P16.15

AUTOMATED SOLAR GAIN CALIBRATION

J. F. Pratte and D. G. Ferraro

NCAR/FOF*, Boulder, Colorado

1. Introduction

The characterization of a radar is accomplished in three stages: calculation from basic assumptions and properties, laboratory measurement, and field testing. Calculations are the foundation for the design, bench measurements confirm the design of components and assemblies, but evaluation in the field is the closest confirmation of total system performance short of actual long-term experience. As part of field evaluation, solar calibration gives a convenient, in-place measurement of several system parameters. With modern meteorological radars designed for quantitative measurement of precipitation, continuous calibration and testing are essential to the preservation of low measurement errors and the discovery of problem conditions. Solar calibration uses the sun as a quantified microwave source for measurements of antenna main beam width, differential attenuation, pointing accuracy and gain, plus receiver bandwidth and noise temperature.

Frush (1984) covered the basics of solar calibration; we give a specific example with the CP-2 radar (Keeler, et al., 1989). Since the advent of digital processors on weather radars, and software-controlled antenna scanning, the effort of collecting and reducing the appropriate measurements has become small. Using the digital signal processor seems like a preferred way to acquire solar data with a meteorological radar. Gain established through solar calibration will likely be reciprocal for transmit, except for CP-2's polarization switched mode, and measurements can be made with the transmitter on or off. Our work suggests that the procedures could be automated, providing very repeatable results, free of manual errors, and consistent with intrinsic uncertainties.

In this note we will review the practice of solar calibration and then describe our procedure. The NEXRAD weather radars will become operational soon. Simultaneous solar calibration across the network would improve the consistency of reflectivity factor Z_e estimates. Hydrologic applications, for example, the have a measurement goal of Z_e within 1 dB (NEXRAD, 1986). Three critical parameters can be measured and monitored through solar calibration (Doviak and Zrnic, 1984): the radar system gain, which includes losses to the antenna, is a squared factor in the weather radar equation; beamwidth is squared, and noise bandwidth appears in the detection loss factor.

1.1 Gain Measurement

Measurement of large antennas with extraterrestrial radio sources is outlined in the IEEE Standard Test Procedures for Antennas (1979). Using the sun as a source avoids the difficulties of setting up a test range for gain-transfer or sphere calibrations.

The LNA and the quality of the antenna in Figure 1 set the system noise power kBT_o. The coupler forward of the LNA is a reference point, the division between antenna and receiver-processor, and the spot to inject a test signal, for example: a "hot" noise source (T_h), a room temperature noise source (T_c), or a gated, coherent carrier (test pulse).

A relatively hot physical object emits significant microwave energy. A fictitious black body temperature approximates its emission behavior over a narrow band of frequencies. Such a temperature assigned to a astronomical source like the sun is called the brightness temperature T_b, and an ideal antenna surrounded by such a source has an antenna temperature T_b. If the source subtends but a small angle then

$$T_a = (U_s/U_a)T_b \qquad (1)$$

where U_s and U_a are the equivalent solid angles of the source and the larger antenna beam (Kraus, 1986).

Antenna temperature has five contributions: the sun, sidelobe pickup, cosmic emission, atmosphere, and the equipment itself; here T_a refers to the total background emission without the sun. The effective noise temperature of the sun is an excess temperature T_s above the background (or blue-sky) T_a. The equivalent noise temperature of the receiver at the reference point is T_r; the sum of T_a and T_r is the system operating temperature T_o at the reference point.

There are three steps in the solar gain measurement. First, the power difference between hot and cold thermal sources, of known noise temperatures establishes the slope of the underlying power versus noise temperature relation for the radar receiving system.

$$P_h - P_c = kB(T_h - T_c) \qquad (2)$$

The difference in noise power P in bandwidth B is proportional to the known source noise temperature difference; k is Boltzmann's constant (1.38×10^{-23} joules/°K). Second, received power difference on and then

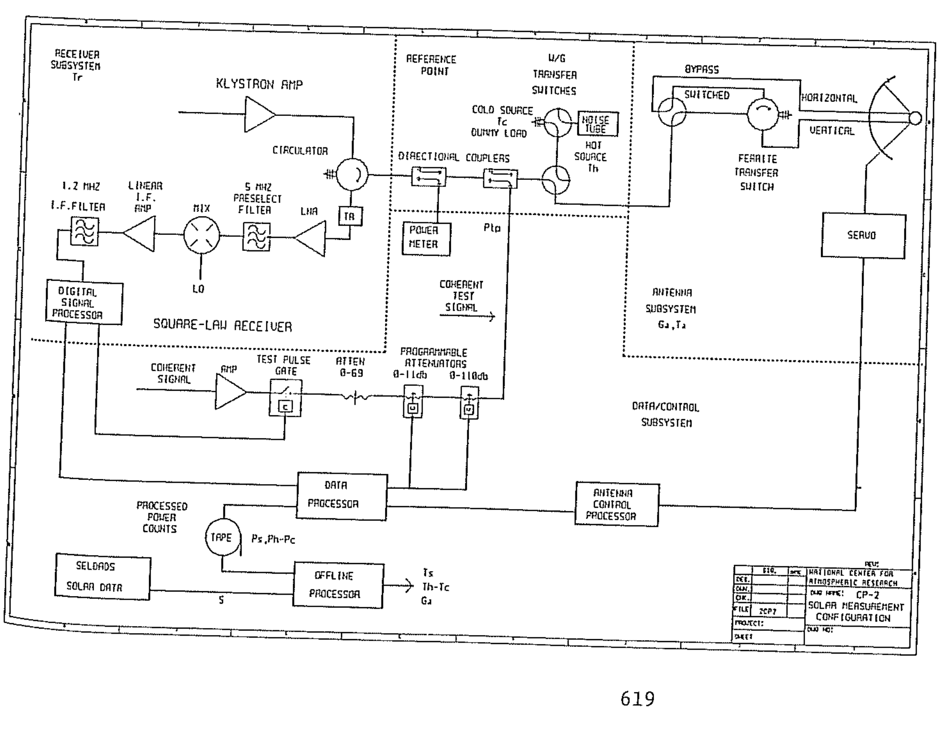

Figure 1. CP-2 solar measurement configuration has permanently installed noise sources, directional couplers, waveguide switches, programmable attenuators, and data processing/recording/antenna control software.

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

off the sun yields Ts, given B, by converting solar power excess P_s into antenna temperature excess T_s. Third, the final gain G_a calculation uses observatory values of solar flux density after appropriate corrections. Further explanation follows.

From differences in received powers and noise-source temperatures, the sun temperature through the antenna system can be calculated from the relationship in Figure 2:

$$T_s = P_s(T_h-T_c)/(P_h-P_c) \tag{3}$$

```
  Th+Tr |                                      +
Ts+Ta+Tr |                           +
   Tc+Tr |                   +
   Ta+Tr |          +                  T = P/kB
      Tr |  +
         +---------------------------------------
            Pr   Pa+Pr  Pc+Pr  Ps+Pa+Pr   Ph+Pr

              Reference Point Noise Powers
```

Figure 2. Receiver noise power, noise temperature line.

The fundamental relationship between effective aperture and excess sun temperature for unpolarized radiation is

$$A_e = kT_s/S \tag{4}$$

where S is the source flux density in $W/m^2/Hz$. Thus the effective antenna collecting area, or gain, is the ratio of the measured solar power density at the reference point to the incident solar flux in the vicinity of the antenna. To measure Ae or G_a

$$G_a = 4\pi A_e/\lambda^2 \tag{5}$$

it is necessary to know the absolute intensity of the incident radiation to better accuracy than that desired in the G_a. From (4) and (5) an estimate can be made of the antenna-system gain G_a

$$G_a = 4\pi kT_s/S\lambda^2 \tag{6}$$

The determination of G_a assumes no sky or receiver noise temperature or bandwidth (except as these enter into the solar observatory's measurement of S). To the gain calculated from (6) we apply corrections for frequency difference of the observed solar flux, for observatory procedural differences, for polarization mismatch (often 3 dB for a linearly polarized antenna), for atmospheric attenuation, for non-centered antenna pointing, for finite source size, for system integration effects, and for non-reciprocal components in the antenna system, as necessary. Radome, waveguide, and impedance-mismatch losses are included implicitly in G_a.

2. Solar Flux Data

An on-line computer connection for solar-terrestrial data, called SELDADS, is maintained by NOAA's Space Environment Laboratory (SEL) and described by Williamson (1976) and Schroeder (1986). Real-time flux measurements are made at fixed frequencies such as 245, 410, 610, 1415, 2695, 2800, 4995, 8800, and 15400 MHz from the US Air Force Radio Solar Telescope Network (RSTN), from the National Research Council (NRC), Ottawa, and from other standard observatories. The Ottawa measurement is the preferred one at S-band in North America. RSTN data have some interference problems at a few sites and frequencies. Solar flux is reported in special units, 1 solar flux unit (sfu) is 10^{-22} $W/m^2/Hz$.

The Ottawa real-time, 2800 MHz, solar fluxes are not adjusted to 1 AU (astronomical unit) distance, but have been corrected to represent the solar output at all polarizations, and have been corrected for atmospheric attenuation. At S-band this correction is very small. Ottawa data are not corrected for the size of the source but a fairly wide antenna beam (5^o) is used. Additionally, the Ottawa staff attempt to remove the effects of solar radio bursts in progress, making the observation representative of the average solar emission. Medd and Covington (1958) and Medd (1961) claimed a probable absolute error of 7% and a relative error of 3% in the Ottawa 10.7cm solar flux observation. With somewhat more stable equipment, a 5% (0.2 dB) probable error is reported nowadays. Tanaka, et al., (1973) describe the method of absolute measurement of solar flux using received power ratios among sun, blue-sky, and zenith.

The RSTN is not a precision observatory network but was set up to patrol the sun's emission and issue real-time reports for the prediction of geophysical effects (AWS, 1988). There are no corrections for antenna beamwidth (3^o at 2695 Mhz), none for atmospheric attenuation, the adjustment from unpolarized emission to a linearly polarized antenna, but the adjustment to 1 AU is made. The RSTN goal is a maximum deviation of 5% from the world standard measurements. Thus the RSTN should have an absolute accuracy of about 7% percent.

Since RSTN corrects the observations in a slightly different way from Ottawa, we expect other world observatories have similar procedural differences of a few tenths of a dB. On SELDADS, comments on the quality of the measurement accompany the daily reported values. If solar radio output is highly variable, generally the observations will be less correlated with ambient flux at the radar.

3. Microwave Emission Characteristics

The sun's radio output varies considerably in time and frequency. Solar conditions are often described by the terms quiet, disturbed, and active. The quiet sun occurs in the absence of localized sources and is due to thermal emission in the solar atmosphere. When there is absolutely no activity the flux at 2800 MHz is roughly 60 sfu. The disturbed sun has an additive component originating from bright regions. Also called the slowly varying component, it exhibits a nominal 27 day periodicity synchronous with solar rotation (see Figure 4). The third or sporadic component is identified with an active sun. Radio bursts, often associated with solar flares, may exceed quiet sun levels by 40 dB. During intense sunspot activity the solar flux density and the apparent center of emission varies unpredictably. This affects precision pointing and gain measurements for very large antennas. Burst enhancement of radio emission has been observed to last up to hundreds of minutes and can increase the solar flux by 3 dB almost instantaneously. These increases are not always reflected in the published solar flux numbers, so it is important to question the short-term stability of the source by checking burst logs on SELDADS. The best time to perform solar calibration is during sunspot minimum; but careful attention to solar variation as seen from collective observatory measurements, and to the radar data itself, should allow calibration even during disturbed solar conditions.

Microwave radiation of different frequencies originate and penetrate the solar atmosphere differently. The quiet sun has an apparent blackbody temperature on the order of 10^{6o}K at low frequencies (100 MHz) and 10^{4o}K at 10000 MHz. The Rayleigh-Jeans radiation law is a useful approximation in the radio spectrum. Given T_b for the frequency band of interest

$$S = 2kT_bU_s/\lambda^2 \tag{7}$$

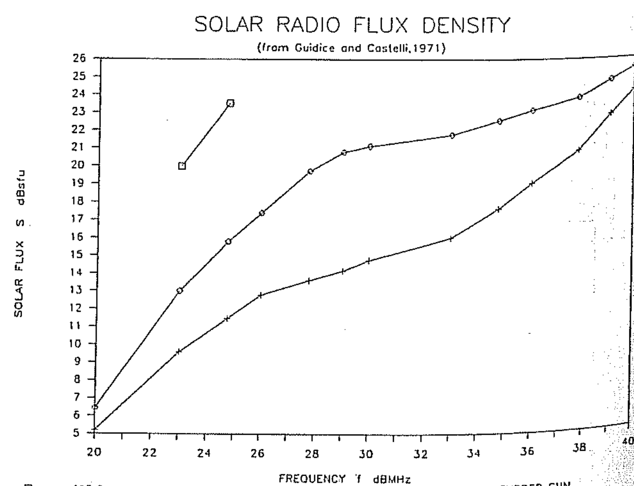

Figure 3. Average radio solar flux density.

The solar flux density is inversely proportional to wavelength squared above and below a knee at about 1000 MHz, whereas the slope in the knee region is less. Altogether the flux spans 20 dB over the radio frequencies of interest. An interpolation formula for solar flux at the radar frequency from measurements at f2 and f1 frequencies follows from Guidice and Castelli, 1971:

$$S = S_2(S_1/S_2)^{[\log(f/f2)/\log(f1/f2)]} \tag{8}$$

An extrapolation formula which may be useful over a band of a few percent under quiet solar conditions is

$$S(f_2) = S(f_1)(f_2/f_1)^{\sigma} \tag{9}$$

where σ is a spectral index different from 2 and varies for S-band from 0.6 at low solar output to 0.4 at high solar flux. With this formula the solar flux at 2695 should average 0.1 dB lower than at 2800 MHz.

The strength of microwave emission is a complicated function of temperature, density, and magnetic field. Meter-wavelength radio emissions originate in the solar corona, the outer layer of the sun's atmosphere, while centimeter-wavelength emissions arise from the lower chromosphere. This affects the size of the sun at any frequency. At meter wavelengths the diameter of the sun is substantially larger than the size of the optical disk (Kundu, 1965). The radio sun at 10cm is about 7% larger at S-band than the optical width, which varies from 0.525 to 0.542° over the year because of earth orbital eccentricity. Emissions from the quiet sun are unpolarized, yet at 10cm and shorter a significant circular polarized component may be present from the active sun. At 3cm up to 30% of the power can be circularly polarized, at 9cm less than 10%, but at 30cm an insignificant amount, during high sunspot activity (Graf et al., 1971). Most observations are made with linearly polarized antennas.

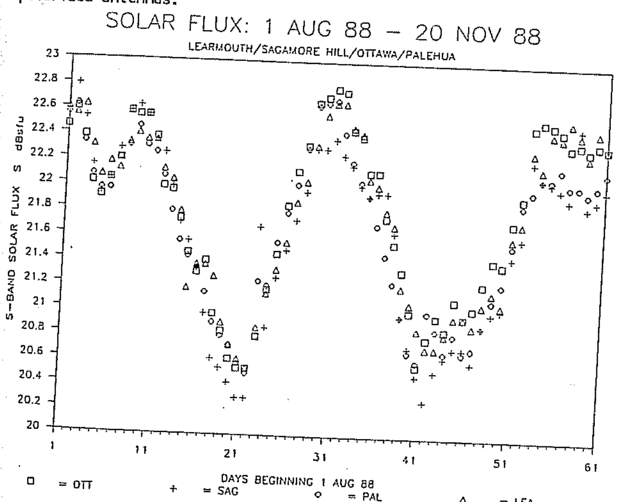

Figure 4. Periodicity of solar output shown from four daily solar flux observations.

We believe Figure 4 illustrates solar variability, where flux reports ranged from 107 to 190 sfu. Uncorrected root mean square differences between Ottawa and each other observatory was about 0.24 dB. As shown, the sun's rotation and activity results in flux variations of a couple dB over a month. Over the 11-year sunspot cycle monthly average 2800 MHz flux varies by more than 10 dB. High fluctuation rate is the rule near sunspot maxima.

4. Procedure

To acquire the solar data we run a sun pointing program and tweak the offset tracking adjustment for maximum solar power. Note that sun tracking must be maintained for a few tens of seconds while solar noise power data collects on tape. Alternating between sun and an azimuth about 60° away measures the power difference between sun and "blue-sky". A feature of CP-2 is the ability to calibrate the receiver over its entire dynamic range with a coherent test pulse and a programmable 1 dB stepped attenuator. This spans the equivalent noise power of the sun, noise tube, and "sky" to well below the system noise floor. The hot source, an argon noise tube, and the cold source, a dummy load, produce nearly the same power as the sun and off the sun, so deviations from a linear (in power) receiver should therefore cause small errors.

An outline of the solar data reduction follows:

1. Average digital processor values while on the sun are proportional to $P_s+P_a+P_r$, and P_a+P_r on blue sky.

2. The 1 dB receiver calibration gives the equivalent test pulse power in dBm, corresponding to the excess solar power $P_s = (P_s+P_a+P_r) - (P_a+P_r)$ from the average processor values above.

3. Likewise, "hot" and "cold" source data produce $(P_h-P_c) = (P_h+P_r) - (P_c+P_r)$.

4. Calculate the sun temperature T_s and then system gain G_a from the formulas (3) and (6).

In dB notation if $T_h = 11100°K$, $T_c = 290°K$, S is in units of 10^{-22} $W/m^2/Hz$, $\lambda = 10.68cm$, and if we define $Q = 4\pi k/\lambda^2$, then

$$T_s \text{ dB}^oK = (T_h-T_c) \text{ dB}^oK + P_s \text{ dBm} - (P_h-P_c) \text{ dBm} \tag{10}$$

$$G_a \text{ (raw) dB} = 10\log Q - 10\log S + T_s \text{ dB}^oK \tag{11}$$

where for CP-2 $(T_h-T_c) = 40.33$ dB°K and $10\log Q = -198.18$ dBQ.

5. Allowances are made for attenuation, source size, antenna alignment, polarization differences, detector time constants, and observatory procedures.

The gain correction for a disk source (U_s) and Gaussian main beam from Guidice and Castelli (1971) is

$$K(dB) = 20\log(1+0.18(U_s/U_a)^2) \qquad U_s/U_a<1 \tag{12}$$

where U_a is the 3 dB beamwidth. For example CP-2: U_a=0.90°, U_s=0.57°, thus K = 0.61 dB. At 2800 MHz the predominant atmospheric attenuation is from molecular oxygen and water vapor. Liquid water has little effect except in heavy rain or when the antenna is wet, and atmospheric attenuation rarely exceeds 0.1 dB. Since Ottawa corrects for atmospheric attenuation, we must add some back in. Finally, all measurements in which the antenna moves with respect to the source must be corrected for the detector time constant.

Table 1. Summary of adjustments to CP-2 G_a

+3.0 dB for unpolarized emission to linear
+0.6 dB for extended source
+0.0 dB average correction for tracking bias
+0.0 dB for system integration bias
+0.1 dB for atmospheric attenuation at S-band
+0.0 dB for observatory AU adjustments
+3.7 dB total correction

5. System Gain Results

To illustrate the calculation procedure, we offer this example:
23 Nov 87 Solar flux, Ottawa, 2800 MHz
$S = 117 \times 10^{-22}$ $W/Hz/m^2$ = -199.32 dBS
$P_s = (P_s+P_a+P_r) - (P_a+P_r) = -98.7$ dBm (bypass)
$P_s = (P_s+P_a+P_r) - (P_a+P_r) = -99.2$ dBm (switched)
$P_h-P_c = (P_h+P_r) - (P_c+P_r) = -97.2$ dBm
T_s (bypass) = 38.8 dB°K , G_a (raw) = 40.0 dB
T_s (switched) = 38.4 dB°K, G_a (raw) = 39.5 dB

Over the last year we performed 14 semi-automated solar calibrations yielding the G_a and Zdr bias (on receive) summarized in Table 2. Zdr bias is the difference in gain between the horizontal and the vertical paths through the polarization switch.

Table 2. CP-2 Solar Calibration Summary

	Mean (dB)	SD (dB)
S (obs, sfu)	21.27	0.78
Ga (bypass mode)	43.66	0.14
Ga (switched mode)	43.23	0.13
Zdr bias	-0.28	0.02

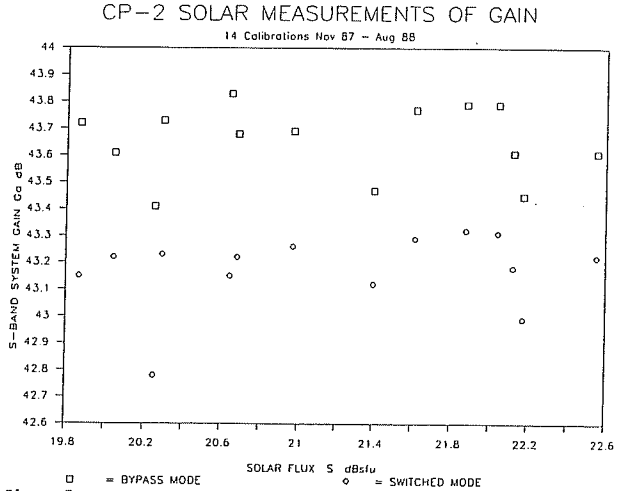

Figure 5. CP-2 system gain G_a measurements as a function of the Ottawa solar flux observations.

5.1 Supporting Measurements

Manual solar calibrations via the Y-factor method (IEEE, 1979), standard horn calibrations, and sphere calibrations over the past 6 years have yielded S-band G_a values between 43.0 and 44.6 dB. There have been minor antenna reconfigurations during the period. Manual solar calibrations taken as part of these tests read within 0.2 dB of the semi-automated results. A recent standard horn calibration over a 7.4 km path, performed to support the present study, resulted in a G_a of 44.5 dB.

5.2 Antenna Beamwidth

By scanning in a vertical plane ahead of the sun, while rotating in azimuth with the sun but slower, we found an uncorrected 3 dB beamwidth $U_o = 0.95^o$ on two occasions. The formula from Baars(1973) corrects for the size of the solar disk U_s, to a Gaussian antenna pattern of 3 dB width U_a:

$$U_a = [U_o^2 - (\ln 2/2)(U_s)^2]^{0.5} \qquad U_s/U_a<1 \qquad (13)$$

For CP-2 $U_a = 0.89^o$, which is consistent with earlier antenna pattern measurements using a remote, continuous source.

6. Errors

A realistic error budget for the solar gain calibration procedure, with independent error sources, gives a standard error of about 1/2 dB.

Table 2. Estimated Standard Error of CP-2 G_a

Source size correction	0.05 dB
Attenuation, S-band	0.05 dB
Solar Flux (5% for Ottawa NRC)	0.2 dB
Directional coupler	0.3 dB
P_s measurement non-linearity	0.1 dB
P_h-P_c measurement non-linearity	0.1 dB
Pilot pulse attenuator inaccuracy	0.3 dB
Hot and cold noise source	0.2 dB
Mismatch, coherent leakage	0.1 dB
Root Sum Square (RSS) error	0.54 dB

Stable extraterrestrial radio sources, such as Cassiopeia A require a G_a/T_o of 34 dB for minimum measurements, whereas the sun needs only about 6 dB. The CP-2 has a G_a/T_o figure of 18 dB. Kreutel and Pacholder (1969) claim an overall gain measurement accuracy from extraterrestrial radio sources, with a Dicke radiometer and the use of a source such as Cassiopeia A, as +/- 0.25 dB.

7. Remarks

Our set of solar gain measurements has a smaller standard deviation than our estimate of RSS error and the solar flux data. Likely we are measuring in a manner that minimizes procedural sources of random error. Perhaps there are systematic errors of several tenths dB, however, in G_a.

The solar calibration procedure described in this memo has advantages over other methods of antenna gain measurement, such as a standard horn or a sphere calibration, though all methods provide important verification of calculated gain. Its advantages are repeatability, efficiency, and the location of a strong source well off the ground at almost any site. In the past, solar calibrations have consumed much staff time, occasionally days if repeats were necessary. With our semi-automated technique, a radar operator can perform the data acquisition phase of the calibration in 15 minutes. Another apparent advantage is that the entire radar receiving, data processing, and recording system is checked at one time, just as in weather operations. All these advantages apply to network radar operations. The disadvantage of using the sun is that it is a variable source in time, frequency, and position.

We cannot say precisely why our standard horn calibrations between the Mesa and Marshall generally yield higher G_a then the solars. We suspect multipath propagation. If we assume an aperture efficiency of 50 to 60%, a theoretical gain of 48 dB (28 ft circular aperture at 2809 MHz) and waveguide losses of 1.5 dB we get G_a = 43.6 to 44.3, consistent with all calibrations. A bit more investigation, and the application to 5cm radars is needed.

We thank C. Frush, B. Lewis, B. Irwin, J. Ziese, J. Keeler, D. Guidice, K. Tapping, W. Preusch, T. North, and K. Lutz for their help.

8. References

AWS, 1988: Fourth Weather Wing Pamphlet 105-10, v 2, Radio Solar Telescope Network (RSTN), Air Weather Service, Scott AFB, IL 62225.

Baars, J.W.M., 1973: The Measurement of Large Antennas with Cosmic Radio Sources. IEEE, AP-21, 4, 461-474.

Doviak R.J., and D.S. Zrnic, 1984: Doppler Radar and Weather Observations, Academic Press.

Frush, C.L., 1984: Using the Sun as a Calibration Aid in Multiple Parameter Meteorological Radars. Preprints 22nd Conf. on Radar Meteor., Zurich

Graf, W., R.N. Bracewell, J.H. Deuter, and J.S. Rutherford, 1971: The Sun as a Test Source for Boresight Calibration of Microwave Antennas. IEEE, AP-19, 606-612.

Guidice, D.A., and J.P. Castelli, 1971: The Use of Extraterrestrial Radio Sources in the Measurement of Antenna Parameters. IEEE, AES-7, 2, 226-234.

IEEE, 1979: Standard Test Procedures for Antennas, STD 149-1979, IEEE and Wiley-Interscience

Keeler, R.J., B.W. Lewis, and G.R. Gray, 1989: Description of the NCAR/FOF CP-2 Meteorological Doppler Radar. Preprints 24th Conf. on Radar Meteor., Tallahassee.

Kraus, J. D., 1986: Radio Astronomy. Cygnus-Quasar Books, Powell, Ohio.

Kreutel, R. W., and A. O. Pacholder, 1969: The Measurement of Gain and Noise Temperature of a Satellite Communications Earth Station. Microwave Journal, Oct, 61-66.

Kundu, M. R., 1965: Solar Radio Astronomy. Wiley Interscience Publishers, New York.

Medd, W. J., and A. E. Covington, 1958: Discussion of 10.7-cm Solar Radio Flux Measurements and an Estimation of the Accuracy of Observations. Proc. IRE, 112-121.

__________, 1961: Daily Calibration Procedures for the 10.7 cm Solar Radio Patrol Radiometer at the Algonquin Radio Observatory. National Research Council of Canada, ERB-595.

NEXRAD, 1986: NEXRAD Technical Requirements, Joint System Program Office, Silver Spring, MD.

NGDC, 1987: Solar-Geophysical Data, Explanation of Reports (Supplement). National Solar Geophysical Data Center, NOAA, Boulder, CO.

Schroeder, D., 1986: Space Environment Laboratory Data Acquisition and Display System (SELDADS): NOAA/ERL, 303-497-3780.

Tanaka, H., J.P. Castelli, A. E. Covington, A. Krueger, T.L. Landecker, and A. Tlamicha, 1973: Absolute Calibration of Solar Radio Flux in the Microwave Region. Solar Physics, 29, 243-262.

Williams, D. J., 1976: SELDADS - An Operational, Real-time, Solar-terrestrial Environment Monitoring System. ERL 357 - SEL 37.