it would be reasonable to compare two drawings of the same day.

Fortunately, Harriot made two drawings each on 22 February 1612 and 21 August 1612 (Figure 8). The text accompanying the twin drawings is identical. In other words, the time of drawing is the same. Here, we superpose repeated drawings with the heliographic grid oriented in accordance with the time of observation specified by Harriot and found that the uncertainty of the sunspot mapping is a few degrees.

To conclude, we would recommend to exploit sunspot positions defined by means of Method I, because it does not neglect useful information, namely the time of observation reported by Harriot which, in turn, sets the longitude of a sunspot. Method II provides average

sunspot latitudes with smallest possible residuals and was not aimed to define the time of drawing.

5. Conclusions

We study sunspot drawings from 18 December 1610 to 28 January 1613 made by Thomas Harriot which are stored in the Cultural Heritage Online. Herr (1978) used them to estimate the differential rotation, and Hoyt and Schatten (1998) derived the sunspot group numbers. However, sunspot areas and coordinates are not publicly available.

Guided by the sunspot group classification by McIntosh (1990), we sorted 753 spots into 293 groups, which cumulatively is 12% more in comparison with the group numbers by Hoyt and Schatten (1998).

In comparison with modern observations, the 14-month period of Harriot's observations provides a larger percentage of sunspot groups with an area above 400 msh. At the same time, the drawings significantly lack small groups with areas below 100 msh (which make up about half of all groups in the Greenwich catalogue) indicating that sunspot group numbers may be undervalued.

To define heliographic sunspot positions, we developed two methods. Method I exploits the time of observation recorded by Harriot. According to his notes, Harriot observed through clouds or misty air usually in the morning hours. On the contrary, Method II omits this information, but determines the angle of the solar axis minimizing the discrepancy between the sunspot latitudes of individual spots during their passage through the solar disk. Note that for 62 drawings the rotation angle in Method II does not match with the Sun being above the horizon. Both methods have their advantages, although we recommend relying on the sunspot positions derived by Method I (in the case of large uncertainties one can refer to the results from Method II).

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