Sunspot positions, areas, and group tilt angles for 1611–1631 from observations by Christoph Scheiner

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ABSTRACT

Aims. Digital images of the observations printed in the books “Rosa Ursina sive solis” and “Prodromus pro sole mobili” by Christoph Scheiner as well as the drawings from Scheiner’s letters to Marcus Welser are analysed in order to obtain information on positions and sizes of sunspots that appeared before the Maunder minimum.

Methods. In most cases, the given orientation of the ecliptic is used to set up the heliographic coordinate system for the drawings. Positions and sizes are measured manually on the screen. Very early drawings have no indication of their orientation. A rotational matching using common spots of adjacent days is used in some cases, while in other cases, the assumption of images being aligned with a zenith–horizon coordinate system appeared to be the most probable.

Results. In total, 8167 sunspots were measured. A distribution of sunspot latitudes versus time (butterfly diagram) is obtained for Scheiner’s observations. The observations of 1611 are very inaccurate, the drawings of 1612 have at least an indication of their orientation, while the remaining part of the spot positions from 1618–1631 have good to very good accuracy. We also computed 697 tilt angles of apparently bipolar sunspot groups observed in the period 1618–1631. We find that the average tilt angle of nearly 4 degrees is not significantly different from 20th-century values.

Key words. Sun: activity – sunspots – history and philosophy of astronomy

1. Introduction

Solar activity is to a large extent characterized by the sunspot number and the latitudinal distribution of spots as functions of time. More information on the activity is of course accessible if enough details of the structures at the solar surface are available.

Extending the sunspot record back in time is not only a matter of obtaining reliable sunspot numbers and related indices for as many cycles as possible, but it is also a matter of reconstructing the solar butterfly diagram of the Sun. With the available sources of pre-photographic observations, we may be able to compile an almost complete butterfly diagram for the telescopic era since AD 1610.

There are not many publications with positional measurements of sunspots observed in the beginning of this era, namely in the first half of the 17th century. Studies of the solar rotation are available for Harriot by Heri (1978) for the period 1611–1613, for Scheiner by Eddy et al. (1977) for the period 1625–1626, for Hevelius by Eddy et al. (1976) and Abarbanell & Wölfl (1981) for 1642–1644, and for Scheiner as well as Hevelius by Yallop et al. (1982), but the sunspot positions were not published. Sunspot positions from Galileo’s observations in 1612 were derived and made available by Casas et al. (2006).

Christoph Scheiner lived from 1573–1650 (Braunmühl 1891) and was a member of the Jesuit society (Societas Iesu). The present paper is based on the copy of Scheiner (1630) stored in the library of the Leibniz Institute for Astrophysics Potsdam (AIP) and Scheiner (1651) at the library of ETH Zürich, available as a high-resolution digital version through the Swiss platform for digitized content, e-rara. The observations cover the years of 1611–1631, albeit most of the data comes from 1625 and 1626. Data from the period before the Maunder minimum are interesting as they may tell us details about how the Sun went into a low-activity phase lasting for about five decades, in particular since Vaquero & Trigo (2015) suggested that the declining phase of the solar cycle started already near 1618.

If information on individual sunspots and pores within sunspot groups is preserved, quantities such as the polarity separation and the tilt angle of bipolar groups may be inferred. It will be of particular interest whether these quantities behaved differently in the period before the Maunder minimum as compared to the cycles after it or present cycles. This is not the first attempt to use sunspot positions derived from Scheiner’s observations. An estimate of the differential rotation was, for example, derived from Scheiner’s book by Eddy et al. (1977) who concluded that the rotation profile was not significantly different from the one obtained for the 20th century. The authors did not publish the obtained spot positions though. Scheiner actually noticed different rotation periods for different spots spanning from 25 d to 28 d (Scheiner, p. 559). He does not, however, say that those periods were attached to specific latitudes of spots.

Scheiner (1573–1650) belongs — together with Johannes Fabricius, Galileo Galilei, Thomas Harriot, Joachim Jungius, Si-

¹ Historical archive of sunspot observations at http://haso.unex.es/.
² Some biographies also give 1575 as the year of birth, e.g. Brockhaus (1992).

3 http://www.e-rara.ch/zut/wihibe/content/titleinfo/765922
Table 1. Numbers of days available for given years as reported by Scheiner (1630), Scheiner (1651), and Reeves & Van Helden (2010).

| Year | Days | Year | Days | Year | Days |
|------|------|------|------|------|------|
| 1611 | 41a | 1622 | 17 | 1626 | 169b |
| 1612 | 31 | 1623 | 9 | 1627 | 55 |
| 1618 | 7 | 1624 | 40 | 1629 | 49b |
| 1621 | 27 | 1625 | 343b | 1631 | 12 |

Total 800

(a) Five days were not analysed because of unreliable positional results. (b) One day showed only faculae. (c) Two days were omitted because groups were not drawn completely.

Scheiner gave the geographical latitude on top of a page of 1611 observations as 48.67. After Scheiner left Ingolstadt in 1616, the observers could have been Scheiner’s pupils, among them Johann Baptist Cysat, Chrysostomus Gall, and Georg Schönberger (Braunmühl 1891). Cysat taught in Luzern, Switzerland, from 1624–1627 though (Zinner 1957). Since the observations from Ingolstadt that were not made by Scheiner cover the period from 1623 Mar 26 to 1625 Sep 15, they were most likely not made by Cysat. Scheiner gives Georg Schönberger as the correspondent of the Ingolstadt observations, but Schönberger taught in Freiburg later, and his books of 1622 and 1626 were published in Freiburg. It remains unclear to us who was the observer in Ingolstadt.

For Douai, we assume approximately 3:1 E, 50:4 N. Since the University of Douai was a conglomeration of colleges and the Jesuits erected their own school in the 1620s, it is less obvious from which exact place they observed, but not really relevant for the scope of this paper. The observer in Douai was Karel Malapert (Charles Malapert, Carolus Malapertius) who published his own observations in two books (Malapertius 1620, 1633). While it was published in Douai, Braunmühl (1891) mentions his observations to be made at Danzig, Poland. This may be a translation error of Duacum, although Malapert did teach in Poland, but at the Jesuit College of Kalisz from 1613–1617 (Birkenmajer 1967). Scheiner regularly compares the observations of the three sites in his figures. We include all spots visible in these drawings in the data set, but if a spot was observed by Scheiner as well as a colleague on the same day, we give only Scheiner’s spot position.

The location of the Jesuit church in Vienna is about 16:4 E, 48:2 N. Scheiner names Johann Cysat as the observer whose life between 1627 and 1631 is not known in detail. At least, we find an indication that Cysat was in Vienna “occasionally” in that period from Zinner (1957). Scheiner compared the Vienna data with the Rome data, so there is eventually only a total of six spot measurements that complemented the Rome data (recorded on 1629 Aug 12, 13, and 20).

Typical figures contain a circle for the solar limb, a horizontal line mostly denoting the ecliptic and a selected number of sunspot groups which are followed on several days. The dates (in many cases together with a precise time and the elevation of the Sun) are given in a small table within the circle.

The next figure gives another set of selected groups for a sequence of days. Note that these sequences of some drawings very often overlap. The figures are made in a way as to show all appearances of a given group on as many days as necessary.

Times are given in 12-hour format, annotated with “m” = matutinus = morning and “u” = occasus = vespers = evening.

For Douai, the Jesuit church next to it were located at 7:85 E, 48:00 N. One probable observer was a pupil of Scheiner, Georg Schönberger (or Schomberger) (Braunmühl 1891) who later observed with Johann Nikolaus Smogulecz (or Jan Mikolaj Smogulecki). The observations are also available in a separate publication by Smogulecz & Schönberger (1626).

Five observing locations contributed to this compilation of results on sunspots. Scheiner was located in Rome, Italy, in the years 1624–1633 and we assume a geographical position of 12:45 eastern longitude and 41:90 northern latitude for his place. The other locations were Ingolstadt in Germany, Douai (Duacum in Latin) in France, Freiburg im Breisgau, Germany, and Vienna, Austria.

The University of Freiburg and the Jesuit church next to it were located at 7:85 E, 48:00 N. One probable observer was a pupil of Scheiner, Georg Schönberger (or Schomberger). The observations are also available in a separate publication by Smogulecz & Schönberger (1626).

For Ingolstadt, we assumed the position of the original university building “Hohe Schule” at 11:42 E and 48:76 N.
Table 2. Assumed times specially for Plate I.

| Printed time | Assumed time | Printed elevation |
|--------------|--------------|------------------|
| Dec 17, a.m. 16:48 | 09:13 | 14:5 |
| Dec 19, a.m. 17:30 | 09:55 | 17:7 |
| Dec 16, a.m. 18:48 | 11:13 | 24:5 |
| Dec 16, p.m. 21:00 | 13:25 | 21:7 |
| Dec 14, p.m. 21:45 | 14:10 | 22:5 |

Fig. 1. Example of an early drawing indicating the directions and an inner circle annotated as the observed circle. All spots appear twice: once in the inner circle and once in the full circle.

The coordinate system of the drawings of 1618–1631

Scheiner describes his observing method as a projection behind the telescope(s). This would mean that the appearance of the Sun was mirrored. There are several indications, however, that disks corresponds to an angle of 0°5 in heliographic coordinates in the disk centre.

The images I to V, IX, X, XVI, XVII contain a smaller circle which is annotated as the “circellus observatorius” = “observed circle”, while the large circle covering almost the entire page is entitled the “circulus ampliatus ex observatorio” = “circle expanded by observatory.” Fig. 1 shows the example of Plate III. Spots are plotted twice in such drawings, once at the scale of the inner circle and once at the scale of the outer circle. We use the large version of the drawing for position and area measurements. As shown in Sect. 5 the accuracy of the positions is remarkable, even though the large images may be the result of post-observational magnifications.

Another peculiarity is shown in Fig. 2 covering the period of 1625 March 20 to April 6. The southern hemisphere of the Sun was so crowded with spots that some sunspot groups were plotted into a rotated coordinate system to avoid overlap with groups of other days. A few spots were actually plotted twice: once within the crowd of spots and once at another location. These spots indicate that it is indeed a rotation of the disk by multiples of roughly 15° that led to the secondary positions, and not a linear shift upward or downward.

Image XXII shows extended faculae at the eastern limb and sunspots for the period 1625 May 2–14. The faculae of May 3 are drawn in rather dark colour, possibly indicating very bright faculae, keeping in mind that faculae needed to be plotted with an inverse grey scale. There is a large c-shaped black area surrounding a blank-paper region which appears “bright” in contrast to the “dark” surrounding faculae. Rek (2010) seem to argue in a footnote that this region may have been a white-light flare. The textual description of May 2–4, 1625, by Scheiner (1630, p. 208) says the following:

On the second day of March, two spots appeared which were preceded by a facula. On the third day, they showed up with a much more luminous retinue of faculae and a more pompous armament of shadows blending into spots. Just as the faculae extended on the forth day and the shadows dissipated, many more spots appeared.

(While Scheiner uses the word “umbra”, we translated it into shadow, since the conception of an umbra may have been different from today’s definition.) Since there is no mention of a phenomenon being variable during the course of the day, there is no strong evidence for a white-light flare despite the presence of a peculiar sunspot group.

There is an unnumbered image plate between images XXVI and XXVII which contains only faculae and covers days that were already shown in images XXIII and XXIV and has therefore not been used in our measurements.

3. The coordinate system of the drawings of 1618–1631

Scheiner describes his observing method as a projection behind the telescope(s). This would mean that the appearance of the Sun was mirrored. There are several indications, however, that
Fig. 3. Cursor shapes used to estimate the sizes of the spot umbrae and pores.

he made the actual images in a non-mirrored way, and the orientation of the drawings is roughly upright.

More precisely, the drawings always show a nearly horizontal line representing the ecliptic. Since the plane of the ecliptic is not easily accessible when observing under the sky, it has apparently been computed by Scheiner from the direction to the local zenith. The direction to the local zenith is marked on a few drawings by little dots at the solar limb. We need to find the angle between the direction of the solar rotation axis and the pole of the ecliptic. As already done in Arlt et al. (2013), we use the output of the angle of the solar rotation axis with the direction to the true-of-date celestial north as provided by the JPL Horizons ephemeris webpage. The ecliptic pole is assumed to be at $\alpha_E = 18^h$, $\delta_E = 66:56$ which is true-of-date by definition (neglecting orbital precession and nutation). We then use a spherical transformation to obtain the missing angle between the celestial north pole and the ecliptic pole for a given date and location. When transforming the celestial coordinates of the ecliptic pole into a system with its pole in the center of the Sun, the new longitudinal angle (new “right ascension”) is the desired angle. Let $\alpha_R$, $\delta_R$ be the celestial coordinates of the Sun and $\alpha_E$ and $\delta_E$ the celestial coordinates of the ecliptic pole, then

$$\sin \delta' = \cos \delta_E \cos \alpha_E \cos \delta_R + \sin \delta_E \sin \delta_R$$

$$\cos \alpha' = (\cos \delta_E \cos \alpha_E \sin \delta_R - \sin \delta_E \cos \delta_R) / \cos \delta'$$

$$y = \sin \alpha_E \cos \delta_E$$

$$\alpha' = \begin{cases} \pi - \alpha' & \text{if } y \geq 0 \\ \alpha' - \pi & \text{otherwise} \end{cases}$$

Looking at the Sun, $\alpha'$ now is also an angle running counterclockwise.

We can now cross-check the accuracy of Scheiner’s determinations of the ecliptic by computing the angle between the zenith and the pole of the ecliptic. This angle can be measured on a few drawings where the zenith is indicated at the solar limb. We are again using the spherical transformation and replace the celestial coordinates of the ecliptic pole by the celestial coordinates of the local zenith at the time of observation. This position is provided by the zepos routine of the IDL Astronomy User’s Library of November 2006 (Landsman 1993). Table 3 gives a comparison of angles between the zenith and the north pole of the ecliptic, one value being measured on the drawing directly, and the other values being computed from the solar ephemeris. The differences are typically a fraction of a degree, but reach 1.9' on 1625 Nov 14.

Since neither the printing of the drawings nor the digitization process ensure that the ecliptic is an exactly horizontal line in the image, we also need to add the angle of the printed line which is obtained by clicking on two points on the line in the image and computing the angle (typically below 1').

4 http://ssd.jpl.nasa.gov/ephemeris.cgi

| Date and time | Drawing | Ephemeris | Diff. |
|---------------|---------|-----------|-------|
| 1625 May 19, 08'00'' | −38.5 | −38.9 | 0:4 |
| 1625 May 20, 16'10'' | 64.2 | 65.0 | 0:8 |
| 1625 May 28, 08'35'' | −41.2 | −42.1 | 0:9 |
| 1625 May 31, 08'10'' | −43.2 | −44.4 | 1:2 |
| 1625 Nov 03, 08'22'' | −54.7 | −55.1 | 0:4 |
| 1625 Nov 12, 09'00'' | −47.6 | −47.0 | 0:6 |
| 1625 Nov 14, 14'30'' | 14.3 | 16.2 | 1:9 |

The actual process of measuring the sunspots consists of the following steps: (i) cutting out the solar disk from the full image by clicking on the left-most, right-most, lowest and uppermost limb of the Sun; this also allows for a certain degree of ellipticity of the solar disk to be measured correctly), (ii) determining the exact angle of the ecliptic line by two clicks, left and right, (iii) setting up the spherical coordinate system as supported by IDL, (iv) clicking on the relevant spots with thirteen different cursor sizes (Fig. 3), for which the best fit in position and size to the umbrae and pores are sought visually.

In the cases where a rotated coordinate system was used to draw spots of crowded regions (see Sect. 2), we can determine the positions if at least one spot was plotted twice, once in the standard eclipsical system, and once in the rotated one. The angle with the disk center gives us the rotation of the coordinate system for the displaced spots. For 15 spots, such a duplicate spot was not available, and we omit the positions of these spots, but do keep corresponding records in the data file.

Physical areas are then derived from the pixel area of the cursor shapes $A_{cur}$ used for the individual spots as compared with the total pixel area of the solar disk, $A_{disk}$. The heliocentric distance of the spot from the disk center $\delta$ yields the correction for the geometrical foreshortening, and we express the final area in millionths of the solar hemisphere (MSH), i.e.

$$A = \frac{1}{2 \cos \delta} A_{disk} \times 10^6.$$

4. The observations of 1611–1612

The observations of 1611 October 21 to 1612 April 7 are Scheiner’s first drawings of sunspot observations and are more difficult to measure. The ones of 1611 October 21–December 14 are compiled on a single page in the Rosa Ursina. The page is essentially the same as the one Scheiner sent to the scientific friend Marcus Welser using the pseudonym Apelles latens post tabulam (Apelles hiding behind the scaffold) written on December 26, 1611, and published by Welser in January 1612, together with two earlier letters (Braunmüll 1891). Additional drawings until 1612 April 7 are available from the letters to Welser of 1612 Jan 16, Apr 14, and Jul 25 (Apelles 1612). We did not have access to the originals, but used the reproductions of the drawings in Reeves & Van Helden (2010) instead.

Some observations show an approximate orientation: the ones of the morning and afternoon of October 22 show the horizon, the ones from 1611 December 10 to 1612 January 11 show the ecliptic; the other drawings have no information about the orientation of the solar disk. The ecliptic was drawn in connection with the expected Venus transit on December 11 which was actually an upper conjunction of Venus and the Sun. The
images of December 10–13 also contain the expected path of Venus. The path is confusing as to whether the images may be upside-down or mirrored, since it lies north of the ecliptic while the true path was south of it. Since the spots are clearly moving from left to right, there was still the possibility that the images are mirrored vertically (a view on a projection screen behind a Galilean telescope). The description reveals, however, that the path was indeed meant to be north of the ecliptic; the accuracy of the ephemeris of Venus was just not good enough (especially of the ecliptic latitude) to place it right at the time (Reeves & Van Helden 2010). For all drawings showing the ecliptic, we computed the angle between the solar axis and the direction to the pole of the ecliptic and set up the coordinate system in the same way as for the observations of 1618–1631. There were 29 observations for which the ecliptic was used in 1611–1612.

There are three options for the analysis of the remainder of the drawings: (i) using two or more drawings to fix their orientation with the spot displacements due to the solar rotation (“rotational matching”); (ii) assuming that all the drawings are plotted in a horizontal system, i.e. the vertical on the book page points to the zenith; or (iii) choosing an arbitrary orientation such that the distribution of spots agrees with our today’s expectation of sunspot latitudes.

The method (i) for the rotational matching is the same as described in Arlt et al. (2013). Two or more spots which can be identified in two or more consecutive drawings are used with their measured Cartesian coordinates for a Bayesian inference of their heliographic central-meridian distances and latitudes and the orientation angles of the drawings. A differential rotation as derived by Balthasar et al. (1986) is used for the solar rotation with a fixed dependence $\Omega = (14.551 - 2.87 \sin^2 \lambda) \degree / \text{day}$, where $\lambda$ is the heliographic latitude. The relation was computed from the sunspot group series of 1874–1976 compiled by the Royal Greenwich Observatory.

A Markov chain Monte Carlo search in the parameter space provides us with full posterior probability density distributions for each of the free parameters. In contrast to a best-fit search, they allow us to judge the quality of the rotational matching by the width of the probability density distribution, its skewness, or possible non-uniqueness of probable solutions. The orientations of a total of 23 observations was fixed with the rotational matching.

Since imposing the differential rotation of the Sun to the solution of the orientation does not allow a subsequent determination of the differential rotation in a possible future study, we try to use method (ii) for as many cases as possible. The celestial position of the Sun is provided by the Horizons ephemeris in a J2000.0 system. Since the angle between the solar axis and the direction to the celestial north pole is given in a true-of-date system, we transform the Sun’s coordinates to a system of 1612 using the precess.pro routine from the IDL Astronomy User’s Library. The position of the zenith is computed by the zenpos.pro routine in a true-of-date system as well.

The observations of March and April 1612 are the only ones with a reliable alignment of the zenith direction with the vertical of the images. This was shown by a comparison of measurements with the zenith-assumption and measurements using the rotational matching. Table 4 shows the average deviations of the spot positions between the two methods. While the
zenith-assumption delivered fairly consistent results of spot motion across the solar disk, the rotational matching yielded rather broad probability density distributions for the position angles and we kept its results only for 1612 Mar 17, 19, and Apr 1. In total, 27 observations were treated with this assumption of a horizontal coordinate system.

Method (iii) was applied only when the first two methods led to improbable spot distributions. We essentially applied a position angle which minimizes the absolute latitudes of the spots. Only four observations were treated with arbitrarily chosen orientations (1611 Nov 7, 13, 14, and Dec 8).

The observations of 1611 Nov 6, 9, 10, 12, and Dec 24 were omitted entirely because no reasonable match with adjacent observations was possible and the spot distribution appears to be highly improbable.

The resulting heliographic latitudes of the spots measured in the 83 observations used from 67 days in 1611–1612 are between −43° and +42°.

The sizes of the spots were strongly enlarged, and groups of smaller spots were combined into one large spot, as described by Scheiner (see Reeves & Van Helden [2010] for a translation). A size estimate can only be arbitrary at this point, and we chose – in order to be able to use the 13 cursor shapes – to select the size class which matches roughly half the diameter of the plotted spot. This choice still gives too large areas when converting the disk area fraction of the cursor shape directly to MSH. The areas in the data file are marked with “!” to indicate that these need to be used with care (see Table 3).

5. Accuracy of the positions and areas

In the first period of 1611–1612 when Scheiner drew the sunspots with poor quality, there are actually two occasions when Harriot observed in the morning and Scheiner in the afternoon. There is a fair agreement on the distribution of spots, except that Scheiner noticed a spot near the eastern solar limb on Dec 13, 1611, which Harriot could not yet detect. Scheiner’s drawings are more detailed, whereas the spots are more exaggerated in size than in Harriot’s drawings. While the drawings look qualitatively similar, we find positional differences of up to 20′ on those two days (assuming Harriot’s vertical lines are the direction to the local zenith). This underlines the limited use of the spots in 1611.

Accidentally, Scheiner plotted the positions of one spot in two different image plates (XLVI, spot labelled as “k”, and XLVII, spot labelled as “a”) from 1625 Nov 6–11. The differences give us an information about how well the positions could be reproduced in the plates and are listed in Table 5. The average distance between the the positions of the spot in plate XLVI and the corresponding positions in plate XLVII is 0.8′. The average

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**Table 4.** Comparison of different coordinate systems adopted for a selected set of observations in 1612.

| Date       | Number of spots | Avg. distance | 1612 Mar 16 | 1612 Mar 17 | 1612 Mar 18 | 1612 Mar 19 | 1612 Apr 02 |
|------------|-----------------|---------------|-------------|-------------|-------------|-------------|-------------|
| 1612 Mar 16| 5               | 0:38          |             |             |             |             |             |
| 1612 Mar 17| 5               | 5:80          |             |             |             |             |             |
| 1612 Mar 18| 4               | 0:30          |             |             |             |             |             |
| 1612 Mar 19| 5               | 3:63          |             |             |             |             |             |
| 1612 Apr 02| 11              | 7:34          |             |             |             |             |             |

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**Table 5.** Comparison of the positions of the same spot in two different image plates.

| Date       | Plate XLVI | Plate XLVII | 1625        | 1625        | 1625        | 1625        | 1625        |
|------------|------------|-------------|-------------|-------------|-------------|-------------|-------------|
| CMD        | λ          | S           | CMD         | λ           | S           | CMD         | λ           |
| Nov 06     | −73:9      | −6:0        | −74:4       | −5:8        | 3           | 0:54        |
| Nov 07     | −60:6      | −5:5        | −61:6       | −6:2        | 5           | 1:22        |
| Nov 08     | −47:1      | −5:9        | −48:3       | −5:9        | 4           | 1:19        |
| Nov 09     | −33:9      | −5:0        | −34:8       | −5:0        | 5           | 0:89        |
| Nov 10     | −20:4      | −4:7        | −20:9       | −4:8        | 4           | 0:51        |
| Nov 11     | −7:4       | −4:8        | −7:8        | −5:0        | 4           | 0:45        |

**Notes.** CMD is the central-meridian distance, λ is the heliographic latitude, S is the cursor size class according to Fig. 3 and δ contains the heliocentric distance between the two measurements.

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**Fig. 5.** Area distribution of 5555 spots drawn by Christoph Scheiner in 1618–1631, all within a central-meridian distance of CMD ≤ 50°.

“error” of the cursor sizes chosen for the various instances of the spot is 0.5 classes. We kept the positions of plate XLVII, since the spot continued to exist for more days after Nov 11.

The areas were taken from pixel counts in the individual cursor shapes and converted into fractions of the solar disk. They are then corrected for foreshortening and given in millionths of the solar hemisphere (MSH). We follow the procedure by Bogdan et al. [1988] to compute the area distribution of the individual umbrae. The result is shown in Fig. 5 and shows a fairly good agreement with their distribution. We interpret the differences from the curve obtained by Bogdan et al. [1988] as follows. Firstly, large spots in particular may be exaggerated slightly in size, an effect seen in many other historic sunspot drawings. At the same time several of the smallest spots were missed due to the observational limits (chromatic telescope). These two effects explain the slight overabundance of spots at large areas and the slight under-abundance of spots between 1.2 and 10 MSH. A correction factor of 0.8 may be suitable for the areas, leading to a perfect match with the curve by Bogdan et al. [1988] at large areas. However, since this is speculation, we have not used any correction factor for the areas in the resulting data file. It would bring the smallest spots to even smaller areas which were very likely not observable.

The smallest spot measurement delivered an area of only 1.2 MSH. A circular spot of this area has an angular extent of 3′ in the center of the solar disk. It may be doubted that the resolving capabilities of Scheiner’s telescopes were as good as that. While King [1955] reported about Galilei’s largest tele-
Table 6. Data format for the positions and areas of individual sunspots observed by Christoph Scheiner and his collaborators.

| Field  | Column | Format | Explanation |
|--------|--------|--------|-------------|
| YYYY  | 1–4    | I4     | Year        |
| MM     | 6–7    | I2     | Month       |
| DD     | 9–10   | I2     | Day referring to the civil calendar running from midnight to midnight, Gregorian calendar |
| HH     | 12–13  | I2     | Hour, times are mean local time at the observer’s location |
| MI     | 15–16  | I2     | Minute, typically accurate to 15 minutes |
| T      | 18     | I1     | Indicates how accurate the time is. $T = 0$ means the time has been inferred by the measurer (in most cases to be 12 hours local time); $T = 1$ means the time is as given by the observer; $T = 2$ means the time was not printed, but inferred from the elevation of the Sun and the morning/afternoon discrimination given by the observer. |
| L0     | 20–24  | F5.1   | Heliographic longitude of apparent disk centre seen from Rome |
| B0     | 26–30  | F5.1   | Heliographic latitude of apparent disk centre seen from Rome |
| CMD    | 32–36  | F5.1   | Central meridian distance, difference in longitude from disk centre; contains NaN if position of spot could not be measured. |
| LLL.L  | 38–42  | F5.1   | Heliographic longitude in the Carrington rotation frame; contains NaN if position of spot could not be measured. |
| BBB.B  | 44–48  | F5.1   | Heliographic latitude, southern latitudes are negative; contains NaN if position of spot could not be measured. |
| M      | 50     | C1     | Method of determining the orientation. ‘E’: ecliptic present in drawing; ‘H’: book aligned with azimuth–elevation; ‘A’: arbitrarily chosen orientation according to the distribution of groups; ‘Q’: rotational matching with other drawings (spots used for the matching have ModelLong ≠ ‘ ′− ′’ , ModelLat ≠ ‘ ′− ′’ , and Sigma ≠ ‘ ′− ′’). |
| Q      | 52     | I1     | Subjective quality, all directly connected to the ecliptic drawn by Scheiner get $Q = 1$. The rotated sunspot groups (cf. Fig. [2]) are probably slightly less accurate and get $Q = 2$. Positions derived from rotational matching may also obtain $Q = 2$ or 3, if the probability distributions fixing the position angle of the drawing were not very sharp, or broad and asymmetric, respectively. Methods ‘H’ and ‘A’ always obtain $Q = 3$, because of the assumptions made. Spots for which no position could be derived, but have sizes, get $Q = 4$. |
| SS     | 54–55  | I2     | Size estimate in 13 classes running from 1 to 13. The classes are different from the ones used in Arlt et al. (2013) and Senthamizh Pavai et al. (2015) by the fact that we introduced a smaller size at the low end and named it “1”. The classes are arbitrary anyway. |
| GROUP  | 57–64  | C8     | Arbitrary group name; the order of numbers has no meaning |
| MEASURER | 66–75  | C10    | Last name of person who obtained position |
| MOD_L  | 77–81  | F5.1   | Model longitude from rotational matching (only spots used for matching have this) |
| MOD_B  | 83–87  | F5.1   | Model latitude from rotational matching (only spots used for matching have this) |
| SIGMA  | 89–93  | F5.3   | Total residual of model positions compared with measurements of reference spots in rotational matching (only spots used for the matching have this). Holds for entire day. |
| DELTA  | 95–98  | F4.1   | Heliocentric angle between the spot and the apparent disk centre in degrees (disk-centre distance); it is NaN if the spot position could not be determined. |
| UMB    | 100–103| I4     | Umbral area in millionths of the solar hemisphere (MSH), corrected for foreshortening; it is NaN if spot position could not be derived. |
| A      | 105    | C1     | Flag (!) marking areas which are highly uncertain since the spots appear to be drawn at too large sizes. |

Notes. The Format column uses the following designations: I denotes integer fields with the number behind being the number of characters; similarly, C is a character text field with the corresponding length, and, e.g. F5.1 is a floating point field of five characters length with one decimal.

The Roman palm measured 74 mm (Brockhaus [1991]) leading to impressive suggested lens diameters of 7–15 cm. We did not find an exact aperture of the actual telescopes used, but conclude that the resolution in the 1620s was significantly better than the one of Galilei’s early telescopes. Since the drawings – especially the ones of 1624–1631 do contain very small spots, we decided to preserve the size information and leave possible recalibrations of the areas to future applications of the sunspot data.

6. Data format and butterfly diagram

We use the same table format as the one employed for the spot positions and sizes derived from the observations by Schwabe (Arlt et al. 2013). The format is detailed in Table 6. While the...
measurements deliver central-meridian distances on the Sun, heliographic longitudes are obtained using the solar disk center provided by the JPL Horizons ephemeris generator seen from the location in Rome (differences to the various other geographical positions in Europe are extremely tiny).

Since Scheiner drew the sunspots – at first glance – to scale in the years of 1618–1631, we computed physical areas in micro-hemispheres (MSH), corrected for the projection effect towards the solar limb. The observations of 1611–1612 do not show realistic areas. We chose cursor sizes of roughly half the diameter of the spot in the image in order to compensate for the exaggerated spots to some degree subjectively. Nevertheless, these areas should be used with extreme care.

We define sunspot groups based on Scheiner’s drawings and assigned group numbers. The order of the group numbers has no meaning; for technical reasons they are not ascending monotonically. The groupings have been more difficult for 1611, since the groups may have been drawn too large in size. The remaining group definitions were fairly straight-forward, since the drawings have a look similar to modern white-light images (except for faculae). The differences to the group definitions made already by Scheiner are not too large. A total of 16 groups were split into two groups, while 10 groups are the result of combining groups together. Those numbers increased slightly as compared to Senthamizh Pavai et al. (2016) after another careful inspection.

A total of about 8152 spot positions were derived for 1611–1631. The exact number may still evolve upon further investigations, since the distinction between spots and faculae is not unambiguous (also drawn by dark ink). The resulting butterfly diagram is shown in Fig. [6]. A considerable part of a cycle is covered only in the years 1624–1631 where the migration of spot emergences appears to be equatorward. Following Zolotova & Ponyavin (2015), we name this cycle −12. The general migration of sunspot emergence latitude towards the equator is clearly seen. The onset of cycle −12 took place first in the southern hemisphere, while no spot was found in the northern hemisphere. During the second half of cycle −12, the average latitudes of the northern wing are farther away from the equator than in the southern one. The positions are compatible with a time of minimum of fall 1620 as suggested by Spöret (1889), while Hoyt & Schatten (1998) obtained very low group sunspot numbers for both 1617 and 1618 which are mainly due to an overabundance of zero-detections inferred from generic statements of Simon Marius and Andrea Argoli (incorrectly reported as seen by Riccioli in Hoyt & Schatten 1998).

Cycle −13 is more poorly covered. The 1612 observations show the presence of the two butterfly wings nicely, while the 1611 positions are too inaccurate to exhibit the hemispheric division. A slight dominance of the northern hemisphere may be detectable in both 1611 and 1612.

The spot positions and areas are publicly available at the astronomical data center CDS. Since none of the observational sources before the Maunder minimum covers a sufficient period in time to deliver useful information about a full cycle – the latitudinal distribution of spots in the first place –, a unified database of the various data sets will be very advantageous.

7. Sunspot group tilt angles

The drawings by Scheiner and his colleagues were then manually inspected for potential bipolar sunspot groups. We restricted the analysis to the very realistic drawings of 1618–1631. The relevant groups were flagged in the positional database and tilt angles were computed according to the method described by Senthamizh Pavai et al. (2015). The data format of the tilt angle data file is exactly the same as in that paper. The total number of tilt angles obtained is 697.
The distribution of the 622 tilt angles within central meridian distances of $\kappa \, \text{CMD} < 60^\circ$ is shown in Fig. 7. The width of the distribution was derived from a Gaussian fit to the histogram. The average tilt angle of $3^\circ.84 \pm 0^\circ.83$ is slightly lower than values of the 20th century. Values by Wang et al. (2015) for cycles 16–23 range from $3^\circ.84 \pm 0^\circ.83$ and is not significantly different from 20th-century values, albeit on the low side. There were $1341$ group instances not selected as being bipolar in 1618–1631.

The data will be made available at the astronomical data center CDS.

8. Summary

The solar disk drawings with sunspots made by Christoph Scheiner and colleagues in 1611–1631 were digitized and measured. The three sources for the drawings are Scheiner (1630), Scheiner (1651), and Reeves & Van Helder (2010). A total of $8167$ spot areas were obtained of which $8152$ are accompanied by heliographic positions. All measurements are provided in a database file. The accuracy of both positions and areas are poor for 1611. The positional accuracy improved in the 1612 observations but the spot areas are still highly exaggerated. High quality drawings of 1618–1631 delivered a positional accuracy of about $1^\circ$–$2^\circ$ in heliographic coordinates in the solar disk centre, thanks to the large scale of the drawings. The database does not contain spotless days. We refer to the detailed tables by Hoyt & Schatten (1998) for estimates of the spotless days which go beyond what Scheiner (1630) reported.

Sunspot numbers may also be incomplete as indicated by two groups in Scheiner (1651). Plate I, belonging to p. 7) seen on 1625 May 23–29 and 1626 Jun 30–Jul 12, respectively, which were not shown in the images of Scheiner (1630). Since this is the only image with overlap between the two books, it is not possible to estimate the general completeness.

The positional data support the migration of sunspot emergences towards the equator through cycles $-13$ and $-12$. Apart from the very inaccurate 1611 data, there were two groups in 1629 which straddle the equator. On some days, just a few small spots are on the other hemisphere, but on two days (one day for each group), the average polarities sit in opposite hemispheres. Near-equator groups may be interesting for the progress of the activity cycle as recently suggested by Cameron et al. (2013). For the accurate period of 1618–1631, we find $18$ bipolar groups having a group center latitudes of $|\lambda| \leq 5^\circ$.

We computed 697 sunspot group tilt angles from a manually selected set of supposedly bipolar group instances (i.e. the same group may be used on more than one day) of 1618–1631 and provide them in a separate data file. The average tilt angle for these observations is $3^\circ.84 \pm 0^\circ.83$ and is not significantly different from 20th-century values, albeit on the low side. There were $1341$ group instances not selected as being bipolar in 1618–1631. The data will be made available at the astronomical data center CDS.

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5 Copies of the positional data file and the tilt angle data file will be available at http://www.aip.de/Members/rarlt/sunspots

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