

### Checking Absolute Calibration of Vertical and Horizontal Polarization Weather Radar Receivers Using the Solar Flux

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**Abstract:** A convenient and effective method for the absolute calibration of vertical and horizontal (dual-) polarization weather radar receivers is presented. The method is based on the relationship between the solar flux accurately measured in the S-band by the DRAO (Dominion Radio Astrophysical Observatory) and the retrieved power in the C-band by the vertical and horizontal receivers. One disadvantage of the method is that it requires the weather radar to be off-line for a few minutes during the tracking of the Sun (antenna radiation pattern beam axis hitting the center of the Sun). In order not to interfere with the operational scan, the method has been applied off-line to the 5<sup>th</sup> and last weather radar that will be integrated in the Swiss network at the beginning of 2016. Both during the Factory Acceptance Tests (FAT5) in summer 2015 and at the Weissfluhgipfel site in autumn 2015, the antenna-mounted Vertical (V) and Horizontal (H) polarization receivers were used to retrieve the maximum solar irradiance hitting the parabolic antenna. For both H and V polarizations, best results were obtained at the site, as a consequence of a better assessment of receiver path losses. The average multiplicative error (Bias) between the H (V) channel and the reference is -0.05 (-0.26) dB; the standard deviation of the error is 0.13 (0.09) dB for the H (V) channel. These preliminary results are so encouraging and promising that MeteoSwiss is planning to repeat such off-line Sun tracking observations using not only this 5<sup>th</sup> and last weather radar but also the other 4 operational ones.

Keywords: Weather radar receivers, monitoring, absolute radar calibration, effective system antenna with radome Gain, solar emission.

### **1. Introduction**

The 10.7 cm solar flux measurements distributed by DRAO Radio the (Dominion Astrophysical Observatory) of the National Research Council of useful calibration Canada are а tool for dual-polarization 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, making it possible to tie together the calibration of several systems belonging to a national weather radar network.

However, state-of-the-art weather radar pencil beam

antennas have usually HPBW (half power beam width) that is not much larger than the apparent solar disc; hence, the sun is not seen with a constant gain even when the antenna beam axis is pointing at the center of the solar disc. To overpass this problem, we use the results of the mapping method, which is thoroughly described in Section 7.2 of the paper by Tapping [1].

Another problem encountered with radars operating at 5.5 cm wavelength is the frequency conversion from 2.8 GHz to 5.45 GHz. Section 5 of the paper by Tapping [1] provides a simple conversion formula that allows to deal with such problem.

In this note, a convenient and effective method for the absolute calibration of vertical and horizontal (dual-)polarization weather radar receivers is presented. The method is complementary to the on-line technique that automatically detects and analyzes Sun signals

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stored in the polar volume radar reflectivity data acquired during operational weather scan program. Such technique, which allows relative calibration and between vertical mutual inter-comparison and horizontal channels has the great advantage of requiring no interruption of the weather surveillance and has been described in a series of papers [2-6]. The main disadvantage of such on-line technique consists in the necessity of retrieving the maximum signal that would have been observed by pointing the beam axis at the center of the solar disk by means of a five-parameter fitting procedure described in detail in [5]. Once the five parameters are derived, for instance by means of the least squares method, the peak solar power that the radar would have received if the beam had hit the Sun's center can be estimated. Probably because of the intrinsic additional uncertainties associated to the retrieval method (antenna radiation pattern deconvolution), the focus of the on-line method has been so far on relative calibration: vertical and horizontal polarization radar signals were compared versus the DRAO reference and shown to be able to capture the slowly varying solar emission during active periods in 2005 (see Ref. [3], horizontal polarization observations from a radar) and 2014 (see Ref. [6], which deals with 3 dual-pol radars observations).

On the contrary, with the method presented in this note we tackle the absolute calibration of the receiver by pointing the antenna radiation pattern beam axis at the center of the Sun; obviously, from a meteorological service viewpoint, the main disadvantage of the method is that it requires the weather radar being off-line for a few minutes during the tracking of the Sun (off-line "Sun-tracking measurement"). In order not to interfere with the operational meteorological surveillance of Switzerland, which is currently accomplished by a network of four state-of-the-art, dual-polarization radars, the method has been applied off-line to the 5<sup>th</sup> (and last) brand new radar that will be integrated in the Swiss network at the beginning of 2016. Both during the Factory Acceptance Tests in July

2015 (FAT5) and at the Weissfluhgipfel site (SAT5) in October 2015, the antenna-mounted receivers, which are able to operate at both vertical and horizontal polarization, were used to retrieve the maximum solar irradiance hitting the radar parabolic antenna. It is worth noting that the observations in July and October have been planned and executed during days with smallest number of Sun spots, which is solar flux close to the quiet emission of the Sun. This choice has the advantage of minimizing uncertainties related to the conversion formula from S-band (DRAO measurements) to C-band (operating frequency of the MeteoSwiss radar network) as stated in Sec. 5 of Ref. [1] and shown in Sec. 6 of Ref. [7].

This note is organized in four Sections: the next one briefly presents the scientific approach. Section 3 and 4 describe the configuration (dry radome and receiver path Losses) of the vertical and horizontal receivers chains at the factory (Neuss, Germany) and at the site (Weissfluhgipfel, Switzerland). Section 5 presents and discusses results obtained at both sites. Summary conclusions and outlook are provided in the last Section.

# 2. Weather Radar Technology and Scientific Approach

A key aspect of the dual-polarization weather radar systems recently installed by MeteoSwiss is the innovative solution based on antenna-mounted receivers; remarkable advantages of such solution (with respect to the conventional one, which is receivers next to the transmitter inside the technical room) are:

• reduced receiver losses;

• avoiding expensive dual-pol rotary joint, which also introduce differential errors in amplitude and phase.

However, one has also to consider that maintenance activities for antenna-mounted receivers are more time consuming and less comfortable than for conventional ones; furthermore, antenna-mounted receivers imply the need of controlling temperature inside the radome as well as inside the receivers box. In particular, the receiver (Rx) box needs rigorous climate control: the lower is the Temperature excursion inside the Rx box, the better is the Rx stability.

Another key aspect of the Swiss weather radars is the use of a stable, white signal generated by a NS (Noise Source) as absolute reference for the calibration of the radar Rx: every 5 minutes (time corresponding to accomplish a full-volume in the 20-elevation Swiss scan program), the NS reference signal (around -90 dBm), NS<sub>ref</sub>, is injected in the Rx Front-End (input of the LNA) and the corresponding Log-transformed value in Analog-to-Digital-Units (dBADU) at the output of the A-D converter is read, NS<sub>out</sub>: in this way the factor for the transformation from dBADU to dBm of any received signal is known and updated every 5 minutes. Important positive aspect of this solutions are:

• white signal thoroughly and homogeneously filling the whole matched-filter band width;

• high stability and "smaller-than-the-receiver" sensitivity on Temperature.

A thorough description of the MeteoSwiss antenna-mounted Rx design is presented in Section 2 of the ERAD 2014 proceedings by Vollbracht et al.

For the experiments presented in this note, it is sufficient to provide the power of the accurate NS signal at the reference point (input of the LNA) for the radar under test: such reference value ("NS<sub>ref</sub>") is -91.52 dBm for the Horizontal (H) channel and -91.26 dBm for the Vertical (V) one. Let  $P_{ref}$  be the power of any received signal we would like to determine, knowing its corresponding level  $P_{out}$  in dBADU read at the output of the A-D converter. Then, it is simply

$$P_{\rm ref} = NS_{\rm ref} + P_{\rm out} - NS_{\rm out}$$
(1)

Where  $[NS_{ref}] = [P_{ref}] = dBm$ , while  $[NS_{out}] = [P_{out}] = dBADU$ .

As a practical example, let us consider the first two Horizontal polarization Sun power observations acquired by the radar at the factory on July 14 and 20 (see next Section): in both cases, P<sub>out</sub> was 22.5 dBADU; one could conclude that the power coming from the Sun in the two days was the same, only if the closest temporal values of  $NS_{out}$  were exactly the same. In this example,  $NS_{out}$  turned out to be 33.05 dBADU on July 14 and 33.10 dBADU on July 20; consequently, the received power values  $P_{ref}$  are -102.07 dBm and -102.12 dBm, as can easily be derived using Eq. (1).

The next step toward the comparison with the unpolarized DRAO reference values, is obviously that of retrieving the received power at another reference point, which is at the input of the antenna. Firstly, this requires an accurate knowledge of the Rx chains Losses,  $L_{Rx}$ , including dry radome attenuation. Secondly, to compare the radar polarized H and V component with the unpolarized DRAO value it is necessary to add 3 dB, which is multiply by a factor of 2. Finally, one has to consider that the solar disc is not seen with a constant antenna gain by weather radar antennas (typical HPBW~1°). Consequently, the contribution of the outer areas of the disc are underestimated, compared with the inner part; hence, the observed flux density starts do deviate (decrease) compared with integrated flux density observed using a broader-beam antenna (for instance, DRAO antenna, whose HPBW is 4.5°). In principle, if the beam axis is pointed precisely at the center of the disc and the solar disc is uniformly bright, it is possible to quantify such non-point-source Losses, L<sub>nps</sub>. For instance, from Sec. 7.1 of Ref. [1] or Eq. (13), page 161, in Sec. 2.d of Ref. [3], by assuming an apparent diameter of the radio Sun equal to  $0.57^{\circ}$  and HPBW =  $1.0^{\circ}$ , one gets Lnps = -10Log (0.8954) = 0.48 dB. However, such condition is met quite often around solar activity minimum, but much more rarely elsewhere in the cycle. Because of this limitation, we have opted for the outcome of the mapping technique (see Ref. [1], Sec. 7.2) during experiments performed by Dr. P. Goelz [8], who has got  $L_{nps} = 0.5 \text{ dB}$ . In formulas, the incident power at the antenna feed, Pant, can simply be estimated as

$$P_{ant} = P_{ref} + L_{Rx} + 3 dB + L_{nps}$$
(2)

where  $P_{ref}$  has been derived thanks to Eq. (1).

As stated in the introduction, DRAO reference values consist of spectral power per unit of area, which is a quantity called irradiance in the radiative transfer theory; at microwave frequencies it is expressed in the so-called Solar Flux Units (SFU), where 1 SFU is equal to  $10^{-22}$  W·m<sup>-2</sup>·Hz<sup>-1</sup>, which is  $10^{-19}$  mW·m<sup>-2</sup>·Hz<sup>-1</sup>. Consequently, for the ultimate comparison, one should know as accurately as possible the radar Rx bandwidth in Hz and the antenna equivalent area, A<sub>eq</sub>, in m<sup>2</sup> in order to transform the estimated incident power at the antenna feed in dBm, P<sub>ant</sub>, into the incident spectral Irradiance at 5.5 cm, I<sub>5.5</sub>, expressed in dBsfu. The equivalent area is derived from the (Horizontal and Vertical polarization) Gain measured at the test range

using the equation  $A_{eq} = G \frac{\lambda^2}{4\pi}$ .

As far as the Rx bandwidth is concerned, the pulse width ( $\tau$ =500 ns) used by the magnetron-based Swiss systems occupies typically 2.4 MHz. However, recent investigations [9] have shown that the bandwidth should be extended to a value of 2.52 MHz to calculate the power for noise signals; this means, on a Log-transformed scale, a value of 64.01 dBHz. In formulas,

$$I_{5.5} = P_{ant} + 190 \text{ dB} - B_{dBHz} + 10 \text{ Log} \left(\frac{4\pi}{\lambda^2}\right) - G_{dB}$$
 (3)

As a practical example, from Eq. (2) we get that for H polarization,  $P_{ant}$  was -96.17 dBm on July 14 and -96.22 dBm on July 20, 2015 (Horizontal Rx path Losses,  $L_{Rx}$  equal to 2.4 dB, see next Section). According to the manufacturer electrical test report [10], antenna Gain for Horizontal (Vertical) polarization is 44.8 (45.0) dB. Consequently, from Eq. (3) the radar estimate of the solar flux at 5.5 cm was 21.2 dBsfu on July 14 and 21.15 dBsfu on July 20.

Such values can be compared with DRAO accurate

measurements after a frequency conversion; DRAO measurements are in fact acquired at the wavelength where the solar slowly varying component is more significant as compared to the quiet radio flux, which is at 10.7 cm. The conversion formula used is the one presented by Tapping in Sec. 5 of Ref. [1] with coefficient tailored to the MeteoSwiss operating frequency, namely Eq. (1) in Ref. [6]. Using such formula, we get a DRAO reference value of 21.6 dBsfu on July 14 and 21.3 dBsfu on July 20. The trivial conclusion is that the H polarization radar observation on July 20 was closer to the nominal value. A complete set of H and V observations at the factory and at the site is presented in the following two Sec. 3 and 4. It is worth noting that while DRAO measurements are corrected for atmospheric attenuation, radar estimates presented in this technical note are not.

### **3. Radar Receivers Characteristics at the Factory (July 2015)**

In preparation of the FAT (factory acceptance test) the radar system was installed on the roof of the factory of Selex ES in Neuss (D) and run for a couple of weeks in operational mode to test stability and performance on calibration, sensitivity, with a focus Sun measurements and antenna mechanics. The coordinates of the Neuss site are: 51°.1313 latitude, 6°.7357 longitude, 44 m altitude. During such period in July 2015, four sun-tracking observations have been executed. The corresponding radar estimates of incoming solar flux for the Horizontal and Vertical channels are listed in the 3<sup>rd</sup> and 4<sup>th</sup> columns of Table 1. These values have been derived using the three equations presented in Sec. 1; the H and V polarization Rx Losses values measured at the factory and used in Eq. (2) are 2.40 and 2.45 dB, respectively.

 Table 1
 Solar Flux values during 4 WEI radar sun-tracking observations at the factory (D).

	0	8				
Date (time)	DRAO	Rx <b>H</b>	Rx V	H-V	V-DRAO	H-DRAO
July 14, 2015 (14 UTC)	21.6 dBsfu	21.2 dBsfu	20.9 dBsfu	0.3 dB	-0.70 dB	-0.40 dB
July 20, 2015 (07 UTC)	21.3 dBsfu	21.15 dBsfu	20.8 dBsfu	0.4 dB	-0.50 dB	-0.10 dB
July 23, 2015 (07 UTC)	21.15 dBsfu	21.0 dBsfu	20.7 dBsfu	0.3 dB	-0.45 dB	-0.15 dB
July 23, 2015 (11 UTC)	21.15 dBsfu	20.8 dBsfu	20.5 dBsfu	0.3 dB	-0.65 dB	-0.35 dB

As stated, DRAO reference values (2<sup>nd</sup> column) have been transformed from S-band to C-band using Eq. (1) in Ref. [6]. The last two columns show the multiplicative error between the radar estimate and the DRAO reference: a negative value means radar underestimation; column 6 refers to the Vertical polarization, column 7 to the Horizontal one. The 5<sup>th</sup> column shows the relative error between the two radar channels.

As previously stated, for such clear sky observations, we have neglected gaseous attenuation: by assuming (at the sea level) a two-way value of 0.016 dB/km and an equivalent atmospheric height (1976 US standard atmosphere) of 8.4 km, this means approximately 0.13 dB at the Zenith and less than 0.2 dB for the angles of elevation used (larger than 20°).

## 4. Radar Receivers Characteristics at the 3,000 m Altitude Site

After installation in Switzerland, radar performance and stability are tested in four steps, which have quite different duration: (1) a couple of weeks of commissioning, hardware measurements and characterization offline as well as testing (ISAT-offline); followed by (2) three weeks of online testing (ISAT-online); then, (3) a six-month period in operational mode (SEAT) starts; followed by (4) a final network test of four months (FA). The seven sun-tracking observations presented in this section have been executed at the Weissfluhgipfel site, namely during the ISAT-offline that took place in October 2015. The corresponding solar flux values are listed in Table 2, which is organized just like Table 1.

The coordinates of the Weissfluhgipfel radar (WEI) site (close to Davos) are: 46°.8350 latitude, 9°.7945 longitude; 2850 m altitude (antenna feed). Several, time-consuming efforts have been spent at the site to accurately assess Rx and Tx Losses as well as to measure Tx power, Noise Figures and other relevant parameters. Regarding Rx Losses of the H and V polarization chains, they result to be a bit larger than at the factory: 2.50 and 2.70 dB respectively. Ideally, one would expect almost equal values, since hardware devices are the same at the factory and at the site. It is worth noting that such values include 0.2 dB (one-way, dry radome attenuation); the same was at the factory. Also at the Weissfluhgipfel site, for our seven clear sky observations, we have neglected gaseous attenuation: at 3000 m altitude, attenuation is approximately 0.04 dB smaller than at the factory (44 m altitude); this means less than 0.16 dB for most of the angles of elevation used (larger than 20°).

Results presented in Tables 1 and 2 are statistically analyzed and thoroughly discussed in the following Section 5.

## 5. Discussion of the Results Obtained at the FAT and at the (3000 m) Site

For what concerns the four sun-tracking observations performed at the factory, the DRAO reference signal at 5.5 cm ranges from 21.15 to 21.6 dBsfu with a standard deviation of  $\pm 0.21$  dB around the average value of 21.30 dBsfu.

Regarding the radar receivers performance, both the Horizontal and Vertical polarization channels show an

	=	=				
Date (time)	DRAO	Rx <b>H</b>	Rx V	H-V	V-DRAO	H-DRAO
Oct. 14, 2015 (08 UTC)	21.4 dBsfu	21.15 dBsfu	20.96 dBsfu	0.19 dB	-0.44 dB	-0.25 dB
Oct. 15, 2015 (10 UTC)	21.5 dBsfu	21.50 dBsfu	21.26 dBsfu	0.24 dB	-0.24 dB	+0.00 dB
Oct. 17, 2015 (08 UTC)	21.7 dBsfu	21.85 dBsfu	21.51 dBsfu	0.34 dB	-0.19 dB	+0.15 dB
Oct. 20, 2015 (08 UTC)	21.9 dBsfu	21.75 dBsfu	21.66 dBsfu	0.09 dB	-0.24 dB	-0.15 dB
Oct. 21, 2015 (08UTC)	22.0 dBsfu	21.90 dBsfu	21.76 dBsfu	0.14 dB	-0.24 dB	-0.10 dB
Oct. 22, 2015 (08UTC)	21.9 dBsfu	21.95 dBsfu	21.71 dBsfu	0.24 dB	-0.19 dB	+0.05 dB
Oct. 22, 2015 (11UTC)	21.9 dBsfu	21.85 dBsfu	21.61 dBsfu	0.24 dB	-0.29 dB	-0.05 dB

 Table 2
 Solar Flux values during 7 sun-tracking observations at the 3000 m WEI site (CH).

average underestimation (negative Bias): -0.25 dB for H and -0.58 dB for V. The **standard deviation of the error**, results to be similar: **0.15 dB** (**0.12 dB**) for the **H** (**V**) channel.

As expected, the relative agreement between the H and V channel is significantly better than the absolute agreement between each channel (H or V) and the reference: the <u>standard deviation of their</u> <u>log-transformed ratio is 0.05 dB</u>. It is straightforward to observe from the figures listed in the previous paragraph that, on average, the H channel is 0.33 dB larger than the V channel.

For what concerns the seven sun-tracking observations (in six different days) performed at the site, the 5.5 cm reference signal ranges from 21.4 to 22.0 dBsfu with a standard deviation of ±0.23 dB around the average value of 21.76 dBsfu. For both channels, the agreement at the site is better: the improvement is remarkable in terms of average error (Bias) and almost indiscernible regarding the dispersion of the error around the mean are smaller than at the factory. In particular, the H channel is almost Bias-free, with an average underestimation as small as -0.05 dB; the average underestimation of the V channel is -0.26 dB. The standard deviation of the error, results to be slightly larger for the H channel (0.13 dB) than for the V channel (0.09 dB). Regarding the relative agreement between the two channels, the standard deviation of their log-transformed ratio is 0.08 dB. It is straightforward to observe that, on average, the H channel is 0.21 dB larger than the V channel.

How do we explain the improvement in the absolute calibration of 0.20 dB for the H channel and of 0.32 dB for the V channel? As stated, a small part (say, ~0.04 dB) is because of smaller gaseous attenuation. For the remaining part, the hypothesis is a more accurate evaluation of the Receiver path Losses, which have been measured twice and with many efforts by Maurizio Sartori and Thomas Drappatz.

Another relevant question concerns a possible

explanation for the larger Bias of the V-channel; our hypothesis is that the antenna Gain of the Vertical polarization is not 45.0 dB as stated in Ref. [10] rather 44.8 dB, which is exactly the same as the H one (see Ref. [10] and the end last paragraph of Sec. 1 in this note). By assuming a V polarization Gain equal to 44.8 dB, then the Bias of the Vertical channel reduces to -0.26 dB, which is a small value, extremely close to the Horizontal one. Hence, with this assumption, also the mutual, relative agreement between the two channels improves significantly: from 0.21 to 0.01 dB that is indeed an amazingly satisfying result. De facto, the two channels would be perfectly aligned with an "uncertainty" (standard deviation) equal to 0.08 dB (5 degrees of freedom).

#### 6. Summary, Conclusions and Outlook

This note presents an effective method for the absolute calibration of vertical and horizontal (dual-)polarization weather radar receivers. The method is based on the relationship between the solar flux accurately measured in the S-band by DRAO (typically with 1 hour integration time) and the retrieved power in the C-band by the vertical and horizontal receivers. It requires the weather radar to be off-line for a few minutes while tracking the Sun. Using the 5<sup>th</sup> and last weather radar of the Swiss network, four observations have been performed at the factory (Neuss) and seven observations at the Weissfluhgipfel (WEI) site: best results were obtained at the WEI site; in both sites, Neuss and WEI, the retrieved value using the horizontal channel is closer than the vertical one to the DRAO reference.

In particular, the average multiplicative error (**Bias**) between the **H** channel and the reference at WEI results to be as low as -0.05 dB; the Bias between the V channel and the DRAO reference is -0.26 dB. The standard deviation of the error is 0.13 (0.09) dB (H) for the H (V) channel. It is interesting to note that by assuming the same antenna Gain for both the Vertical and the horizontal polarization, the **Bias** between the V

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channel and the DRAO reference reduces to **-0.06 dB**, which is a remarkably small value, extremely close to the Horizontal one. This would mean a "perfect" alignment  $(0.01\pm0.08 \text{ dB})$  between the two channels, which are both less than 0.1 dB from the DRAO reference.

These preliminary results are so encouraging and promising that MeteoSwiss is planning to repeat such off-line Sun tracking observations using the other 4 operational radars: we are going to check the absolute multiplicative difference between the DRAO reference and the other eight receiver chains. Eventually, one could think of adjusting those that are "too far" from the DRAO reference by assuming a different value of Gain and/or Rx Losses and/or dry radome Losses. This is exactly what has been postulated in the present note regarding the vertical polarization: according to test range measurements [10], antenna Gain for Horizontal (Vertical) polarization is 44.8 (45.0) dB. However, under the assumption that the Vertical polarization Gain is also 44.8 dB, then the average Bias with respect to DRAO decreases from -0.26 dB to -0.06 dB.

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