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RECALIBRATING THE SUNSPOT NUMBER (SSN): THE SSN WORKSHOPS

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Abstract. The sunspot number (SSN) is the primary time series in solar and solar-terrestrial physics. Currently there are two widely-used sunspot numbers, the International SSN and the Group SSN, which differ significantly before ∼1885. Thus the SSN is potentially a free-parameter in models of climate change or solar dynamo behavior. To reconcile the International and Group SSNs, we have organized a series of workshops. The end goal of this effort is a community-vetted time series of sunspot numbers for use in long-term studies. We are about half way through the process, with the International and Group SSN time series reconciled back to 1826. We hope to have the reconciliation completed back to the beginning of the SSN time series (1610) by mid-2014. We have learned or relearned some interesting things along the way: (1) the International or Wolf SSN time series is not based solely on sunspots; (2) the simple formula from Wolf for the SSN that is found in all solar physics textbooks is not used in practice (all sunspots are not equal); and (3) the Group SSN appears to be too low before 1885. When completed, the reconciled ∼400-yr SSN time series will serve as a bridge to the millennia-scale record of solar variability from cosmogenic nuclide concentrations in tree rings and ice cores.

Key words: sunspot number - climate change - solar dynamo

1. Introduction

The sunspot number (SSN) is the primary time series in solar and solar-terrestrial physics. Here primary is meant both in the sense of timing (dating to Wolf, 1856) and application (based on the role of the SSN in studies of the solar dynamo, terrestrial climate change, and space climate). The key role the SSN plays is underscored by the unusual solar activity of the past decade which has prompted numerous comparisons with previous episodes of such low solar, i.e., SSN, activity.

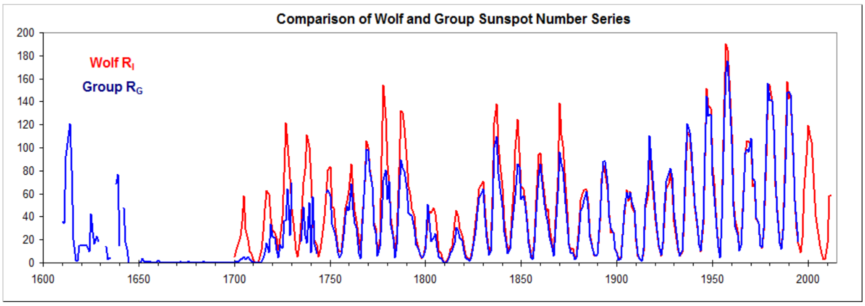

Figure 1: Comparison of yearly mean values of the Wolf (R_I) and Group (R_G) SSN time series (adapted from Hoyt & Schatten, 1998b).

But there is a problem with the sunspot number time series. There are two of them - the series that dates to Wolf (variously referred to as the International, Wolf, or Zürich SSN) and the alternative Group SSN developed by Hoyt & Schatten (1998a,b) - with no clear consensus on which to use. To illustrate this state of affairs, we note a recent discussion of the use of proxy data to deduce solar irradiance (Schmidt *et al.*, 2012) that cited a number of irradiance reconstructions (Wang *et al.*, 2005; Muscheler *et al.*, 2007: Steinhilber *et al.*, 2009; Fröhlich, 2009; Vieira *et al.*, 2011; Shapiro *et al.*, 2011). Of the listed authors, Wang *et al.* (2005), Steinhilber *et al.* (2009), and Shapiro *et al.* (2011) used the Group SSN in their analyses while Muscheler *et al.* (2007) and Vieira *et al.* (2011; see Krivova *et al.*, 2007) used both the Group and International SSNs and Fröhlich (2009) used the International SSN. Some of the "mixed use" results because the International SSN is not available before 1700 while the Group SSN is not available after 1995 (an update of the Group SSN is in preparation at SIDC).

The use of two SSNs might be acceptable if the differences between the two time series were insignificant. Figure 1 shows that that is not the case. The choice of which sunspot time series to use can have a substantial difference on the conclusions drawn. For example, the report that we have just experienced the most active period of solar activity in the last ~8,000 years (Solanki *et al.*, 2004; cf., Usoskin *et al.*, 2006) is based on the use of the Group SSN.

To address the problem of the two discordant sunspot numbers, we have, with the sponsorship of the US National Solar Observatory (NSO), the Royal Observatory of Belgium (ROB), and the US Air Force, initiated a series of SSN Workshops. The first SSN Workshop was held in September 2011 at the National Solar Observatory in Sunspot, New Mexico and the second was held in May 2012 at the Royal Observatory of Belgium in Brussels, where the Solar Influences Data Center (SIDC) has had the responsibility for calculating the International SSN since 1981 (Clette *et al.*, 2007). We expect to hold at least two more workshops, with the next being held at the National Solar Observatory in Tucson, Arizona in January 2013. The goal of these workshops is to understand the cause of the differences between the International and Group SSNs and to reconcile them, if possible. At the halfway, or near halfway, point of this process, we think both of these goals are achievable. Thus far, we have been able to reconcile the two time series back to the beginning of Schwabe's observations in 1826. Of course, the task becomes more daunting as we go further back in time where observations are scarce.

In section 2 we briefly review the origins of the International and Group SSNs and in section 3 we examine the two principal discontinuities between these two time series. In section 4 we discuss in broader terms the effort to reconcile the SSNs - why we have taken this approach, what we hope to achieve (a community-vetted bridge to millennia of cosmic ray data in tree rings and ice cores) and avoid (yet a third SSN choice for modelers), the desirability of "purity" in an index and the need for independent checks. Finally, we stress that this is a work in progress, with more work ahead.

2. The Two SSN Time Series

2.1. The International SSN (R_I)

Rudolf Wolf (1816-1893; Figure 2(a)) proposed the following definition of the sunspot number in 1856

$$R_I = 10 * G + S \tag{1}$$

where R_I is the relative SSN (hereafter referred to as the International SSN), G is the number of sunspot groups, and S is the number of individual spots (counted at a given time on a given day). Wolf's observational experience led him to this simple formula which gives a sunspot group ten times the weight of an individual sunspot.

Figure 2: (A) Rudolf Wolf, 1816-1893, Director of Zürich Observatory, and originator of the SSN. (B) Alfred Wolfer, 1854-1931, Wolf's successor and curator of the SSN from 1893-1925.

In addition to making his own systematic observations which began in 1849, Wolf also searched the available literature to see if the ~10-yr cycle of sunspot activity reported by Schwabe (1844) could be found for years before 1826 when Schwabe began observing. Wolf was able to extend the SSN series, and identify an 11-yr cycle, back to 1700, where he was met with a scarcity of reported sunspots. As we now know, the year 1700 occurred in the late phase of the sunspot drought known as the Maunder Minimum (Eddy, 1976) which lasted from 1645-1715.

Because of differences in eyesight, seeing conditions, and telescope aperture/quality, different observers will not count the same number of spots on a given day (not to mention spot evolution during a UT day). As a result, Wolf introduced "k-factors" to normalize spot counts from other observers to his own counts.

$$R_I = k(10 * G + S) \tag{2}$$

To make this normalization, Wolf relied not only on sunspot observations, but also compared his and other observers' counts with the daily range of geomagnetic variation. Wolf and Gautier had independently discovered the relationship between the sunspot number and the daily range in 1852. Wolf used this relationship to make wholesale adjustments of Staudacher's spot counts in 1861 (a 100% increase) and of Schwabe's observations in 1880 (a 25% increase). This use of magnetometer observations by Wolf was criticized by Hoyt & Schatten (1998a,b) who speculated that he may have done so to keep the level of solar activity "... roughly constant in each of the 50-year intervals from 1700 to the present..."

2.2. The Group Sunspot Number (R_G)

The first, and thus far only, significant revision of Wolf's SSN time series was made by Hoyt el al. (1994) and Hoyt & Schatten (1998a,b). They undertook this task because

> The Wolf Sunspot Numbers before 1893 ... have remained unchanged [and unexamined] since their original publication ([Wolfer, 1902]; Waldmeier, [1961]; McKinnon, 1986). These numbers were derived by hand using a single primary observer whose missing days were filled by secondary observers. The time series has no error bars associated with it. Finally, a considerable portion of the older observations were not located by Wolf in his research.

Hoyt and Schatten accomplished all of their intended goals. For the years 1610-1995, they compiled 455,242 observations of daily sunspot group counts from 463 observers. For the years before 1874, when Greenwich began systematic reporting of sunspots, they tabulated 147,462 observations from 330 observers vs. 81,521 observations compiled by Wolf from 213 observers. Hoyt and Schatten rederived the SSN on the basis of group counts alone and gave error bars for the different portions of the time series. Finally, they digitized all of the observations on which their new group sunspot number (R_G) was based and made them publicly available. As noted above (Figure 1), the time series derived by Hoyt and Schatten is significantly different from that obtained by Wolf.

The Group SSN is given by the formula

$$R_G = 12.08(K_G * G) \tag{3}$$

where K_G is the normalization factor to a standard observer and the factor of 12.08 was introduced to make the average R_G match R_I from 1874-1976.

Hoyt and Schatten based their new sunspot index solely on the counts of sunspot groups because (1) 90% of the variance in R_I is caused by changes in the number of groups, and (2) many observers specify only the number of groups (Hoyt *et al.*, 1994, Hoyt & Schatten, 1998a,b). R_G also has the advantage of being a "pure" index, i.e., it is only based on sunspot observations.

As can be seen from the references in the Schmidt *et al.* (2012) paper mentioned above, the Group SSN is widely used today. The acceptance of R_G is based on two factors. Since R_G was based on a critical assessment of R_I, it is implicit that "new" is "improved". Equally as important, R_G is based on a more extensive data set. As noted, for example, by Owens & Lockwood (2012), "Where possible, we use group sunspot number, R_G [Hoyt and Schatten, 1998], as it represents a more complete record than Zürich/International sunspot, R_Z, particularly prior to 1850 [Hathaway *et al.*, 2002]."

3. Reconciling R_I and R_G

3.1. The Waldmeier Discontinuity

Our attempt to reconcile the differences between R_I and R_G, or to at least understand the reasons for the differences, begins with the detailed comparison of the two activity indices in Figure 3 (Svalgaard, 2012a,b) which is a plot of monthly ratios of R_G to R_I from 1750-2000. Two discontinuities can be seen in this time series, one at ~1945 and another at ~1885. Svalgaard (2010, 2012a) has dubbed the first of these the "Waldmeier Discontinuity" after Max Waldmeier (1912-2000). In 1945, Waldmeier took over the directorship of the Zürich sunspot program from William Brunner (1878-1958). It now appears that changes Waldmeier instituted in the program are responsible for the decrease in the R_G/R_I ratio at that time. The principal change was to weight individual sunspots. Waldmeier (1968) wrote that "A spot like a fine point is counted as one spot; a larger spot, but still without penumbra, gets the statistical weight 2, a smallish spot with penumbra gets 3, and a larger one gets 5." Thus the simple expression in Equation (2) should be rewritten as

$$R_I = k(10 * G + S'), \quad where\ S' = \sum W_i S_i \tag{4}$$

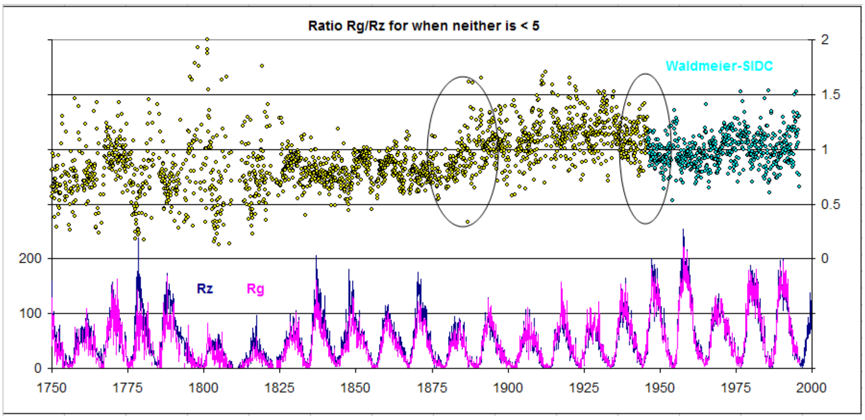

Figure 3: (Top) Ratio between monthly values of R_G and R_I (or R_Z), 1750-2000. The ovals indicate the Waldmeier Discontinuity in ∼1945 and an earlier discontinuity in ∼1885. (Bottom) Monthly values of R_G and R_I. (From Svalgaard, 2012a,b.)

and W_i is the weight assigned to each individual spot S_i. An example of the effect of this weighting can be seen in Figure 4. The sunspot drawing in the figure is taken from Locarno in Switzerland. This station is the standard observatory used by SIDC in the computation of R_I. In this example from 15 April 2006, it can be seen that the daily sunspot count is inflated from 33, corresponding to three groups with a single spot each, to 39. As a secondary factor affecting R_I, Waldmeier introduced a new sunspot group classification which increased the group count (G) in Equation (4). Together, the individual spot weighting and group classification changes instituted by Waldmeier increased R_I by ∼20% over that of his predecessor Brunner. A percentage increase of ∼20% in R_I is confirmed by reference to several other solar and terrestrial parameters, e.g., the calcium plage index and the daily geomagnetic range, which do not show a discontinuity at this time (Svalgaard, 2010). To correct for this offset, all annual R_I values before 1947 need to be multiplied by 1.2 (leaving values for recent (post-1946) years unchanged).

3.2. The Discontinuity in ∼1885

The jump in the R_G/R_I ratios in ∼1885 occurs during the time of transition from Rudolf Wolf to his assistant Alfred Wolfer (1854-1931; Figure 2(b))

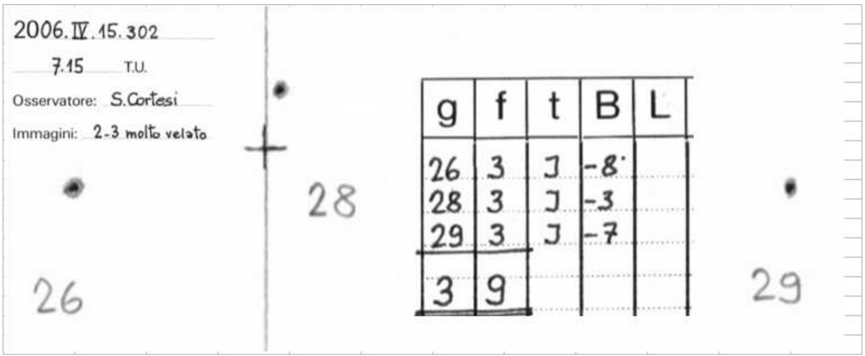

Figure 4: Drawing of three sunspots groups (Group numbers 26, 28, and 29), each having a single sunspot with penumbra, on 15 April 2006 from the Locarno station in Switzerland and the tabulated sunspot count for the day. Weighting of the spots increases the daily count from 33 (10 * 3 + 3) to 39.

who was the curator of R_I from 1893, when Wolf died, until 1926, when Brunner assumed this responsibility. We attribute the "1885 Discontinuity" to an inhomogeneity in the R_G time series. From data published by Wolf and his successors in the 'Astronomische Mitteilungen', we can compare the numbers of sunspot groups that Wolf and Wolfer counted during their period of overlap from 1876-1893. Figure 5 shows that during these years, Wolfer counted 1.65 times as many groups as Wolf, both because Wolfer used a larger telescope and also because he counted all spots that he could see while Wolf ignored, or could not see, fine points and gray pores. In contrast, Hoyt & Schatten (1998a,b) determined that the ratio between K_G-factors for Wolf and Wolfer was 1.021, i.e., that both observers saw very nearly the same number of groups. We believe that the lack of a significant adjustment between the group counts of these two principal observers (whose combined observations run from 1849-1928) reveals a serious flaw in the normalization technique of Hoyt and Schatten and that this flaw is the principal cause of the 1885 Discontinuity. To correct for this effect, we multiply all R_G values before 1885 by 1.47.

The result of the corrections for the Waldmeier and 1885 Discontinuities to the ratios in Figure 3 is given in Figure 6 where it can be seen that the two SSN series are reconciled back to 1826, the year in which Schwabe began his observations. The claim, based on the Wolf and Wolfer Group SSN K_G-factors, that it is the Group number that is too low before 1885

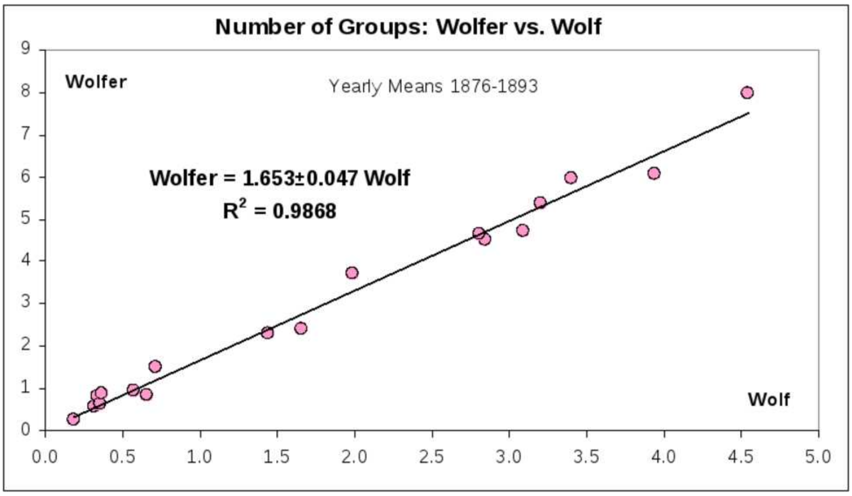

Figure 5: Comparison of the number of sunspot groups counted by Wolfer and Wolf during their period of overlap from 1876-1893. Wolfer counted 65% more groups than Wolf. (From Svalgaard, 2012b.)

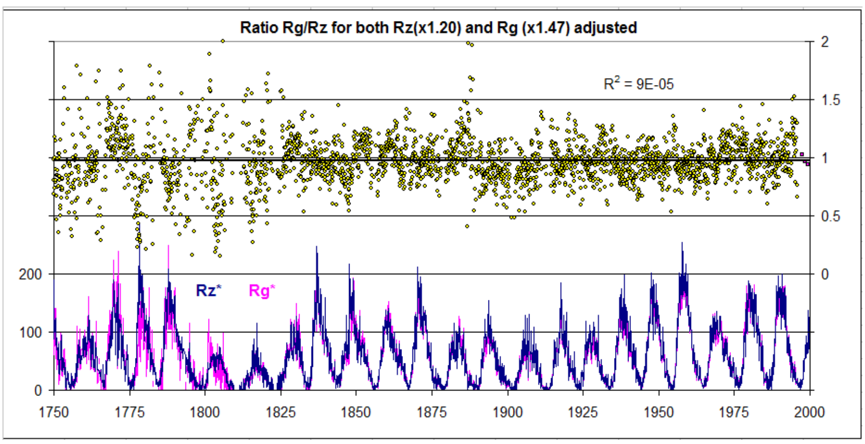

Figure 6: (Top) Ratio between corrected monthly values of R_G and R_I (or R_Z), 1750-2000. (Bottom) Monthly values of corrected R_G and R_I.

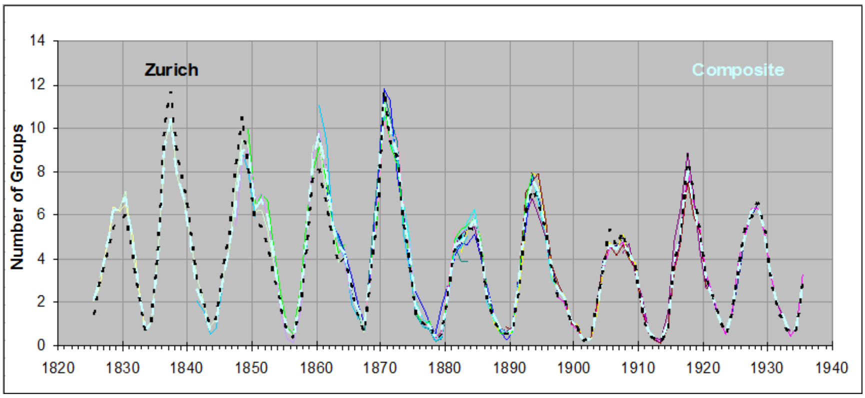

Figure 7: Normalized sunspot group counts of major observers who overlapped with Wolf and Wolfer (1849-1928). The light blue line is the composite (average) for all of these observers. The dashed black line is a group sunspot count obtained by dividing R_I by 12, the average ratio between annual values of R_I and R_G from 1874-1976 [From Svalgaard, 2012b.]

rather than International SSN being too high, has been substantiated in a straight-forward way. Svalgaard (2012b), using the Wolf-Wolfer composite record as a backbone, determined K_G-factors for 22 mutually overlapping observers stretching back to Schwabe and forward to Brunner to construct a composite series. As Figure 7 shows there is no significant difference between the composite group count obtained in this manner and that obtained by dividing the International SSN time series by a factor of twelve. Thus the cause of the drop in the R_G/R_I ratios before 1885 (Figure 3) lies in an inhomogeneity in the current R_G time series. This result receives corroboration from a comparison of the daily range of geomagnetic variation (rY) and scaled R_I (R_I*) in Figure 8 where no discontinuity is seen between the two parameters near 1885.

3.3. Before Schwabe

The Waldmeier Discontinuity was a focus of the first SSN Workshop and the 1885 Discontinuity was a focus of the second. At the third workshop in Tucson we hope to extend the reconciliation back from 1826 through the beginning of Johann Staudacher's (1731-1796(?)) observations in 1749, years for which a broad scatter can be seen in the time series of R_G/R_I in

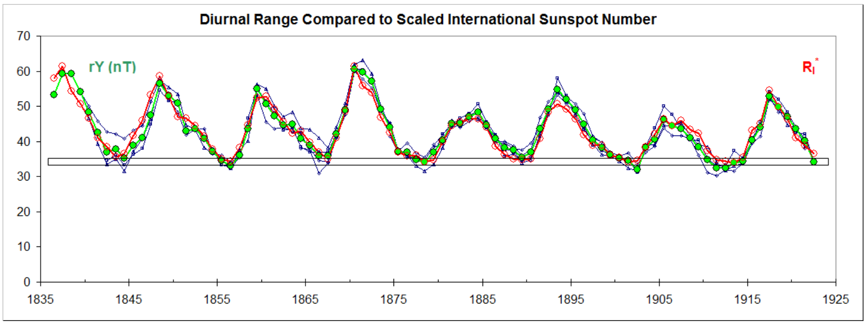

Figure 8: Time series of the daily magnetic range (rY, green dots; the blue curves give a measure of the uncertainty) and scaled R_I (R_I*; red dots) from ∼1835-1925. The correlation holds across the 1885 Discontinuity at the center of the time series.

Figure 6. This extension will necessarily rely on group counts compiled by Hoyt and Schatten and, if data are available, geomagnetic observations to confirm the sunspot record. The fourth and possibly fifth workshops will cover the data-challenged and scientifically fascinating period from 1749 back to 1610 that includes the Maunder Minimum (1645-1715).

4. Generally Speaking

Recalibrating the sunspot number or, alternatively, reconciling R_I and R_G, is a topic whose time has come. It can no longer be ignored - the discrepancies are too large and the applications (solar dynamo, climate change, space climate) too prominent. One solution would be for modelers to simply consider both R_I and R_G, in turn, in their calculations. But that is inherently unsatisfying and, at the halfway point of the SSN workshops, it does not appear that such equivalence or uncertainty is warranted.

Our efforts to reconcile R_G and R_I have met with some resistance. There have been two principal, somewhat disparate, lines of criticism regarding the workshops. One line stresses purity, arguing that one time series should not be used to calibrate another, e.g., the use of the "magnetic needle" by Wolf to adjust k-factors. We agree, but point out that comparison of the SSN record with other historical data sets is a key aid to the recalibration process. For example, the first indication that R_G was too low in the 19th century came from comparisons of R_G with the geomagnetic daily range for intervals before and after ∼1885 (Svalgaard, 2010, 2012a). The independent derivation of R_G (Figure 7), based on sunspot data alone, followed. The daily range, where available, may well provide further service in the reconciliation of R_I and R_G before 1826.[1] In order to extend the SSN thousands of years back in time via cosmogenic nuclide data, we need to be confident that we have both the sunspot and the ^{10}Be records "right" during their ∼400 year period of overlap. The surest way to do this is through comparison with other data sets, of which the geomagnetic time series is the longest-term, being sporadically (continuously) available after ∼1720 (∼1830).

The second line of argument regarding the value of the workshops is that the SSN is an outdated parameter that doesn't represent solar activity in a meaningful way for today's needs and we would do well to replace it with something better - e.g., a more objective index based on sunspot area or a composite index - rather than working to correct it. One answer to this argument is that we are primarily looking backward, not forward, and counts of sunspot numbers provide our best knowledge of the mid-term (century-scale) solar past. But that would not be the full story. We remind that the sunspot number works remarkably well as a general index of solar activity, with a long record of utility. Correlations of geomagnetic data with spot counts were first used to infer a magnetic connection between the Sun and the Earth by Sabine, Wolf, and Gautier in 1852. One hundred years later Forbush (1954, 1958) showed that the cosmic ray intensity was anti-correlated with the SSN. More recently, the SSN has been correlated with solar/interplanetary parameters ranging from *F10.7* (Covington, 1969, Hathaway *et al.*, 2002), to the rate of coronal mass ejections (Webb & Howard, 1994), to heavy ion abundances in corotating interaction regions (Mason *et al.*, 2012).

In the SSN workshops we have examined the homogeneity of *F10.7*, the calcium plage index, sunspot area, and the daily range of geomagnetic activity with a two-fold purpose: (1) as independent checks to keep the SSN "on track", and (2) as probes of the underlying physics when discrepancies arise. In regard to (1), we recognize that different indices measure different physical parameters and will not track each other perfectly. Nonetheless, as we have shown, comparisons of the SSN with rY and the calcium plage

[1] Cnossen *et al.* (2012) recently modeled the dependence of the daily geomagnetic range on Earth's changing dipole and obtained an increase in rY of ∼4 nT over the last century. Their model provides a tool to correct for this effect.

Figure 9: Participants at the 1st SSN Workshop, Sunspot, NM, 19-22 September 2011. Bottom row, left to right: K.Balasubramaniam, A. Pevtsov, F. Clette, W. Livingston, J. Vaquero, R. Howe. Top row, left to right: T. Dudok de Wit, L. Bertello, A. Tritschler, I. Cnossen, T. Henry, L. Svalgaard, L. Lefevre, K. Tapping, D. Biesecker, E. Yigit, D. Hathaway, A. Rouillard, A. Kilcik, S. White, E. Cliver, R. Radick.

index helped to correct significant inhomogeneities in R_I in ∼1945 and R_G in ∼1885, respectively. As an example of (2), we cite the deviation between *F10.7* and R_I during the recent extended solar minimum (e.g., Svalgaard & Hudson, 2010). This offset provides possible insight into the behavior of the Sun during low sunspot number conditions, such as the Maunder Minimum. It appears to be related to the Livingston-Penn effect which has been vigorously discussed at the workshops (Penn & Livingston, 2006, 2011; Livingston & Penn, 2009; Livingston *et al.*, 2012; Pevtsov *et al.*, 2011, 2013; Nagovitsyn *et al.*, 2012).

In the SSN Workshops, we are revisiting the same question that Hoyt *et al.* (1994) raised when they undertook their monumental work: "Do we have the correct reconstruction of solar activity?" Hoyt & Schatten (1998a,b) did tremendous service in uncovering new sunspot data (work that continues under the workshops; Vaquero, 2012; Vaquero *et al.*, 2012). Equally as valuable as the addition of 80% more data before 1874 than was available to Wolf was their questioning, 100 years after the death of Wolf, of the validity of the long-term homogeneity of R_I.

Figure 10: Participants, 2nd SSN Workshop, Brussels, Belgium, 21-25 May 2012. Bottom row, left to right: W. Pötzi, J. Vaquero, R. Howe, F. Clette. Top row, left to right: E. Cliver, L. Van Driel-Gesztelyi, K. Mursula, M. Laurenza, I. Cnossens, N. Crosby, T. Friedli, G. de Toma, R. Arlt, L. Wauters, I. Usoskin, L. Lefevre, A. Tlatov, D. Willis, A.Pevtsov, H. Hudson, R. Brajša, L. Svalgaard, L. Bertello, M. Kretzschmar.

In this same spirit, we have recruited scientists with a variety of expertise/opinions on recalibration/reconciliation of the SSN. In addition, at each workshop we have invited knowledgeable senior scientists as reviewers to provide critiques and offer guidance. By engaging a broad cross-section of space physicists (Figures 9 and 10), we hope to be able to produce a community-vetted time series of annual SSNs with stated uncertainties that becomes the standard for long-term studies (rather than yet a third choice for modelers along with the current R_I and R_G). We recognize that such a time series is subject to revision as we learn more.

Much remains to be done. We welcome all who are interested to participate.

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