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6.6: Solar Monitoring as a Tool for improving the Homogeneity of Radar Networks

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Abstract. Radar observations of the solar radiation provide a useful tool for daily monitoring of the antenna pointing, receiver stability, signal processing and the polarimetric properties of the radar. The method uses solar hits which are collected during the operational scanning of the radar. Hence the radar operations need not be stopped for the monitoring and no operational scanning time is lost. The operational use of the method has proven to be highly effective in keeping radars calibrated, antennas pointed correctly and in revealing features and problems which otherwise are difficult to notice and diagnose. The method is already in use in several countries in Europe and beyond, and the number of installations is continuously increasing. Within the EUMETNET weather radar programme, OPERA, a project is ongoing with aim of applying the method to all radar data collected at the OPERA Radar Data Center Odyssey. This will provide a centralized service to homogenize the weather radar data which is most important for the use of the data in applications such as compositing and numerical weather prediction. In this paper we will describe the method and show first results of the work.

1 Introduction

The solar monitoring is a method in which the data collected during the normal operational scanning of a radar are used to determine antenna azimuth and elevation biases (Huuskonen and Holleman, 2007), to monitor the receiver stability (Holleman et al., 2010b), the width of the solar iamge as seen by a radar antenna (Huuskonen et al., 2014a; Altube et al., 2015) and of the polarimetric properties of a radar (Holleman et al., 2010a; Figueras i Ventura et al., 2012; Frech, 2013; Gabella et al., 2015; Huuskonen et al., 2016). A recent summary of the method is given by (Huuskonen et al., 2016), who also describe a set of methods to improve the quality of the solar hit data.

EUMETNET, the network of European Meteorological Services, runs a number of projects and operational services dealing with various observation systems and networks (http://eumetnet.eu). OPERA (Operational Exchange of Weather Radar Information) deals with weather radar and has been running since 1999 (Huuskonen et al., 2014b). For the present five year period (OPERA 4, 2013-2017) a work package (known as OD5 within OPERA) is established to extend the solar signal analysis to the whole OPERA radar network, so that 31 OPERA members need not all establish such a facility themselves. The centralized processing makes use of the radar volume data which are collected by the OPERA Radar Data Center Odyssey for producing European wide composites (Matthews et al., 2012). In this paper we describe first results of the work.

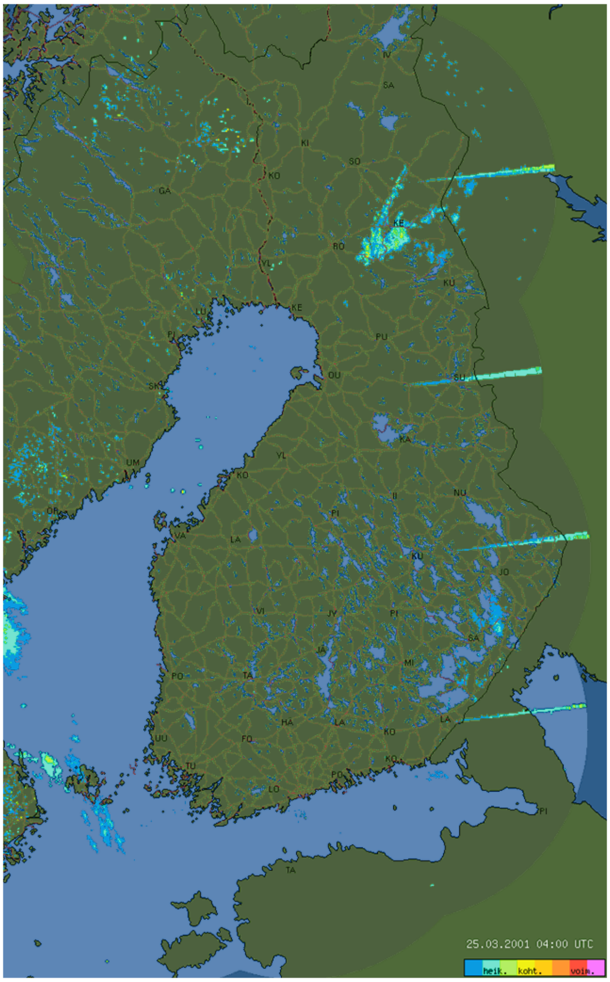

Figure 1. Solar signal observed simultaneously by four radars in Finland on March 25, 2001 at 4:00 UTC.

2 Method

The detection and analysis of solar signatures in radar volume data is described in a series of papers mentioned in the Introduction. We will summarize the main points of the method here for convenience.

In the method a reflectivity signal originating from a continuous microwave source are searched along radials in the operational scan data. Figure 1 shows an example where four radars observe the solar signal simultaneously close to the spring equinox. As a radar signal processor usually corrects the received echoes for the range dependence and the atmospheric attenuation, the signals from the sun appear to increase with the range. The received solar spectral power at the antenna feed P (per MHz in dBm) can be calculated from the reflectivity signature as a function of the range $Z(r)$ (in dBZ) using:

$$P = Z(r) - 20\log_{10} r - 2ar - C - 10\log_{10}\Delta f \qquad (1)$$

where C is the radar constant in dB according to Probert-Jones (1962), a is the one-way gaseous attenuation in dB km^{-1}, and Δf is the receiver 3 dB bandwidth in MHz. In the case of a proper solar signal the power P is constant along the range (> 50 km), as illustrated in Fig. 2.

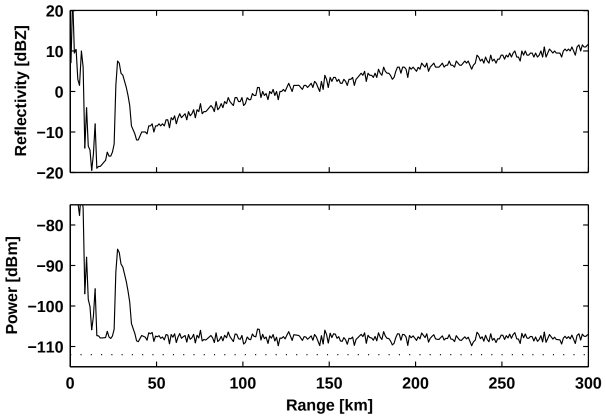

Figure 2. The reflectivity data with a sun signal uncorrected (upper panel) and the received power calculated applying Eq.1 (lower panel). The noise level of the radar is indicated by the dotted line.

The mean and standard deviation of this signal, together with the antenna pointing and timing information, are the data used in the subsequent analysis. The possible contamination by rain and ground clutter can be avoided by using data from far ranges only. As this would reduce the amount of usable data unnecessarily, we use the two-stage estimation method by Huuskonen et al. (2016) in which a first estimate of the mean and standard deviation is first calculated from the long ranges and these are used to filter out the contaminated range bins at the shorter ranges. In the present work the first estimate is made using data measured above 8 km, and the final estimate using data measured above 4 km altitude and using a fixed width of 2 dB for the outlier filtering window. This is roughly 3 times the standard deviation of a typical solar hit. A solar hit estimate is stored if more than 70% of the data passes the filtering, i.e. less than 30% of the data points are recognized as contaminated by rain or clutter.

Depending on the hardware of the radar, the volume coverage pattern, the season and the latitude of the radar, several tens of sun hits are found per day. When these hits are plotted as a function of the azimuth and elevation, a symmetric distribution is seen which is slightly wider in azimuth than in elevation, as shown in Fig. 3. Uncorrected reflectivity data are

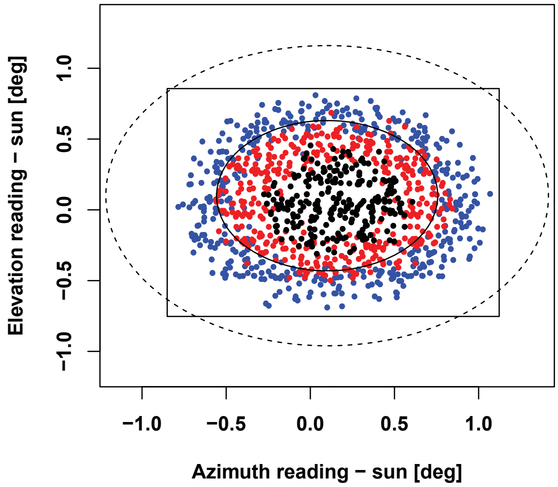

Figure 3. Solar hits as a function of azimuth and elevation. The sun hit power is shown relative to maximum (black within 1 dB of maximum, red 1 ... 3 dB below the maximum, blue 3 ... 7 dB below the maximum, and magenta more than 7 dB below the maximum). An ellipse with axes of 1.06° and 1.31° is provided to show the half power (3 dB) widths in elevation and azimuth, respectively. The dashed lines show ellipses with axes lengths twice that. The rectangular box is the data selection area as described in the text.

rather used for this analysis as (time-domain) Doppler clutter filters can attenuate the solar signal by several dBs, and the interference filtering applied to remove RLAN signatures efficiently remove solar signal as well.

The sun hit distribution of linear powers is well approximated by a Gaussian form, and hence the power P in dB can be written as:

$$P(x,y) \equiv a_x \cdot x^2 + a_y \cdot y^2 + b_x \cdot x + b_y \cdot y + c \tag{2}$$

where the coordinates x and y are defined as:

$$x = (\phi_{\mathrm{read}} - \phi_{\mathrm{sun}}) \cdot \cos\theta_{\mathrm{sun}} \tag{3}$$

$$y = \theta_{\mathrm{read}} - \theta_{\mathrm{sun}} \tag{4}$$

where ϕ and θ denote azimuth and elevation, "read" refers to the angle reading of the radar antenna and "sun" refers to the calculated sun position. The observed azimuth differences are multiplied by $\cos\theta_{\mathrm{sun}}$ to make them invariant to the elevation (e.g. Doviak and Zrnić, 1993, p. 516). For refraction we use the analytical formulas of (Holleman and Huuskonen, 2013) with $k = 5/4$.

The elevation and azimuth biases (B_θ, B_ϕ), and widths (Δ_θ, Δ_ϕ), and the power when the antenna is pointing directly to the sun, $\hat{P}_{\mathrm{sun}}$, can be calculated from the linear parameters a_x to c solved from Eq. 2 (Huuskonen and Holleman, 2007; Huuskonen et al., 2016):

$$\Delta^2_{\phi,\theta} = -\frac{40\log_{10}2}{a_{x,y}} \approx -\frac{12}{a_{x,y}}, \tag{5}$$

$$B_{\phi,\theta} = -\frac{b_{x,y}}{2a_{x,y}}, \tag{6}$$

$$\hat{P} = c - \frac{b_x^2}{4a_x} - \frac{b_y^2}{4a_y}. \tag{7}$$

In case the number of data points is not sufficient for a full 5-parameter analysis, the widths can be fixed to values based either on data collected over long times, or calculated based on the known properties of the antenna and the azimuth scanning.

The quality of the data and the number of daily solar hits varies greatly across the network and hence a number of methods have been developed to cope with the variability of the data. Firstly the solar hits power are scaled using the solar fluxes measured at the Dominion Radio Astrophysical Observatory (DRAO). Many radars produce only a few hits per day and hence data from several days or weeks need to be analyzed together. Without the scaling the variability of the solar flux, which in the C-band amounts to several dB, would decrease the quality of the results.

Also, one cannot assume *a priori* that a radar is correctly pointed. Hence the usual method in which only solar hits within, say, 2° of the known solar position is not usable. We instead assume that the majority of the data points are genuine solar hits and analyze the distribution of the hits. We have noticed than in the present dataset a robust estimate of the distribution limits is obtained by first calculating the 0.16 and 0.84 quantiles, i.e. approximate 1σ limits, and then calculating upper and lower limits r_u and r_l as:

$$\begin{aligned} r_u &= \frac{p(0.84)+p(0.16)}{2} + (p(0.84)-p(0.16)) \\ r_l &= \frac{p(0.84)+p(0.16)}{2} - (p(0.84)-p(0.16)). \end{aligned} \tag{8}$$

The first term estimates the center of the distribution, and for a Gaussian distribution the second term is roughly the 2σ width. This operation is carried out separately for azimuth and elevation and any point beyond the rectangular area defined by the limits is discarded from the further analysis (see Fig. 3). This is an efficient method of removing strong outliers, such as RLAN signatures, before the fitting. The fitting is carried out twice so that any solar hit which is further away from the fit curve than a set limit is removed before the second fit is performed. This is an efficient method if a small number of outliers is present in the data. In addition data measured at elevations below 1° are discarded to avoid severe refraction. The upper elevation limit is set to 10° to reduce the effects of possible non-linearities of the antenna readings.

For polarimetric radars the above procedure is applied separately to horizontal and vertical polarization. In case the

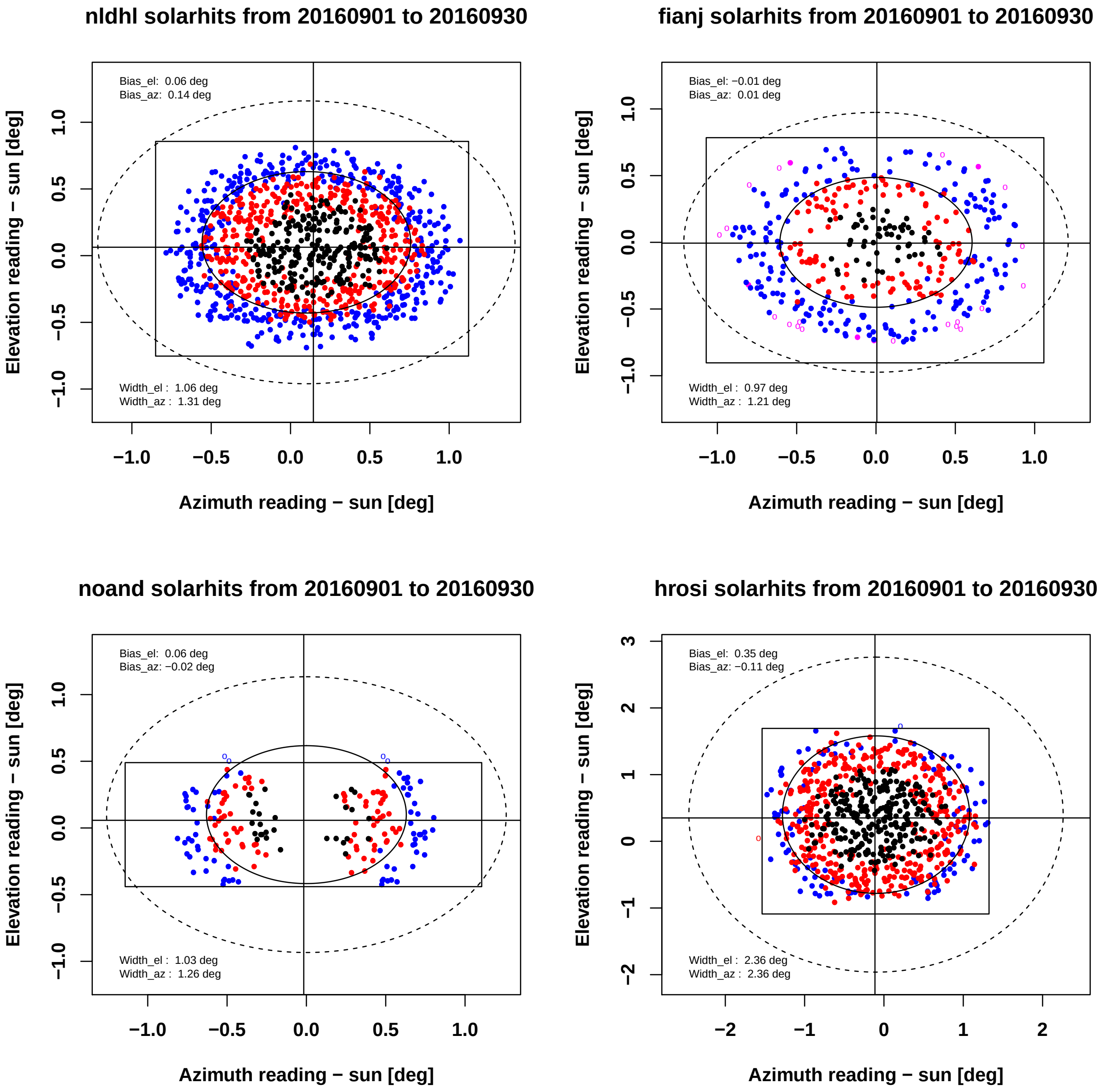

Figure 4. Solar hits collected at the OPERA data center during September 2016 for radars in Den Helder (nldhl, Netherland), Anjalankoski (fianj, Finland), Andenes (noand, Norway) and Osijek (hrosi, Croatia). The colours and ellipses are as in Fig. 3. The elevation and azimuth biases are shown in the upper left corner and are also designated by the horizontal and vertical lines, respectively. The elevation and azimuth widths are shown in the lower left corner.

radar measures P_H and the differential reflectivity Z_{dr}, the vertical power is calculated first as $P_V = P_H - Z_{\mathrm{dr}}$. An estimate of the solar Z_{dr} is then obtained as a difference of the estimated horizontal and vertical solar fluxes. This method is better than performing the analysis directly to the measured Z_{dr}, as pointed out by Huuskonen et al. (2016). A separate analysis of the two polarization sets gives also the pointing biases separately and show how well the pointings of the two polarizations agree. The data selection is not done separately for both polarizations, but the same solar hits as selected e.g. for the horizontal polarization are used in the analysis of the vertical polarization data as well.

As part of the work package OD5, the processing improvements described above have been included in the solar hit detection algorithm of KNMI (Royal Netherlands Meteorological Institute) and this code has been integrated into the BALTRAD software (BALTRAD, 2015), deployed at Odyssey. The present solar hit analysis is built on the FMI analysis program, with additions described in this paper.

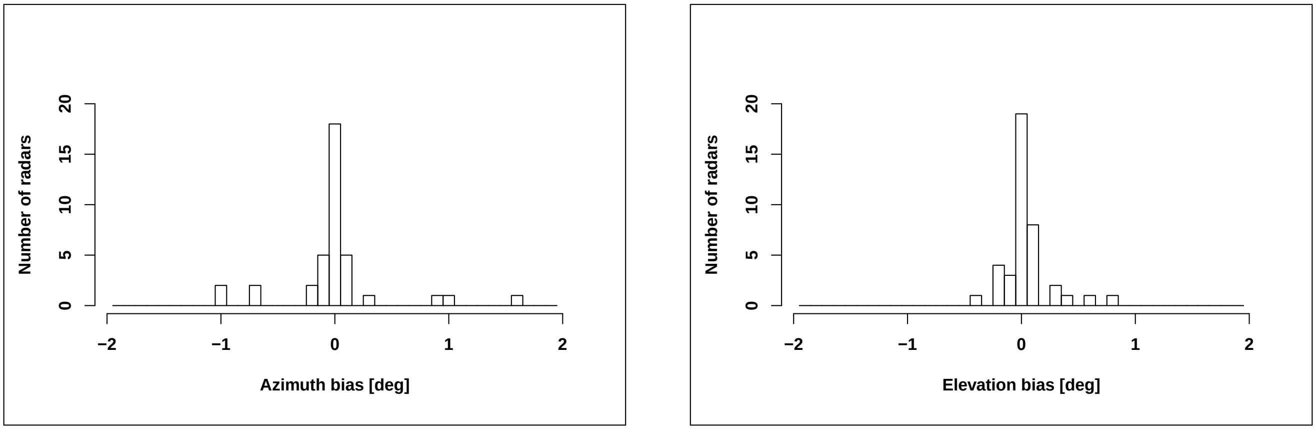

Figure 5. The distribution of the azimuth and elevation biases in September 2016 for the OPERA network.

3 Data and Results

The OPERA Radar Data Center Odyssey collects radar volume data of more than 150 radars and produces a European composite at every 15 minutes. For compositing Odyssey uses corrected reflectivity (DBZH) but for some radars Odyssey receives also uncorrected reflectivity (TH) and radial velocity data. In September 2016, altogether 149 radars of 24 OPERA members supplied DBZH and 74 radars of 12 OPERA members TH data. The frequency of data varies so that roughly half of the radars report at every 5 minutes, and the remaining at every 10-15 minutes.

Figure 4 shows four example cases. In each panel all hits from September 2016 are displayed together with the results on antenna pointing and widths. The examples include both C and S-band radars, radars providing TH and DBZH, with variable reporting frequency. The differences in the solar hit distribution can be explained by these facts.

The Den Helder radar (nldhl, upper left panel) provides TH data at every 5 minutes. The total number of solar hits exceeds 1000 and hence the data can be analyzed on a daily basis as more than 30 solar hits are found each day. The antenna biases are small, and the width values typical. The Anjalankoski radar (fianj, upper right panel) data are very similar except that the number of solar hits is roughly one third compare to the Den Helder radar. The data reporting frequency is once in every 15 minutes which explains the difference.

The Andenes radar (noand, lower left panel) looks peculiar because no solar hits are seen close to the solar direction and there is a cone of missing solar hits which appears to be slighlty wider for larger elevation differences. These data are corrected reflectivities and hence the disappearance of the solar hits is probably connected to the filtering process when DBZH data are calculated. The amount of data is fully sufficient for the analysis, and the bias and width values are normal. This example also explains why the center point of the distribution is calculated using the 1σ point instead of the median in Eq. 8. The empty region in the middle means that a median would not be a robust estimator of the center point.

The Osijek radar (hrosi, lower right panel) data shows a large number of solar hits with a much higher width of the distribution. The radar operates in the S-band with a small antenna, and hence the beam width is larger than in the other examples which are all from the C-band. The widths in azimuth and elevation are roughly identical, contrary to the other cases in which the azimuth widths are larger than the elevation widths. As described by Huuskonen et al. (2014a), the width in azimuth depends also on the windowing which is applied in the azimuth direction. A rectanglar window procudes the best statistics and largest azimuth widths but other windows are used e.g. in the ground clutter removal.

The number of solar hits varies greatly from radar to radar in the OPERA network. The maximum number is just above 1000 and the quartiles are found at 50, 110 and 350. This means that roughly one quarter of the radars provide sufficient number of data points for a daily analysis and another quarter for a weekly based analysis. Others are best analyzed on a monthly basis.

Figure 5 shows a summary of the azimuth and elevation biases based on the solar hit data recorded in September 2016. We note that the azimuth and elevation biases for a majority of radars is less than 0.15^{o}, which is considered as good. These results are very useful in improving the pointing, especially in elevation, where other suitable reference sources are difficult to find.

4 Discussion and outlook for the future

The first results presented in this paper demonstrate that an operational solar hit detection and analysis system is now available for the OPERA community. This extends significantly the use of the online solar method, which in various forms has been in use at least in Finland, Netherlands, Denmark, Germany, Poland, Switzerland, Catalonia, United Kingdom, Canada, Australia, South Africa, and USA.

At present we obtain results from about 50 OPERA radars which is roughly one third of the number of radars used in the compositing. Hence our first priority is to increase the number of successfully analyzed radars and the quality of the results by urging our members to send more TH data and to increase the frequency of data transmission to 5 minutes. In many cases DBZH data has been filtered to remove RLAN signatures and hence the solar signatures. Sending TH data would hence increase the number of successfully analyzed radars. This goal can be reached in the near future; in fact many OPERA members are in the process of adding TH to their data sets. As soon as polarimetric data is obtained, information on the solar ZDR will be made available, as well as information on the pointing biases of the two polarizations and how well they agree.

A more distant goal is to extend the analysis to the receiver stability and calibration levels. Correct estimation of the solar flux requires metadata which is not needed in the compositing (e.g. radar constant, pulse widths, receiver band width, receiver losses, the calibration reference point) and hence are considered optional and are missing to a large extent. Hence the fluxes determined are at present mostly on an arbitrary scale. However, they can be used to monitor the receiver stability of a radar as long as the metadata mentioned above remain unchanged. Further extensions to comparisons of calibration levels within radar networks require that the metadata are made available, noting the fact that the solar method is able to monitor the receiver chain only, and changes in the transmitter chain will remain unnoticed.

Since its introduction in 2004 the solar monitoring method has proven to a valuable tool for monitoring the antenna pointing, antenna system stability, and receiver stability. In addition it is a good tool for studying the working of the data processing which affect the width of the solar image. With the introduction of polarimetry it has found new uses in monitoring the differences in the polarization channels of the radar. The present work demonstrates the extension of the use of the method to the OPERA radar network which covers a whole continent. First antenna pointing results have been delivered to the members. When appropriate data from all the network are available, full harmonization of the measurement angles is possible. Future work will then continue towards monitoring the receiver stability, and the use of the solar fluxes in harmonization of the calibration levels.

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