and often proposed younger faculty members on his committees (author included).

In his later years at the NAS, Richard's portfolio grew to include a role as the US's international representative to the Committee on Space Research (COSPAR). He fostered international cooperation in space science and organized joint advisory meetings for NASA and the European Space Agency (ESA). In recognition of his career achievements fostering international cooperation in space science, Richard was awarded COSPAR's Distinguished Service Medal in 1996.

Our memories of Richard include his always warm and sincere greeting to colleagues, his dedication to hard work, his multiple professional achievements, and valued friendship. He is survived by his son David and daughter Jenny, and their families.

[By Michael Mendillo, Boston University, USA]

Research Highlights

The Sunspot Number:

Reconstructing the Past Solar Cycle for the Future

[Frédéric Clette (World Data Center for the Sunspot Index and Long-term Solar Observations, Belgium, and Royal Observatory of Belgium)]

A multi-purpose tool for today and the future

The sunspot number time series is the most widely used reference for retracing the past evolution of solar activity, and in particular the highly variable amplitude of the solar cycle. While it spans the last 400 years, it is still actively maintained today by the World Data Center SILSO (Sunspot Index and Long-term Solar Observations), which makes it the longest scientific experiment still currently running (Owens 2013).

The value of the sunspot number comes from the fact that starting from a very simple measurement, the visual count of sunspots, available since the invention of the telescope (Figure 1), this index proves to be a very good measure of the total emergence rate of magnetic fields at the solar surface, i.e. of solar activity. In this sense, it provides the base observational constraint for the current state-of-the-art physical models of the sub-surface dynamo mechanisms. This should ultimately enable solar physicists to provide mid- and long-term forecasts of the solar cycle evolution, one of the ultimate quests of solar physics since the 11-year cycle was identified by Schwabe in the mid-19th century (Schwabe 1844).

However, given the direct influence of the Sun on our planet and human activities, the sunspot number also plays a key role in various applications and scientific domains, well beyond solar physics itself. The long-term information that is specifically brought by the sunspot time series addresses three main categories of needs:

- Quantifying cumulative effects of solar activity over months to decades, like total radiation doses or high-energy particle fluxes.
- Determining the levels of probability and risks associated with short-term disturbances, like solar flares or coronal mass ejections and the associated geomagnetic storms, as the recurrence rate of those violent solar events follows closely the evolution of the sunspot cycle.
- The reconstruction of past long-term effects of the Sun on the Earth environment, i.e. the so-called solar forcing.

Although it is rooted in a past heritage of very old data, this sunspot series thus remains a key player in many of the most critical issues and applications of our 21st century.

Just considering space assets, sunspot-based information is used to forecast atmospheric drag on low-Earth-orbit satellites, for orbit maintenance and the planning of controlled final re-entry in the atmosphere. It also tracks the rate of SEP events (solar energetic particles) and of material ageing affecting space hardware, and for this reason, is taken into account e.g. in the scheduling of remote interplanetary missions. Regarding manned space missions, the mid-term evolution of the solar cycle based on the past cycle trends is essential for the long-term planning of launch windows. Over coming years, this will become even more important for long-duration missions venturing far outside the protection of the Earth magnetosphere, like the ARTEMIS missions to the Moon or the envisioned missions to Mars and permanent bases on either the Moon or Mars.

Closer to us, this solar-cycle monitoring is needed for space-based technological services, like telecommunication or GNSS. Finally, even at ground level, it forms the base for planning infrastructure maintenance and its associated budgets (geomagnetic ground-induced currents in power grids or pipelines), or for determining the career-long cumulative radiation doses for aviation personnel.

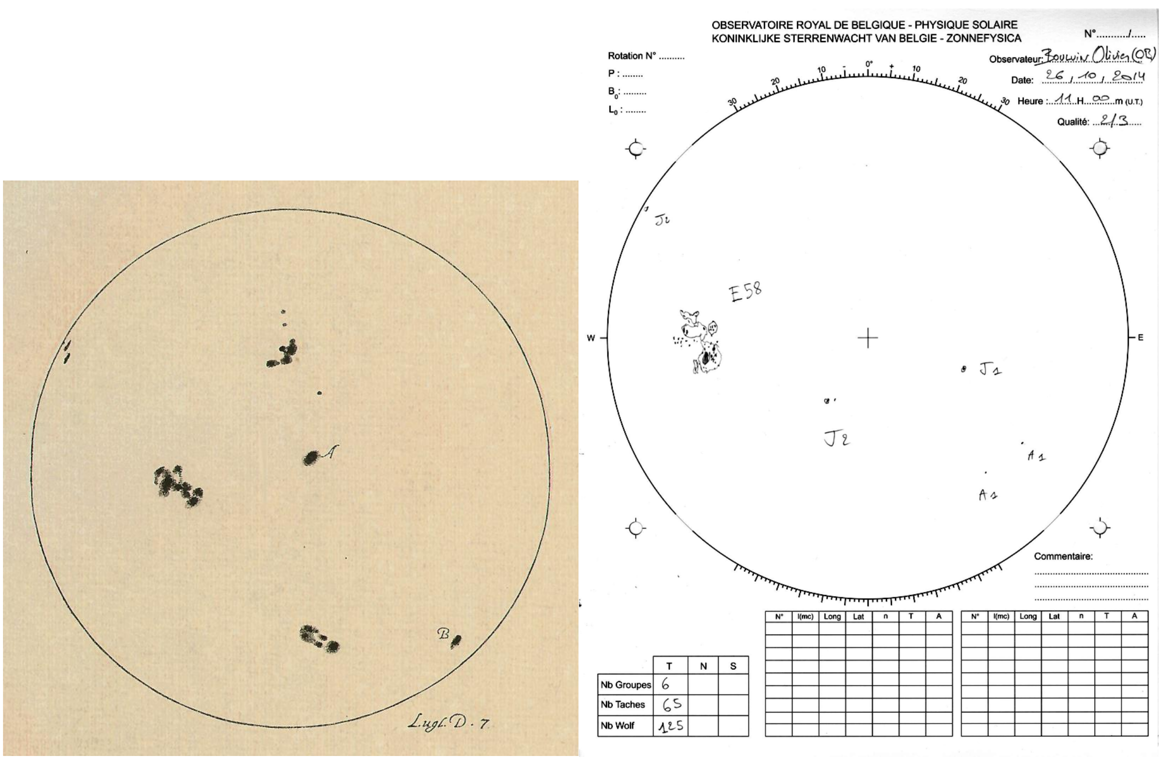

Figure 1: Two fully exploitable sunspot drawings separated by four centuries. Left, Galileo Galilei on 7 July 1613 (Source: Galileo Project, Rice University; http://galileo.rice.edu/index.html). Right, O. Boulvin, USET station, Royal Observatory of Belgium, on 26 October 2014 (www.sidc.be/uset/).

A composite heritage and its necessary revision

Although the knowledge of the secular variation of solar activity is fundamental, maintaining a continuous and homogeneous series over such durations poses a major challenge. Indeed, it rests on a long chain of successive observers, and even more importantly on generations of scientists who processed the base data with the concepts and tools available at widely different epochs.

To make things even more complicated, it turns out that we must consider two main sunspot-based series. The construction of the primary series, the sunspot number (SN), was initiated by Rudolf Wolf in 1849 and was continued without interruption at the Observatory of

Zurich, until 1980, when the data centre was transferred to the Royal Observatory of Belgium, in Brussels. The base sunspot number for a single observation includes both the number of groups, thus of active regions, and the number of spots, which gives a measure of the size of those regions, according to the simple standard formula: W = 10 g + s, with g the total number of groups and s the total number of spots counted on the solar disk in one observation.

The daily SN is then derived by combining statistically all available observations from multiple observers. As defined by Wolf (1856), its calibration base was always a pilot observer, supposed to be intrinsically stable. Namely, Wolf himself and three successive directors of the Zurich Observatory, and since 1980, the Specola Solare Ticinese Observatory, in Locarno, Switzerland.

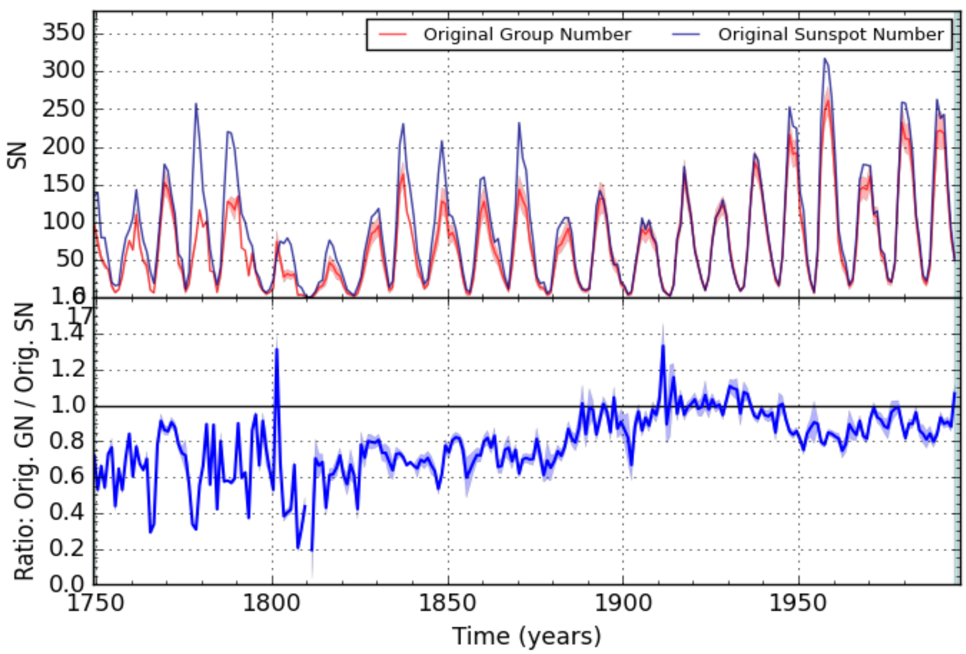

Figure 2: Top panel: comparison of the original sunspot number (blue) and group number series (red), here illustrated by yearly mean values. Lower panel: yearly mean G_N/S_N ratio. The error associated with the G_N series is shown by the shaded interval around the curve. The ratio, which should be uniform, varies in time with two clear jumps at the end of the 19th century and in the mid-20th century.

Figure 3: Group picture of the "Sunspot Number re-calibration" Team at the International Space Science Institute (ISSI, Bern, Switzerland) in August 2019 (www.issibern.ch/teams/sunspotnoser/)

Before 1849, the series was built from recovered historical observations, but given the data that he could find in the mid-19th century, Wolf limited the series to 1700, which is still its current starting point. However, numerous sunspot observations exist in the 17th century, going back to the very first telescopic observations by Harriot, Galileo and Scheiner. It turns out that this early epoch includes the last protracted period when the Sun remained in a quiescent state during several decades, the so-called Maunder Grand Minimum. This prompted the much more recent creation of another sunspot-based series, the sunspot group number (GN), constructed by Hoyt and Schatten (1998). The group number only includes the total number of groups, and does not go into the details of spots inside groups. It is thus a cruder index, but as the sunspot information is often missing or unreliable in early observations, this was the only practical solution to build a usable series going fully back to 1610. Note that the GN series was designed to improve the very early part of the sunspot record, including the Maunder Minimum, but was not designed as a primary series for the modern period. This is why it stops in 1995 and was not extended since then.

Moreover, as this series was not based on an organized and systematic observing base like the sunspot number, its stability is based on statistics over all observers, exploiting the temporal overlap between the available successive observers. Now, it turns out that the two series disagree significantly in spite of the fact that they are largely based on the same underlying data and similar counts (Figure 2). This was already realized back in 1998, but it is only more recently that this very inconvenient and confusing incompatibility called for a long-needed investigation of the homogeneity of both series. This was prompted in part by the increasing need to connect or merge this information with other more recent solar or geomagnetic records.

In particular, while the sunspot number showed that past cycles in the 19th and 20th century reached amplitudes comparable to the recent strong cycles that dominated the second half of the 20th century, the group number showed a strong progressive rise of the cycle strength since the end of the Maunder Minimum up to the 20th. This upward trend inspired the concept of a modern Grand Maximum (Solanki *et al.*, 2004, Usoskin *et al.*, 2007), with recent cycles exceeding the amplitude of all cycles of the previous centuries, by a factor 2 or more. Those two incompatible scenarios cannot be accounted for by any solar effect.

A wave of recent re-constructions

In 2011, this awkward situation prompted a joint effort to diagnose and correct flaws in those heritage series. Initiated by F. Clette, E. Cliver and L. Svalgaard, it took the form of a series of "Sunspot Number Workshops", which continue nowadays. The last incarnation was the international expert Team funded by the International Space Science Institute (ISSI) in Bern in 2018-2019 (www.issibern.ch/teams/sunspotnoser/) (Figure 3).

The first output of this work was the release of the very first revision of the original sunspot number series in July 2015, at the occasion of the General Assembly of the International Astronomical Union (IAU). This marked the very first end-to-end re-calibration of the SN series since its creation. An entire volume of the *Solar Physics* journal was dedicated to this work and its implications (Volume 291, Issue 9-10, Springer, 2016, ISSN 0038-0938 print, ISSN 1573-093X elec.).

The corrections that were introduced in the SN series are significant and reach almost 20%. They are illustrated in Figure 4 and consist in three main changes:

- The early numbers from Wolf, from the start of his observations in 1849 to the opening of the Zurich Observatory in 1864, are raised by 15%, to correct for the use of two different telescopes by Wolf and by his first assistant recruited in July 1864.
- All Zurich numbers after 1947 are lowered by a factor that varies with the level of solar activity but are on average reduced by 17%. This factor corrects for an overestimate of the

numbers due to the introduction of a new counting method used by the last two Directors of the Zurich Observatory. In this method, spots are weighted in the total counts according to their size, thus deviating from the original definition by Wolf, which was applied for the first and longest part of the SN series. This is the most important correction to the series, as it changes globally the amplitude of all recent solar cycles, since cycle 18, relative to all preceding cycles.

- The last part of the SN series, which was produced in Brussels using the Locarno reference, was entirely recomputed from base data, by replacing the single reference station by a set of more than 20 long-duration stations. This allowed to eliminate a variable drift affecting the counts of the Locarno station, where the above-mentioned weighted counting method was still in use.

In this new version of the SN series, a full reconstruction was only possible for the recent period, thanks to the fact that all original input data are fully preserved at WDC-SILSO (more than 500,000 individual observations). As the Zurich data before 1980 were only partly available, corrections could be derived only for the main deviations, and applied as factors to the original Zurich series.

The Group number: still an unclear picture

In parallel and independently, an entirely new GN series was re-constructed from the original input data collected by Hoyt and Schatten (1998). There, the purpose was to avoid the main weakness of the original group number: the scale of recent modern numbers was propagated backward in time by daisy-chaining the successive observers, and by deriving the mean ratios between the simultaneous numbers where each pair of observers overlap.

As errors accumulate and as any bias in the chain will propagate over the entire series before the disruption, Svalgaard and Schatten (2016) used instead a limited set of reference observers, with a long and stable history and spanning the whole interval 1750-2000, the so-called "backbone" observers. This delivered a new series which largely matches the original one after 1900, but is much higher, by 40%, before the 20th century, largely eliminating the rising trend characterizing the original GN series. The 40% trend is found when the original series switches from early visual observers to photographic data from the Greenwich Observatory, a convenient "shortcut" solution adopted by Hoyt and Schatten (1998) for the last part of the original GN series. The correction is thus interpreted as an artificial trend affecting the early photographic material, in the first years of solar photography. The improvement in the new "backbone" GN thus also comes from the replacement of this photographic reference by visual observers throughout the entire duration of the series. It thus avoids this technological-evolution factor, by using exclusively a detector that did not evolve over past centuries: the human eye.

However, this first revision of the GN series immediately faced criticisms. The principle of backbone observers still includes a form of daisy-chaining, in particular because the primary reference observers are generally not overlapping directly in time. So, two alternative reconstructions were subsequently proposed.

One approach consisted of calibrating each separate observer based on the statistics of the number of spotless days that they report. This active-day fraction method (ADF; Usoskin *et al*., 2016, 2021) thus avoids completely the need for chained inter-comparison between observers. Another series still started from the concept of "backbone" observers, but improving it by eliminating some of the pitfalls of the initial version (Chatzistergos *et al*., 2017). It uses a larger set of reference observers, with direct overlap between them, and the non-linearity in the relation between numbers from different observers are taken into account by a non-parametric conversion matrix.

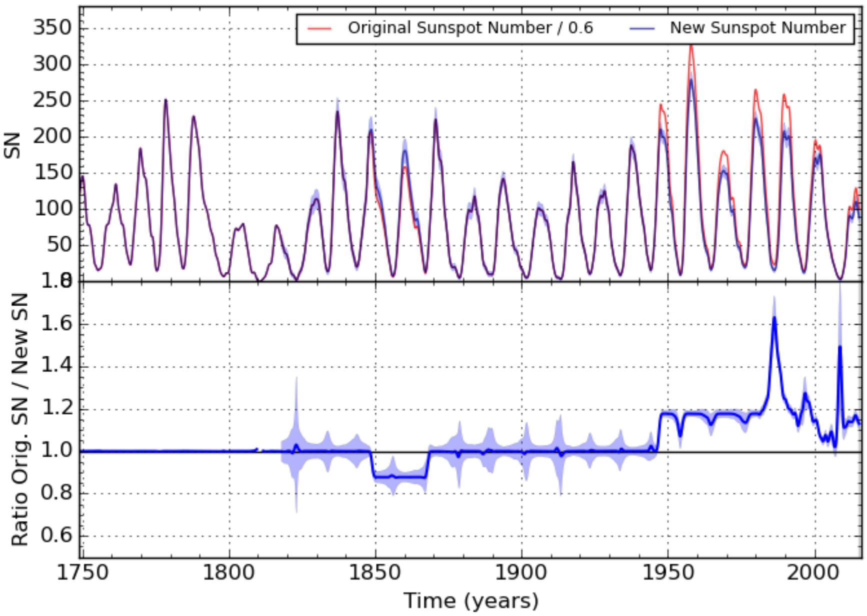

Figure 4: Corrections included in the SN V2.0 series. Top panel: a comparison of the two series (12-month smoothing), with the original SN in red and the new SN series in blue, with standard errors (shading). Lower panel: SN V1.0 / SN V2.0 ratio, with standard error (shaded range). The main long-term correction is the 18% jump in 1947, which lowers recent activity levels relative to previous centuries (Source: Clette *et al.*, 2016).

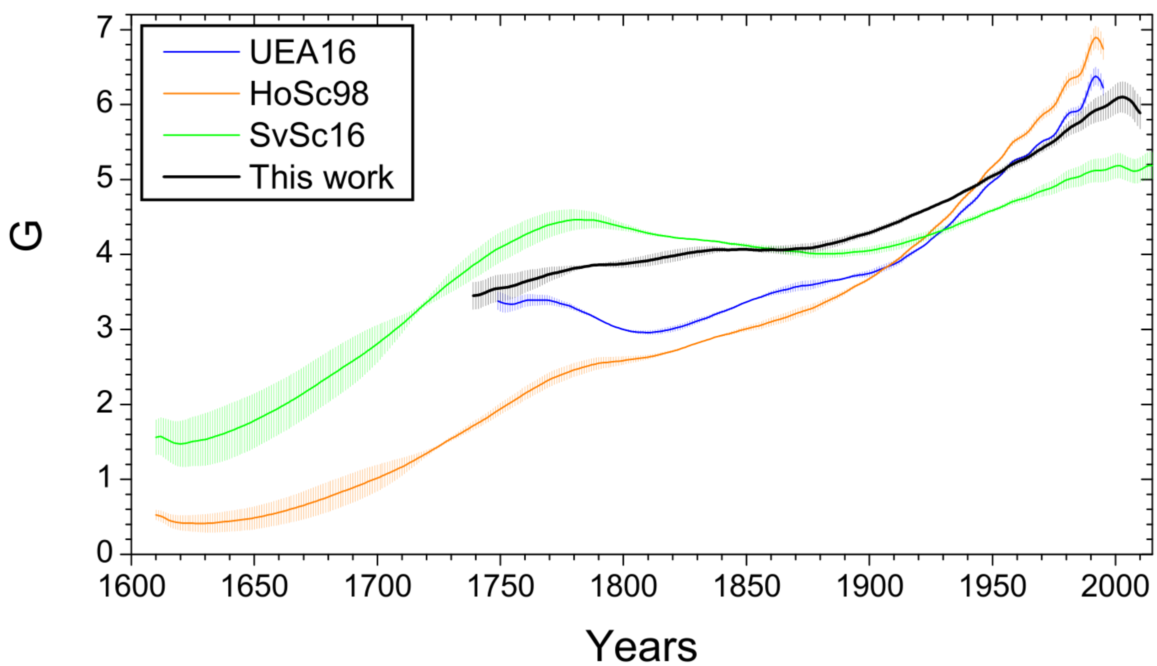

Figure 5: Secular trend in different GN series, given by the low-frequency component of the singular spectrum analysis, with a window of 80 to 100 years. In orange, the original GN series (Hoyt and Schatten 1998), in green the "backbone" GN series (Svalgaard and Schatten 2016), in blue the ADF GN series (Usoskin *et al.*, 2016) and in black the improved "backbone" series (Chatzistergos *et al.*, 2017). All new series indicate a much smaller rising trend towards the 20th century. The latest re-constructions are intermediate between the low original GN series and the high "backbone" GN series, which is almost constant since the end of the Maunder Grand Minimum (low-activity period between 1650 and 1710). (Source Chatzistergos *et al.*, 2017)

Those new versions still closely agree over the 20th century but both are lower than the first "backbone" GN series (Figure 5). They indicate an intermediate solution, between the low original series by Hoyt and Schatten (1998) and the high "backbone" version by Svalgaard and Schatten (2016). However, although the new methods avoid earlier pitfalls, recent verifications revealed other aspects capable of biasing those new series: correlation between the cadence of observations and solar activity, mixed role of visual acuity and sunspot group splitting practices, mismatch between the activity level in data to be corrected and in the training data set, few data and large uncertainties at high levels of activity near cycle maxima. So, regarding the GN series, the situation is still unclear and all series published so far still require further scrutiny.

We can just note that the high version of the GN is the one that best matches the SN series, which was produced completely independently. Moreover, in an Occam's razor experiment, taking as reference a straight GN reconstruction without any normalization of raw data, Cliver (2016) concludes that the low and even intermediate versions of the GN seem to be in contradiction with the known steady improvement of observing techniques and astronomical instrumentation.

Where are we now? Sunspot number Version 2.0

Since its publication, sunspot number Version 2.0 could be validated by different comparisons with independent external "benchmarks". Over long duration, the only parallel measures of solar activity are geomagnetic indices, which are however only indirect indicators, as their variation includes other non-solar factors. Recently, an ISSI expert team also re-calibrated the long-term geomagnetic series, which extend back to the mid-19th century (Cliver and Herbst 2018). The new series indicate similar peak activity levels in the 19th and 20th century. By taking the various published SN and GN series as input for models of the solar wind, they find that the new SN series, as well as the high version of the GN, gives the closest match with the geomagnetic record over the past 150 years.

For recent decades, other solar series become available and can also be compared with the recent part of the SN series: space-based UV indices, like the MgII core-to-wing ratio, the CaII K index, the $F_{10.7cm}$ radio flux, the total emerging magnetic flux derived from solar magnetograms. Stenflo (2012) found a very high correlation with the total magnetic flux. Likewise, a recent in-depth study by Clette (2021) shows that the linear correlation with the $F_{10.7cm}$ radio flux is very high (Figure 6) and was further improved with Version 2.0 compared to the original SN series, in particular after 1980 (Figure 6, blue curve), i.e. during the interval over which the series was entirely re-constructed from base data (cf. Figure 4). Therefore, a consensus has been reached, concluding that the new Version 2.0 stands currently as our best reference series, keeping in mind that there is still room for further refinements.

New unit convention

Together with the release of the corrected SN series, the decision was taken to get rid of an old convention inherited from the late 19th century. Indeed, in order to scale the entire series to the initial counts made by Wolf until 1893, all modern numbers obtained by the more recent observers were down-scaled by a factor 0.6. This past choice caused two main drawbacks. This factor is based on an inter-comparison between R. Wolf and his successor, A. Wolfer, over a limited period of 17 years. It is thus subject to errors which can globally affect all recent numbers. Moreover, today, in the 21st century, this downscaling does not make sense anymore and leads to confusion, as the sunspot number is systematically lower than the counts made by most contemporary observers. Therefore, this factor was eliminated, and the new numbers have largely a 1-to-1 correspondence with raw contemporary observations. Now instead, all historical numbers before 1893 are raised by a factor 1/0.6 to bring them to the scale of modern sunspot observations.

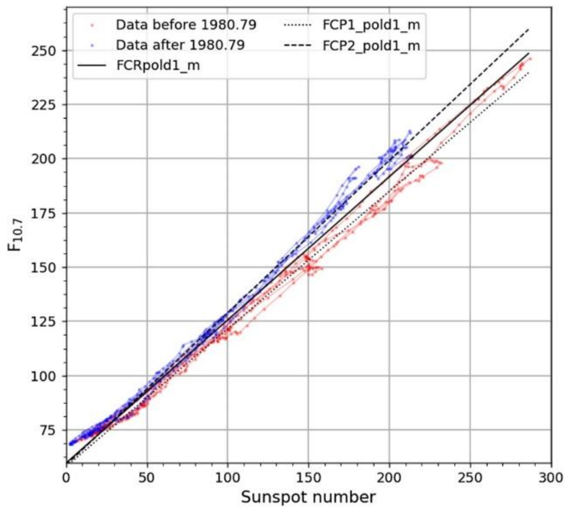

Figure 6: Plot of the SN V2 series versus the $F_{10.7cm}$ radio flux over their entire overlapping interval 1947-2020 (12-month smoothed values). It shows the very high correlation and the almost fully linear relation between the two indices over long timescales. This comparison with the re-calibrated SN series allowed to detect a scale jump affecting the $F_{10.7cm}$ series and splitting it in two homogeneous halves. This leads to two linear relations before 1980 (red points and dotted line) and after 1980 (blue points and dashed line), differing by about 10%. The solid black line is the global fit to the entire series. (Source: Clette 2021).

For users, this new normalization is the most obvious change when switching from the original SN to Version 2.0. It must be considered as a change of unit for the series, from the Wolf scale to the Wolfer scale, which matches modern counts as there are obtained nowadays.

Likewise, a 12.08 scaling factor adopted by Hoyt and Schatten (1998) to bring the first GN series to the same mean scale as the SN, was abandoned for the recent series, which simply gives the mean group count as a real number, with decimals. Although this does not influence the uniformity of the series, this eliminates an artificial dependency of the overall normalization on another series. The mean ratio between the current GN and SN is close to 20, due to the fact that the mean number of spots in a group is about 10.

Note that those changes in conventional units were a one-shot operation, and will not need to be repeated again, as the new scale is now directly linked to raw data, and thus avoids underlying assumptions and comparisons that are subject to future revision.

New modern methods: revisiting old data with a 21st century look

Some key lessons emerged from the critical analyses of the heritage series:

- The subjectivity of visual observations does not play a major role in the long term stability of the SN series. In fact, the statistical noise in the raw daily sunspot counts proved to be very similar to Poissonian photon shot noise in an electronic detector (Dudok de Wit *et al*., 2016).
- As the smallest sunspots can be resolved with modest telescopes widely available over the last three centuries, the evolution of telescope technology had a limited impact on the stability of the sunspot counts, except for very early data from the 17th century.
- On the other hand, nearly all the identified flaws were due to changes in the methods and assumptions used to process the raw data or to combine data from multiple observers, when deriving the final calibrated measurement. The problems affecting the sunspot number are thus closely similar to those affecting more modern solar measurements acquired by electronic devices and sensors in space and on the ground.

This indicates that a key road to progress is the development of state-of-the-art analysis methods to re-visit the base data with new eyes. Recent work has already progressed in that direction, as outlined above, and other advanced statistical approaches and data mining techniques are currently experimented, like orthogonal and non-linear regression, Bayesian statistics, expectation minimization, alternate error distributions (binomial, Poissonian), Anscombe transform, etc.

This array of state-of-the-art tools is necessary to address the very challenging characteristics of the historical sunspot data: sparse and unequally spaced data, non-simultaneous data, temporal gaps, slow trends, and also non-ergodicity of the data series.

In this respect, a primary objective is now to derive the standard errors on the sunspot number, which evolved over time, with step-wise decreases (Figure 7). Errors were not provided in the original series, or were crudely estimated using outdated methods. SN Version 2.0 now includes error values, which are directly derived from the data after 1980, and for now, are only global estimates before 1980. Moreover, inhomogeneity in such long series often results from the fact that they were built progressively by successive curators over multiple generations. Therefore, our present capacity to re-do entirely the processing of the whole data set in one batch can also bring major improvements. But to enable this, a fundamental requirement is to get access to the maximum amount of data in digital form.

New data recoveries: a never-ending quest

In this respect, major progress has been accomplished over the past few years in the recovery of those precious past data.

For the GN, the original archive collected by Hoyt and Schatten (1998) has been significantly expanded, both with old historical data and with modern data in the 20th century (Vaquero *et al.*, 2016).

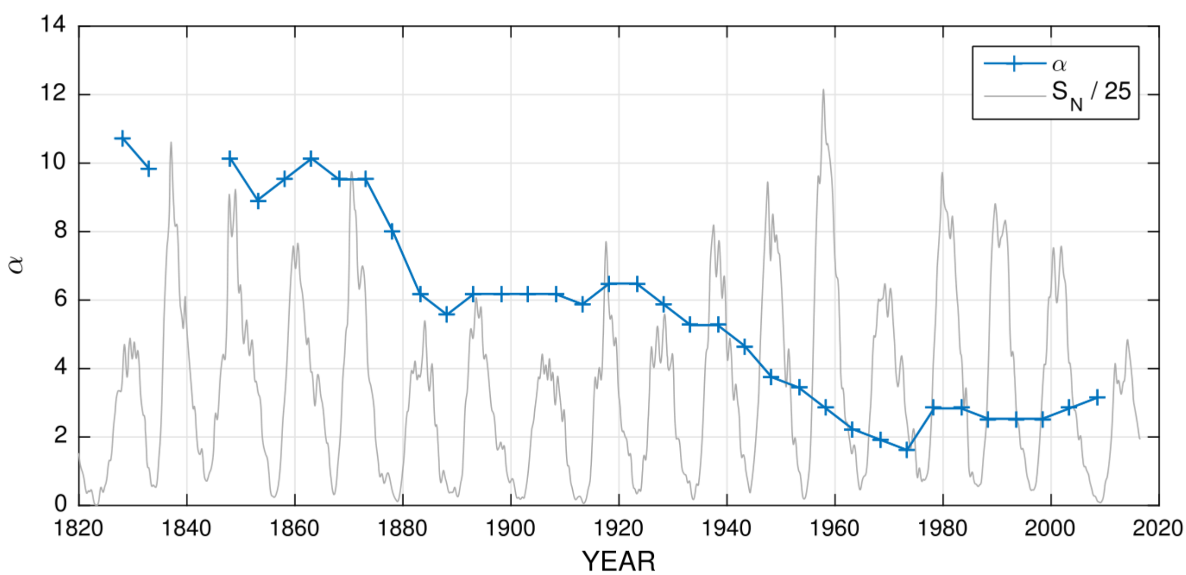

Figure 7: Temporal evolution of the errors in the sunspot number (blue curve and pluses), superimposed on the SN series. The error is represented here by the α gain factor of the generalized Anscombe transform of the sunspot numbers. The evolution is marked by a step-wise decrease, which tracks fairly well the evolution of the number of contributing stations and the total number of available raw data. The uncertainties decreased as the amount of data progressively increased. (Source: Dudok de Wit *et al.*, 2016).

For one part, new early data were located and digitized, filling gaps and enriching the series. Moreover, data sources were critically re-visited, and improper interpretations of source documents have now been corrected, reshaping the evolution of past solar cycles, in particular at the onset and exit of the Maunder Minimum. This sometimes involved full re-counting from original sunspot drawings. This new digital archive is now at the base of most of the recent incarnations of the GN.

On the other hand, no equivalent archive of source data existed for the SN over the whole Zurich era before 1980. Now, the full digitization of published raw data is approaching completion, based on printed tables. However, attempts to recover archives of unpublished data covering the period 1919-

1980 have failed for many years. Fortunately, in late 2018, the whole set of lost data from 1945 to 1980 was recovered. This forms a key missing link between the present sunspot number produced by WDC-SILSO and the preceding Zurich series. For the first time, we have now an uninterrupted chain of data from the earliest numbers by Wolf and today's SN. This includes a large amount of data (more than 300,000 individual observations) that now needs to be fully encoded into the SN database. Moreover, lost archives for the period 1919-1944 still need to be recovered. Nevertheless,

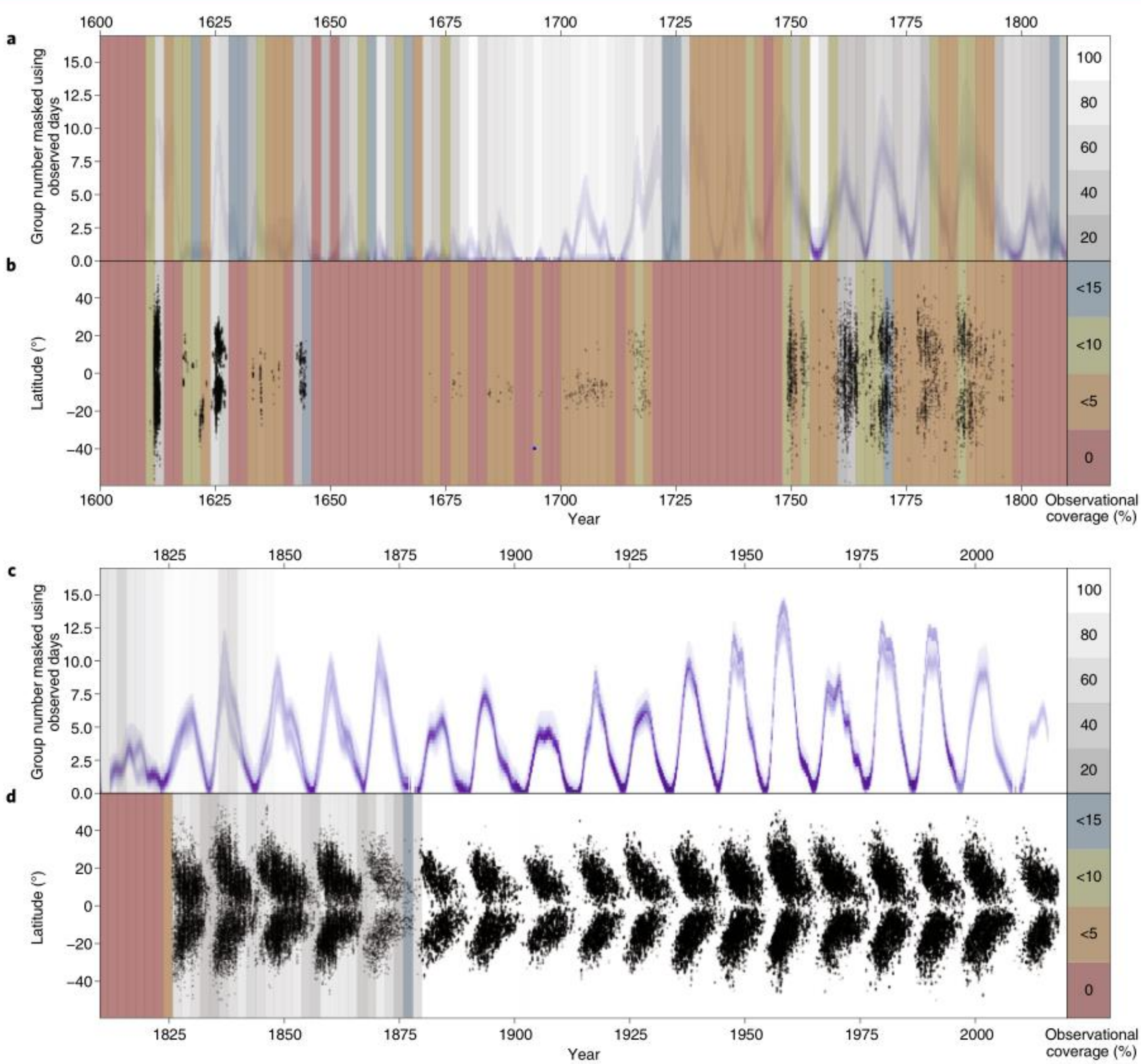

Figure 8: Visualization of the temporal data coverage of source sunspot data. Top plot for the time interval 1600 to 1815, and the lower plot for 1815 to the present. Top panel: the sunspot number. Bottom panel, the latitudinal distribution of sunspots ("butterfly" diagram) derived from drawings, when available. The contrast of the plotted data is proportional to the amount of underlying data and the coloured vertical strips go from white for full coverage, to red for the absence of data, i.e. data gaps. Such gaps create loose segments mainly in the 16th and 17th centuries and will be the main challenges for future progress in the re-constructions (Source: Muñoz-Jaramillo and Vaquero 2019).

this new database opens the way to the first end-to-end re-construction of the SN series, which should lead to Version 3 of the SN in the coming years. As new historical observations are still discovered every year, including from so-far unexplored archives in Japan or China, the recovery of sunspot data is definitely a never-ending quest.

So, more surprises and progress can be expected, in particular for early data. Indeed, in the 17th and 18th centuries, a few intervals are very poorly populated, creating disconnected segments in the historical time series, as illustrated in Figure 8. Here, the keyword is "patience", as uncovering, decoding and digitizing archived solar observations is a time-consuming process.

The next steps: version 3 and beyond ...

After more than 150 years of immobility, the recent revisions mark a major transition in the reconstruction of the past history of the solar cycle. The original static sunspot record has now become a very dynamical data set, which follows the evolution of contemporary knowledge, and methods in data science. From now on, validations and releases of new versions of the SN series, and of the parallel GN series, can be expected at intervals of a few years. In order to track this fast evolution, the WDC-SILSO introduced a versioning scheme, where each new numbered version is fully documented and past versions are kept accessible to users for reference.

This new data curation scheme will be further expanded by adopting open licenses (Creative Commons), permanent identifiers (DOI) and with the publication of associated software. The SN series is thus evolving from occasional upgrades to a continuous data insurance process, a profound change to which the users will need to adapt, after being used to a seemingly immutable data series.

Although the future sunspot number will be regularly updated, future changes will be smaller than the first set of corrections included in Version 2.0. The corrections will probably also be more local and will involve short intervals, instead of large parts of the series. The accuracy can be further improved over the well-covered 19th and 20th, but the largest progress will probably be accomplished for the historical period before the early 19th century, including the elusive quasi-spotless Maunder Minimum. Last-resort strategies may even be considered when sunspot information temporarily vanishes, including using geomagnetic information to connect the loose ends.

But the production of the sunspot numbers also continues today. All the knowledge and methods developed for the re-calibration of the past series will be ported to the operational software that is currently used to compile the daily sunspot number from the worldwide network of 80 stations coordinated by WDC-SILSO. This will ultimately lead to a fully seamless fusion between the entire historical series and its continuous extension. The core SILSO software has now been entirely rewritten in order to easily accommodate such future upgrades.

We are truly witnessing the prolific fusion of heritage data with cutting-edge data mining techniques of the 21st century.

Why continue this old index nowadays?

Although visual counting of spots may sound archaic in comparison with the many advanced modern solar data collected by ground-based observing networks and space missions (25-year old SoHO, SDO, Parker Probe, Solar Orbiter), they remain our sole link to the distant past. In order to put this detailed but mostly very recent solar knowledge in a temporal perspective, it must be attached to a long-term standard. We need to be able to answer the question: is the Sun, as we observe it today, equivalent and representative of the state of the Sun several centuries or millennia in the past and in the future?

Therefore, today, we need to continue this heritage series in parallel with all other techniques, in order to calibrate the relation between various solar parameters (spectral irradiance, solar wind flux, global magnetic fields) and the sunspot number, and this over the whole range of possible activity regimes (See for example Kopp *et al* 2016). This means that we must continue for at least one or more solar cycles. Fortunately, over timescales longer than a few months, most solar variables show a good and consistent correlation with the sunspot number.

In addition, when contemplating more broadly all the deep changes and violent episodes that marked human history over the last four centuries, the counting of sunspots stands out by its extreme robustness. The simplicity of the technique and the low hardware requirements allowed the participation of a large number of observers all over the world, making the entire process immune to natural disasters, wars, revolutions, economic crises, changing politics and arbitrary budget cuts. For such timescales, which are inherent to our star, this high level of resilience proved to be a vital asset. This proven temporal robustness and unbeatable cost-to-benefit ratio suggests that the sunspot number has a unique “backbone” role to play even for the future.

Now, the essence of this resilience has always been the possibility for volunteering amateur observers to contribute to this collective data acquisition. In that sense, the sunspot number is not only the longest ongoing scientific experiment, but it is probably also the first implementation of scientific crowdsourcing, well before the trendy notion of Citizen Science emerged in the Internet age. The sunspot number thus provides a major educational link between the broad public and the solar physics and astrophysics community. With new motivated and skilled observers offering their participation to the SILSO network every few months, the original collaborative spirit is definitely still there, in the footprints of Galileo, 400 years later!

All sunspot and group numbers series and the associated documentation can be found on the Web site of the World Data Center SILSO (www.sidc.be/silso), together with hemi-spheric numbers, real-time estimated numbers and 12-month activity forecasts.

Acknowledgements

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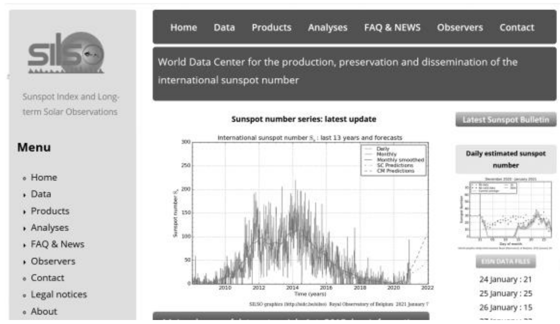

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Investigation of Extreme Space Weather Events in Historical Archives

[Hisashi Hayakawa (Nagoya University, Japan/Rutherford Appleton Laboratory, UK), and Yusuke Ebihara (Kyoto University, Japan)]

Major solar eruptions frequently launch interplanetary coronal mass ejections (ICMEs). When they hit the terrestrial magnetic field with sufficient velocity, mass, and southward interplanetary magnetic field (IMF), these ICMEs result in significant geomagnetic storms and equatorward extension of the auroral oval (Gonzalez *et al*., 1994; Daglis *et al*., 1999; Daglis, 2006). Owing to our accelerated dependency on technological infrastructure, modern civilization has become increasingly fragile to such space weather events (Baker et al., 2008; Hapgood and Thomson, 2010; Riley *et al*., 2018).

The magnitudes of such geomagnetic storms have been quantitatively evaluated using the Dst index. Their amplitude of the negative variation has been used as a proxy for the ring-current intensity (Gonzalez *et al*., 1994; Daglis *et al*., 1999). The Dst index has been constructed with the average of horizontal component *H* of the geomagnetic field of four mid-latitude magnetograms since the International Geophysical Year (IGY) of 1957–1958 (Sugiura, 1964; Sugiura and Kamei, 1991). The geomagnetic superstorm in March 1989 recorded the greatest intensity (minimum Dst = −589 nT) within the chronological coverage of the Dst index, extended the auroral visibility down to the Caribbean coasts, and caused serious space weather hazards such as blackouts in Québec State (Allen *et al*., 1989; Silverman, 2006; Boteler, 2019).

However, historical evidence has shown the occurrence of even more intense geomagnetic superstorms before the Dst index since 1957. The geomagnetic superstorms in September 1859 and May 1921 were particularly considered as benchmarks owing to their significant geomagnetic disturbances and equatorial auroral extensions (Silverman and Cliver, 2001; Tsurutani *et al*., 2003; Green and Boardsen, 2006; Cliver and Dietrich, 2013). Their magnitudes have been estimated as ≈ −900 nT in the estimated minimum Dst range (Dst*), based on hourly *H* variations (Cliver and Dietrich, 2013). In addition, their modern consequences have been considered catastrophic (Baker *et al*., 2008; Riley *et al*., 2018). In fact, Hapgood and Thomson (2010, p. 15) warned about their consequence that "the longer the power supply is cut off, the more society will struggle to cope, with dense urban populations the worst hit. Sustained loss of power could mean that society reverts to 19th century practices".

Fortunately, such superstorms are rare. The occurrence frequency of Carrington-class superstorms (minimum Dst* ≈ −900 nT) has been statistically considered once a century (Riley *et al*., 2018). Empirically, only five geomagnetic storms have developed beyond the threshold of minimum Dst ≤ −400 nT since 1957 (Riley *et al*., 2018; Meng *et al*., 2019). This has, in turn, made each event rather unique, and their statistical analyses slightly challenging. Therefore, it is important to chronologically extend our knowledge and quantitatively understand the magnitude of historical geomagnetic superstorms. This article presents a brief overview of re-constructions of time series and intensities of historical superstorms using the Dst estimates since 1900, setting their threshold as minimum as Dst ≤ −500 nT.

Data and Method

It is challenging to directly extend the Dst index beyond the IGY to measure the magnitudes of historical superstorms. The Dst index has been regularly derived from the hourly *H* values at the reference stations of Kakioka, Hermanus, San Juan, and Honolulu, to represent mid-latitude geomagnetic variations at various magnetic longitudes. Here, Hermanus started its operation only in 1941. The substitution of Hermanus data with observational data at Cape Town allows us to extend the Dst estimates or their equivalences (*e.g.,* Dcx index) back to 1932 (Mursula *et al*., 2008). Furthermore, even these reference stations suffered saturations during the extreme geomagnetic storms. Such saturations affected any attempts to extend their Dst estimates for such superstorms using the standard Dst reference stations (Riley, 2017).

However, the time series and magnitude in the Dst estimate for such extreme events could be quantitatively reconstructed, substituting these data with those obtained from other mid/low-latitude stations. Here, we considered hourly data with quasi-completeness and reasonable longitudinal separations to remove affections from observational saturations and local storm enhancements. By obtaining the hourly data from four reference stations, we subtracted the baseline value and solar quiet field variation from the hourly observational data obtained from each station.

These values were averaged by weighting the contemporary magnetic latitudes of each station by using the IGRF-12 model (Thébault *et al*., 2015). We applied this method to the extreme geomagnetic storms in September 1957 (minimum Dst = −427 nT) and April 2001 (minimum Dst = −387 nT) to compute their magnitude according to the minimum Dst* values of −399 and −361 nT, respectively (Love *et al*., 2019b; Hayakawa *et al*., 2020c). With minor variations (≈ 7% – 8%), these cases validate our calculation method of using alternative stations.

Geomagnetic Superstorm of March 1946

So far, at least four geomagnetic storms surpassed the threshold (minimum Dst ≤ −500 nT) before the IGY. Retrospectively, the first known geomagnetic superstorm occurred in March 1946 during the ascending phase of Solar Cycle 18. Its source flare was reported to at least at Kodaikanal (4:10–4:45 GMT) and Tashkent (4:30–7:32 GMT) on 27 March 1946, as shown in Figure 1a.

This storm was so intense that the Kakioka magnetogram failed to record the local magnetic disturbances for 3 h from 12 to 15 GMT (Hayakawa *et al*., 2020b). Fortunately, the hourly geomagnetic measurements during the 1930s and 1940s are widely available in the World Data Centers for Geomagnetism at Kyoto and Edinburgh.

In this study, we substituted the data obtained from Kakioka with those from Watheroo in Australia, with similar geomagnetic longitude and quasi-completeness (admitting an off-scale in 14:06–14:23 GMT). The results are summarized in Figure 1b. After a large sudden commencement at ≈8 GMT, this storm formed a steep negative excursion, and its maximum intensity was recorded as approximately −512 nT at ≈14 GMT. This value should be considered as a conservative estimate, as Watheroo scaled off around here. Therefore, we estimated the magnitude as the minimum Dst* of ≤−512 nT (Hayakawa *et al*., 2020b). As a corona aurora was reported in Watheroo (−41.8° MLAT) during the main phase, the magnetic footprint of the equatorial auroral boundary was estimated at ≤ 41.8° in invariant latitude (ILAT) (Hayakawa *et al*., 2020b).

Geomagnetic Superstorm of May 1921

The second geomagnetic superstorm occurred in May 1921, and it has been associated with one of the most outstanding auroral events (*e.g.*, Chapman, 1957; Silverman and Cliver, 2001). Its occurrence was in the declining phase of Solar Cycle 15. While its source flare has not yet been robustly identified (*c.f.*, Lefèvre *et al*., 2016), the sunspot group RGO 933404 has been associated with its source.

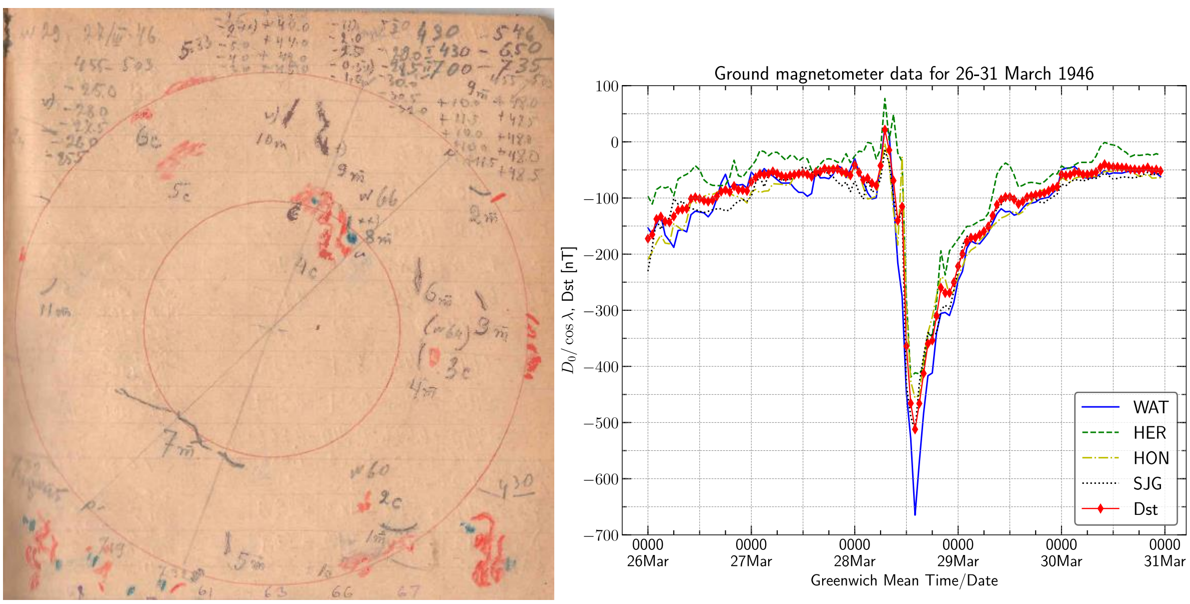

Figure 1: (a) Solar flare recorded at Tashkent on 27 March 1946 (courtesy of Ulugh Beg Astronomical Institute of the Uzbekistan Academy of Sciences). (b) Reconstructed Dst* time series of the geomagnetic superstorm on 28 March 1946. These figures have been reproduced from Hayakawa *et al*. (2020b), with all rights reserved.

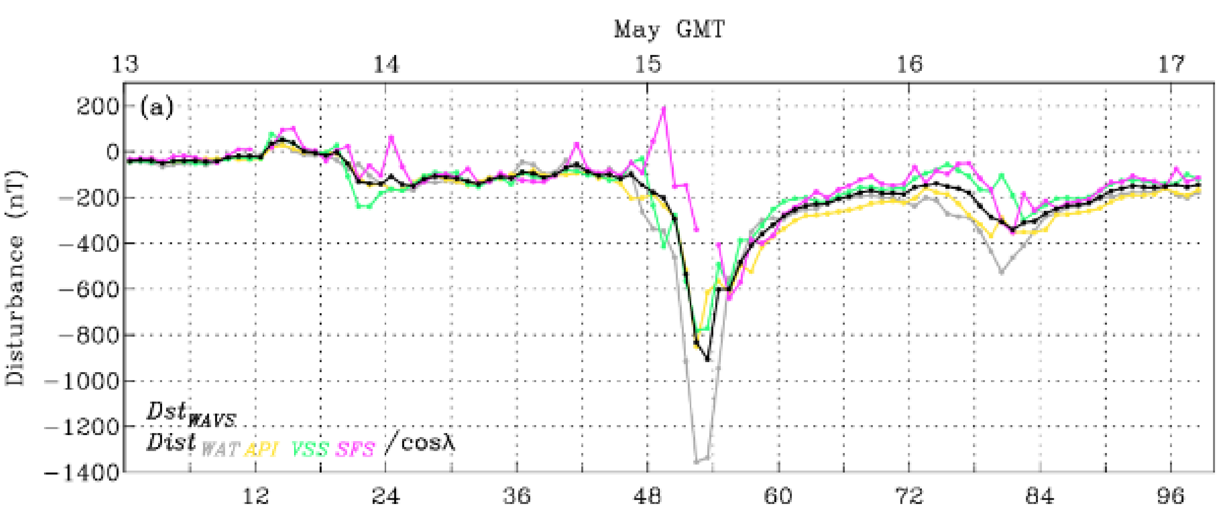

Figure 2: Dst* time series of the geomagnetic superstorm in May 1921. This figure has been reproduced from Love *et al*. (2019b) with all rights reserved. Here, the abbreviations read as follows: WAT (Watheroo), API (Apia), VSS (Vassouras), and SFS (San Fernando).

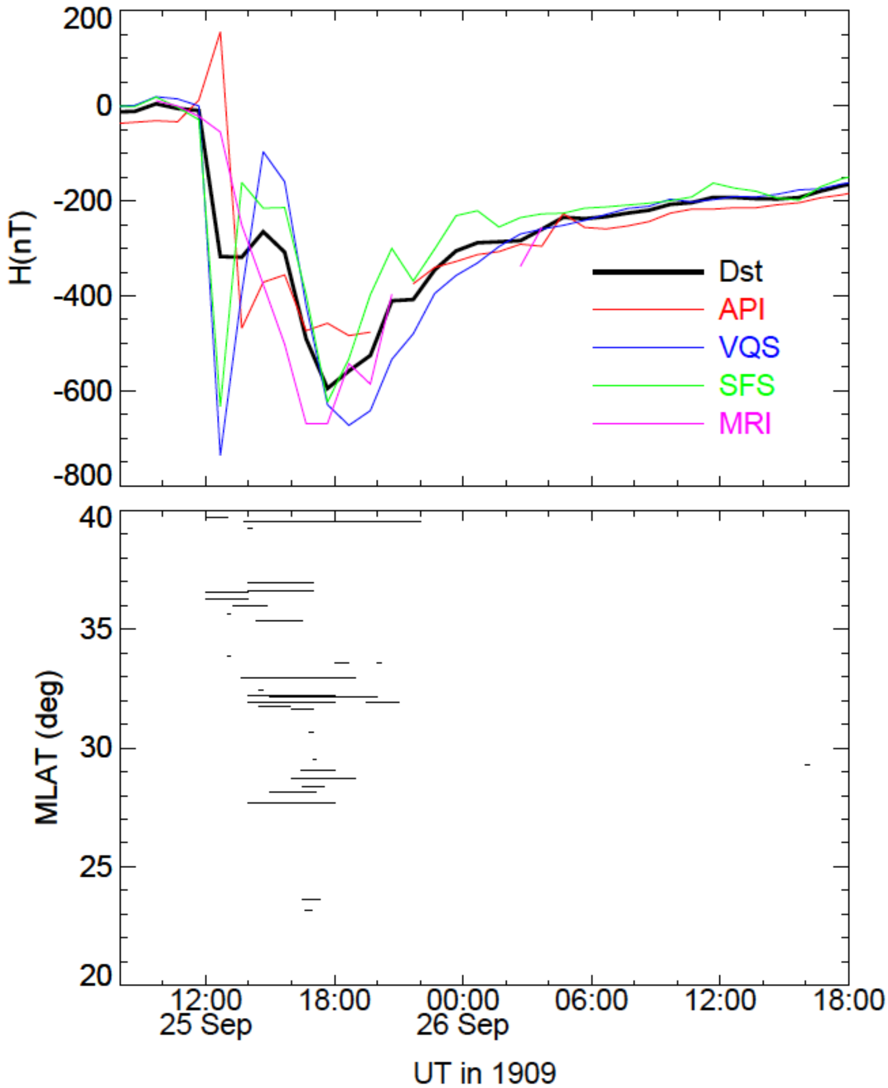

Figure 3: Reconstructed Dst* time series of the storm on September 1909 (above), and distribution of the MLAT of the auroral visibility, reproduced from Hayakawa *et al*. (2019a) with all rights reserved

This sunspot group was visible from 8 to 19 May 1921, and is likely associated with up to 6 sudden impulses from 12 to 20 May 1921 (Love *et al*., 2019b). After a significant sudden impulse at 22:13 GMT on 14 May 1921, the geomagnetic superstorm extended the auroral visibility even down to Apia in Samoa Island, where an exceptional geomagnetic disturbance (≈ 900 nT) was recorded (Silverman and Cliver, 2001; Kappenman, 2006).

The estimation of its magnitude was challenging, as this storm was so intense that many contemporary magnetograms, including the Dst reference stations, went off the scale. Nevertheless, we located relatively complete magnetograms at Apia, Watheroo, San Fernando, and Vassouras in their yearbooks and computed the Dst* time series during May 1921. The intensity of the geomagnetic superstorm developed after the impulse at 22:13 GMT with significant asymmetry. Its storm maximum (minimum Dst* ≈ 907 nT) was recorded at ≈ 5 GMT on 15 May 1921. As San Fernando went off the scale around the storm peak, this intensity was derived from the other three stations with an error margin of ± 132 nT. Therefore, the intensity of this storm was estimated as the minimum at Dst* ≈ 907 ± 132 nT (Love *et al.*, 2019b). The equatorial auroral boundary was estimated at 27.1° ILAT, because of the auroral visibility up to 22° at an elevation in Apia (−16.2° MLAT) (Hayakawa *et al.*, 2019b)

Geomagnetic Superstorms of September 1909

The third known geomagnetic superstorm occurred in September 1909, and has been indicated as one of the most outstanding auroral events (Chapman, 1957; Silverman, 1995). It occurred in the declining phase of solar cycle 14, one of the weakest solar cycles since the end of the Dalton Minimum (Lefèvre *et al*., 2016). Its source flare was plausibly identified as a solar eruption at 10:05–12:20 GMT on 24 September 1909 (Lockyer, 1909), which was quasi-synchronized with a large magnetic crochet at 11:00–12:30 GMT on the same date (Hayakawa *et al*., 2019a; Love *et al*., 2019a).

Approximately 24.75 h after this eruption, the ICME caused a large SSC at ≈11:40 GMT on 25 September, 1909. A significant storm developed thereafter with a significant disturbance such that several mid-latitude magnetograms went off the scale. In this study, we located quasi-complete magnetograms at Mauritius, San Fernando, Vieques, and Apia according to their yearbooks and archival materials. Accordingly, we reconstructed the Dst* time series, as shown in Figure 3 (upper panel). As observed, the storm shows a two-step development and extreme local asymmetry, especially in its main phase. This storm reached its maximum (minimum Dst* ≈ −595 nT) at ≈18 GMT on 25 September 1909 (Love *et al*., 2019a).

The main phase of this storm roughly corresponded to the local night in the East Asian and Australian sectors and located them as favourable positions for auroral observations. In fact, aurorae were visible down to Matsuyama (23.2° MLAT) up to 30° altitude. Accordingly, we computed the equatorial auroral boundary at ≈31.6° ILAT. The time series is summarized in Figure 3 (lower panel), in the crucial and early-recovery phases of this geomagnetic superstorm (Hayakawa *et al*., 2019a).

Geomagnetic Superstorm of October/ November 1903

The fourth known geomagnetic superstorm occurred in October/November 1903 and has been associated with the earliest recorded space weather hazard in the Iberian Peninsula (Ribeiro *et al*., 2016). Interestingly, this superstorm occurred slightly after the onset (minimum) of Solar Cycle 14, despite its unfavourable chronological context and small cycle amplitude (see Kilpua *et al*., 2015). The flare-productive sunspot group of RGO 5098 caused several flares. In particular, a magnetic crochet at ≈2 GMT on 30 October 1903 has been plausibly associated with the source flare that resulted in this geomagnetic superstorm.

It was challenging to reconstruct the Dst* time series of this geomagnetic superstorm was challenging, as it was so significant that several contemporary magnetograms went off the scale. Nevertheless, we located quasi-complete magnetograms at Zi-Ka-Wei, Colaba, Coimbra, and Cuajimalpa, based on which we reconstructed the Dst* time series, as shown in Figure 4. Accordingly, approximately 27.5 h after this eruption, an ICME arrival was recorded as a large SSC at ≈5:35 GMT on 31 October 1903. Later, this superstorm steeply developed and reached its maximum intensity (minimum Dst* ≈ −531 nT) at ≈15 GMT on 31 October 1903 (Hayakawa *et al*., 2020a). This superstorm also extended the auroral oval equatorward. The overhead auroral visibility at Sydney (−42.2° MLAT) indicates its equatorial auroral boundary as ≈44.1° ILAT (Hayakawa *et al*., 2020a).

Summary and Future Outlooks

This article reviewed the geomagnetic superstorms (minimum Dst* ≤ −500 nT) in 1900-1957. To cope with the difficulties of magnetogram availabilities and measurement saturations, we selected alternative magnetograms from mid-latitude stations with reasonable longitudinal separations. This methodology was validated according to two case studies of extreme geomagnetic storms that occurred in September 1957 and April 2001. We extended the surveys and reconstructions to past geomagnetic superstorms and identified at least four cases after 1900. Table 1 summarizes their dates and intensities compared with the known geomagnetic superstorm in March 1989 in the official Dst index (Allen *et al.*, 1989; Rich and Denig, 1992; Boteler, 2019) and historical geomagnetic superstorms in September 1859

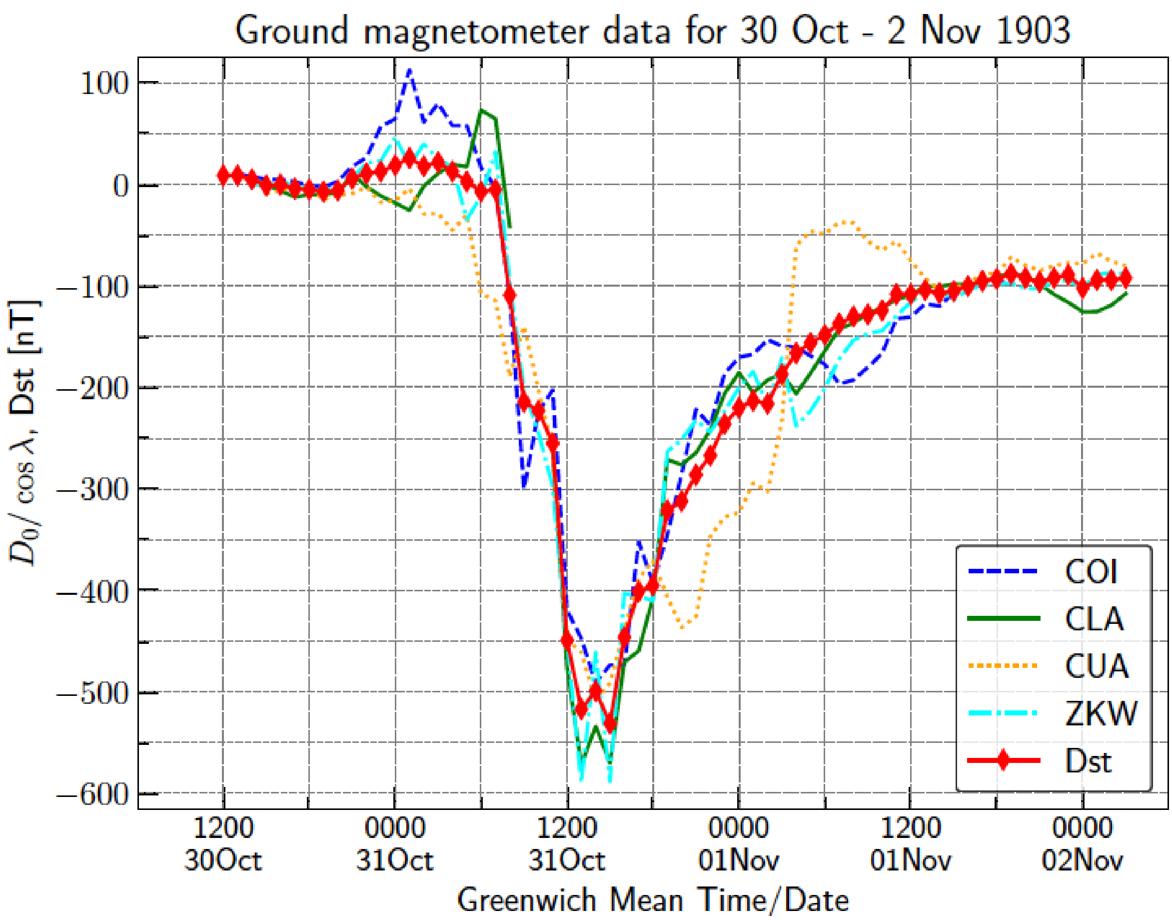

Figure 4: Dst* time series of the geomagnetic superstorm in October/November 1903, reproduced from Hayakawa *et al*. (2020a), with all right reserved.

and February 1872 (Tsurutani *et al.*, 2003; Cliver and Dietrich, 2013; Hayakawa *et al.*, 2018, 2020d).

These data exhibit at least four geomagnetic superstorms during 1900–1956. These cases chronologically bridge the known geomagnetic superstorm in March 1989 in the official Dst index and two historical geomagnetic superstorms that occurred in September 1859 and February 1872. However, the magnitudes of the latter two superstorms are known only with respect to single-station estimates and can be easily affected by local magnetic enhancements. As such, their magnitudes must be revised using appropriate Dst calculation procedures with four reference stations. These data form the bases for further applications in statistical analyses and simulations to evaluate their relevant issues such as their chronological distributions and resultant space-weather effects (*e.g.*, Riley *et al.*, 2018; Oliveira *et al.*, 2020).

Table 1: Summary of the geomagnetic superstorms reviewed in this article, and their comparison with the known geomagnetic superstorm in March 1989, as defined in the official Dst index, and historical geomagnetic superstorms in September 1859 and February 1872. This table is an extension of table 1 presented in the study by Hayakawa *et al.* (2019b) with the latest results summarized in this article.

Date	Minimum Dst* (nT)	EAB (°)	References
02-09-1859	−900 (+50, −150)*	25.1 ± 0.5	CD13, H20d
04-02-1872	< −830*	24.2	H+18
31-10-1903	−531	44.1	H+20a
25-09-1909	−595	31.6	H+19a, L+19a
15-05-1921	−907 ± 132	27.1	L+19b, H+19b
28-03-1946	≤ −512	≤ 41.8	H+20b
14-03-1989	−589**	40.1***	RD92, B19

Notes: The minimum Dst* values denoted by * and ** are derived from single-station estimates and the official Dst index, respectively. The EAB (equatorial auroral boundary) denoted by * was derived from DMSP satellite data (Rich and Denig, 1992). The reference abbreviations read as follows: B19 (Boteler, 2019), CD13 (Cliver and Dietrich, 2013), H+18 (Hayakawa *et al*., 2018), H+19a (Hayakawa *et al*., 2019a), H+19b (Hayakawa *et al*., 2019b), H+20a (Hayakawa *et al*., 2020a), H+20b (Hayakawa *et al*., 2020b), H+20d (Hayakawa *et al*., 2020d), L+19a (Love *et al*., 2019a), L+19b (Love *et al*., 2019b), and RD92 (Rich and Denig, 1992).**

Furthermore, more geomagnetic superstorms and extreme geomagnetic storms should exist in history. In this context, although the extreme geomagnetic storms in November 1882, January 1938, and March 1941 were analyzed (Love, 2018; Hayakawa *et al*., 2021a, 2021b), they did not develop beyond the threshold of geomagnetic superstorms (Dst* ≤ −500 nT).

Further case studies for historical magnetic storms are needed to quantitatively evaluate their magnitudes and reconstruct their time series. In this regard, it is important to call for preservations of historical data such as solar observations, geomagnetic measurements, and auroral reports (*e.g.*, Pevtsov and Clette, 2017; Pevtsov *et al*., 2019). Richer data could allow us to improve our understanding and existing models of space weather events.

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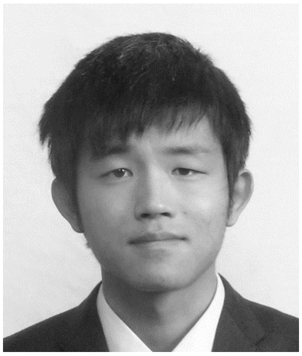
About the Author



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He is working on both oriental history and space physics. In space physics, he is mainly working on the reconstruction of extreme space weather events and long-term solar variability using historical observational records. He received the Kyoto University President Prize in 2016 and the EPS Young Researcher Award in 2017.

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COSPAR Business

Revised COSPAR By-Laws

The COSPAR Council met virtually during the Sydney Scientific Assembly. During the second session of its meeting, 29 January 2021, the Council adopted revisions to the COSPAR by-laws which had been endorsed earlier by the Bureau. The full text of the revised by-laws is available at https://cosparhq.cnes.fr/about/by-laws/. We highlight two of the most important changes below.

Diversity, Equity and Inclusion (DEI)

COSPAR is committed to improving gender balance, as well as to evolving and reinforcing its DEI policy, beyond statements and declarations. The new by-laws now include the appointment by the President of a Compliance Officer whose task will be to oversee DEI matters in COSPAR and help enforce the COSPAR DEI policy decided by the Bureau and approved by the Council. The Compliance Officer will report to the President and Bureau.

Committee on Industrial Relations (CIR)

The new by-laws establish the CIR, which reports to and advises the President of COSPAR on how best to integrate the capabilities of industry into COSPAR's activities and by doing so, to serve the interests of industry. The Members of the Committee are corporate officers who are responsible for strategic engagement with organizations such as COSPAR. The Members are drawn from COSPAR Industry Partners and Industry Supporters, other industries that are affiliated with COSPAR through the Associated