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Sunspot Positions and Areas from Observations by Cigoli, Galilei, Cologna, Scheiner, and Colonna in 1612 – 1614

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Abstract Digital images of manuscripts stored in the Galilean collection of the Central National Library of Florence are analyzed to obtain sunspot groups, their areas and heliographic positions. Overall, 142 drawings were processed. The way of drawing is usually schematic resulting in area uncertainty which may exceed a factor of two for small sunspots. We suggest that there is an upper limit of a factor of two between sunspot group numbers from the drawings and the actual ones. The computed penumbra-to-umbra ratio is consistent with modern observations. A distribution of sunspot latitudes versus time is reconstructed by means of two methods: exploiting the observation time noted by an observer and minimizing the day-to-day variability of sunspot latitudes.

Keywords Sunspots · Solar cycle, observations

1. Introduction

Gradually, butterfly diagrams are being reconstructed from drawings made before the photographic era (Muñoz-Jaramillo and Vaquero, 2019): by Christoph Scheiner in 1611 – 1631 (Arlt et al., 2016), Johannes Hevelius at the onset of the Maunder minimum (Carrasco et al., 2019), Gottfried Kirch in the last decades of the Maunder minimum (Neuhäuser, Arlt, and Richter, 2018), Christian Horrebow in the second half of the 18th century (Karoff et al.,

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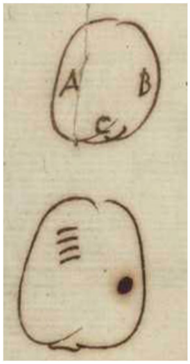

Figure 1 Sunspot drawing from the letter of Cigoli to Galilei on 13 September 1611 (Firenze, BNC, ms. Gal. 89, f. 41r).

2019), etc. Recently, Galaviz et al. (2020) developed a software to determine sunspot parameters from historical observations, if the orientation of the solar disk is known.

Not only the number of sunspot groups measure solar activity in the past. Sunspots areas might be an alternative measure of solar activity (Petrovay, 2020). Area-weighted latitudes and longitudes provide the accurate location of large elongated sunspot groups.

Sunspot parameters extracted from historical archives are suitable to define the solar differential rotation, average sunspot group tilt angles, hemispheric asymmetries, and other solar features (Arlt and Vaquero, 2020).

In this article, we process sunspot drawings made in 1610s. Section 2 gives a detailed description of the analyzed archives. Section 3 is devoted to the comparison of sunspot group numbers with those by Hoyt and Schatten (1998). Sunspot areas are analyzed in Section 4. In Section 5, we study the penumbra-to-umbra ratio of sunspot groups. In Section 6, we address the time-latitude distribution of the sunspot groups. A summary is given in Section 7. Supplementary information files provide sunspot data.

2. Data

We examine sunspot drawings stored in the archives of the Biblioteca Nazionale Centrale of Florence (BNCF).

Bredekamp (2019) gives a detailed account of the history of observations of the Sun, methods and instruments in the 1610s. He mentioned two schematic sketches of the solar disk with sunspots from a letter of Lodovico Cardi (known as Cigoli) to Galileo Galilei (Cigoli, 1611) dated 16 September 1611, which we do not include in this work as the sketches are too schematic to extract sunspot areas and positions. Cigoli reported about observations by Domenico Passignano on 13 September 1611 (Figure 1). The upper sketch shows the diurnal A – B – C path of the sunspot group consisting of four parallel spots. The lower sketch shows this sunspot group and one large individual sunspot.

2.1. Cigoli: 18 February – 23 March 1612

The first set of 26 images drawn with pen and ink by Cigoli (1612a) are attached to the letter addressed to Galilei dated 23 March 1612. The average diameter of the disks is 3.7 cm (Bredekamp, 2019). Cigoli observed through a thick green glass at the Basilica of Santa Maria Maggiore in Rome (Vaquero and Vázquez, 2009).

The solar disks are accompanied by a date, a day of the week, an observing time (hours after sunset of the previous day), and number of spots. Two drawings on 23 February were made at 17 and 21 hours. Moreover, the first drawing contains two sunspots from the previous observation on 22 February at 18 hours. Note that sunspots of the previous day were imposed without additional turn of the solar disk due to its diurnal rotation in the sky. Similarly, on 24 February two drawings were made at 18 (near 11:00 UT) and 12 hours (near sunset). The sunspots observed at 18 hours were included in the drawing made at 12 hours, again without taking into account the diurnal rotation of the disk. The size, shape, and position of the sunspots were illustrated roughly and the drawings are schematic. Sunspot areas may differ by more than a factor of two even on the same day drawings. This affects the reliability of the reconstructed sunspot parameters.

Two solar disks on 2 and 4 March 1612 are blank and accompanied by the short note "non vidi niente" (I did not see anything). In the supplementary information, these days are filled with NaN (Not-a-Number) instead of zeroes, as the schematic observations of the time may have ignored small sunspots.

Vaquero and Vázquez (2009) translated the description that Cigoli gave of his telescope in a letter to Galileo: "I do not believe I have told you that I have a telescope, and it is sufficiently good to enable me to see the clock of St. Peter's and its hand from St. Maria Maggiore, but not the numbers of the hours as distinctly as I saw it with yours." Analyzing the Moon on the paint by Cigoli on the dome of the Pauline Chapel, Panofsky (2013) suggested that Cigoli exploited a Galilean telescope. According to the sunspot positions defined here, sunspots move from left (east limb) to right (west limb) with a large longitude scatter up to 20° and with an average value of 7°. This also suggests to us that Cigoli used a Galilean telescope.

2.2. Cigoli: 29 April – 6 May 1612

These five drawings by Cigoli (1612b) were sent in a letter to Galilei on 30 June 1612 from Rome. Diameter of the solar disks is about 5 cm. The drawings are accompanied by a date and a time (in hours after sunset). The spots were drawn in detail, but their areas are significantly enlarged and positions seem to be inaccurate. Sunspot parameters from these drawings should be used with extreme care, and especially on 29 and 30 April 1612 sunspot positions suffer from great uncertainties.

2.3. Cigoli: 18 – 25 August 1612

On 31 August, Cigoli (1612c) sent seven sunspot observations to Galilei. These drawings of stipulated size (disk diameter occupies a full page width) were made to compare observations of the two researchers (Bredekamp, 2019). Apparently, Cigoli exploited an improved telescope, or a new one. Drawings are accompanied by a day of the week, a date, and an observing time (again, in hours after sunset). For several sunspot groups, umbra and penumbra are distinguished by darker and lighter ink. In the original image, these drawings are shown reversed. Therefore, we flipped images from top to bottom.

This orientation of the images suggests that Cigoli observed by means of projection behind a Galilean telescope. Bredekamp (2019) cited the following text from the letter by Cigoli to Galilei on 3 May 1613, where Cigoli retroactively writes: "me le aveva fatte osservare di quella stressa sua grandezza, et dettomi il modo da farto" (he had pointed them [drawings] out to me of that great size, and told me how to do it).

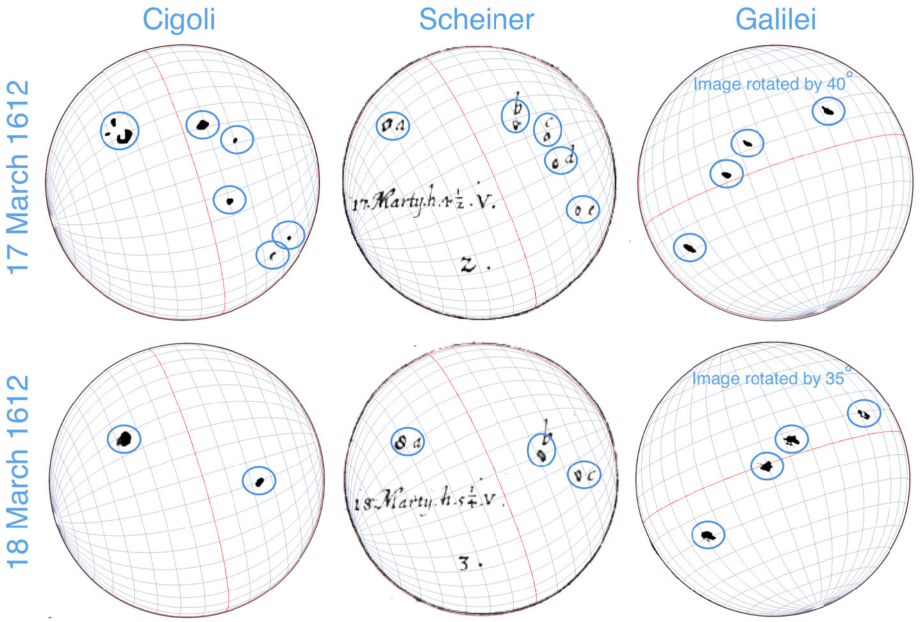

Figure 2 Original sunspot drawings on 17 and 18 March 1612 with orientation of the solar grids corresponding to the time of observation indicated by the observer: Cigoli (*left*) (from BNCF, ms. Gal. 57, f. 61r), Scheiner (1612) (*middle*); Galilei (*right*) (from BNCF, ms. Gal. 57, f. 68v). These two drawings by Galilei were rotated by 40° and 35° correspondingly. Blue ovals define sunspot groups.

2.4. Galilei: 12 February – 3 May 1612

The next portion of 23 drawings with pen and ink were made by Galilei (1612). Circles vary in diameter between 3.6 and 5.9 cm (Bredekamp, 2019). The first and the last solar disks are almost perfect circles, while the interjacent disks are freehand circles. This affects the accuracy of sunspot parameters reconstruction. We suppose that Galilei observed at 15 km from Florence at the Villa Le Selve. Drawings are supplemented by a date and short notices on sunspots. In most cases, Galilei wrote that he observed at sunset (occasus) or sunrise (exortus). On 16 April, he observed "mane H. 1. ab ortu", on 19 April and 3 May, "mane ab ortu H. 3.". This means the observations were made in the morning in the first and third hours from sunrise.

Bredekamp (2019) noted that after 23 February until 16 March 1612 Galilei interrupted his observations due to bad weather. In the manuscript, Galilei wrote "D. 1. Martij nec in ortu nec i occi aderat macula... D. 2. Martij ... nulla apparuit macula... Die 15. Martij nulla apparuit macula...". We translated as "*On 1 March, there were no sunspots at sunrise or sunset... On 2 March, there were no sunspots. On 15 March, there were no sunspots.*". Again, these days are filled with NaN in the supplementary information.

Galilei's drawing of 16 April is flipped upside down. It is seen by comparison with the next day drawing and with Harriot's images containing the same sunspot group. Another uncertainty of the image orientation occurred on 17 and 18 March 1612. Comparing with observations by Scheiner (1612) and Cigoli (1612a), we rotated Galilei's drawing of 17 March by 40° and the drawing of 18 March by 35° clockwise (Figure 2). We do not know the origin of such orientations.

2.5. Galilei: 19 – 21 August 1612

These drawings by Galilei (1613) were published in Istoria e dimostrazioni intorno alle macchie solari. We compared these engravings with those by Cigoli (1612c) and found that Galilei's images in the book were rotated 90° clockwise.

This may have been done for the following reason. Sunspot drawings on 2 June – 8 July 1612 were made by Galilei after 11:30 UT, when the solar rotation axis inclined to the right from the vertical and hence sunspots move from the top left corner to the bottom right corner. However, on 3 August drawings sunspots have to move from the bottom left to the top right corner, because these drawings were made in the morning, when the solar rotation axis is inclined to the left from the vertical. Nevertheless, in Istoria August sunspots progress across the solar disk in the same way as on drawings of June and July. We hypothesize that Marcus Welser, the publisher, or the engraver, or someone else involved in publishing Galilei's letters to Welser, mistakenly rotated August drawings by 90°.

The August drawings are accompanied by the time notes "Hor. 14". Unaware that images were rotated, neither Casas, Vaquero, and Vazquez (2006) nor Vokhmyanin and Zolotova (2018a) could find a relation between these notes and a suitable orientation of the solar grid. Hence, sunspot positions defined by Vokhmyanin and Zolotova (2018a) for August 1612 are incorrect due to the incorrect orientation of the printed engravings. Here, to define sunspot positions we derotated drawings, and now "Hor. 14" (hours after sunset) clearly corresponds to the time at about 8:00 UT in the morning. This is a nice example of how every little piece of information matters in such researches.

Particular attention should be paid to the quality of the etchings in Galilei (1613) made by Mattheus Greuter. Thanks to the exceptional way of engraving, the fine structure of the sunspot umbra and penumbra was thoroughly reproduced (Noyes, 2016, for details).

2.6. Cologna: 6 September – 9 October 1612

On 10 October 1612, Monreale Sigismondo di Cologna (1612) sent a series of 21 drawings to Benedetto Castelli. 20 small drawings are of a perfect circle and one rough drawing is an epigraph on the first page. Solar disks are accompanied by a date and an observing time in hours after sunset. Sunspots are labeled with Latin letters. Two drawings on 10 September 1612 were made at 13 and 19 hours after sunset. The style of drawings is similar to that by Scheiner in 1611 and 1612.

We flipped these images from top to bottom, as they are shown reversed in the original publication. Additional comparison of Cologna's drawings with those by Harriot shows that the orientation of some solar disks does not correspond to the indicated time (Figure 3). To fix this: (i) on 10 September 1612 at 19 hours after sunset and on 25 and 26 September, the images were rotated by 90° counter-clockwise, (ii) on 27 September, by 180°, and (iii) on 20 and 21 September (only for Method I; see Section 6), by 50° counter-clockwise.

2.7. Scheiner: 1 August 1613

This illustration by Christoph Scheiner was redrawn by Welser (1613) in his letter to Galilei dated 18 October 1613. Welser quoted Scheiner (translated by Mitchell (1916)): "*I add, therefore, an observation made on the first day of August, in which you will see examples of this new sight. However, these are not sun-spots, but are "little torches" (faculae), that is, regions which are brighter than those surrounding them...*". Faculae are mentioned to be marked with letters *a*, *b*, and *c* on the drawing ("*...secus tres a,b,c, Sunt autem eæ non*

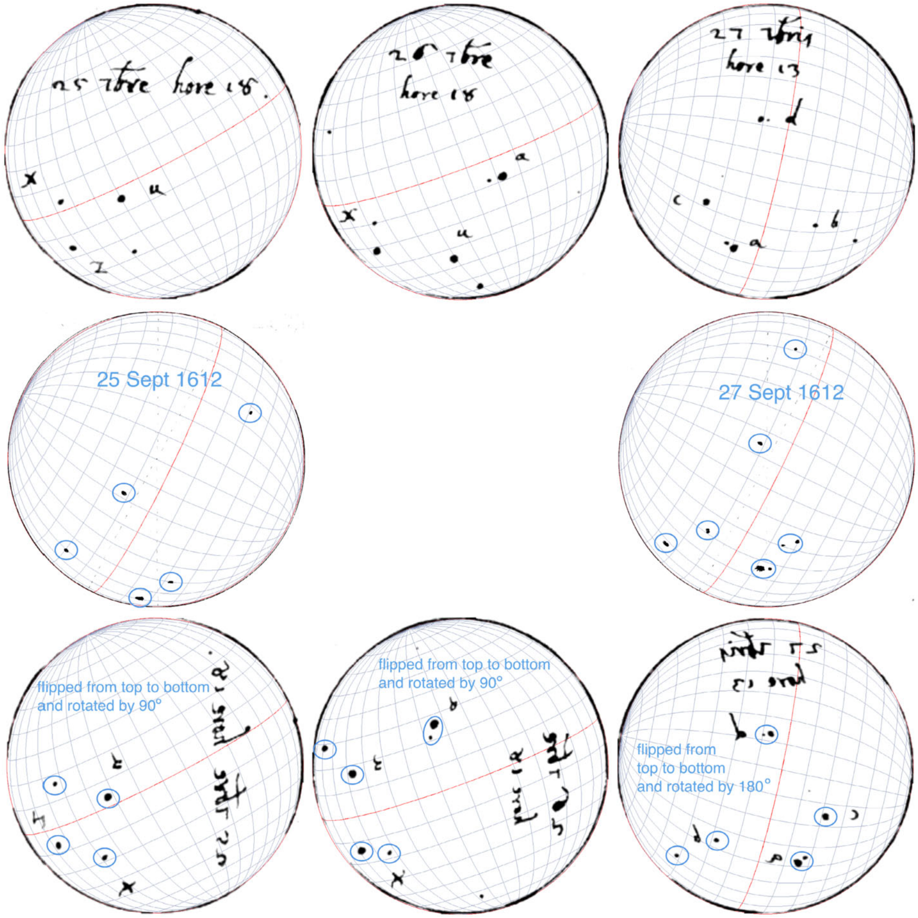

Figure 3 Original sunspot drawings by Cologna on 25 – 27 September 1612 (*top*) from BNCF, ms. Gal. 95, f. 35r. Orientation of the solar grids corresponds to the time of observation indicated by the observer. Sunspot drawings by Harriot (*middle*) from ECHO, vol. VIII: spots on the Sun, HMC 241 VIII. The heliographic grid was reconstructed according to the time of observation. Blue ovals define sunspot groups. Flipped drawings by Cologna which match the corresponding solar grids (*bottom*).

maculae Solis, sed faculae,.."). We separated faculae from sunspots when processing this drawing.

This drawing is schematic and its style is similar to that by Cigoli in February – March 1612 and Galilei in February – May 1612. The solar disk is almost a perfect circle with a diameter of a few centimeters. Scheiner's original observation was made by means of projecting with a tube on a card. The drawing is supplemented by a note "1. Aug. P.M. solis elevatio. 26 deg 0′.". Location is Ingolstadt (Arlt et al., 2016). In the following sections, this single observation is added to the set of observations by Colonna.

2.8. Colonna: 1 August – 30 September 1613

These 50 sunspot drawings were made by Fabio Colonna (1613) in Naples. Colonna imitated the observations by Galilei (1613). These drawings accompanied the letter to Galilei, where

Colonna mentioned that he used the projection technique and the size of the solar disk (disk diameter occupies full page width) is similar to that used in Istoria. Colonna also indicated that his telescope is not good enough to reveal the fine structure (umbra and penumbra) of the sunspots as shown in the book of Galileo (Gargano, 2019, for an accurate translation of the letter).

These drawings are reversed in the original publication, therefore we flipped them from top to bottom, which is the natural choice for observations by projecting the Sun behind a Galilean telescope. Images are accompanied by a date and an observing time in hours after sunset. Most of sunspot groups are labeled with Latin letters. On 4 September 1613, Colonna indicated that it was partly cloudy "nebuloso interdu[m]". Drawing of 22 September has a note that on 23 and 24 it was cloudy as well.

2.9. Colonna: 3 October 1614

On 3 October 1614, Colonna (1614) observed the partial solar eclipse. Colonna's letter, however, does not contain any hint on the type of telescope he used. Gargano (2019) translated the letter to Galilei, where Colonna wrote: "I send you six images of today's eclipse... marking both the path of the Moon, or better to say of the Sun, which moved rapidly, and the precise sunspots and their size; due to the rush and the little thought I could not do better... Your Lordship will see a very rough sketch; you will be able to recognize the accurate parts, taking what is possible, and you will invert them..."

These schematic and rough drawings are arranged in such a way that the image is conveniently viewed when flipped vertically. It is therefore very likely that Colonna used a Galilean telescope in projection, while a Keplerian telescope was in the process of making at Naples at the same time (Gargano, 2019). The first observation is supplemented by a note "h. 18 ÷", and the last "hor. $19\frac{1}{4}$". The diameter of the solar disks is of a few centimeters. The second drawing additionally shows the edge of the Moon from the first observation.

3. Sunspot Groups

To sort sunspots into groups, we rely on the classification described by McIntosh (1990). Commonly, we assigned that the linear size of a sunspot group is on average limited to 7° of latitude and 15° of longitude. In complicated cases, groups were assigned arbitrarily. We also take into account groups defined in the observations by Thomas Harriot (Vokhmyanin, Arlt, and Zolotova, 2020).

On 38 drawings by Cigoli we sorted 221 sunspots into 46 groups, on 26 drawings by Galilei, 255 sunspots were sorted into 39 groups, whereas on 21 drawings by Cologna, 68 sunspots composed 30 groups. The single observation by Scheiner was added to the reports by Colonna, where 293 sunspots from 57 drawings were sorted into 56 groups.

Figure 4 compares daily numbers of sunspot groups from the database by Hoyt and Schatten (1998) with the results of this work. Further, the numbers of groups with the prefix G and the numbers of spots with the prefix Sp are indicated according to the numbering used in the supplementary information. We would like to mention several discrepancies. On 24 February 1612 (Figure 4a), Hoyt and Schatten (hereafter HS) assigned seven sunspot groups. On that day, Cigoli made two drawings. On the first one, we assigned seven sunspot groups, while on the second one, eight sunspot groups. Moreover, group G7 appears only on the first drawing, while groups G9 and G10 appear only on the second one. We think that Cigoli reported 9 sunspot groups on 24 February 1612. Additionally, we compared the observations

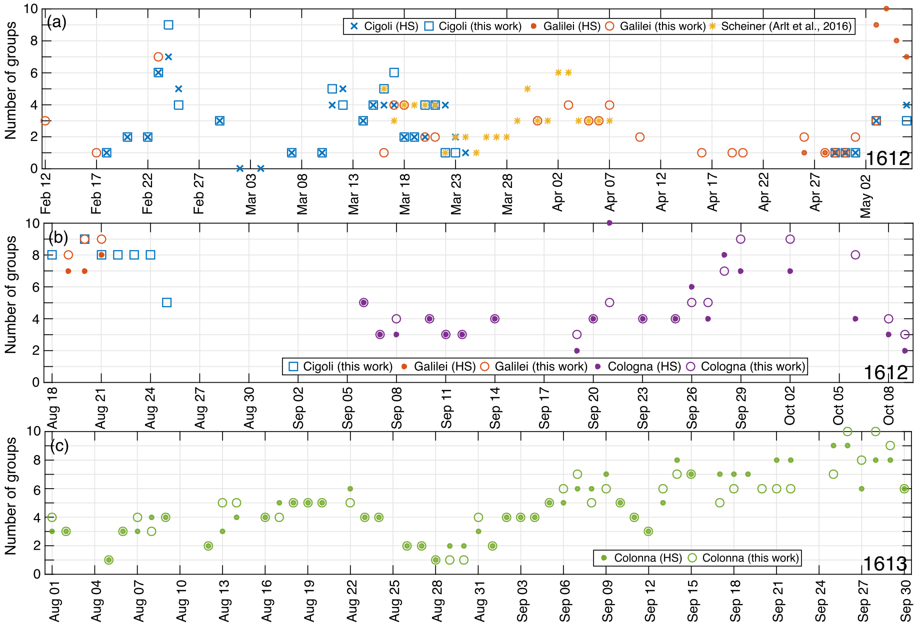

Figure 4 Daily number of groups according to Hoyt and Schatten (1998), Arlt et al. (2016) and derived in this work: (**a**) observations by Cigoli, Galilei, and Scheiner in February – May 1612; (**b**) observations by Cigoli, Galilei, and Cologna in August – October 1612; (**c**) observations by Colonna in August – September 1613.

by Cigoli with Harriot's. Note that groups G7 and G9 are absent from Harriot's drawing, instead group G48 was missed by Cigoli. Eventually, we believe that on 24 February 1612 there were at least 10 sunspot groups on the Sun. For convenience, in the supplementary information we added the column G_Harr, which is the group number, according to the Harriot numbering in Vokhmyanin, Arlt, and Zolotova (2020).

Another discrepancy (Figure 4a) appears on 22 March 1612, when HS detected four groups, though we identified only one large sunspot and two paper defects. On this drawing, Cigoli himself also wrote that there was one object. On 23 March, HS detected two groups, while we identified one large group. We think that the tiny spot at the lower edge of the solar disk is a paper defect, because it differs from the other spots by the ink color.

The database by Hoyt and Schatten (1998) does not include observations by Galilei (1612) from 12 February to 3 May 1612 from the Florence manuscript. The few red dots (Galilei's observations in HS on 26 – 30 April 1612) in Figure 4a apparently belong to Galilei (1613, the first letter to Welser dated 4 May 1612), where Galilei thoroughly described the evolution of a large sunspot group. However, the red open circles show that in the Florence manuscript Galilei (1612) drew two sunspot groups on 26 April and 1 May 1612. Since 3 May, HS apparently assigned sunspot groups from the letter by Galilei to Maffeo Barberini.

Since the images from 19 – 21 August 1612 by Galilei (1613) were rotated by 90° (see Section 2.5), we modified the sunspot groups sorting. Namely, sunspots Sp218 and Sp219 are now located almost at the same latitude (one degree difference), hence they are likely to compose one group, not two, like in Vokhmyanin and Zolotova (2018a). Comparing August drawings by Galilei and Cigoli, we also combine sunspots Sp245 – Sp247 into one group, instead of two. The HS database does not contain data from observations by Cigoli in August

1612, while for Galilei, Hoyt and Schatten specified a smaller number of groups compared to this work (red dots and open red circles in Figure 4b).

Furthermore, on 21 September 1612 in the observations by Cologna (1612) there is a large difference in sunspot group numbers (dark purple dots and open circles in Figure 4b). On this image, we ignore five objects, because they are different in color. Hence, we conclude that these are paper defects. Two of them are tiny, and two medium-size; however, neither appear on previous or subsequent drawings, nor are they present in Harriot's observations. Besides, Cologna did not label them with Latin letters.

A significant difference in sunspot groups between HS and this work appears on 6 October 1612 (Figure 4b). Here, we compare several of Cologna's drawings with Harriot's and assign more groups in comparison to HS.

In Figure 4c, from 14 to 25 September 1613 we systematically define one or two sunspot groups less in comparison with HS. Here, Colonna drew abundant populations of sunspots occupying up to 30° in longitude. Hoyt and Schatten joined sunspots into a larger number of smaller groups, while we join sunspots into a lower number of larger groups.

4. Sunspot Areas

To measure sunspot areas, we need to define whether the observers drew the whole sunspot or only the umbra. Drawings by Cigoli and Galilei in August 1612 show the fine structure of sunspots with umbra and penumbra (see Section 5). Figure 5 shows few examples illustrating the drawing style. In August – September 1613, Cologna drew sunspots in hatching manner, with which the distinction of umbra and penumbra could be sometimes discerned (Figure 5a). In the other series of observations, the style of drawing is usually schematic resulting in a large area uncertainty which exceeds factors of 1.5 and sometimes 2. Nevertheless, the size of the sunspots indicates that the observers drew the whole sunspots (including the penumbra).

Figure 5b demonstrates the superimposed drawings of 24 February 1612 at 18 and 12 hours by Cigoli (1612a). For comparison, red and blue colors denote sunspot groups G42 and G44. Here, there is a significant uncertainty in the area of sunspots.

In Figures 5c and d, drawings of the large sunspot group on 3 May 1612 by Cigoli (1612b) and Galilei (1612) are shown. Cigoli's drawings are highly schematic. On both images, the longitudinal size of this large sunspot group is about 40°, while the more detailed observations by Harriot and Galilei (from the letter to Maffeo Barberini) gave a longitudinal extent of about 25°.

Next three images (Figure 5e – g), show the full-disk drawings on 28 September 1612 by Cologna (1612), illustration of 1 August 1613 by Christoph Scheiner redrawn by Welser (1613), and the partial solar eclipse on 3 October 1614 by Colonna (1614). Recall that letters a, b, and c on the drawing by Scheiner mark faculae. On these three images the drawing style is also rather schematic. Therefore, sunspot areas from these drawings should be used with care.

To define the intensity-weighted coordinates of sunspots and their areas, we rescale all solar disks to the same diameter of 1400 pxl. We estimate sunspot areas in microhemispheres (often called millionths of a solar hemisphere—msh). In a few cases, the pages around the stitch are bent, which affects the accuracy of parameter reconstruction of sunspots near the limb (especially for objects with a large angular distance).

Figure 6 compares the distributions of sunspot group area of historical and modern observations. We consider only Colonna (2 August - 30 September 1613) and Scheiner (1 August

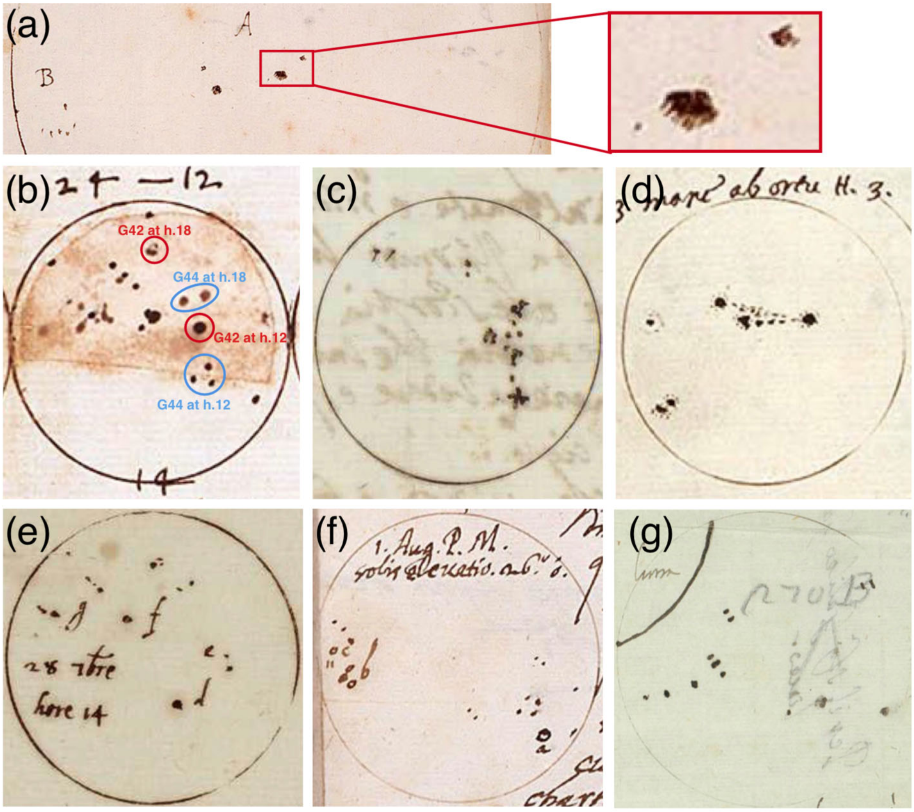

Figure 5 Examples of sunspot drawings: (**a**) part of the drawing by Colonna of 19 August 1613 (BNCF, ms. Gal. 57, f. 78r) with a zoomed fragment. (**b**) Superimposed drawings of 24 February 1612 at 18 and 12 hours by Cigoli (BNCF, ms. Gal. 57, f. 61r). Large sunspot group on 3 May 1612: (**c**) drawn by Cigoli (BNCF, ms. Gal. 89, f. 117r), (**d**) drawn by Galilei (BNCF, ms. Gal. 57, f. 68v). Three solar disks: (**e**) by Cologna on 28 September 1612 (BNCF, ms. Gal. 95, f. 35r), (**f**) by Christoph Scheiner on 1 August 1613 redrawn by Welser (BNCF, ms. Gal. 57, f. 59r), and (**g**) eclipse observation by Colonna on 3 October 1614 (BNCF, ms. Gal. 90, f. 204ar).

1613) observations in blue bars. Colonna also observed on 1 August 1613; however, he drew less sunspots compared to Scheiner. The largest sunspot group was registered on 9 August 1613 (1181 msh) and the smallest one (29 msh) on 9 September 1613 (Figures 6a and b). The remaining series of drawings are either too short or schematic, resulting in a large area uncertainty.

In order to compare Colonna's observations with other datasets, we select observing periods of the same two-month duration. Historical observations may lack a significant portion of small sunspots, so we choose the period with the highest percentage of small sunspot groups. From more than a year of regular observations by Harriot, we choose September – October 1612 (deep blue in Figure 6c). The distribution maxima for the other two-month periods in Harriot's observations are shifted towards larger sunspot groups.

On the contrary, modern catalogues contain a lot of small sunspots, we therefore select the periods, when the highest percentage of large groups of sunspots was recorded. Moreover, we suggest that Colonna's observations fall on the ascending phase of a solar cycle

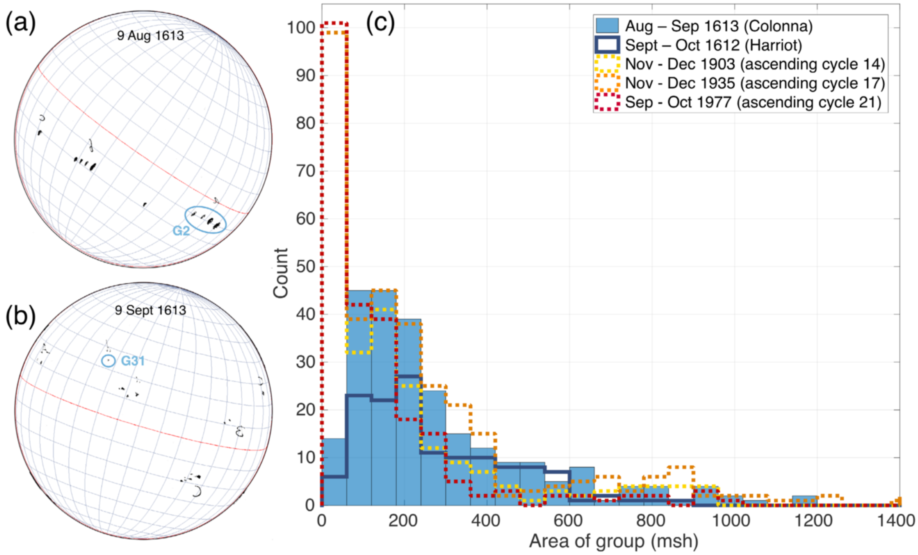

Figure 6 (**a**) and (**b**) are examples of Colonna's drawings. Blue ovals mark the largest and smallest sunspot groups G2 and G31 correspondingly, (**c**) shows the probability density functions of the sunspot group area from Colonna's drawings (filled blue), from a two-month period of Harriot's drawings (dark blue), and three two-month periods of the Greenwich catalogue (dotted lines).

(Vokhmyanin and Zolotova, 2018b, Figure 8 therein). With these conditions, we calculate the medians of the area distribution of two-month periods within the Royal Greenwich Observatory (RGO), United States Air Force (USAF), and National Oceanic and Atmospheric Administration (NOAA) databases after 1900. Figure 6c shows three periods of RGO observations in dotted yellow, orange, and red. Since numbers of groups are not significantly different in these datasets, we do not normalize the distributions by the total number of groups.

Figure 6c demonstrates that Colonna's and Harriot's drawings lack sunspot groups with an area less than 60 msh, while in the three Greenwich intervals these small groups make up 30 – 40%. Note that in other Greenwich intervals with lower area medians, the portion of such small groups can be up to 60%.

The accuracy of sunspot area measurement is very difficult to assess. On the same day drawings made by Cigoli, Galilei, or Cologna, sunspot areas may differ by more than a factor of two, as they have a schematic style. The high quality of the engraving in Istoria by Galilei (1613) suggested to us that the average uncertainty of sunspot area measurement should be roughly 30% (Vokhmyanin and Zolotova, 2018a). However, note that there are several copies of this book. Figure 7 shows sunspot group G31 on 20 August 1612 according to three copies provided by the Austrian National Library, Bibliotheque municipale de Lyon, and Biblioteca Nazionale Centrale di Roma. Apparently, the penumbra areas differ. Since we have to recalculate the coordinates of sunspots (see Section 2.5), here, we also define sunspot areas from another copy of the book than the one that was used previously. A comparison of the new results with sunspot areas by Vokhmyanin and Zolotova (2018a) shows that large sunspot groups can differ in size by 30%, while areas of small groups, by a factor of two. Various digitization options of old manuscripts provide copies of different brightness, contrast, and DPI image resolution, which affects sunspots area estimation.

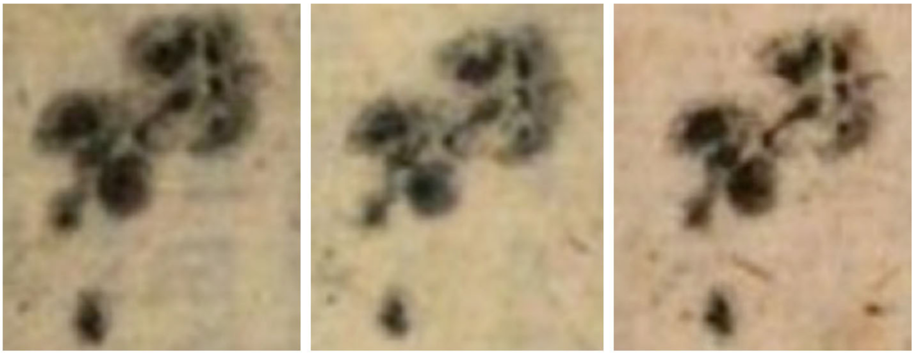

Figure 7 Group G31 on 20 August 1612 in three copies of Istoria e dimostrazioni intorno alle macchie solari by Galilei (1613).

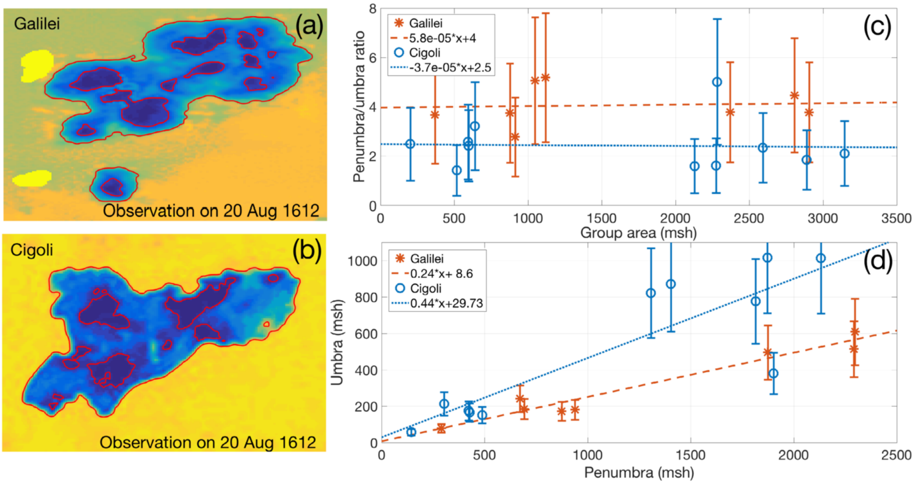

Figure 8 Example of sunspot group G31 drawn by Galilei (1613) (**a**) and Cigoli (1612c) (**b**). The red contours highlight the umbra – penumbra boundaries. (**c**) Penumbra-to-umbra area ratio as a function of total sunspot group area for Galilei's and Cigoli's sunspot groups (red and blue markers, respectively). (**d**) Umbral area as a function of penumbral area for the same datasets.

5. Sunspot Penumbra to Umbra Area Ratio

The penumbra to umbra area ratio is potentially related to the variations in strength and orientation of the sunspot magnetic fields, possible secular changes in convective velocities with consequences for solar irradiance. In August 1612, Cigoli and Galilei provided 19 detailed illustrations of 7 sunspot groups with visible penumbrae, so we are able estimate the penumbra-to-umbra ratio.

Figures 8 shows two images of sunspot group G31 on 20 August 1612 by Galilei (1613) and Cigoli (1612c). Figure 8a provides a detailed engraving, while Figure 8b shows a rough rendering with blurred ink, where the umbra–penumbra boundaries (red contours) are hard to highlight. This suggests better reliability of the drawings made by Galilei.

Figure 8c shows the penumbra-to-umbra ratio as a function of the whole group area for Galilei (red stars) and Cigoli (blue circles). A linear relationship for Galilei's engravings yields a penumbra-to-umbra ratio of 4 and for Cigoli's manuscript of 2.5 which is lower than 5 – 6 for the Royal Greenwich Observatory and Kodaikanal data (Hathaway, 2013; Jha, Mandal, and Banerjee, 2019).

Figure 8d represents the umbral versus penumbral area which give a linear relation with a slope of 0.44 ± 0.15 yielding an average ratio A_u/A_p of 0.47 ± 0.15 for Cigoli, where A_u and A_p are areas of umbra and penumbra. For Galilei's images, the slope is 0.24 ± 0.06 and an average $A_u/A_p = 0.26 \pm 0.05$. Note also that sunspots from Galilei's drawings fit the linear approximation better than Cigoli's ones.

Analyzing pixel areas of sunspots in the period of 1660 – 1709, Carrasco et al. (2018) obtained a slope for the linear relation of 0.25 and a mean $A_u/A_p = 0.27$. At the maximum of Cycle 21, Brandt, Schmidt, and Steinegger (1990) obtained an average $A_u/A_p = 0.24$ for small spots and 0.32 for large spots.

Despite the very poor statistics available in this study and possible uncertainties of historical sunspot drawings, we do not find significant deviation of penumbra-to-umbra ratio on Galilei's drawings from that of the modern epoch. The discrepancy between Galilei and Cigoli seems to be explained by the lower quality of Cigoli's drawings.

6. Sunspot Positions

To define sunspot positions, similarly to Vokhmyanin, Arlt, and Zolotova (2020), we use two methods. Method I constructs the heliographic grid based on the time noted by an observer. For simplicity, we operate with time in UT format.

To account for inaccuracies in the observation time indicated by the observer, we introduce a window of one hour. If the researcher noted that he was observing at sunrise or sunset, then we suggest that the drawing was made within one hour after sunrise or before sunset. If the observation time is N hours after sunset or sunrise, then we count N hours from the moment when the altitude of the Sun is zero and assign the window ± 0.5 hour around hour N. To determine the probable hour and minute (HH and MI) of the observation and the corresponding ephemeris, we minimize the latitude scatter of sunspots within the assigned time window (see (Vokhmyanin and Zolotova, 2018a), for details).

Method II rotates an image from -90° to 90° (in increments of 0.2°) and minimizes the day-to-day variability of sunspot latitudes. The best-fitting rotation angle of the image provides us with a set of ephemerides, the observation time, and the heliographic coordinates of the sunspots.

In Method II, in a few days the rotation angle of an image does not fall into a range when the Sun is above the horizon. On these days, position and parallactic angles are not defined and the heliographic latitude B_0 and longitude L_0 of the apparent disk center were assigned from B_0 and L_0 defined by Method I.

We also applied both methods for six partial eclipse drawings made by Colonna on 3 October 1614. To define the observation time in Method I, we compare the transit of the Moon over the solar disk from the report by Colonna with better suited images of the eclipse phases simulated with the CalSky Project[1] by Arnold Barmettler. The eclipse phase (coverage in percent) on Colonna's third image differs from that calculated by the CalSky by less than 1%. For the second and sixth images, the difference is less than 2%; for the first and fifth

[1] calsky.com (the project has been closed on October 2020).

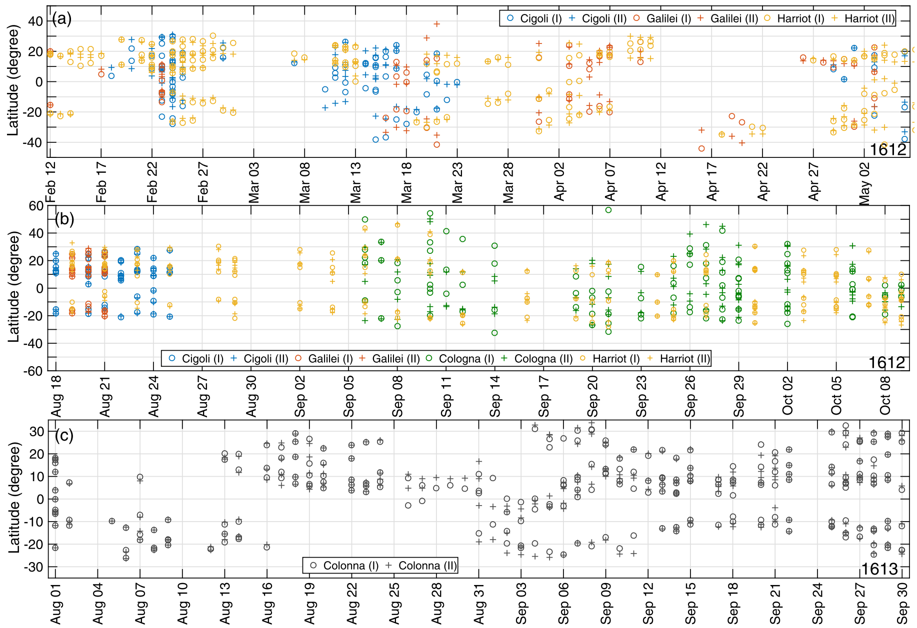

Figure 9 Time-latitude diagrams reconstructed by Methods I and II: (**a**) observations by Cigoli, Galilei and Harriot in February – May 1612; (**b**) observations by Cigoli, Galilei, Cologna, and Harriot in August – October 1612; (**c**) observations by Colonna in August – September 1613.

images, slightly more than 4%. On the fourth image, the area covered by the Moon is 11% larger than the coverage form the CalSky. Method II provides average sunspot latitudes, so the observation time is determined by the position angle of the heliographic grid. This results in not sequential time determined by Method II for sequential images.

Figure 9 shows the time-latitude diagram of sunspot groups in 1612 and 1613 reconstructed by means of Method I (circles) and Method II (crosses). Theoretically, sunspot positions have to be close in these two methods. This is true for better quality observations made by Cigoli and Galilei in August 1612 and by Colonna in 1613 and 1614. For the small schematic drawings made by Cigoli and Galilei in February – May 1612 and by Cologna in September – October 1612, the discrepancy may exceed 10°. Also note that better quality drawings provide smaller spread of sunspots over latitudes which rarely exceeds 30°, while for schematic drawings, sunspot groups may reach 40° and in a few cases they approach the range of 55° – 60°. For comparison sunspot latitudes from Harriot's observations are shown in yellow. In September 1612, the latitude spread of sunspot groups from Harriot's reports is narrower than that of Cologna's reports.

We recommend to exploit parameters defined in Method I, because latitudes and longitudes are defined according to the time of observation indicated by the observer. On the other hand, Method II provides average sunspot latitudes which may be useful for observations by Cigoli and Galilei in February – May 1612 and Cologna in September – October 1612, when the dispersion of spot positions increases.

The uncertainty of sunspot latitude and longitude was estimated similarly to Vokhmyanin, Arlt, and Zolotova (2020). The average uncertainty of sunspot position caused by drawing quality is about 5° in latitude and longitude for observations by Cigoli and Galilei in August

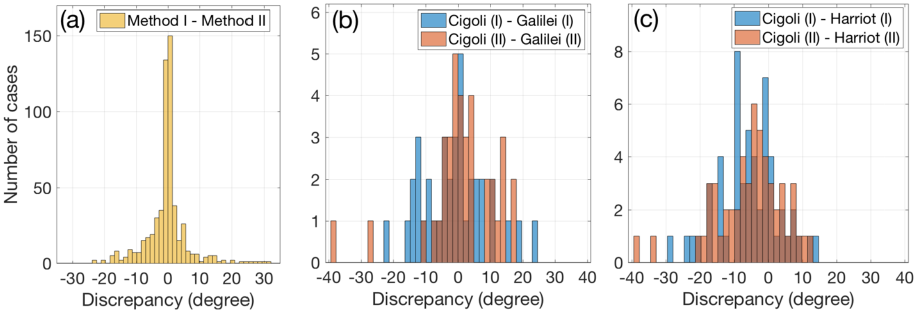

Figure 10 Histograms of latitude discrepancies of sunspot groups: (**a**) Method I versus Method II for all observers; (**b**) Cigoli versus Galilei for both methods; (**c**) Cigoli versus Harriot for both methods.

1612 and Colonna in 1613, about 10° in latitude and 15° in longitude for Cigoli and Galilei in February – May 1612, and Cologna in September – October 1612.

Figure 10 shows the distributions of latitude discrepancies of sunspot groups. Figure 10a compares sunspot group latitudes defined by means of Method I and Method II (for all the observers: Cigoli, Galilei, Cologna, Scheiner, and Colonna). There are few cases when discrepancy (in degrees of latitude) reaches 30°. These are the observations by Colonna in the first half of September 1612 suffering from great uncertainties. Figure 10b shows the latitude discrepancies of the same sunspot groups drawn for the same day by Cigoli and Galilei for both methods. Because the vast majority of these drawings are small and schematic, the discrepancy is significant for both methods. Critical discrepancy occurred on 20 and 21 March 1612, divergence peaks at almost 30° and 40°. Despite the large difference, we think that Cigoli and Galilei have drawn the same sunspot group. Figure 10c compares observations by Cigoli and Harriot. Here, there is large discrepancy on 11 and 12 March 1612 due to significant uncertainty in the drawings by Cigoli on those days.

7. Conclusion

We study sunspot drawings from observations by Cigoli, Galilei, Colonna, Cologna and Scheiner in 1612 – 1614. Reports by Cigoli in August 1612, Galilei from 12 February to 3 May 1612, and Scheiner on 1 August 1613 were not contained in the well-known Hoyt and Schatten (1998) dataset.

Cumulatively, we process 142 drawings. We sort 837 spots into 171 groups according to the sunspot group classification by McIntosh (1990). In comparison with the group numbers by Hoyt and Schatten (1998), we assign nearly the same number of groups except for several days when the difference exceeds 1 – 2 groups.

We also estimate the areas covered by these groups. We compare distributions of sunspot group area from the detailed two-month periods of drawings by Colonna and the Greenwich catalogue. Historical observations reveal a lack of small groups with areas below 60 msh, which make up almost half of all groups in the Greenwich catalogue. While this seems to suggest that sunspot group numbers were underestimated by a factor of two, we also need to consider the fact that sunspot areas are typically exaggerated in size in historical drawings. Several of the groups $>$ 60 msh would, in reality, have fallen in smaller categories, making the lack of small groups somewhat less severe. We therefore conclude that there is an upper limit of a factor of two between sunspot group numbers from the drawings and the actual ones.

We compare drawings from three digital copies of the book Istoria by Galilei (1613), which provide drawings for August 1612. Discrepancy in the fine structure and area of penumbra of the same sunspots were found. Areas of large sunspot groups can differ by 30% and those of small ones by a factor of two. The reason might be in the different quality of digitization.

Using observations by Cigoli and Galilei in August 1612, we estimate the penumbra-to-umbra ratio. We conclude that in the beginning of the seventeenth century this ratio is similar to that of the modern epoch. The difference of the ratios obtained from observations by Cigoli and Galilei apparently arises from the poorer quality of Cigoli's drawings.

Sunspot positions were defined by means of two methods. We recommend to exploit both latitudes and longitudes from Method I, which is based on the observation time noted by the observers. For small schematic drawings by Cigoli and Galilei in February – May 1612 and Cologna in September – October 1612, sunspot latitudes should be taken with extreme care, when they significantly differ from those in Method II, which in turn provides average sunspot latitudes. Longitudes also should be taken with extreme care due to great uncertainties on small drawings.

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