Calibration of the Doppler on Wheels System Gain using Solar Flux

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Abstract

A convenient method of calibrating mobile weather radar is presented. This method utilizes the relationship between solar flux and power to calculate the effective system gain. On 14 April 2002 the Doppler On Wheels (DOW) was utilized to measure the maximum solar power emitted by the Sun at 2136 UTC. Using the solar flux measured by the Dominion Radio Astrophysical Observatory in Penticon, British Columbia the DOW system gain was calculated.

1 Introduction

To maximize the usefulness of weather radar as a remote sensing device it must be able to provide accurate measurements including backscattered power and calculate reliable values of equivalent reflectivity. In order to achieve this the radar system must be properly calibrated. Perhaps the most important calibration is the measurement of the effective antenna system gain G_e, a weather radar equation variable. Continuous calibration and testing are essential to the preservation of low measurement errors and the discovery of problem conditions. Various techniques exist to calculate G_e but arguably the most convenient method involves using the sun as a wideband source of quantized electromagnetic energy. In this technique, the Sun is used as an extraterrestrial radio source of known intensity to which the radar listens passively while measuring its radiation received in the radar's bandwidth. The data made available in this way can be used to determine the effective antenna system gain.

The methods described herein have the advantage that the radar is calibrated while assembled in its actual operating configuration, so the performance measurements made will represent the operational behavior of the system. Little or no test equipment is required. The techniques are simple and require no modification of the radar (Whiton *et al.*, 1976).

2 Theory of antenna gain measurement using solar flux

The gain of an antenna is the ratio of the power that is received at a specific point in space (on the center of the bean axis, i.e., at the point where the maximum power exists) with the radar reflector in place to the power that would be received at the same point from an isotropic antenna (Rinehart, 1997). An isotropic antenna is a hypothetical antenna that radiates or receives equally in all directions. Isotropic antennas do not exist physically but represent convenient reference antennas for expressing directional properties of physical antennas.

The determination of antenna gain lies in the fixed relationship between antenna gain and antenna effective area. Silver (1949) defines the antenna gain, g (unitless), by

$$g = \frac{4\pi A_e}{\lambda^2}, \tag{1}$$

where A_e is the antenna effective area (m^2) and λ is the radar wavelength (m). The solar flux can be used to estimate antenna gain by the following simplified steps (Sirmans *et al.*, 2001):

The solar power received by the radar is given by

$$\hat{P}_r = S \cdot BW_n \cdot A_e, \tag{2}$$

where $\hat{P}_r$ is the DOW received solar power (watts), S is the solar flux (W m^{-2} Hz^{-1}), BW_n is the receiver noise bandwidth (Hz), and A_e is the antenna effective area (m^2). Using the known solar flux and the relationship between gain and effective area, the antenna estimated gain is:

$$g_e = \frac{4\pi}{\lambda^2}\left[\frac{\hat{P}_r}{S \cdot BW_n}\right] \tag{3}$$

Since antenna gain g_e is actually a power ratio, we can thus write it in logarithmic form as:

$$G_e = 10Log_{10}\left[\frac{4\pi}{\lambda^2}\left(\frac{\hat{P}_r}{S \cdot BW_n}\right)\right] \tag{4}$$

Therefore, if the solar flux density and receiver noise bandwidth are known, the received power provides an estimation of the antenna effective area, which specifies antenna gain.

There are several other gain calibration methods that are much more rigorous but provide a higher degree of accuracy. These methods are beyond the scope of this paper but are discussed in detail by Brunkow (1998) and Sirmans (2001).

3 Characteristics of Solar Flux

3.1 Solar observatory measurements

Solar flux density measurements are utilized routinely for antenna pointing accuracy verification and have also been examined for antenna gain checks for some time [Andrews, 1969; Pratt and Ferraro, 1989; and Tapping, 1994]. However, only recently has the accuracy of observatory measured solar flux values become accurate enough to provide a useful verification for antenna gain. Several considerations should be taken when using reported values of solar flux including the frequency, quality, and time of observation. Numerous solar observatories report daily flux values though the quality varies widely. As an example, Robinson (2000) notes that Sagamore Hill doesn't make an absolute measurement but does maintain consistency within their network. Any site that deviates from their mean by more than 10% are adjusted to agree. About once a decade observatories compare their measurements with a known celestial source.

A reliable source of daily solar flux values is the Dominion Radio Astrophysical Observatory in Penticon, British Columbia. These measurements typically have an absolute accuracy of 1% or 1 solar flux unit (sfu, 10^{-22} Wm^{-2} Hz^{-1}), whichever is larger, and an observational frequency of 2800 MHz (Tapping, 2000). Archived daily values may be found on the observatory's web site at `http://www.drao.nrc.ca/`.

The Penticon observatory expresses the 10.7cm solar flux in three values: The "observed", "adjusted" and "URSI Series D" value. The "observed" value is the number measured by the solar radio telescope. It's a function of solar activity and the changing distance between the Earth and the Sun. Since it's a measure of the emissions due to solar activity hitting the Earth, this is the quantity used in this study. The "adjusted" value is the solar flux corrected for variations in the Earth-Sun distance, and given for the average distance. Finally, the "URSI Series D" flux is the "adjusted" value multiplied by 0.9. All values are given in solar flux units.

The daily schedules of the Penticon observations vary with the time of year due to the combination of location in a mountain valley and relatively high latitude. Between March and October, measurements are made at 1700, 2000, and 2300 UTC. From November through February, the flux determination times are changed to 1800, 2000, and 2200 so that the Sun is high enough above the horizon for a good measurement to be made. It is especially important during intense solar activity to coordinate the DOW solar power measurements to coincide with solar flux measurements being made at the observatory. This will limit any variability in the data caused by solar bursts.

3.2 Solar flux adjustments

The observation frequency is important since the solar flux density varies with frequency. The DOW transmits at a frequency of 9370 MHZ and as such, the reported solar flux must be adjusted. For estimating solar flux at frequencies other than 2800 MHz, an extrapolation formula offered by Tapping (1994) is given by

$$S_f = (\alpha S_{10} + \beta)(f - 2800) + S_{10}, \tag{5}$$

where S_f is the flux density at the required frequency (sfu), S_{10} is the flux density at 2800 MHz (sfu), f is the required frequency (MHz), α is equal to 0.0002, and β is equal to -0.01. Tapping established the relationship using theory and empirical data and most of the time has an error of only 2%.

All observations are solar flux measurements at all polarizations and must be reduced by a factor of two for comparison with the single polarization measurements of the DOW. This should be done after the flux density for the required frequency has been extrapolated via Equation (5).

4 Data collection using the Doppler on Wheels

4.1 Deployment site

Data was collected on Sunday 14 April 2002. A clear stretch of highway south of Mustang, Oklahoma was chosen for its flat topology and unobstructed view of the Sun. A cold front had passed through central Oklahoma the previous night leaving in its wake dry air and subsidence. The sky was cloudless and provided perfect conditions to collect solar power measurements.

4.2 Scan strategies

To aid in pointing the dish, the Sun's altitude and azimuth for the day, in 2-minute intervals, were calculated via the U.S. Naval Observatory's web site (`http://aa.usno.navy.mil/`). The first scans performed were a set of range-height indicators (RHIs) in 5-degree increments centered near the Sun. Though the dish may not have passed directly through the center of the Sun it was obvious between which azimuths the Sun was located. Approximately 20 minutes of single-azimuth RHI scans, several degrees ahead of the Sun, were then performed. The benefit of this was that data was collected of the Sun passing completely into and out of the radar's plane, insuring that the maximum solar power was measured. A pulse repetition frequency of 2667 Hz was chosen somewhat arbitrarily, providing a gate length of 13 meters.

It should be noted this data was not collected in passive mode; in fact the truck was transmitting at the time. Though this oversight did not contaminate the measured signal, future system gain calculations using the solar technique should be conducted with the transmitter turned off or in stand-by mode.

Figure (1) shows the RHI scan when the maximum signal was present. Notice the sharp concentration of high power values in an approximate 1-degree arc centered at an elevation of 40 degrees. Because the transmitter was operating at the time the boundary layer is also evident in the scan. The maximum solar power measured by the DOW (as derived using the Solo2 program) was -102.4 dBm at 2137 UTC. This value was converted to units of watts using the following equation

$$P = 10^{\frac{P[dBm]}{10}} [mW], \tag{6}$$

resulting in a power measurement of 5.75x10^{-11} mW or 5.75x10^{-14} W.

4.3 Beamwidth correction

The DOW observed solar power requires a beamwidth correction for comparison with the observation. Sirmans *et al.* (2001) explain that since the radio sun (0.56 to 0.58 degrees) subtends an appreciable fraction of the 3 dB antenna beamwidth (0.93 degrees), the radar measurement is a weighted average, not the peak value reported by the observatory. (The Penticon antenna beamwidth is 5 degrees and no correction for beamwidth is made.) The beamwidth correction is derived by averaging the product of the antenna pattern and solar radiation over the angle subtended by the solar disk. Beamwidth correction factor, k, is given as

$$k = \left[1 + 0.18\left(\frac{\theta_s}{\theta_3}\right)^2\right]^2, \tag{7}$$

where θ_S is the angle subtended by the optic Sun (degrees) and θ_3 is the antenna 3 dB beamwidth (degrees). In the northern hemisphere, the angle subtended by the radio Sun is at a minimum on the winter solstice and a maximum on the summer solstice. Because the 14^{th} of April is about halfway between these two dates (perhaps a crude approximation) the average solar disk angle of 0.5708 degrees was used.

5 Antenna gain calculation

Once the maximum solar power was determined and the observatory measured solar flux values were reported the effective system gain could be calculated. The following are the steps taken to calculate this value:

5.1 Solar flux

On the day in question the Penticon Observatory conducted solar flux measurements at 2000 and 2300 UTC. The "observed" flux was

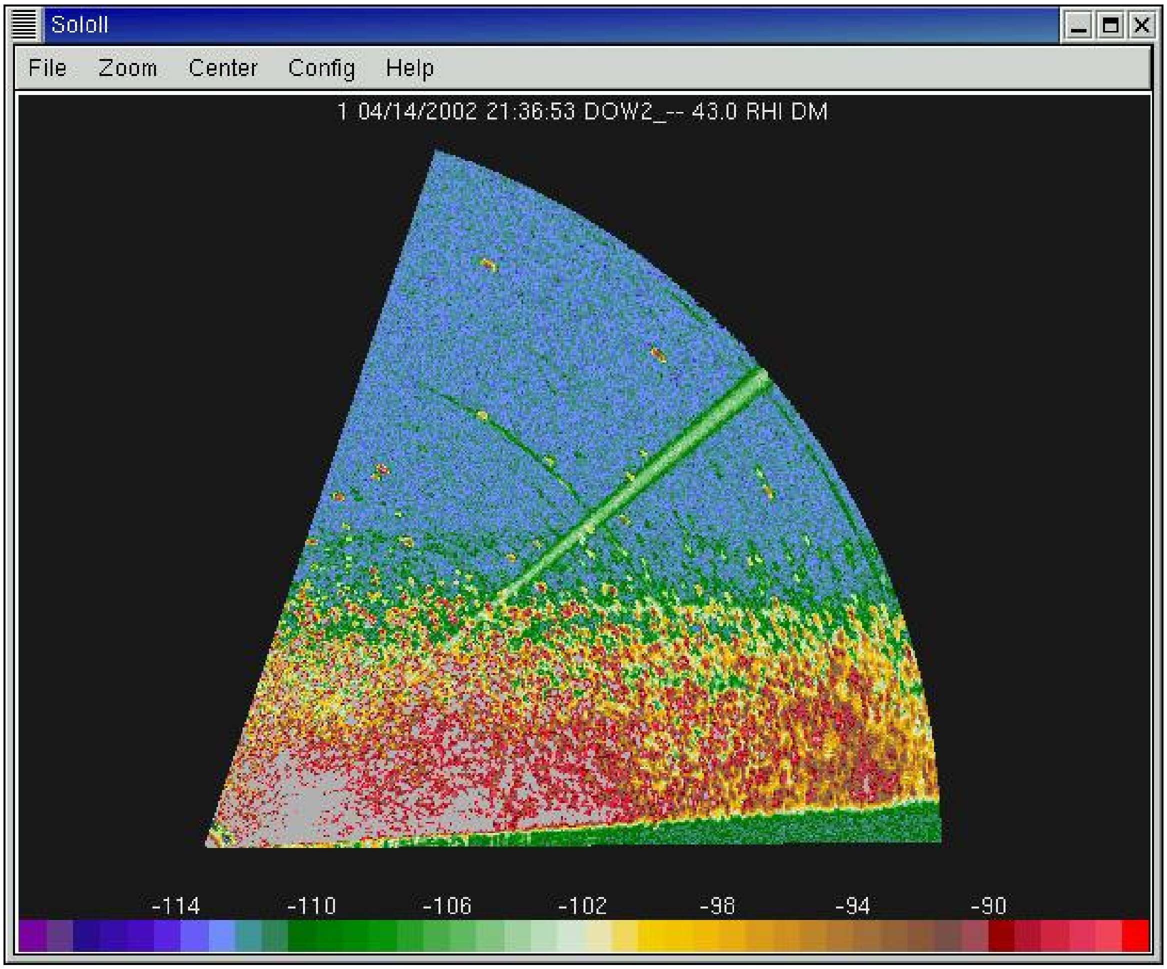

Figure 1: RHI scan showing maximum solar power of -102.4 dBm at 2136 UTC on 14 April 2002.

reported to be 210.3 sfu at 2000 UTC and 214.5 sfu at 2300 UTC. The maximum solar power recorded by the DOW occurred roughly halfway between these times and thus an average of the two was used, 212.4 sfu.

Recall that this value is the solar flux at 2800 MHz and must be estimated for the frequency of the DOW. Using a frequency, f, of 9370 MHz and a solar flux density at 2800 MHz, S_{10} , of 212.4 sfu, Equation (5) produces a corrected solar flux density, S_f, of 425.79 sfu.

This value must be reduced by a factor of two in order to correct for polarization issues as discussed in Section 3.2. Thus, the final solar flux value at the DOW frequency was calculated to be 212.90 sfu.

5.2 Solar power

The maximum solar power recorded by the DOW was -102.4 dBm or $5.75\text{x}10^{-14}$ W. Equation (7) provides a beamwidth correction factor of 1.1402, resulting in a final DOW maximum recorded solar power value of $6.56\text{x}10^{-14}$ W.

5.3 Receiver noise bandwidth

The receiver noise bandwidth was estimated by Dr. Josh Wurman to be 12 MHz. This was, in part, a function of the gate length used while collecting the solar power.

5.4 Effective system gain

The following values were then used with Equation (3):

$$\hat{P}_r = 6.56\text{x}10^{-14}\ \text{W}$$
$$\lambda{=}0.032\ \text{m}$$
$$S_f{=}212.90\text{x}10^{-22}\ \text{Wm}^{-2}\text{Hz}^{-1}$$
$$BW_n{=}12\text{x}10^{6}\ \text{Hz},$$

resulting in an effective antenna system gain of 3151.1 or, using Equation (4), a gain of 35.0 dB.

6 Conclusions

The effective antenna system gain of portable weather radars can be measured by simple solar techniques well suited to the field environment. The gain of the Doppler On Wheels truck was measured to be 35.0 dB. On first inspection this number seemed a bit low. This could be caused, in part, by an inflated receiver noise bandwidth value or system attenuation resulting in an underestimated maximum solar power. The techniques described herein lay the groundwork for future solar calibrations of the DOW trucks and provide a convenient test of possible system failures.

7 Acknowledgments

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