AFRL-RV-PS-TR-2020-0088

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SUB-DAY F10.7 INDICES GENERATED FROM RSTN DATA

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15 November 2016

Final Report

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
15-11-2016	Final Report	01 Oct 2015 – 30 Sep 2016

4. TITLE AND SUBTITLE
Sub-day F10.7 Indices Generated from RSTN Data

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Stephen M. White

5d. PROJECT NUMBER
3001

5e. TASK NUMBER
EF99991225

5f. WORK UNIT NUMBER
V1KR

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RV-PS-TR-2020-0088

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBX

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited (377ABW-2016-12760 dtd 02 Dec 2016).

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We investigate the suitability of Radio Solar Telescope Network (RSTN) measurements as a source of sub–day–cadence proxies for the solar–activity index F10.7. We demonstrate the limits on the reliability of the RSTN calibration and its variation across the four RSTN observatories. We show that fitting a spectrum to the RSTN frequencies around 2.8 GHz does not provide a useful proxy when the raw RSTN data are used. Instead, we demonstrate a method in which the 2.7 GHz fluxes at each observatory are scaled to F10.7 using a median ratio over 10–day periods. The scaled RSTN data results in relative errors around 4% over a solar cycle, improving to 2% when obvious outliers in the RSTN data are excluded. This is less than the day– to–day variation in F10.7 itself, demonstrating that the proxy proposed can function as a sub–day F10.7 index.

15. SUBJECT TERMS
space weather; solar radio emission; F10.7 index; Radio Solar Telescope Network, RSTN

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. Stephen M. White
Unclassified	Unclassified	Unclassified	Unlimited	22	**19b. TELEPHONE NUMBER** *(include area code)*

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1. INTRODUCTION

The "F10.7 index", which is actually the solar radio flux measured at a wavelength of 10.7 cm (frequency of 2.8 GHz, e.g. see [1, 6, 7, 8]), is a widely used proxy for the impact of the Sun's radiation on the Earth's atmosphere. The radiation impact is mostly mediated by the Sun's ultraviolet (UV), extreme ultraviolet (EUV) and soft X-ray (SXR) emissions. These heat and ionize the atmosphere at different heights, but since these wavelengths are all absorbed by the atmosphere they cannot be measured directly from the ground. Fortunately, the Sun's steady radio emission is produced by the same coronal plasma that radiates the bulk of the EUV and X-ray emission, and once it was realized that F10.7 showed a strong correlation with solar activity, it was found to be a better proxy for solar ionizing radiation than sunspot number and its use in atmospheric models became widespread.

The value of F10.7 used in atmospheric models results from a very careful measurement procedure established by Arthur Covington in the 1950s and currently carried out by Ken Tapping at the Dominion Radio Astronomy Observatory in Penticton, Canada. Three measurements are made every day: the nominal measurement at local noon, 20 UT (actually 19:58:30 UT at Penticton's longitude), and measurements at ± 3 hours (17, 23 UT) in summer, or ± 2 hours (18, 22 UT) in winter. Corrections to the flux for (the small) atmospheric absorption at 2.8 GHz are also applied. The painstaking calibration process employed at Penticton results in one of the most precise solar indices available, with a measurement uncertainty as low as 1%.

There is interest in F10.7 values at a cadence higher than daily. Sub-daily values, for example, would allow for timely "nowcast" corrections to improve real-time 1 to 3 day forecasting of F10.7 (see, e.g.,[3]). The time separations of the three daily F10.7 measure- ments at Penticton are not sufficient to use them for trends in time given the presence of low–level solar variability, so instead they are compared to identify anomalies due to solar radio bursts occurring during individual measurements, and generally a single daily value is quoted and used in modelling. The purpose of this report is to investigate whether the USAF Radio Solar Telescope Network (RSTN) measurements, which have 24-hour coverage of the Sun at wavelengths other than 10.7 cm, can be used to provide a reliable proxy for F10.7 at sub-day intervals. We initially investigate an effective 6–hour cadence using the daily calibrated flux values taken at local noon at each of the 4 RSTN sites.

2. BACKGROUND

The RSTN Radio Interference Monitoring Sets (RIMS) system observes at 8 discrete frequencies, of which the three most relevant to 2.8 GHz are at 1.415, 2.695 and 4.995 GHz. RSTN observes all frequencies with 1-second time resolution from sunrise to sunset, but in addition at noon (and dawn) each day RSTN makes a calibrated measurement in which a noise source of known effective temperature is (manually) switched into the signal path and the observed resulting offset from the cold–sky level is used to convert the peak measurement in a subsequent drift scan of the Sun into a flux. This flux is reported as the daily flux for that observatory, and may be used to adjust the flux scale for the 1-second data taken after the noon measurement. The four RSTN sites are at Sagamore Hill, Massachusetts (SGMR, local noon

16:42 UT), Palehua, Hawaii (PALE, 22:32 UT; moved a short distance north–west to Kaena Point in 2011), Learmonth, Australia (LEAR, 04:24 UT) and San Vito, Italy (SVTO, 10:42 UT). Their separations are uniformly close to 6 hours, providing suitable sub–day sampling. Note that daily flux values are generally quoted in two forms: the actual measurement at the current distance of the Earth from the Sun, and a distance–corrected value corresponding to the flux observed at a uniform distance of 1 astronomical unit (AU) from the Sun. The variation of the distance of the Earth from the Sun during its annual orbit results in flux variations of ±3.4%. The RSTN noon flux values reported by RSTN to the National Geophysical Data Center (NGDC) are the distance–corrected values.

While the four RSTN sites provide good sub-daily coverage, there are issues with maintaining reliable calibration of the RSTN daily flux values. The procedure is described in AFWAMAN 15-2 and in an unpublished document by Kennewell [4][1]. Possible drifts in the output of the noise sources or changes in components ahead of the noise source injection (e.g., antenna efficiency, feed response) are addressed either by "network standardization" or by recalibration at solar minimum. Network standardization consists of making all 4 sites consistent with each other. However, this method only works if 3 of the sites are all in agreement, which is often not the case. Solar minimum recalibration uses the fact that the flux at a given frequency generally returns to the same (low) value every solar minimum. However this method obviously can only be carried out every 11–13 years, leaving long periods with reliance on network standardization. There is also the possibility of using other sources as a calibration reference. As noted above, F10.7 is extremely well calibrated and can generally be used as a reference for RSTN 2.7 GHz. In addition, the National Astronomical Observatory of Japan (NAOJ) has been operating well-calibrated polarimeters at 1.0, 2.0, 3.75, 9.4 and 17.0 GHz for over 50 years. The calibration of these systems (labelled NoRP; see[5]), now located at Nobeyama in central Honshu, is irregularly checked against horn receivers similar to those used by Ken Tapping at Penticton: the latest such calibration is being carried out at the time of writing and so far indicates that the polarimeter calibration has not drifted significantly since the last measurements, over 15 years ago (K. Iwai, National Institute of Information and Communications Technology, private communication)[2].

3. METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Analysis Methods

Figure 1 illustrates the non–flare solar radio flux spectrum in the vicinity of 2.8 GHz typical of solar minimum (plus symbols) and solar maximum (cross symbols) using data from RSTN (red) and the Nobeyama polarimeters (purple). Solar radio fluxes are normally quoted in "solar flux units" (sfu): 1 sfu = 10^{-22} W m^{-2} Hz^{-1}. In the frequency range around 2.8 GHz, the solar corona is optically thin in quiet Sun regions (producing a flux contribution that is essentially flat with

[1] John Kennewell was an employee of the Australian Ionospheric Prediction Service, which operated Learmonth Observatory in cooperation with the USAF. He was closely involved in many of the technical aspects of RSTN.
[2] Currently the Nobeyama polarimeters are monitored by a multi–institution group in Japan that meets monthly by telecon to discuss calibration and other issues that may arise.

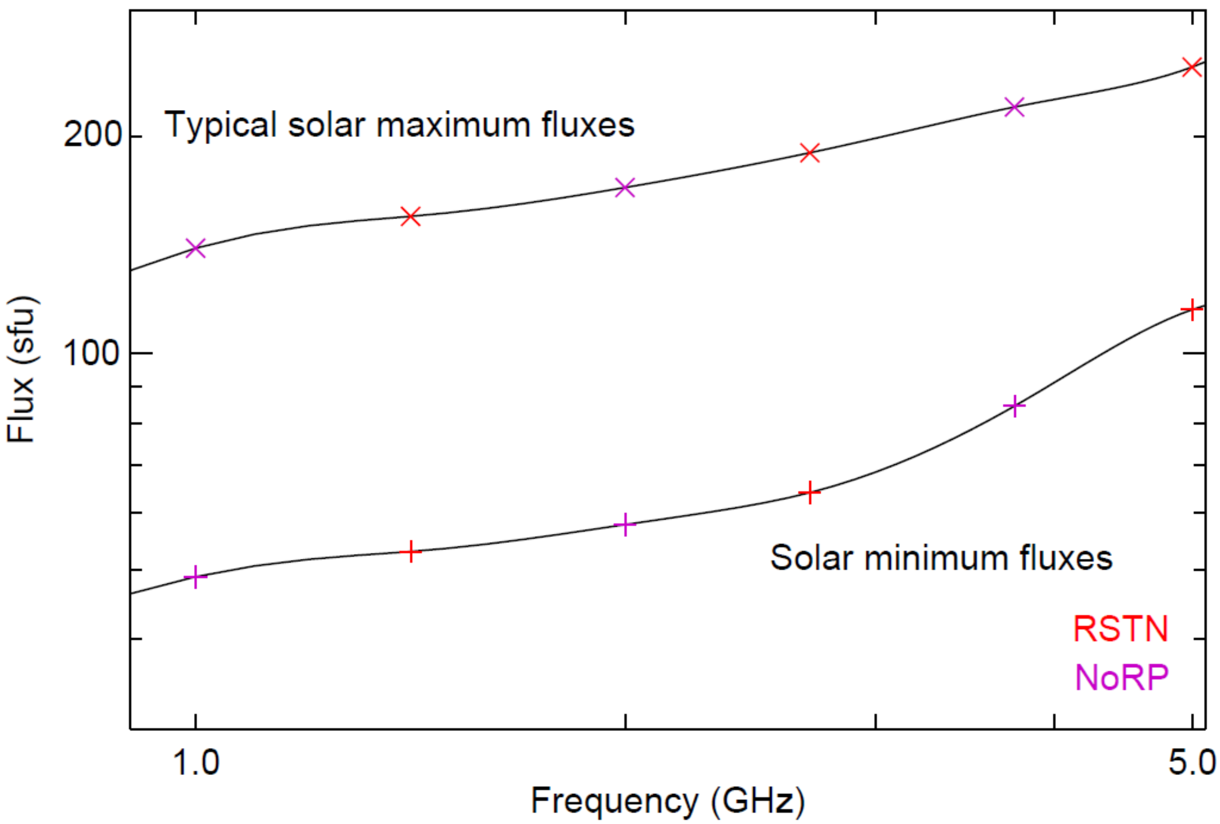

Figure 1. Non-flare solar radio spectrum

frequency) but may be optically thick in intense active regions (with a rising flux spectrum, but typically less steep than frequency–squared; e.g., [2, 9]). In addition, there is a significant component from the lower solar chromosphere that rises with frequency. These components combine to produce the spectra seen in Fig. 1, with a much larger contribution from active regions being present at solar maximum. At frequencies above 2 GHz much of this active region contribution may be optically thin and (since optically–thin thermal emission has a flat spectrum) can produce a flatter radio spectrum than in the same frequency range at solar minimum. The non–flare solar radio spectrum should always monotonically increase with frequency since all the components have either flat or rising spectra.

The simplest approach to use RSTN data to generate a proxy value for F10.7 (2.8 GHz) would be to apply a correction to the nearby RSTN 2.7 GHz value. Note (Fig. 1) that the spectral shape near 2.8 GHz can change with solar activity, so a single correction factor to get from 2.7 GHz to 2.8 GHz likely may not suffice. We investigate the behavior of the ratio of 2.8 to 2.7 GHz flux in Figure 2, where the top panel shows the variation of F10.7 (2.8 GHz flux) for the years 1997–2008 (loosely corresponding to solar cycle 23), while the bottom panel shows the ratio of F10.7 to the 2.7 GHz flux measured at the RSTN Sagamore Hill Observatory, one of the two RSTN observatories about 3 hours of longitude away from Penticton (the other being Palehua).

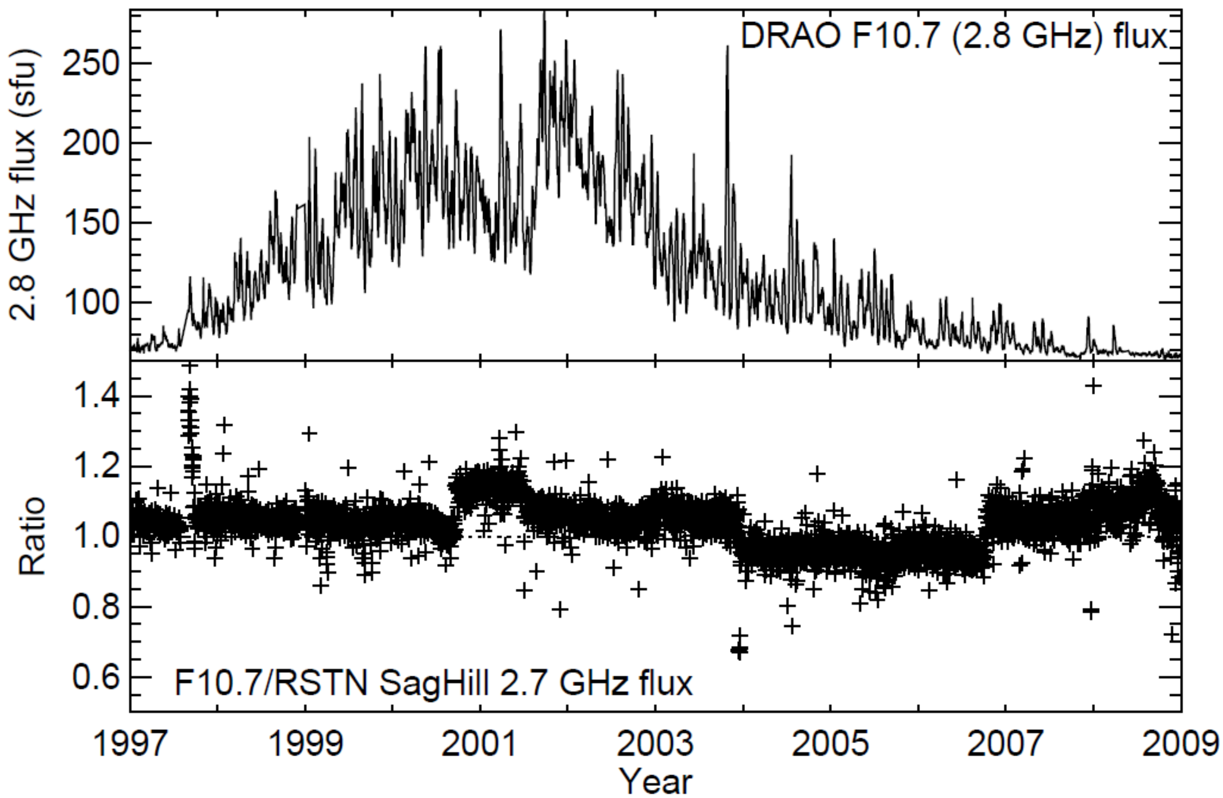

Figure 2. The solar radio flux at 2.8 GHz in Cycle 23, and ratio to 2.7 GHz

The ratio of 2.8 to 2.7 GHz in Fig. 2 consists mostly of sections of relatively constant values separated by steps. We assume that these steps likely represent “network standardization” corrections carried out by RSTN, since as far as we know Penticton does not carry out any such corrections.

To clarify this result further, Figure 3 shows a 60–day running median value of the ratio of the Penticton 2.8 GHz flux to the RSTN Sagamore Hill 2.7 GHz flux, together with the rms spread in the ratio. A typical ratio is around 1.05 with a spread of ± 0.02, but as noted there are step–like corrections to one of the fluxes that change the ratio, and for a period the 2.7 GHz flux was being reported as larger than the 2.8 GHz flux, which is inconsistent with the known rising flux spectrum of solar radio emission (e.g., Fig. 1). A flux ratio of 1.05 from 2.7 to 2.8 GHz corresponds to a spectral index α (where flux S ~ f^{α}, f being frequency) of 1.28.

Figure 4 shows the 60–day running medians for all 4 RSTN observatories. Distinct step changes in the ratio followed by periods of constant ratio are not as clear in the observatories other than Sagamore Hill, although it appears that a correction was made to all observatories around the beginning of 2003 which resulted in all four reporting 2.7 GHz fluxes larger than those measured at 2.8 GHz. This confirms that the step corrections evident in Fig. 3 have been applied to the Sagamore Hill data, not the F10.7 values.

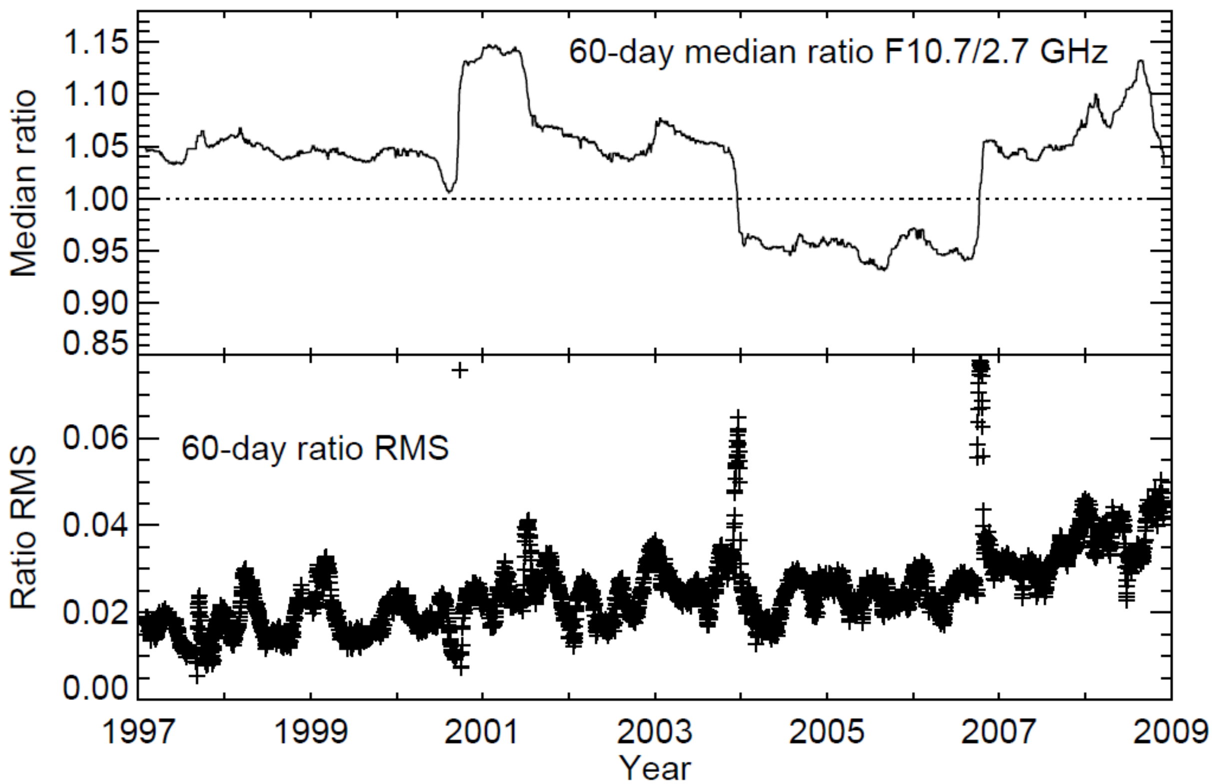

Figure 3. 60-day running median of the ratio of 2.8 GHz flux to Sag. Hill 2.7 GHz flux.

The differences between the 4 ratio curves in Fig. 4 illustrate the difficulties that will be encountered in deriving proxy F10.7 values from RSTN data: typically the RSTN calibration across the 4 observatories has a significant spread, and this will limit the accuracy of any sub–day F10.7 values that we derive from RSTN.

3.2 Using Radio Spectra Derived from RSTN

An obvious approach to using RSTN data to generate a proxy value for F10.7 (2.8 GHz) is to use the 1.4, 2.7 and 5.0 GHz RSTN values to derive a model for the spectrum in this region, and then use that spectrum to derive 2.8 GHz fluxes. In this section we investigate such an approach. We proceed by fitting a parabola to the three flux values and evaluating this parabola at 2.8 GHz. Fitting a parabola to 3 points produces a result that can be significantly perturbed by a single bad value, but in practice we find that similar spectral indices are derived for all 4 observatories, with a definite solar-cycle dependence. This is shown via a 60–day running median of the spectral index ($\alpha = \mathrm{alog}(S_{2.8}/S_{2.7})/\mathrm{alog}(2.8/2.695)$, where $S_{2.8}$ is the proxy resulting from the quadratic fit to the RSTN fluxes) in Figure 5. All 4 observatories show a similar trend, with spectral index decreasing as activity increases in the initial years of cycle 23, then increasing again starting at around solar maximum (2001-2002). There are some clear anomalies in this figure, notably the sharp jump at all 4 observatories in 2001, and the sharp drops at different times at each

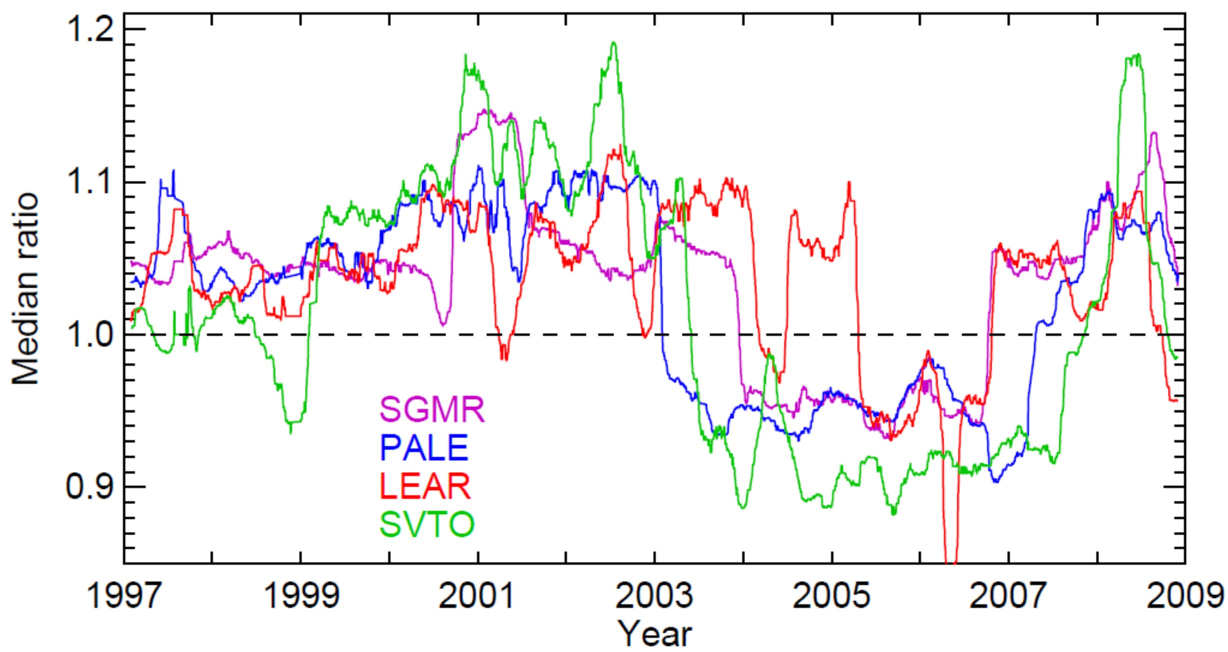

Figure 4. 60-day running median of the 2.8/2.7 GHz ratio for each RSTN site.

observatory after 2006. The general consistency in behavior between all four observatories is encouraging for this method.

Figure 6 addresses the question of how well this 2.8 GHz proxy matches up with the measured F10.7 value. The figure shows the percentage error represented by the RSTN proxy 2.8 GHz fluxes $P_{2.8}$ compared to the actual measurements at Penticton, i.e., $100 \times (P_{2.8} - \mathrm{F10.7})/\mathrm{F10.7}$, for each observatory. Errors of ± 10% are common, as are offsets. The plot also indicates some issues with the RSTN data: the Sagamore Hill proxy shows distinct annual variation which should not be present, since the nominally distance–corrected flux values are used both to generate the proxy and for the F10.7 values used to determine the error. The Palehua proxy also appears to show annual modulation due to the changing solar distance, while Learmonth and San Vito do not. The proxies consistently overestimate F10.7 during the period 2004–2007.

The bottom panel in Fig. 6 shows the daily percentage change in the measured F10.7 values. This represents the error incurred by assuming that tomorrow's flux is the same as today's, and serves as a reference point for the RSTN proxies: if the proxy cannot do better than the assumption of no change, then its value is questionable. This panel shows that indeed changes of 10% from one day to the next do occur, but not surprisingly such large changes tend to be sporadic and short–lived, unlike the large offsets seen in the RSTN proxy errors.

3.3 Comparison with Nobeyama Polarimeter Fluxes

As noted above, the Nobeyama polarimeters are widely regarded as very well–calibrated devices, perhaps second only to F10.7 in precision. Here we investigate whether they show

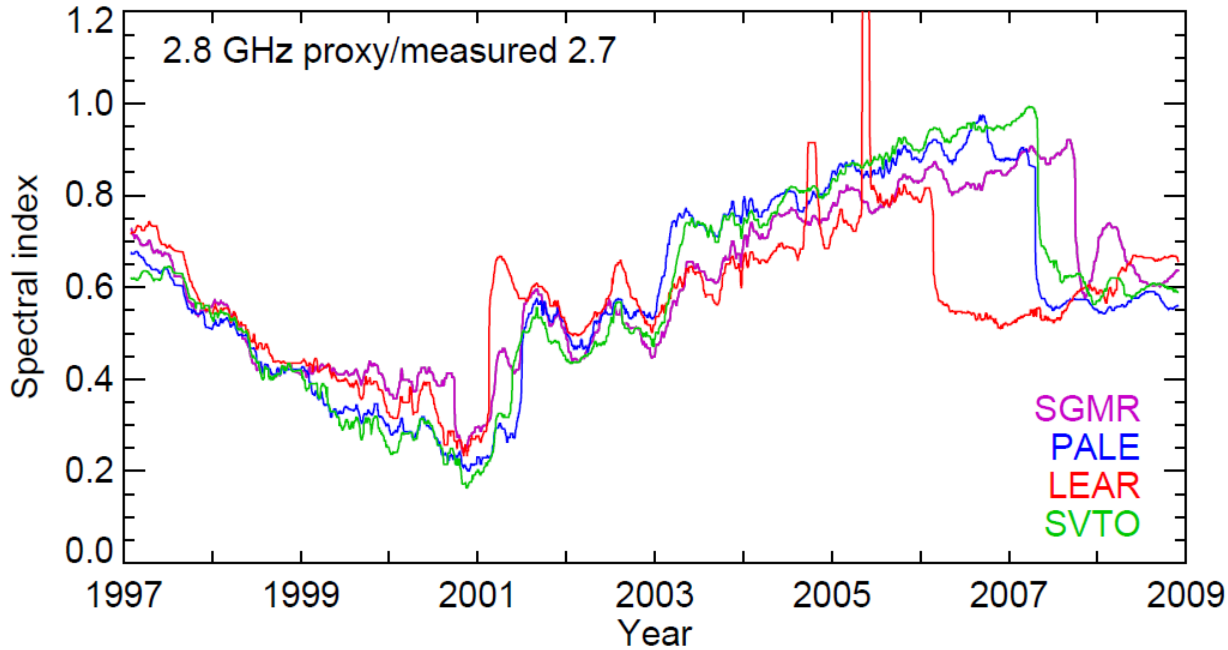

Figure 5. 60-day running median of the pseudo-spectral index for each RSTN site.

significant improvement over RSTN data as a source of proxies for F10.7. We must first mention a puzzling aspect of this comparison that apparently remains unresolved after more than 50 years[3]. This is the fact that despite both measurement procedures making use of the same type of pyramidal horns (whose gain can be calculated analytically, and, e.g., were used in the 3 K blackbody cosmic background discovery by Penzias and Wilson) for occasional checks on absolute calibration, there is a 10% discrepancy in the flux scales at the two observatories. This was first noted long ago when efforts were made to reconcile the flux scales at different solar observatories [5] . At that time the F10.7 measurements were assigned a correction factor of 0.9 to bring them into line with other observatories, reflected in the publication of an “URSI Series D Flux” in the F10.7 data reports that is 0.9 times the distance–adjusted F10.7 measurement. Per recent discussions with K. Iwai (NICT) and M. Shimojo (NAOJ), it remains true that NoRP data should be compared with F10.7 multiplied by 0.9 (also mentioned by Tapping [6]).

The NoRP frequencies closest to F10.7 are 2.0 and 3.75 GHz. At solar minimum the 2.0 GHz flux is generally about 10 sfu less than F10.7 while the flux at 3.75 GHz is about 15 sfu larger. Figure 7 shows the ratio of (0.9×)F10.7 over these two NoRP frequencies for cycle 23, using the same running median format as in previous figures. Since local noon at Nobeyama is 02:46 UT, its noon measurement takes place almost 7 hours after the nominal time for F10.7. Ratios with larger frequency separation are expected to show a larger influence due to changes in the solar radio spectrum with the solar cycle, and we believe this to be the source of the small but significant gradual decline in the ratio of F10.7 to the 2 GHz flux during the rise of solar cycle

[3] and that I previously thought, erroneously, was no longer an issue.

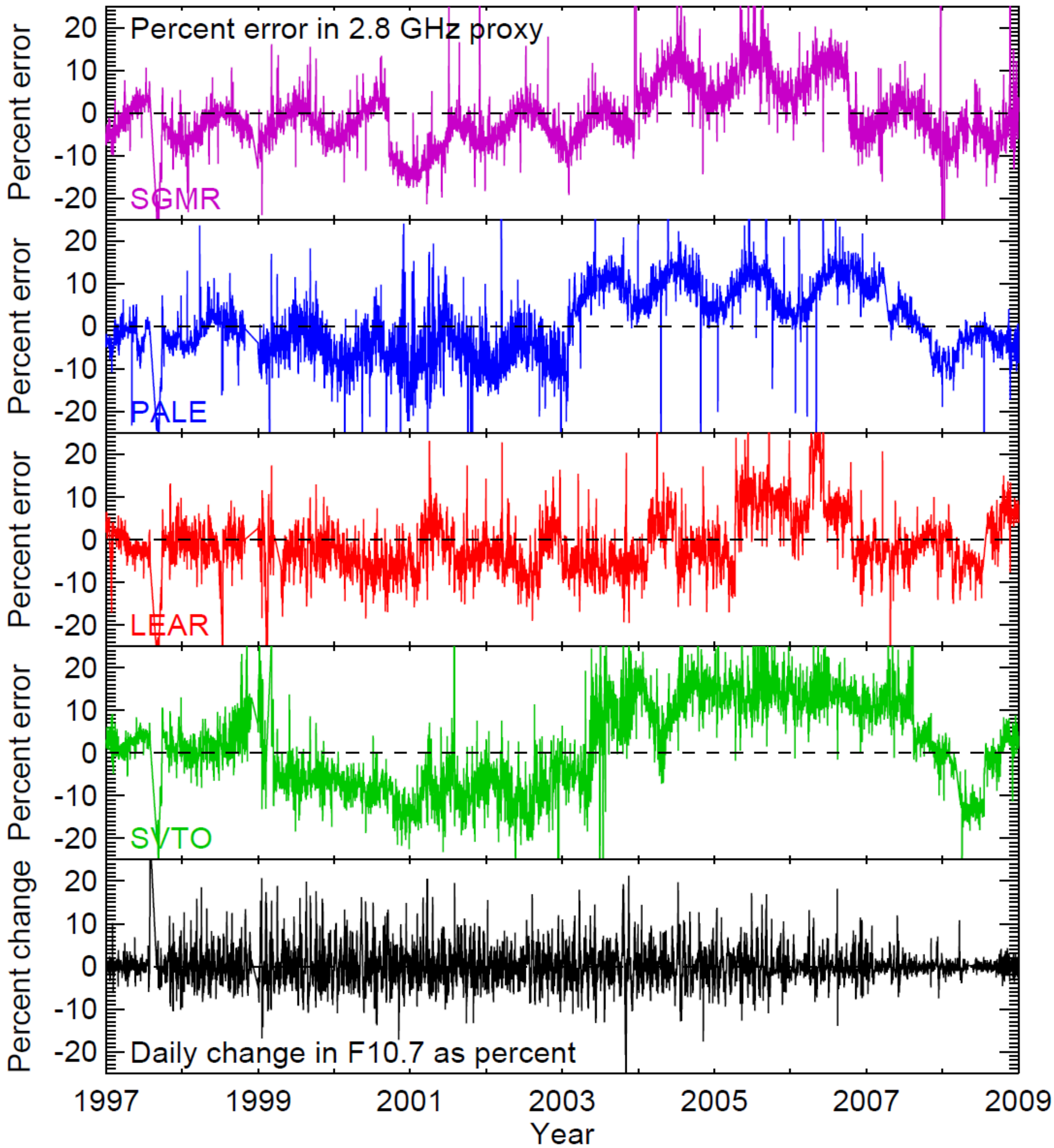

Figure 6. The percentage error of the proxy 2.8 GHz values $P_{2.8}$

23, and the corresponding rise in the ratio during the decline of the cycle. The F10.7/3.75 GHz ratio shows the opposite behavior as expected. Superimposed on the gradual behavior in the ratio F10.7/2 GHz appears to be a small and irregular annual modulation. The ratio of F10.7 to the Learmonth 2.7 GHz flux does not show long-term trends, but shows frequent short–term fluctuations of 10% or more followed by periods of roughly constant ratio.

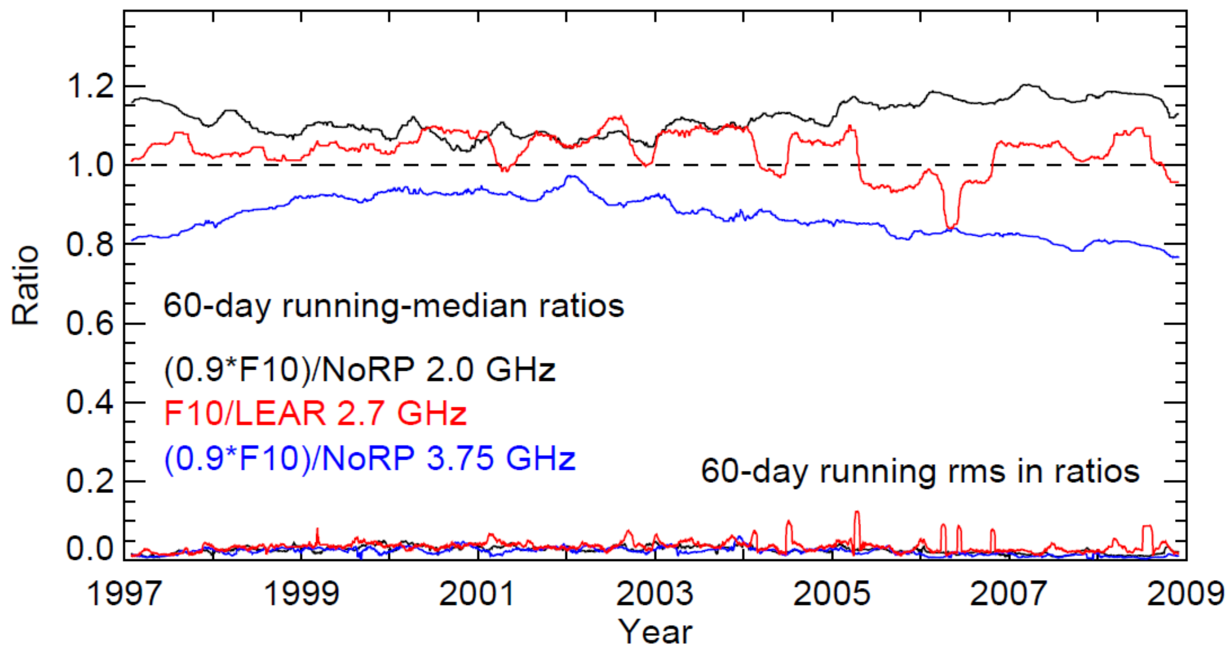

Figure 7. The 60-day running median of the ratio of F10.7 to NoRP 2.0 & 3.75 GHz

We generated proxy F10.7 values from the NoRP data both by fitting a polynomial to the 1.0, 2.0 and 3.75 GHz fluxes, and by fitting a power law from 2.0 to 3.75 GHz. The results are shown in Figure 8: both methods gave proxy values that were consistently in the range 1-2% above

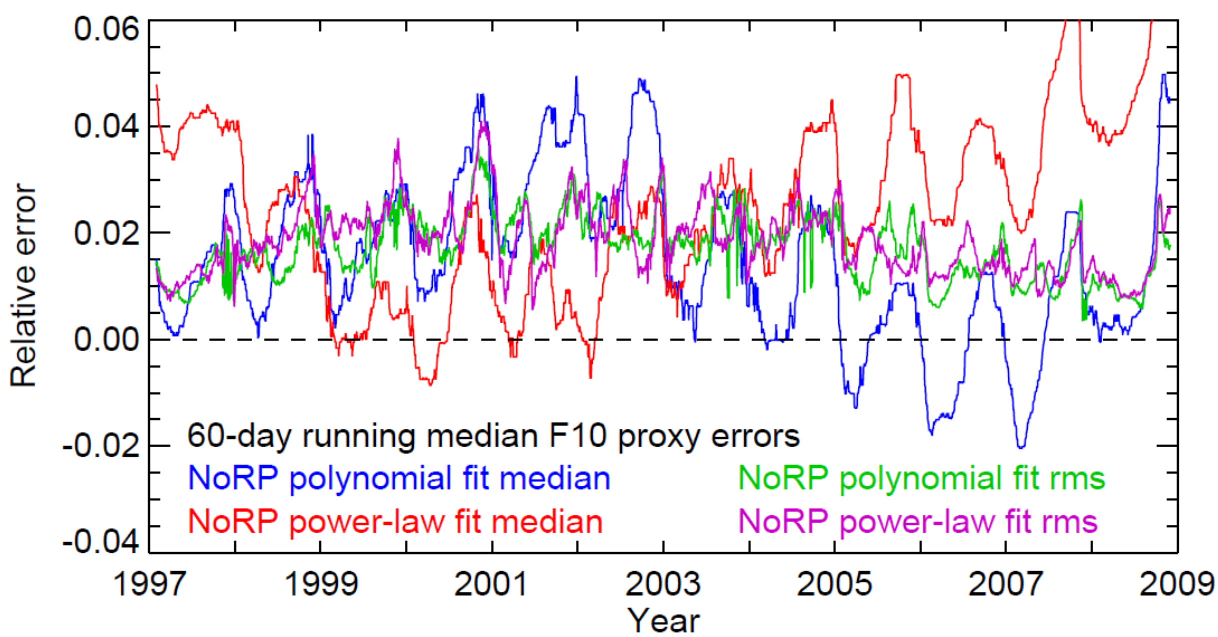

Figure 8. The 60-day running median of the relative error of the proxy, ($P_{2.8}$ − F10.7)/F10.7

F10.7 (with a spread of just a few percent). We assume that the consistent offset results from the fact that 2.0 and 3.75 GHz are well separated from 2.8 GHz and the spectral shape is not adequately represented by either a quadratic or a power law. However a 1-2% correction from the power– law fit will generally reproduce F10.7 to within a few percent. There is also a distinct annual modulation in the relative error that should not be present, and we have not identified the source of this. We do not pursue this line further here since NoRP only provides a single daily value, but conceivably NoRP data could help strengthen the method discussed in the next section.

4. RESULTS AND DISCUSSION

In this section we discuss what we believe to be the most realistic approach to using RSTN data to produce sub–day proxies for F10.7, i.e., values of F10.7 every 6 hours. Since 2.7 GHz is so close to the F10.7 measurement at 2.8 GHz, we use only the RSTN 2.7 GHz fluxes. The method needs to account for the differences in calibration between the different RSTN observatories, and correct for the slight frequency difference from the F10.7 measurement. The procedure we suggest is as follows:

- Separate the 2.7 GHz measurements from each RSTN observatory.
- Interpolate (using a spline fit) the daily 2.7 GHz measurements at each observatory to 20 UT, the time of the F10.7 measurement. (To avoid interpolation problems at the ends of the sequence, we add a day to the beginning and end of the sequence for the spline fit.)
- Take the ratio of F10.7 to this 20 UT 2.7 GHz value.
- Determine the median of this ratio over some period of time for each RSTN observatory separately.
- Use this median ratio at each observatory to scale all 2.7 GHz values over this period of time to 2.8 GHz. Since we have used actual F10.7 measurements for the scaling process, the RSTN proxies are on the same average calibration scale as F10.7 and will share any systematic errors that it may have.

We have chosen a 60–day period to demonstrate the suggested procedure. The period starts on 2002 July 11, and has quite a large variation over the 60 days. The RSTN 2.7 GHz measurements (plus symbols) as well as the F10.7 values for this period are shown in Figure 9. Clear systematic trends can be seen in the 2.7 GHz data: the Sagamore Hill measurements are consistently higher than the other RSTN sites, while the San Vito fluxes are consistently lower.

The description of the approach given above leaves one parameter unspecified: the interval used to determine the optimum relative scaling of F10.7 to the RSTN 2.7 GHz fluxes. This interval should be long enough to average over daily fluctuations, but short enough to follow trends in the scaling and track any jumps in the RSTN calibration such as those evident in Fig. 4. A very short scaling interval is probably not desirable from an operations perspective, since any missing data will likely cause problems. Here we compare scaling over 60–day and 10–day periods: thus, for the 10–day scaling 6 different factors are used corresponding to each 10–day period within the 60–day test interval. The results for the 60–day test interval in Fig. 9 are shown in Figure 10, which illustrates the results of the technique. The upper panels in the plot compare the scaled RSTN proxies $P_{2.8}$ at each observatory with the actual F10.7 value, while the lower panels show

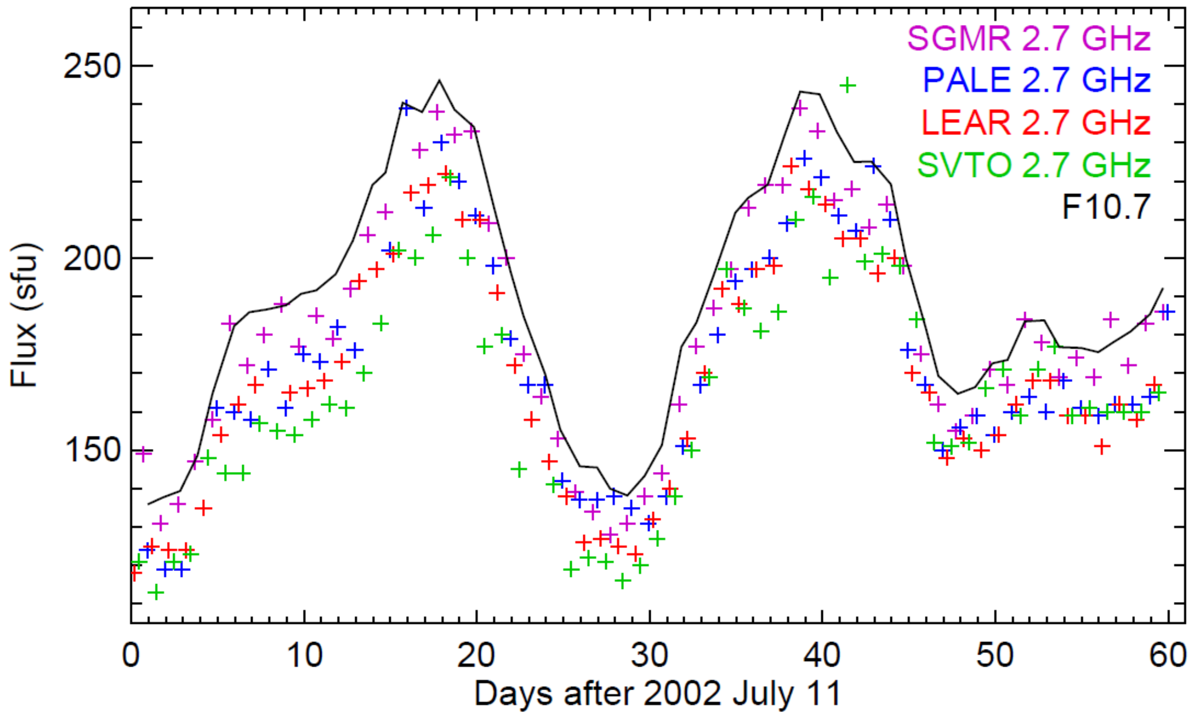

Figure 9. Comparison of 60 days of RSTN 2.7 GHz fluxes (symbols) with F10.7 (line)

the relative errors, ($P_{2.8}$ − F10.7)/F10.7. Note that the F10.7 values have been interpolated (using a spline fit) to the times of the RSTN observations for the error calculation. This plot indicates that the 10–day scaling generally does a better job of tracking F10.7, e.g. over the last 10 days the SVTO fluxes are relatively higher than earlier in the period and the 10–day scaling is able to bring them closer to the actual F10.7 values than the single 60–day scaling can.

The standard deviations of the relative errors in the RSTN proxies for each observatory over the 60–day test period are reported as percentages in Table 1. As a reference point, the standard deviation of the daily changes in the measured values of F10.7 for the same 60–day period was 5.1%. It can be seen that the different observatories do not all perform equally well, but errors around 3% are seen for three of the four RSTN observatories, with SVTO showing significantly more variation than the other observatories. At 3% errors, the 6–hour–cadence RSTN proxies may be valuable given that the errors are smaller than the day–to–day variation of F10.7.

Table 1. : RSTN proxies for F10.7: 60-day and 10-day errors

Error standard deviation (%)	SGMR	PALE	LEAR	SVTO	F10.7 daily variation
60 day scaling	3.3	3.8	2.4	6.8	5.1
10 day scaling	2.6	3.4	2.4	5.1	
10 day scaling 1997-2008	4.2	4.8	3.2	4.6	4.2
10 day scaling 1997-2008, outliers removed	1.9	1.6	1.9	2.3	2.7

We extend this result by calculating the 10–day–scaled proxies for the entire cycle 23. The result is shown in Figure 11, which plots over 4000 points for each RSTN observatory. The main point of this plot is to show the typical spread of each observatory about zero error, and periods of poor performance show up as repeating outliers (e.g., Palehua in 2000-2001 and SGMR in 2007-2008). The standard deviations of the errors over the entire cycle are reported in the third line of Table 1: over the entire cycle the spread in errors is larger than in the 60–day test period, being 4-5% for three of the RSTN observatories while Learmonth does better at 3%. Over the cycle, the measured changes in F10.7 from day to day had a standard deviation of 4%, i.e., about the same as the error in the RSTN proxies. At this threshold it becomes questionable as to whether the proxies offer an improvement for the purposes of modelling. However, from Fig. 11, a lot of the spread in the RSTN proxy values results from outlier values that obviously should not be included. If we remove those from the calculation of the RMS error and fit a Gaussian to the resulting distribution of errors, we obtains the results in the final line of Table 1, i.e., errors of order 2%. However, removing the "outliers" from the day–to–day variation of F10.7 (which are valid data) also brings its RMS down considerably.

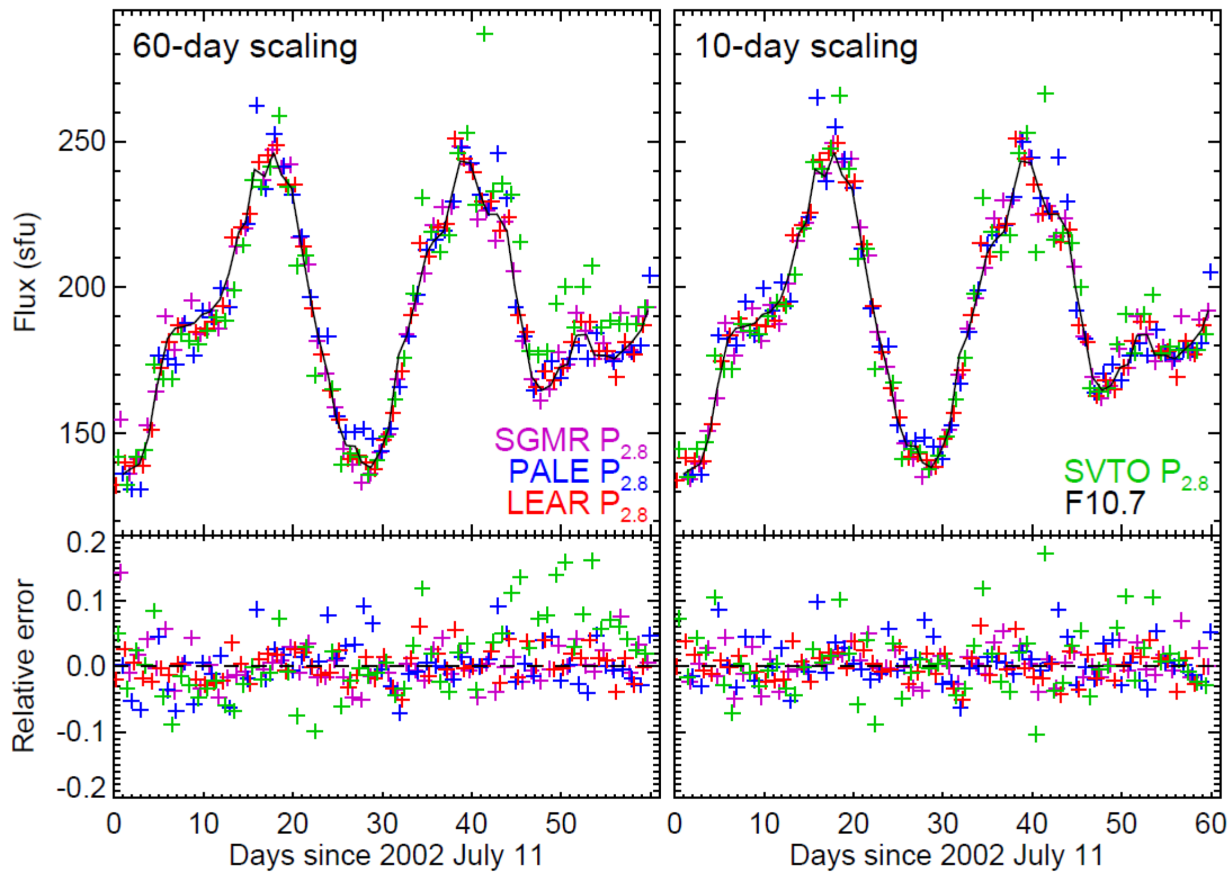

Figure 10. RSTN F10.7 proxies (symbols) and F10.7 (line) for 2 scaling intervals

5. CONCLUSIONS

We have demonstrated that by applying scaling techniques to address calibration drifts in the individual RSTN observatories, it is possible to generate F10.7 proxies at a 6-hour cadence that should track time variability with a modest improvement over the variability of daily F10.7 measurements. If implemented, this method could be used operationally as follows: on a daily basis the scaling is carried out for the previous 10 days of data from each RSTN observatory, using the corresponding F10.7 values. That scaling is then applied to the RSTN local–noon measurements taken over the following 24 hours in real time, and those values would constitute the RSTN real– time proxy with a cadence of 6 hours. If desired, higher cadence can be explored utilizing averages of the real–time 1-second measurements taken by RSTN.

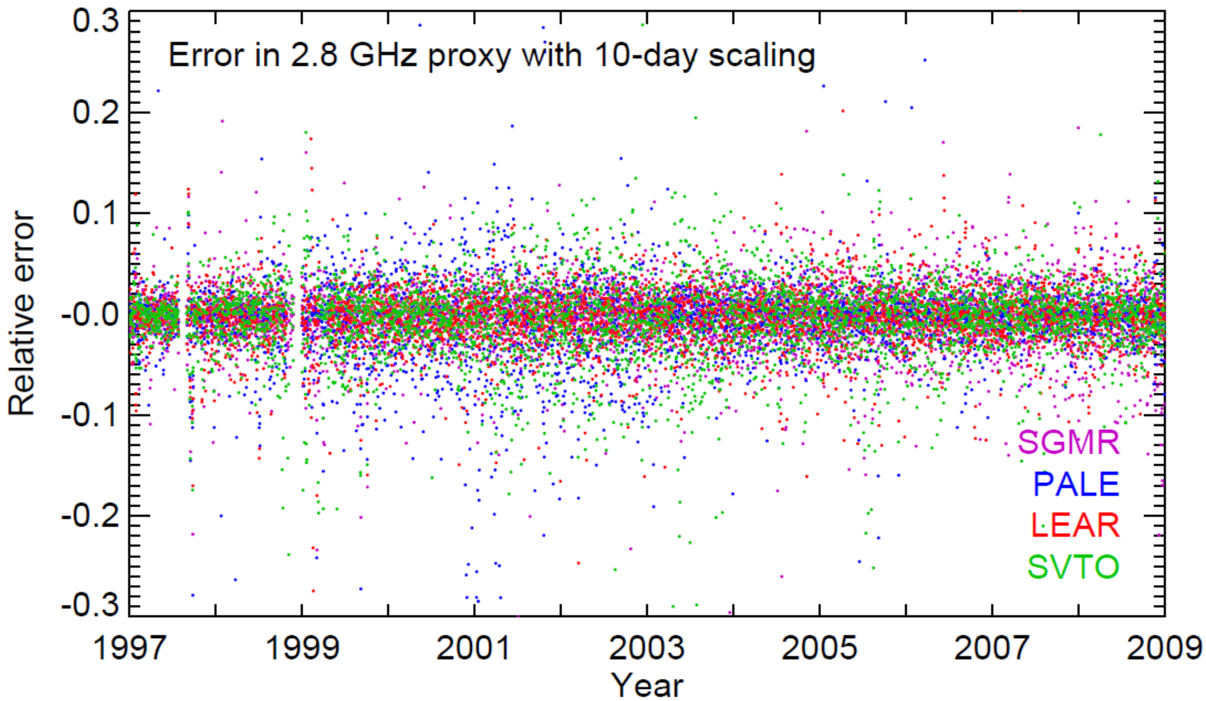

Figure 11. Errors in the 10-day scaled RSTN F10.7 proxies for Cycle 23

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APPENDIX: Data Sources

The data used here may be obtained from the following sources:

- The RSTN noon fluxes have traditionally been archived by the National Geophysical Data Center (NGDC) at ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/ solar-features/solar-radio/noontime-flux/. However, NGDC ceased storing the RSTN daily fluxes at the end of February 2011, although they continue to store other RSTN data. The RSTN noon fluxes continue to be reported daily by the Space Weather Prediction Service (SWPC) in their "Current Space Weather Indices" product (ftp://ftp.swpc.noaa.gov/pub/latest/curind.txt) and their "Solar Radio Data" product (ftp://ftp.swpc.noaa.gov/pub/lists/radio/rad.txt). However these products are not archived, so it is unlikely that we have a continuous record of the RSTN noon fluxes since 2011.

- The F10.7 measurements are made under the Solar Radio Monitoring Program operated jointly by the National Research Council Canada and Natural Resources Canada with support from the Canadian Space Agency. Daily and archived data are available at http://spaceweather.gc.ca/solarflux/sx-en.php and ftp://ftp.geolab.nrcan.gc.ca/data/solar flux/daily flux values/.

- The Nobeyama polarimeters are operated by the National Astronomy Observatory of Japan. The data are archived daily at the ftp site ftp://solar-pub.nao.ac.jp/pub/nsro/norp/xdr/.

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