Proceedings of ERAD (2002): 318–323 © Copernicus GmbH 2002

ERAD 2002

A method for estimating antenna beam parameters using the Sun

M. Leskinen[1], **P. Puhakka**[2], **and T. Puhakka**[1]

[1]Division of Atmospheric Sciences, P.O.Box 64 (Gustaf Hällströminkatu 2), FIN-00014 University of Helsinki, Finland
[2]Metsähovi Radio Observatory,Metsähovintie 114, FIN-02540 Kylmälä, Finland

Abstract. A simple method is described by which one can find estimates for the beam width and the pointing error of an unknown antenna system by using passive measurements of the Sun. The method is based on the assumption of a gaussian main lobe for the antenna under investigation. Assuming the Sun as a circular disc of known radiation pattern on a known background, the power captured by the gaussian main lobe of the antenna can be theoretically calculated for any beam width and any pointing direction. Antenna parameters can now be obtained by finding the width of the beam and the pointing error which together minimize the difference between the actual radiation pattern measured by the antenna and the theoretical gaussian pattern. The method can be applied for more complicated beam patterns too, if needed. Preliminary test results are presented for two different antennas: a typical C-band weather radar antenna and a commercial satellite antenna intended for measuring the activity of the Sun at 11.7 GHz.

1 Introduction

Quantitative weather radar measurements require absolute calibration of the signal response of the whole radar system including transmitter, waveguides, antenna and receiver. The pointing accuracy of the antenna is another fundamental question. This paper is a review of some possibilities to estimate antenna parameters using the Sun, and presents results of measurements made in Southern Finland using a C-band weather radar and an experimental 11.7 GHz solar radiometer.

Usually antenna patterns have been measured by the manufacturer. These values, if available, can be used as a “first guess”, and in most cases they give acceptable results. Significant changes in antenna parameters can occur, however, due to even small deviations from the correct alignment of the feed. Such deviations are likely when an antenna is reinstalled. Gravitational forces may also cause modifications in the reflector shape and in the tensions of the feed supports at different elevation angles. Finally wetting and aging of the radome may also cause deviations from the nominal beam parameters measured at the factory.

Correspondence to: T. Puhakka
(timo.puhakka@helsinki.fi)

Beam parameters can in principle be estimated at the radar site using a signal generator with a standard gain antenna in the far field of the radar antenna, or by using artificial targets of known backscattering properties (Smith 1968). The main difficulty in these methods is caused by reflections from the ground and other obstacles, which cannot be avoided in most radar environments. The methods are also difficult and laborious, require additional equipment, and cannot be used easily at high elevation angles.

The Sun has been widely used in checking the pointing accuracy of an antenna (see, for example, Whiton et al., 1976; Eastment et al., 2001; Manz et al., 2001). Use of the Sun to calibrate the whole receiver chain over the 100 dB dynamic range of weather echoes does not seem feasible due to the relatively low power level of the solar radiation at radar frequencies. However, to find the half-power beam width of the main lobe should be possible, as this is related to only a 3 dB range of received power. The basic principles of using the Sun and other extraterrestrial sources for antenna alignment and gain pattern measurements are presented in Kuz’min and Salomonovich (1966).

2 General principles

2.1 Theory

In the ideal case of a point radiation source in the far field of the antenna, the normalized beam pattern is simply the distribution of the received power from different pointing directions divided by its maximum value obtained with the beam axis pointing towards the source.

$$P_n(\theta,\varphi) = \frac{P(\theta,\varphi)}{P_{max}}. \quad (1)$$

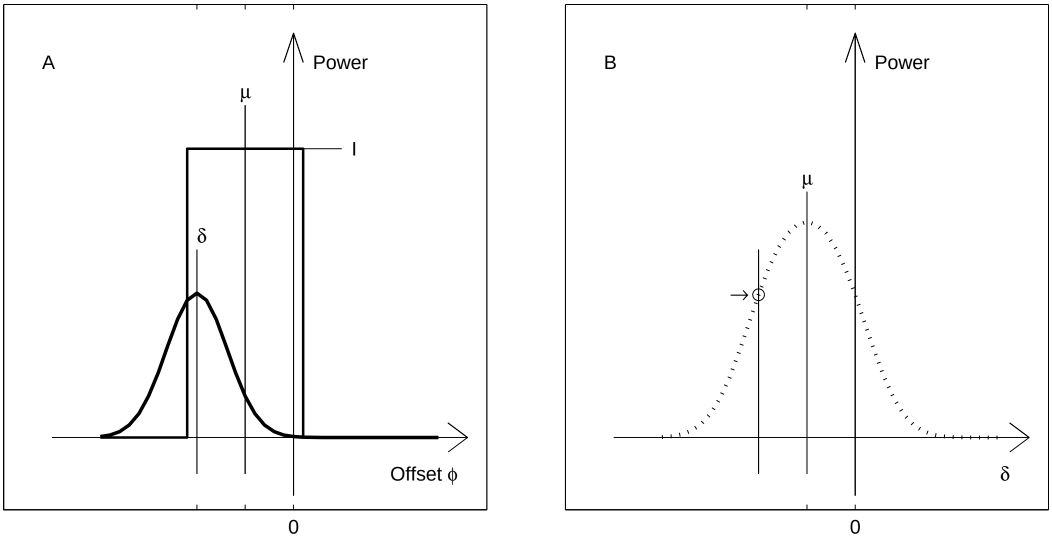

Figure 1. Illustration of the principle of modelling the power captured by an antenna scanning over the Sun. (A) Antenna coordinate system ϕ with the rectangular intensity distribution of the Sun. The apparent pointing error of the antenna is μ. The gaussian beam pattern pointing in the direction δ is also shown. (B) Distribution of power received from various directions δ. The value corresponding to the situation in Fig. 1A is denoted by an arrow.

Scanning the beam over the point source would thus give a two-dimensional picture of the beam pattern. The situation is more complicated in the case of the Sun, since it is not a point source but a finite circular disc with an optical angular dimension of about 0.5 degrees. This is half of the beam width of a typical 1 degree weather radar antenna. As a result, a scan over the Sun does not produce a picture of the radar beam pattern but a combined picture of the beam and the source. In order to extract the real beam pattern from this kind of measurement one should know the spatial distribution of radiation over the whole solar disc and have some a priori information on the shape of the beam under investigation (Kuz'min and Salomonovich 1966).

Assuming the antenna main lobe to be gaussian and assuming the Sun to be a circular disc of known radiation pattern on a known background, the power captured by the antenna can be theoretically calculated for any beam width and any pointing direction. Antenna parameters can now be obtained by finding the values of the width of the beam and the pointing error which together minimize the difference between the measured radiation pattern and the theoretical gaussian pattern.

Following the derivation by Puhakka (2002), let ϕ denote the angular coordinate (azimuth or elevation) in the coordinate system of the antenna, where the Sun's centre is assumed to be at the origin, i.e. $\phi = 0$, (see Fig. 1A). Due to pointing errors in the antenna system, the centre of the Sun is actually not exactly at $\phi = 0$ but displaced by an angle μ from the origin. If δ denotes the pointing direction of the antenna in this coordinate system, the normalized power in the gaussian main lobe (as a function of ϕ) can be written as

$$P_n = e^{-B(\phi-\delta)^2}, \tag{2}$$

where B is related to the half-power beam width α by

$$\alpha = 2\sqrt{\frac{\ln(2)}{B}}. \tag{3}$$

Assuming the intensity of radiation I constant over the whole cross-sectional area of the Sun, the power received by the antenna from the Sun can be calculated by multiplying I by the normalized beam pattern Eq. (2) integrated over the angular diameter of the Sun (from $-\omega$ to $+\omega$, Fig. 1B). Integration limits should be adjusted according to the pointing error μ of the antenna and we get

$$\begin{aligned} P &= I \int_{\mu-\omega}^{\mu+\omega} e^{-B(\phi-\delta)^2} d\phi \\ &= \frac{I}{2}\sqrt{\frac{\pi}{B}} \left(\mathrm{erf}\left(\sqrt{B}\,(\mu+\omega-\delta)\right)\right) \\ &\quad -\frac{I}{2}\sqrt{\frac{\pi}{B}} \left(\mathrm{erf}\left(\sqrt{B}\,(\mu-\omega-\delta)\right)\right). \end{aligned} \tag{4}$$

By adding the constant part of the background radiation P_c and its angle-dependent component P_g (mainly radiation and reflections from the ground), we get finally

$$\begin{aligned} P &= \frac{I}{2}\sqrt{\frac{\pi}{B}} \mathrm{erf}\left(\sqrt{B}\,(\mu+\omega-\delta)\right) \\ &\quad -\frac{I}{2}\sqrt{\frac{\pi}{B}} \mathrm{erf}\left(\sqrt{B}\,(\mu-\omega-\delta)\right) + P_c + P_g\delta\,. \end{aligned} \tag{5}$$

By optimizing the constants B, I, μ, P_c and P_g, the difference between values obtained from Eq. (5) and the real measurement can be minimized. Thus one measurement gives both the half-power beam width α and the apparent pointing error of the antenna μ.

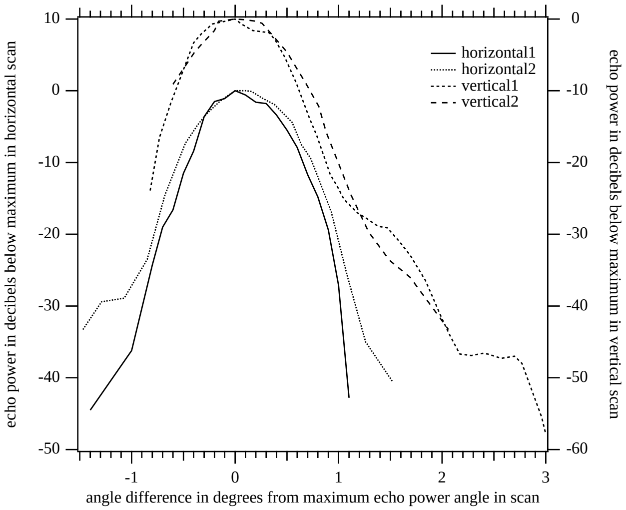

Figure 2. Relative received power from two telecommunication masts 27.2 km (mast 1) and 49.1 km (mast 2) away from the radar site. These measurements give half-power beam widths of $0.87°$ and $0.97°$ (mast 1) and $1.03°$ and $1.01°$ (mast 2) for the horizontal and vertical beams, respectively.

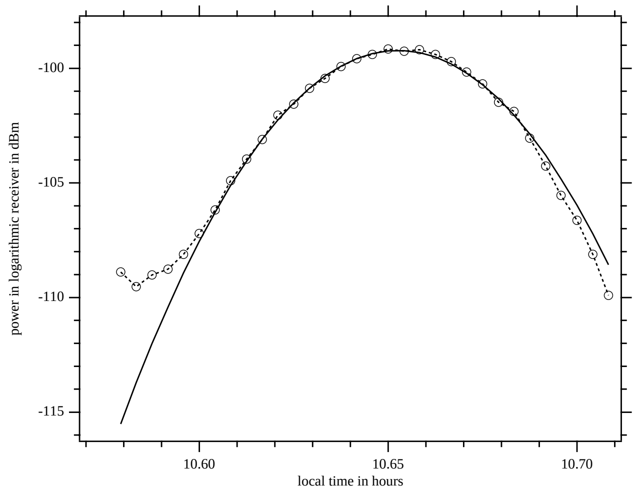

Figure 3. Observed values of the received power during a passage of the Sun through a stationary beam as a function of local time (small circles). The unbroken line shows the corresponding simulated values obtained using a gaussian main lobe with a beam width of 0.94 degrees.

The derivation above assumes a constant intensity I over the solar disk and a gaussian main lobe of the beam. If either of these assumption are incorrect, the optimizion is still possible, provided that the distribution of the intensity and the general shape of the main lobe are known. In this case the intensity I should be moved inside the integral in Eq. (4), in which the beam pattern should also be changed if it is not gaussian. With these modifications the integral should be estimated 2-dimensionally.

2.2 Scanning strategies

In this model the beam is scanned only once through the centre of the Sun. As both the antenna beam pattern and the solar radiation pattern are two-dimensional, the complete model should be two-dimensional as well. However, in the case of a symmetrical beam and circular Sun, a scan through the centre of the Sun gives a good approximation to the whole beam. Scanning the Sun in two perpendicular directions yields information on the ellipticity of the beam.

Two different ways of doing the scan over the Sun were used in the present study. In the first method, the antenna tracks the centre of the Sun continuously while scanning the angle δ over a certain sector, say from $-1.5° \ldots 1.5°$. The method allows rather fast and simple measurements of both horizontal and vertical scans, but it demands a specialized astronomical control program and high precision in antenna positioning. This method was used with the experimental antenna in this study intended primarily to monitor the activity of the Sun at 11.7 GHz.

A pointing accuracy of about 0.1 degree, typical for most weather radars, does not allow such accurate tracking. For this reason the antenna of the C-band weather radar used in our experiment was held stationary in the track of the Sun, and the power received was measured while the Sun was passing. Thus only one inclined track was measured. In this scanning strategy any tracking errors are avoided. Both scanning strategies require a precise algorithm for locating the Sun as a function of time.

3 A C-band weather radar antenna

The Department of Meteorology of the University of Helsinki has operated a C-band Doppler weather radar (WSR81C-D manufactured by Enterpise Electronics Corp.) since 1984. According to the measurements made at the factory in 1983, the beam widths of its parabolic 4.3 m dish without the radome were $0.89°$ and $0.97°$ in the horizontal and vertical respectively. At its present location in Helsinki the beam pattern has been studied primarily using isolated ground targets, such as telecommunication masts and lighthouses some 20–50 km from the radar. The results (e.g. in Fig. 2) have in general been comparable with the factory measurements.

Isolated targets were also used to check the azimuth scale of the antenna. Attempts to use the Sun in a similar way to determine the pointing errors in the elevation angle were unsuccessful, mainly due to the poor manual pointing accuracy of the antenna.

For this reason a new approach was used. The position of the Sun was calculated using equations published by WMO (1983). The antenna was pointed to the expected azimuth and elevation, and the power received was measured while the Sun was passing. The time of the maximum power could now be considered to be related to the actual azimuth angle of the Sun. The deviation of this azimuth from the simultaneous

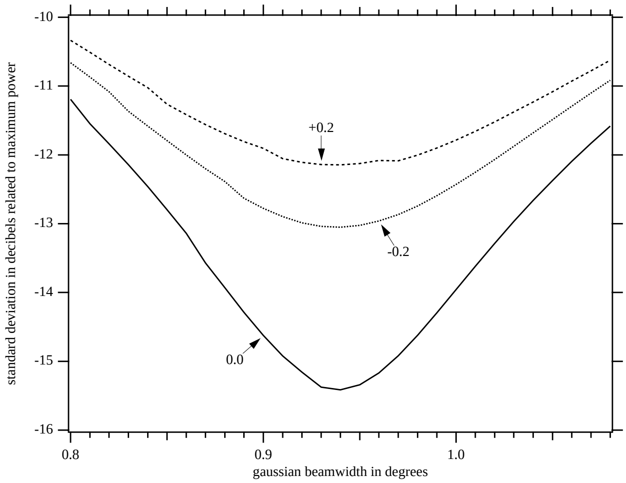

Figure 4. Root mean square (RMS) difference [dB] between the powers received in a real solar measurement and the corresponding simulated measurements as a function of the gaussian beam width used in the simulation. Results achieved using three different values of the elevation angle error (-0.2, 0 and $+0.2$ degrees) are shown.

reading from the antenna system is the azimuth error of the antenna.

To find the beam width and the error in the elevation angle, the power values received during the passage were compared to corresponding simulated values. The antenna was simulated using a gaussian beam, defined by its horizontal and vertical half-power beam widths. The Sun was simulated using a number of hypothetical radiating point sources distributed over the area of the solar disc. The intensities at the radiating points were normalized so that the maximum values obtained by the simulation and by actual measurement were equal. The time difference between each measurement and the measurement giving the maximum power was used to position the solar disc in relation to the antenna beam. These numerical procedures do not limit the forms of the beam pattern or the radiation pattern over the solar disk.

Figure 3 gives an example of measured values together with a simulation having the best-fitting beam width. The simulations were further repeated by inserting small errors in the elevation angle. All the simulations were finally compared with the actual power distribution received during the passage of the Sun.

Figure 4 represents the root mean square (RMS) differences between the actual measurement and the simulations as a function of simulated beam width for three elevation angle errors. The elevation angle error corresponding to the smallest RMS difference is an estimate of the actual error in the elevation. The simulated antenna beam width corresponding to the smallest RMS difference is an estimate of the actual beam width in the case of a circularly-symmetric gaussian beam. According to Fig. 4 the elevation angle error is obviously 0 degrees and the beam width is 0.94 degrees. One can also see that the beam width estimate is not influenced by small errors in the elevation angle.

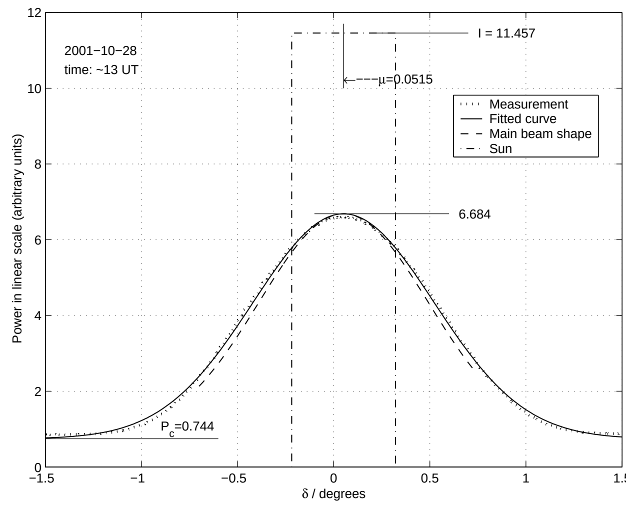

Figure 5. A vertical scan over the Sun with the Metsähovi solar antenna. The apparent pointing error was 0.0515 degrees. The optimized simulation corresponds well to the measured signal from the scan. For comparison, the gaussian main lobe ($\alpha = 1.037°$) giving the best fit in the simulations is plotted on the same scale as the other curves.

Both the analog logarithmic receiver and the linear receiver followed by an RVP7 digital IF-receiver/signal processor were used in this experiment. Using the RVP7, the received power was estimated from 2048 samples of the incoming signal. The signal from the conventional logarithmic receiver was sampled by a digital oscilloscope, and about 13 000 samples were integrated. As a result the RMS differences had a clearly more pronounced minimum when using the logarithmic receiver than with the digital IF receiver.

4 Commercial satellite-TV antenna at 11.7 GHz

A total power radiometer for continuous 11.7 GHz solar observations was built at the Metsähovi Radio Observatory between 1999 and 2000 (Puhakka 2002). The telescope is based on commercial and affordable technology. For example, the antenna itself is a parabolic 1.8 m satellite-TV dish equipped with a universal C120 microwave front end used normally to receive satellite-TV broadcasts. In this specific application, only the increase in noise level caused by the observed source is of interest. The receiver band-width is 2 GHz and the dynamic range in the linear channel of the receiver is approximately 5000 K in antenna temperature, corresponding to a received power of 0.14 nW. The radiation power of the quiet Sun lies in the middle of the dynamic range, corresponding to 2500 K.

The beam measurements on the antenna were done between 28 October and 1 November 2001 while the Sun was above the horizon at the observatory site (Puhakka, 2002). The antenna tracked the Sun, making short $\pm 1.5°$ scans over it both in the horizontal and vertical directions. This kind of cross scan was repeated every half hour between 07:00 and

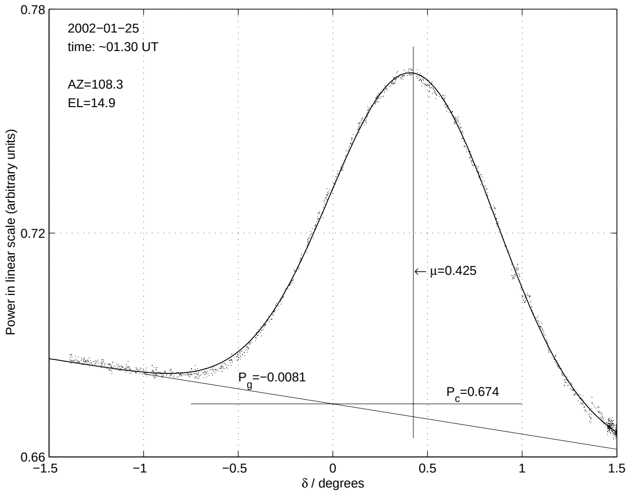

Figure 6. An example of an elevation scan at low elevation angles. Radiation from the ground decreases linearly with increasing elevation. This measurement was made with the Metsähovi solar antenna scanning the Moon, but was not used for calculations of the main beam shape.

13:30 UT.

The signal received, as well as the values of δ for both azimuth and elevation, were recorded as a function of time. The observed signal level was expressed as a function of offset by combining these records, following which the difference between the measured signal and Eq. (5) was minimized using a method in the Matlab program (fmins-function). This is based on the Nelder-Mead method of direct search, which also allows one to minimize functions having non-linear behaviour. For each day the angular radius ω of the Sun given in the Astronomical Almanac 2001 was used (USNO, 2001). This value was multiplied by 1.03 in order to get the correct value for centimetre wavelenghts (Kuz'min and Salomonovich, 1966).

An example of an elevation scan is given in Fig. 5. In principle the antenna should be scanned precisely through the centre of the Sun. However, if there is a small pointing error, say less than one tenth of the size of the source, its effect is not important. Since the pointing error varies systematically during the day, only the observations having the smallest errors were selected. These were obtained around noon in condiotions of minimum atmospheric refraction.

In the derivation of the optimized simulation curve in Fig. 5, the background radiation level was assumed constant (P_c). For comparison, a scan over the Moon is presented in Fig. 6. There both P_c and P_g have to be taken into account because of the low elevation angle and the low radiating intensity of the Moon.

The horizontal and vertical beam widths, α_H and α_V, were calculated as mean values of all the successful measurements (35 per direction in total). The results, with their standard deviations, are given in Table 1.

As can be observed, the radiation pattern of the antenna

Table 1. Results for the main beam parameters of the Metsähovi solar antenna. α is the half-power beam width calculated from the parameter B of the gaussian function of the main beam shape. Subscripts H and V refer to horizontal and vertical respectively.

Symbol	Value	Unit
B_H	2.10 ± 0.06	$(^\circ)^{-2}$
α_H	1.15 ± 0.02	$^\circ$
B_V	2.50 ± 0.03	$(^\circ)^{-2}$
α_V	1.05 ± 0.01	$^\circ$

is slightly elliptical, the vertical beam width being approximately 10 percent smaller than the horizontal. However, the values are in good agreement with the rough approximation of approx. 1 degree for a dish of radius 0.9 m receiving at a frequency of 11.7 GHz.

5 Concluding remarks

The present method for estimating antenna beam parameters uses the Sun as an external radiation source. No artifical radiation sources or reflectors are needed. As the Sun travels through a considerable range of elevation angles, beam parameters can easily be obtained for various elevation angles. This is not possible with other methods.

No exact absolute values of the solar radiation are needed for estimating the beam width and pointing error. All one has to know is that the activity of the Sun is steady during the measurement. The transmission properties of the atmosphere should also remain constant. Sudden rain showers or clouds, for example, cause major fluctuations in signal level.

A small error in the elevation angle does not cause an error in the estimation of the beam width. Although the root mean square difference between the actual received power and the model increases, the minimum is still found at the same beam width.

Non-standard equipment is not needed. The measurements can in principle be made using standard radar signal processors and receivers. However, standard weather radar signal processing methods do not perhaps give optimal results as they are based on range sampling and integrating echoes from some 256 or so pulsed transmissions. As the Sun is a continuous source of radiation, simple continuous integration of the incoming signal, as with the solar radiometer used in this study, can increase the signal-to-noise ratio considerably. This increases the otherwise small dynamic range available for the weak signals from the Sun.

Sun measurements also open up some interesting possibilities for comparing different receiving systems. For instance, unlogarithmical features in the logarithmic receiver and effects caused by the signal being near the background noise level are present in the measured power values. Weather echoes are quite often rather weak, especially at long ranges.

Thus, better knowledge of the receiver response for weak signals is important.

Measurements were rather simple to implement with the solar radiometer and an explicit result for beam width was obtained. However, it should be noted that this antenna is primarily dedicated to solar observations and therefore the experimental setup and signal processing did not need any special adjustments. The solar signal lies in the middle of the dynamic range of the radiometer, whereas with the weather radar the signal is close to the noise floor of the receiving system.

References

Eastment, J.D., Goddard, J.W.F., Davies, G.J., Ladd, D.N., and Twort, K.J., Boresight pointing calibration for the Chilbolton radar using galactic radio sources and satellite targets, 30th International Conference on Radar Meteorology, Munich, A.M.S., 23-25, 2001.

Kuz'min, A.D., Salomonovich, A.E., Radioastronomical Methods of Antenna Measurements, Academic Press, New York, 182 p., 1966.

Manz, A., Smith, A.H., and Hardaker, P.J., Comparison of different methods of end calibration of the UK weather radar network, International Conference on Radar Meteorology, Munich, A.M.S., 20-22, 2001.

Puhakka, P., Total Power Radiometer in Solar Microwave Research, Master's Thesis in physics (written in Finnish), University of Helsinki and Metsähovi Radio Observatory, 70 p., 2002.

Smith, P.L., Calibration of weather radars, Thirteenth Radar Meteorology Conference Proceedings, Montreal, A.M.S., 60-65, 1968.

USNO, 2001, Astronomical Almanac, United States Naval Observatory, C1-C19, 2001.

Whiton, R.C., Smith, P.L., and Harbuck, A.C., Calibration of weather radar systems using the Sun as a radio source, 17th Conference on Radar Meteorology, Seattle, A.M.S., 60-65, 1976.

WMO, 1983, Guide to meteorological instruments and methods of observation, World Meteorological Organization (WMO–No. 8), Fifth edition, 1983.