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SUNSPOT NUMBER RECALIBRATION

The Greenwich Photo-heliographic Results (1874 – 1885): Observing Telescopes, Photographic Processes, and Solar Images

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Abstract Potential sources of inhomogeneity in the sunspot measurements published by the Royal Observatory, Greenwich, during the early interval 1874 – 1885 are examined critically. Particular attention is paid to inhomogeneities that might arise because the sunspot measurements were derived from solar photographs taken at various contributing solar observatories, which used different telescopes, experienced different seeing conditions, and employed different photographic processes. The procedures employed in the Solar Department at the Royal Greenwich Observatory (RGO), Herstmonceux, during the final phase of sunspot observations provide a modern benchmark for interpreting the early sunspot measurements. The different observing telescopes used at the contributing solar observatories during the interval 1874 – 1885 are discussed in detail, using information gleaned from the official RGO publications and other relevant historical documents. Likewise, the different photographic processes employed at the different solar observatories are reviewed carefully. The procedures used by RGO staff to measure the positions and areas of sunspot groups on photographs of the Sun having a nominal radius of either four or eight inches are described. It is argued that the learning curve for the use of the Kew photoheliograph at the Royal Observatory, Greenwich, actually commenced in 1858, not 1874. The RGO daily number of sunspot groups is plotted graphically and analysed statistically. Similarly, the changes of

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metadata at each solar observatory are shown on the graphical plots and analysed statistically. It is concluded that neither the interleaving of data from the different solar observatories nor the changes in metadata invalidates the RGO count of the number of sunspot groups, which behaves as a quasi-homogeneous time series. Furthermore, it is emphasised that the correct treatment of days without photographs is quite crucial to the correct calculation of Group Sunspot Numbers.

Keywords Greenwich photo-heliographic results · Instrumentation · Solar activity cycle · Sunspots · Homogeneity of the early RGO data

1. Introduction

Characterising the varying levels of solar activity is complicated by the fact that there are currently two main sunspot-number indices: i) the International Sunspot Number and ii) the Group Sunspot Number (Cliver, Clette, and Svalgaard, 2013; Clette *et al.*, 2014; Cliver *et al.*, 2015). The International Sunspot Number [R_{I}], formerly known as the Wolf [R_{W}] or Zürich [R_{Z}] Sunspot Number, is based on telescopic sunspot observations made by a large number of solar observers over the past four centuries (Waldmeier, 1961; McKinnon, 1987; Clette *et al.*, 2007). The Group Sunspot Number [R_{G}], which was introduced by Hoyt, Schatten, and Nesmes-Ribes (1994) and Hoyt and Schatten (1998a, 1998b), is based on the number of sunspot groups observed, rather than a combination of the number of groups and the number of individual spots (as is the case for R_{I}). Several attempts have been made to reconcile the discrepancies between R_{G} and R_{I} (Cliver, Clette, and Svalgaard, 2013; Clette *et al.*, 2014; Cliver *et al.*, 2015; Cliver and Ling, 2016).

As discussed in detail in the companion article by Willis, Wild, and Warburton (2016), the programme of sunspot observations conducted under the aegis of the Royal Observatory, Greenwich, which later became the Royal Greenwich Observatory (RGO), plays a key role in the derivation of Group Sunspot Number for two main reasons (Hoyt and Schatten 1998a, 1998b). First, the equation for the Group Sunspot Number includes a normalisation number (12.08) that is chosen to make the mean Group Sunspot Number equal to the mean International Sunspot Number for the interval 1874 – 1976, during which the RGO was acquiring and publishing sunspot data. Second, each individual (or comparison) solar observer's personal correction factor [k'] is chosen to place that observer on the same scale as the RGO. Therefore, there are strong reasons for being meticulously careful about the determination of the daily number of sunspot groups on the solar disk according to the programme of sunspot observations conducted under the aegis of the RGO. Accordingly, Willis, Wild, and Warburton (2016) derived a new dataset for the RGO count of the number of sunspot groups for the interval 1874 – 1885, which differs from that published by Hoyt and Schatten (1998a, 1998b).

It should also be noted that Cliver and Ling (2016) found they could reproduce the personal correction factors [k'] for the solar observers listed by Hoyt and Schatten (1998a: see their Appendix 1) only if they used the interpolated filldata files of observer matrices from the NOAA National Geophysical Data Center website (http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-indices/sunspot-numbers/group/archive/), rather than the un-interpolated alldata files of observer matrices. As pointed out by Willis, Wild, and Warburton (2016), the situation is complicated further by the fact that the allegedly un-interpolated dataset (alldata files) actually contains interpolated or infill data. This initial interpolation or infilling of data occurs mainly on days for which no photograph exists. Consequently, Willis, Wild, and Warburton (2016) have argued that days for which no RGO photograph was acquired originally should be regarded, without exception, as being days without meaningful sunspot data. Implementing this improvement would change the calculation of some personal correction factors, particularly those using observations during the interval 1874 – 1885, thereby potentially changing the arithmetical calculation of Group Sunspot Numbers over a wider time interval.

In this same context of accuracy and precision, it must be acknowledged that the RGO count of the number of sunspot groups on the solar disk is inhomogeneous in the *strict* sense that this count is derived from solar photographs acquired at different solar observatories, which used different telescopes, experienced different seeing conditions, and employed different photographic processes. However, with this *strict* definition, the RGO count of the number of sunspot groups on the solar disk is inhomogeneous throughout the entire interval 1874 – 1976. Inspection of the metadata in the *Greenwich Photo-heliographic Results* for the restricted interval 1874 – 1885 (Royal Observatory, Greenwich, 1907) reveals several further possible causes for an inhomogeneous series of RGO sunspot counts in this 12-year interval (see also Cliver *et al.*, 2015). These changes in the metadata are listed explicitly, plotted graphically and investigated statistically in Section 7.

It has also been claimed that some allowance should be made for the evolution of observer expertise at the contributing solar observatories and the gradual refinement of the procedures adopted by RGO staff, which collectively constitute what might be termed an "observer learning curve" (Cliver *et al.*, 2015; Cliver and Ling, 2016). In addition, any possible subjectivity in the way sunspot groups were delineated by different RGO measurers of the solar photographs should perhaps be added to this list of possible sources of inhomogeneity in the RGO count of the number of sunspot groups. All of these potential shortcomings in the RGO count of the number of sunspot groups for the interval 1874 – 1885 are examined carefully in this article. Moreover, one of the authors (G.M. Appleby) worked in the Solar Department at the RGO during the interval 1968 – 1973. Therefore, the procedures adopted in the Solar Department during the latter stages of the RGO programme of sunspot observations are summarised at the beginning of the present article, with the ultimate aim of bridging the time interval between the third quarter of the twentieth century and the last quarter of the nineteenth century.

2. The Solar Department at the Royal Greenwich Observatory (1960s – 1976)

The Solar Department's operations at the RGO in Herstmonceux were twofold: i) to provide a rapid-response solar activity monitoring service using white-light and Hα imaging, and ii) to continue the daily sunspot measurement programme for the *Greenwich Photo-heliographic Results*. Each day, weather permitting, an 8-inch white-light photograph was taken by one member of the small team of up to four scientific assistants using the Dallmeyer photoheliograph (Section 4.3) and developed immediately. If there were any problems with the image, such as under-exposure due to the presence of thin cloud, or an over-dense image from over-development, then another photograph was taken at the earliest opportunity. A further complication and refinement serves to illustrate the care that was taken to obtain a useful image: differential refraction across the 0.5 degree solar image reaches significant levels and has to be allowed for in the reduction of the measurements if the Sun's zenith angle is greater than 75°. Therefore, to avoid this computational complication, if the weather on a given day appeared to be settled, the photograph was taken after the Sun's elevation reached

15°; any doubt in the weather, a photograph was taken as soon as possible and a second one at higher elevation as conditions permitted. The images were examined as soon as the plates were dry, and if a new sunspot group looked as if it would have a corrected area larger than 500 millionths and thus be of immediate interest to several UK radio-communication agencies, the plate was measured right away and a hand-calculation performed to derive the group's heliocentric coordinates plus its projected and corrected total areas. Note that exactly the same processes were employed during the period at Herstmonceux for determining the zero of position angle on the plate and for measuring sunspot positions and areas that were being used at Greenwich during the period of interest of 1874 – 1885; these points are described in full in Section 6.

On a regular basis, photographic plates of daily 8-inch images of the Sun were received from the Cape Observatory, South Africa. For each year, usually one or two years in arrears, the best photographs in terms of seeing and ideal exposure from Herstmonceux and the Cape were selected in order to obtain one good-quality plate for each day. For those days where no plate was available, images were requested from the Kodaikanal Solar Observatory in southern India and, exceptionally, from Mt. Wilson, USA. The next, and very important, step was to set up some 20 or so of the plates in date order in a large frame, so that the images could be viewed easily using artificial light transmitted through the images and 'marked up' ready for measuring. Glass-side up, and using the identification information gleaned from studying the daily images of individual spot groups, these groups were delineated ("ringed") as such using a marker pen, usually only by the Head or an experienced member of the Solar Department. As an occasional but very useful guide to ensuring the correct identification of the individual groups as they crossed the Sun day-to-day, their latitude and longitude could be estimated using so-called Stonyhurst disks, which are transparent, gridded overlays that were placed on the solar plates. This technique allowed, for example, the exclusion of spots that clearly did not belong to a specified group, given its positional history on the surface of the Sun. When it was clearly identified as such, each spot group was given a unique temporary spot number (TSN) that was used to identify it with the subsequent measurements. These TSNs would be replaced by the continuous Carrington Sunspot Numbers before publication of the results in the *Greenwich Photo-heliographic Results*. At the same time, regions of faculae that were visible against limb darkening were also marked up ready for area estimation. After all the plates in the frame had been marked up, the measurements were carried out, as described in Section 6, using a large position-micrometer. Working in pairs, one person measuring, one writing down, members of the team took turns to make the measurements of spot and group total areas, radial distances, and position angles, and to record the measurements in a ledger. Finally, mean values of areas and positions were made for each group, and any anomalies investigated for possible measurement error. From the mid-1960s onwards, computer programs were used to reduce the raw measurements and print for publication the camera-ready pages of results.

Responsibility for the programme of solar observations conducted under the aegis of the RGO was transferred formally to the Heliophysical Observatory, Debrecen, Hungary, at the end of 1976 (Graham-Smith, 1978). Before this formal transfer of responsibility, the Heliophysical Observatory, Debrecen, Hungary, had kindly sent five photographs, taken during the interval 1966 – 1970, for measurement by RGO staff. Subsequently, the Heliophysical Observatory, Gyula, Hungary, sent a further five photographs, taken during the interval 1973 – 1976, for measurement by RGO staff (Willis *et al.*, 2013; see their Table 1). Further information on the transfer of responsibility from the RGO to the Heliophysical Observatory, Debrecen, Hungary, can be found in the article by Baranyi, Győri, and Ludmány (2016).

Table 1 A list of solar observatories that contributed to the *Greenwich Photo-heliographic Results* in the interval 17 April 1874 – 31 December 1885. Also given are the new four-letter observatory codes (Willis *et al.*, 2013); the number of solar photographs contributed by each known solar observatory (`DHRA`, `GREN`, `HARV`, `MAUR`, and `MELB`) and the appropriate (date ranges); the number of solar photographs contributed by unknown, or uncertain, solar observatories (`UNKN`); and the numbers of days for which no photograph was acquired originally (`NONE`). It is readily verified that the sum of the numbers in the right-hand column is 4277, the total number of days in the interval 17 April 1874 – 31 December 1885.

Solar observatory	New code	Number of photographs (days)
Dehra Dun Observatory, Uttar Pradesh, India	DHRA	1126 (1878 – 1885)
Royal Observatory, Greenwich, London, UK	GREN	1998 (1874 – 1885)
Harvard College Observatory, Cambridge, MA, USA	HARV	112 (1874 – 1876)
Royal Alfred Observatory, Pamplemousses, Mauritius	MAUR	172 (1878 – 1885)
Melbourne Observatory, Victoria, Australia	MELB	161 (1875 – 1881)
Photograph acquired but observatory unknown	UNKN	52 (1874 – 1881)
No photograph acquired	NONE	656 (1874 – 1885)

3. The Dataset Defining the RGO Number of Sunspot Groups (1874 – 1885)

It is first necessary to define the primary sources of information used in this investigation. As noted by Willis *et al.* (2013), the publication entitled *Greenwich Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907), which contains supplementary results from photographs of the Sun taken at Greenwich (UK), at Harvard College (USA), at Melbourne (Australia), at Dehra Dun (India), and at Pamplemousses (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 separate 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. Therefore, the publication entitled *Greenwich Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907) provides a later revision and extension of the *Greenwich Photo-heliographic Results* for the interval 1874 – 1885.

An intermediate goal of the companion article by Willis, Wild, and Warburton (2016) is an attempt to achieve complete consistency, in the RGO daily count of the number of sunspot groups, between the three main sections in the *Greenwich Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907); namely, i) "Measures of Positions and Areas of Sun Spots and Faculae" (abbreviated to "Measures"); ii) "Ledgers of Areas and Positions of Groups of Sun Spots" (abbreviated to "Ledgers"); and iii) "Total Projected Areas of Sun Spots and Faculae" (abbreviated to "Total Areas"). Implementing the Errata and Additions listed in the *Greenwich Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907) is a vitally important part of this attempt to achieve consistency in the RGO count of the number of sunspot groups for each day in the interval 1874 – 1885.

Therefore, the RGO publications used in the article by Willis, Wild, and Warburton (2016) and also used in the present investigation are i) the *Greenwich Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907), ii) the separate publication by the Solar Physics Committee (1891), and iii) the annual *Greenwich Photo-heliographic Results* for the interval 1882 – 1885 (Royal Observatory, Greenwich 1882, 1883, 1884, 1885).

These latter publications are required in order to extract the information in the “Measures” sections of the *Greenwich Photo-heliographic Results* for the four years 1882, 1883, 1884, and 1885. These RGO sources of information have been used to derive the new dataset discussed in the article by Willis, Wild, and Warburton (2016). This new dataset is also used to derive the quantitative results presented in this article (see Figures 2a – 2l and Table 2). The same RGO sources of information are used as a starting point for specifying the relevant metadata, although other historical documents are used both to corroborate and to revise these metadata.

4. Observing Telescopes (1874 – 1885)

Table 1 provides a list of the solar observatories that contributed photographs used for measuring the positions and areas of sunspots and faculae during the interval 17 April 1874 – 31 December 1885. Also shown in this table are the new four-letter observatory codes (Willis *et al.*, 2013); the number of solar photographs contributed by each known solar observatory, namely Dehra Dun (DHRA), Greenwich (GREN), Harvard (HARV), Mauritius (MAUR), and Melbourne (MELB), together with the appropriate date ranges (in parentheses); the number of solar photographs contributed by unknown (or unspecified) solar observatories (UNKN); and the number of days for which no photograph was acquired (NONE). It is readily verified that the sum of the numbers in the right-hand column is 4277, the total number of days in the interval 17 April 1874 – 31 December 1885.

It is convenient to consider the telescopes used at the solar observatories listed in Table 1 for the three following consecutive four-year intervals: 1874 – 1877, 1878 – 1881, and 1882 – 1885. The relevant information on the various telescopes has been gleaned largely, but not exclusively, from the supplementary publication (Royal Observatory, Greenwich, 1907) that augments the *Measures of the Positions and Areas of Spots and Faculae upon Photographs of the Sun* for the years 1874 to 1885, as published in the volumes of the *Greenwich Astronomical Observations* for these twelve years. The intention in issuing the supplementary publication (Royal Observatory, Greenwich, 1907) was to render the results for the interval 1874 – 1885 uniform with the similar results published for 1886 and the succeeding years.

4.1. The Time Interval 1874 – 1877

The Introduction to the *Greenwich Photo-heliographic Results 1874 – 1885* (Royal Observatory, Greenwich, 1907) contains the following statement: “The Greenwich photographs were taken with the Kew Photoheliograph of 3.6 inches aperture up to 1875 September 17, and after that date with the Dallmeyer Photoheliograph of 4 inches aperture returned from the Transit of Venus Expedition to New Zealand.” However, both the Minutes of the British Association for the Advancement of Science (1857) and a report by De La Rue (1860) indicate that the object glass of the Kew photoheliograph had an aperture of 3.4 (3 4/10) inches, not 3.6 inches. The original Kew photoheliograph is now housed in the Science Museum, London. Following a request by one of the authors (L.T. Macdonald), a member of staff at the Science Museum has kindly measured the aperture and found it to be approximately 3.4 inches. This measurement was difficult to make, owing to the instrument currently being in an extremely awkward position in the display case: a definitive measurement will be made in due course. The telescope’s aperture was normally stopped down to 2 inches with a stop in front of the object glass, as discussed later in this section.

Table 2 Results of a statistical test for randomness, or non-randomness, applied to the changes in metadata shown in Figures 2a to 2l (see Section 7.2). Column 1 specifies the solar observatory and column 2 defines the associated change in metadata. Column 3 shows the selected date range before and after the change in metadata; these are chosen to ensure that N_1 and N_2 are both ≥ 10. Column 4 defines the criterion used in this investigation for a meaningful change in the number of sunspot groups. Specifically, the modulus of the difference between the number of sunspot groups seen on a photograph acquired at the observatory implementing the change of metadata and the number of sunspot groups seen on a photograph acquired at any other observatory on a strictly adjacent day should be ≥ 1 (see Section 7.2 for further details). Columns 5 to 10 give the values of N_1, N_2, R, μ, σ, and Z that arise in the runs test for randomness; these quantities are defined in Section 7.1 and in the Appendix. Column 11 indicates the part (or parts) of Figure 2 that shows graphically the number of sunspot groups for the selected date range. Column 12 indicates whether the statistical test shows random or non-random changes at the specified solar observatory before and after the change in the metadata.

Solar observatory	Change in metadata (before and after)	Selected date range (N_1 and $N_2 \geq 10$)	Criterion (|diff. in G|)	N_1 (‘Yes’)	N_2 (‘No’)	R (Runs)	μ (Mean)	σ (S.D.)	Z	Figure(s) (2a – 2l)	Random or non-random
Greenwich (GREN)	Kew photoheliograph	1875-05-01 – 1875-09-17	$\|\Delta G\| \geq 1$	13	22	16	17.34	2.72	−0.49	2b	Random
	Dallmeyer photo	1875-09-18 – 1876-01-31	$\|\Delta G\| \geq 1$	12	13	12	13.48	2.44	−0.61	2b & 2c	Random
Greenwich (GREN)	Wet plates	1882-08-01 – 1882-11-28	$\|\Delta G\| \geq 1$	24	14	17	18.68	2.82	−0.60	2i	Random
	Dry plates	1882-11-29 – 1883-03-31	$\|\Delta G\| \geq 1$	30	11	19	17.10	2.46	+0.77	2i & 2j	Random
Dehra Dun (DHRA)	4 inch diam. Sun	1882-07-01 – 1882-11-06	$\|\Delta G\| \geq 1$	27	16	21	21.09	3.02	−0.03	2i	Random
	8 inch diam. Sun	1882-11-07 – 1882-12-08	$\|\Delta G\| \geq 1$	There are insufficient data in this short interval to perform the runs test							
Dehra Dun (DHRA)	4 inch diam. Sun	1882-12-09 – 1883-05-20	$\|\Delta G\| \geq 1$	41	17	25	25.03	3.12	−0.01	2i & 2j	Random
	8 inch diam. Sun	1883-05-21 – 1883-10-31	$\|\Delta G\| \geq 1$	31	23	27	27.41	3.56	−0.11	2j	Random
Greenwich (GREN)	4 inch diam. Sun	1883-10-01 – 1884-04-01	$\|\Delta G\| \geq 1$	40	13	20	20.62	2.65	−0.23	2j & 2k	Random
	8 inch diam. Sun	1884-04-02 – 1884-10-01	$\|\Delta G\| \geq 1$	25	12	13	17.22	2.62	−1.61	2k	Random
Mauritius (MAUR)	4 inch diam. Sun	1884-05-01 – 1885-02-28	$\|\Delta G\| \geq 1$	There are insufficient data in this long interval to perform the runs test							
	8 inch diam. Sun	1885-03-01 – 1885-12-31	$\|\Delta G\| \geq 1$	There are insufficient data in this long interval to perform the runs test							

In the *Report of the Astronomer Royal to the Greenwich Board of Visitors* (Astronomer Royal, 1874), dated 6 June 1874, it is asserted (on page 8) that "The Kew Photoheliograph has been adjusted to focus, and brought into good working order. It has been used regularly since 1874, April, on every day on which the Sun could be seen; before that date the photographs for the regular series were taken with one of the photoheliographs constructed by Mr. Dallmeyer, under Mr. De La Rue's superintendence, for the Transit of Venus Expeditions." Later in the same report (Astronomer Royal, 1874) it is stated (on page 10) that "A large number of photographs of the Sun have been taken since 1873, June 1, either with the Kew photoheliograph or with one of the other instruments, and of these 266 have been selected for preservation, two photographs being usually reserved on every day of observation." These two quotations suggest that from 1 June 1873 until an unspecified time in April 1874, one or another of the Dallmeyer instruments prepared for the transit of Venus expedition was used to take the solar images, as well as the Kew photoheliograph; thereafter only the Kew photoheliograph was used at Greenwich up to 17 September 1875.

Two further comments should perhaps be made on the previous quotations. First, as noted by Willis, Wild, and Warburton (2016), the RGO system of numbering sunspots began on 21 July 1873 (not 1 June 1873). The number 1 was assigned to one of four sunspot groups (numbers 1, 2, 3, and 4) present on the solar disk on 21 July 1873 (Royal Observatory, Greenwich, 1874), although the format of the data before 17 April 1874 is slightly different to that published subsequently in the *Greenwich Photo-heliographic Results 1874 – 1985* (Royal Observatory, Greenwich, 1907). Second, although it is stated in the latter quotation that 266 photographs were selected for preservation, the official RGO archives at the Cambridge University Library contain just 20 contact prints with dates lying in the inclusive interval 1 June 1873 – 30 April 1874 (MSS.RGO.51/1 – 20; janus.lib.cam.ac.uk/db/node.xsp?id=EAD/GBR/0180/RGO 51). Apparently, therefore, many valuable solar photographs are no longer extant.

The Kew photoheliograph is the one described by De La Rue (1862) in relation to the total solar eclipse of 18 July 1860, observed at Rivabellosa, near Miranda de Ebro, in Spain: this reference is cited in the article by De La Rue, Stewart, and Loewy (1869) on the heliographical positions and areas of sunspots observed with the Kew photoheliograph during the years 1862 and 1863. Indeed, the photoheliograph was completed at the Kew Observatory in 1858 and was temporarily removed for photography of the 1860 eclipse in Spain (Macdonald, 2015). The photoheliograph was essentially a conventional refractor with an object glass 3.4 inches in diameter and 50 inches in focal length, giving a solar image 0.466 inches across. However, it is worth recording here a comment made on page 150 of a report by De La Rue (1860): "The object-glass (made by the late Mr. Ross) is specially corrected to ensure the coincidence of the visual and chemical foci; but, as might be anticipated, the rays, after passing through the secondary lens, are in some degree dispersed, and this coincidence of foci no longer exists." Thus the photoheliograph, with its corrected lens, was not quite 'a conventional refractor', although De La Rue notes the degradation of the image due to the eyepiece, which enlarged the image to 4 inches. However, the aperture was normally reduced to 2 inches using a stop in front of the objective, as also noted on page 150 of the report by De La Rue (1860). Moreover, as mentioned by De La Rue (1862), in this instrument the primary focal image of the Sun is enlarged from about half an inch (0.466 inches) in diameter to nearly 4 inches, which is a scale amply sufficient to counterbalance the disadvantages of the collodion process (see Section 5). On the other hand, the light is thus attenuated sixty-four times, in addition to being absorbed to some extent in passing through the two lenses composing the secondary magnifier – an ordinary Huyghenian eyepiece.

Five photoheliographs of an identical, but improved, design by De La Rue were made for the Royal Observatory, Greenwich, by J. H. Dallmeyer of London, in preparation for the then eagerly awaited 1874 transit of Venus (Howse, 1975). These photoheliographs were ordered in 1871. The precise locations of the (differently numbered) Dallmeyer photoheliographs used first at Greenwich and then at Herstmonceux is outlined by Howse (1975), who also refers to the introduction of the Thompson photoheliograph during the interval 1891 – 1894 (which is outside the time interval considered in this article).

As described in the Introduction to the *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich, 1882), the Dallmeyer photoheliograph (Dallmeyer No. 3) used at Greenwich after 17 September 1875 has an object-glass of 4 inches aperture and 5 feet focal length, forming an image of the Sun about half an inch in diameter. On page 255 of the book by Maunder (1900), it is stated that the image of the Sun in the principal focus of the Dallmeyer photoheliograph is about six-tenths of an inch in diameter; on page 92 of the book by Howse (1975) it is stated that the primary image of the Sun is a little over half an inch in diameter. This image is enlarged by a secondary magnifier to 4 inches on the camera screen, where the sensitive plate is inserted; the whole length of the instrument being about 8 feet. The exposure is given by a shutter having a slit of adjustable width, which is carried by a spring across the primary image. Cross-wires are placed at the principal focus, which give facilities for determining the position angles of spots on the photographs. The instrument is equatorially mounted, although this is not absolutely necessary to its efficient action, as the exposure is practically instantaneous, amounting only to a few thousandths of a second in ordinary cases.

There is corroborative evidence that supports the claim that the Dallmeyer photoheliograph was used at Greenwich after 17 September 1875. A letter written by Henry Toynbee to Samuel Jeffery, Superintendent at the Kew Observatory, dated 21 September 1875, indicates the wish of Sir George Airy (Astronomer Royal) to return the photoheliograph to Kew (Toynbee, 1875). Further supporting evidence is provided by the following extract from the *Greenwich Astronomical Observations* (Royal Observatory, Greenwich, 1876, page xxxii): "In 1873, February, the Kew Photoheliograph was erected, with the consent of the Royal Society and of the Kew Committee, in a new dome connected with the magnetic offices in the south ground, and photographs of the Sun were taken regularly with that instrument. One of the Dallmeyer photoheliographs for the Transit of Venus Expedition, of which there are five, was erected in place of the Kew Photoheliograph in 1875, September, and from that time has been used exclusively for solar photographs." Therefore, the date of 17 September 1875 as the last day on which the Kew photoheliograph was used at Greenwich is entirely plausible.

In a wider context, it should be noted that the preamble (12 unnumbered pages) to the *Greenwich Astronomical Observations* (Royal Observatory, Greenwich, 1876) contains the following statement: "It has been considered advisable to defer the Measures of the Photographs in the year 1876, referred to in Section 16 of the Introduction, to the volume for 1877, where they will appear in due sequence with the Photographic Results for the years 1874 to 1877." The main body of the *Greenwich Astronomical Observations* (Royal Observatory, Greenwich, 1876) presents a brief discussion of the organisation of the Royal Observatory, Greenwich, and a detailed discussion of the various instruments and associated scientific observations (pages i to cxxxiii) but does not contain any tables of sunspot positions and areas. As stated in the quotation, publication of the sunspot positions and areas for the year 1876 was deferred to the corresponding publication in following year, namely the *Greenwich Astronomical Observations* (Royal Observatory, Greenwich, 1877), where sunspot positions and areas were presented in the standard tabular form for the four-year interval 1874 – 1877.

It is important to emphasise that the Dallmeyer photoheliographs used for the transit of Venus expedition were closely modelled on the original Kew instrument. When taking the daily solar images at Greenwich, the 4-inch aperture was stopped down to 3 inches – rather as the Kew instrument was stopped down from 3.4 to 2 inches. This would have slightly reduced the telescope's resolution. Moreover, the shutter used to make the very short exposures was of exactly the same design as that in the Kew instrument (Macdonald, 2015): a narrow slit in a strip of brass was passed very quickly across the light-sensitive plate, using a powerful spring. The instrument in use in 1900 is described in some detail in E.W. Maunder's contemporary description of the Royal Observatory, Greenwich (Maunder, 1900).

For the period 1874 – 1877, a number of solar photographs taken at the Harvard and Melbourne Observatories were placed by the Directors of those two observatories in the hands of the Astronomer Royal, and were measured and reduced at the Royal Observatory, Greenwich. The results from Harvard and Melbourne were then collated with the measures of the solar photographs taken at Greenwich for the same years.

The photographs acquired at the Melbourne Observatory, Victoria, Australia, were taken with an instrument of the same pattern and aperture as the Dallmeyer Photoheliograph used at the Royal Observatory, Greenwich. As noted by Clark and Orchiston (2004), this instrument still exists. According to these authors, it has a flint-first air-spaced objective with an aperture of 102 mm and a focal ratio of f/15. In its original state, a secondary 'Rapid Rectilinear' type lens projects a 100-mm (approximately 4-inch) diameter solar image onto a ground glass screen for focusing, or onto a 6-inch (152-mm) square glass photographic plate. The photographs acquired at Harvard College Observatory, Cambridge, MA, USA, were taken in the primary focus of a "horizontal photoheliograph"; the sunlight being received upon a movable mirror from which it was reflected into a stationary lens of 5 inches aperture and about 39 feet focal length (Royal Observatory, Greenwich, 1907). The horizontal photographic telescope was invented by Joseph Winlock, Director of the Harvard College Observatory. Brief experimental details on this horizontal photoheliograph are presented in the book by Cottam and Orchiston (2015). This type of photoheliograph produced relatively large and distortion-free images that could be photographed for later measurement (Janiczek, 1983; Lankford, 1987; Dick, Orchiston, and Love, 1998). The mean diameter of the Sun on the photographs acquired at both Harvard and Melbourne was about 4 inches (Royal Observatory, Greenwich, 1907).

From a historical perspective, it should be noted that Joseph Winlock may not have received proper recognition for his work on the horizontal photoheliograph (McEachern, private communication, 2015). Reference is made in Volume VIII of the *Annals of the Astronomical Observatory of Harvard College* (Harvard College Observatory, 1876) to Winlock's idea for a simple ("cheap and rude") apparatus for obtaining photographs of the Sun (pp. 35 – 42). The horizontal telescope is described together with the process of assembling it, although the word "photoheliograph" is not used explicitly. Moreover, it is noted in Volume VIII of the *Annals* that the Harvard College Observatory had two lenses of considerable focal length that were used to photograph the Sun. One of these lenses was of plate glass, uncorrected, with a focal length of about 40 feet and an aperture of 4 inches, not 5 inches, as stated in the RGO publication cited previously (Royal Observatory, Greenwich, 1907). The other lens was corrected for chemical rays; its focal length (for photography) was 32 feet 5 inches and its aperture was 4 inches.

There is a later section (pp. 58 – 65) in Volume VIII of the *Annals of the Astronomical Observatory of Harvard College* (Harvard College Observatory, 1876) describing the solar eclipse of 1870, which was the event for which Winlock was planning to use the horizontal photoheliograph. Arthur Searle, who was "Assistant in Charge of the Observatory" at that time, has a preface in Volume VIII for which he is credited but there is no accreditation for the person who actually wrote the main text in this volume. Similarly, Jones and Boyd (1971) have noted that "Winlock's annual reports are to this day buried in the obscurity of handwritten notebooks and not one of the projects representing his own research was published in the *Annals* during his lifetime". Jones and Boyd (1971) also note that Winlock explained his horizontal photoheliograph and its potential value for transit of Venus observations in a letter to Simon Newcomb, dated 10 February 1872. Moreover, an article with the title "On the Horizontal Photographic Telescope of Long Focus" was published posthumously in the journal *Nature* (Winlock, 1875). A footnote indicates that this article was read by the late Prof. Wenlock [*sic*] to a private scientific Club in Cambridge, USA, shortly before his death (11 June 1875): it was forwarded to the journal for publication, at the request of the Club, by Prof. Asa Gray. In his published article, Winlock (1875) is quite critical of the Kew photoheliograph designed by De La Rue.

A final comment should be made on the photoheliographs used in the programme of sunspot observations conducted under the aegis of the RGO. As already noted, during the years leading up to the 1874 transit of Venus, some astronomers believed that photoheliographs of the Kew design, which used eyepiece projection to magnify the Sun's image, would give less sharp images than long-focus instruments using an object glass alone, because a secondary magnifier introduces optical distortions. In a report published in 1859 (Kew Committee, 1859), it was noted that "certain improvements in the arrangements of the secondary magnifying lens are under consideration, with the view of avoiding the depiction on the collodion negative of the inequalities in the glasses which compose it". A horizontal-type photoheliograph employing an object glass alone, similar to the Harvard instrument just described, was used by the American Transit of Venus Commission, and this gave much better results on the transit than the British photoheliographs (Newcomb, 1872; Dick, 2003; Ratcliff, 2008).

The mean diameter of the Sun for *all* of the photographs acquired during the interval 1874 – 1877 was about 4 inches. In the figures presented in this article (Figures 2a – 2l), a visual distinction is made only between photographs for which the mean diameter of the Sun was about 4 inches and those for which the mean diameter of the Sun was 8 inches (see Section 4.3). It must be remembered that the aperture of the Kew photoheliograph (used up to 17 September 1875) was 3.4 inches, whereas the aperture of the Dallmeyer photoheliograph (used thereafter) was 4 inches. However, it is not feasible or practicable to illustrate such minor distinctions in the figures, although this particular change in photoheliograph, and hence aperture, is indicated in Figure 2b.

4.2. The Time Interval 1878 – 1881

The photographs taken with the Dallmeyer photoheliograph at Greenwich during these four years were measured and reduced there under the direction of the Astronomer Royal, and the results were published in the annual volumes of the *Greenwich Astronomical Observations* for the years 1878 – 1881, and also in the *Greenwich Spectroscopic and Photographic Results* extracted from those volumes of the *Greenwich Astronomical Observations*. The photographs taken at Dehra Dun, and at Melbourne, in addition to a few taken in Mauritius, were measured and reduced at the Solar Physics Observatory, South Kensington, under the direction of Sir J. Norman Lockyer, and were published in 1891 (Royal Observatory, Greenwich, 1907), together with the Greenwich reductions (extracted from the volumes of the *Greenwich Astronomical Observations*) for the sake of completeness (Solar Physics Committee, 1891). At this time, the position-angles, longitudes, and latitudes given in the

Greenwich Photo-heliographic Results were changed from degrees and minutes to degrees and tenths of a degree (*cf.* Willis *et al.*, 2013; see their Section 5).

It is important to reiterate that during the interval 1878 – 1881 the photographs taken at Greenwich were measured and reduced by staff at the Royal Observatory, Greenwich, whereas the photographs taken at Dehra Dun, Melbourne and Mauritius were measured and reduced retrospectively by staff at the Solar Physics Observatory, South Kensington. Presumably, therefore, there was some degree of independence in the way sunspot groups were delineated and measured by staff at these two establishments. The fact that there was such a high level of consistency in the daily number of sunspot groups after the interleaving, or merging, of the results from the four solar observatories (DHRA, GREN, MAUR, MELB) during the four-year interval 1878 – 1881 (see Figure 2), suggests that there was also good agreement in the way sunspot groups were delineated at the two establishments. Further historical and scientific research might yield additional information on the method used to delineate sunspot groups in the early years.

No explicit mention is made in the *Measures of Positions and Areas of Sun Spots and Faculae on Photographs Taken at Greenwich, Dehra Dun, and Melbourne* (Solar Physics Committee, 1891) of the type of photoheliograph used at Dehra Dun and Melbourne (and also Mauritius) during the four-year interval 1878 – 1881. However, for consistency with the photoheliographs known to have been used at these three observatories during at least one of the adjacent four-year intervals, 1874 – 1877 and 1882 – 1885, it seems virtually certain that the photoheliographs used at all three solar observatories were Dallmeyer photoheliographs of very similar design to the Dallmeyer photoheliograph used at Greenwich.

Whenever two photographs were measured on any day, the means of the two photographs were taken in the preparation of the ledgers, both as to the times of the photographs, and as to the areas and positions of the spots.

The majority of the photographs taken in Mauritius under the superintendence of the Director, Dr. C. Meldrum, showed neither spots nor faculae because they were taken at the time of a pronounced minimum in solar activity; the absence of any features requiring measurement was recorded in the volume published by the Solar Physics Committee (1891). However, thirty-five photographs, taken in Mauritius and placed by Dr. Meldrum in the care of the Solar Physics Committee, showed spots or faculae or both and hence filled up gaps on twenty-three days for which no other photographs were available. These photographs were subsequently measured at the Royal Observatory, Greenwich, so far as the areas of the spots and faculae are concerned. However, as the photographs were not provided with wires, it was not possible to compute the heliographic coordinates of the spot groups, which have therefore been simply interpolated from the results on the days immediately preceding and following those on which the Mauritius photographs were taken. (In the RGO tabulations, these interpolated values, like the values interpolated for days whereon no photograph is available, have been enclosed in brackets but have been used in taking the final means of the spot-groups.)

The mean diameter of the Sun for all photographs acquired during the interval 1878 – 1881 was about 4 inches.

4.3. The Time Interval 1882 – 1885

The photographs measured during the interval 1882 – 1885 were taken at the Royal Observatory, Greenwich, London, under the direction of the Astronomer Royal; at Dehra Dun, North-West Provinces, India, under the superintendence of J.B.N. Hennessey, F.R.S., Deputy Superintendent, Trigonometrical Survey of India; and at the Royal Alfred Observatory, Mauritius, under the superintendence of the Director, Dr. C. Meldrum.

The photographs acquired at Greenwich were taken with the Dallmeyer photoheliograph returned from the transit of Venus expedition to New Zealand. The scale of the photographs was about 4 inches to the solar diameter up to 1 April 1884, and nearly 8 inches from 2 April 1884 onwards.

The photographs acquired at Dehra Dun were taken with a Dallmeyer photoheliograph giving an image of the Sun about 4 inches in diameter, except for the period from 7 November to 8 December 1882, when another secondary magnifier giving an image of the Sun 8 inches in diameter was adapted to the photoheliograph under the auspices of the Solar Physics Committee. The image of the Sun reverted to 4 inches in diameter for the interval 9 December 1882 to 20 May 1883, after which the solar diameter changed back again to 8 inches.

The photographs acquired in Mauritius were taken with a Dallmeyer photoheliograph, giving an image of the Sun about 4 inches in diameter up to 28 February 1885, but this was altered so as to give an image 8 inches in diameter from 1 March 1885 onwards.

It is clear that the final four-year interval, 1882 – 1885, is particularly interesting in the sense that the diameter of the Sun on the solar photographs changed from “about 4 inches” to “nearly 8 inches” at different times for the three solar observatories Dehra Dun, Greenwich, and Mauritius. Moreover, the diameter of the Sun on photographs acquired at Dehra Dun changed three times during this four-year interval, whereas it changed only once on photographs acquired at the other two observatories (Greenwich, Mauritius).

5. Photographic Processes (1874 – 1885)

In the photographic process adopted at Greenwich up to 28 November 1882, iodized cadmium collodion was used in connection with the pyro-gallic acid development (Royal Observatory, Greenwich, 1882; Howse, 1975). After that date, bromo-iodized gelatine dry plates with alkaline development were used regularly.

At Greenwich, over-exposure might have caused problems when measuring the number of sunspot groups on images obtained using wet plates that were coated with a film of iodized cadmium collodion, and developed with pyro-gallic acid (*i.e.*, up to 28 November 1882). The wording on page 151 of the report by De La Rue (1860) clearly indicates that the high sensitivity (for its time) of collodion made it necessary to construct a device for the Kew photoheliograph that would give an exposure of a tiny fraction of a second. This explains the origin of the spring-loaded shutter device described in the previous section. De La Rue notes how the length of exposure was adjusted in two different ways: i) by varying the strength of the vulcanised rubber spring that propelled the shutter aperture, and ii) by varying the width of that aperture, between 1/10 and 1/20 of the diameter of the Sun’s image at the prime focus.

The amount of variation in the exposure time thus provided was, nevertheless, very modest. Therefore, the density of the photographic image was still subject to variations in atmospheric transparency. The sensitivity of the collodion surface itself was also variable: in 1859 the Kew Committee and its assistants were still performing experiments as to the best type of light-sensitive surface for solar photography (British Association for the Advancement of Science, 1859), because it had been discovered “that the plates are more liable to stains of the various kinds, known to photographers, under the circumstance of exposure to

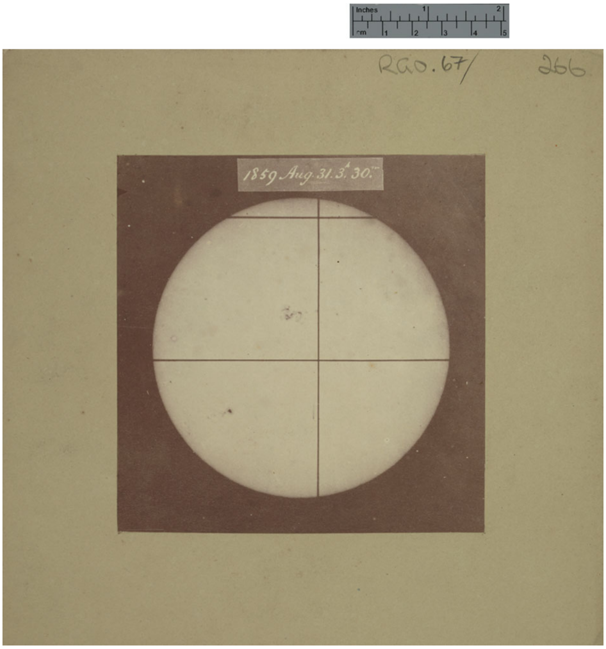


Figure 1 A photograph (contact print) of the Sun acquired on 31 August 1859 (MS.RGO.67/266), using the Kew photoheliograph. The main sunspot group in this photograph is the one responsible for the Carrington event on the following day (see Cliver and Keer, 2012). The photograph was taken with the same instrument and photographic process as was initially used at Greenwich fifteen years later and illustrates one of the technical problems encountered by the RGO staff. The photograph is slightly overexposed, hence reducing the contrast of the sunspots, which has the potential to make the fainter sunspots difficult or impossible to see, thereby affecting the sunspot count. (Figure 1 is reproduced by kind permission of the Syndics of Cambridge University Library.)

intense sun-light, than they would be if employed in taking ordinary pictures in the camera.” Therefore, the sensitivity of the wet collodion plates, at least in the early days, was not always consistent, either between plates or even across the same plate.

An example of this variable sensitivity of the collodion plates is provided in Figure 1, which shows a photograph (contact print) of the Sun acquired on 31 August 1859 (MS.RGO.67/266), using the Kew photoheliograph. Although this photograph was taken about fifteen years before the start of the period under discussion (1874 – 1885), it was taken with the same instrument and photographic process as were initially used at Greenwich and so is illustrative of the technical problems encountered there. The photograph is slightly over-exposed, thereby reducing the contrast of the sunspots. Such over-exposure has the potential to make the smaller and fainter sunspots difficult or impossible to see, thus affecting the sunspot count. The main sunspot group in this photograph is the one responsible for the Carrington event on the following day (1 September 1859). Cliver and Keer (2012; see their Figure 5) have compared this photograph with the carefully executed drawing by Carrington (1860) of the same sunspot group on 1 September 1859, which shows the initial and final positions of the white-light emission producing the first visual record of a solar flare.

It should be noted that the following cautionary statement is made in the Introduction to the *Spectroscopic and Photographic Observations Made at the Royal Observatory, Greenwich* (1884): “Many of the Greenwich photographs taken during the months of May and June [in 1884] are badly defined, the focal adjustment of the photoheliograph having been completely disturbed by an accidental alteration of the position of the tube carrying the wire frame and secondary magnifier. The cause was not discovered for some time.” No contact prints, made from these badly defined Greenwich photographs, are stored in the RGO Archives at the Cambridge University Library (janus.lib.cam.ac.uk/db/node.xsp?id=EAD/GBR/0180/RGO 51), so further investigation of these badly defined Greenwich photographs in May and June in 1884 would appear to be precluded. It is just possible, however, that these particular photographs influence the results presented in Table 2 (see Section 7.2) for the randomness, or non-randomness, of the Greenwich observations in the interval 2 April – 1 October 1884, following the change in the radius of the Sun on the Greenwich photographs from about 4 inches to nearly 8 inches on 2 April 1884.

In the photographic process adopted at both Dehra Dun and Mauritius, bromo-iodized collodion was apparently used in connection with iron development throughout the interval 1878 – 1885 (see Table 1): corroborative evidence certainly exists for the interval 1882 – 1885 (Royal Observatory, Greenwich 1882, 1883, 1884, 1885). It seems likely that the photographs taken at Harvard during the interval 1874 – 1876 (see Table 1) employed the “wet plate” process (Newcomb, 1872).

Clark and Orchiston (2004) have noted that after the transit of Venus observations in 1874, the photoheliograph at Melbourne continued in daily use to photograph the Sun, weather permitting, from 1874 to 1895. Wet plates were used originally, but dry plates were introduced in 1883. However, since the photographs taken at Melbourne were used to help compile the *Greenwich Photo-heliographic Results* for the interval 1874 – 1881 (Table 1), the photographic process adopted at Melbourne was the same as that employed at Greenwich for this first eight-year interval, since wet plates were also used at Greenwich up to 28 November 1882.

6. Measurement of the Solar Photographs (1874 – 1885)

As described in the *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich 1882, 1883, 1884, 1885), the measures of the four-inch photographs were made with a position-micrometer, specially constructed by Mr. Simms. The photograph was held with the collodion-side uppermost, on two cross-slides, which gave the means of accurately centring it on the large position-circle, which rotated with it. A positive eye-piece, having at its focus a glass diaphragm, ruled into squares, with sides of one-hundredth (1-100th) of an inch (for measurement of areas), was carried by a micrometer-screw diametrically across the photograph, the diaphragm being nearly in contact with the photographic film, so that parallax was avoided.

For the measurement of the eight-inch photographs a larger position-micrometer, constructed by Messrs. Troughton and Simms on the same principle but with some improvements, was used. In this instrument the distance of a spot or facula from the Sun’s centre was read off to 1-250th of an inch by means of a scale and vernier instead of a long micrometer-screw.

The procedures involved in the measurement of a photograph may be explained as follows. By means of the cross-slides mounted on the position-circle, the image of the Sun was centred as accurately as possible by rotation. The position-circle was then set to the readings 0°, 90°, 180°, and 270° in succession, and the micrometer-readings taken for the two limbs. The mean difference of the readings for the two limbs was taken as the Sun’s mean diameter on the photograph, and the mean of the half-sum as the reading for the Sun’s centre.

At the principal focus of the photoheliograph were two cross-wires, which served to determine the zero of position-angles on the photograph.

The zero of the Dallmeyer photoheliograph employed at Greenwich was determined by allowing the diurnal motion to carry the spot or the Sun’s limb along the wire, a correction for the inclination of the Sun’s path being applied to the reading of the position-circle so obtained, and also by running the image along the wire by the use of the right-ascension slow motion, the mean of the two determinations being adopted as the zero.

In the use of the Dallmeyer photoheliograph at Greenwich, the position-circle was usually set to some convenient reading near that for zero, so that the wires were respectively parallel and perpendicular to the circle of declination, and a correction for zero of position of the photoheliograph for the mean of the two wires was applied to the zero of the position-circle of the micrometer. This latter was determined from the readings of the position-circle for the four extremities of the two wires. The resulting combined correction was applied to all position-circle readings for spots and faculae, so as to give true position-angles.

In the use of the photoheliograph at Dehra Dun, the position-circle was always set to the zero as determined by allowing the diurnal motion to carry a spot or the Sun's limb along the horizontal wire, and the accuracy of the adjustment was tested at short intervals. No correction for zero of the photoheliograph was therefore required for the reduction of the photographs taken in India.

The uncorrected distance from the Sun's centre for the four-inch images of the Sun was given by the difference between the micrometer-readings for spots and faculae, and the centre-reading. In the new micrometer used for the measurement of the eight-inch photographs the zero of the scale was adjusted to coincide with the centre, and the distance from the centre was given directly.

Two sets of measures of the Sun's limb and of spots and faculae on each photograph were taken and the mean of these two sets was adopted (Royal Observatory, Greenwich 1882, 1883, 1884, 1885). This rather brief statement in the original RGO publications can be amplified in the light of the modern practices employed in the Solar Department at Herstmonceux (Section 2). Two individuals each took a set of measures of the Sun's limb and of spots and faculae on each photograph. The position micrometer allowed a full 360° rotation under the graticule-carrying eyepiece that itself could be moved a full diameter across the plate. The two individuals each independently measured the radial distances and sizes of the spots, one person moving the eyepiece from centre to left as they rotated the plate, and the other person working from centre to right. The position angles were recorded in such a way as to remove the 180° difference that these two routes would give. Thus, by averaging, any machine-dependent and plate-position-dependent bias in the polar coordinates would be minimised.

Corrections were then applied for optical distortion of the photoheliographs and for refraction. The distortion was determined for the Dallmeyer photoheliographs giving a solar image of four inches diameter from measures of photographs of a scale of equal parts, 16 feet long, constructed by De La Rue, and lent by him for this purpose. The scale had eight plates of iron with edges carefully planed, the plates being each exactly one foot in breadth, and attached to a braced iron framework, so as to leave equidistant spaces of exactly one foot between the plates. The scale was photographed at a distance of about 1,200 feet, and extended completely across the field of view, as explained in the *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich, 1883, 1884, 1885). Further historical research might shed additional light on the design and operation of this apparatus for determining the distortion of the Dallmeyer photoheliographs.

Tables giving the distortion of the Dallmeyer photoheliographs for images of the Sun, of about four inches in diameter, determined for every tenth of an inch distance from the centre of the field, are presented for the years 1882, 1883, 1884, and 1885 in the *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich 1882, 1883, 1884, 1885). No correction was applied to photographs of the Sun with a radius of eight inches on account of distortion.

Tables giving the correction for the effect of refraction are also presented in the *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich 1882, 1883, 1884, 1885).

Moreover, the *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich, 1885) include a detailed discussion of two possible sources of error in measurements of solar photographs: i) the probable error in measurements on eight-inch photographs; and ii) the effect of personality in the measurement of areas on four-inch photographs. The main conclusions on these two possible sources of error, based on the tables and text presented in that publication, may be summarised as follows:

i) The means of two measures of distance and position-angle, as printed, may be taken as correct to the last figure – the probable error in distance (r/R) being 0.0004, and in position-angle (at distance R) being 0.033° (*cf.* Willis *et al.*, 2013; see their Section 5). As regards areas of umbrae and whole spots, it was found that the mean discordance may be taken to vary as the square root of the measured area, and that it does not sensibly depend on the distance from the Sun's centre.

ii) The measures of area by the different observers were considered to be comparable, without the application of any correction for systematic difference in habit. Sensible differences of this kind had been suspected, and there appeared to be some evidence of their reality. On investigation, however, it was found that the determination of such differences, which after all are not large compared with the probable error of observation, was subject to much uncertainty. The tables indicated that such corrections were generally smaller than the probable error of the mean of two measures (as determined from the results for eight-inch photographs) and that in the case of whole spots they were insignificant. Therefore, it seemed unnecessary to apply them to the measured areas as printed (in the RGO publications), except in cases of special discussions of changes of area from day to day, where extreme accuracy is desired.

Although it is clear from the previous discussion that some sources of possible error were considered in meticulous detail by the RGO staff, no explicit mention has been found in the RGO publications of possible errors in the daily count of the number of sunspot groups on the solar disk. As noted in the Introduction to this article, any possible subjectivity in the way sunspot groups were delineated by RGO staff is a further potential source of error. This matter warrants further investigation, but such refinement is beyond the intended scope of this initial investigation.

7. Investigation of the Inhomogeneities in the RGO Dataset (1874 – 1885)

As noted in the Introduction, it must be acknowledged that the RGO count of the number of sunspot groups on the solar disk is inhomogeneous in the *strict* sense that this count is derived from solar photographs acquired at different solar observatories, which used different telescopes, experienced different seeing conditions, and employed different photographic processes. However, as already noted, with this *strict* definition, the RGO count of the number of sunspot groups on the solar disk is inhomogeneous, by definition, throughout the entire interval 1874 – 1976. Inspection of the metadata in both the *Greenwich Photo-heliographic Results* for the interval 1874 – 1885 (Royal Observatory, Greenwich, 1907) and in the *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich, 1882, 1883, 1884, 1885) reveals the following further (specific) possible causes for an inhomogeneous series of RGO sunspot counts in this interval: i) the change at Greenwich from the use of the Kew photoheliograph of 3.4 inches (revised from 3.6 inches to 3.4 inches in Section 4.1) aperture up to and including 17 September 1875 to the use of the Dallmeyer photoheliograph of 4 inches aperture thereafter; ii) the change at Greenwich from the use of wet photographic plates up to and including 28 November 1882 to the use of dry photographic plates thereafter; iii) the change at Dehra Dun from an image of the Sun about 4 inches in diameter to an image of about 8 inches in diameter for the inclusive interval 7 November to 8 December 1882; iv) the reversion at Dehra Dun to an image of the Sun of about 4 inches in diameter for the inclusive interval 9 December 1882 to 20 May 1883; v) the change back at Dehra Dun to an image of the Sun about 8 inches in diameter from 21 May 1883 onwards; vi) the change at Greenwich from an image of the Sun of about 4 inches in diameter up to 1 April 1884 to an image of about 8 inches in diameter from 2 April 1884 onwards; and vii) the change at Mauritius from an image of the Sun of about 4 inches in diameter up to 28 February 1885 to an image of about 8 inches in diameter from 1 March 1885 onwards (see Sections 4 and 5).

There are just possibly one-day uncertainties in the dates of the change at Dehra Dun to an image of the Sun from 4 inches in diameter to 8 inches in diameter (on 7 November 1882) and the reversion back to an image of 4 inches in diameter (from 9 December 1882). The reason for these uncertainties is the slight differences in wording between the *Greenwich Photo-heliographic Results, 1874 – 1885* (Royal Observatory, Greenwich, 1907) and the original *Greenwich Spectroscopic and Photographic Results* (Royal Observatory, Greenwich, 1882). Difficulties arise over the exact interpretation of the terms “up to” and “from”. Priority is given to the earlier publication (Royal Observatory, Greenwich, 1882) in resolving this particular matter; otherwise priority is given to the later publication (Royal Observatory, Greenwich, 1907).

Every effort has been made in the preceding sections to discuss as objectively as possible the various changes in equipment and procedures at the solar observatories listed in Table 1 that could conceivably compromise the RGO series of sunspot measurements. However, it is still necessary to discuss the integrity, or soundness, of the RGO daily number of sunspot groups on the solar disk, if considered as a time series representing variable solar activity during the interval 1874 – 1885. This is accomplished using the new dataset for the RGO daily number of sunspot groups derived in the article by Willis, Wild, and Warburton (2016). First, the daily variation in the RGO number of sunspot groups is presented visually in a way that illustrates both the changes in the solar observatory and the changes in the metadata. Second, statistical techniques are used to investigate the time series.

Before presenting the figures showing the changes in the solar observatory and in the metadata, a few comments should be made on the learning curves experienced by the RGO staff. It seems likely that the learning curve for the use of the Kew photoheliograph at the Royal Observatory, Greenwich, actually commenced in 1858, not 1874. This photoheliograph became operational at the Kew Observatory in mid-March 1858, although it was not used continuously to take daily photographs at Kew until five years after that date (Macdonald, 2015). Even though there was no direct exchange of personnel between the Kew Observatory and the Royal Observatory, Greenwich, the evidence presented in Section 4.1 strongly suggests that there was an exchange of information at director level. De La Rue, designer of the Kew photoheliograph, and Airy, Astronomer Royal, were close friends and corresponded about starting solar photography at Greenwich. Although no technical details have been found in their correspondence, it is not difficult to imagine them holding such discussions verbally. Conversely, it could be argued that there was a separate learning curve for the irregular interleaving, or merging, of the photographs supplied by different solar observatories, which commenced in December 1874 with the provision of two photographs taken on 9 and 12 December at the Harvard College Observatory (Willis, Wild, and Warburton, 2016).

7.1. The Interleaving of Photographs from Different Solar Observatories

The RGO daily number of sunspot groups on the solar disk, as derived by RGO staff from photographs supplied by the solar observatories listed in Table 1, is illustrated in Figures 2a – 2l for the interval 1874 – 1885. To distinguish between the photographs supplied by the different solar observatories, the following colour-coding scheme is used: Dehra Dun (red), Greenwich (green), Harvard (dark blue), Mauritius (orange), Melbourne (light blue), unknown observatory (purple), and no photograph (black). Smaller coloured circles (circumferences) are used to represent an image of the Sun of about 4 inches in diameter, and larger coloured circles are used to represent an image of about 8 inches in diameter. Days for which no solar photograph was acquired are represented by diminutive black circles, quite deliberately located below the zero level for the number of sunspot groups with a radius that avoids overlap. Figures 2a – 2l illustrate the large number of missing photographs, particularly in the first four-year interval 1874 – 1877. As emphasised by Willis, Wild, and Warburton (2016), the correct treatment of days without solar photographs is absolutely crucial to the correct determination of Group Sunspot Numbers. All of the changes in the metadata listed at the beginning of this section are also indicated explicitly in Figures 2a – 2l.

Visual inspection of Figures 2e and 2f for the two-year interval 1878 – 1879, which spans a sunspot minimum (1878.9), reveals that there are a large number of occasions when a change in the solar observatory, over two consecutive days, is not associated with a corresponding change in the number of sunspot groups on the solar disk. Indeed, the number of changes in solar observatory that are not associated with a change in the number of sunspot groups far exceeds the number of changes in the solar observatory that are associated with a change in the number of sunspot groups. Since some genuine changes in the number of sunspot groups on two consecutive days are to be expected, even at sunspot minimum, it is clear that differences in observing telescopes, seeing conditions, and photographic processes at the different solar observatories (DHRA, GREN, MAUR, MELB) are not dominant factors in the determination of the RGO daily number of sunspot groups on the solar disk during the interval 1874 – 1885, at least near sunspot minimum (1878 – 1879). Moreover, since there are no changes in the metadata in the interval 1878 – 1879, the interleaving of the data from the different solar observatories appears to be a valid procedure, at least near sunspot minimum.

Interpreting the data presented in Figures 2a – 2l for the entire interval 17 April 1874 – 31 December 1885, by visual inspection alone, is rather more challenging. Therefore, the time series representing the RGO number of sunspot groups for this entire interval is now examined using a standard statistical technique. The particular test used in this investigation is the runs test for randomness (Spiegel, Schiller, and Srinivasan, 2013). As this is a non-parametric test, it is independent of population distributions and associated parameters. The essential theory is presented in the Appendix. The present application of the theory of runs considers whether or not there is a change in the RGO number of sunspot groups following a change in the solar observatory, *strictly over two consecutive days*, for which the answer is either 'Yes' (Y) or 'No' (N). Days for which the solar observatory is unknown (UNKN) or for which no solar photograph is available (NONE) are excluded from the statistical analysis. The runs test can be quantified, as explained in the Appendix. The terms introduced in the Appendix and used in the statistical calculations are defined as follows: N_1 denotes the number of Ys ('Yes'), N_2 denotes the number of Ns ('No'), $N = N_1 + N_2$; R denotes the number of runs, μ_R denotes the mean of the sampling distribution of the statistic R, σ_R denotes the standard deviation (S.D.) of the sampling distribution of the statistic R, and Z denotes the standardised variable [*i.e.*, $Z = (R - \mu_R)/\sigma_R$; see the Appendix].

Although the main goal is to use the theory of runs to investigate the full twelve-year interval 1874 – 1885, it is instructive to use the theory first to investigate the two-year interval 1878 – 1879, which has already been considered semi-quantitatively by visual inspection of Figures 2e and 2f. This limited time interval is doubly important because there are no complicating changes of metadata within the time interval. For the time interval 1878 – 1879, which spans the sunspot minimum, the relevant numerical values are as follows: $N_1 = 29$, $N_2 = 266$, $N = 295$, and $R = 45$. It then follows from Equations (A.1) and (A.2) in the Appendix that $\mu_R = 53.30$ and $\sigma_R = 3.02$. Finally, using Equation (A.3), $Z = -2.75$. For a two-tailed test at the 0.05 significance level, the hypothesis (H_0) of randomness would be accepted if $-1.96 \leq Z \leq +1.96$ and would be rejected if otherwise. Since $Z = -2.75$ and $-2.75 < -1.96$, the hypothesis of randomness (H_0) can be rejected at the 0.05 level. The test shows that there are too few runs near sunspot minimum, which implies a preponderance (or bunching, or clustering) of cases for which the number of sunspot groups remains unchanged when the solar observatory changes on consecutive days, as already inferred from visual inspection of Figures 2e and 2f. The largest run of Ns (‘No’) in the interval 1878 – 1879 is 76, and this occurs during the long seven-month interval 23 November 1878 – 24 June 1879.

For the entire interval 17 April 1874 – 31 December 1885, the relevant numerical values are as follows: $N_1 = 598$, $N_2 = 709$, $N = 1307$, and $R = 460$. It then follows from Equations (A.1) and (A.2) in the Appendix that $\mu_R = 649.79$ and $\sigma_R = 17.94$. Finally, using Equation (A.3), $Z = -10.58$. Once again, for a two-tailed test at the 0.05 significance level, the hypothesis (H_0) of randomness would be accepted if $-1.96 \leq Z \leq +1.96$ and would be rejected if otherwise. Since $Z = -10.58$ and $-10.58 < -1.96$, the hypothesis of randomness (H_0) can be rejected at the 0.05 level. The test shows that there are too few runs in the interval 17 April 1874 – 31 December 1885, which again implies a clustering (or bunching) of cases for which the number of sunspot groups remains unchanged when the solar observatory changes on consecutive days. Even for the final six-year interval 1880 – 1885, $Z = -3.26$ ($N_1 = 484$, $N_2 = 291$, $N = 775$, and $R = 322$) and $-3.26 < -1.96$, which implies non-randomness in the time interval leading up to, and a year beyond, sunspot maximum (1883.9).

7.2. Effects of Changes in the Metadata

Changes in the metadata were also investigated using the runs test for randomness (Spiegel, Schiller, and Srinivasan, 2013). In such cases, the application of the theory of runs considers whether there is a change (‘Yes’ = Y or ‘No’ = N) in the number of sunspot groups seen on photographs acquired at the specified solar observatory, compared with the number seen on photographs acquired at a different solar observatory on either the strictly preceding or following day. Clearly, this definition restricts the statistical sample to those situations in which the number of sunspot groups changes, *again strictly over two consecutive days*, when one of the pair of observatories is always the one for which the metadata changes. Moreover, the runs test for randomness must now be performed over selected time intervals before and after the change in metadata at the specified observatory. The results are presented in Table 2. Column 1 presents the specified observatory (*e.g.*, Greenwich) and column 2 defines the change in the metadata (before and after) at that observatory. The third column shows the selected time intervals before and after the change in metadata; these are chosen to ensure that both the number of Ys (N_1) and the number of Ns (N_2) are either greater than or equal to 10. The fourth column defines the criterion used to determine a meaningful change in the number of sunspot groups; in this investigation the criterion is the simple one that there should be a change in the modulus of the difference in the number of sunspot groups

($|\Delta G|$) over two consecutive days, namely $|\Delta G| \geq 1$. Obviously, different results would be obtained if this criterion were to be changed. The fifth to tenth columns give the values of N_1, N_2, R, μ, σ, and Z, respectively, which are all defined in Section 7.1 and the Appendix. The eleventh column indicates the part (or parts) of Figure 2 that shows the number of sunspot groups for the selected time interval. Finally, the twelfth column indicates whether the differences in the number of sunspot groups observed at the specified solar observatory, compared with the number of sunspot groups observed at other observatories, are random or non-random, both before and after the change in metadata at the specified solar observatory.

It is clear from Table 2 that there are no statistically significant changes in the number of sunspot groups recorded at Greenwich or Dehra Dun following the various changes in metadata at these solar observatories, since all such changes are random. It should be noted that the 32-day interval 7 November 1882 – 8 December 1882, when the diameter of the Sun on the photographs acquired at Dehra Dun was first about 8 inches instead of about 4 inches, is far too short to apply the runs test for randomness (in this case $N_1 = 7$ and $N_2 = 1$; hence both N_1 and $N_2 \leq 10$). Similarly, the number of photographs from Mauritius that were used to compile the RGO count of the number of sunspot groups in the long intervals 1 May 1884 to 28 February 1885 and 1 March 1885 to 31 December 1885 (the end of the interval considered in this study) are too few to apply the runs test for randomness. As an obvious corollary, the number of photographs supplied by Mauritius is too small to influence significantly the RGO count of the number of sunspot groups.

A few further comments should be made about the criterion $|\Delta G| \geq 1$. As already mentioned, this criterion merely requires that the modulus of the difference between the number of sunspot groups observed at the observatory implementing a change of metadata and the number of sunspot groups observed at any other observatory on an adjacent day should be greater than or equal to 1. Note also that no stipulation is made about the sign of this difference. Furthermore, visual inspection of Figures 2a – 2l reveals instances of the number of sunspot groups measured on a photograph of the Sun having a radius of about 8 inches being equal to or smaller than the number of sunspot groups measured on a photograph of the Sun having a radius of about 4 inches (acquired at a different observatory on an adjacent day). The present application of the runs test for randomness only requires the number of sunspot groups observed at the test observatory to be different to the number of sunspot groups observed at any other comparison observatory on an adjacent day. However, changing the criterion $|\Delta G| \geq 1$ would make it extremely difficult, if not impossible, to retain the necessary constraints $N_1 \geq 10$ and $N_2 \geq 10$ over realistic date ranges. It should also be noted that there are many instances of the number of sunspot groups measured on a series of consecutive days at the test observatory itself satisfying the criterion $|\Delta G| \geq 1$, as is to be expected for even moderately varying levels of solar activity and the known occurrence of sunspots that exist for just a single day (Willis, Wild, and Warburton, 2016).

Therefore, the present application of the theory of runs searches for *consistent differences* between the test observatory and any other comparison observatory on an adjacent day, over date ranges selected to ensure that $N_1 \geq 10$ and $N_2 \geq 10$. If any change in the metadata at a particular observatory were statistically significant, it might be expected to find random differences before the change in the metadata and non-random differences afterwards. In general, the statistical evidence presented in Table 2 does not support such a conclusion. However, it should be noted here that the photographs taken at Greenwich during the months of May and June in 1884 are badly defined, as mentioned in Section 5. These badly defined photographs might possibly influence the results in Table 2 for the interval 2 April – 1 October 1884, following the change in the radius of the Sun on the Greenwich photographs from about 4 inches to nearly 8 inches.

On the basis of the arguments presented in this section, which are summarised in Table 2, it is concluded that changes in the metadata at the two main solar observatories listed in Table 1 (in terms of the number of photographs supplied for measurement by RGO staff), namely Dehra Dun and Greenwich, do not undermine the validity of the RGO daily number of sunspot groups on the solar disk during the interval 1874 – 1885. The other solar observatories listed in Table 1 each contributed far fewer photographs for measurement by RGO staff than either Dehra Dun or Greenwich, and hence these other observatories are unlikely to play a major role in the determination of the RGO daily count of the number of sunspot groups on the solar disk. Therefore, the RGO daily count of the number of sunspot groups behaves as a quasi-homogeneous time series during the interval 1874 – 1885.

8. General Discussion

Considerable attention has recently been focused on attempts to reconcile the discrepancies between the International and Group Sunspot Numbers (Cliver, Clette, and Svalgaard, 2013; Clette *et al.*, 2014; Cliver.*et al.*, 2015; Cliver and Ling, 2016). From comparisons between the annual means of the number of sunspot groups recorded by the Royal Observatory, Greenwich, and those recorded by other long-term observers in the approximate time interval 1874 – 1925, some authors have argued that the RGO group-count time series for the years before about 1915 is "not stable" (Clette *et al.*, 2014) or is "inhomogeneous" (Cliver *et al.*, 2015; Cliver and Ling, 2016). Cliver *et al.* (2015), and Cliver and Ling (2016) suggest an observer "learning curve" or instrumentation/technique changes at the various solar observatories supplying photographs (see Table 1) for measurement by staff at the Royal Observatory, Greenwich (or the Solar Physics Observatory, South Kensington), as possible causes of an "inhomogeneous" RGO dataset. The main goal of this article is to examine, as objectively as possible, all of the potential inhomogeneities in the data published by the Royal Observatory, Greenwich. The statistical definition of homogeneity, or inhomogeneity, used in this article is outlined in the following paragraph. Thus all matters related to the internal structure of the RGO dataset, such as an observer learning curve and instrumentation or technique changes are investigated in detail, but comparisons with other external time series are considered only briefly.

Accordingly, before summarising the main results and conclusions, it is appropriate to make a few general comments on the reliability of the RGO sunspot measurements. In simple, non-technical terms, a homogeneous dataset is one for which everything remains unchanged apart from the variable being measured, which in this investigation is the number of sunspot groups on the solar disk. Stated more accurately, *homogeneity* relates to the validity of the (often) convenient assumption that the statistical properties of any one part of a dataset are the same as any other. With this definition of *homogeneity*, the count of the number of sunspot groups on the solar disk published by the Royal Observatory Greenwich is *inhomogeneous* in the strict sense that this count is based on information derived from solar photographs acquired at different solar observatories, which use different telescopes, experience different seeing conditions, and employ different photographic processes. However, as mentioned previously in the Introduction and at the beginning of Section 5, with this strict definition the RGO count of the number of sunspot groups on the solar disk is *inhomogeneous* (by definition) throughout the entire interval 1874 – 1976, and not just before a somewhat arbitrary date such as 1915.

The fact that the annual Group Sunspot Number is appreciably smaller than the annual International Sunspot Number before about 1885 (Clette *et al.*, 2014; Cliver *et al.*, 2015;

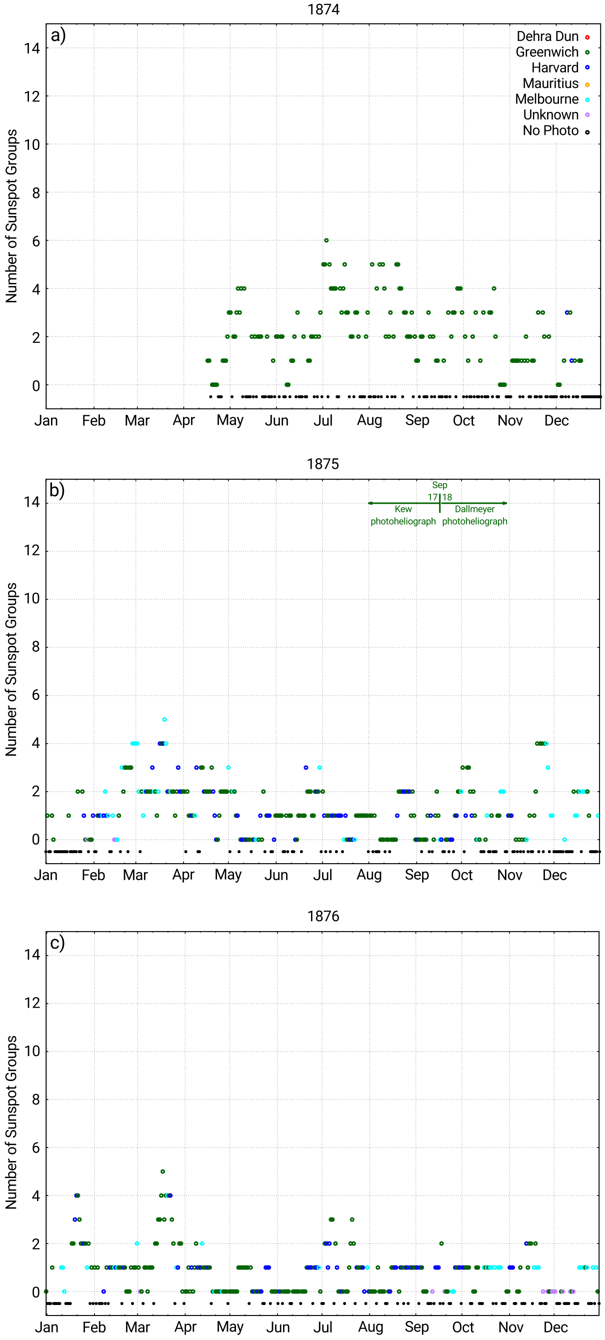
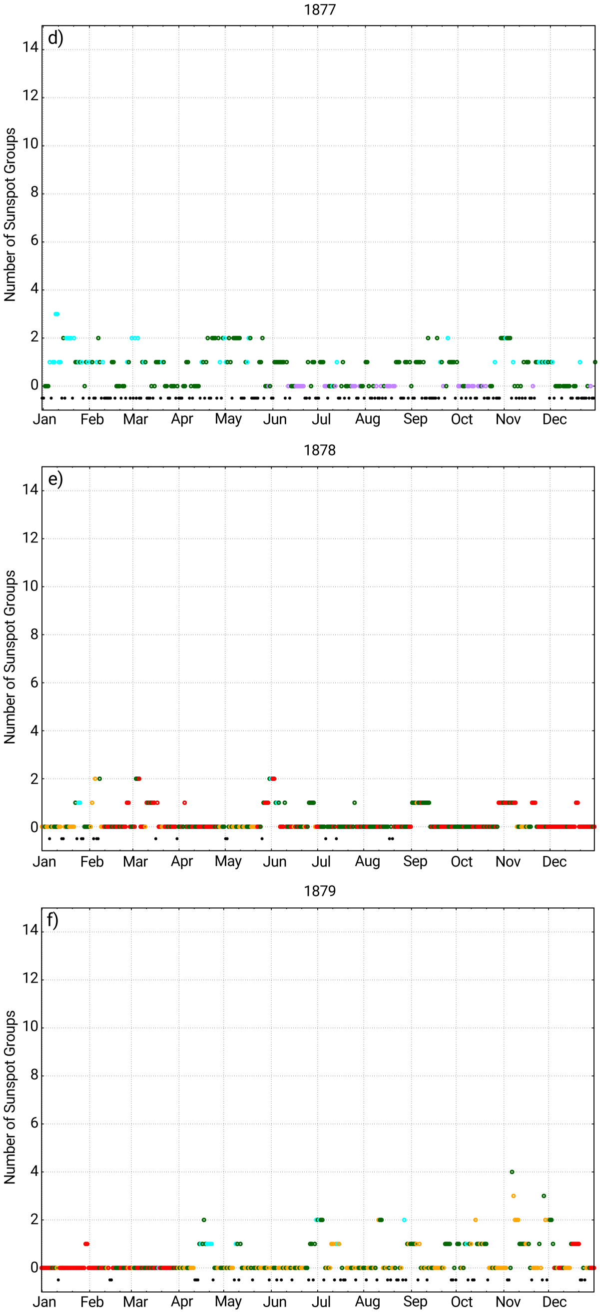


Figure 2 Daily number of sunspot groups, as derived by the RGO staff from photographs supplied by the solar observatories listed in Table 1. The twelve parts of Figure 2 (Figures 2a – 2l) show the daily variation in the number of sunspot groups for the twelve individual years 1874 to 1885. The following colour-coding scheme is used: Dehra Dun (red), Greenwich (green), Harvard (dark blue), Mauritius (orange), Melbourne (light blue), unknown observatory (purple), and no photograph (black). Smaller coloured circles represent an image of the Sun of about 4 inches in diameter, and larger coloured circles represent an image of about 8 inches in diameter. Diminutive black circles represent days for which no photograph was acquired originally. These non-overlapping diminutive black circles illustrate the large number of missing photographs, particularly for the four-year interval 1874 – 1879. All changes in the metadata are indicated explicitly in Figures 2a – 2l; these changes are colour-coded and annotated to indicate the relevant solar observatory and the type of change in the metadata.

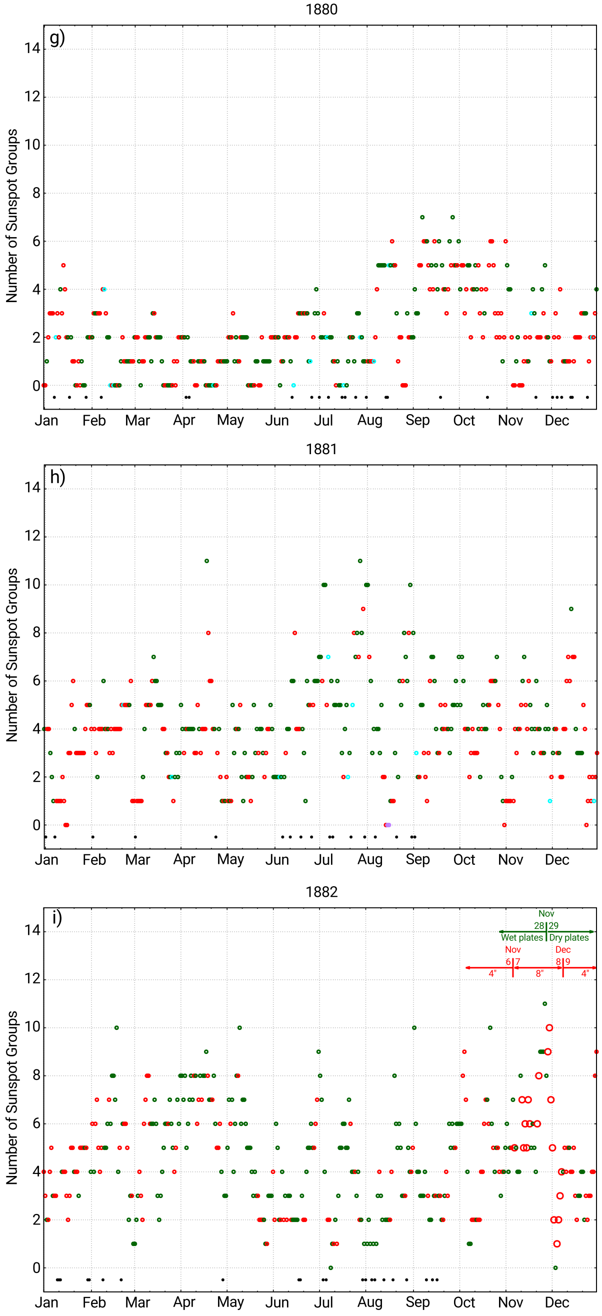
Cliver and Ling, 2016) does not *necessarily* (*by itself alone*) imply that the RGO count of the number of sunspot groups is flawed in the early years. The difference between the Group and International Sunspot Numbers could arise from an error not related to the Royal

Figure 2 (*Continued*)



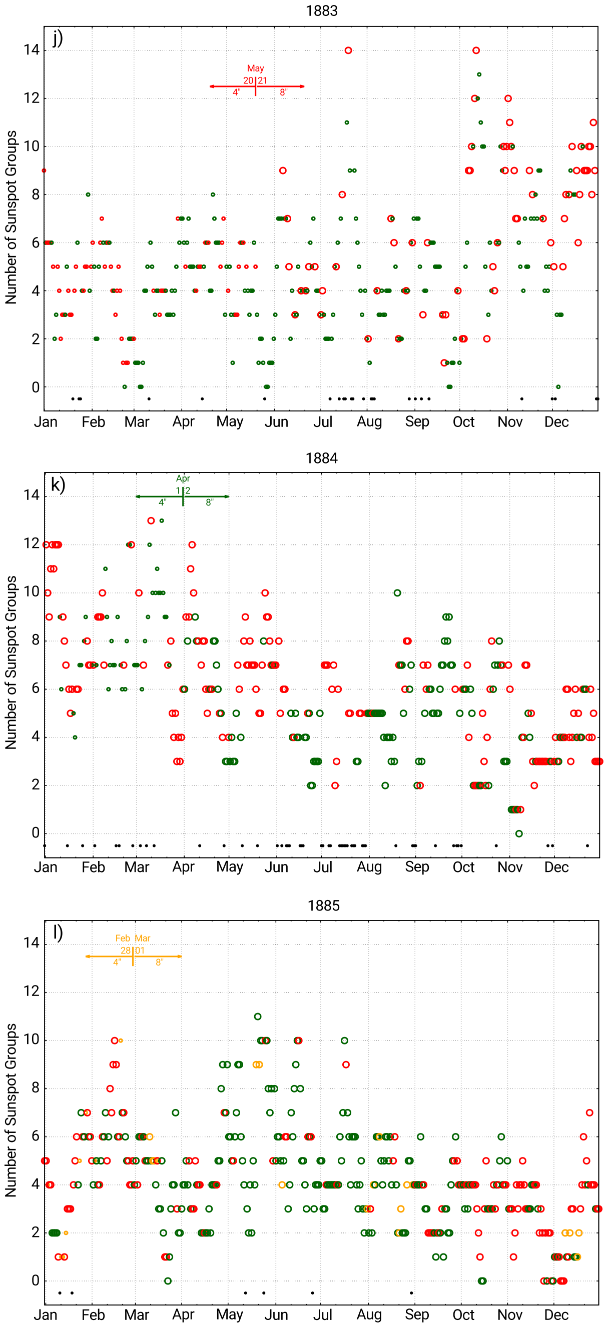
Observatory, Greenwich, such as the procedure adopted by Hoyt and Schatten (1998a) for deriving the Group Sunspot Number. Indeed, Cliver and Ling (2016) argue that the indirect normalisation procedure used by Hoyt and Schatten to obtain personal correction factors [k] for observers who overlapped with the RGO contributes to the difference between the

Figure 2 (*Continued*)



International and Group time series before about 1885. However, the published differences between the ratio of the RGO annual group counts to those of several other selected observers (Figure 24 in Clette *et al.*, 2014; Figure 3 in Cliver *et al.*, 2015; and Figure 2 in Cliver and Ling, 2016) have been invoked to suggest that the RGO daily count of the num-

Figure 2 (*Continued*)



ber of sunspot groups is flawed before about 1915. Cliver and Ling (2016) have shown that upward adjustment of the RGO counts (tapering from about 60 % for 1874 – 1876 to approximately 0 % for 1915) and direct comparison of these adjusted counts with those of

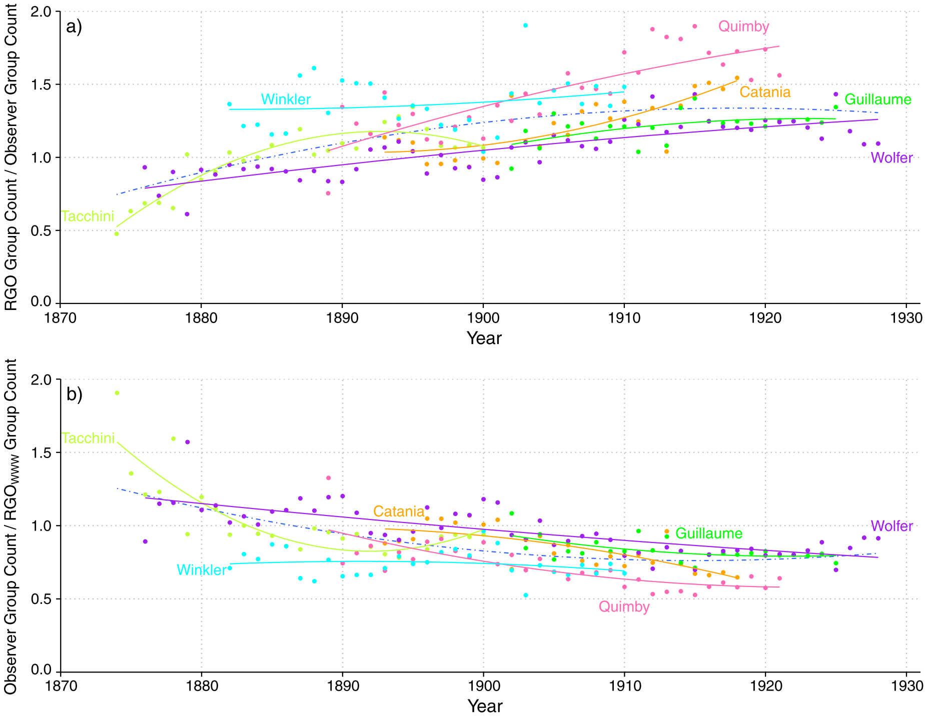


Figure 3 (a) Ratios of the mean annual RGO group counts to those of Tacchini, Winkler, Catania, Quimby, Wolfer, and Guillaume for the interval 1874 – 1928. The input data used to calculate these ratios are the alldata files compiled by Hoyt and Schatten (1998a). Second-order polynomials are fitted separately for each of the six observers, and the single second-order fit to all the observers is shown as a broken (dash–dot) line. This figure is compared with Figure 3 in Cliver *et al.* (2015) in the text. (b) Ratios of the mean annual group counts of Tacchini, Winkler, Catania, Quimby, Wolfer, and Guillaume to those of the RGO, now modified to include the corrections to the RGO alldata files compiled by Willis, Wild, and Warburton (2016) for the interval 1874 – 1885 (denoted by $\mathrm{RGO}_{\mathrm{WWW}}$), for the same interval 1874 – 1928. Second-order polynomials are again fitted separately for each of the six observers, and the single second-order fit to all the observers is again shown as a broken (dash–dot) line.

other selected observers apparently removes much of the difference between the two time series.

In view of the serious nature of these criticisms of the early sunspot observations conducted under the aegis of the Royal Observatory, Greenwich, the results presented in Figure 3 of the article by Cliver *et al.* (2015) have been reinvestigated. Noticeably different results are presented in Figure 3a of this article, which is based *solely* on the information presented in the alldata files published by Hoyt and Schatten (1998a) and not on the filldata files used by Cliver and Ling (2016) for consistency with the Hoyt and Schatten approach. Stated more precisely, it is assumed that the alldata files currently represent the best available information for the set of all 463 observers considered by Hoyt and Schatten (1998a), although the article by Willis, Wild, and Warburton (2016) outlines a possible strategy for deriving better datasets in the future (see their Section 5). It is clear that there are discrepancies between the ratios of RGO group counts to observer group counts in Figure 3a and Figure 3 in the article by Cliver *et al.* (2015), both with respect to the size of certain ratios, as indicated by the different scales on the ordinates on the left-hand side of the figures, and with respect to the relative positions of some data points. However, as indicated in a note added to the article by Cliver and Ling (2016), Figure 3 in the article by Cliver *et al.* (2015) actually shows the ratios of RGO annual mean group counts to the counts of other observers, after the other observers have been normalised to the count of Wolfer (E.W. Cliver, private communication, 2015). Nevertheless, the validity of fitting a second-order polynomial to the ratios of the RGO annual average group counts to those of a number of selected observers, rather than just a single observer, is at least questionable. Therefore, second-order polynomials (coloured continuous lines) have been fitted to each of the six observers separately in Figure 3a, whereas the single second-order fit to all the observers is shown as a broken (dash–dot) line.

Figure 3b shows the mathematically reciprocal ratios of the annual average group counts of the six other observers to the corresponding RGO counts. This figure is based on the information presented in the alldata files published by Hoyt and Schatten (1998a), modified to include the corrections to the RGO alldata files compiled by Willis, Wild, and Warburton (2016) for the interval 1874 – 1885 (hence RGO is replaced by $\mathrm{RGO}_{\mathrm{WWW}}$ in Figure 3b). It seems more logical to normalise the six different observer counts to the single RGO count. Once again, individual second-order polynomials (coloured continuous lines) have been fitted to each of the six observers separately in Figure 3b, whereas the single second-order fit to all the observers is again shown as a broken (dash–dot) line. However, as the discrepancies between Figure 3 in the article by Cliver *et al.* (2015) and Figure 3a in this article are not absolutely crucial to the central theme of the present article, which is the homogeneity, or inhomogeneity, of the RGO dataset itself, considered as a *daily* time series, the consequences of any required revision to Figure 3 in the article by Cliver *et al.* (2015) will not be considered further in this article.

Figures 2a – 2l show the true variation in the daily number of sunspot groups on the solar disk during the interval 1874 – 1885, as recorded by the programme of sunspot observations performed under the aegis of the Royal Observatory, Greenwich, and subsequently the Royal Greenwich Observatory (RGO). These figures show separately the daily variation in the number of sunspot groups for each of the twelve calendar years 1874 to 1885, according to the revised dataset compiled by Willis, Wild, and Warburton (2016). All changes in the metadata at the solar observatories supplying photographs for measurement by the RGO staff are depicted in the figures. It is the homogeneity, or inhomogeneity, of the basic dataset embodied in Figures 2a – 2l that should be investigated statistically, not any derived dataset based on further arithmetical procedures applied to this basic dataset. A start has been made in the present investigation by applying the runs test for randomness to the basic dataset. No statistical evidence has yet been found to suggest that the interleaving of solar photographs from the different observatories invalidates the RGO measurements. Likewise, changes in metadata at the different observatories do not appear to produce any subsequent non-random variations in the RGO number of sunspot groups. Clearly, further statistical tests should be performed to confirm these initial conclusions.

9. Summary and Conclusions

Potential sources of inhomogeneity in the RGO dataset for the early interval 1874 – 1885 were examined critically in this article. The procedures employed in the Solar Department of the Royal Greenwich Observatory (RGO) during the final phase of the programme of sunspot observations (1960s – 1976) provide a modern benchmark for interpreting the early sunspot measurements (Section 2). The ultimate aim is to bridge the time interval between the third quarter of the twentieth century and the last quarter of the nineteenth century, using all the official RGO publications for the long interval 1874 – 1976, as well as additional information gleaned either from the books written by individual scientists who worked in the Solar Department at the RGO (Maunder, 1900; Newton, 1958) or from a major treatise on the work of the RGO (Howse, 1975).

The details of the telescopes used at the solar observatories that contributed photographs to the RGO during the interval 1874 – 1885 (Table 1) were considered in Section 4 for each of the three four-year intervals 1874 – 1877, 1878 – 1881, and 1882 – 1885. For the first four-year interval, the Kew and Dallmeyer photoheliographs used at Greenwich were discussed in detail to determine the likely reliability of these instruments. The change from the use of the Kew photoheliograph to the Dallmeyer photoheliograph in September 1875 does not result in any obvious visual change in the number of sunspot groups recorded (Figure 2b). After September 1875, the Dallmeyer photoheliographs used at Dehra Dun, Greenwich, Mauritius, and Melbourne were of a similar design and should be expected to give similar results, apart perhaps from the use of different photographic processes. The photoheliograph used at Harvard was different to the Dallmeyer photoheliographs used at the other observatories. It comprised a horizontal photoheliograph with an object glass alone. Visual inspection of Figures 2a – 2d does not reveal any dramatic differences between the numbers of sunspot groups observed on photographs taken at Greenwich and Harvard on approximately adjacent days.

The different photographic processes used at the various solar observatories were discussed in Section 5. In the early years (1874 and 1875), over-exposure might have caused problems when measuring the number of sunspot groups on images obtained at Greenwich, using wet plates that were coated with a film of iodized cadmium collodion, and developed with pyro-gallic acid. Figure 1, which shows a photograph (contact print) of the Sun acquired on 31 August 1859, using the Kew photoheliograph, provides an example of this variable sensitivity of the collodion plates.

The procedures for measuring the positions and areas of sunspots on the solar disk were reviewed in Section 6. In general, it appears that these measurements were made extremely carefully, with cross-checking of the values by different RGO measurers. Corrections were applied for both optical distortion of the photoheliographs and for refraction. In addition, two possible sources of error in measurements of the solar photographs were considered by the RGO staff; namely the probable error in the measurements on eight-inch photographs and the effect of personality in the measurement of areas on the four-inch photographs (the latter essentially being equivalent to considering the "personal correction factors" of the different RGO measurers). These detailed studies indicated that such corrections were generally insignificant.

The precise way in which the RGO staff delineated different sunspot groups has not been documented carefully in the early RGO publications. Clearly, any subjectivity in the delineation or identification of distinct sunspot groups will affect the RGO determination of the number of sunspot groups on the solar disk, and hence the calculation of Group Sunspot Numbers, following the arithmetical procedure published by Hoyt and Schatten (1998a; see their Equation (2)). Further research is required on the delineation of sunspot groups in the early years.

As noted in Section 7, the claim that some allowance should be made for the evolution of observer expertise at the contributing solar observatories and the gradual refinement of the procedures adopted by RGO staff, which commenced in 1874, is not completely convincing for the following reason. Expertise in the use of the photoheliograph and the measurement of solar photographs started some sixteen years earlier, in 1858, with the pioneering work undertaken by De La Rue at the Kew Observatory. It seems likely that this expertise would have been transferred, albeit indirectly, to staff at the Royal Observatory, Greenwich.

Conversely, it could be claimed that the RGO staff experienced a new learning curve at the start of the irregular interleaving, or merging, of solar photographs, which began in December 1874 with the provision of two photographs taken at the Harvard College Observatory on 9 and 12 December. The result of the interleaving of photographs supplied by different solar observatories is illustrated in Figures 2a – 2l, which show the daily variation in the number of sunspot groups against time for the 12-year interval 1874 – 1885. These figures illustrate the large number of missing photographs, particularly in the first four-year interval 1874 – 1887. The correct treatment of days without solar photographs is absolutely crucial to the correct determination of Group Sunspot Numbers (Willis, Wild, and Warburton, 2016).

As noted in Section 7.1, visual inspection of Figures 2e and 2f for the two-year interval 1878 – 1879, which spans a sunspot minimum, reveals a large number of occasions when a change in solar observatory, over two consecutive days, is not associated with a change in the number of sunspot groups. Therefore, differences in observing telescopes, seeing conditions and photographic processes at the different solar observatories are not major factors in the determination of the RGO number of sunspot groups at least near sunspot minimum (1878 – 1879).

Interpreting the data presented in Figures 2a – 2l for the entire 12-year interval by visual inspection alone is more difficult. Therefore, the time series was investigated statistically using the runs test for randomness. The theory was applied first to the two-year interval 1878 – 1879 spanning a sunspot minimum (1878.9). The runs test showed that the changes in the number of sunspot groups following a change in solar observatory, occurring strictly over two consecutive days, are non-random at the 0.5% significance level. Hence the statistical test confirmed the result inferred from visual inspection of Figures 2e and 2f.

The entire interval 17 April 1874 – 31 December 1885 has also been investigated using the runs test for randomness. Once again, the runs test showed that the changes in the number of sunspot groups following a change in solar observatory, occurring strictly over two consecutive days, are non-random at the 0.5% significance level. This result suggests that no significant problems arise from the interleaving of photographs taken at the different solar observatories.

All changes in the metadata at the different solar observatories are also shown in Figures 2a – 2l. The statistical significance of these changes has also been investigated using the runs test for randomness (Section 7.2). The results are presented in Table 2. It is clear from this table that there are no statistically significant changes in the number of sunspot groups recorded at Greenwich and Dehra Dun, following the various changes in metadata at these solar observatories.

Based on the arguments and information presented in this article, which are summarised in Table 2, it was concluded that changes in the metadata at the two main solar observatories listed in Table 1, namely Dehra Dun and Greenwich, do not undermine the validity of the RGO number of sunspot groups on the solar disk during the interval 1874 – 1885. Each of the other solar observatories listed in Table 1 (Harvard, Mauritius, and Melbourne) contributed far fewer photographs for measurement by RGO staff than either Dehra Dun or Greenwich. Further research is required on possible changes in the metadata at Harvard.

The main conclusion of this article is that the number of sunspot groups on the solar disk, according to the programme of sunspot measurements performed under the aegis of the Royal Observatory, Greenwich, during the interval 1874 – 1885, behaves as a quasi-homogeneous time series. A minor caveat should be expressed over the delineation of sunspot groups by the RGO staff, at least in the sense that there appears to be no definitive explanation of this procedure. In addition, further statistical techniques should be used to confirm the conclusion that the RGO number of sunspot groups behaves effectively as a quasi-homogeneous time series.

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Appendix: The Runs Test for Randomness

As noted in Section 7.1, the theory of runs is used in this study to consider whether there is a change in the RGO number of sunspot groups following a change in the solar observatory, *strictly over two consecutive days*, for which the answer is either ‘Yes’ (Y) or ‘No’ (N). Days for which the solar observatory is unknown (UNKN) or for which no solar photograph is available (NONE) were excluded from the statistical analysis. Considering the changes in solar observatory chronologically yields a long sequence of Ys and Ns of the *illustrative* form N N | Y | N N N | Y Y | N | Y | N N N N | Y Y Y | N N | Y |, *etc.*, where the vertical bars separate *runs* of Ys and Ns. Such a sequence is considered non-random if there are either too many or too few runs, and random otherwise.

The runs test can be quantified as follows. Consider the formation of all possible sequences consisting of N_1 Ys and N_2 Ns for a total of Npossibilities ($N_1 + N_2 = N$). The collection of all these sequences constitutes a sampling distribution. Each sequence has an associated number of runs, denoted by R. This leads to the sampling distribution of the statistic R, and it transpires that this sampling distribution has a mean and variance given, respectively, by the following equations (Spiegel, Schiller, and Srinivasan, 2013):

$$\mu_R = 2[N_1N_2/(N_1 + N_2)] + 1, \tag{A.1}$$

and

$$\sigma_R^2 = 2[N_1N_2(2N_1N_2 - N_1 - N_2)]/[(N_1 + N_2)^2(N_1 + N_2 - 1)]. \tag{A.2}$$

Using Equations (A.1) and (A.2), it is possible to test the hypothesis of randomness at appropriate levels of significance. If both N_1 and N_2 are at least equal to 8, the sampling distribution of R is very nearly a normal distribution (Spiegel, Schiller, and Srinivasan, 2013). In this study the slightly stricter constraint that both N_1 and N_2 should be at least equal to 10 was imposed in all applications of the runs test. Thus the standardised variable, Z, defined by the equation

$$Z = (R - \mu_R)/\sigma_R, \tag{A.3}$$

is normally distributed with mean 0 and variance 1, and therefore the areas below the standard normal curve can be used to determine statistical significance. For a two-tailed test at the 0.05 significance level, the hypothesis (H_0) of randomness can be accepted if $-1.96 \leq Z \leq +1.96$ and rejected otherwise (Spiegel, Schiller, and Srinivasan, 2013).

Further information on the runs test for randomness can be found in the publications by Stevens (1939), Mood (1940), Wald and Wolfowitz (1940), Swed and Eisenhart (1943), and Stuart and Ord (1991).

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