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The new Sunspot Number: continuing upgrades and possible impacts

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Abstract. The first-ever revision of the sunspot number was released in 2015 by the World Data Center (WDC) SILSO. We describe the main diagnosed corrections to the sunspot and group number series, and also review newly published alternate reconstructions. We show the convergence of the determinations of the 1947 scale jump in the sunspot number around a value of 1.18 for cycle maxima. We also assess new proposed reconstructions of the group number, like the "backbone" and "active-day fraction" methods. No agreement was reached yet for this series.

We highlight the main impacts of those recent upgrades on different scientific applications. As this first revision also marks a transition towards a dynamical series open to future improvements, we finally introduce the ongoing collaborative process for preparing the next upgrade (Version 3). From now on, our scientific users must be prepared for a flexible integration of an evolving sunspot number series.

Keywords. Sun: sunspots, Sun: photosphere, Sun: activity, methods: data analysis

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1. Introduction

By its unequaled multi-century duration, the sunspot number (S_N) provides a unique reference for long-term studies of solar activity. Until recently, this series was only extended on a monthly basis using the visual counts from a worldwide observing network coordinated by the World Data Center SILSO (*http://www.sidc.be/silso*). Past numbers produced decades ago were left untouched.

However, an inconvenient disagreement appeared with the publication of the parallel sunspot group number (G_N) by Hoyt & Schatten (1998). This alternate sunspot-based series showed deviations by more than 40% in particular in the 19^{th} century, inspiring doubts about the homogeneity of either or both time series. In 2011, this enduring mismatch finally motivated a joint revision work that involved several workshops gathering more than forty specialists (Cliver *et al.* 2015). This work led to the official release of the first upgraded version of the S_N series (Version 2) in July 2015 (Clette *et al.* 2016a). The publication of this corrected series immediately prompted several independent studies and the publication of several alternate reconstructions.

In this review, we first describe the main corrections included in S_N version 2, and the current status of the determination of the main scale jump affecting the S_N series. We then summarize the different methods recently proposed for the G_N series, in terms of successes and failures. Finally, we consider the various impacts of the current changes in the reference sunspot series, and we outline the current coordinated work undertaken to prepare future upgrades of the series and implement a continuous quality control.

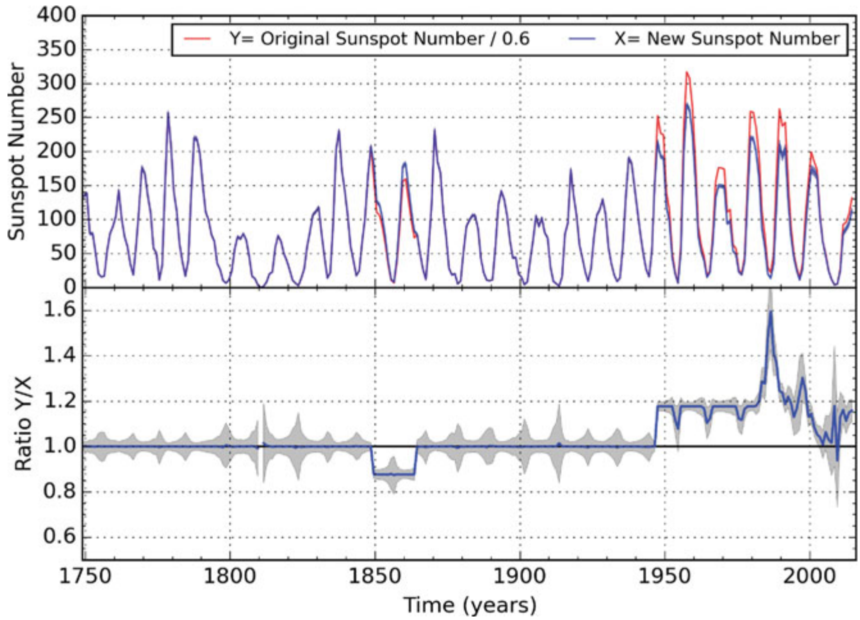

Figure 1. Comparison of the original sunspot number series (S_N version 1; top panel red) and the new official version (Version 2; top panel blue). The lower panel shows the S_N(V1)/ S_N(V2) ratio (uncertainties in grey shading), where the three main corrections appear clearly.

2. Sunspot number status

Three corrections were applied to the original S_N series, as shown in Figure 1. The first one corresponds to the early Wolf period (1849-1864), when the system of k scaling coefficient was not yet fully implemented. Another correction affecting a limited time interval corresponds to a variable drift of the new pilot station (Specola Solare Observatory, Locarno), when it replaced the Zurich Observatory after 1980 (Clette *et al.* 2016b).

However, one correction is of particular importance: a sharp upward jump in the S_N scale occurring in 1947. Indeed, it changes the scale of the entire series after 1947, relative to data before 1947, thus reducing the upward trend towards the mid-20th century that characterized the original S_N series. The new SILSO S_N uses a jump factor that varies with solar activity, from 1 for low sunspot numbers to 1.177 for the large numbers and thus for cycle maxima. This was established from double counts, based on the conclusion that this inflation was due to the introduction at the Zurich Observatory of weighted counts according to spot size (Clette *et al.* 2014, Clette & Lefèvre 2016, Svalgaard, Cagnotti, & Cortesi 2017). Several alternate studies indicated lower jump amplitudes of about 1.12 (Lockwood, Owens & Barnard 2014, Lockwood *et al.* 2016a, Lockwood, Owens & Barnard 2016). However, several flaws were identified in those determinations: incorrect choice of the transition year, use of comparison data containing uncorrected trends (Clette & Lefèvre 2016). Even when including all those determinations, by taking into account the corresponding uncertainties, we can now conclude that all determinations are compatible with a mean 1947 inflation factor of 1.14 +/- 0.02 when averaged over durations longer than a solar cycle, and of 1.177 +/- 0.005 for solar cycle maxima (Fig. 2).

Therefore, we can conclude that the current S_N version (V2) falls within this range, compatible with all proposed determinations. Moreover, Owens *et al.* (2016) recently presented a full revision of the reconstruction of the solar open magnetic flux B, which is based on long-duration geomagnetic records back to 1845. This allows an external

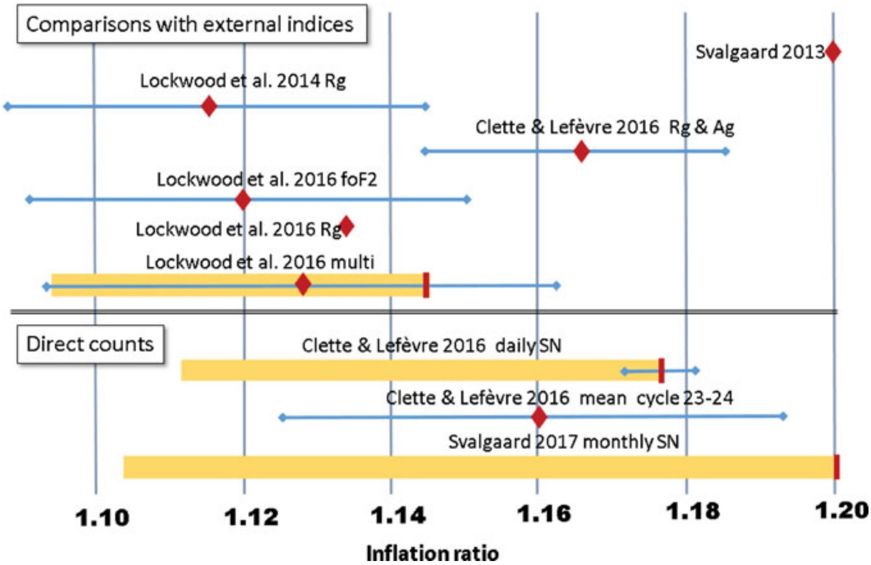

Figure 2. Values of the 1947 jump factor derived by various recent studies. Diamonds indicate mean inflation factors over durations longer than a solar cycle, with horizontal arrows for the uncertainty range. Vertical bars indicate inflation factors for solar cycle maxima, with horizontal strips showing the range of this factor from minimum to maximum.(Reference comparison series are indicated: RGO group number R_g, RGO sunspot areas A_g, ionospheric index $foF2$)

validation of the new sunspot number series. This study indicates that there is almost no difference in activity level between the 19^{th} and 20^{th} centuries, contrary to earlier reconstructions, which showed a marked upward trend towards the 20^{th} century. This is in agreement with the new trend-less version of the sunspot number S_N (Fig. 4). Among several alternate sunspot series, this study finds that the best match with the geomagnetic record is obtained by using S_N V2.

3. Group number status

While the validity of the S_N series seems now already confirmed, the group number G_N is still a matter of debate. The new reconstruction based on so-called "backbone observers" (Svalgaard & Schatten 2016) uses an alternate scheme to the daisy-chaining principle of the original G_N series (Hoyt & Schatten 1998). It identified an 40% upward drift between 1885 and 1915, which could be attributed to the use of inhomogeneous photographic data from the Royal Greenwich Observatory (RGO) as demonstrated by Cliver & Ling (2016). This correction raises all G_N data before 1900, leading to more uniform activity levels over the last centuries in good agreement with the new S_N V2 series, thus apparently reconciling the S_N and G_N series.

However, several shortcomings in the "backbone" method were pointed out by more recent studies: use of yearly averages, application of ordinary least-square linear fits (Lockwood *et al.* 2016b), non-overlapping main backbone observers. This inspired a completely different approach, that avoids the use of inter-comparison between observer pairs. This so-called "active-day fraction" method (ADF; Usoskin *et al.* 2016) considers only the cumulative distribution of the monthly fraction between days when no spots or one or more spots are reported by an observer. This fraction is used as a measure of observer acuity (capacity to distinguish the tiniest spots). Then, via a statistical model built from

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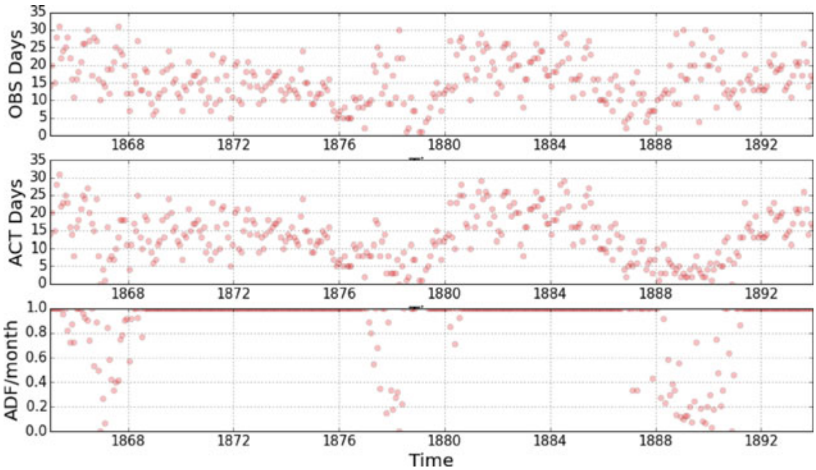

Figure 3. Temporal variations of the number of observed days (top panel), of the number of active days (middle panel) and of the active-days fraction per month for G. Spörer. As expected, the two lower panels show a clear modulation by the solar activity cycle, with a drop of the ADF during minima. However, the top panel also shows a dependency of the observation rate with solar activity, dropping to low values near minima (many spotless days). Therefore, the ADF is overestimated during those periods.

the RGO photographic data, a self-consistent correction factor is derived, bringing the raw counts to the level of a perfect observer.

However, we identified several unrealistic base assumptions in this method. As this ADF principle can only be used for ADF values below 80%, the correction factor is only established for rather low activity levels, around cycle minima. Still, this same factor is used for the entire series, thus assuming that the same factor remains valid for cycle maxima. The calculated correction is thus extrapolated outside its determination range. Moreover, the ADF method assumes that the only cause of differences between the counts of different observers is their acuity, while the group counts also depend on how each observer uses to split the groups. Svalgaard & Schatten (2016) point out how changes in group splitting practices can influence the scale of G_N, but this second factor is ignored in the ADF approach.

More importantly, the ADF method rests entirely on the assumption that the sampling, i.e. the fact that an observer makes an observation, is random (e.g. weather conditions) and does not depend on the level of solar activity. However, by studying the statistics of various observers, we find in some cases a strong decrease in the number of observations during cycle minima (Fig. 3). In other words, many observers do not bother to report null numbers when the Sun is spotless. In those cases, the ADF becomes artificially high, suggesting that the observer has a high acuity and is thus closer to a perfect observer. Consequently, the correction applied to the raw numbers is lower and closer to unity. The normalized values are thus underestimated, thereby lowering the early part of the G_N series, which is precisely the case for the ADF reconstruction.

Finally, a recent attempt to fix weaknesses of the original "backbone" G_N reconstruction was published by Chatzistergos *et al.* (2017), replacing linear fits by non-parametric correspondence matrices between observers, and using a larger number of mutually overlapping primary observers. It leads to intermediate values between the high original "backbone" numbers and the low ADF series over the 19^{th} century. Consequently, although all G_N reconstructions closely agree for the 20^{th} century, more work is still needed

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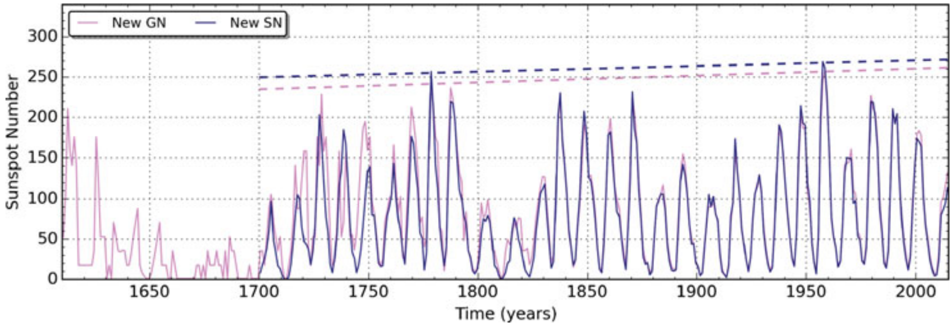

Figure 4. Comparison of the new S_N V2 series and the recent "backbone" G_N series by Svalgaard & Schatten (2016) showing the good match over the common interval 1700-present (dashed lines highlight the low secular trend between the highest cycle maxima).

to clarify the discrepancies in the early part of the G_N reconstructions, and identify which G_N version is the most homogeneous. For now, as shown in Figure 4 we can just observe that the best agreement with the current version of the sunspot number S_N and with the geomagnetic record (cf. section 2) is obtained by the Svalgaard & Schatten "backbone" G_N (Clette *et al.* 2014, Owens *et al.* 2016).

4. A new production framework: future perspectives

Beyond the recent corrections, this first 2015 revision of the S_N series also paved the way to a much deeper transition in the way this series will be maintained in the future. This transition is threefold:

(*a*) From a static series that was left untouched since it was created by R. Wolf in 1849, to a dynamical series that is open to improvements over its entire temporal extent, based on new recovered data and new state-of-the-art statistical tools. In that sense, it will be upgraded like any other modern solar data set.

(*b*) While the original series did not provide any error estimate, the error statistics will be determined and added to the new series. A first study revealed a dual-component nature of random errors in sunspots numbers, as well the temporal variability of errors in the S_N series (Dudok de Wit, Lefèvre & Clette 2016).

(*c*) From a disparate production by individual scientists, in particular the Zurich Observatory from 1849 to 1980, to a coordinated work combining the expertise of all specialists investigating past sunspot data and solar indices.

In this respect, the community-wide work implemented by the past Sunspot Number workshops is now continued through new Team Meetings hosted by the International Space Sciences Institute (ISSI, Bern, Switzerland). A first meeting took place in January 2018 and defined several working groups who will focus on the various pending issues mentioned in the above sections (*http://www.issibern.ch/teams/sunspotnoser/*). Within about two years, this joint work should lead to a new upgrade of both the S_N and G_N series. This new framework will also lay the foundations for a future permanent version-maintenance and quality-control process under the supervision of the International Astronomical Union.

For now, the main impacts for scientific users of the sunspot number series will certainly be:

• adapting models to a new S_N reference unit for the current and all future S_N values: the conventional Wolf 0.6 factor was removed, taking modern counts since A. Wolfer as unit. This was a one-shot change, but it requires rescaling or full re-calculation of e.g.

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sunspot-based scaling laws or proxies (irradiance, ionospheric models) or of mid-term activity forecast methods.

• investigating the effects of changes in the long-term steady trends in the solar cycle amplitudes, in regard of parallel trends in solar or terrestrial processes, like the global Earth climate warming or the production of cosmogenic radionuclides.

• re-calibrating the relations formerly established between the sunspot number and direct solar measurements available only over recent decades (e.g. spectral irradiance, solar wind). Indeed, former mismatches with the original S_N series have now been eliminated (e.g. for the $F_{10.7cm}$ radio flux; Clette *et al.* 2016b), thus allowing to obtain more accurate proxies.

Overall, from now on, users of the sunspot number should be aware that they must adopt more flexibility for regular changes in the S_N and G_N series. However, such changes will occur at a minimum interval of a few years, and future modifications will be smaller and more localized than the main corrections brought by this first major revision.

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