The Greenwich Photo-heliographic Results 1874 – 1976

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Structure of the Talk: Background Information

- **The importance of sunspot areas in Solar–Terrestrial Physics.**
- **The programme of solar observations supported by the Royal Greenwich Observatory (RGO).**
- **The printed RGO publications and the digital datasets.**
- **Summary of the observations, applications, datasets, definitions and errors.**
- **Typographical, systematic and isolated errors.**
- **Procedures for checking and correcting the sunspot digital datasets.**
- **Initial corrections to the RGO printed publications.**
- **Archives of the original RGO solar observations.**

A Tribute to Previous Researchers

Any discussion of sunspot areas inevitably results in lists of errors in the digital and printed datasets.

Therefore, it is important to emphasise at the outset that this talk should not be misconstrued as a criticism of any previous work.

On the contrary, the goal is to build on the sterling endeavours of many individuals over more than one-and-a-quarter centuries.

It is hoped that this talk will form a fitting tribute to the meticulous efforts of the many scientists (and publishers) who have sought to provide a largely homogeneous record of variable solar activity extending over more than a century.

Sunspot Areas in Historical STP

Unaided-eye sunspot observations were recorded in East Asian histories throughout the long interval 165 BC – AD 1918.

The Greenwich Photo-heliographic Results span the interval AD 1874 – 1976. Further results (contact prints) from the Ely and Kew observatories span part of the interval AD 1862 – 1873.

Oriental unaided-eye sunspot observations can therefore be compared with the Occidental 'photographic' sunspot observations in the interval 1862 – 1918.

East Asian Observations of Sunspots: Historical Records

Unpublished sunspot catalogue compiled by F. Richard Stephenson and S. S. Al-Dargazelli in 1998.

This catalogue was constructed by supplementing the revised catalogue of Far Eastern observations of sunspots (165 BC to AD 1918) published by Yau and Stephenson (*Q. J. Roy. Astron. Soc*, 29, 175–197, 1988) with additional sunspot records included in the list published (in Chinese) by the Beijing Observatory (1988).

Typical Examples of East Asian Sunspot Records

AD 359 November 7

[China] Shengping reign-period, 3rd year, 10th month, day *bingwu* (43). "Within the Sun there was a black spot as large as a hen's egg. Shortly afterwards the Emperor died". (*Jinshu*, 12)

[N.B. The Emperor Mu Di actually died two years later.]

AD 1853 August 5 – September 2 (only lunar month given)

[China: Shanxi] Xianfeng reign-period, 3rd year, 7th month. "Within the Sun there was a black form like a ball of wool with pointed rays shooting out on all sides." (*Tunliu Xianzhi*, 1)

[The *Tunliu Xianzhi* is a local gazette, not an official mainstream history, and the observer would almost certainly not be an experienced astronomer. Hence the reliability of this record may be questionable.]

High Resolution Image of a Sunspot in Visible Light
New Solar Telescope at the Big Bear Solar Observatory
Image Published: 2010 August 30

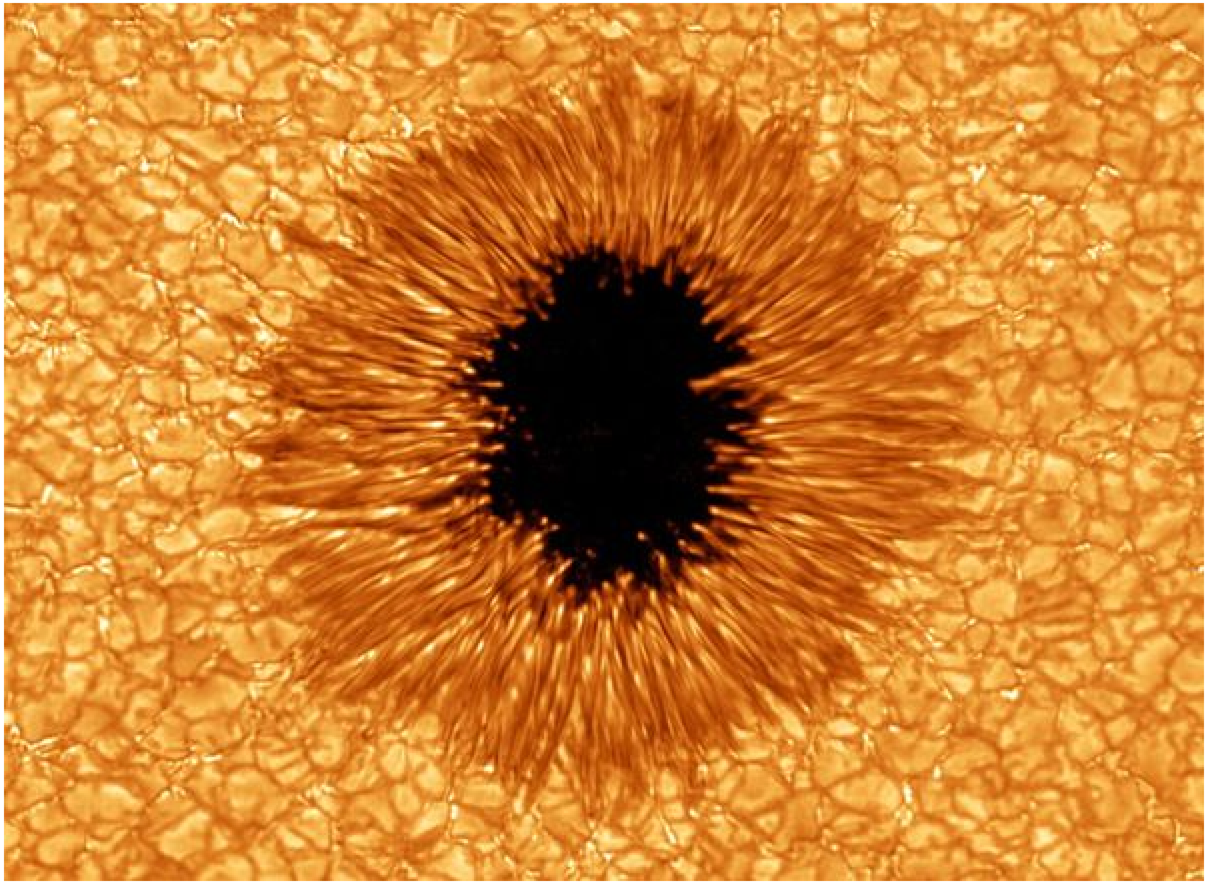


Image Courtesy BBSO/NJIT

Typical Examples of East Asian Sunspot Records

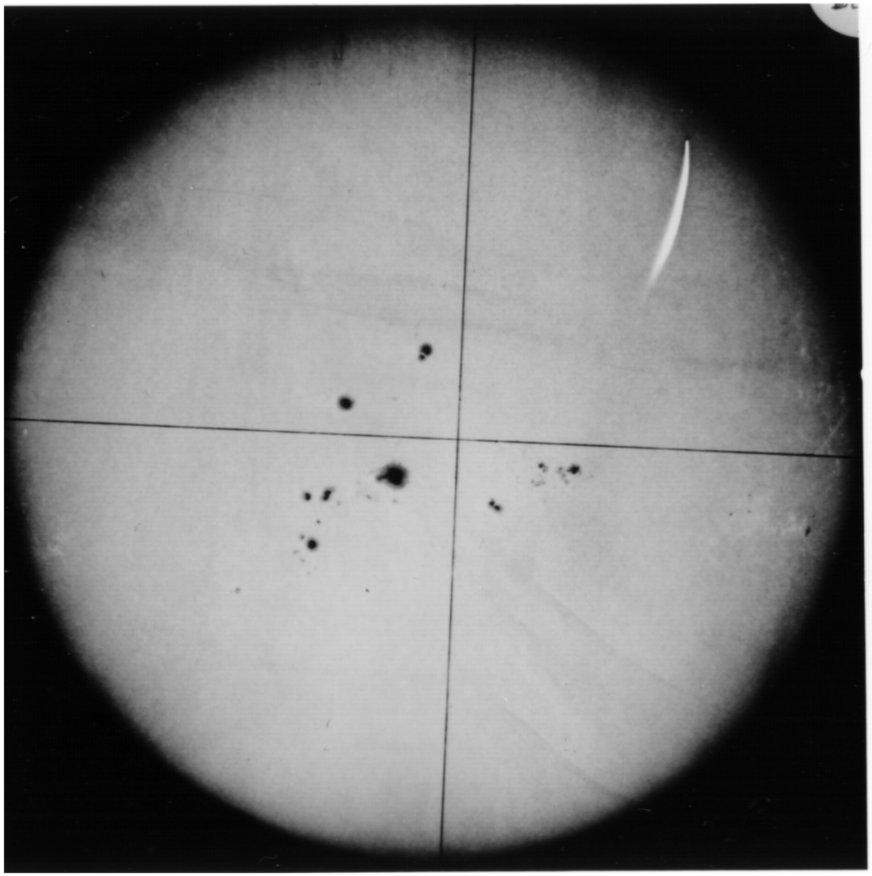
AD 851 December 2

[Japan] Ninju reign period, 1st year, 11th month, day *jiaxu* (11). "The Sun was dim. Within it there was a black dot as large as a plum." (*Montohu Jitzurohu*) [N.B. This is the only known Japanese record of a sunspot until recent centuries.]

AD 1883 December 26

[China: Shandong] Guangxu reign period, 9th year, 11th month, 27th day. "At sunset, a black spot rocked to and fro for a long time." (*Loan Xianzhi*, 13)

Royal Greenwich Observatory Contact Print: 1883 December 26



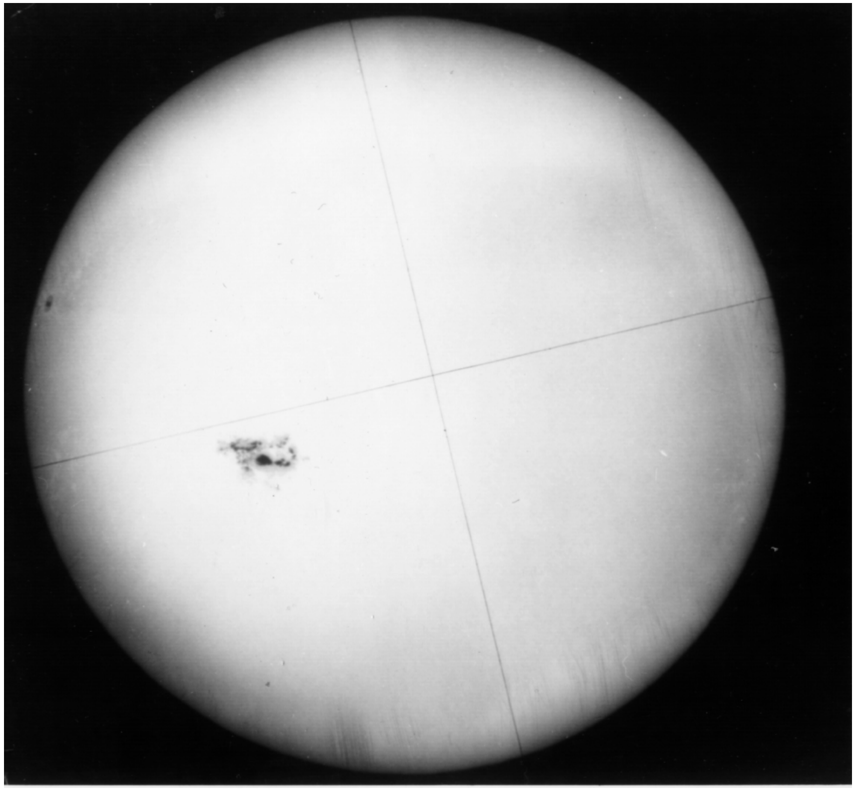
Typical Examples of East Asian Sunspot Records

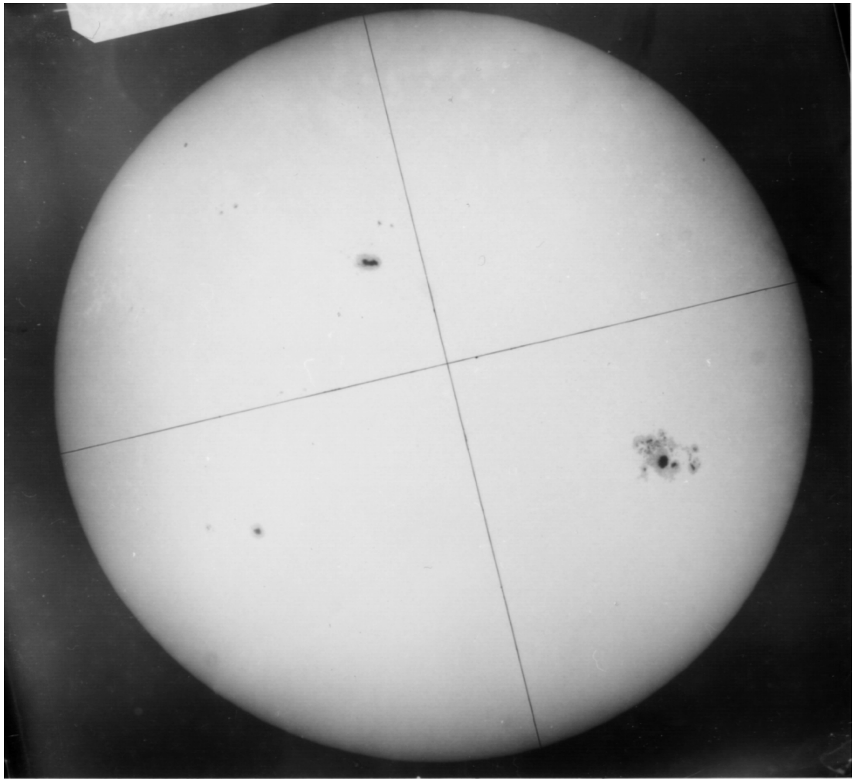
AD 1905 February 4

(i) [China: Sichuan] Guangxu reign-period, 31st year, 1st month, 1st day. "At sunrise, within (the Sun) there was a black spot as large as a clenched fist; it lasted for five minutes and then was extinguished." (*Xuxiu Dazhu Xianzhi*, 15) [The *Xuxiu Dazhu Xianzhi* is another local gazette and the observer was unlikely to be an experienced astronomer.]

(ii) [China: Hebei] Guangxu reign-period, 31st year, 1st month, 1st day. "At dawn, within the Sun there was a black spot. Suddenly there was a thick fog and all the trees turned white." (*Nanpi Xianzhi*, 14) [The *Nanpi Xianzhi* is yet another local gazette.]

Royal Greenwich Observatory Contact Prints: 1905 February 2 and 1905 February 7





Comparison Between Oriental and Occidental Sunspot Observations

The Oriental sunspot sightings from 1863 to 1918 have been compared with contemporaneous Occidental white-light images of the Sun acquired by the Royal Greenwich Observatory.

The goal was to see if sunspots large enough to be seen with the unaided eye were present on the solar disk at the times sunspot observations were recorded in East Asian histories.

An immediate direct comparison yields a success rate of 67%.

If allowance in made for possible uncertainties in the oriental dates, the success rate increases to 89%.

(Willis, Davda and Stephenson, *Q. J. Roy Astron. Soc.*, 37, 189–229, 1996)

The Greenwich Photo-heliographic Results 1874 – 1976

The comparison between the historical East Asian unaided-eye sunspot observations and the RGO photographic sunspot observations revealed some errors in the original digital dataset.

Subsequently, more detailed researches have identified both systematic and isolated errors in the digital datasets and a smaller number of typographical errors in the printed RGO publications.

The Greenwich Photo-heliographic Results 1874 – 1976

Recent work on the Greenwich Photo-heliographic Results can be discussed under three separate headings (or subtitles):

1. Summary of the Observations, Applications, Datasets, Definitions and Errors (Paper 1).
2. Procedures for Checking and Correcting the Sunspot Digital Datasets (Paper 2).
3. Initial Corrections to the Printed Publications (Paper 3).

The Greenwich Photo-heliographic Results: Summary of the Observations, Applications, Datasets, Definitions and Errors.

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The RGO Programme of Solar Observations

The Royal Greenwich Observatory (RGO), formerly the Royal Observatory, Greenwich, organised a very valuable programme of solar observations for more than a century.

With the help of other solar observatories, the RGO acquired white-light photographs (photo-heliograms) of the Sun during an interval extending from 1874 April 17 until 1976 December 31.

Thereafter, responsibility for the RGO programme of solar observations was formally transferred to the Heliophysical Observatory, Debrecen, Hungary.

The RGO Programme of Solar Observations

The majority of white-light photographs obtained by the RGO were taken using photo-heliographs located at the following solar observatories:

- The Royal Observatory, Greenwich, until 1949 May 02
- The Royal Greenwich Observatory, Herstmonceux, from 1949 May 02
- The Royal Observatory, Cape of Good Hope, South Africa
- The Kodaikanal Observatory, Southern India (Tamil Nadu)
- The Dehra Dun Observatory, North-West Provinces (Uttar Pradesh), India
- The Royal Alfred Observatory, Mauritius

The RGO Programme of Solar Observations

The remaining gaps in the combined collection of photographs from these named solar observatories were largely filled by photographs generously supplied by a number of other solar observatories, including:

- **Harvard College Observatory**
- **Melbourne Observatory**
- **Mount Wilson Observatory**
- **US Naval Observatory**

The RGO Printed Publications

The RGO published the measured positions and areas of individual sunspots or distinct groups of sunspots in a series of publications that constitute the *Greenwich Photo-heliographic Results (GPR) 1874 – 1976*:

- ***Greenwich Observations (1874 – 1955)***
- ***Royal Greenwich Observatory Bulletins (1956 – 1961)***
- ***Royal Observatory Annals (1962 – 1976)***

The RGO Printed Publications

The RGO publications provide tabulations of the measured positions and areas (umbral and whole-spot = umbral plus penumbral) of every sunspot group for most days of the year.

The positions are referred first to a system of apparent polar coordinates (radial distance and position angle) on the Sun's disk and second to a system of heliographic coordinates (latitude and Carrington longitude) on the Sun's surface.

The measured areas (in polar coordinates) are corrected for foreshortening and the resulting corrected areas (in heliographic coordinates) are expressed in millionths of the Sun's visible hemisphere.

The RGO Printed Publications

The RGO printed publications are divided into separate sections:

- **"Measures of the Positions and Areas of Sun Spots and Faculae on Photographs Taken at [List of the Relevant Solar Observatories] With the Deduced Heliographic Longitudes and Latitudes." Footnotes give the duration of groups.**
- **"Ledgers of Areas and Positions of Groups of Sun Spots Deduced From the Measurement of the Solar Photographs for Each Day in the Year [e.g., 1884]."**
- **"Total Projected Areas of Sun Spots and Faculae for Each Day in the Year [e.g., 1884]."**

The Original RGO Sunspot Digital Dataset

An “original” digital dataset that contains some of the information on sunspot positions and areas published by the RGO was distributed many years ago by the World Data Center A, Boulder, Colorado.

This dataset is available online at the NOAA National Geophysical Data Center (NGDC)

(ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/Sunspot_REGIONS/Greenwich or http://www.ngdc.noaa.gov),

and also at the UK Solar System Data Centre (UKSSDC) at the Rutherford Appleton Laboratory

(http://www.ukssdc.ac.uk/wdcc1/greenwich).

The Original RGO Sunspot Digital Dataset

The original RGO sunspot digital dataset was compiled in 1981 – 1982. The starting point was a magnetic tape prepared previously by F. Ward This magnetic tape contained the RGO data for the interval 1876 – 1954.

It seems likely that that these data were taken from the “Ledgers of Areas and Positions of Groups of Sunspots” sections of the RGO publications and that they were key-entered twice, although there is now no absolute confirmation of these conclusions.

The Original RGO Sunspot Digital Dataset

The RGO data for the intervals 1874 – 1875 and 1955 – 1976, which were added by D. V. Hoyt and J. A. Eddy, were taken directly from:

(i) The "Ledgers of Areas and Positions of Groups of Sunspots" sections of the RGO publications (1874 – 1875);

(ii) The "Ledgers of Groups of Sunspots" section in a single RGO publication (1955);

(iii) The "Positions and Areas of Sunspots for Each Day of the Year" sections, as well as the "General Catalogue of Sunspots" sections, of the subsequent RGO publications (1956 – 1976).

The Original RGO Sunspot Digital Dataset

The additional data for the intervals 1874 – 1875 and 1955 – 1976 were typed in twice; the two versions were compared and errors corrected.

[However, it appears possible that for the interval 1876 –1954, the polar coordinates were calculated from the heliographic coordinates. Conjecture!!!]

[In addition, a different definition of the polar angle (clockwise, anti-clockwise) was initially used by the different compilers.]

Extension of the RGO Programme of Solar Observations

After the cessation of the RGO programme of solar observations, at the end of 1976, the sunspot dataset has effectively been extended to the present time through the Region Summary section of the NOAA Preliminary Report and Forecast of Solar Geophysical Data (called "The Weekly").

(http://www.swpc.noaa.gov/weekly/index.html)

Most data are from the from the US Air Force (USAF) Solar Optical Observing Network (SOON) and its predecessor.

The Extension of the Original RGO Sunspot Digital Dataset

Although responsibility for the RGO programme of solar observations was transferred formally to the Heliophysical Observatory, Debrecen, Hungary, at the end of 1976, the original sunspot digital dataset has been extended throughout the interval 1977 – 1982 (August 15) using solely data from SOON, as given in "The Weekly" reports.

Data from SOON were used after 1976 because data from the Heliophysical Observatory, Debrecen, were not available initially.

The Extension of the Original RGO Sunspot Digital Dataset

By considering the sunspot data recorded at a number of different solar observatories, L. Balmaceda et al. (2009) have developed a homogeneous dataset of sunspot areas extending over more than 130 years.

However, my talk is concerned exclusively with the various errors in the printed and digital datasets resulting from the programme of sunspot observations supported by the RGO during the interval 1874 – 1976.

The Extension of the Original RGO Sunspot Digital Dataset

The digital sunspot dataset generated by D. V. Hoyt and J. A. Eddy (1982) has been updated regularly by D. H. Hathaway, who maintains this updated version of the original RGO sunspot digital dataset at the NASA Marshall Space Flight Center (MSFC), despite the fact that funding for this dataset was terminated in 2005.

(http://solarscience.msfc.nasa.gov/greenwch.shtml)

However, the various corrections that have been made to the MSFC version have not been fully documented.

The RGO Sunspot and Facular Digital Dataset

A more detailed digital dataset, which also includes information on the positions and areas of solar faculae on the solar disk (up to 1955 December 31), has subsequently been prepared under the auspices of the NOAA National Geophysical Data Center, Boulder Colorado.

As a result of a data-rescue project initiated by the NGDC in 1999, the published values in the "Measures of the Positions and Areas of Sunspots and Faculae" have been keyed-in anew.

(ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_WHITE_LIGHT_FACULAE or http://www.ngdc.noaa.gov)

The RGO Sunspot (and Facular) Digital Datasets

Neither digital dataset (either with or without information on solar faculae) has yet been subjected to the most rigorous tests in terms of quality assurance.

Indeed, it is known that both digital datasets contain some errors.

However, the existence of two independently prepared digital datasets, which both contain information on sunspot positions and areas, makes it possible to formulate a strategy for the development of a more accurate digital dataset.

The Sunspot Digital Datasets: Definitions and Format

The format of the data in the original RGO sunspot digital dataset may be summarised in terms of the 80 characters (including blanks) used to define the relevant variables.

The date and time of the observation are specified by the year (e.g., 1874), month (numerical), day of the month, and time in thousandths of a day (e.g., 0.500 represents 12:00 UT).

The Sunspot Digital Datasets: Definitions and Format

Sunspots are defined by the Greenwich sunspot group number until 1976 December 31, when the programme of Greenwich sunspot observations ceased, and by the NOAA/USAF (National Oceanic and Atmospheric Administration/United States Air Force) group number thereafter.

Groups that appear on one day only have group numbers comprising the Carrington rotation number followed by a two-digit number (e.g., 28401 denotes the number of the first group to appear for one day only during Carrington rotation 284).

For the earlier observations, two or more groups were occasionally given the same number. In such cases a further digit is used to distinguish between them.

Classification Schemes for Sunspot Groups: Scheme 1

In Scheme 1, F. Ward used the Mount Wilson classification scheme (Bray and Loughhead, 1964) for sunspot data recorded during the interval 1922 – 1955:

0 = classification missing;

1 = alpha, a unipolar group in which all spots have the same polarity;

2 = beta, a bipolar group;

3 = beta gamma, a bipolar group with some spots out of place with respect to polarity;

4 = gamma, a complex group in which polarities are completely mixed;

5 = unclassified, if the classification did not match types 1– 4.

Classification Schemes for Sunspot Groups: Scheme 2

In Scheme 2 (RGO), a single digit is used to specify the type of Greenwich sunspot group, observed during the interval 1874 – 1976, according to a tenfold classification system:

0 = a single spot;

1 = a single spot with a few small spots;

2 = a pair of spots;

3 = a pair of spots with a few small spots;

4 = a stream;

5 = a stream and one spot;

6 = a stream and two spots;

7 = a cluster of sunspots or composite group;

8 = a pair of clusters or composite groups;

9 = other.

Sunspot Areas and Positions

The original sunspot digital dataset provides four separate measures of sunspot area associated with each sunspot group:

(i) Mean observed (projected) umbral area in millionths of the solar disk;

(ii) Mean observed (projected) whole-spot (umbral plus penumbral) area in millionths of the solar disk;

(iii) Mean umbral area, corrected for foreshortening and expressed in millionths of the visible solar hemisphere;

(iv) Mean whole-spot area, corrected for foreshortening and expressed in millionths of the visible solar hemisphere.

All areas are quoted to the nearest millionth of the solar disk or hemisphere.

Sunspot Areas and Positions

In the original sunspot digital dataset, the position of the centre of a sunspot group is specified in terms of five quantities:

(i) Distance from the centre of the solar disk in disk radii (0.000 to 1.000);

(ii) Polar angle measured anti-clockwise (N→E→S→W→N) from the north pole of the Sun's axis (0.0° to 360.0°);

(iii) Carrington heliographic longitude;

(iv) Heliographic latitude (positive = North, negative = South);

(v) Central meridian (angular) distance (positive = West, negative = East).

Sunspot Areas and Positions

All angles are quoted to an accuracy on one tenth of a degree, although some of the very early angular data (up to 1881 December 21) were originally expressed in degrees and minutes.

The recorded values of heliographic latitude and longitude are based on the assumption of a (sidereal) solar-rotation period that is invariant with respect to latitude and is approximately equal to 14.184 degrees per day, which corresponds to one (sidereal) solar rotation every 25.38 days.

The Sunspot Digital Dataset

- The original sunspot dataset does not provide information on the positions and areas of sunspots for every day in the interval 1874 – 1976.
- Table II in the paper by Willis, Davda and Stephenson (1996) indicates the annual number of days for which sunspot positions and areas are archived up to 1918.
- Subsequently, archived data are available for most days of the year.

The Sunspot Digital Dataset

Throughout the interval 1874 – 1976, no information is stored in the original sunspot digital dataset if no sunspots are present on the solar disk.

[This statement is not true for the sunspot and facular dataset, since information is stored when only solar faculae are present.]

The Sunspot Digital Dataset

The original sunspot digital dataset was generated mainly by using the information published in the RGO annual tables initially entitled "Ledgers of Areas and Positions of Groups of Sunspots".

This conjecture is based on two facts:

1. Projected sunspot areas are given explicitly as well as corrected sunspot areas.
2. Interpolated values (in parentheses) are given when no photograph exists.

The Sunspot and Facular Digital Dataset

The sunspot and faculae digital dataset has been generated by using the information published in the RGO annual tables initially entitled "Measures of Positions of Sun Spots and Faculae [1874 – 1955]".

This digital dataset contains only corrected (not projected) sunspot areas but has the advantage of including a single-letter observatory code.

Old Observatory Codes

The single letter observatory codes in the sunspot and faculae digital dataset (1874 – 1955) are:

A = Melbourne, Australia (Me);

C = Cape of Good Hope, South Africa;

D = Dehra Dun, India;

E = Ebro, Spain;

F = Fraunhofer Institut, Germany;

G = Greenwich *and* Herstmonceux, UK;

H = Harvard College, USA;

Old Observatory Codes

The single letter observatory codes in the sunspot and faculae digital dataset (1874 – 1955) are:

I = India (Dehra Dun);

K= Kodaikanal, India;

M = Mauritius;

T = Mount Wilson (Mt. W), USA;

W = Washington, USA;

Y = Yerkes, USA.

Observatory Codes

At present, the sunspot and faculae digital dataset extends only up to the end of 1955, when publication of the facular measurements ceased.

In the interval 1956 – 1976, the printed RGO publications use some of the defunct single-letter observatory codes again for other observatories.

For example, D is used for Debrecen, whereas this letter had previously been used for Dehra Dun.

Observatory Codes

Therefore, a new four-letter observatory code is introduced.

This unambiguous four-letter observatory code is based on the one employed at the National Geophysical Data Center, Boulder, Colorado.

(ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/CATALOGS/Solar_Observatories_List)

There are a few minor exceptions.

Contributing Solar Observatories

A table has generated that gives (in columns):

Reference Number (01 –18);

Observatory Name;

Old Observatory Code(s);

New Observatory Code;

Latitude (Degrees, N)

Longitude (Degrees, E)

Altitude (Metres)

Details of Solar Observations (Date range, or dates, and [total number of solar photographs measured]).

Contributing Solar Observatories

Examples:

01; Royal Observatory, Cape of Good Hope, South Africa; C; CAPE; – 33.9343 (N); + 18.4775 (E); 18 (m); 1910 – 1976 [8120].

04; Royal Observatory, Greenwich, London, UK; G; GREN; + 51.4773 (N); + 00.0000 (E); 47 (m); 1874 Apr 17 – 1949 May 02 [14756].

07; Royal Greenwich Observatory, Herstmonceux, Sussex, UK; G, H; HERS; + 50.8717 (N); + 00.3376 (E); 34 (m); 1949 May 03 – 1976 Dec 31 [6633].

Contributing Solar Observatories

Examples:

10; Melbourne Observatory, Victoria, South Africa; Me; MELB; – 37.8315 (N); + 144.9733 (E); 28 (m); 1874 – 1877 [123].

12; Astronomical Observatory of Rome, Monte Mario, Rome, Italy; R; MMAR; + 41.9217 (N); + 12.4517 (E); 152 (m); 1972 Dec 04 [1].

13; Mount Wilson Observatory, Los Angeles, CA, USA; Mt. W, W, P; MWIL; + 34.2165 (N); – 118.0597 (E); 1742 (m); 1941 – 1976 [48].

The Greenwich Photo-heliographic Results: Procedures for Checking and Correcting the Sunspot Digital Datasets

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H. E. Coffey[3] • W. Denig[3] • E. H. Erwin[3] • D. V. Hoyt[4]

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Approximate Reconstruction of Solar Images

A technique has been developed for reconstructing solar images from the information included in the original sunspot digital dataset (Willis, Davda, and Stephenson, 1996).

Assumptions:

1. The umbral and umbral plus penumbral (whole-spot) areas of each sunspot group can be represented by concentric circular areas (or, more accurately, zones of one base) on the visible hemispherical solar surface.
2. The common centre of these two circular areas is located at the centre ("centre of mass") of the sunspot group.

Approximate Reconstruction of Solar Images

This approach allows for foreshortening but is based on the assumption that the boundaries of the observed (i.e. projected) umbral and penumbral areas are exact ellipses.

An assumption of this type is an almost inevitable consequence of the fact that no information on the irregular shapes of individual sunspots, and only limited information on the irregular distribution of spots within groups (i.e., the tenfold Greenwich classification system) has been archived in the *Greenwich Photo-heliographic Results, 1874 – 1976.*

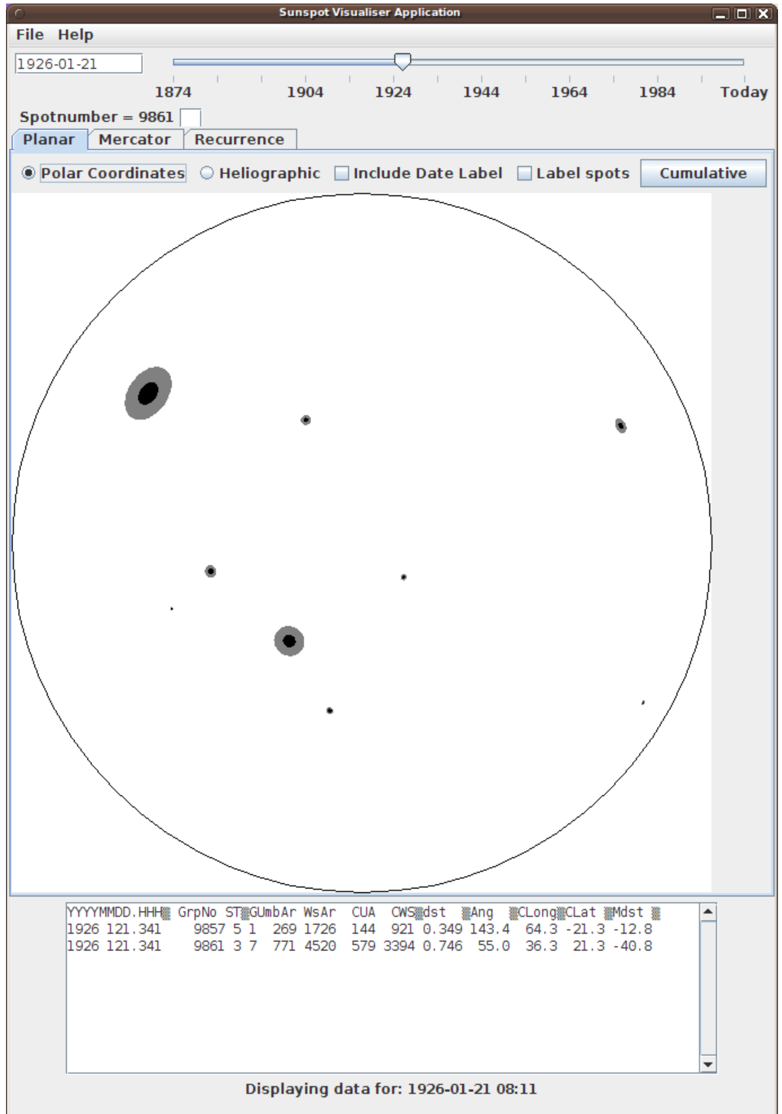
Approximate Reconstruction of Solar Images

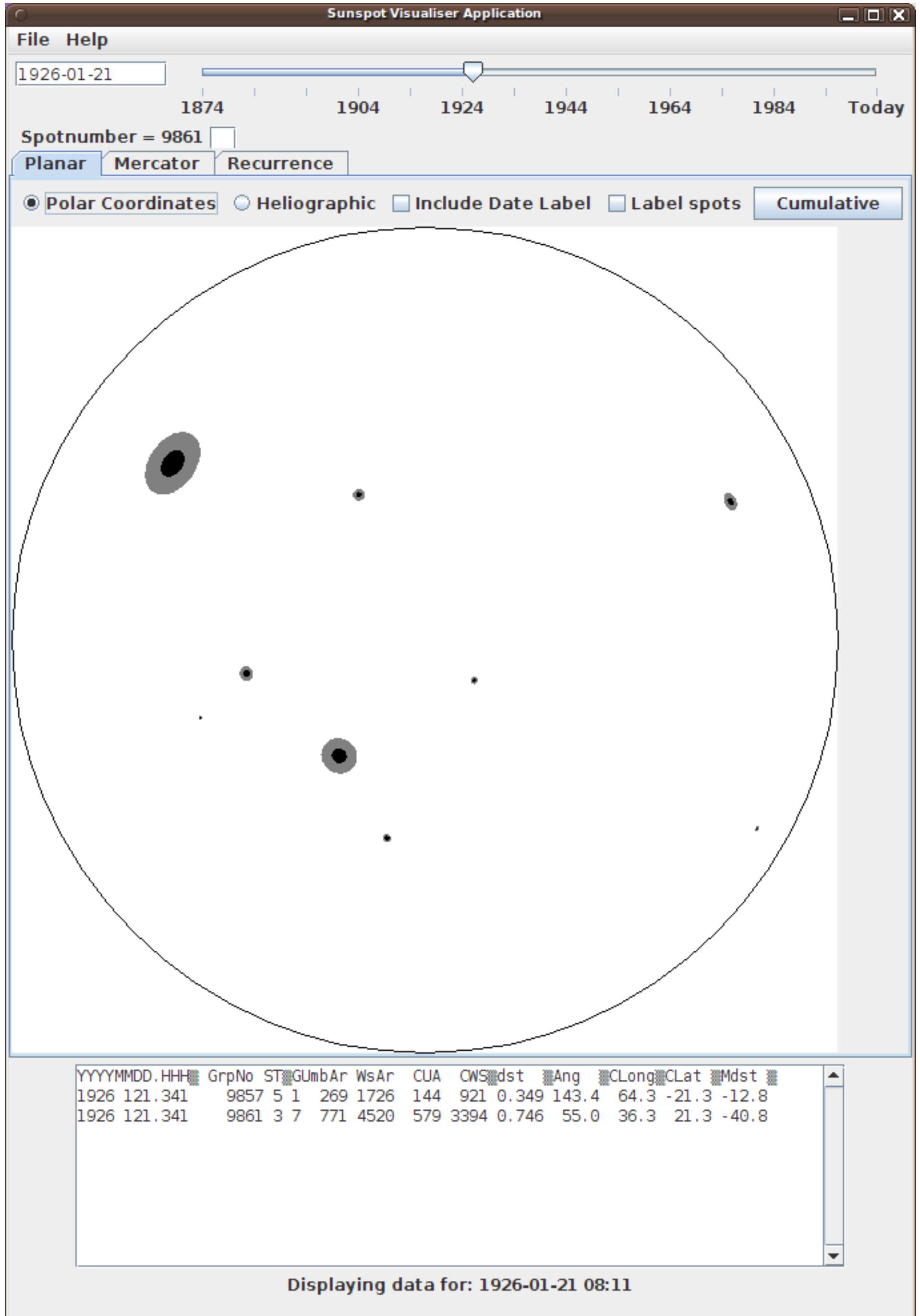
This procedure for reconstructing solar images provides an acceptably accurate visual representation of an individual sunspot that is not too close to the limb of the Sun.

In the case of a complex sunspot group, however, the procedure only provides an approximate visual representation in the sense that the total umbral and penumbral areas are correct but the assumed distribution of the areas on the solar surface is a rather extreme simplification.

Nevertheless, as already mentioned, reconstructed solar images have been used to determine whether or not a sunspot large enough to be seen with the unaided eye were present on the solar disk at the times of unaided-eye sunspot sightings recorded in East Asian histories during the interval 1862 – 1918.

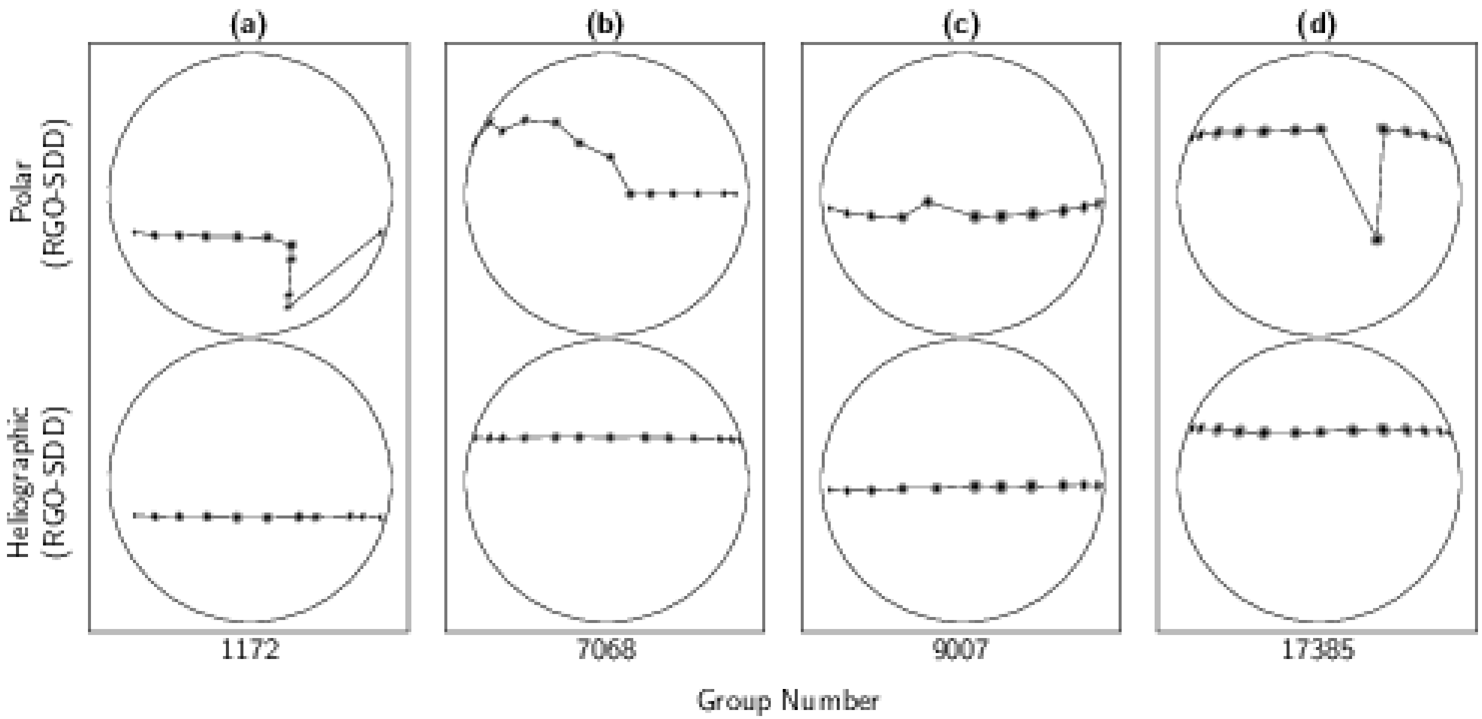
Tool for Visualising the Positions and Areas of Sunspot Groups (1926 January 21; 08:11 UT)





Sunspot Visualiser Application
File Help
1926-01-21
1874 1904 1924 1944 1964 1984 Today
Spotnumber = 9861
Planar Mercator Recurrence
Polar Coordinates Heliographic Include Date Label Label spots Cumulative
YYYYMMDD.HHH GrpNo ST GUmbAr WsAr CUA CWS dst Ang CLong CLat Mdst
1926 121.341 9857 5 1 269 1726 144 921 0.349 143.4 64.3 -21.3 -12.8
1926 121.341 9861 3 7 771 4520 579 3394 0.746 55.0 36.3 21.3 -40.8
Displaying data for: 1926-01-21 08:11

Systematic and Typographical Errors in the Original Sunspot Digital Dataset (RGO–SDD)



Systematic and Typographical Errors in the Original Sunspot Digital Dataset (RGO–SDD)

Date ranges of the figures:

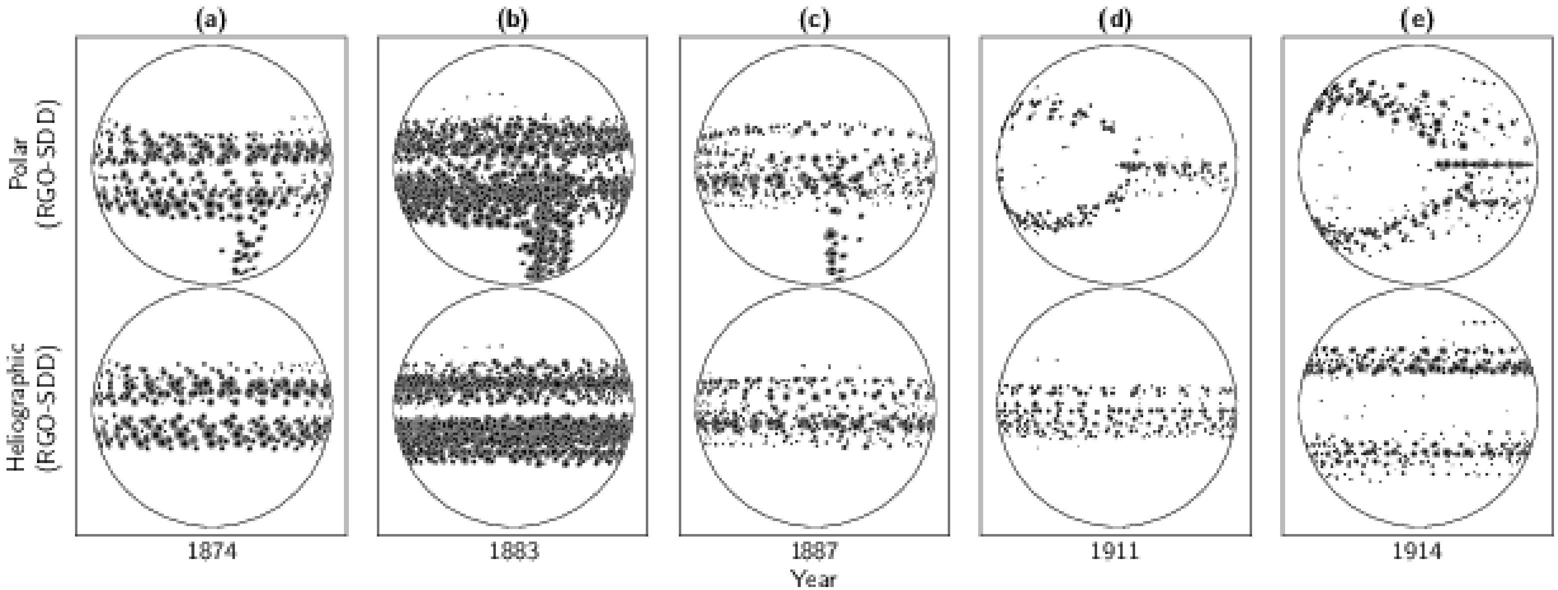
(a) 1883 November 09 – 20, Group Number 1172 (systematic error in the original sunspot digital dataset);

(b) 1914 September 10 – 22, Group Number 7068 (systematic error in the original sunspot dataset);

(c) 1919 August 14 – 25, Group Number 9007 (typographical error in the printed RGO publications);

(d) 1956 March 11 – 23, Group Number 17385 (typographical error in the printed RGO publications).

Systematic Errors in the Original Sunspot Digital Dataset (RGO–SDD): Annual Accumulations



Systematic Errors in the Original Sunspot Digital Dataset (RGO–SDD)

It is important to note that the systematic errors in the years 1874, 1883, 1887, 1911 and 1914 are in the polar coordinates, not the heliographic coordinates.

This is surprising because the polar coordinates were the primary measurements determined from the solar photographs.

The heliographic coordinates were then derived from the polar coordinates, using a set of mathematical equations.

Why are there systematic errors in the <u>polar coordinates</u>?

Mathematical Equations

The normal method of analysing solar photographs is to measure the areas and positions of all sunspots on the photograph and define the position of each sunspot or sunspot group in terms of a system of centred polar coordinates on the apparent solar disk.

A set of mathematical equations is then used to derive heliographic latitude and longitude in the corresponding system of heliographic coordinates.

The appropriate mathematical equations can be found in a paper by De La Rue, Stewart and Loewy (1869), in several of the annual publications of the Royal Greenwich Observatory (e.g., Royal Greenwich Observatory, 1975) and in the Debrecen Photo-heliographic Results for the Year 1977 (Debrecen Heliophysical Observatory, 1987).

Mathematical Equations

Definitions:

r **– the measured distance of a sunspot from the centre of the Sun's apparent disk;**

χ **– the position angle of the spot from the Sun's axis (measured anti-clockwise from the North Pole);**

R **– the measured radius of the Sun on the photograph;**

S **– the tabular semi-diameter of the Sun in arc;**

ρ **– the angular distance of the spot from the centre of the apparent disk, viewed from the Sun's centre;**

ρ' **– the angular distance of the spot from the centre of the apparent disk, viewed from the Earth.**

Mathematical Equations

The heliocentric angle ρ is obtained from the following equations:

$$\rho' = (r/R)\ S$$

and

$$\sin(\rho + \rho') = r/R$$

The tabular semi-diameter of the Sun in arc (*S*) has to be taken from the Nautical Almanac or the Astronomical Ephemeris or, alternatively, derived using a reliable algorithm.

Mathematical Equations

If B_0 and φ are the heliographic latitudes and L_0 and λ the heliographic longitudes of the Earth and spot respectively, the following equations hold:

$$\sin \varphi = \sin B_0 \cos \rho + \cos B_0 \sin \rho \cos \chi \,,$$

and

$$\sin (L_0 - \lambda) = \sin \chi \sin \rho \sec \varphi \,.$$

The position angle χ is found by subtracting P, the position angle of the north end of the Sun's axis measured eastwards (anticlockwise) from the north point on the Sun's disk, from the position angle of the spot also measured eastwards (anticlockwise) from the north point.

The Quantities P, B_0 and L_0

The three quantities P, B_0 and L_0 for the time of exposure of each photograph are derived from the appropriate *Ephemeris for Physical Observations of the Sun* (i.e., the *Nautical Almanac* or the *Astronomical Ephemeris*).

The values of P, B_0 and L_0 are given in the printed RGO publications in the order P, L_0 and B_0 throughout the interval 1905 – 1976.

Printed values of B_0 and L_0 are also available for the interval 1874 – 1877 (from the compendium *Photo-heliographic Results 1874 – 1885*, HM Stationery Office, Edinburgh, 1907) and also for the interval 1888 – 1904.

The Quantities *P*, B_0 and L_0

The three quantities *P*, B_0 and L_0 are given in digital form (in the order *P*, L_0 and B_0) in the sunspot and faculae digital dataset

(ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_WHITE_LIGHT_FACULAE)

for most years up to 1955 (*P* is not given before 1879 but B_0 and L_0 are given for all days).

However, it is important to note that some of the "missing" values in the RGO printed publications have been derived using the Multiyear Interactive Computer Almanac 1800 – 2050 (MICA, 2005) and inserted into the sunspot and faculae digital dataset.

In this digital dataset, the values of *P* (when given) , B_0 and L_0 are presented in parentheses in the last row (line) of information for each day, in the order *P*, L_0 and B_0.

The Quantities *P*, B_0 and L_0

Therefore, the relevant values of *P* (when given), B_0 and L_0 could be extracted from the sunspot and faculae dataset and added to the original sunspot digital dataset.

However, it should be noted that dates and times in these two digital datasets must be matched exactly in this process because for some days there are entries in the sunspot and faculae digital dataset but not in the original sunspot digital dataset (e.g., when only solar faculae are present).

For simplicity, in an initial study, the values of *P*, B_0 and L_0 are obtained using an algorithm published by Meeus (1991). The accuracy of this algorithm can be tested.

Mathematical Equations

In addition to the equations already presented, the following equation also holds:

$$\cos \rho = \sin B_0 \sin \varphi + \cos B_0 \cos \varphi \cos (L_0 - \lambda).$$

This equation has been presented explicitly by Győri (Thesis, 1989; personal communication, 2008).

Using this equation and the previous equations, it can be shown that the following three trigonometric relations hold for χ:

$$\sin \chi = [\cos \varphi \sin (L_0 - \lambda)]/\sin \rho,$$

$$\cos \chi = [\cos B_0 \sin \varphi - \sin B_0 \cos \varphi \cos (L_0 - \lambda)]/ \sin \rho,$$

$$\tan \chi = \sin (L_0 - \lambda)/[\cos B_0 \tan \varphi - \sin B_0 \cos (L_0 - \lambda)].$$

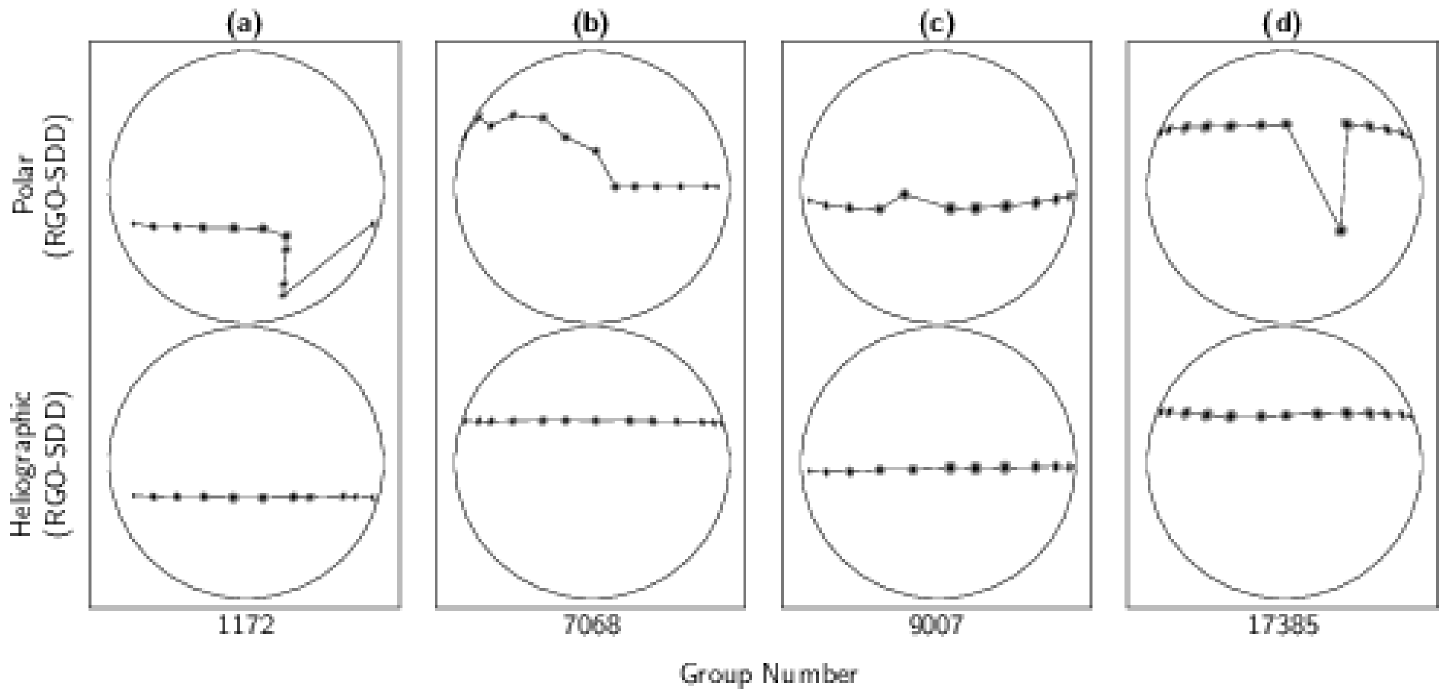
Mathematical Equations

These equations can be solved for χ if the heliographic coordinates φ, λ, B_0 and L_0 are all known.

This inverse, or reverse, solution of the mathematical equations is valuable if the heliographic coordinates are believed to be correct and the polar coordinates (particularly the position angle χ) are suspected to be incorrect, as in the figures already presented.

REMINDER

Systematic and Typographical Errors in the Original Sunspot Digital Dataset (RGO–SDD)



Mathematical Equations

(Reminder)

In addition to the equations already presented, the following equation also holds:

$$\cos \rho = \sin B_0 \sin \varphi + \cos B_0 \cos \varphi \cos (L_0 - \lambda).$$

This equation has been presented explicitly by Győri (Thesis, in Hungarian, 1989; personal communication, 2008).

Using this equation and the previous equations, it can be shown that the following three trigonometric relations hold for χ:

$$\sin \chi = [\cos \varphi \sin (L_0 - \lambda)]/\sin \rho,$$

$$\cos \chi = [\cos B_0 \sin \varphi - \sin B_0 \cos \varphi \cos (L_0 - \lambda)]/ \sin \rho,$$

$$\tan \chi = \sin (L_0 - \lambda)/[\cos B_0 \tan \varphi - \sin B_0 \cos (L_0 - \lambda)].$$

Mathematical Equations

The last equation in the set of three equations can be solved to give <u>two</u> values of χ .

However, two of this set of three equations for χ must be solved to find the correct value of χ (i.e., the value of χ in the correct quadrant).

Does this fact account for the error in the polar coordinates?

The first equation can be solved to find the value of ρ.

This value of ρ can then be substituted into the first two equations in the set of three equations, either of which can be solved to give <u>two</u> values of χ .

Only one value of χ from the pairs of solutions is in common. This is the required value of χ, the position angle measured anticlockwise from the North Pole of the Sun's axis.

Mathematical Equations

At this stage the quantities ρ , χ , φ , λ , B_0 and L_0 are all known.

The equations

$$\rho = (r/R)\,S$$

and

$$\sin(\rho + \rho') = r/R$$

can be combined to give the following equation for r/R :

$$r/R = \sin[(r/R)S + \rho]$$

Mathematical Equations

In the equation

$$r/R = \sin[(r/R)S + \rho]$$

The symbol S denotes the semi-diameter of the Sun in arc, which has to be taken from the Nautical Almanac or the Astronomical Ephemeris or, alternatively, derived using a reliable algorithm.

To be strictly rigorous, the above equation must be solved for r/R using an iterative procedure such as Newton's method, which is the approach adopted in this work.

Mathematical Equations

If it is believed that only the position angle (χ) is incorrect, the problem is essentially solved once the correct value of χ has been determined.

Nevertheless, the archived value of r/R and the tabulated value of S can be substituted into the equation

$$\rho' = (r/R)\,S$$

to find ρ', which can then be substituted into the equation

$$\sin(\rho + \rho') = r/R$$

to verify that this equation actually holds.

Solution of the Mathematical Equations

It is assumed initially that the heliographic coordinates (φ and λ) are correct and the mathematical equations are then used to calculate, or re-evaluate, the polar coordinates (r/R and χ) from these "correct" heliographic coordinates.

For simplicity, in this initial investigation, the solar ephemerides (P, B_0 and L_0) have been obtained using the algorithm published by Meeus (1991) and the semi-diameter of the Sun in arc (S) has been obtained from the JPL Horizons On-Line Ephemeris System.

Solution of the Mathematical Equations

However, as a check on the accuracy of the solar ephemerides derived from the algorithm of Meeus (1991), the solar coordinate transformations have also been performed with software developed at the Rutherford Appleton Laboratory (RAL) by P. T. Wallace, in connection with pointing systems for ground-based solar telescopes.

In this latter development, the adopted ephemeris models are taken from Seidelmann (1992) and a minor inaccuracy perpetuated since the work of Carrington has been corrected.

Solution of the Mathematical Equations

Specifically, the North Pole of the sun defined by Carrington (1863), and used canonically thereafter, is ambiguous, in the sense that the relevant equations appear to define a pole that is moving with respect to the stars (P. T. Wallace, private communication, 2010).

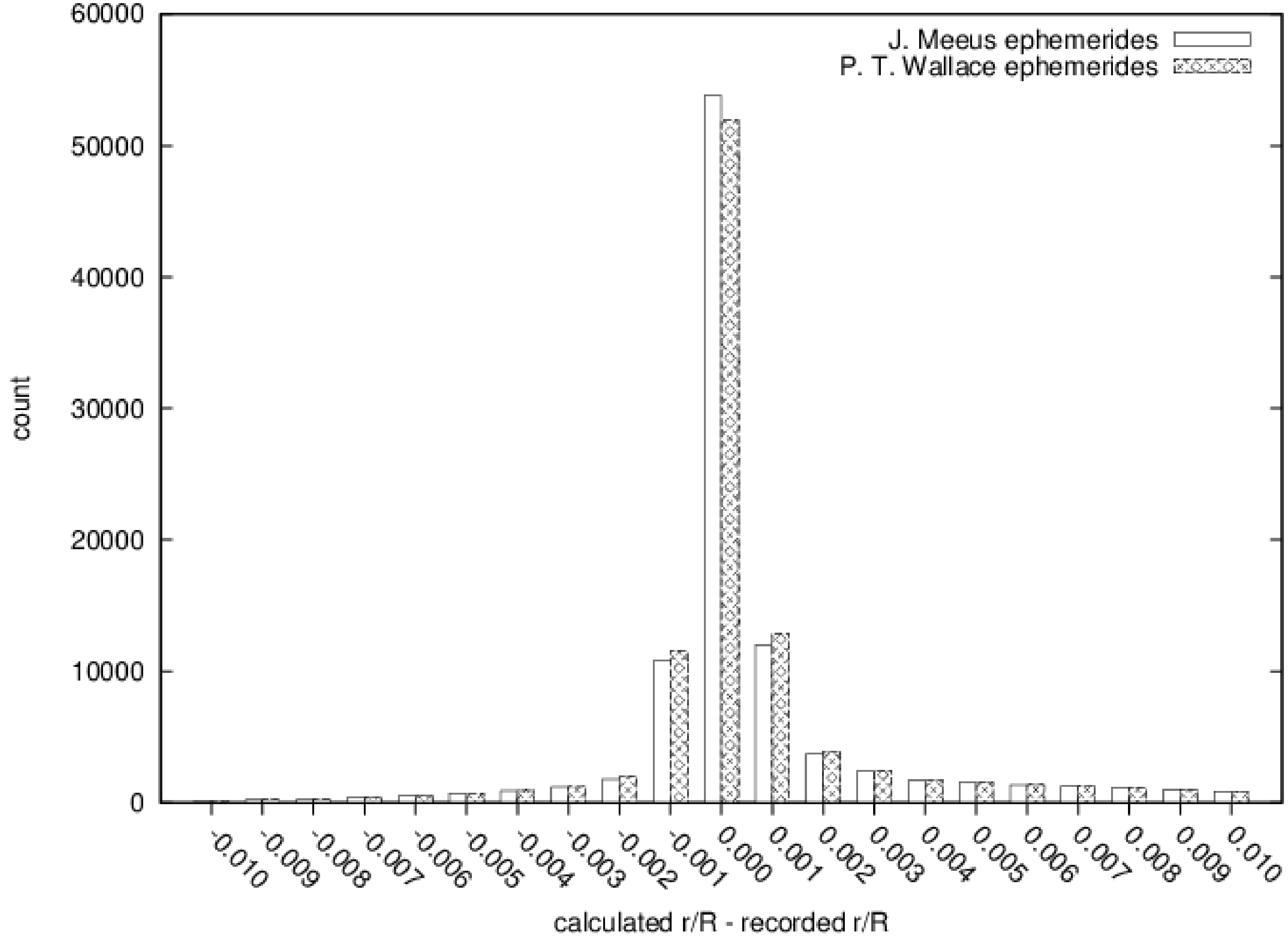
This minor inaccuracy arose because Carrington used ecliptic coordinates but neglected planetary precession — the slow (47'' per century) change in the orientation of the ecliptic plane caused by planetary perturbations of the Earth's orbit.

Solution of the Mathematical Equations

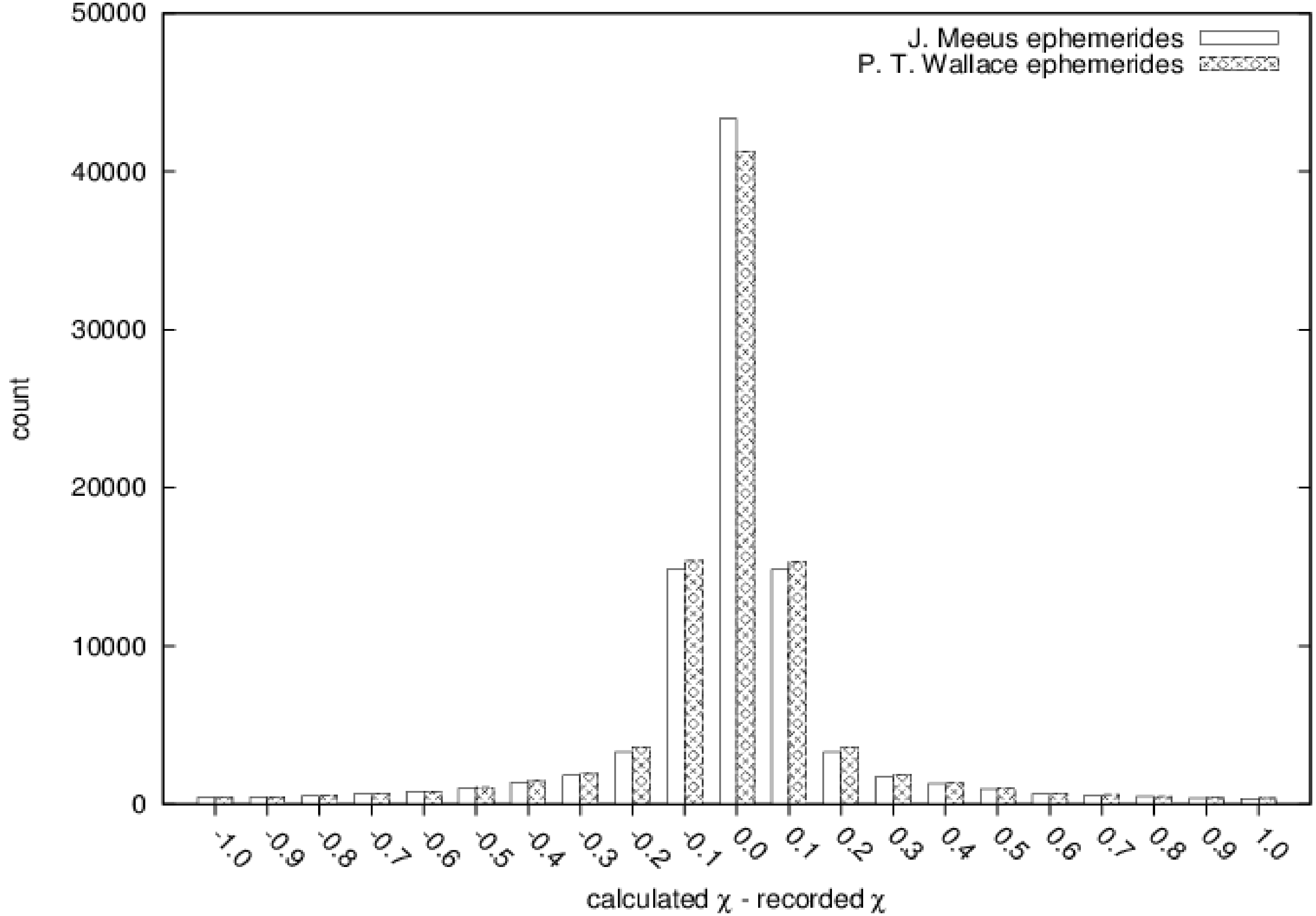
In addition, the software developed at RAL allows for the geographic coordinates and altitudes of the contributing solar observatories ("topographic coordinates"). The geographic coordinates and altitudes used in this study are those mentioned previously.

Conversely, the algorithm of Meeus (1991) is based on a simpler system of geocentric coordinates, which neglects the observer's position. This simpler system of coordinates is the one used by RGO staff to convert from polar coordinates to heliographic coordinates.

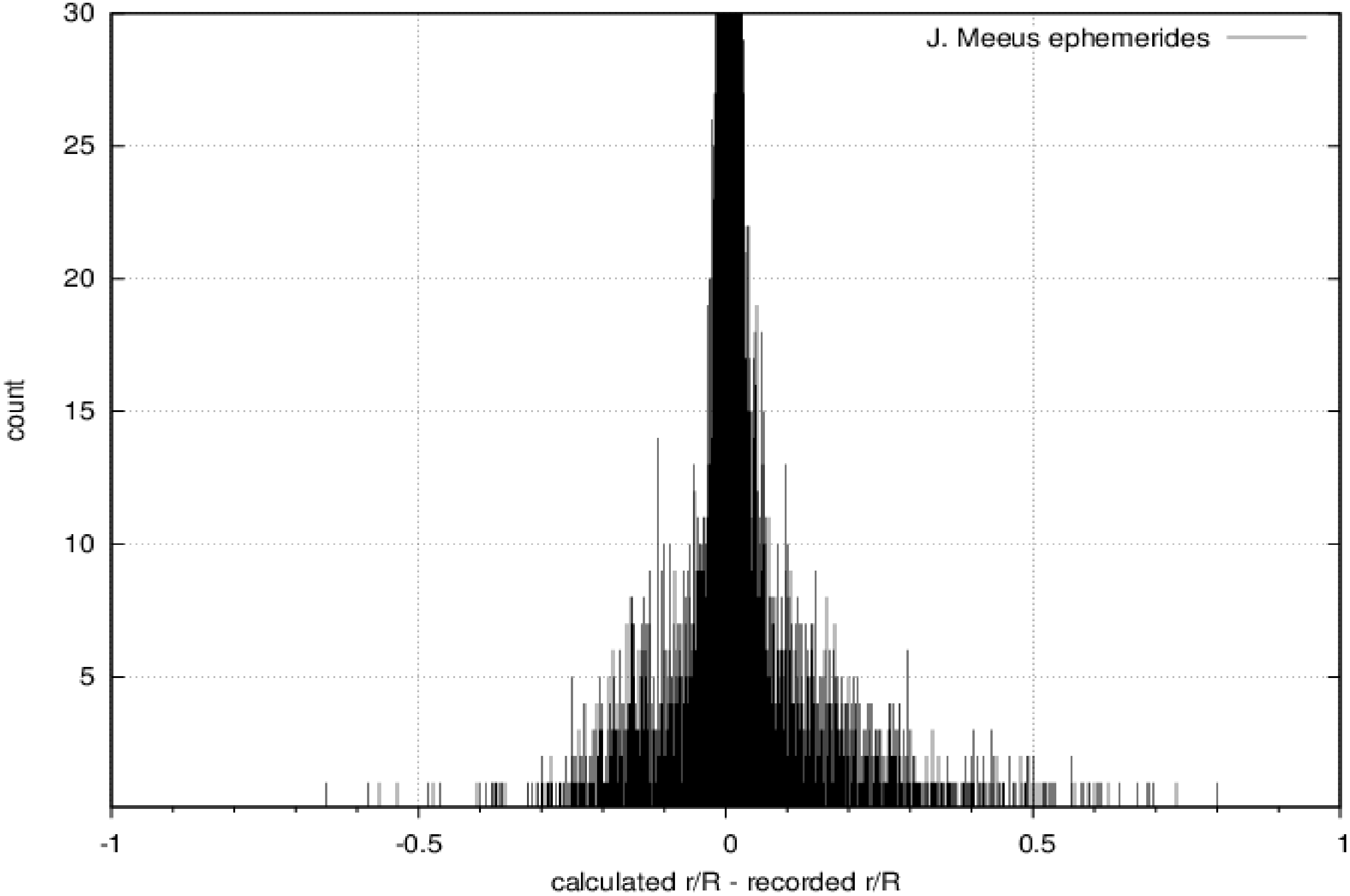
Differences Between Calculated and Recorded Values of *r/R* for Small Discrepancies Δ (*r/R*): [– 0.01 ≤ Δ(*r/R*) ≤ + 0.01]



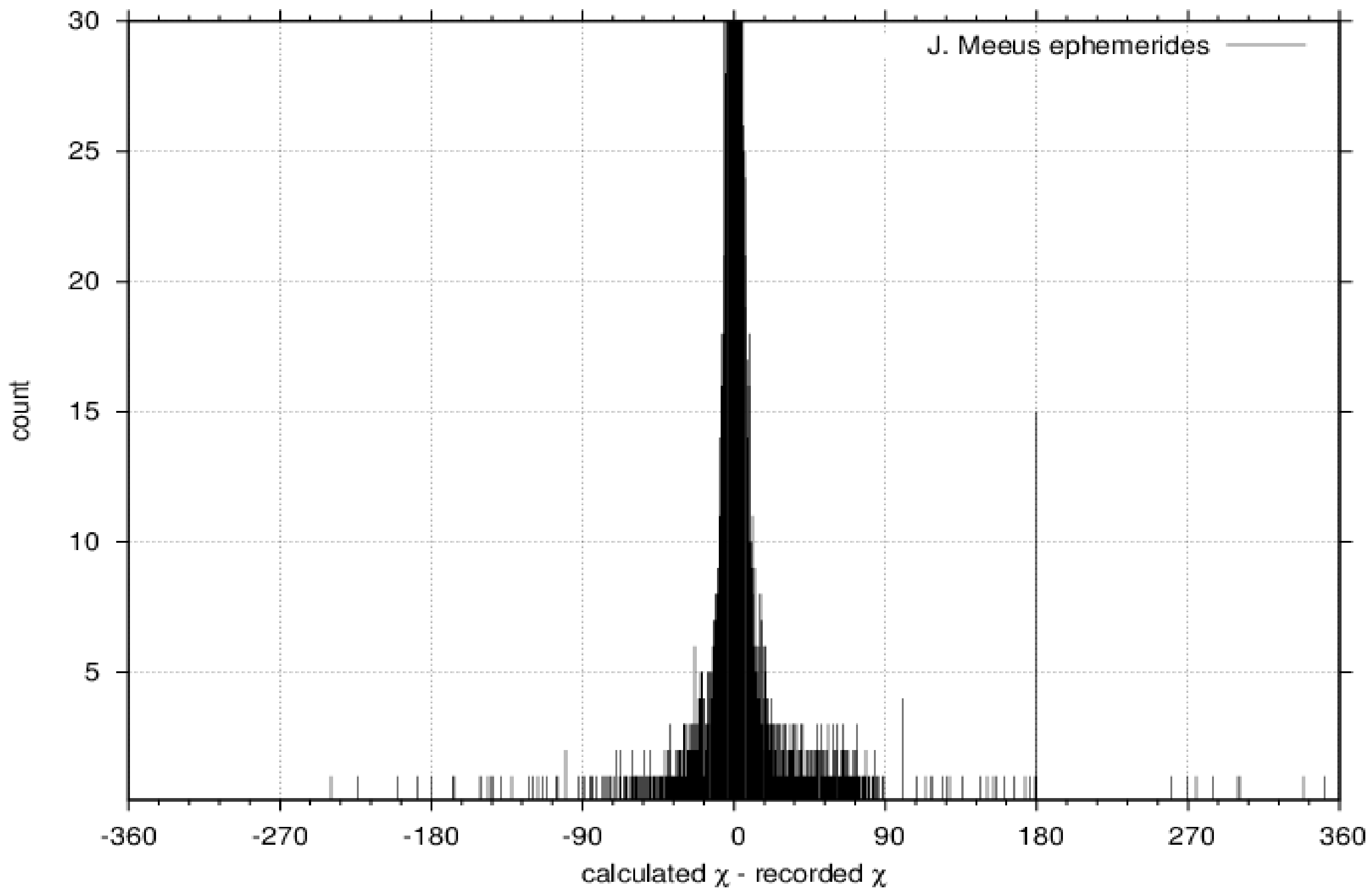
Differences Between Calculated and Recorded Values of χ for Small Discrepancies $\Delta\chi$: $[-1.0° \leq \Delta\chi \leq +1.0°]$



Differences Between Calculated and Recorded Values of *r/R* for All Discrepancies $\Delta\,(r/R)$: $[-1 \leq \Delta(r/R) \leq +1]$



Differences Between Calculated and Recorded Values of χ for All Discrepancies $\Delta\chi$: $[-360° \leq \Delta\chi \leq +360°]$



Corroboration of the Procedure

In the process of generating the previous figure, it was found that just <u>two</u> values of $\Delta\chi$ lie outside the full range $-360° \leq \Delta\chi \leq +360°$.

Both cases arise from typographical errors in the printed *Greenwich Photo-heliographic Results.*

On 1941 December 08 (341.424), the position angle of Group Number 13976 is recorded as χ = 626.6°, whereas the correct value is χ = 262.6°.

On 1950 January 02 (1.271), the position angle of RGO Group Number 16354 is recorded as χ = 821.5°, whereas the correct value is χ = 281.5°.

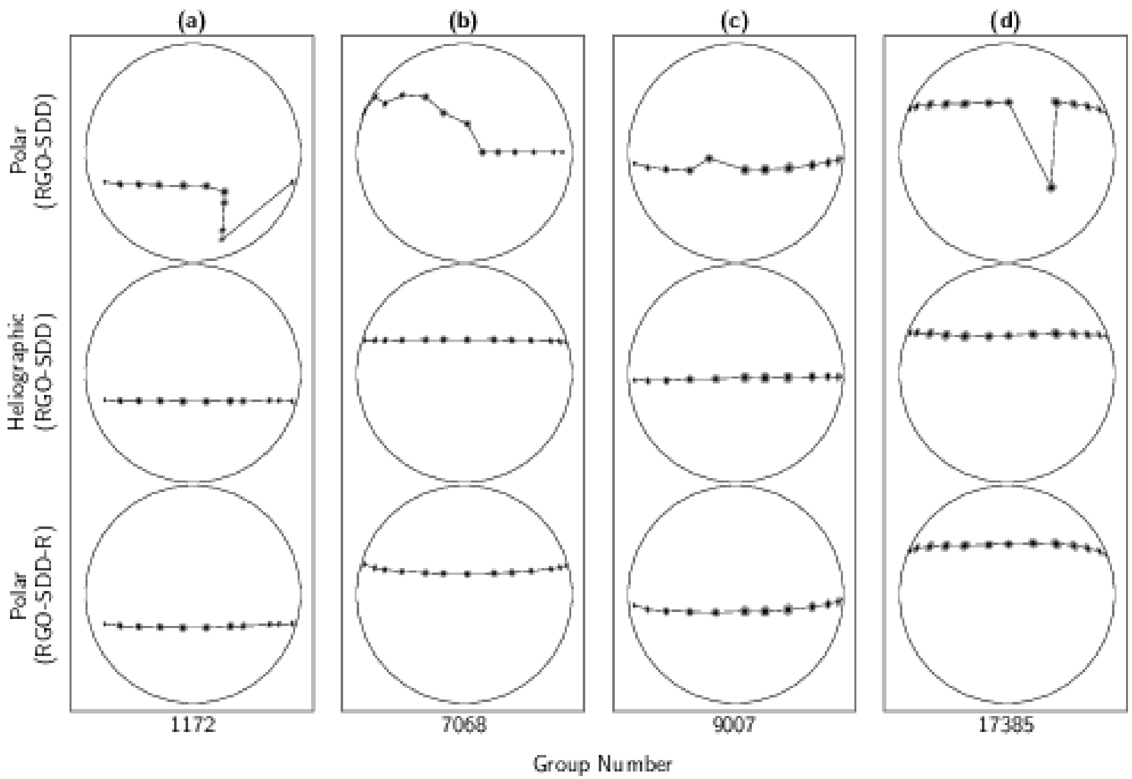
Corroboration of the Procedure

These two typographical errors have been perpetuated in the original sunspot digital dataset, which accounts for the two values of $\Delta\chi$ that lie outside the full range $-360° \leq \Delta\chi \leq +360°$.

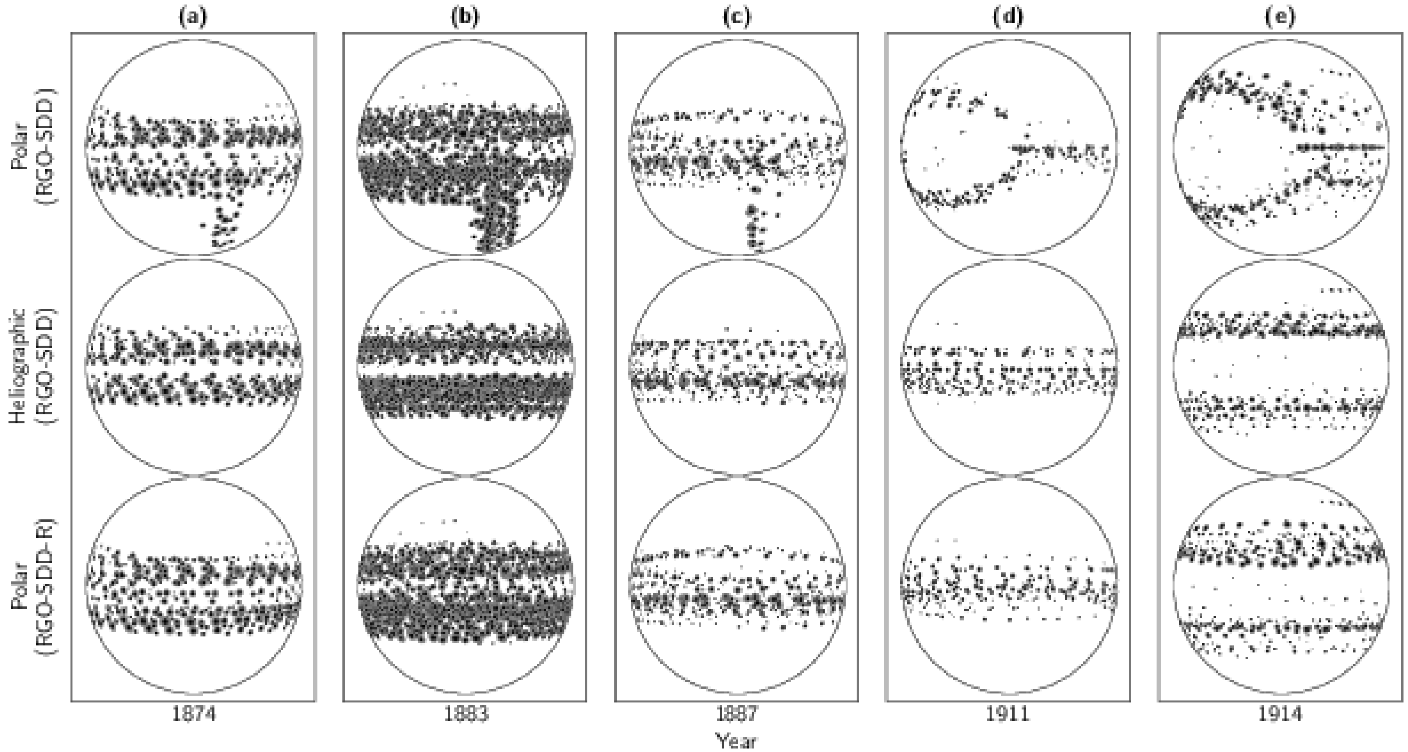
The identification of these two typographical errors in the printed RGO publications corroborates the intrinsic merit of the procedures formulated for the correction of the original sunspot digital dataset.

The mathematical equations can now be used to re-evaluate , or revise, the polar coordinates (r/R and χ) for the entire sunspot digital dataset, on the assumption that the heliographic coordinates (φ and λ) are correct .

Revised Polar Coordinates

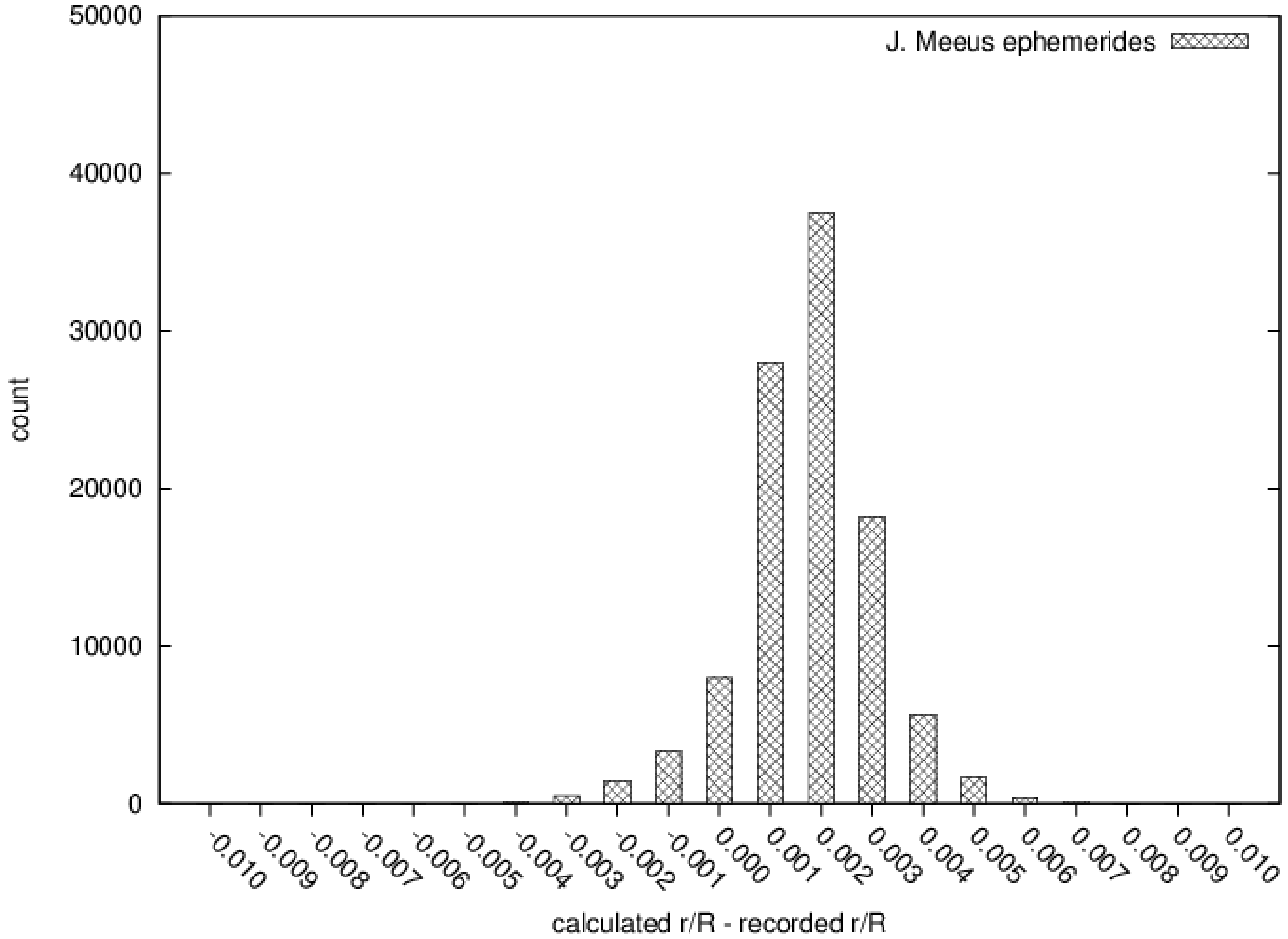


Revised Polar Coordinates



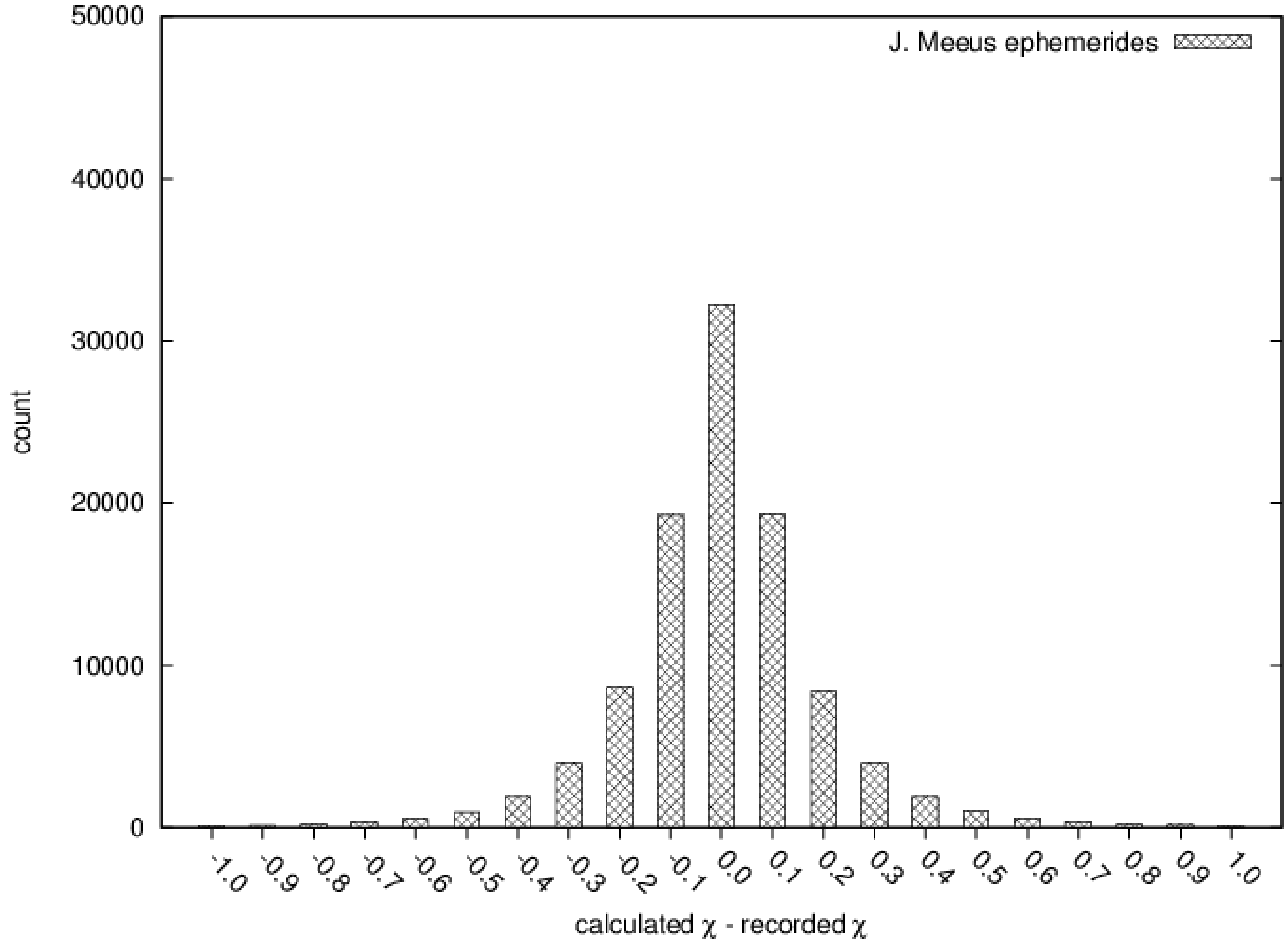
Marshall Space Flight Center Dataset

Small Discrepancies Δ (*r*/*R*): [– 0.01 ≤ Δ(*r*/*R*) ≤ + 0.01]



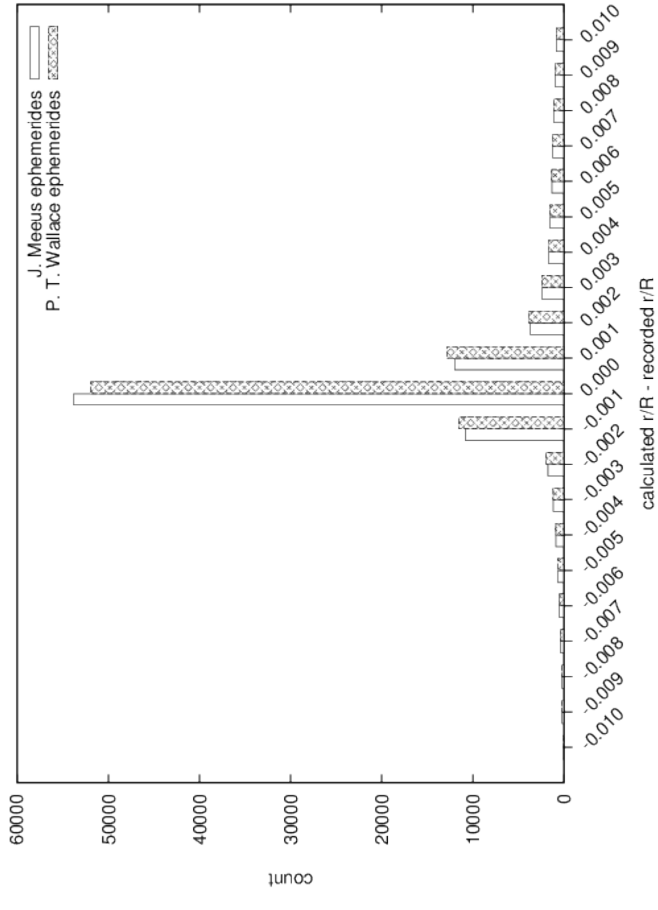
Marshall Space Flight Center Dataset

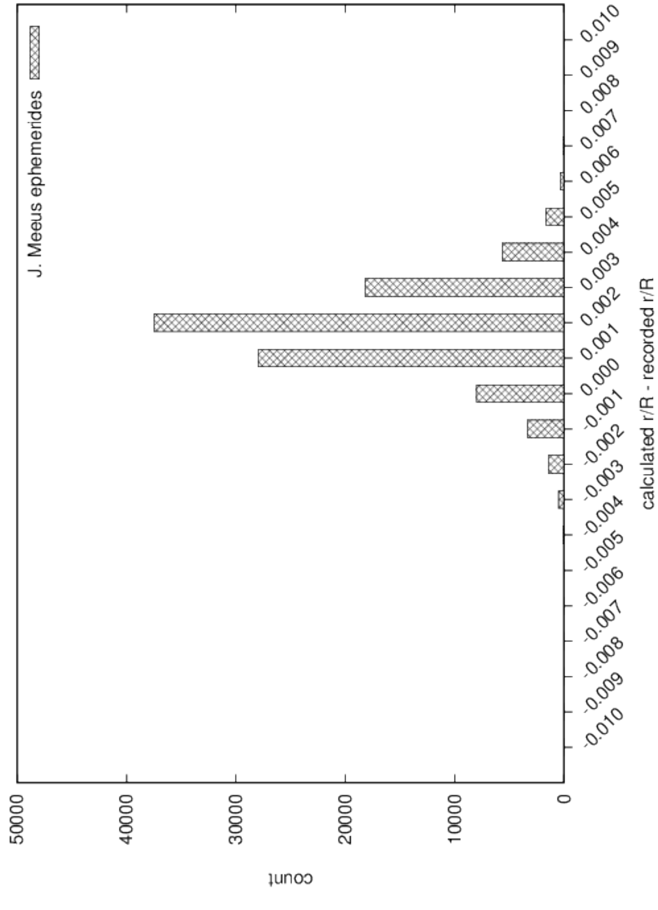
Small Discrepancies $\Delta\chi$: $[-1.0° \leq \Delta\chi \leq +1.0°]$



Comparison: NGDC versus MSFC

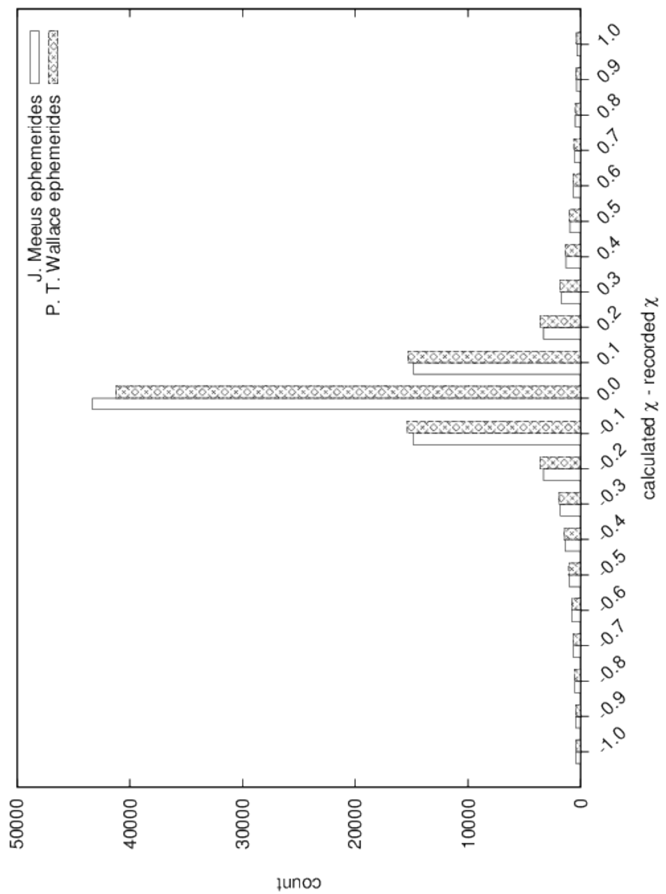
Small discrepancies Δ (*r/R*): [– 0.01 ≤ Δ(*r/R*) ≤ + 0.01]

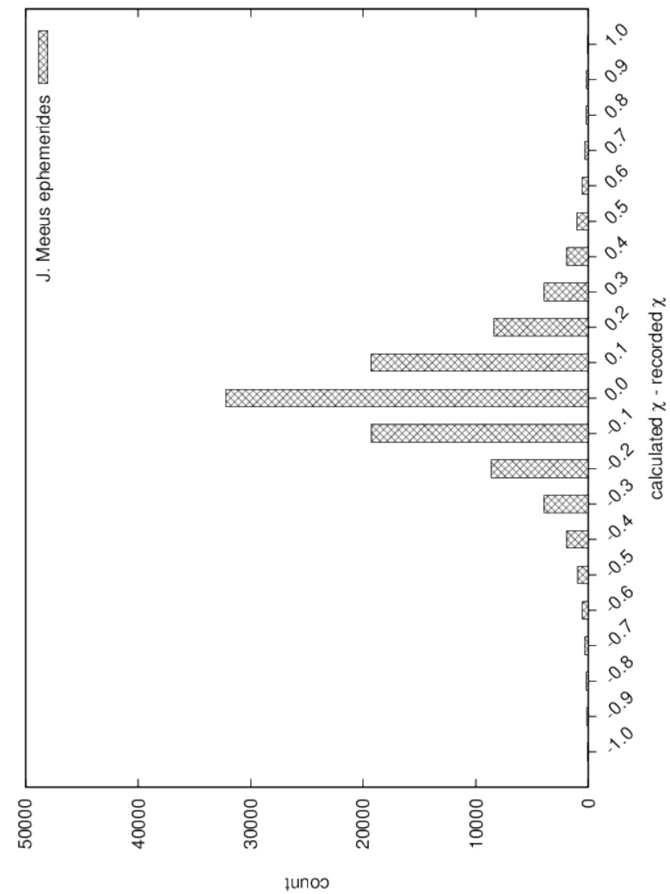




Comparison: NGDC versus MSFC

Small Discrepancies $\Delta\chi$: $[-1.0° \leq \Delta\chi \leq +1.0°]$





Formal Procedure for Detecting and Correcting Errors in the Greenwich Photo-heliographic Results

A comprehensive and detailed procedure for checking the original sunspot digital dataset has been formulated in an Appendix to Paper 2.

However, this procedure has not yet been implemented.

A somewhat simpler procedure has been developed at the National Geophysical Data Center to check the sunspot and faculae dataset.

(ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_WHITE_LIGHT_FACULAE or http://www.ngdc.noaa.gov)

The Greenwich Photo-heliographic Results: Initial Corrections to the Printed Publications

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Quality Control Procedures (NGDC)

Test 1: The data for each day should be from the same observatory and have the same single-letter code.

Test 2: The date should be consistent for a given month: this check is important when converting from a day number in the year to a calendar date.

Test 3: Date and time should be logical (month must be between 1 and 12; day must be between 1 and 31; and the time of observation must be between 00:00 and 24:00 UT).

Quality Control Procedures (NGDC)

Test 4: Latitude must be between 0 and 70 degrees and be preceded by “N” or “S”; central meridian (angular) distance must be between 0 and 90 degrees and be preceded by “E” or “W”.

Test 5: No data other than a space can be in a field designated a blank.

Test 6: The summation of individual sunspot and facular areas for a day should equal the total area in the summary line.

Table of Errors in the Published Greenwich Photo-heliographic Results (1874 – 1917)

Date: 1880 Feb 13

GMT (Civil): 43.437

Page Number: 65

Line Number: 26

Column Number: 18

Change From: (1886)

Change To: (1885)

Type of Error: Summation Error

Reason for the Change: Incorrect Arithmetic (Facular Area)

Table of Errors in the Published Greenwich Photo-heliographic Results (1874 – 1917)

Date: 1891 Jun 22

GMT (Civil): 172.473

Page Number: 35

Line Number: 39:

Column Number: 13

Change From: 2343

Change To: 2243

Type of Error: Group No. Error

Reason for the Change: Gr. 2243: Jun 21 – 29; Gr. 2343: Nov 7 – 12 (F)

Table of Errors in the Published Greenwich Photo-heliographic Results (1874 – 1917)

Date: 1906 Oct 15

GMT (Civil): 287.121

Page Number: 81

Line Numbers: 26 – 44

Column Numbers: 15 – 17

Type of Error: Multiple Omissions

(Reason for the Change): Position Angle, Longitude and Latitude Omitted.

Error Rate in the Printed Greenwich Photo-heliographic Results (1874 – 1917)