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History and Calibration of Sunspot Numbers

Leif Svalgaard · Edward W. Cliver · and Kenneth H. Schatten

Abstract Lorem ipsum dolor sit amet, consectetuer adipiscing elit, sed diam nonummy nibh euismod tincidunt ut laoreet dolore magna aliquam erat volutpat. Ut wisi enim ad minim veniam, quis nostrud exerci tation ullamcorper suscipit lobortis nisl ut aliquip ex ea commodo consequat. Duis autem vel eum iriure dolor in hendrerit in quis nostrud exerci tation ullamcorper suscipit lobortis nisl ut aliquip ex ea commodo consequat. Duis autem vel eum iriure dolor in hendrerit in .

Keywords: Sunspots, Historical Record, Calibration, Rudolf Wolf, Diurnal Geomagnetic Variation

1. Roadmap

I. Introduction

A. Importance of the SSN

- Primary time series in solar & solar-terrestrial physics. Implications for dynamo model, space weather forecasting, solar variability & climate change. Accuracy of SSN series critical: Used to calibrate longer-term reconstructions based on cosmogenic nuclei.

B. Problems with the SSN

- Despite importance, not vetted or verified by independent means. As a result we have at present not one, but three, widely-used sunspot number (SIDC & Group & NOAA). Undesirable, confusing, unacceptable situation. And it gets worse.

- As we will show, the sunspot numbers from the 19th century derived by Wolf and accepted as writings on a stone tablet since went through a series of revisions based on the geomagnetic data available to Wolf at the time. Together with the existence of separate sunspot series, this evolution of the Wolf number gives the lie to the sacredness of the current time series.

- To underscore the composite nature (i.e., based on both sunspot & geomagnetic observations) of the sunspot number handed down from Wolf, we note that all modern observers have ... personal observing equations that increase the

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number of spots for agreement with Wolf (when one would assume that modern equipment is superior and therefore capable of seeing more spots). [No, as the limiting factor is seeing, not telescope]

C. A Way Out

- Suggested by Wolf. Using geomagnetic technique and more comprehensive access to early observations than available to Wolf, it is possible to improve his early construction of the SSN. In addition, the same technique reveals more recent inhomogeneities in the SSN and allows us to correct these as well (and to monitor the forward extension of the series).

- In this paper, we will:

(1) Recount the history of the sunspot number from Wolfs invention and geomagnetic adjustment through its evolution under Wolfer, Brunner, Waldmeier and the SIDC;

(2) Describe and refine Wolfs SSN calibration technique based on the geomagnetic daily range;

(3) Apply this calibration technique to both the group and international sunspot series and obtain a unified and corrected series.

II. Origin and Evolution of the SSN

III. SSN Calibration Technique Based on the Daily Range of Geomagnetic Activity

IV. New SSN Series

V. Conclusion

A. Summary

B. Discussion

- Remaining issues: (a) Long-term trend in daily variation;

(b) Livingston & Penn;

(c) Archival & Digitization of 18th & 19th century geomagnetic data;

(d) International standardization/monitoring of SSN

2. Rudolf Wolf's Relative Sunspot Number

Johann Rudolf Wolf's observation, almost by happenstance, on December 4th, 1847 of a large sunspot (Wolf, 1856) excited an enduring (46+ year) interest in the sunspot phenomenon, its observation, and quantitative description. The discovery (Schwabe, 1844) by Heinrich Schwabe of the sunspot cycle and by Wolf himself (Wolf, 1852; Wolf, 1853) and, independently, by Gautier (Gautier, 1852) that the amplitude of the diurnal variation of the geomagnetic Declination (angle between compass needle and true North) seemed to vary in step (Lamont, 1851) with the newly discovered sunspot cycle gave further impetus to the observations and that study of the cycle, which would last for the rest of Wolf's life. Today, the sunspot record initiated by Wolf is often the primary input to reconstructions of various aspects of solar activity used in both solar and climate research (Krivova *et al.*, 2010).

Wolf started his regular observing program in 1849 using a 4-foot refractor at magnification 64. He recorded for each day, on which observations were made, two numbers: the first giving the number of sunspot groups and the second the

Sonnenfleckenbeobachtungen im Jahre 1849.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
1	9.31	3. 6	4. –	10.70	9.30	8.48	4.13	4 15	7.64	8.10	5.16	—
2	9.34	7.40	5. –	7. –	9.40	9.64	3. 3	6.18	5.35	7.10	7.41	8. 9
3	15. –	2. –	6.12	10.38	5.12	8.50	3. 6	6.15	4.27	3. 4	3.10	8.17
4	9.31	7.27	7.15	12.58	7.45	10.50	3 10	4.12	5.41	2. 3	4.31	—
5	9. –	9.22	2. –	8.20	8 50	8.45	7. –	5.20	1. 1	1. 2	—	9.47
6	8. –	10 34	7.24	10.60	7.38	7.45	4. 8	4.18	6.25	4. 6	—	2. 2
7	—	3. –	3. –	8.24	1. –	5. –	5.10	3.20	7.48	—	6.22	—
8	8.28	10.21	4. –	6.20	6.20	5.12	6.15	3.15	5.38	5.16	7.35	—
9	8.30	10.35	3. –	9.45	6.25	3. –	7.20	4.14	7.50	5.26	6.20	—

Figure 1. Format of observations for the year 1849. For each day the number of groups, g, and the total number of spots, f, are given in this form $g.f$. So, the 10.38 for April 3rd, denotes 10 groups with a total of 38 spots for a Relative Sunspot Number of 138 (Wolf, 1856).

total number of spots contained in all groups. All observations were recorded in this same basic format (as shown in Figure 1) and published until 1945 when it unfortunately was discontinued by Waldmeier. In order to compile monthly and yearly values of the observations, Wolf formed his daily Relative Sunspot Number, R, as 10 times the number of groups, g, plus the total number of spots, f, so that $R = 10\,g + f$. The formation of a new group is clearly a much more important event than the formation of one more spot within an existing group, so giving the number of groups a high weight captures that importance. The specific weight '10' emerged from a combination of experience and convenience.

Later (Wolf, 1861), Wolf introduced a 'scale' factor $R = k(10\,g + f)$ to enable observations by observers using different instruments, different selection criteria, and having different Snellen ratios (acuity) to be brought on to the same scale, namely his own (so $k = 1$ for Wolf).

3. The Observers

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4. Weighting According to Size

After Waldmeier took over the production of the sunspot series he stated (Waldmeier, 1948):

> *Allerdings hat Wolfer, während seiner Assistentenzeit 1877-1893 eine andere Zählweise wervendet [...] dass die Hofflecken, die bei Wolf nur als* ***ein*** *Fleck galten, je nach ihrer Grösse und Unterteilung mehrfach*

gezählt werden. (Though Wolfer used an different counting method during his tenure as assistant 1877-1893 [...] that spots with penumbra, that by Wolf was counted as ***one*** *spot, would be counted multiple times according to size and complexity).*

and (Waldmeier, 1968):

Around 1882 Wolf's successors changed the counting-method, which since then has been in use up to the present. This method counts also the smallest spots, and those with a penumbra are weighted according to their size and structure of the penumbra.

and (Waldmeier, 1968):

Später wurden den Flecken entsprechend ihrer Größe Gewichte erteilt: Ein punktförmiger Fleck wird einfach gezählt, ein größerer, jedoch nicht mit Penumbra versehener Fleck erhält das statistische Gewicht 2, ein kleiner Hoffleck 3, ein größerer 5. (Later the spots were weighted according to size: A pore was counted as one, a larger spot but still without penumbra get a statistical weight of 2, a small spot with penumbra one of 3, and a larger of 5).

Kopecký and colleagues note (Kopecký *et al.*, 1980), essentially quoting Waldmeier with a twist, that:

beginning with Wolfer, a "modified" method of calculating the number of sunspots, but ***without mentioning it****, is being used in Zürich. (our emphasis added).*

Table 1. Areas (in $\mu\odot$) of sunspot groups observed at Locarno (top) and at MWO, RGO.

Year Month Day. fraction UT	Region number	Locarno number	Obs. Area	Corr. Area	Center dist.($R_\odot$)	Lat	CM dist.
2010 10 21.500	11113	102	134	80	0.533	16.0	31.0
2010 10 21.500	11115	104	223	140	0.595	-29.0	13.0
2010 10 21.500	11117	107	104	80	0.760	23.0	-48.0
1920 11 21.550	9263	MWO	223	118	0.328	18.3	9.8
1912 06 20.310	6992	RGO	239	183	0.598	-6.0	-35.9
1912 06 21.316	6992	RGO	271	169	0.407	-5.9	-22.7
1912 06 22.306	6992	RGO	283	155	0.215	-5.9	-9.4
1912 06 23.474	6992	RGO	317	162	0.179	-5.8	6.4

This counting method is still in use at the reference station used by SIDC. As a typical example we take the drawing made at Locarno on 21st October, 2010 (Figure 2). Three sunspot groups are visible, numbered 102, 104, and 107, corresponding to NOAA active region numbers 11113, 11115, and 11117.

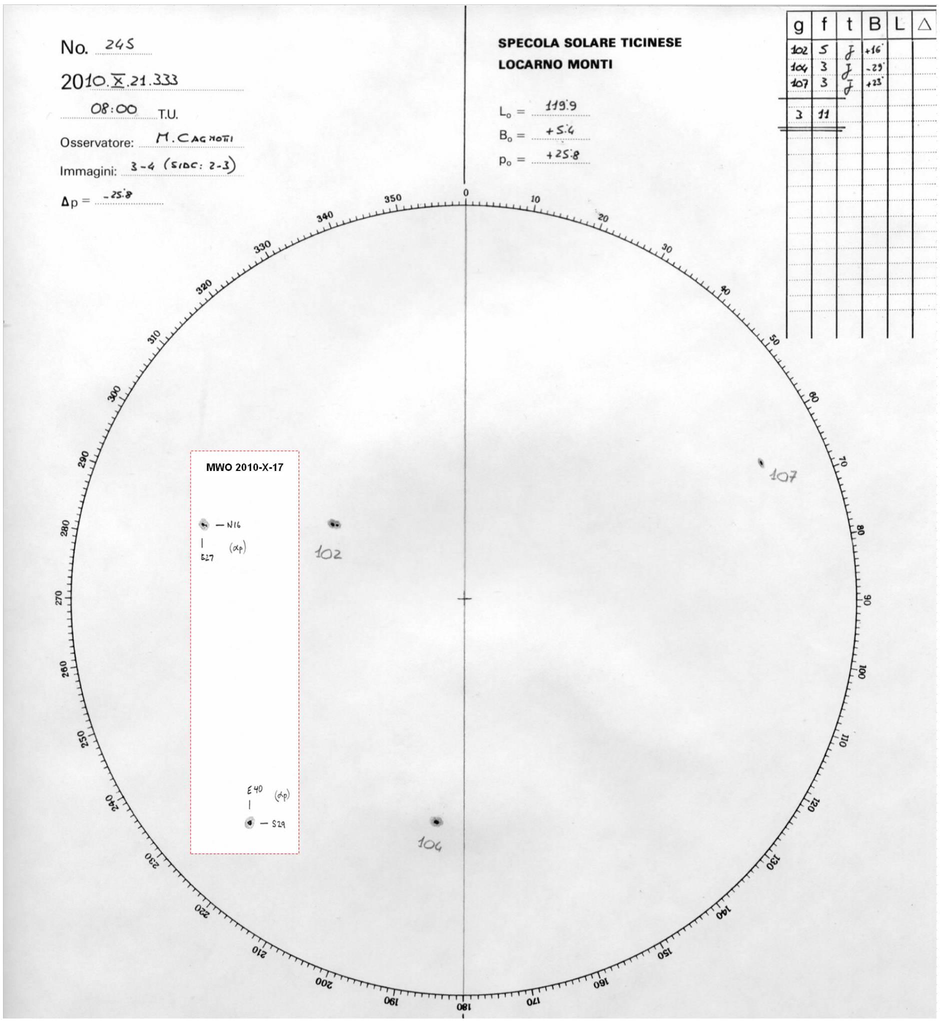

Figure 2. Drawing from Locarno 21 October, 2010 showing the three Locarno Regions 102, 104, and 107. The table at the upper right gives the weight assigned to each group. An insert (red border) shows the regions as observed at MWO on the 17th October (no observation the 21st). (http://www.specola.ch/drawings/2010/loc-d20101021.JPG)

From http://solarscience.msfc.nasa.gov/greenwch.shtml we list in Table 1 pertinent data, in particular the observed (*i.e.* projected) areas in μHemispheres of the disk.

The raw sunspot number reported by Locarno (upper right-hand table in Figure 2: $g = 3$, $f = 11$) was $3 \times 10 + 11 = 41$, which with Locarno's standard k-factor of 0.60 translates to a reduced relative sunspot number on the Wolf scale of $0.6 \times 41 = 25$ which is indeed what SIDC reported for that day.

If we take Waldmeier at face value then Wolfer would have introduced and used the weighting scheme, although there is no mention of such a scheme before Waldmeier's. Can we check this? As Wolfer reported (see format in Figure 1) the

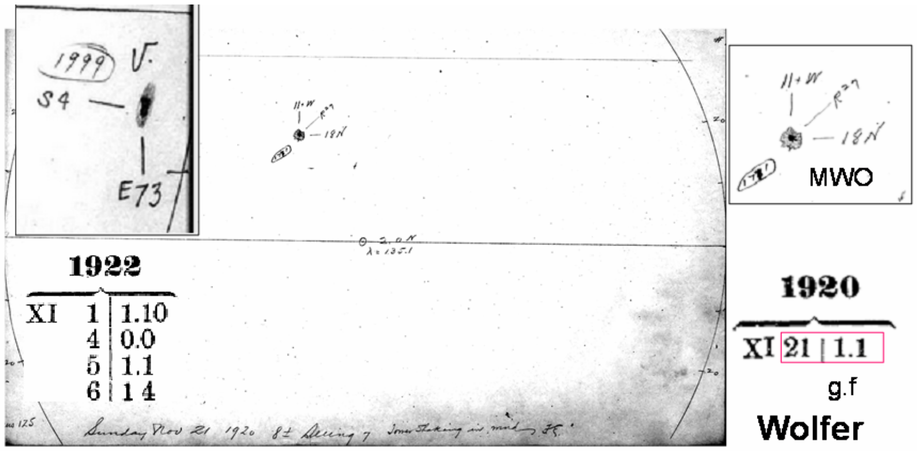

Figure 3. Drawing from Mount Wilson Observatory (MWO) 21 November, 1920 showing a solitary spot with the same area as Locarno Region 104. An insert shows a similar group observed at MWO on 5th November, 1922. For both groups, Wolfer recorded the observations as 1.1, clearly counting the large spot only once (thus with no weighting). (ftp://howard.astro.ucla.edu/pub/obs/drawings/1920/dr201121.jpg.) On November 6th, 1922, Wolfer recorded (1.4) three additional small spots that do not show on the MWO drawing for that day.

number of groups and spots for the whole disk we need to find an observation by Wolfer of a single group with only one spot with an observed area similar to that of Locarno group 104. Such was the case on 21st November, 1920, also listed in Table 1 with, as luck will have it, precisely the same observed area (223 μHem). Figure 3 shows the drawing from Mount Wilson Observatory (MWO) for 21 November, 1920 of a solitary spot with the same area as Locarno Region 104. An insert shows a similar group observed at MWO on 5th November, 1922. For both groups, Wolfer should have recorded the observation as 1.3 if he had used the weighting scheme, but they were recorded as 1.1, clearly counting the large spots only once (thus with no weighting). The Zürich sunspot number was 7 $(= 0.6 \times (1 \times 10 + 1))$ on both those days, consistent with no weighting. This comparison removes the doubt that the recorded values were unweighted, but that weighted values (not recorded anywhere) were, nevertheless, used for the calculation of the daily sunspot number.

There are many other such examples, *e.g.* 16th September, 1922 and 3rd March, 1924 for which MWO drawings are readily available. Or from the Haynald Observatory, Figure 4. We thus consider it established that Wolfer did not apply the weighting scheme contrary to Waldmeier's assertion. This is consistent with the fact that nowhere in Wolf's and Wolfer's otherwise meticulous yearly reports in the *Mittheilungen über Sonnenflecken* series is there any mention of a weighting scheme. Furthermore, Wolf was still very much alive in 1882 and in charge of things, and was not 'succeeded' at that time.

We shall not here speculate about the motive or reason for Waldmeier ascribing the weighting scheme to Wolfer. Waldmeier himself was an assistant to Brunner since 1936 and performed routine daily observations with the rest of the

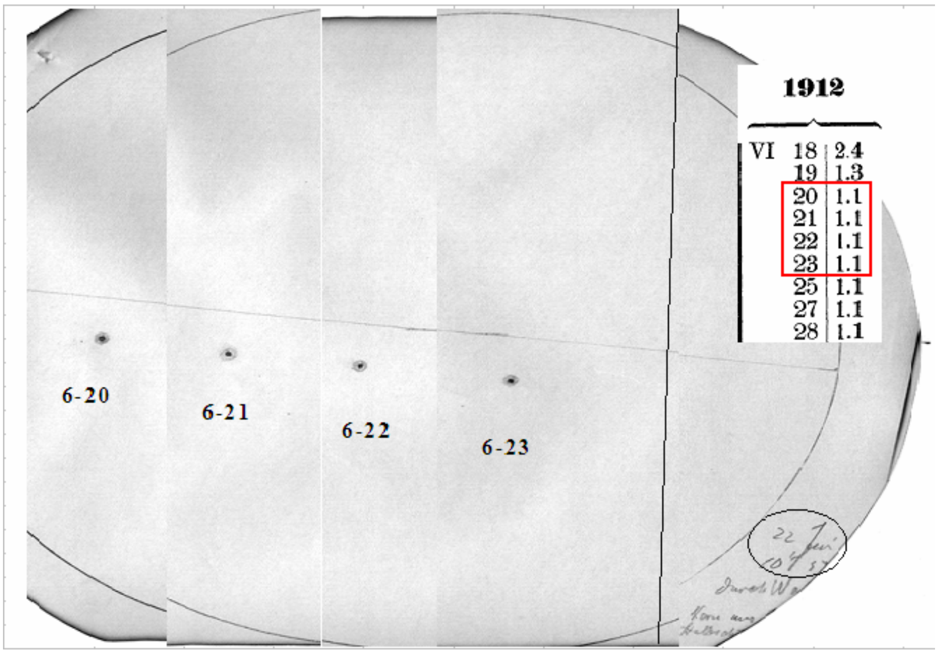

Figure 4. Drawings from Haynald Observatory 20-23 June, 1912 showing a large solitary spot (spot areas given in Table 1). Wolfer recorded the observations as 1.1, clearly counting the large spot only once (thus with no weighting). (http://fenyi.solarobs.unideb.hu/HHSD.html.). The sunspot numbers for those days were all recorded as the un-weighted 7 ($= 0.6\times(1\times10+1)$.

team so would have known what the rules were. Figure 5 shows that Brunner and Waldmeier were observing very close to the same scale in 1937, which, of course, is somewhat mysterious.

In spite of the lack of drawings or other original material it is perhaps possible to perform a statistical analysis as follows. From the RGO series of sunspot areas (http://solarscience.msfc.nasa.gov/greenwch.shtml) we select days where only one group was recorded on the disk. If that group had precisely one spot, the sunspot number for that day would be recorded as 11 by Wolf and as 7 ($0.6\times(10\times1+1)$) by Wolfer and later observers, if there were no weighting by size and complexity. During the Wolf period, the largest single-spot groups had a sunspot number of 11 (there were scattered lower values due to averaging with Wolfer). Starting with Wolfer, there were many large groups with a single spot counted as just one spot (sunspot number 7), *i.e.* no weighting. Curiously, with Brunner and later, the 7*s* disappear, showing the influence of, at least, some weighting. This seems to indicate that some weighting scheme originated already with Brunner, explaining why Waldmeier matched Brunner's counts. On the other hand, there are many 8*s*, so any weighting must have been slight.

In (Brunner, 1927) xx

It is, however, well documented (**?**) that Wolfer disagreed with Wolf about not counting the smallest spots and pores and that every observer beginning with Wolfer has agreed to this much more sensible criterium, as the rule now is simple: count all you can see. Let the telescope, your acuity, and the seeing deter-

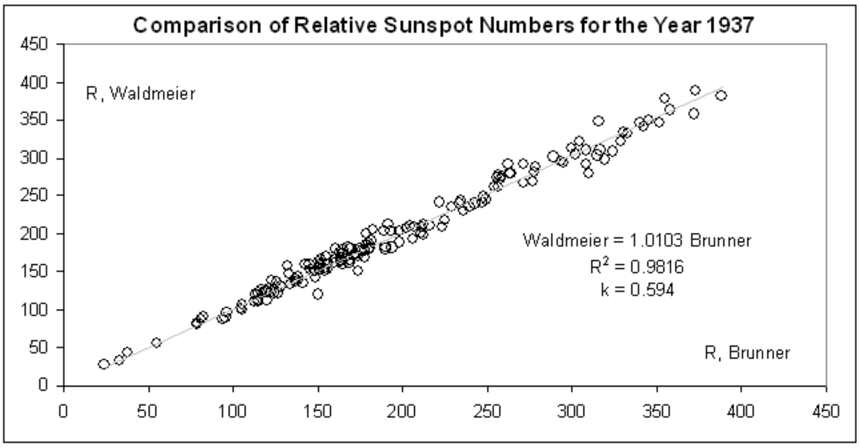

Figure 5. Comparison of daily 'raw' (i.e. with no k-factor applied) relative sunspot numbers derived by Waldmeier and Brunner for the year 1937. The k-factor for Waldmeier comes to $0.594 = 0.6/1.0103$ (Brunner reports 0.59).

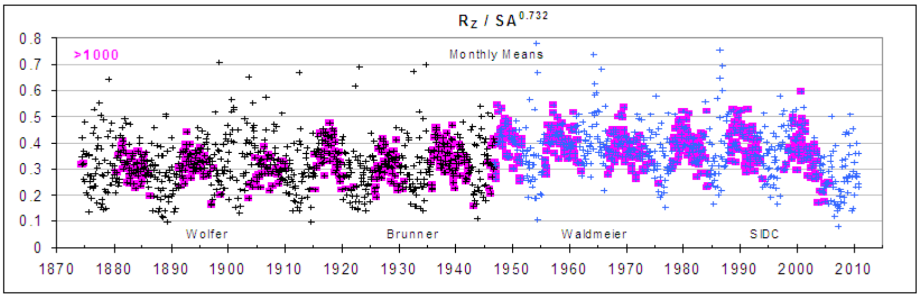

Figure 6. Comparison of daily 'raw' (i.e. with no k-factor applied) relative sunspot numbers derived by Waldmeier and Brunner for the year 1937. The k-factor for Waldmeier comes to $0.594 = 0.6/1.0103$ (Brunner reports 0.59).

mine what should be counted, not a non-reproducible (even for you tomorrow), subjective decision. The k-factor of about 0.6 that Wolfer derived from 16 years of observations overlapping with Wolf reflects the reduction factor necessary to 'remove' the spots that Wolf chose not to count. It would have made more sense to increase the earlier sunspot numbers (as Wolf already did for his observations with the hand-held telescope, see section 5), but perhaps Wolf and, later, Wolfer were victims to the tyranny of the 'installed base', not wishing to change already published values.

5. Telescope Characteristics

All of Wolfer's through Waldmeier's (and their assistants') sunspot counts were made by direct visual observations with the same telescope, an 80/1100mm Fraunhofer refractor at magnification 64: "Das für die Bestimmung der Relativzahlen verwendte Fernrohr stammt aus der Fabrik von Fraunhofer und besitzt

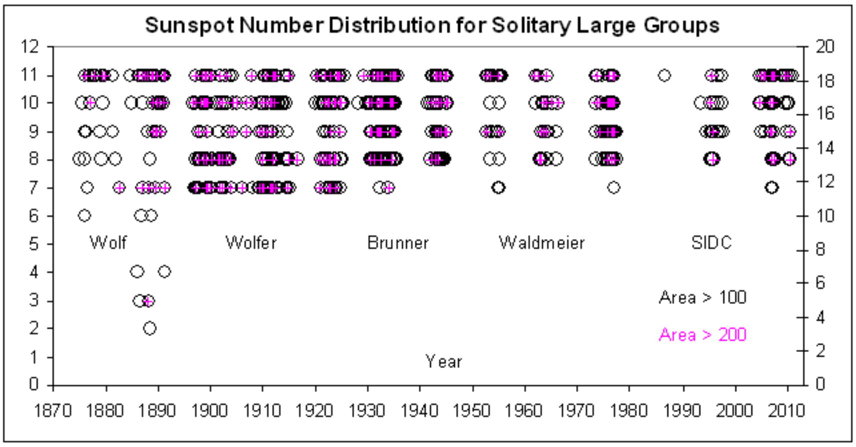

Figure 7. For days where only *one* group was observed, the sunspot number (if less than 12) for that day (*i.e.* for that solitary group) is plotted if the projected area of the group is larger than 100 $\mu\odot$ (circles) and larger than 200 $\mu\odot$ (pink plus symbols). The right-hand scale is for sunspot number divided by 0.6, *i.e.* for the original Wolf scale.

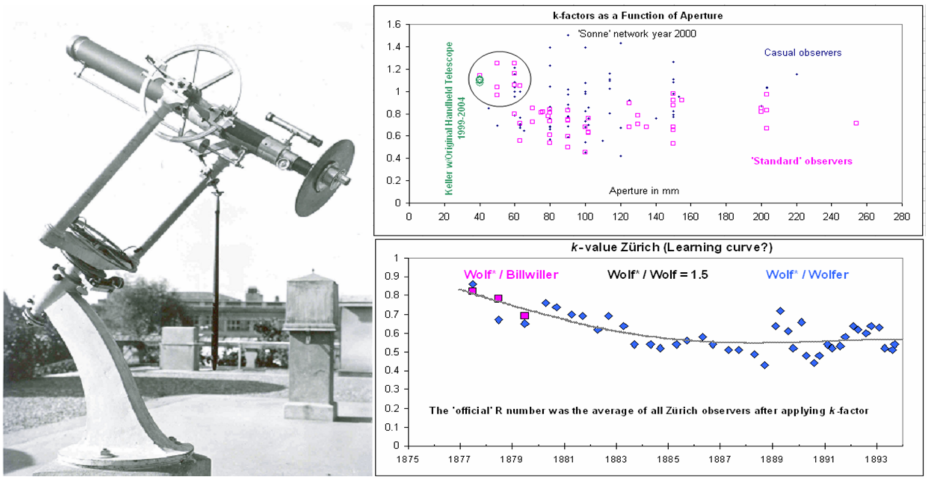

Figure 8. (Left) the 80/1100mm Fraunhofer refractor used by the Zürich observers, equipped with a Merz polarizer to allow direct visual observation. (Right, upper) k-factor dependence on telescope aperture. The circle marks telescopes that are too small for optimal viewing. The green symbols show the k-factor for Wolf's original hand-held telescope. (Right, lower) The k-factor for assistants Wolfer and Billwiller as a function of time showing a possible 'learning curve' before becoming experienced observers.

ein Objektiv von 8 cm Öffnung und 110 cm Brennweite. Es wird mit einem Okular verwendet, das eine 64fache Vergrösserung liefert" (Waldmeier, 1979).

The original telescope (Figure 8) still exists and is still in active use (Keller and Friedli, 1995). It was, in fact, used by the Zürich observers (M. Waldmeier, A. Zelenka and H. U. Keller) to maintain the Zürich sunspot series up through 1995, long after the 'official' sunspot work had been transferred to SIDC. In

Figure 9. (Left) the 40/600mm hand-held refractors (at magnification 40) used by Wolf increasingly from 1860 and exclusively from 1870 for direct visual observation.The left-most is the 'Pariser 2-füßer' with which most of the work was done.

Figure 10. (Left) the 40/600mm hand-held refractors (at magnification 40) used by Wolf increasingly from 1860 and exclusively from 1870 for direct visual observation.The left-most is the 'Pariser 2-füßer' with which most of the work was done.

January 1996 a new series of sunspot numbers called Swiss Wolf Numbers has been initiated by T.K. Friedli still using the original Fraunhofer refractor used by Wolf, in collaboration with an international network of professional and amateur astronomers.

The issue about the size of the telescope becomes important because Wolf, due to extensive travel, often (and increasingly since the 1860s, almost exclusively since 1870) did not use the 'standard' telescope, but smaller 40mm (magnification x40) hand-held, portable telescopes (Figure 9). He estimated for these a k-factor of 1.5. So, when Wolfer reports a k-factor of 0.60 he compares his own observations with the 80mm to 1.5×Wolf's with the 40mm. An example: say, Wolf reports $R_{Wolf40} = 20$; Wolf multiplies this by 1.5, getting $R_{Wolf80} = 30$; Wolf does not count the smallest spots visible with 80mm (with the 40mm, he couldn't anyway, so there is an automatic cutoff), so Wolfer's count on the 80mm would be higher, $R_{Wolfer80} = 50$, for a final k-factor of $30/50 = 0.60$.

We note that the oft repeated statement that the k-factor of 0.6 that Wolfer and all subsequent observers use to reduce the counts to Wolf's original 80mm-based values is based on 16 years of simultaneous observations by Wolf and Wolfer supposedly referring to simultaneous observations using the same instrument, namely the 80mm. This is not the case. During all these years, Wolf used exclusively the smaller hand-held 2½-foot telescopes and multiplied his count by 1.5, and it is for those (already adjusted) values that Wolfer's reduction factor applies. Keller (Keller, 1993) has started a new series of sunspot counts with Wolf's original, portable telescopes, aiming to verify the historical k-factor of these instruments compared with today's counting mode with the standard Fraunhofer telescope (Figure 8 upper-right).

When the objective size exceeds ≈60mm, atmospheric seeing and experience of the observer become the dominant factors and the size and other details of the telescope are essentially irrelevant (Figure 8 upper-right). Observers often step down the objective aperture to get better results. Even as Locarno uses a 150mm telescope, it has been stepped down to 80mm for sunspot observations (Cortesi, Personal Communication). Table 2 shows how the k-factor varies with seeing at a typical observatory. Figure 11 shows the influence of seeing by comparing two observatories, Catania with excellent seeing and Locarno with typical, medium seeing. Note that the seeing scale (from 1 to 5) is sometimes being used in reversed form, with 1 best and 5 worst.

Table 2. k-factors as a function of seeing for Kandilli Observatory (Atlas *et al.*, 1998)

Seeing	1(worst)	2	3	4	5(best)
Days	244	473	812	682	126
k	0.96	0.95	0.90	0.83	0.74

It takes several years to become an experienced sunspot observer working at the limit of visibility (Figure 8 lower-right). The exhaustive study by Schaefer (Schaefer, 1993) documents the effect of (in)experience in terms of discernible contrast ratio. A novice needs four times the contrast to see a feature. The Zürich observers dealt with this problem by determining the k-factor for assistants-in-training up to several times per year. For each observer a series for the year would be formed with the appropriate k-factors applied and then the series for all observers would be averaged to produce the final values (Wolfer, 1894).

6. More to come

Zelenka states that perhaps the new Zurich Classification of groups might have changed the group count... (Kopecký *et al.*, 1980) since 1938.

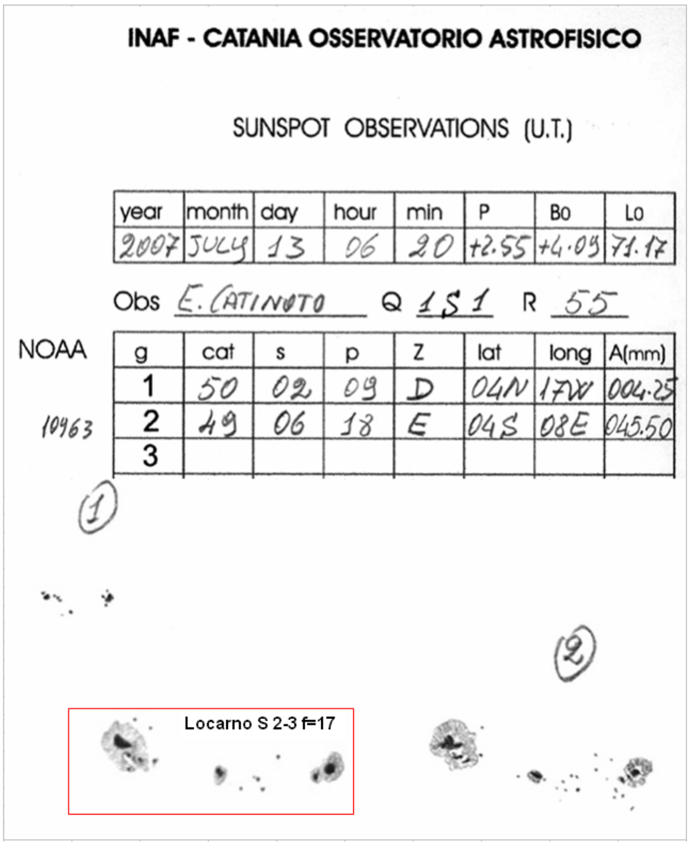

Figure 11. Locarno count 2x10+23= 43. SIDC has 26 [43*0.6=25.8 also]. NOAA 38. Catania 55 [w/o pores 28, close to 26]. Keller ?

7. The Diurnal Variation of the Geomagnetic Field

The discovery of the relationship between the diurnal variation and the sunspots – "not only in average period, but also in deviations and irregularities" – establishes a firm link between solar and terrestrial phenomena. This was immediately realized by Wolf and recognized by many distinguished scientists of the day. Faraday wrote to Wolf on 27th August, 1852 (Wolf, 1857):

> *I am greatly obliged and delighted by your kindness in speaking to me of your most remarkable enquiry, regarding the relation existing between the condition of the Sun and the condition of the Earths magnetism. The discovery of periods and the observation of their accordance in different parts of the great system, of which we make a portion, seem to be one of the most promising methods of touching the great subject of terrestrial magnetism...*

Wolf soon found (Wolf, 1859) that there was a simple, linear relationship between the amplitude, v, of the diurnal variation of the Declination and his relative sunspot number: $v = a + b\,R$ with coefficients a and b, allowing him to calculate the terrestrial response from his sunspot number, determining a and b by least squares. He marveled "Who would have thought just a few years ago about the possibility of computing a terrestrial phenomenon from observations of sunspots".

Later researchers, e.g. (Chree, 1913; Chapman *et al.*, 1971), wrote the relationship in the equivalent form $v = a(1 + mR/10^4)$ separating out the solar modulation in the unit-independent parameter m (avoiding decimals using the device of dividing by 10^4) with, it was hoped, local influences being parameterized by the coefficient a. Chree also established that a and m for a given station [geomagnetic observatory] were the same on geomagnetically quiet and geomagnetic disturbed days, showing that the relationship found (Sabine, 1852) with *magnetic disturbances* hinted at a different nature of that solar-terrestrial relation; a difference that for a long time was not understood and that complicates the analysis of the old data. (Macmillan and Droujinin, 2007) xx

8. Much more to come

Zelenka states that perhaps the new Zurich Classification of groups might have changed the group count... (Kopecký *et al.*, 1980) since 1938.

The most important solar observatory in the 19th century was the ETH observatory (fig. 1), built in 1861-1864 by the famous architect Gottfried Semper (1803-1879); the dome was built according to the ideas and specifications of the astronomer Rudolf Wolf (1816-1893) and the well-known engineer Franz Reuleaux (1829-1905). The second floor was used by the meteorological central institute. Semper was appointed as first professor for architecture in 1854 in the just founded Eidgenssisches Polytechnikum (today Federal Institute of Technology (ETH) Zurich). Semper was admired already by his contemporaries as "Michelangelo of the 19th century" (Friedli et al. 1998). Semper is famous besides his buildings - like the Semper Opera in Dresden und Frankfurt, London, the ETH in Zurich and monumental buildings like the Kaiserforum in Vienna - for his theoretical and reformatoric work in architecture. The main instrument of the ETH observatory was a refractor in the dome. By analyzing sunspot observations carried out by many different astronomers using various instruments and observing techniques, Rudolf Wolf defined the relative sunspot number. Already since 1928 new buildings like the university hospital and the district heating plant were added near the observatory and disturbed the observations. The ETH observatory in Zurich (Schmelzbergstrasse 25) was used until 1980, put under monument protection in 1981 and restored in 1995-1997, then the Collegium Helveticum, an interdisciplinary research institute of the ETH, took over the building (1997). Friedli, T.K.; Fröhlich, M.; Muschg, A.; Rebsamen, Hp. und B. Schnitter: Sempers ehemalige Eidgenössische Sternwarte in Zurich. Bern: Schweizerische Gesellschaft fr Kunstgeschichte 1998.

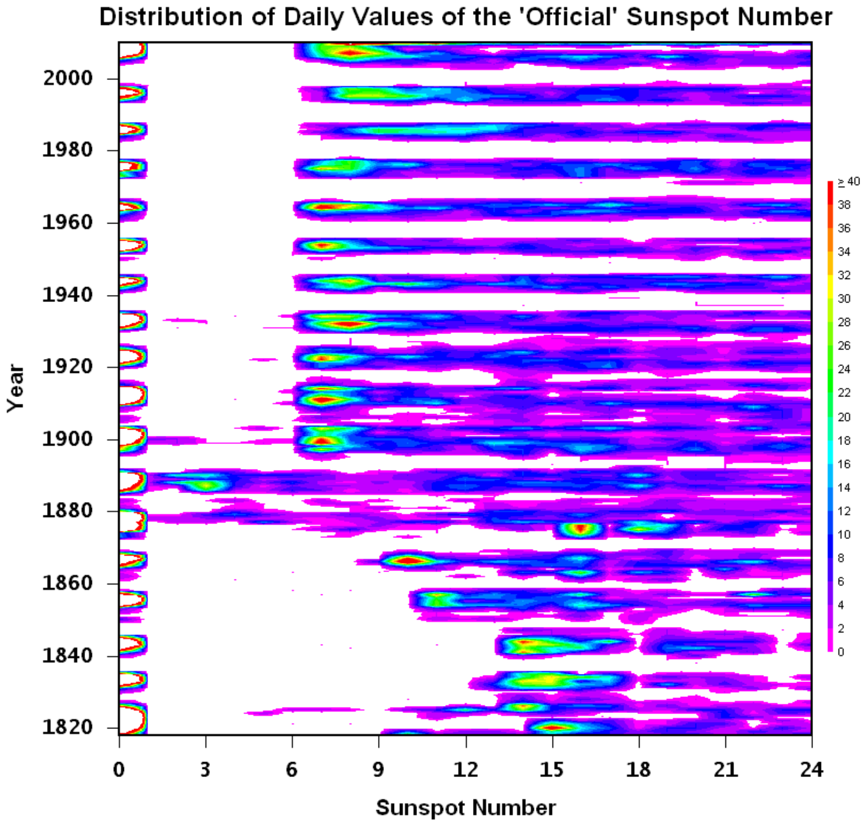

Figure 12. (Left) the 80/1100mm Fraunhofer refractor used by the Zürich observers, equipped with a Merz polarizer to allow direct visual observation. (Right, upper) k-factor dependence on telescope aperture. The circle marks telescopes that are too small for optimal viewing. The green symbols show the k-factor for Wolf's original hand-held telescope. (Right, lower) The k-factor for assistants Wolfer and Billwiller as a function of time showing a possible 'learning curve' before becoming experienced observers.

9. Conclusion

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