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The Greenwich Photo-heliographic Results (1874 – 1976): Summary of the Observations, Applications, Datasets, Definitions and Errors

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Abstract The measurements of sunspot positions and areas that were published initially by the Royal Observatory, Greenwich, and subsequently by the Royal Greenwich Observatory (RGO), as the *Greenwich Photo-heliographic Results (GPR), 1874 – 1976*, exist in both printed and digital forms. These printed and digital sunspot datasets have been archived in various libraries and data centres. Unfortunately, however, typographic, systematic and isolated errors can be found in the various datasets. The purpose of the present paper is to begin the task of identifying and correcting these errors. In particular, the intention is to provide in one foundational paper all the necessary background information on the original solar observations, their various applications in scientific research, the format of the different digital datasets, the necessary definitions of the quantities measured, and the initial identification of errors in both the printed publications and the digital datasets. Two companion papers address the question of specific identifiable errors; namely, typographic errors in the printed publications, and both isolated and systematic errors in the digital datasets. The existence of two independently prepared digital datasets, which both contain information on sunspot positions and areas, makes it possible to outline a preliminary strategy for the development of an even more accurate digital dataset. Further work is in progress to generate an extremely reliable sunspot digital dataset, based on the programme of solar observations supported for more than a century by the Royal Observatory, Greenwich, and the Royal Greenwich Observatory. This improved dataset should be of value in many future scientific investigations.

Key words Greenwich photo-heliographic results · Positions and areas of sunspots and faculae · Solar observations · Printed publications · Digital datasets · Scientific applications · Identifiable errors · Correcting the datasets

1. Introduction

An important series of measurements that provide the positions and areas of sunspots and faculae on the solar disk was published in printed form by the Royal Observatory, Greenwich, before 1948 and by the Royal Greenwich Observatory from 1948 onwards. In order to conform to current nomenclature and usage, all the sunspot and faculae data acquired during the long interval 1874 – 1976 will be ascribed to the Royal Greenwich Observatory (RGO) in this paper and the two following companion papers. This unprecedented series of sunspot and faculae measurements has been archived in both printed and digital form in several libraries and data centres throughout the World. Inevitably, there are some errors in both the printed publications and the digital datasets. The purpose of the present paper is to begin the important task of identifying and correcting these errors, primarily by providing a summary of essential background information on the *Greenwich Photo-heliographic Results (1874 – 1976)*. Particular attention is directed towards a comprehensive discussion of the original solar observations, their various applications in scientific research, the format of the different digital datasets, the necessary definitions of the quantities measured, and the identification of errors in both the printed publications and the digital datasets. The intention is to provide in this first paper all the basic definitions and information required to understand subsequent detailed discussions of particular errors. Following this strategy, two companion papers address the question of certain specific errors found in the initial investigations; namely, systematic and isolated errors in the digital datasets and typographic errors in the printed publications.

For brevity, the term “Paper 1” is used to refer to the present paper, the term “Paper 2” is used to refer to the first companion paper (Willis et al., 2013) on systematic and isolated errors in the first (original) sunspot digital dataset, and the term “Paper 3” is used to refer to the second companion paper (Erwin et al., 2013) on typographic errors in the printed *Greenwich Photo-heliographic Results (1874 – 1917).*

In a rather wider context, it is important to emphasise that the present set of three papers should not be misconstrued as a criticism of any previous work. On the contrary, the goal is to build upon the sterling efforts of many individuals over more than one-and-a-quarter centuries, using both new semi-automatic checking procedures and standard quality-control techniques. Indeed, the authors hope that the present papers and any sequels will form a fitting tribute to the meticulous efforts of the many scientists who have sought to provide an invaluable and largely homogeneous record of variable solar activity extending over more than a century.

2. The Royal Greenwich Observatory Programme of Solar Observations

The Royal Greenwich Observatory (RGO), formerly the Royal Observatory, Greenwich, maintained a very valuable programme of solar observations for more than a century. In particular, with the help of other solar observatories, the RGO acquired white-light photographs (photo-heliograms) of the Sun during an interval extending from (at least) 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 majority of white-light photographs obtained by the RGO were taken using photo-heliographs located at the following observatories: The Royal Observatory, Greenwich, until 1949 May 02 and the Royal Greenwich Observatory, Herstmonceux, from 1949 May 03; the Royal Observatory, Cape of Good Hope, South Africa; the Dehra Dun Observatory, North-West Provinces (Uttar Pradesh), India; the Kodaikanal Observatory, Southern India (Tamil Nadu); and the Royal Alfred Observatory, Mauritius. The remaining gaps in the combined collection of photographs from these named observatories were largely filled by photographs generously supplied by a number of other solar observatories, including Harvard College Observatory, Melbourne Observatory, Mount Wilson Observatory and the US Naval Observatory.

The exact method of measuring the areas of sunspots on the solar photographs has been described in the books by Newton (1958) and Howse (1975) and also in the RGO publication *Royal Observatory Annals Number 11* (Royal Greenwich Observatory, 1975). The paper by Willis, Davda, and Stephenson (1996) provides further details of the method of extracting sunspot information from the solar photographs. It suffices to note here that the sunspot areas were measured from the photographs with the aid of a large position micrometer that could be used for photographs of the Sun up to 12 inches in diameter. In the case of large or complex groups of sunspots, the chief components were measured individually; similarly in the case of groups near to the East or West limbs of the Sun, where the effects of foreshortening are appreciable. In other cases, the position of the centre of the group was either estimated by the measurer using the micrometer or derived during the subsequent computations. Whenever necessary, corrections have been applied to the measured distances and position angles (defined later) to allow for differential refraction: the details of this correction are given in the Introduction to the *Greenwich Photo-heliographic Results 1909* (Royal Observatory, Greenwich, 1910).

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)]. These RGO publications provide tabulations of the measured positions and areas (umbral and 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), that is the "projected areas" on the solar photographs, are corrected for foreshortening and the resulting corrected areas (in heliographic coordinates) are expressed in millionths of the Sun's visible hemisphere. The printed versions of the *Greenwich Photo-heliographic Results (GPR)* are now available online as PDF files at both the NOAA National Geophysical Data Center (NGDC), Boulder, Colorado (http://www.ngdc.noaa.gov/stp/solar/greenwich.html; use the 'GPR Publications' link) and at the UK Solar System Data Centre (UKSSDC) at the Rutherford Appleton Laboratory (http://www.ukssdc.ac.uk/wdcc1/RGOPHR/).

A brief statement should be made about the archiving of the RGO solar plates and contact prints within the United Kingdom. The reference collection of contact prints for the interval 1874 – 1917 is stored in the Cambridge University Library, although it is important to note that contact prints are not available for all days on which archived data can be found in the printed RGO publications. The collection of original solar plates for the interval 1918 – 1976 forms part of the entire archival collection of RGO plates, which are currently stored in the Momart warehouse in east London but will probably be moved to the Bodleian Library, Oxford, in due course, to ensure proper curation and public access. Digitised images made from the RGO solar plates (1918 – 1976) are available on request from the Mullard Space Science Laboratory (MSSL), University College London. A smaller collection of contact prints is stored in the UK Solar System Data Centre at the Rutherford Appleton Laboratory. These visible-light prints exist for most days in the interval 1910 – 1936 (June 30). Further details of these archive collections, as well as their accessibility, are given in Appendix A.

3. The RGO Sunspot Digital Datasets

A digital dataset that contains some of the information on sunspot positions and areas published (in printed form) by the Royal Greenwich Observatory (RGO) was distributed many years ago by the World Data Center A, Boulder, Colorado. The provenance of this original digital dataset, which is available online at the NGDC (http://www.ngdc.noaa.gov/stp/solar/greenwich.html; use the 'Sunspot Regions' link) and at the UKSSDC (http://www.ukssdc.ac.uk/wdcc1/greenwich) may be summarised succinctly as follows. This original digital dataset was compiled in 1981 – 1982. The starting point was a magnetic tape prepared previously by F. Ward, when working at the Air Force Cambridge Research Laboratories (AFCRL). This magnetic tape contained the RGO data for the interval 1876 – 1954. It seems likely 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 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); and (iii) the "Positions and Areas of Sunspots for Each Day in the Year" sections, as well as the "General Catalogue of Sunspots" sections, of the subsequent RGO publications (1956 – 1976). The additional data for these two intervals were typed in twice; the two versions were then compared and errors were corrected.

However, it appears possible that, at least for sunspot measurements in the interval 1876 – 1954, the polar coordinates were calculated from the heliographic coordinates. In addition, a different definition of the polar angle (clockwise, anticlockwise) was initially used by the different compilers. Further information on the historical development and use of this original sunspot digital dataset is presented in Section 4. Finally, it should be noted that the format of this original digital dataset has some advantages in certain scientific investigations (e.g., Willis, Henwood, and Stephenson, 2006, 2009) because the projected sunspot areas, which were obtained directly from measurements of sunspot areas on the solar photographs, are given explicitly and do not have to be re-derived from the corrected sunspot areas.

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"). Pages 7 – 9 of the User Guide (PDF format) describe the format of the sunspot data information in the Region Summary section of "The Weekly" (see http://www.swpc.noaa.gov/weekly/index.html). Most data are from the US Air Force (USAF) Solar Optical Observing Network (SOON) and its predecessor. This network comprises solar observatories located in such a way that 24-hour synoptic monitoring can be maintained (Balmaceda et al., 2009). The basic observatories are Boulder (a joint NOAA/USAF observatory) and the constituents of the network of the USAF (Holloman, Learmonth, Palehua, Ramey and San Vito). In addition, data from the Mount Wilson Observatory are included. For the Region Summary list, the Boulder Solar Observatory was used as the primary data source during the interval 1976 – 1982, with other SOON stations filling in when Boulder data were not available. This extension to the RGO programme is referred to variously in the literature; for example, SOON, USAF, USAF/NOAA and USAF/Mount Wilson.

Although responsibility for the RGO programme of solar observations was transferred formally to the Heliophysical Observatory, Debrecen, Hungary, at the end of 1976 (Graham Smith, 1978), the original (or first) sunspot digital dataset (see Section 5) has been extended throughout the interval 1977 – 1982 (August 15) using data solely from the Solar Optical Observing Network (SOON), as given in “The Weekly” reports. These data are quick-look preliminary data, however, and have some limitations because they are estimated values from sunspot drawings and consequently have possible large errors in measurements, particularly near the limb of the solar disk. Data from the Solar Optical Observing Network (SOON) were used after 1976 because data from the Heliophysical Observatory, Debrecen, were not available initially. By considering the sunspot data recorded at a number of different solar observatories, Balmaceda et al. (2009) have developed a homogeneous dataset of sunspot areas extending over more than 130 years. However, the present paper and the two companion papers are concerned exclusively with the various errors in the printed and digital datasets resulting from the programme of solar observations supported by the RGO during the interval 1874 – 1976.

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 (NGDC), 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” sections of the RGO publications have been key-entered anew. Until recently, this second dataset has been of slightly more limited value to the scientific community because, in its initial form, it did not contain digital data for a few of the earlier years. At the inception of the project, the relevant RGO printed publications for the interval 1878 – 1885 were not immediately available at the NGDC but this omission has since been rectified by the inclusion of digital data prepared separately by a contractor sponsored by an individual scientist. The digital data for the interval 1878 – 1885 have now been reformatted and hence this second digital dataset, which is also available online at the NGDC (http://www.ngdc.noaa.gov/stp/solar/greenwich.html; use the ‘Solar White Light Faculae’ link), will probably be of even greater value to the scientific community in the future.

It must be conceded, however, that 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 definitely contain some errors. More specifically, during the early years (before 1918), the position of a sunspot sometimes appears to change anomalously in the original digital dataset, which contains only sunspot information. Such “anomalies” appear in the polar (projected) coordinates, namely radial distance and position angle, and not in the heliographic coordinates, namely heliographic latitude and longitude, as shown in Paper 2. Similarly, there are some errors in the second dataset, which also contains data on faculae, particularly during the (initially) “missing” years (1878 – 1885). Although the transcriptional errors have now largely been eliminated, further errors arise from typographic errors in the printed Greenwich Photo-heliographic Results. The identifiable typographic errors found in the interval 1874 – 1917 are discussed and tabulated in Paper 3.

4. Historical Development of the Sunspot Database and its Scientific Applications

As already mentioned, the observations of sunspot positions and areas compiled at the Royal Greenwich Observatory (RGO) provide information on variations in solar activity over more than a century. This series of observations is one of the few long-term solar datasets available to the scientific community, although it is not as long as the well-known series of sunspot numbers. Over many years, different authors have used this unique and expanding dataset for various investigations of solar activity. In particular, the RGO sunspot observations have been used for developing solar circulation models, for studies of differential rotation rate, for studies of total solar irradiance, and most recently for developing models of solar meridional circulation and for solar-cycle prediction studies. These topics have been reviewed in a comprehensive survey article by Lockwood (2005).

Research papers that are especially relevant in the context of the development of the RGO sunspot digital datasets are referenced individually in the following discussion.

Carrington (1858) investigated the distribution of solar spots in latitude and published the position measurements of sunspot observations made from his observatory at Redhill, Surrey, England, during the interval 1855 November 9 to 1861 March 24 (Carrington, 1863). Maunder (1904) and his wife plotted the famous “Maunder” butterfly diagram for the interval 1874 – 1902, using Greenwich sunspot position data, to illustrate the equator-ward movement of sunspot groups during the course of a solar cycle. Figure 1 shows the extended butterfly diagram for the entire interval 1874 – 1976. Tuominen (1941) computed mean latitudinal drifts from Greenwich sunspot data, using only those spots observed during two consecutive solar rotations: his dataset consisted of 1151 recurrent groups observed during the interval 1874 – 1935. This work was extended in subsequent papers to cover the interval 1874 – 1976 (Tuominen and Kryöläinen, 1981, 1982; Tuominen, Tuominen, and Kyröläinen, 1983). Other scientists have used the Greenwich sunspot data for similar research (e.g., Li, Yun, and Gu, 2001).

As noted in Section 3, Ward (1964) key-entered the published Greenwich data from the “Ledger” tabulations (second section in the RGO books) into a digital dataset that forms the basis of the present digital dataset on the NOAA National Geophysical Data Center (NGDC) website. Ward’s interest was the general circulation of the solar atmosphere. He hypothesised that the layer in which sunspots are imbedded should exhibit a non-axially symmetric pattern of the Rossby type. Using ten years of Greenwich data (1935 – 1944), he found significant correlation of spot group proper motions. These waves may transport angular momentum from higher latitudes towards the equatorial regions. Ward (1965) extended these results to three sunspot cycles (1925 – 1954). In addition, Ward (1966) determined the solar-rotation rate from the motion of identifiable features. He found that the average longitudinal motion of a sunspot is a function of its size and shape. Ward (1973) investigated the latitudinal motion of sunspots as a function of size, spot-group shape, group lifetime, and magnetic class, as well as the latitudinal motions of leading and following spots.

As also noted in Section 3, Hoyt and Eddy (1982) updated Ward's RGO sunspot digital dataset and used it to develop a model for total solar irradiance. These authors reconstructed the day-to-day variations of the solar constant for slightly more than a century (1874 – 1981). Moreover, Hoyt was the first to use the NOAA/USAF SOON (Solar Optical Observing Network) data to update sunspot areas after the programme of solar observations at the Royal Greenwich Observatory was terminated at the end of 1976. This updated digital dataset was deposited at the NOAA National Geophysical Data Center (NGDC). Much more recently, Balmaceda et al. (2009) have generated a homogeneous sunspot-areas dataset covering more than 130 years. These authors have shown that the use of uncalibrated sunspot-areas datasets can seriously affect the estimate of solar irradiance variations.

The digital dataset generated by Hoyt and 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 work was terminated in 2005. Some of the errors mentioned in Section 3 do not occur in the version of the digital dataset stored at the MSFC, which is also available online (http://solarscience.msfc.nasa.gov/greenwch.shtml), although the various corrections that have been made to the MSFC version have not been fully documented (D. H. Hathaway, personal communication, 2008). Hathaway, Wilson, and Reichmann (2002) investigated sunspot-cycle characteristics, using the Greenwich sunspot-area data for the interval 1874 – 1976, augmented with data from the NOAA/USAF SOON network. An inter-comparison between Greenwich, NOAA and overlapping Mt. Wilson data indicated that the NOAA sunspot areas need to be increased by 40% to match earlier Greenwich data, in order to give a reasonably uniform dataset. This conclusion has been confirmed independently by Balmaceda et al. (2009). Hathaway et al. (2003) analysed butterfly diagrams for the latitudinal migration of sunspots with time over a period of 128 years. In particular, these authors examined the drift of the centroid of sunspot area towards the equator in each hemisphere, using the extended Greenwich dataset (1874 – 2002), and found that the drift rate slows as the centroid approaches the equator. Moreover, Hathaway and Choudhary (2008) used the updated Greenwich dataset (130 years of data) to determine the decay rate of sunspot group areas. They excluded observations of groups more than 60 degrees in longitude from the central solar meridian and only included data when at least three days of observations were available following the date of maximum area for a group's passage across the solar disk. With these constraints, they found that high-latitude spots tend to decay faster than low-latitude spots. The dataset for the interval 1874 – 2002 consists of 18 000 measurements of sunspot-group decay rate.

Other recent papers have used the valuable RGO sunspot dataset for studies of solar-cycle characteristics, as well as for various predictions and models. For example, Ruždjak et al. (2004) studied the deceleration of the rotational velocities of sunspot groups during their evolution. Javaraiah, Bertello, and Ulrich (2005) provided an interpretation of the differences in solar differential rotation during even and odd sunspot cycles, while Kitchatinov and Olemskoi (2005) studied active longitudes of the Sun and their rotation periods and statistical significance. A new model of total solar irradiance, based on sunspot areas, has been proposed by Preminger and Walton (2005). Brajša et al. (2007) have investigated the dependence of solar rotation on both solar activity and the interplanetary magnetic field. Ivanov (2007) studied active longitudes in terms of their structure, dynamics and rotation for Solar Cycles 12 – 23, while Dikpati (2008) predicted Solar Cycle 24 using various dynamo-based tools. The cycle dependence of the longitudinal-latitudinal sunspot motion correlations has been investigated by Muraközy and Ludmány (2008). Tlatov (2009) discussed the prediction of the amplitude of solar activity cycles, using the recorded number of sunspot groups, and Miletskii and Ivanov (2009) studied the latitude characteristics of the sunspot formation zone and the 11-year solar activity cycle. Babij, Efimenko, and Lozitsky (2011) examined the statistical characteristics of large sunspots in Solar Cycles 17 – 23, and Badalyan (2011) studied the latitude distributions of sunspots and their north-south asymmetry. The solar-cycle variations in the growth and decay of sunspot groups have been investigated by Javaraiah (2012).

Similarly, some recent papers have indicated the value of sunspot areas and associated solar-activity indices for studying solar variability over prolonged periods of time. For example, Vaquero, Gallego, and Sánchez-Bajo (2004) reconstructed a monthly homogeneous sunspot-area series since 1832, and Baumann and Solanki (2005) investigated the size distribution of sunspot groups in the interval 1874 – 1976. Pelt, Tuominen, and Brooke (2005) investigated century-scale persistence in the longitude distribution in sunspot groups. Sarychev and Roshchina (2006) used Greenwich data to study total sunspot area as a solar activity index and, by utilising proxy data, these authors extended the series back to 1700. Nagovitsyn, Makarova, and Nagovitsyna (2007) discussed the series of classical solar activity indices available from the Kislovodsk data. Tuominen, Pelt, Brooke and Korpi (2007) noted that the sunspot distribution is highly clustered in longitude, with a coherence time of about 10 Carrington rotations. Zhang, Wang, Du, Cui and He (2007) studied the long-term behaviour of active longitudes for solar X-ray flares. Sarychev and Roshchina (2009) compared three solar activity indices, namely relative sunspot number, normalised sunspot group number and total sunspot area; they claim that the Hoyt–Schatten series of group sunspot numbers may be less reliable than the well-known Wolf series of sunspot numbers. Henwood, Chapman, and Willis (2010) examined long-lived recurrent sunspot groups in the Greenwich data to search for evidence of decadal change, developing machine-learning procedures to identify these long-lived groups. Solar active regions have been studied by Pelt, Korpi, and Tuominen (2010), using a nonparametric statistical analysis.

Jiang, Cameron, Schmitt, and Schussler (2011) have studied the solar magnetic field since 1700, using a physical reconstruction of total, polar and open flux.

5. Definitions and Format of the Sunspot Digital Datasets

For clarity and precision, it is first necessary to introduce some simplifying terminology. This terminology will be helpful not only in the present paper but also in the following companion papers. The printed 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)] will be referred to as the “RGO printed observations, bulletins and annals”, which can conveniently be abbreviated to RGO–POBA. The first (original) RGO sunspot digital dataset that contains information on only sunspots will be referred to as the “RGO sunspot digital dataset”, which is abbreviated to RGO–SDD. Similarly, the second digital sunspot dataset that contains information on both sunspots and faculae will be referred to as the “RGO sunspot and (&) faculae digital dataset”, which is abbreviated to RGO–S&FDD. The abbreviation RGO–POBA is essentially synonymous with the abbreviation GPR (Greenwich Photo-heliographic Results) but the former abbreviation is preferred because it indicates explicitly the changes in the titles of the Greenwich publications and also because it is analogous to the abbreviations RGO–SDD and RGO–S&FDD.

The printed RGO publications (RGO–POBA) are based largely on a standard format used throughout the long interval 1874 – 1976. Certain differences in the presentation of information on the positions and areas of sunspots (and faculae) inevitably occurred over this approximately 100-year interval. Several of these differences are mentioned briefly in the present section but a full discussion of every minor change in the format of the RGO printed publications is beyond the intended scope of the present paper. Fortunately, most of these minor changes of format are unlikely to cause researchers any real difficulties, although the intention is to issue an informative *User Guide* to the various printed and digital RGO sunspot datasets in due course.

As Paper 2 considers errors in the first RGO sunspot digital dataset (RGO–SDD), it is necessary to discuss in detail the format of this particular dataset. The format of the RGO–SDD may be summarised succinctly 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). Sunspots are defined by the Greenwich sunspot group number until 1976 December 31, when the programme of Greenwich sunspot observations ceased (see Sections 2 and 3), 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 single digit is used to distinguish between them.

Two separate classification schemes have been used to describe the various types of sunspot group. Dr F. Ward of the Air Force Cambridge Research Laboratories (currently the Air Force Research Laboratory, Kirtland Air Force Base, New Mexico) used the Mount Wilson magnetic classification scheme (Bray and Loughhead, 1964) for sunspot data recorded during the interval 1922 – 1955. In this scheme, a single digit is used to define five different categories: 0 = classification is missing; 1 = alpha, a unipolar group in which all spots have the same magnetic 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; and 5 = unclassified, if the classification did not match types 1 – 4. In the second scheme, 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; and 9 = other.

Strong reservations must be expressed about the integrity and value of the "Greenwich" tenfold classification system. First, the origin of this classification system is not completely clear. Although it appears to be based on the RGO Footnotes that are presented in the "Measures" sections of the *Greenwich Photo-heliographic Results*, which give the positions and areas of sunspots and faculae, it is not presented explicitly in any RGO publication. It seems likely that the tenfold classification system was added during the compilation of the original sunspot digital dataset (RGO–SDD). Second, a preliminary inspection of the digital scans of the glass plates, for the largest projected sunspot areas in each of the ten classes (0 – 9), has indicated that the "Greenwich" tenfold classification system is an unrealistic simplification of the more detailed information presented in the printed RGO Footnotes. It is important to emphasise, however, that the limitations of this tenfold classification system do not compromise other information in the original sunspot digital dataset (RGO–SDD), which is extracted directly from the RGO publications. Although beyond the intended scope of the present paper, future effort should be directed towards providing links in the digital datasets to the detailed RGO Footnotes. Moreover, any new "Greenwich" classification system should take account of the existing Zürich sunspot classification systems; both the revised Waldmeier system summarised by Kiepenheuer (1953) and the modified system introduced by McIntosh (1990).

The RGO–SDD provides four separate measures of sunspot area associated with each sunspot group: (i) observed (projected) umbral area in millionths of the solar disk; (ii) observed (projected) whole-spot (umbral plus penumbral) area in millionths of the solar disk; (iii) umbral area, corrected for foreshortening and expressed in millionths of the visible solar hemisphere; and (iv) 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 visible hemisphere.

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) the polar angle measured **anticlockwise** (N → E → S → W → N) from the north pole of the Sun's axis (0.0º to 360.0º); (iii) Carrington heliographic longitude; (iv) heliographic latitude (positive = North, negative = South); and (v) central meridian (angular) distance (positive = West, negative = East). All angles are quoted to an accuracy of 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 (Ward, 1964). The recorded values of heliographic latitude and longitude are based on the Carrington rotation rate, which assumes a (sidereal) solar-rotation period that is invariant with respect to latitude and approximately equal to 14.184 degrees per day — corresponding to one (sidereal) solar rotation every 25.38 days.

The RGO–SDD does not provide information on the positions and areas of sunspots for every day in the interval 1874 – 1976. The fourth column of 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 (i.e., data archived in the RGO–POBA). Subsequently, archived data are available for most days of the year. In addition, throughout the interval 1874 – 1976, no information is stored in the RGO–SDD if no sunspots are present on the solar disk. (This last statement is not true for the RGO–S&FDD, since information is stored when only solar faculae are present.) In certain scientific investigations (cf. Willis, Henwood, and Stephenson, 2006, 2009), however, it is helpful to know the exact time of the appropriate solar photograph, even if no sunspots are present on the solar disk.

Moreover, position data are subject to large and irregular fluctuations near the solar limb. For his scientific studies, Ward (1964, 1965) eliminated all spots greater than or equal to 0.9 of the (apparent) distance from the centre of the solar disk to the limb, thereby eliminating roughly 26 degrees of solar longitude near each limb, or about 29 percent of the available data. More data were eliminated to allow for large errors in the published data, errors in transcription to a suitable form for analysis, and changes in position of the centre of gravity of the groups (due to factors other than large-scale fluid motions). Groups with a daily change in latitude greater than or equal to 2 degrees, or a daily change in longitude greater than or equal to 3 degrees, were eliminated (Ward, 1965). As shown in the earlier study (Ward, 1964), these constraints resulted in the elimination of 4 percent of the usable data. However, Ward (1965) also noted that, if no data were eliminated, the results were similar in all respects to those with the cut-offs (Ward, 1964) but there was a higher variability as a function of time and latitude.

In addition, Hathaway (http://solarscience.msfc.nasa.gov/greenwch.shtml) notes that quantities such as sunspot area are not uniform across datasets or even within a given dataset. For example, the ratio of the umbral area (the darker part of the sunspot) to whole-spot area (including the lighter penumbra) changes abruptly in 1941/1942 and the ratio of the whole-spot area to the sunspot number changes dramatically with the start of the USAF/NOAA data. In an effort to correct for such variations, Hathaway compared these data with the more uniform data compiled by Howard, Gilman, and Gilman (1984) for the Mount Wilson photographic plate collection from 1917 to 1982. This comparison identified three epochs for discrepant sunspot areas: for 1917 – 1941, Mt. Wilson umbral area = 0.35 RGO umbral area and Mt. Wilson whole-spot area = 0.067 RGO whole-spot area; for 1942 – 1968, Mt. Wilson umbral area = 0.41 RGO umbral area and Mt. Wilson whole-spot area = 0.067 RGO whole-spot area; for 1969 – 1981, Mt. Wilson umbral area = 0.59 RGO/USAF/NOAA umbral area and Mt. Wilson whole-spot area = 0.094 RGO/USAF/NOAA whole-spot area.

The sunspot digital dataset (RGO–SDD) was generated mainly by using the information published in the annual tables initially titled "Ledgers of Areas and Positions of Groups of Sun Spots" (which are included in the RGO–POBA). This conclusion is based partly on the fact that projected sunspot areas (in millionths of the solar disk) are given explicitly, as are the corrected sunspot areas (in millionths of the visible solar hemisphere), and partly on the fact that there are entries (interpolated values) when no photograph exists. Conversely, the sunspot and faculae digital dataset (RGO–S&FDD) has been generated by using information published in the annual tables initially titled "Measures of Positions and Areas of Sun Spots and Faculae" (which are also included in the RGO–POBA) and hence this digital dataset only contains corrected sunspot areas. Otherwise, the format used in the RGO–S&FDD is essentially similar to that used in the RGO–SDD, although the former has the added advantage of including a single-letter observatory code.

This single-letter observatory code is a minor modification of the original RGO observatory code (A = Me and T = Mt. W) and applies exclusively to the interval 1874 April 17 – 1955 December 31. In the interval 1956 – 1976, the printed RGO publications (RGO–POBA) use some of the defunct single-letter observatory codes again for other observatories (see Appendix B). To overcome this difficulty, a new four-letter observatory code is defined in Table 1, together with the original observatory codes employed in the printed RGO publications — some of which are clearly ambiguous.

For future reference, Table 1 also gives the geographic coordinates and altitude of each solar observatory that has contributed to the *Greenwich Photo-heliographic Results* (1874 – 1976), along with brief details of the appropriate range of dates and the total number of photographs supplied by each observatory that were used to derive the published measurements (RGO–POBA). A total of 36 788 solar photographs were measured to produce the published values of the positions and areas of sunspots and faculae. Therefore, the programme of solar observations organised under the aegis of the Royal Greenwich Observatory provided invaluable sunspot information over a remarkably high proportion (98%) of the time interval 1874 April 17 – 1976 December 31 (37 514 days).

Further information on the assignment of the old and new observatory codes and a summary of the sources used to determine the geographic coordinates and altitude of each contributing solar observatory are presented in Appendix B.

Researchers referring back to the *printed* copies of the *Greenwich Photo-heliographic Results (GPR)* should note that in the early years (up to the end of 1884) time was reckoned from Greenwich Mean Noon (Solar Time) and not Greenwich Midnight (Civil Time). Moreover, January 1 is defined to be Day 0 in the interval 1874 – 1955 but is defined to be Day 1 in the interval 1956 – 1976. Likewise, in the early years (up to 1881 December 21) angles were measured in degrees and minutes not decimal degrees, as noted previously in this section. The scope for confusion between these different ways of measuring time and angles is compounded by the fact that an improved and supplementary printed version of the "Measures of Positions and Areas of Sun Spots and Faculae" sections of the GPR for the interval 1874 – 1877 was issued much later in the publication titled *Photo-heliographic Results, 1874 – 1885* (Royal Observatory, Greenwich, 1907), in which time is reckoned from midnight and angles are measured in decimal degrees. However, in the original sunspot digital dataset (RGO–SDD) stored at the NOAA National Geophysical Data Center (NGDC) and the UK Solar System Data Centre (UKSSDC), all times are reckoned from Greenwich Midnight (Civil Time), January 1 is always defined to be Day 1, and all angles are given in decimal degrees. Conversely, January 1 is defined to be Day 0 in the sunspot and faculae digital dataset (RGO–S&FDD) within the interval 1874 – 1955.

It is important to note that the publication *Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907), which also contains supplementary results from photographs of the Sun taken at Greenwich, at Harvard College (USA), at Melbourne, in India, and in Mauritius, provides a list of errata and additions for the years 1877 – 1885 (pages xiii to xxiii). The first part of this list (pages xiii to xviii) provides amendments to the *original* RGO publications for the years 1877 – 1885; the second part (pages xix to xxi) provides amendments to a publication by the Solar Physics Committee (1891), which includes additional results for Dehra Dun and Melbourne for the years 1878 – 1881; and the third part (pages xxii to xxiii) provides amendments to the subsequent tables (pages 1 – 321) in the *same* publication as the list of errata and additions, namely *Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907). Most of these errata and additions appear to have been incorporated in the RGO–SDD. However, rigorous checking is very time-consuming because almost all of the errata and additions refer to the "Measures" sections of the RGO–POBA, whereas the RGO–SDD is based largely on the "Ledgers" sections. Some of the errata and additions have already been incorporated in the RGO–S&FDD and the remainder are currently being incorporated in this latter dataset.

A further brief comment should be made on the content of the RGO–SDD, which includes sunspot data up to 1982 August 15. Since the programme of RGO solar observations ceased at the end of 1976, sunspot information in the interval 1977 – 1982 has been gleaned from other sources, as noted in Section 3. There has been some discussion in the scientific literature about the homogeneity of this extended dataset (Foster, 2004; Balmaceda et al., 2009) and hence it should be stressed again that the present set of papers is concerned exclusively with the programme of solar observations (1874 – 1976) maintained by the Royal Greenwich Observatory (RGO).

The many research papers referenced in Section 4 discuss various characteristics of solar activity that were found using the first sunspot digital dataset (RGO–SDD), which was prepared originally by Ward (1964). Over the years, this digital dataset has been corrected as needed for specific applications, with no detailed record being kept of the various changes. The primary goal of the present set of papers is to identify some remaining errors in the sunspot digital datasets (RGO–SDD and RGO–S&FDD) and also identify a relatively small number of errors in the printed Greenwich Photo-heliographic Results (RGO–POBA). A secondary goal is to initiate a policy of compiling and maintaining a proper record of all changes to the digital datasets.

6. Preliminary Strategy for Correcting the RGO Sunspot Digital Datasets

The purpose of this section is to outline in rather general terms a possible strategy for correcting the RGO sunspot digital datasets. An appendix to the following paper (Paper 2) by Willis et al. (2013) provides a more formal specification of a detailed procedure for checking the original sunspot digital dataset (RGO–SDD). The fact that the two separate sunspot digital datasets (RGO–SDD and RGO–S&FDD) have been prepared quite independently means that there is “duplication” of some of the information on sunspots but not faculae. This “duplication” is a valuable asset from the viewpoint of correcting the sunspot digital datasets. In principle, the two digital datasets could be used to compare semi-automatically the two independent entries for specific variables such as time, sunspot position and sunspot area, provided two independent entries co-exist. Any discrepancies between the values in RGO–SDD and RGO–S&FDD could then be resolved by recourse to the printed publications (i.e., RGO–POBA). This semi-automatic checking procedure should be much more efficient than checking either sunspot digital dataset against the printed publications, which would be an inordinately time consuming task. Ideally, the semi-automatic checking procedure should be performed in conjunction with the quality control procedures discussed in the companion paper (Paper 3) by Erwin et al. (2013), in order to ensure the veracity of the results in the printed publications.

It should be noted, however, that comparisons between the two separate sunspot digital datasets, namely RGO–SDD and RGO–S&FDD, involve some preparatory computations for sunspot observations in the interval 1874 – 1915. These preparatory computations are required because the former dataset (RGO–SDD) gives only average daily values of the areas and positions for each sunspot group, whereas the latter dataset (RGO–S&FDD) provides separate daily values of these quantities for each individual component of a sunspot group up to the end of 1915, as in the printed observations, bulletins and annals (RGO–POBA). Therefore, for sunspot observations in the interval 1874 – 1915, it is necessary to derive weighted averages of these individual components in the RGO–S&FDD before comparing the two separate digital datasets. Following the procedure adopted in the preparation of the *Greenwich Photo-heliographic Results (GPR)* throughout the subsequent interval 1916 – 1976, these weighted averages are formed using the whole-spot (umbral plus penumbral) area of each individual component of a sunspot group as the appropriate weight. Specifically, let m_i denote the measurement of any quantity (e.g., radial distance or polar angle) for the *i*-th component (or element) of a sunspot group comprising n components, and let W_i denote the measured whole-spot area of this component. Then the weighted average, $\overline{m}$, of the measured quantities m_i ($1 \le i \le n$) is defined by the following equation:

$$\overline{m} = \left(\sum_i^n W_i m_i \right) \Bigg/ \left(\sum_i^n W_i \right). \qquad (1)$$

The existence of two sunspot digital datasets also makes it possible to derive a single improved dataset. For example, there is no entry in the RGO–SDD if no sunspots were detected on the solar disk, whereas there are entries in the RGO–S&FDD when only solar faculae were detected. Therefore, it would be possible to derive an improved sunspot digital dataset that includes the precise time of some (but not all) photographs devoid of sunspots. There are other minor differences between the two digital datasets. In the early RGO observations, two photographs were often taken on the same day. In such situations, the RGO–SDD presents average values of the variables applicable to the mean time of the two photographs, whereas the RGO–S&FDD presents the values of the variables separately for both photographs. Therefore, a user of the RGO–S&FDD can select just one of the actual observations (rather than an average of two observations) on those days when two solar photographs were taken.

Moreover, the RGO–SDD sometimes contains entries for days on which no solar photograph exists, at least during the early years. This "fabrication" of data appears to have occurred because the "Ledgers of Areas and Positions of Groups of Sunspots" for the years 1874 – 1885 give interpolated values of some quantities (in parentheses) when no photograph exists. These interpolated values are based on measurements derived from photographs taken on days immediately before and after the day for which no photograph exists. The authors believe that it would be preferable to exclude interpolated values in any improved sunspot digital dataset because their inclusion without qualification implies an unwarranted accuracy of measurement. A user of an improved sunspot digital dataset can always elect to use interpolated values in particular applications.

Likewise, there is some "redundancy" in both datasets, in the sense that the positions of sunspots (but not faculae) are given in both polar coordinates and heliographic coordinates (see Figures 1 and

7 in Paper 2). The normal procedure to determine the positions and areas of sunspots on the solar surface is to measure these quantities on the solar photographs (see Section 2). The position of each sunspot or sunspot group is then expressed in polar coordinates on the apparent solar disk. These polar coordinates are the measured distance of the spot from the centre of the Sun's apparent disk and the position (polar) angle of the spot from the North Pole of the Sun's axis measured anticlockwise. Other vital information is the measured radius of the Sun on the photograph, the tabular semi-diameter of the Sun in arc seconds (taken from the *Nautical Almanac* or *Astronomical Ephemeris*) and the heliographic latitude and longitude of the Earth. A set of mathematical equations is then used to derive the heliographic latitude and longitude (i.e., the heliographic coordinates) of the sunspot or sunspot group, as summarised briefly in the *Royal Observatory Annals Number 11* (Royal Greenwich Observatory, 1975). This set of mathematical equations, which is presented in Paper 2, can be solved in the inverse (or reverse) sense to determine the polar coordinates if the heliographic coordinates are known. Since the heliographic coordinates shown in Figure 1 (lower frames) of the companion paper (Paper 2) by Willis et al. (2013) appears to be correct, it is possible to recalculate all polar coordinates from the heliographic coordinates and then compare these recalculated polar coordinates with the original polar coordinates in the RGO sunspot digital dataset (RGO–SDD), or the archived values in the RGO printed publications (RGO–POBA).

The recalculation of polar coordinates from heliographic coordinates is complicated by the fact that the solution of the mathematical equations requires prior knowledge of the position angle (P_0) of the north end of the Sun's axis, measured eastwards (anticlockwise) from the geocentric north point (N) on the solar disk, as well as the heliographic latitude (B_0) and longitude (L_0) of the Earth, as defined in the *Royal Observatory Annals Number 11* (Royal Greenwich Observatory, 1975). In general, these solar ephemerides can be extracted from the sunspot and faculae digital dataset (RGO–S&FDD).

However, in the early years, the value of P_0 is often missing and sometimes all three values (P_0, B_0 and L_0) are missing. In such cases, solar ephemerides must be obtained from another source. Both the solution of the mathematical equations and the use of solar ephemerides are discussed in greater detail in Paper 2.

7. Summary and Conclusions

The main purpose of this paper and the two following companion papers is to draw attention to the existence of typographic, systematic and isolated errors in the different datasets that contain the measurements of sunspots and faculae published as the *Greenwich Photo-heliographic Results (GPR) 1874 – 1976* [*Greenwich Observations* (1874 – 1955); *Royal Observatory Bulletins* (1956 – 1961); *Royal Observatory Annals* (1962 – 1976)]. The specific aim of this first paper is to provide all the necessary background information on the *Greenwich Photo-heliographic Results* that is required to understand the various corrections presented in the two companion papers.

A secondary purpose of this introductory paper is to outline a possible strategy for correcting the RGO sunspot digital datasets (Section 6). The fact that two sunspot digital datasets (i.e., RGO–SDD and RGO–S&FDD) have been prepared quite independently means that there is some "duplication" of the information on sunspots but not faculae. Therefore, the two sunspot digital datasets could be used to compare semi-automatically the two independent entries for variables such as time, sunspot position and sunspot areas. Moreover, the existence of two digital datasets makes it possible to derive a single enhanced digital dataset, by combining correct data from the two independent datasets.

Similarly, there is some "redundancy" in both digital datasets because the positions of sunspots are given in both polar coordinates and heliographic coordinates. A set of mathematical equations defines the transformation between these two coordinate systems. Therefore, it is possible to calculate the polar coordinates from the heliographic coordinates for the entire sunspot digital dataset (RGO–SDD) and then compare these calculated polar coordinates with the original or archived values. Thus the mathematical equations provide yet another means of eliminating errors and thereby deriving an improved sunspot digital dataset. The use of the mathematical equations to correct systematic and isolated errors in the sunspot digital datasets is discussed in greater detail in Paper 2.

A possible strategy for correcting the RGO sunspot datasets, both printed and digital, has been outlined in Section 6. It is clearly feasible to implement the necessary changes incrementally, in a series of separate smaller tasks. Indeed, it would be virtually impossible to correct every error in a single paper. Nevertheless, an appendix to the following paper (Paper 2) by Willis et al. (2013) provides a rather more formal specification of a detailed procedure for checking the original sunspot digital dataset (RGO–SDD). The ultimate goal of these investigations is an even more reliable Royal Greenwich Observatory sunspot and faculae dataset, which will provide invaluable information on solar variability during the long interval 1874 – 1976.

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Appendix A: The Archival Collections of RGO Solar Plates and Contact Prints

A.1 Aim of the Appendix

The aim of this appendix is to provide brief details of the locations of the archival collections of the Royal Greenwich Observatory (RGO) Solar Plates and Contact Prints within the United Kingdom, and information on how they can be accessed.

A.2 Catalogues of the RGO Collections of Solar Plates and Contact Prints

The RGO collections of *Solar Plates* and *Solar Plates Contact Prints*, namely classes RGO.50 and RGO.51 respectively in the numerical sequence of the archival class-marks, were housed on the RGO Herstmonceux Castle site until the move of the RGO to Cambridge in 1990; before the move both collections were catalogued. The glass plates were then moved to purpose-designed accommodation in the RGO Cambridge Building on Madingley Road, whilst the contact prints were accessioned into the main run of RGO Archives when the whole body of the archival collection was transferred to Cambridge University Library (CUL) during 1989 – 1990.

The two catalogues were retrospectively converted by CUL archival staff in 2009 May–June and made available over the Internet from the Library web-pages using the University of Cambridge archival catalogue server named *Janus*; RGO.50 at http://janus.lib.cam.ac.uk/db/node.xsp?id=EAD%2FGBR%2F0180%2FRGO%2050 and RGO.51 at http://janus.lib.cam.ac.uk/db/node.xsp?id=EAD%2FGBR%2F0180%2FRGO%2051.

Today, the original paper contact prints (1874 – 1917) are available for study in the Department of Manuscripts Reading Room of Cambridge University Library — for advice on access contact Adam Perkins (ajp21@cam.ac.uk), Curator of Scientific Manuscripts, Cambridge University Library. Digital copies can be made from an original print if the print is in sufficiently good condition.

In 1998, the entire archive of RGO glass plates, including the original solar plates, was transferred to the Momart warehouse in east London. However, it is hoped to transfer this entire collection of RGO plates to the Bodleian Library, Oxford, in due course, in order to ensure proper curation and public access. At present, requests to access the RGO solar plates (1918 – 1976) should be addressed to Dr Colin Vincent (colin.vincent@stfc.ac.uk), Head of Astronomy, Programmes Directorate, Science and Technology Facilities Council.

The archive collection of RGO solar plates has been scanned by scientists at the Mullard Space Science Laboratory (MSSL), University College London, although the digital images have not yet been calibrated. There is currently no online link to this dataset and requests for further information about the digital images should be sent to Sarah Matthews (sam@mssl.ucl.ac.uk).

A.3 Archive Material Stored in the UK Solar System Data Centre

The UKSSDC holds almost 20 000 images of the Sun as contact prints and over 9 000 images on glass plates. The visible-light contact prints were acquired at some of the contributing solar observatories listed in Table 1 (including the Cape, Dehra Dun and Greenwich) and cover the time interval 1910 – 1936 (June). There is also a completely separate collection of glass plates that spans the time interval 1903 – 1942. Most of these plates are in K light, with a few in Hα light. An online catalogue provides information on the availability of the various types of image (http://www.ukssdc.ac.uk/cgi-bin/wdcc1/secure/rog_image_availability.pl) and requests for specific images should be sent to the UKSSDC (support@ukssdc.ac.uk).

Appendix B: Observatory Codes and Coordinates

B.1 Aim of the Appendix

The aim of this appendix is twofold. The first goal is to gather together all of the information on the observatory codes used to identify the locations at which the measured solar photographs were acquired. The second goal is to provide details of the bibliographic references used to determine the geographic coordinates and altitudes of all the contributing solar observatories.

B.2 Original Observatory Codes

As noted in Section 5, the RGO–S&FDD includes a single-letter observatory code to identify the source of each solar photograph. These codes are as follows: A = Melbourne (Me), Australia; C = Cape of Good Hope, South Africa; D = Dehra Dun, India; E = Ebro, Spain; F = Fraunhofer Institut, Germany; G = Greenwich, UK, *and* Herstmonceux, UK; H = Harvard College, USA; I = India (Dehra Dun); K = Kodaikanal, India; M = Mauritius; T = Mount Wilson (Mt. W, W, P), USA; W = Washington, USA; Y = Yerkes Observatory, USA. The codes in parentheses are those used in the RGO printed observations, bulletins and annals (RGO–POBA) It should be noted that the two separate codes (D, I) for Dehra Dun, India, have been retained in the sunspot and faculae digital dataset (RGO–S&FDD) because they both appear in the RGO–POBA; initially I was used but subsequently D was introduced to distinguish Dehra Dun from Kodaikanal (K), India. It should also be noted that the code T is used for the Mount Wilson Observatory in the RGO–S&FDD to distinguish this observatory from the US Naval Observatory, Washington (W). The code Y is used for the Yerkes Observatory.

B.3 New Observatory Codes

The single-letter observatory code defined in Section B.2, which is a minor modification of the original RGO observatory code (A = Me and T = Mt. W), applies exclusively to the interval 1874 April 17 – 1955 December 31. At present, the sunspot and faculae digital dataset (RGO–S&FDD) only extends up to the end of 1955, when publication of the faculae measurements ceased. In the interval 1956 – 1976, the printed RGO publications (RGO–POBA) use some of the defunct single-letter observatory codes again for other observatories (e.g., D is used for Debrecen, whereas this letter had been used previously for Dehra Dun). To overcome this difficulty, a new four-letter observatory code is defined in Table 1, together with the original observatory codes employed in the printed RGO publications. It is clear from Table 1 that some of the old single-letter observatory codes are ambiguous. The new unambiguous four-letter observatory code is based on the one employed at the National Geophysical Data Center, Boulder Colorado (see: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/CATALOGS/Solar_Observatories_List), with a few exceptions. In particular, the code GREN is preferred to GREE for Greenwich; the codes DEBR and GYUL are introduced for the Debrecen and Gyula sites of the Heliophysical Observatory, Hungary; and, since the code MWIL is used for the Mount Wilson Observatory (Los Angeles), it seems more logical to use MMAR (rather than MONT) for the Astronomical Observatory at Monte Mario (Rome).

B.4 Detailed Notes on the Observatory Codes Presented in Table 1

The photoheliograph was moved from Greenwich to Herstmonceux Castle, Sussex, on 1949 May 02. The last photograph of the Sun taken at Greenwich was on May 02, although a second photograph was taken on the same day with the re-erected Dallmeyer photoheliograph, strapped to the Newbegin 6¼-inch refractor in the 22-foot dome at Herstmonceux Castle (Howse, 1975). The code 'G' is used for Greenwich in the printed publications (RGO–POBA) within the interval 1874 – 1949 (May 02); the code 'G' is used for Herstmonceux in the printed publications within the interval 1949 (May 03) – 1955; and the code 'H' is used for Herstmonceux in the printed publications within the interval 1956 – 1976. Therefore, as indicated in Table 1, the new code GREN is used up to 1949 May 02 and the new code HERS is used from 1949 May 03.

The code 'Mt. W' is used for the Mount Wilson Observatory in the printed publications (RGO–POBA) within the interval 1874 – 1958; the abbreviated code 'W' is used in the printed publications within the interval 1959 – 1966; and the code 'P' (Palomar) is used in the printed publications within the interval 1967 – 1976.

The code 'Y' is used for the measurements on two days in 1929 that were derived from plates provided by the Yerkes Observatory. The introduction to the *Greenwich Photo-heliographic Results, 1929*, states: "The Director of the Yerkes Observatory, Washington kindly lent for measurement plates taken on June 30 and November 6. The measures made from these plates have been included in these *Results*, thus preserving the daily measures of spots and faculae." The code given in the "Positions and Areas of Sun Spots and Faculae" section of the *Results* on both June 30 and November 6 is 'YERKES' (in full), whereas the single-letter code 'Y' is given in the "Total Areas of Sun Spots and Faculae for Each Day in the Year (1929)" section of the *Results*. A report from the United States Naval Observatory (Washington) for the for the interval 1927 – 1928 (i.e., the year ending 1928 June 30) includes the following statement: "Publication of the current solar observations in the *Monthly Weather Review* has been continued, Harvard Laboratory, Yerkes, and Mount Wilson supplying dates missed by the Naval Observatory" (Reports of Observatories, 1931). A similar report from the Yerkes observatory for the interval 1928 – 1929 includes the statement: "Heliographic positions of the sunspots were measured on 30 days for completing the series published by the Naval Observatory in the *Monthly Weather Review*" (Reports of Observatories, 1930). Moreover, a search of the files of solar images at the Yerkes Observatory has confirmed conclusively that the plates for 1929 June 30 and November 6 were indeed supplied to the Royal Greenwich Observatory by the Yerkes Observatory; the 12-inch telescope was used to obtain these observations (W. H. Osborn, private communication, 2011).

The full code 'EBRO' is used consistently for three plates kindly lent by the Ebro Observatory, Tortosa, Spain in 1930 (August 23, December 23 and 24), whereas the single-letter code 'E' is used consistently for two plates kindly lent in 1925 (July 23 and November 26).

Furthermore, on 20 days in 1888 both an Indian and a Mauritius photograph were measured (November 6 – 11, November 13 – 22, November 27 and December 7 – 9). In these cases the code 'M. and I.' is used in the printed publications (RGO–POBA), although it is not explained how the measurements from two photographs on the same day were actually combined.

B.5 Geographic Coordinates and Altitudes of the Solar Observatories

Table 1 also gives the geographic coordinates and altitude of each solar observatory that has contributed to the *Greenwich Photo-heliographic Results* (1874 – 1976), along with brief details of the appropriate range of dates and the total number of photographs supplied by each observatory that were used to derive the published measurements (RGO–POBA). The following notes provide sufficient information to explain, albeit briefly, how the values in Table 1 have been determined. With the aid of the following information, it should be relatively simple to include corrections, improvements and refinements in the future.

The basic information has been extracted from *The Astronomical Almanac* and *The Nautical Almanac* in the belief that such information is presented to a reasonably uniform standard. Whenever practicable, however, the precision has been confirmed and occasionally refined; in such cases acknowledgement is made to the individual scientists and curators who have provided confirmation or greater precision. Early listings of the geographic coordinates of those solar observatories that were operational towards the end of the nineteenth century can also be found in *Liste Générale des Observatoires, etc.* (Lancaster, 1886, 1890), In addition, specific scientific publications are referenced [in parentheses] if they provide further background information on the particular solar observatory.

In summary, the information presented in Table 1 has been compiled using the following specific bibliographic sources:

01. CAPE: *Astronomical Almanac* (2010). Confirmation and additional precision provided by I. Glass and C. Hettlage.

02. DEBR: *Astronomical Almanac* (2010). Confirmation and additional precision provided by T. Baranyi. [See also: Dezső (1982)].

03. DHRA: *Astronomical Almanac* (1990).

04. GREN: *Nautical Almanac* (1941). Confirmation provided by R. Higgitt (Curator of History of Science and Technology, National Maritime Museum, London). [See also: Howse (1975)].

05. GYUL: *Astronomical Almanac* (2010). Confirmation and additional precision provided by T. Baranyi. [See also: Dezső (1982)].

06. HARV: *Astronomical Almanac* (2010). Confirmation and additional precision provided by A. Doane (Curator of Astronomical Photographs, Harvard College Observatory).

07. HERS: *Nautical Almanac* (1959). [See also: Howse (1975)].

08. KODA: *Astronomical Almanac* (2010). Confirmation provided by K. Sundara Raman. [See also: Kochhar (2002)].

09. MAUR: *Nautical Almanac* (1941).

10. MELB: *Nautical Almanac* (1941). Confirmation provided by B. A. J. Clark. [See also: Clark and Orchiston (2004)].

11. MITK: *Astronomical Almanac* (2010). [See also: Nagasawa (1967)].

12. MMAR: *Astronomical Almanac* (2010). [See also: Cimino (1967)].

13. MWIL: *Nautical Almanac* (1941). [See also: Howard (1969)].

14. SCHA: *Astronomical Almanac* (2010). [See also: Wöhl (2005)].

15. TORT: *Astronomical Almanac* (2010). Confirmation and additional precision provided by J. Battló and J. J. Curto. [See also: Selga (1915)].

16. USNO: *Nautical Almanac* (1941). Confirmation and additional precision provided by G. R. Chester (US Naval Observatory). [See also: Peters and Wagman (1930)].

17. YERK: *Astronomical Almanac* (1981). Confirmation and additional precision provided by W. H. Osborn (Yerkes Observatory). [See also: Reports of Observatories (1930, 1931)].

18. ZURI: *Astronomical Almanac* (2010). [See also: Waldmeier (1968)].

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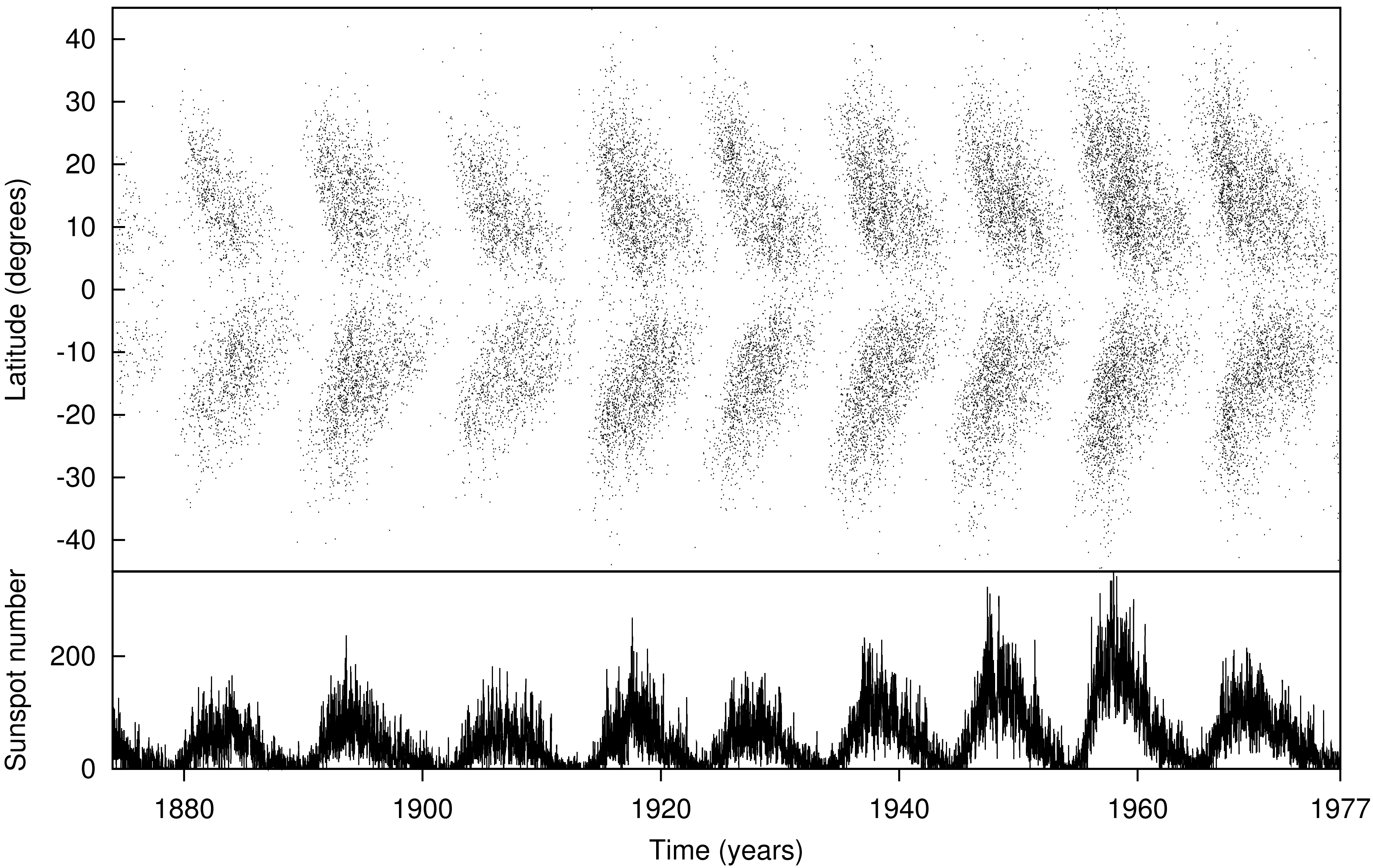
Legend for the Figure

Figure 1 The upper panel shows the migration of sunspots towards the equator during the course of a solar cycle, for all sunspots recorded in the *Greenwich Photo-heliographic Results, 1874 – 1976*. This is the so-called "butterfly" diagram, which was first presented by Maunder (1904) for the interval 1874 – 1902. Sunspots appear at high latitudes at the beginning of a solar cycle but appear at increasingly lower latitudes as the solar cycle progresses. At the transition between solar cycles, sunspots from the old cycle can be observed at low latitudes while sunspots from the new cycle can be observed at high latitudes. The lower panel presents the daily International Sunspot Number, which is compiled by the Solar Influences Data Analysis Center (SIDC). This latter index provides another important measure of solar activity.

Table 1 Solar Observatories contributing to the Greenwich Photo-heliographic Results (1874 – 1976). Detailed notes on the compilation of this table are presented in Appendix B.

Ref. No.	Observatory	Original Code(s)	New Code	Latitude (Degrees, N)	Longitude (Degrees, E)	Altitude (m)	Details of Solar Observations (Date range, or dates, and [total number])
01	Royal Observatory, Cape of Good Hope, South Africa	C	CAPE	–33.9344	+18.4774	18	1910 – 1976 [8405]
02	Heliophysical Observatory, Debrecen, Hungary	D	DEBR	+47.5603	+21.6225	132	1966 – 1970 [5]
03	Dehra Dun Observatory, Uttar Pradesh, India	I, D	DHRA	+30.3150	+78.0483	681	1878 – 1925 [4653]
04	Royal Observatory, Greenwich, London, UK	G	GREN	+51.4773	+00.0000	47	1874 Apr 17 –1949 May 02 [14981]
05	Heliophysical Observatory, Gyula, Hungary	D	GYUL	+46.6528	+21.2705	135	1973 – 1976 [5]
06	Harvard College Observatory, Cambridge, MA, USA	H	HARV	+42.3800	–71.1292	22	1874 – 1876 [133]
07	Royal Greenwich Observatory, Herstmonceux, Sussex, UK	G, H	HERS	+50.8717	+00.3376	34	1949 May 03–1976 [6786]
08	Kodaikanal Observatory, Tamil Nadu, India	K	KODA	+10.2306	+77.4686	2343	1904 – 1976 [685]
09	Royal Alfred Observatory, Pamplemousses, Mauritius	M	MAUR	–20.0942	+57.5525	55	1878 – 1908 [850]
10	Melbourne Observatory, Victoria, Australia	Me	MELB	–37.8315	+144.9733	28	1875 – 1881 [206]
11	National Astronomical Observatory, Mitaka, Tokyo, Japan	J	MITK	+35.6717	+139.5417	58	1974 Nov 24 [1]
12	Astronomical Observatory of Rome, Monte Mario, Rome, Italy	R	MMAR	+41.9217	+12.4517	152	1972 Dec 04 [1]
13	Mount Wilson Observatory, Los Angeles, CA, USA	Mt. W, P	MWIL	+34.2165	–118.0597	1742	1927– 1976 [50]
14	Fraunhofer Institut, Schauinsland Observatory, Freiburg, Germany	F	SCHA	+47.9150	+07.9067	1240	1955 Dec 06 [1]
15	Ebro Observatory, Roquetas, Tortosa, Spain	E	TORT	+40.8206	+00.4933	50	1925 & 1930 [5]

16	US Naval Observatory, Washington, DC, USA	W	USNO	+38.9196	−77.0654	78	1928 – 1945 [16]
17	Yerkes Observatory, Williams Bay, Wisconsin, USA	Y	YERK	+42.5703	−88.5542	328	1929 Jun 30 & Nov 06 [2]
18	Swiss Federal Observatory, Zürich, Switzerland	Z	ZURI	+47.3767	+08.5517	469	1966 Nov 28, 72 Oct 18 & 74 Nov 23 [3]



40
30
20
10
0
-10
-20
-30
-40
Latitude (degrees)
200
0
Sunspot number
1880
1900
1920
1940
1960
1977
Time (years)