atmosphere

MDPI

Technical Note

Calibration Accuracy of the Dual-Polarization Receivers of the C-Band Swiss Weather Radar Network

Marco Gabella *, Marco Boscacci, Maurizio Sartori and Urs Germann

MeteoSwiss, via ai Monti 146, Locarno-Monti CH-6605, Switzerland; marco.boscacci@meteoswiss.ch (M.B.); maurizio.sartori@meteoswiss.ch (M.S.); urs.germann@meteoswiss.ch (U.G.)

* Correspondence: marco.gabella@meteoswiss.ch; Tel.: +41-58-460-9692; Fax: +41-58-460-9002

Academic Editor: Guifu Zhang
Received: 18 March 2016; Accepted: 24 May 2016; Published: 31 May 2016

Abstract: The electromagnetic power that comes from the Sun has been proved to be an effective reference for checking the quality of dual-polarization weather radar receiver. Operational monitoring methods have been developed and implemented for determining the electromagnetic antenna pointing, assessing the receiver stability, and the differential reflectivity offset. So far, the focus has been on relative calibration: horizontal and vertical polarization have been mutually compared and evaluated *versus* the reference mainly in terms of standard deviation of the error. Radar receivers have been able to capture and describe the monthly variability (slowly varying component) of the microwave signal emitted by the Sun. In this paper, we present results from a novel Sun-based method aiming at the absolute calibration of dual-polarization weather radar receivers. To obtain best results, the radar receiver has to be off-line for a few minutes during the tracking of the Sun in order to have the antenna beam axis pointing at the center of the Sun. Among the five polarimetric weather radar receivers of the Swiss network, radar "WEI" located at an altitude of 2850 m next to Davos shows the best absolute agreement with the Dominion Radio Astrophysical Observatory (DRAO) reference for both horizontal (H) and vertical (V) polarization. Albis radar, which is located at an altitude of 938 m near Zurich, shows the largest difference: the radar receiver is too low compared to the Sun reference by −1.62 (−1.25) dB for the H (V) channel. Interestingly, the standard deviation of the error is smaller than ±0.17 dB for all Swiss radar receivers. With a standard deviation of ±0.04 dB Albis radar shows the best relative agreement between H and V. These results are encouraging and MeteoSwiss is planning to repeat off-line Sun-tracking measurements in the future on a regular basis.

Keywords: weather radar receivers; monitoring; absolute calibration; dual-polarization; quiet solar emission

1. Introduction

The electromagnetic power that comes from the Sun has been proved to be an effective reference for checking the quality of dual-polarization weather radar receivers. Operational monitoring methods have been developed and implemented for determining the electromagnetic antenna pointing [1], assessing the receiver stability [2], and the differential reflectivity offset [3]; results from such methods were successfully applied, at first during a period of quiet solar flux activity (in 2008), subsequently to the currently active Sun period [4]. The ten C-band radar receivers analyzed in Finland, Switzerland, and the Netherlands were able to capture and describe the monthly variability of the Sun microwave signal [5].

So far, the focus has been on relative calibration: C-band horizontal and vertical polarization signals have been mutually compared and evaluated *versus* the reference S-band signal mainly in terms of standard deviation of the difference between radar-retrieved and reference flux values in solar flux units (SFUs), where 1 SFU is equal to 10^{-22} W·m^{-2}·Hz^{-1}. The S-band solar flux measurements distributed by the Dominion Radio Astrophysical Observatory (DRAO) of the National Research Council of Canada provide a useful reference for weather radar receivers. Such measurements, precisely acquired three times per day, are consistent and accurate; furthermore, the same source can be observed simultaneously over a large area. A problem encountered with C-band radar receivers is the frequency conversion from 10.7 to 5.5 cm. Section 5 of the paper by Tapping [6] provides a simple conversion formula that allows one to overcome such a problem. In particular, we use the coefficients presented in Equation (1) of [4], which are tailored to the Swiss frequency band (5430–5470 MHz). In this paper, we present results focusing on absolute calibration of vertical and horizontal polarization receivers. In other words, we also put emphasis on the absolute difference (bias) between the log-transformed radar-retrieved value and the reference value accurately measured by the DRAO.

Such absolute calibration results are obtained thanks to a convenient and effective method recently presented in [7]. The method is complementary to the on-line technique that automatically detects and analyzes Sun signals stored in the polar volume radar reflectivity data acquired during the operational weather scan program [1–4]. Such a technique, which allows relative calibration and mutual inter-comparison between vertical and horizontal channels, has the great advantage of requiring no interruption of the weather surveillance. On the contrary, the method here applied and presented in [7] tackles the absolute calibration of the receiver by pointing the antenna beam axis towards the center of the Sun; hence, it requires that the weather radar be off-line for a few minutes during such a special purpose scan. This idea has been applied many times in radio astronomy. In radar meteorology, it was developed in the late 1970s by Frush and Lewis at the National Center for Atmospheric Research, preliminarily presented in 1984 [8] and thoroughly described by Pratte and Ferraro in 1989 [9]. Subsequently, Pratte, Ferraro and Keeler have further extended it and eventually transferred to Nexrad (USA) where Ice and colleagues developed it for use with the WSR-88D [10].

The method has been applied to the five weather radar receivers of the recently renewed Swiss weather radar network. As described in [7], radar observations of the solar signal are performed only in fair weather conditions. In this way, wet-radome attenuation and attenuation along the path are avoided. Section 2 briefly presents the operational Swiss weather radar receivers, the acquired and reference data, as well as the formula for the retrieval. Results are given in Section 3 for the ten dual-polarization receivers of the Swiss weather radar network: a set of 27 observations by the five radar receivers is presented. A detailed discussion and interpretation of the results is presented in Section 4. A summary, conclusions, and an outlook are provided in the last section.

2. Description of Instruments, Acquired Data, and Retrieval Formula

In recent years, MeteoSwiss has renewed its weather radar network with an innovative, state-of-the-art solution. From 2011 to 2015, five new polarimetric systems have been installed. Fully digital, antenna-mounted receivers, which are capable of simultaneously measuring vertical and horizontal linear polarization components, have been introduced. With respect to the conventional solution, where the receivers are installed next to the transmitter inside the technical room, this system architecture does not require the installation of a dual channel rotary joint, which may introduce differential errors in amplitude and phase; it also provides a significant reduction of Rx-losses. Another key aspect of the Swiss weather radar receivers is the use of a stable, white signal generated by a noise source (NS) as an absolute reference for the calibration of the radar Rx. Every 5 min, which is the time required to accomplish a full-volume in the 20-elevation Swiss scan program [11], the NS reference signal (NS_{ref}, around −90 dBm) is injected into the Rx front-end (input of the LNA) and the corresponding log-transformed value in analog-to-digital-Units (ADUs) at the output of the A/D converter is read, NS_{out}. In this way, the factor for the transformation from dBADU to dBm of any received signal is known and updated every 5 min [12].

The Dominion Radio Astrophysical Observatory (DRAO) is located at a site near Penticton (British Columbia, Canada), which is characterized by low interference levels at decimeter and centimeter wavelengths. Accurate observations of the daily solar flux have been performed since 1946; they are acquired three times per day at 10.7 cm, which is the wavelength where the slowly varying solar component is more significant compared to the quiet radio flux [13]. The 10.7-cm solar flux measurements can be converted into other radio frequencies with some bias uncertainty. This is possible thanks to the remarkable stability of the spectrum of the slowly varying component of solar activity. As stated in the introduction, for the conversion from 10.7 cm to 5.5 cm, we used the formula listed in [6] with the coefficients presented in Equation (1) of [4]. For the set of measurements presented in this paper (a total of 17 days from 2 November 2013 until 22 March 2016), we have, on the one hand, checked that the spectral component was not distorted by contributions from flares or other events having spectra and variability with time that are a function of frequency, but, on the other hand, pointed the radar antennas toward the Sun in days close to the Sun minima. During active periods (*i.e.*, the last few years), in fact, the number of active regions (Sun spots) that enhance the radio emission with respect to the quiet component, as seen from the Earth, varies because of the Sun's rotation around its axis. This result is an oscillation with an amplitude of a couple of decibels and a period of ~27 days. For instance, using the above cited Equation (1), in 2014, the min/max values (excluding solar flares) at 5.5 cm were around 21.3 and 23.5 dBsfu; in 2015, they were around 21.0 and 22.7 dBsfu. Note that, in Equation (1), the quiet Sun emission is assumed to be 113 sfu (*i.e.*, 20.53 dBsfu). Note also that, in this paper, we will use log-transformed values of solar flux units (spectral irradiances) coming from the Sun: $S = 10\log(s/S_0)$, where $S_0 = 10^{-19}$ mW·m^{-2}·Hz^{-1} and $[S]$ = dBsfu.

Finally, we need a way to transform the observed Sun signal at the output of the receiver A/D converter, S_{out} ($[S_{out}]$ = dBADU), into equivalent spectral irradiance at 5.5 cm, incident on the radome and subsequently on the antenna, $I_{5.5}$, where $[I_{5.5}]$ = dBsfu. This transformation is conceptually done in three steps that are thoroughly described in Section 2 of [7]. For the sake of brevity, we only list an overall transformation formula, which results from the three equations presented in [7]:

$$I_{5.5} = S_{out} + NS_{ref} - NS_{out} + 193.5\,\mathrm{dB} - B_{dBHz} + L_{Rx} + 10\log(4\pi/\lambda^2) - G_{dB} \quad (1)$$

where G_{dB} is the radar antenna gain in dB; L_{Rx} represents the overall receiver insertion losses (including radome); λ is the wavelength in meter; and $B_{dBHz} = 10\log(BW)$, where the bandwidth (BW) is in Hz. The number 193.5 dB reflects two deterministic factors and a problematic one: 193 is simply because the Sun radiation is unpolarized (3 dB) and 1 sfu = 10^{-19} mW·m^{-2}·Hz^{-1} (190 dB). The additional 0.5 dB is an estimate (hence characterized by some uncertainty) of the "additional losses" due to the fact the Sun is not a point source for the highly directive weather radar antennas. The apparent diameter of the radio Sun (~0.57°) is not negligible with respect to the half power beam width of the weather radar antenna (1.0°); consequently, the solar disc is not detected with a constant antenna gain so that the contribution of outer areas of the disc are underestimated, with respect to the center (see [7] for a detailed discussion). For all five MeteoSwiss radar receivers, we used $\lambda = 0.055$ m and BW = 2.52 MHz (see [14] for details). This means that the 5th and 7th terms on the right-hand side of Equation (1) are 64.01 dBHz and 36.18 dBm^{-2}, respectively. Regarding the two dimensionless terms in Equation (1)—L_{Rx} and G_{dB}—the values are listed in Table 1 for both polarization and each Swiss radar. Antenna gain was measured at the manufacturer test range, while Rx losses were measured at the site during the site acceptance tests.

Table 1. Overall receiver losses (1st line) and antenna gain (last line) of the five MeteoSwiss radar receivers.

Weissfluhgipfel		*Monte Lema*		Albis		*La Dole*		*P. de la Plaine Morte*	
H	V	H	V	H	V	H	V	H	V
2.5 dB	2.7 dB	2.6 dB	2.15 dB	2.25 dB	2.4 dB	2.7 dB	2.8 dB	2.25 dB	2.55 dB
44.8 dB	45.0 dB	45.0 dB	45.0 dB	45.2 dB	45.0 dB	45.0 dB	45.1 dB	44.6 dB	44.7 dB

3. Results

This section presents results observed so far by comparing the estimates derived by the five stations of the latest Swiss weather radar generation with the DRAO reference. In summer, DRAO takes measurements of the Sun at 17, 20, and 23 UTC, corresponding to 9, 12, and 15 solar time. In winter, the times are slightly shifted due to low sun angles and hilly terrain, and measurements are taken at 10, 12, and 14 solar time. For each day presented in this section, the reference is derived by averaging the five closest-in-time DRAO values; it is worth noting that the variability of these five values is so small that the use of a decibel scale with two digits after the decimal point renders the "log of the mean" indistinguishable from the "mean of the log" in all the analyzed days. Such a two-digit average of DRAO flux values is expressed in dBsfu in the second column of Tables 2–6 and called "DRAO Reference". These are followed by a three-digit standard deviation, calculated using the 5 values on a logarithmic scale.

3.1. Weissfluhgipfel (WEI) Radar at an Altitude of 2850 m in Grisons (Next to Davos)

The WEI radar is the fifth and most recent dual-polarization system installed in Switzerland. It is located next to Davos on the top of the *Weissfluhgipfel* (lat.: 46.2843°; long.: 8.5120°) at an altitude of 2850 m. During the site acceptance tests of the WEI system in autumn 2015, we were able to perform seven sun-tracking observations during six days (from 14 to 22 October, close to a Sun relative minimum). Two additional ones were acquired on 22 February and 21 March 2016, also close to a relative minimum. Results are listed in Table 2. Taking the average in logarithmic units, the mean solar flux from DRAO measurements is 21.64 ± 0.30 dBsfu. As expected, the dispersion associated with the radar-retrieved values is slightly larger, that is, ±0.37 (0.32) dB for H (V).

Table 2. Solar flux values from nine Sun-tracking observations at the 2850-m WEI site in Grisons and corresponding nearest-in-time reference values by the Dominion Radio Astrophysical Observatory.

Date	DRAO Reference	$I_{5.5}$ Rx H	$I_{5.5}$ Rx V	10 log (H/V)	10 log (H/DRAO)	10 log (V/DRAO)
14 October 2015	21.40 ± 0.067	21.15	20.96	0.19 dB	−0.25 dB	−0.44 dB
15 October 2015	21.51 ± 0.074	21.50	21.26	0.24 dB	−0.01 dB	−0.25 dB
17 October 2015	21.71 ± 0.084	21.85	21.51	0.34 dB	+0.14 dB	−0.20 dB
20 October 2015	21.92 ± 0.009	21.75	21.66	0.09 dB	−0.17 dB	−0.26 dB
21 October 2015	21.95 ± 0.060	21.90	21.76	0.14 dB	−0.05 dB	−0.19 dB
22 October 2015	21.90 ± 0.075	21.95	21.71	0.24 dB	+0.05 dB	−0.19 dB
22 October 2015	21.90 ± 0.075	21.85	21.61	0.24 dB	−0.05 dB	−0.29 dB
22 February 2016	21.30 ± 0.024	21.25	21.21	0.04 dB	−0.05 dB	−0.09 dB
21 March 2016	21.16 ± 0.017	20.95	20.91	0.04 dB	−0.21 dB	−0.25 dB
Average	21.64	21.57	21.40	+0.17	−0.07	−0.24
Standard dev.	±0.30	±0.37	±0.32	±0.10	±0.13	±0.10

In absolute terms, the average value obtained by the radar H (V) channel is −0.07 (−0.24) dB smaller. The difference between the two channels corresponds to an average mutual bias between H and V equal to +0.17 ± 0.10 dB. DRAO values are corrected for atmospheric attenuation, whereas no correction is applied for the values retrieved from the radar. At an altitude of 3000 m, clear sky gaseous attenuation at zenith is in the order of 0.1 dB. This fact, once properly modeled and taken into account, will reduce the negative bias of both radar channels. It is also worth noting that the measured signal S_{out} is actually the sum of the Sun power plus the system noise, which is of the order of 9 dB smaller than the total S_{out}; we will see in Section 4 that the subtraction of this system noise causes a reduction of *ca.* 0.5 dB of the retrieved values of $I_{5.5}$.

3.2. Monte Lema (Near Lugano) Radar at an Altitude of 1626 m

The *Monte Lema* radar (lat.: 46.0408°; long.: 8.8332°) is located at an altitude of 1626 m near Lugano. Six Sun-tracking observations are available so far: the corresponding values are listed in Table 3. The average solar flux of these five different days is 21.98 ± 0.50 dBsfu. As expected, the dispersion associated with the radar-retrieved values is larger: ±0.52 (±0.54) dB for the horizontal (vertical) polarization. In absolute terms, the retrieved average value by means of the radar H (V) channel is –0.18 (−0.27) dB smaller, which corresponds to an average mutual bias between H and V equal to +0.09 dB. Similarly to radar WEI, Lema also shows a small underestimation. For a more accurate estimate, we have to subtract the noise component from the Sun signal (Section 4) and eventually compensate for clear sky atmospheric attenuation.

Table 3. Solar flux values from six Sun-tracking observations at the *Monte Lema* site (near Lugano) and corresponding nearest-in-time reference values by the DRAO in Canada.

Date	DRAO Reference	$I_{5.5}$ Rx H	$I_{5.5}$ Rx V	10 log (H/V)	10 log (H/DRAO)	10 log (V/DRAO)
2 November 2013	22.34 ± 0.079	22.32	22.17	0.15 dB	−0.02 dB	−0.17 dB
29 April 2014	21.88 ± 0.037	21.52	21.37	0.15 dB	−0.36 dB	−0.51 dB
7 August 2014	22.17 ± 0.039	21.97	21.87	0.10 dB	−0.20 dB	−0.30 dB
28 January 2015	22.56 ± 0.039	22.32	22.37	−0.05 dB	−0.24 dB	−0.19 dB
7 April 2015	21.76 ± 0.125	21.67	21.57	0.10 dB	−0.09 dB	−0.19 dB
21 March 2016	21.16 ± 0.017	20.98	20.90	0.08 dB	−0.18 dB	−0.26 dB
Average	21.98	21.80	21.71	+0.09	−0.18	−0.27
Standard dev.	±0.50	±0.52	±0.54	±0.07	±0.12	±0.13

3.3. Albis (Near Zurich) Radar at an Altitude of 938 m

The Albis radar is located near Zurich (lat.: 46.2843°; long.: 8.5120°) at an altitude of 938 m. Six Sun-tracking observations (see Table 4) are available so far for the absolute calibration of the horizontal and vertical receivers. On a logarithmic scale, the average solar flux from DRAO measurements is 21.97 ± 0.58 dBsfu. As expected, the dispersion associated with the radar-retrieved values is larger (±0.65 dB, approximately). In absolute terms, the average obtained from the radar H (V) channel is −1.13 (−0.75) dB smaller; this corresponds to an average mutual bias between H and V equal to −0.38 dB. The issue of differential reflectivity calibration is crucial for the successful application of polarimetric weather radar. Whether a small average offset such as +0.09 dB observed for Lema, or +0.17 dB observed for WEI, should be compensated or not, is debatable. For sure, one has to investigate and eventually correct the −0.38 dB mutual bias of Albis, especially considering the small standard deviation of ±0.04 dB among the seven measurements.

Table 4. Solar flux values from seven Sun-tracking observations at the Albis site (near Zurich) and corresponding nearest-in-time reference values by the DRAO in Canada.

Date	**DRAO Reference**	**$I_{5.5}$ Rx H**	**$I_{5.5}$ Rx V**	**10 log (H/V)**	**10 log (H/DRAO)**	**10 log (V/DRAO)**
2 November 2013	22.34 ± 0.079	21.27	21.67	−0.40 dB	−1.07 dB	−0.67 dB
2 April 2014	22.51 ± 0.070	21.57	21.92	−0.35 dB	−0.94 dB	−0.59 dB
6 August 2014	22.19 ± 0.031	20.97	21.37	−0.40 dB	−1.22 dB	−0.82 dB
28 January 2015	22.56 ± 0.039	21.47	21.87	−0.40 dB	−1.09 dB	−0.69 dB
7 April 2015	21.76 ± 0.125	20.47	20.87	−0.40 dB	−1.29 dB	−0.89 dB
28 May 2015	21.28 ± 0.021	20.07	20.47	−0.40 dB	−1.21 dB	−0.81 dB
21 March 2016	21.16 ± 0.017	20.07	20.37	−0.30 dB	−1.09 dB	−0.79 dB
Average	21.97	20.84	21.22	−0.38	−1.13	−0.75
Standard dev.	±0.58	±0.64	±0.65	±0.04	±0.12	±0.10

3.4. La Dole (Near Geneva) Radar at an Altitude of 1682 m

The *La Dole* (lat.: 46.4251°; long.: 6.0995°) radar is located at an altitude of 1681 m near Geneva. Out of the seven Sun-tracking measurements, only two are reliable: both were taken in 2015, on the same days as Albis and Lema (Table 5). The remaining measurements at the *La Dole* site cannot be used due to the presence of parasitic noise.

Table 5. Solar flux values from two Sun-tracking observations at the *La Dole* site (near Geneva) and corresponding nearest-in-time reference value by the DRAO in Canada.

Date	**DRAO Reference**	**$I_{5.5}$ Rx H**	**$I_{5.5}$ Rx V**	**10 log (H/V)**	**10 log (H/DRAO)**	**10 log (V/DRAO)**
28 January 2015	22.56 ± 0.039	22.24	22.04	0.20 dB	−0.32 dB	−0.52 dB
7 April 2015	21.76 ± 0.125	21.59	21.54	0.05 dB	−0.17 dB	−0.22 dB
Average	22.10	21.91	21.79	0.13	−0.19	−0.31

3.5. Pointe de la Plaine Morte (PPM) Radar at an Altitude of 2937 m in Valais (Next to Crans-Montana)

The PPM (lat.: 46.3706°; long.: 7.4863°) radar is located at an altitude of 2937 m. Three observations are available after the exchange of the calibration unit in June 2015. The corresponding values listed in Table 6 present promising results in terms of reproducibility. However, it is obvious that three observations is a small sample. Additional observations will be collected in order to acquire a more reliable assessment regarding the absolute calibration of PPM.

Table 6. Solar flux values from three Sun-tracking observations at the PPM site (next to Crans Montana) and corresponding nearest-in-time reference values by the DRAO in Canada.

Date	**DRAO Reference**	**$I_{5.5}$ Rx H**	**$I_{5.5}$ Rx V**	**10 log (H/V)**	**10 log (H/DRAO)**	**10 log (V/DRAO)**
22 February 2016	21.30 ± 0.024	21.50	21.55	−0.05 dB	+0.20 dB	+0.25 dB
14 March 2016	21.27 ± 0.024	21.50	21.65	−0.15 dB	+0.23 dB	+0.38 dB
22 March 2016	21.14 ± 0.023	21.05	21.50	−0.45 dB	−0.09 dB	+0.36 dB
Average	21.24	21.35	21.57	−0.22	+0.11	+0.33
St. Deviation	±0.09	±0.18	±0.07	±0.21	±0.18	±0.07

4. Discussion of the Results Including a Preliminary Attempt of Noise Subtraction

As previously stated, our radar-retrieved estimates of solar flux can be improved in two directions, which are characterized by opposite signs: (1) on the one hand, the retrieved estimates are slightly low because atmospheric attenuation is neglected; (2) on the other hand, the retrieved estimates are somewhat too high because of the contamination of receiver noise, which is not negligible compared to the solar signal.

Total clear sky atmospheric attenuation at the zenith is 0.076 (0.060) dB at an altitude of 1000 (3000) m—this by assuming a one-way attenuation value of 0.01 dB/km at sea level, and an equivalent atmospheric height of 8.5 km. For the typical angles of elevation used during sun-tracking, and assuming a flat atmosphere, this produces attenuation values between 0.12 dB and 0.18 dB for Albis and between 0.1 dB and 0.14 dB for WEI. Regarding noise subtraction, since the log-transformed ratio of sun to noise (*i.e.*, the measured quantity) divided by noise is of the order of 9 dB, the typical reduction of the retrieved solar flux is about 0.5 dB smaller than the one presented in Section 3. Adding up, between these two second-order effects, noise subtraction is more influent than the atmospheric correction. Hence, we will attempt noise subtraction on the 22 observations coming from WEI, *Monte Lema*, and Albis. Results are presented and discussed below.

The Swiss radar receivers operationally measure system noise every 2.5 min at angles of elevation of 35° and 40°, respectively. The noise measurements are taken between 60 and 70 km, integrating 120 range bins and 420 pulses within a 10° sector in azimuth. Each noise measurement is thus the average of 120 × 420 = 50,400 raw measurements. We then combine 20 noise measurements, keeping the median out of the 20 values as representative of the noise floor. This is done for both channels separately. In the present example, we use the observed noise value at 40° elevation, N_{EL40} (namely, the last one before the Sun-tracking started), and subtract it from the observed value, S_{out} (both obviously in linear ADU). The observed value consists of the solar flux, plus an "unknown" noise component. In formula: $S_{out} = S_{Sun} + N_{unknown}$. Our estimate after noise subtraction, simply consists of subtracting the nearest-in-time observed value of N from the S values listed in Section 3. Table 7 shows that noise subtraction results in an average decrease of approximately 0.5 dB.

Table 7. Agreement between radar estimates (without and with noise subtraction) and the DRAO reference in terms of average error (Log-transformed values) for both polarization channels.

Average Error between Radar and DRAO Reference	Albis		*Monte Lema*		*Weissfluhgipfel*	
	H	V	H	V	H	V
$S_{Sun} + N_{unknown}$ (as per Section 3)	−1.13 dB	−0.75 dB	−0.18 dB	−0.27 dB	−0.07 dB	−0.24 dB
$S_{Sun} + N_{unknown} - N_{EL40}$	−1.62 dB	−1.25 dB	−0.67 dB	−0.76 dB	−0.58 dB	−0.77 dB

An important question: Does this kind of noise subtraction improve the agreement between the weather radar and DRAO? As can be seen in Table 8, there is no improvement in terms of standard deviation of the error. However, one can also ask whether the agreement improves in terms of correlation and for this purpose. Table 9 shows the percentage of explained variance (100 times the square of the correlation coefficient) for both polarizations of Albis, Lema, and WEI. It is worth noting that the number of samples is so small that the degrees of freedom are only 5 (Albis), 4 (*Monte Lema*), and 7 (WEI). Noise subtraction increases the correlation for both channels of WEI and Albis. For *Monte Lema*, the correlation slightly decreases. We conclude that the median-observed noise at angles of elevation of 40° is not always representative for the real (unknown) noise affecting the Sun signal measurement during the off-line Sun-tracking. For future sun-tracking experiments, we plan to use noise samples as close as possible to the sun signal, both in space and time.

Table 8. Same as in Table 7, but in terms of dispersion of the error (Log-transformed values).

Standard Deviation of the Error between Radar and DRAO Reference	**Albis**		***Monte Lema***		***Weissfluhgipfel***	
	H	**V**	**H**	**V**	**H**	**V**
S_{Sun} + $N_{unknown}$ (as per Section 3)	0.12 dB	0.10 dB	0.12 dB	0.13 dB	0.13 dB	0.10 dB
S_{Sun} + $N_{unknown}$ − N_{EL40}	0.16 dB	0.17 dB	0.15 dB	0.18 dB	0.16 dB	0.12 dB

Table 9. Agreement between the estimates of three MeteoSwiss radar receivers and the DRAO reference (Log-transformed values) in terms of percentage of explained variance before and after noise subtraction.

% of Explained Variance between Radar and DRAO Reference	**Albis**		***Monte Lema***		***Weissfluhgipfel***	
	H	**V**	**H**	**V**	**H**	**V**
S_{Sun} + $N_{unknown}$	97.3%	98.6%	94.8%	94.8%	90.6%	91.4%
S_{Sun} + $N_{unknown}$ − N_{EL40}	97.8%	98.7%	94.7%	94.4%	91.7%	91.7%

5. Summary, Conclusions, and Outlook

An effective method for the absolute calibration of vertical and horizontal polarization radar receivers has been applied to the five dual-polarization radar receivers of Switzerland. Five observations are available for two radar receivers (*La Dole* and PPM); for the other three radar receivers, a total of 22 observations are available.

Regarding the absolute error, which is related to the absolute radar calibration, WEI and *Monte Lema* show the best results, *La Dole* and PPM show intermediate results, while Albis shows an underestimation of approximately −1.62 (−1.25) dB for the horizontal (vertical) channel (including noise subtraction but neglecting clear sky attenuation). The standard deviation of such an error in terms of stability is better than ±0.18 dB for both channels of Albis, Lema, and WEI. For *La Dole* and PPM, the sample is too small to calculate the standard deviation. It is interesting to compare these results obtained during solar relative minima and Sun-tracking with those obtained by the operational, automatic method for the continuous monitoring of weather radar receivers through the comparison of daily radar-derived solar flux values with the DRAO reference [2–4]. Using such a different technique for more than two hundred days in 2014, the standard deviation of the error of the horizontal channel of Albis (*Monte Lema*) was, as expected, much larger than with this Sun-tracking method: ±0.35 (±0.48) dB (see Table 2 in [4]). By restricting the analysis to 100 days (see Table 4 in [5]), the standard deviation of the error results is smaller: ±0.26 (±0.34) dB for Albis (*Monte Lema*), which is still considerably larger than with the Sun-tracking method. Similar results are obtained if we consider other C-band radar receivers in Europe: for the same 100-day period, the standard deviation of the error was ±0.26 dB for the Dutch Den Helder radar and ±0.36 dB for the Finnish Anjalankoski (ANJ) radar. When comparing the figures of the Swiss radar receivers with those from the Dutch and Finnish radar receivers, it is worth noting that the MeteoSwiss operational algorithm is based on the median of the strongest 21 daily hits, while the others are based on a full five-parameter linear model fit to both polarization channels separately. Not surprisingly, the 22 Swiss observations using Sun-tracking and avoiding solar relative maxima show a considerably smaller standard deviation of the error: better than ±0.16 dB for the horizontal channels of Albis, Lema, and WEI.

The correlation between radar estimates and the DRAO reference is also significant (see Table 9 in the previous section). For Albis and WEI, it increases after the noise subtraction.

The method shows stability not only of the absolute error between the radar and the DRAO reference, but also in terms of the difference between the vertical and horizontal channels: for WEI, the average of 9 values of 10 log(H/V) is ~0.2 dB with ±0.1 dB standard deviation. For *Monte Lema* (6 values), it is ~0.1 dB with ±0.08 dB standard deviation. For Albis (7 values), the standard deviation is as small as ±0.04 dB. It is interesting to compare this very small dispersion of the difference between

H and V with the one obtained using the operational method [2–4] for daily monitoring: during 220 (204) days in 2014, it was ±0.05 (±0.06) dB, as can be seen in Table 4 in [4]; during the same set of 100 days in 2014, the dispersion of the difference between H and V was 0.06 dB for Albis and 0.08 dB for ANJ (see Table 3 in [5]). In a recent manuscript that reviews several aspects of the monitoring of dual-polarization receiver using solar hits found in operational scans [15], a dispersion as low as 0.02 dB was found for the Finnish ANJ and LUO radar. These figures refer to a shorter period: April 2015. During that month, the standard deviation was 0.03 (0.04) dB for the KES (KOR) radar.

In summary, the results obtained so far are promising and MeteoSwiss is planning to repeat off-line Sun-tracking observations on a regular basis. We aim at the alignment of all ten radar receivers by the end of 2016 after having acquired more samples and further evaluated the effect of noise subtraction and eventually atmospheric correction.

Acknowledgments: The authors would like to thank Peter Goelz, Dennis Vollbracht, and Andreas Leuenberger for stimulating discussions and helpful hints regarding radar measurements of the solar spectral irradiance. The Sun-tracking software has been implemented by Scott Harper, Eldes (Firenze, Italy). The daily solar flux values were freely provided by the Dominion Radio Astrophysical Observatory (DRAO) of the National Research Council of Canada. The valuable comments from three anonymous reviewers are highly appreciated.

Author Contributions: Marco Gabella conceived the experiment and designed it together with Maurizio Sartori and Marco Boscacci. Marco Boscacci thoroughly checked the Eldes code and run most of the listed Sun-tracking. Marco Gabella analyzed the data and presented the results; after extensive feedback, comments and changes by Maurizio Sartori and Urs Germann, Marco Gabella wrote the submitted (18 March) and revised (2 May) version of this note.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Huuskonen, A.; Holleman, I. Determining weather radar antenna pointing using signals detected from the Sun at low antenna elevations. *J. Atmos. Ocean. Technol.* **2007**, *24*, 476–483. [CrossRef]
2. Holleman, I.; Huuskonen, A.; Kurri, M.; Beekhuis, H. Operational monitoring of weather radar receiving chain using the Sun. *J. Atmos. Ocean. Technol.* **2010**, *27*, 159–166. [CrossRef]
3. Holleman, I.; Huuskonen, A.; Gill, R.; Tabary, P. Operational monitoring of radar differential reflectivity using the Sun. *J. Atmos. Ocean. Technol.* **2010**, *27*, 881–887. [CrossRef]
4. Gabella, M.; Sartori, M.; Boscacci, M.; Germann, U. Vertical and Horizontal Polarization Observations of Slowly Varying Solar Emissions from Operational Swiss Weather Radars. *Atmosphere* **2015**, *6*, 50–59. [CrossRef]
5. Gabella, M.; Huuskonen, A.; Sartori, M.; Holleman, I.; Boscacci, M. The solar slowly varying component as detected by dual-and single-polarization C-band weather radars in Europe. In *Electromagnetic Wave Propagation and Scattering in Microwave Remote Sensing*; Technische Universität Chemnitz Publikationen: Chemnitz, Germany; 29; September; 2015.
6. Tapping, K. *Antenna Calibration Using the 10.7 cm Solar Flux*; Preprints, Workshop on Radar Calibration; American Meteor Society: Albuquerque, NM, USA, 2001.
7. Gabella, M. Checking absolute calibration of vertical and horizontal polarization weather radar receivers using the solar flux. *J. Electr. Eng.* **2015**, *3*, 163–169.
8. Frush, C.L. Using the Sun as a calibration aid in multiple parameter meteorological radars. In Proceedings of the 22nd Conference on Radar Meteorology, Zurich, Switzerland, 10–13 September 1984; pp. 306–311.
9. Pratte, J.F.; Ferraro, D.G. Automated solar gain calibration. In Proceedings of the 24th Conference on Radar Meteorology, Tallahassee, FL, USA, 27–31 March 1989; pp. 619–622.
10. Ice, R.J.; Heck, A.K.; Cunningham, J.G.; Zittel, W.D.; Lee, R.R.; Richardson, L.M.; McGuire, B.J. Polarimetric weather radar antenna calibration using solar scans. In Proceedings of the AMS Annual Meeting, Phoenix, AZ, USA, 7 January 2015; p. 6.
11. Germann, U.; Boscacci, M.; Gabella, M.; Sartori, M. Radar design for prediction in the Swiss Alps. *Meteorol. Technol. Int.* **2015**, *4*, 42–45.

12. Vollbracht, D.; Sartori, M.; Gabella, M. Absolute dual-polarization radar calibration: Temperature dependence and stability with focus on antenna-mounted receivers and noise source-generated reference signal. In Proceedings of the 8th European Conference on Radar in Meteorology and Hydrology (ERAD2014), Garmisch-Partenkirchen, Germany, 1–5 September 2014; pp. 91–102.
13. Benz, A.O. Radio emission of the quiet Sun. In *Landolt-Börnstein Numerical Data and Functional Relationships in Science and Technology*; Trümper, J.E., Ed.; Springer: Berlin, Germany, 2009; p. 14.
14. Gölz, P.; Vollbracht, D.; Gekat, F. Calibration of a weather radar receiver with a noise diode. In Proceedings of the 36th International Conference on Radar Meteorology, Breckenridge, CO, USA, 16 September 2013.
15. Holleman, I.; Huuskonen, A. Improved analysis of solar signals for differential reflectivity monitoring. *Atmos. Meas. Tech.* **2016**. under review.