Antenna Calibration Using the 10.7cm Solar Flux

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1 Introduction

The 10.7cm Solar Flux measurements distributed by the National Research Council of Canada are a useful calibration tool for antenna measurements. The source is definitely in the far field of the antenna, and the measurements are consistent and accurate. In addition the same source can be seen simultaneously by antennas over a large geographic area, making it possible to tie together the calibration of many antennas. However, problems encountered when using the 10.7 cm solar flux for calibrating antennas include: (i) relating those values to antenna calibration at other frequencies, (ii) that the sun is not a point source; it is a disc, and not always uniformly bright, (iii) there are only three precise measurements made each day. In this paper we discuss the use of the 10.7 cm solar flux to calibrate antennas and methods to address the difficulties listed above. To safely apply these methods something has to be known about the character of the signals and the radio astronomical techniques used to measure them. Some background information is therefore included.

2 Contents

- Section 9: Where's the Sun?
- Section 10: Discussion and Summary

3 Basic Radio Astronomy

Most of the signals observed in radio astronomy are produced by the interaction of individual electrons with ions and/or magnetic fields. Each interaction produces a short pulse, which has a bandwidth equal to $1/t_p$, where t_p is the pulse duration. Not all interactions produce pulses of equal amplitude or duration, and the pulses are not generally produced at a constant rate. The result of very large numbers of electrons making such pulses independently of one another is a broad band of more-or-less white noise. There is some frequency dependence, especially in some mechanisms and propagation conditions, but the spectrum is broad, extending from kHz to many GHz. The power involved is usually specified in terms of *spectral density*, *i.e.* watts per Hz of bandwidth. The amount of power received is equal to the spectral density multiplied by the bandwidth of the receiver. In general, bandwidths are as large as interference and engineering will allow.

If these pulses are narrower than the receiver bandwidth (which in general they are), the receiver RF and IF systems act as a low-pass filter which stretches the pulses to duration $\approx 1/B$, where B is the pre-detection bandwidth in Hz. In essence, the receiver is taking samples at a rate of $\approx B$ per second. After detection there is a low-pass filter of time-constant τ seconds. In radar applications τ is of the order of microseconds or less. In radio broadcasting it will be fractions of a millisecond. In radio astronomy is is often seconds or even hours, where part of the time-constant is usually obtained digitally.

The number of samples obtained per second at the receiver output is roughly $B\tau$. The sensitivity limit of a radio telescope is set by the random fluctuations in the receiver output, the r.m.s. amplitude of which is given by:

$$< T >= \Psi \frac{T_{sys}}{(B\tau)^{\frac{1}{2}}} \tag{1}$$

where T_{sys} is the noise temperature of the receiver plus all unwanted noise contributions to the system (such as that emitted by the ground). The factor Ψ is a *degradation factor* depending upon the system design and the way the signals are processed. It typically varies between 1 and 2 in theory, but could reach 3 or 4 in practice. The amount of noise entering the radio telescope antenna is often described by the *antenna temperature* T_a. This is defined as the temperature of a black body which, if connected instead of the antenna, would produce the same receiver output power as the antenna. To get from antenna temperature to incident energy flux requires knowledge of the antenna.

Most cosmic radio emission processes are statististial phenomena, involving large numbers of incoherent, sporadic radiators. They occur in variously-sized "patches" in the sky, ranging in size from several degrees down to small fractions of an arc-second. We therefore measure the emission in terms of energy flow per second, incident on one square meter of collecting area, per unit bandwidth, per unit solid angle over the source, *i.e.* watts per square meter per Hz, per steradian, that is $\mathrm{wm^{-2}Hz^{-1}St^{-1}}$. A steradian is a unit of solid angle, and is equal to a square radian. A radian is 57.29 degrees, and a steradian is 3282 square degrees. An astronomical radio source, such as the Sun or the Milky Way, is generally not uniformly bright over its surface. The *Brightness Distribution* describes the spatial distribution of the emission in units of $\mathrm{wm^{-2}Hz^{-1}St^{-1}}$ as a function of sky coordinates, *e.g.* $\Phi(\xi, \eta)$, which could be the celestial coordinates right ascension and declination (see Kraus, 1986 and Section 8 of this paper), or azimuth and elevation. Since antennas are not uniformly sensitive to all points in the sky, we need to include the properties of the antenna in calculating the power received. We can describe the shape of the antenna beam in terms of the *power pattern* $P(\theta, \phi)$, where the parameters are offsets from the antenna boresight, measured parallel with and in the same senses of ξ and η. The function P is normalized, with a maximum value of unity.

If the antenna boresight is directed at a point ξ_0, η_0 in the sky coordinate frame, then the flux density received from a small element of that object at coordinates ξ, η is:

$$\Delta S = \Phi(\xi, \eta).P(\theta, \phi).\Delta\xi.\Delta\eta = \Phi(\xi, \eta).P(\xi - \xi_0, \eta - \eta_0).\Delta\xi.\Delta\eta \tag{2}$$

where the product $\Delta\xi \times \Delta\eta$ is the solid angle subtended by the element, and $\theta = \xi - \xi_0$ and $\phi = \eta - \eta_0$. The flux density observed at that position by the antenna is therefore:

$$S(\xi_0, \eta_0) = \int\int \Phi(\xi, \eta).P(\xi - \xi_0, \eta - \eta_0).d\xi.d\eta \tag{3}$$

where the integration is over a wide enough range of angles to include all the source and the antenna sidelobes. The flux density S is in units of $\mathrm{w.m^{-2}.Hz^{-1}}$.

The power collected by the receiver is

$$W = \frac{1}{2} A_{eff} S(\xi_0, \eta_0) B \text{ watts} \tag{4}$$

where A_{eff} is the effective collecting area in square meters, and B the bandwidth in Hz. The factor of $\frac{1}{2}$ is included because the cosmic radio emission is unpolarized, and the antenna can only pick up half of it. The effective collecting area of an antenna is less than its physical area because it is not possible to collect all the signal power from everywhere on the dish. For example, some sort of illumination taper is required to reduce the power at the dish edge (to minimize sidelobes and picking up of stray radiation). The effective area of an antenna may also be reduced by surface errors. The relationship between the effective and actual areas is known as the *aperture efficiency*, and in most systems is about 60%. The effective collecting area is related to the antenna (boresight or on-axis) gain by

$$G_0 = \frac{4\pi A_{eff}}{\lambda^2} \tag{5}$$

where λ is the wavelength, so the power equation becomes

$$W = \frac{1}{2}\frac{G_0\lambda^2}{4\pi}S(\xi_0, \eta_0)B \tag{6}$$

The antenna temperature T_a is related to the flux density $S(\xi_0, \eta_0)$ by the relationship

$$kT_a = \frac{1}{2}A_{eff}S(\xi_0, \eta_0) = \frac{1}{2}\frac{G_0\lambda^2}{4\pi}S(\xi_0, \eta_0) \tag{7}$$

The constant k is Boltzmann's constant, 1.39×10^{-23} Joules per Kelvin.

For a source subtending a solid angle much smaller than the antenna beam, the entire source is seen with constant antenna gain, so $P = 1$ over all the source, and the integration of the flux density is done without moving the antenna. In this case the integral becomes simply the integral of the brightness distribution:

$$S_0 = \int\int \Phi(\xi, \eta).d\xi.d\eta \tag{8}$$

which is the integrated flux density of the source in $w.m^{-2}.Hz^{-1}$. This is the case with our solar flux monitor antennas. This condition is satisfied in the case of the Sun for antennas with beamwidths larger than about 4°.

The flux densities observed in radio astronomy are very small; they are usually given in power per unit bandwidth per unit collecting area of the antenna, that is, *flux density*, expressed in $w.m^{-2}.Hz^{-1}$. Since these powers are very small, they are often expressed in *flux units* (10^{-26} $w.m^{-2}.Hz^{-1}$). The Sun is a strong radio source, and its flux density may be given in *solar flux units* (10^{-22} $w.m^{-2}.Hz^{-1}$).

A typical radio astronomical measurement, such as a determination of the 10.7 cm flux, consists of pointing the dish at the source, and determining the increase in antenna temperature it produces. This is done by comparing the received power with a calibrated noise source, which injects noise of a known temperature into the receiver system as close to the feed as possible. The effective collecting area has to be known (determined by absolute measurement or observation of calibrated cosmic sources). The flux density is obtained using $S = 2kT_a/A_{eff}$. The effective collecting area is related to the boresight antenna gain, G_0, by $4\pi A_{eff} = G_0\lambda^2$.

Our flux monitors see the entire solar disc with constant gain, so they measure the integrated flux density S_0. If, for example the measured flux density is $S_{sun} = 300$ solar flux units, and we assume this emission to be uniformly distributed all over the disc (rarely the case), which subtends a solid angle of $\Omega = 6.85 \times 10^{-5}$ steradians,we get an average of $S_{sun}/\Omega = 300/(6.85 \times 10^{-5})$ solar flux units per steradian, or 4.38×10^{-16} $wm^{-2}Hz^{-1}St^{-1}$. More background information on radio astronomical techniques and measurements can be obtained from Kraus (1986).

4 The 10.7 cm Solar Radio Flux Monitoring Programme

4.1 Background

Figure 1: The two solar flux monitors at the Dominion Radio Astrophysical Observatory. The left-hand flux monitor is to the south of the building and the right-hand one, on the tower, is to the north. This gives both instruments an uninterrupted view of the Sun. The antennas are 1.8-m (6ft) solid paraboloids on equatorial mounts.

Canada's first radio telescope was built in 1946 by Arthur Covington and his colleagues. By modern standards the instrument was very crude. It consisted of an old (2.8 GHz) *ex*-WWII radar receiver, using a small dish. The antenna beamwidth was a few degrees. The noisy receiver and small antenna, together with the relative weakness of cosmic radio sources at 2.8 GHz ($\lambda = 10.7$ cm), made it impossible to detect any sources other than the Sun. However, as observations were repeated over following days and weeks, the Sun was found to be highly variable. A programme of monitoring its daily intensity variations was launched and has continued to the present day. The data have provided an important index of solar activity and used worldwide in research, and by various governmental and other agencies, and industry. Examples include solar and space physics, environmental research, natural resources and many technical, commercial and idustrial activities.

The programme was originally based in Ottawa, with the flux monitors based at locations close to that city. In 1985, when the last members of the original Solar Radio Group retired, a completely new group was formed with the mandate to upgrade all aspects of the programme. This included implementation of new control and data logging systems and more stable, modern receivers. Automatic data distribution was introduced, and the entire database made accessible on the World Wide Web.

In 1990 the programme was relocated to the NRC's Dominion Radio Astrophysical Observatory, near Penticton, British Columbia. That site enjoys extremely low interference levels at decimeter and centimeter wavelengths. The quality of the environment is maintained through strong local, provincial and federal protection. Figure 1 shows the two flux monitors and the solar building currently in use at the observatory.

4.2 Solar Radio Emission

The first radio telescopes used to observe the Sun had antennas that were too small to resolve the distribution of radio brightness over the disc; they could only measure the integrated emission. On the basis of characteristic timescales of intensity variation, this integrated emission was divided into three components: a *rapidly varying, or R-component* consisting of the second and minute-duration bursts produced by flares and other transient activity, a *slowly-varying or S-component*, comprising all slower variations, over hours to decades, and a constant, base level corresponding to an extrapolated zero of activity - the *quiet sun* emission. The bursts of radio emission associated with flares are short-lived, intense, highly variable in spectrum and time, and are of no use in antenna calibration. From this standpoint they can be regarded as interference that can degrade the desired measurements. The flux values used in antenna calibration are the totals of the quiet sun level and the slowly-varying component. The quiet sun component consists of free-free thermal emission from the hot gas in the solar atmosphere. The emission process involves deflection of electrons by heavy ions and is very similar to that taking place in a plasma noise tube. It is unpolarized.

As solar magnetic activity ebbs and flows over its roughly 11-year cycle, varying numbers of *active regions* appear on the disc. These consist of areas of enhanced magnetic flux, which are varying in size and structure with time. The magnetic fields act as plasma traps, supporting higher-density concentrations of plasma. A large active region can occupy up to a percent or so of the total area of the solar disc. Sunspots are the most obvious features in active regions.

Centimeter-wavelength radio emissions are produced in active regions through at least three processes. Free-free thermal emission is produced by electron/ion interactions in the trapped plasma. Magnetic fields in the source and media through which the waves propagate may generate a small degree of circular polarization ($< 5\%$). However, the degree of polarization varies in amount and sense within the active region and over the solar disc, so integrating the emission over the entire disc will probably lead to this polarization averaging out. Close to sunspots, where the magnetic fields are strong, the gyration of electrons around the magnetic field lines can be more important than ion-electron collisions. In this case bright, highly-circularly polarized (up to 80% or so) emissions can be produced. Sometimes instabilities in the magnetic fields and trapped plasmas accelerate electrons to high energies. These interact with the magnetic fields to produce bright, variable emission. This may be unpolarized or polarized to some degree depending upon the structure of the source and medium through which the emissions have to propagate. Active regions can appear almost anywhere on the disc, and at radio wavelengths stand out brightly against the background.

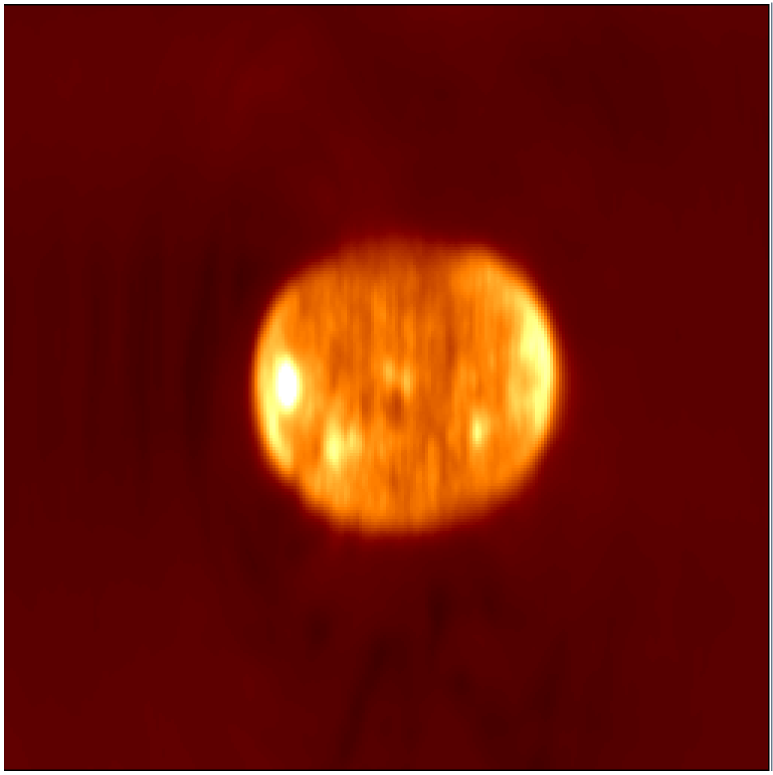

Figure 2a: Sun imaged at 21 cm wavelength using the DRAO Synthesis Radio Telescope. This shows the solar disc on 29th July, 1995, close to solar activity minimum. There are slight variations in brightness over the disc. The contrast range is somewhat exaggerated. At this point in the solar activity cycle it would have been acceptable to assume the Sun to be a uniformly-bright disc. This and the following image were obtained using the 7-element synthesis radio telescope at DRAO.

At centimeter wavelengths, the Sun shows a more-or-less uniformly bright disc with - at some wavelengths - traces of limb-brightening on the east and west sides of the disc. This is due to higher electron densities overlying the latitude range in which the active regions are occurring. Upon the disc are bright areas coinciding with active regions. These occur in large numbers around solar activity maximum, but can be completely absent at solar minimum. Figures 2a and 2b show the radio sun at solar activity minimum and maximum.

The slowly-varying component originates in active regions. This component of solar radio emission is most easily observed at wavelengths around 10 cm. This property of the emission, together with the entirely fortuitous choice of 10.7 cm for the solar monitoring programme, has been a major factor in the making the 10.7 cm Solar Flux an important index of solar activity.

The flux monitors used to measure the 10.7 cm solar flux use small antennas that integrate all sources of emission on the solar disc with equal weight. The widely-changing brightness distribution over the solar cycle has therefore no effect on the data. Figure 3 shows monthly mean values of the 10.7 cm Solar Flux over more than 50 years. More comprehensive accounts of solar radio emission and solar radio astronomy are given by Kundu (1965) and Krüger (1979) and a more focussed discussion of the issues pertaining to the 10.7 cm solar flux is given by Tapping (1987).

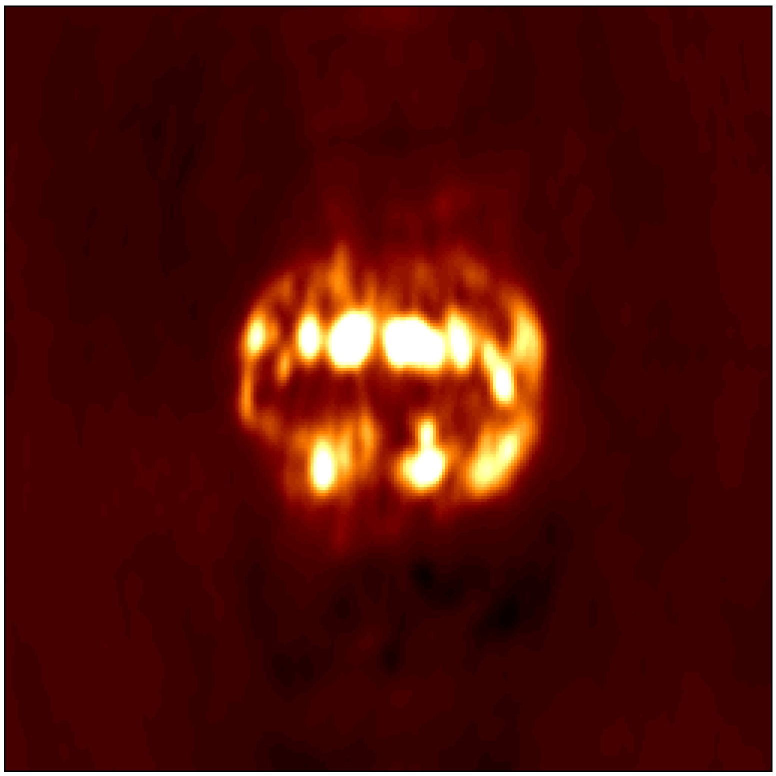

Figure 2b: Sun imaged at 21 cm wavelength on 19th June, 2000, close to solar activity maximum. Many bright active regions are distributed over the disc. They are so bright that maintaining the dynamic range of the images has led to the disc level being suppressed somewhat by the imaging software. Note that the regions are not randomly distributed over the solar disc; they lie in preferred latitude bands. It is clear that the Sun cannot always be regarded as a uniformly-bright disc.

4.3 The Instruments

Each flux monitor consists of an equatorially-mounted 1.8-m paraboloid. The beamwidth to half-power points is about 4.5 degrees. When the antenna boresight is pointed at the centre of the solar disc, the antenna gain at the solar limb is less than 1% lower than at disc centre. Due to increased problems with ground radiation and lower signal-to-noise ratios, experiments with antennas with larger beams have not yielded any significant improvements in accuracy. The antenna mounts are driven by stepping motors and are fitted with 14-bit position encoders, which yield the antenna position to better than 2 arc-minutes.

The signals are taken to the receivers by a run of about 10 m of WR284 waveguide. Each flux monitor is equipped with two receivers, each one a Tuned Radio Frequency receiver (no downconversion), consisting of three GaAsFET amplifiers coupled through filters and attenuators. Each pair of receivers are embedded in a thermally and electrically isolated aluminium slab 8 cm thick and 60 cm square. This has yielded a system with enormous thermal time constant and very high stability. The DC amplifiers on the detector outputs have two channels: a high-sensitivity one (used for most observations and for the flux measurements), and another channel about 20dB less sensitive, which is used for recording large bursts. Each flux monitor has its own data logging and control computer. The two levels of duplication (two flux monitors each with two receivers) provides good fault tolerance and opportunities for internal checking of data consistency. Periodically (at least over one several-day session a year), the system calibration is checked using a dual-horn receiver. The horn gain is calculable and the two horns make it possible to check one against the other. Each receiver is equipped with a terminator flap that can be switched into the waveguide close to the feed, effectively terminating the waveguide run with a matched load. A calibrated noise source injects noise into the waveguide close to the feed. These two components are the main elements in the calibration process. An additional coupler and noise source at the receiver end of the run is used to monitor the state of rotating joints and waveguide. The termination flap and calibration noise source are fitted with temperature sensors. Measuring the temperatures of the calibration devices and applying appropriate corrections has proved easier than trying to adequately stabilize their temperatures.

4.4 The Measurements

Every day, as soon as the Sun rises, the two flux monitors move to the Sun and start tracking it. Five-second averages of the receiver output are recorded in "Chart Record" files, which are used for studying bursts, evaluating perturbations of the flux determinations, and for system maintenance. This procedure is continued until sunset. Three times each day precise measurements of the flux are made. In summer this is at 1700, 2000 (local noon) and 2300 UT. The hilly horizon and the relatively high latitude (50° North), make the Sun too low for those times to be maintained during the winter, so during that season, the flux determinations are made at 1800, 2000 and 2200 UT. Each flux determination takes an hour. At the end of the measurement, the values from the two flux monitors are sent automatically to the data distribution computer. If the value from the default flux monitor is outside acceptable bounds or is missing, the value from the backup instrument is sent.

The small (1.8 m) antennas "see" the whole solar disc with almost equal gain. When the antenna is on-source, with the antenna boresight pointed at the centre of the solar disc, the input to the receiver consists of contributions from the source being observed, the sky, the ground and (by convention) the receiver.

The contributions to the receiver input are

$$T_{in} = \alpha(T_{sun} + T_{cosmos}) + T_{sys} + T_{ground} + (1 - \alpha)T_{atm} \tag{9}$$

where

- α = the transmission coefficient of the atmosphere. At 10.7 cm wavelength, the atmospheric constituent contributing most to the absorption of solar radio emission is oxygen.
- T_{sun} = the antenna temperature increase due to the Sun. This is related to the flux value by

$$S = 2\frac{4\pi k T_{sun}}{G_0 \lambda^2} \tag{10}$$

  The factor of 2 arises because the solar radio emission is unpolarized, so the receiver can actually receive only half of it. G_0 is the antenna (boresight) gain, which, due to the relatively broad antenna beam, is assumed to apply over the whole solar disc.
- T_{cosmos} = noise from the galaxy, the cosmic background and other cosmic sources. This emission originates in space, beyond the Solar System. It is a small but detectable constribution to the total emission, and along with the solar radio emission, is attenuated by the atmosphere.
- T_{sys} = the receiver system noise temperature. The system noise temperature of the flux monitor receivers, taking into account the long waveguide run and the presence of two rotating joints, is about 120K. The antenna temperature increase due to the quiet Sun is about 300K. The contribution to the detector output voltage from the receiver's own noise cannot be ignored compared with the noise power received from the Sun.
- T_{ground} = noise power picked up from the ground. The outer sidelobes of the antenna pick up significant thermal emission from the ground. When the Sun is low in the sky, thermal noise from the hills is received through the inner sidelobes. These contributions (typically a few Kelvins) are not negligibly small compared with the solar radio emissions.
- T_{atm} = average temperature of the troposphere. There is a small but detectable contribution by thermal noise from the troposphere. This is related to the tropospheric attenuation and the average temperature.

The power is related to the temperature by $W = kTB$, where T is the sum of all the inputs expressed as temperatures and B the bandwidth in Hz. If the gain-bandwidth product of the receiver is Γ, $P_{out} = kG_R B \sum_i T_i = k\Gamma \sum_i T_i$, where G_R is the net gain of the receiver. Provided that the power input to the detector is sufficiently small, its ouput voltage is proportional to the input power. However, before being recorded, the detector output passes through a number of filters and DC amplifiers, and in the process inevitably picks up a small offset voltage. A fixed voltage is added deliberately to bias the the analogue/digital converters to convenient parts of their operating characteristics.

The flux determination process involves two steps: (i) to measure the contribution to the antenna temperature due to the Sun without including other contributions to the receiver output, and then (ii) to calibrate that value in terms of absolute flux density. Pointing the antenna at the Sun, determining the output power from the receiver, moving the antenna off source, beyond the main sidelobes, and measuring the “off-source” power, and then subtracting the off-source power to leave the solar contribution is not an acceptable method because when the antenna is moved, the ground radiation and sky noise change from what they were when the antenna was pointed at the Sun. Moving the antenna off-source at constant elevation is also not an acceptable option because the DRAO observatory site is surrounded by hills, so the ground radiation is a function of azimuth. In addition, because the flux monitor antennas have equatorial mounts, the beam patterns rotate with respect to the ground. The same disadvantage arises when the antenna is scanned across the Sun.

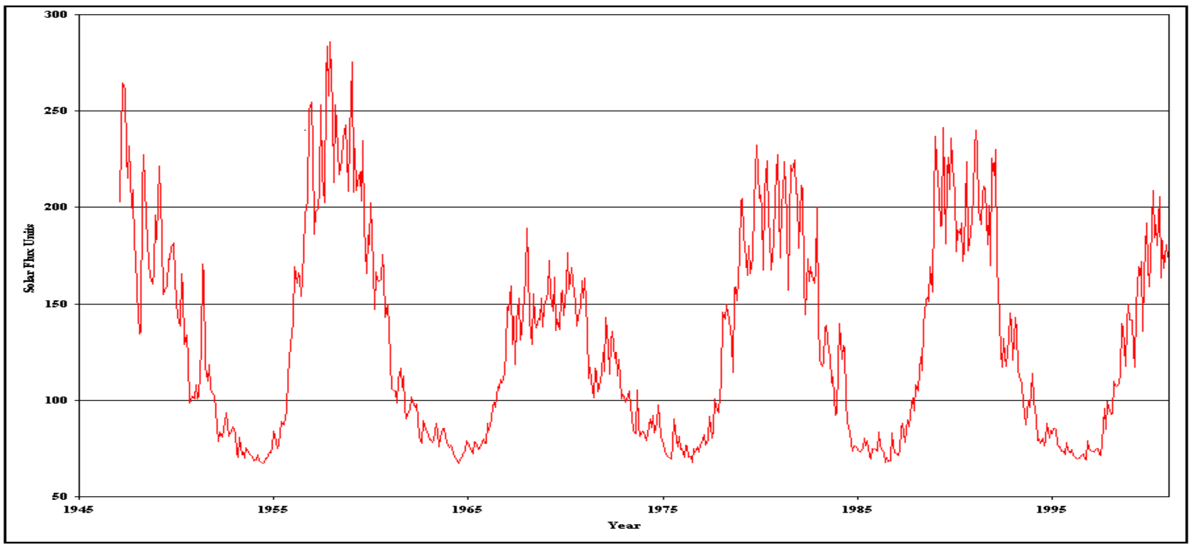

Figure 3: A plot of monthly means of the *observed* values of the 10.7 cm solar flux from the beginning of observations in 1946 to the the end of December, 2000. The 10-13 year solar activity cycle is very evident. The “noise” on the waves is due to shorter-time-scale variations of activity and solar rotation.

Another applicable method is to point the antenna ahead of the Sun, stop it, and allow the Sun to drift through the antenna beam. With the antenna stationary, the ground radiation and sky noise are very nearly constant, and the only varying input to the receiver comes from the Sun. This has the disadvantages that one can only use the peak of the transit. If one integrates over the whole transit one needs to know the antenna beam pattern with great accuracy. Moreover, in the thirty to sixty minutes a drift scan would take to complete with one of our antennas, the receiver gain-bandwidth product could have drifted significantly.

The method used - in simplified form - consists of making measurements at two positions in the sky.

Each *observation* involves recording an average of 1200 blocks of receiver output samples, accumulated over about two minutes.

- Peak up on Sun. While tracking it, measure $V_{sun,1}$.
- Move telescope to where the Sun will be 45 minutes later.
- While tracking this position, measure $V_{sky,2}$.
- Do various other calibration things, such as switch in calibration noise sources etc., each being a complete *observation*
- Move to Sun when it is at position 2.
- Peak up on Sun. While tracking it, measure $V_{sun,2}$.
- Move antenna to where the Sun was when the measurements started.
- While tracking this position, measure $V_{sky,1}$.

In principle we measure two positions in the sky, in each case when the Sun is there and when it isn't. By subtracting $V_{sky,1}$ from $V_{sun,1}$ and $V_{sky,2}$ from $V_{sun,2}$ we get two measurements of the Sun's contribution to the receiver output with the other contributions from that point in the sky removed. Gain variations during the measurements are monitored using the calibration noise sources. In practice each flux determination takes an hour and involves six positions in the sky. The disadvantage of this method is that the antenna choreography is complicated and has to be carefully timed to ensure that the same parts of the sky are measured with and without the Sun in them. These six measurements are estimates of the antenna temperature increase due to the Sun. To convert them to flux density requires knowledge of the antenna gain. This is measured as required by making simultaneous measurements of the solar flux using dual 3×4 ft pyramidal horns, which are of known gain. On completion of every flux determination, the flux density values are examined by the processing software to detect deviant values, which could arise due to the occurrence of bursts during the measurement. Any value differing by more than 5% from the other samples is discarded.

4.5 Correcting for Tropospheric Absorption

The objective of the measurement process is to obtain an estimate of the solar flux density at 10.7 cm wavelength as would be measured above the atmosphere. The numbers are then a useful indicator of the Sun's influence in the vicinity of the Earth. The flux values are then easily scaled for observers located anywhere on the Earth, seeing the Sun at a range of elevation angles. Fortunately, at 10.7 cm wavelength, the main abosrbing agent in the Earth's atmosphere is oxygen, the concentration of which remains fairly constant. Rain has little effect unless heavy, because the antenna is looking upwards at a reasonably steep angle.

It is easy in principle to measure the tropospheric loss per unit length along a horizontal path in the troposphere, and to obtain a loss in (say) dB/km. However, in the case of our flux measurements, the optical path is directed upwards. The properties of the atmosphere, particularly density and temperature, change along that path, so the absorption and emission coefficients vary, and it's not clear what the optical thickness is. We therefore obtain an estimate of the net transmission coefficient of the atmosphere (from space to the ground) by measuring the antenna temperature with the antenna pointed at the zenith and deriving the transmissivity from that. This process is complicated and tedious, so is therefore done only rarely.

The antenna temperature of an antenna pointed at the zenith is the sum of a number of contributions:

$$T_a(zenith) = \alpha_z T_{cosmos} + (1 - \alpha_z)\bar{T}_{atm}) + T_{ground} \tag{11}$$

where T_{cosmos} is the strength of radio emission from space, $\bar{T}_{atm}$ is the average temperature of the atmosphere, and T_{ground} the ground radiation being picked up through the antenna backlobes. The gain of the backlobes might be very small compared with that at the antenna boresight, but the backlobes cover a large solid angle and are filled by the ground. The total atmospheric transmission coeffient from space to the ground is α_z. Rearranging, we get:

$$\alpha_z = \frac{\bar{T}_{atm} + T_{ground} - T_a}{\bar{T}_{atm} - T_{cosmos}} \tag{12}$$

We estimate T_a to be 10 K, with $T_{cosmos} = 4$ K, with 3K coming from the (well-measured) cosmic background radiation and 1 K from other cosmic sources. The ground noise contribution we estimate to be 3-4 K (say 3.5 K). If the mean temperature of the atmosphere when looking at the zenith is 250 K, we get $\alpha = 0.986$. If the effective thickness of the atmosphere is (say) 10 km, the average attenuation along a vertical path would therefore be about 0.006 dB/km.

If we assume the atmosphere to be an isothermal slab, the transmissivity as a function of angle of elevation is simply $\alpha = \alpha_z \sin\theta$, where θ is the angle of elevation. This model breaks down for small angles of elevation. However,it works well at 10.7 cm wavelength, over the elevation range covered by the Sun.

4.6 The Observed, Adjusted and Series D Flux

The value obtained above is the *Observed Flux*, which is the observed radio power falling on the Earth after correction for atmospheric loss. This is the value that should be used for antenna calibration and studies of terrestrial phenomena driven by the Sun. If the observed flux is being used to calibrate an antenna, the signal being measured has to be corrected for atmospheric loss, or the observed flux needs to be "uncorrected" so that it is a true measure of what is falling on the ground.

The Earth's orbit around the Sun is not circular; it is slightly elliptical. The changing distance significantly modulates the observed flux. This is of no consequence when terrestrial effects are being studied. However, when solar activity is being studied, this modulation is undersirable. For each flux determination the distance between the Earth and Sun is computed and the flux value corrected to correspond to the average distance. This "corrected" value is called the *Adjusted* flux.

In the early history of solar radio astronomy, when many observers measured the strength of solar radio emissions over a wide range of frequencies, there were also a variety of measurement errors. The various measurements were plotted as a function of wavelength and a best-fit curve drawn through them. Then, the ratio between each measurement and the corresponding value on the curve was derived for use as a correction factor. The value for the early Canadian measurements was 0.9. The *Series D* flux is accordingly the adjusted value multiplied by 0.9.

5 Applying the 10.7 cm Flux Measurements to Other Frequencies

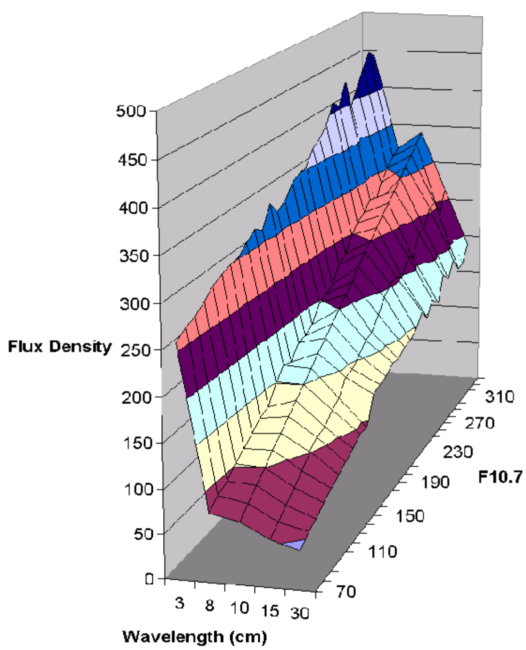

Figure 4: The total flux density at 3, 8, 10, 15 and 30 cm plotted against $F_{10.7}$.

To be rigorous, the only way to have accurate calibration data for other wavelengths is have have absolute measurements of the solar radio flux made at those wavelengths. However, if one is prepared to accept a little uncertainty, it is often possible to use the 10.7cm Solar Flux to estimate to within a dB or so the flux density at other wavelengths. This makes use of the remarkable stability of the spectrum of the slowly-varying component of solar activity. However the spectrum can be distorted by superimposed contributions from flares or other events having a widely differing spectra and variability with time that is a function of frequency.

The method for using the 10.7 cm solar flux to estimate integrated flux densities at other frequencies is based upon two well-documented properties of solar radio emission: (i) that in the absence of flares, the solar emission at centimeter wavelengths can be divided into two distinct components: a steady base level - the quiet sun, and a superimposed slowly-varying (or S-)component; (ii) that as solar activity rises and falls, the amplitude of the spectrum changes but the shape remains almost unchanged.

Independent observations of the integrated flux density from the Sun, at wavelengths of 3, 8, 10, 15 and 30 cm have been catalogued over two complete solar cycles (Nicolet and Bossy, 1984). These data were used to formulate the model described here. A plot of the total emission at those wavelengths over a range of activity level is shown in Figure 4.

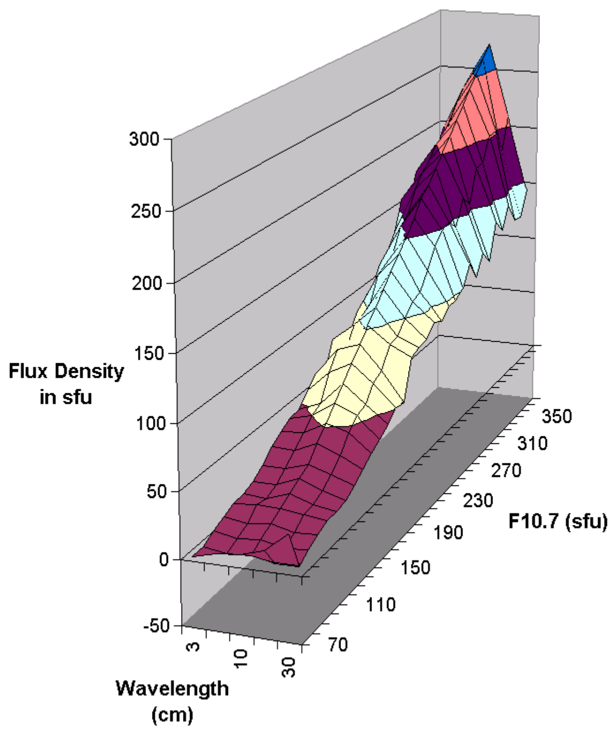

Figure 5: The S-component spectrum as a function of activity level.

Some magnetic activity is almost always present, even at solar minimum, so the quiet sun component is almost never observed in isolation. However, by plotting the flux density against other indices of solar activity, such as sunspot number or area, and extrapolating the flux density back to zero activity, it is possible to estimate the quiet sun flux density. At 3, 8, 10, 15 and 30 cm wavelength, the respective quiet sun flux densities are 259, 77, 67, 53 and 44 solar flux units, and 64 sfu at 10.7 cm. Using a slab model for the solar atmosphere, the spectrum of free-free thermal emission was calculated as a function of wavelength for the quiet sun, using a standard model for electron density. This was then scaled slightly for best fit with the observed measurements, and a complete set of quiet sun flux densities for the wavelength range 1 - 30 cm was calculated. These can be used to estimate the S-component flux density value at any wavelength in that range.

For each value of the integrated flux density, for every wavelength, the appropriate value of the quiet sun flux density is subtracted. This leaves the contribution from the slowly-varying component. The spectrum of the S-component becomes very evident.The spectrum is surprisingly stable in shape. It peaks at about a wavelength of about 10 centimeters and, as solar activity rises and falls, simply changes amplitude. This property of the spectrum is crucial in the development of the process discussed here for using the 10.7 cm solar flux to calculate the integrated flux density at other wavelengths.

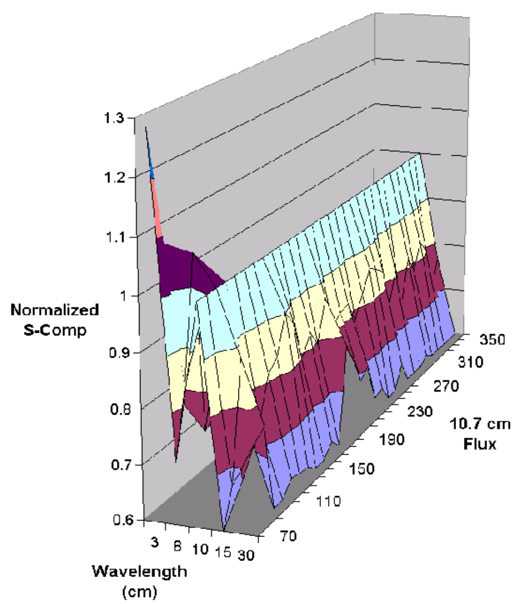

Figure 6: The normalized spectrum of the S-component plotted against activity level as indicated by the 10.7 cm solar flux. Note the change in vertical scale. The method for producing an estimate of the flux density at a different wavelength from the 10.7cm solar flux is simple. First subtract the quiet sun flux density at 10.7 cm wavelength from the 10.7 cm solar flux. This gives the S-component flux density at that wavelength. To convert this to the S-component flux density at the desired wavelength, multiply it by the appropriate scale factor from the table. The solar flux density at the desired wavelength is

then obtained by adding the quiet sun flux density at that wavelength.

Since the spectrum scales linearly with activity, it is possible to normalize the spectra and combine them into one spectrum, which provides a range of scaling values that make it possible to use the flux density of the slowly-varying component at one wavelength to estimate what it would be at another. Accordingly, for each spectrum, the flux density of the slowly-varying component at each wavelength was divided by the value at 10.7 cm wavelength (lying at the peak). This scales the maxima of all spectra to unity. The resulting normalized spectra are shown in Figure 6. The shape of the normalized spectra show no significant variation with level of activity.

Wavelength (cm)	Minimum Flux (sfu)	Scale Factor (ξ)
1	1980	0.67
2	495	0.68
3	255	0.69
4	170	0.70
5	126	0.71
6	102	0.73
7	88	0.78
8	76	0.84
9	72	0.96
10	68	1.00
11	64	1.00
12	61	0.98
13	58	0.94
14	55	0.90
15	54	0.85
16	53	0.80
17	52	0.78
18	51	0.77
19	50	0.76
20	49	0.75
21	48	0.74
22	48	0.73
23	47	0.72
24	47	0.71
25	47	0.70
26	46	0.69
27	46	0.68
28	45	0.67
29	45	0.66
30	45	0.65

All the scaled spectra were then averaged together to produce one normalized spectrum. However, it comprises values for wavelengths of 3, 8, 10, 10.7, 15 and 30 cm only. Using a combination of theory and empirical curve fitting, a spectrum was derived to give scaling factors for all wavelengths between 1 and 30 cm, with a resolution of one centimeter. These values are independent of the activity level.

The process of using the 10.7 cm solar flux to estimate the corresponding flux densities at other wavelengths is summarized in the equation:

$$F_\lambda = \gamma \times (F_{10.7} - S_{10.7}) + S_\lambda \tag{13}$$

where γ is the scaling factor for the desired wavelength, as taken from the table, $F_{10.7}$ is the 10.7 cm Solar Flux, $S_{10.7}$ is the quiet sun flux (64 sfu), and S_λ the quiet sun flux density at the desired wavelength. For example, if the 10.7cm Solar Flux is 150 sfu, and we want the flux density at 5 cm wavelength, using the table, it is given by $F_{\lambda=5} = 0.71 \times (150 - 64) + 126 = 187$ sfu.

6 Applying the 10.7 cm Flux to Other Times

Three flux determinations are made each day; each takes an hour. If we need flux values for other times of the day, we can

- take the measurement made as close to the required time as possible and use that;
- interpolate between measurements to produce and estimate of the flux at the required time;
- use a combination of interpolation and the "CR" files (described later in this section) to estimate the flux density for the desired time.

The slowly-varying component varies over timescales ranging from hours to days. Three measurements each day, lying within an interval of several hours unavoidably undersamples this variability. Moreover, individual measurements can be degraded or entirely negated by solar bursts occurring during the measurement. Therefore, one could ask how good is a single flux determination as an estimator of the daily average value of the 10.7 cm solar flux? An investigation over several months by Tapping and Charrois (1994) indicated that in 95% of cases, a single measurement of the 10.7cm flux made at local noon (20:00 UT) was within 2 solar flux units of a flux density obtained by averaging the signal over an entire observing day. Taking the flux determination made closest to the required time is therefore applicable when the above limitations are acceptable. Taking measurements made over a day or longer, then fitting a curve and extrapolating is an effective means for detecting individual measurements that might be affected by flares and for identifying trends in solar activity. In 95% of cases, this should get within a flux unit of the desired measurement.

A more consistent estimate to better than a flux unit can be obtained by using the "CR" (chart record) files. These are records of the four receiver output channels in each flux monitor in averaged 5-second blocks. They show the analogue-digital converter signals in uncalibrated form and with an offset. However, by using calibration information in the file header and inspection of the record it is possible to calibrate the records with usable accuracy. The episodes of various changes in level that occur three times each day are when the precise flux determinations are made, when the antenna is driven on and off-source, and various calibration devices used. Channels A1 and B1 are the high-sensitivity records from the two receiver channels. The data in the low-sensitivity channels, A2 and B2, are of value only in studying strong bursts, and should not be used here. The three daily flux determinations are clearly identifiable. The minima are off-source blocks, where the antenna is pointed away from the Sun. Figure 7 shows an example taken on the 7th November, 2000. It shows the three flux determinations and a fairly large flare. Most records show less or no flare activity. These files can be downloaded (along with the flux determinations), from the DRAO web pages http://www.drao.nrc.ca.

The structure of the file is as below:

- Line 1: Filename (cr + date (year, month, day) + T (for Flux Monitor 2, and S for Flux Monitor 1) and the hour UT the file was opened.
- Line 2: Identifies flux per bit values
- Line 3: Flux per bit values
- Line 4: Data column identification
- Line 5 *etc.*. UT Date (yyyymmdd), UT (hhmmss) and receiver channel 5-second averages.

The table below shows the first few lines of a typical "cr" file.

```
cr000711.T13
flux per bit for A1, B1, A2 and B2
00.37, 00.32, 39.52116 , 43.88
Time, Rx o/p Channels A1, B1, A2, B2
20000711, 132628, 001410, 001411, 000621, 000625
20000711, 132633, 001630, 001660, 000623, 000627
20000711, 132638, 001629, 001659, 000623, 000627
20000711, 132643, 001625, 001654, 000623, 000627
20000711, 132648, 001621, 001650, 000623, 000627
20000711, 132653, 001614, 001642, 000623, 000627
20000711, 132658, 001611, 001638, 000623, 000627
20000711, 132703, 001607, 001635, 000623, 000627
20000711, 132708, 001603, 001629, 000623, 000627
20000711, 132713, 001603, 001629, 000623, 000627
20000711, 132718, 001603, 001631, 000623, 000627
20000711, 132723, 001599, 001625, 000623, 000627
20000711, 132728, 001599, 001626, 000623, 000627
20000711, 132733, 001597, 001623, 000623, 000627
20000711, 132738, 001591, 001617, 000623, 000627
20000711, 132743, 001587, 001613, 000622, 000626
20000711, 132748, 001588, 001614, 000623, 000626
```

Note: The date is made part of the file because the times are UT, and the dates change during the observing day.

By averaging all the blocks or applying a polynomial fit to all the off-source blocks during the day, it is possible to get a value for the receiver output when off the Sun, $x_0(t)$. The total receiver output is $x(t)$. The increase due to the Sun over the day is therefore $\Delta x = x(t) - x_0(t)$. This gives the solar signal received in analogue/digital converter units. At the head of the file are calibration values giving the flux density per bit (of a/d value) for each channel. In the file header these are referred to as *flux per bit*. The solar signal over the day expressed in terms of flux density is given by:

$$S(t) = \beta(x(t) - x_0(t)) \tag{14}$$

where β is the flux per bit value in solar flux units per bit. The accuracy of $S(t)$ can be improved by fixing the values at the centre of each flux determination to the precise measurements. In this way it is possible to get a very good estimate of the flux density at times other than the epochs of the flux determinations.

7 Calibrating Antennas with Beamwidths Smaller than $\approx 4^\circ$

When one observes the Sun with a small antenna, where the beamwidth is larger than about 4°, the whole solar disc, which is about 0.5° across, is seen with an almost constant antenna gain. The antennas used in the solar flux monitors are small dishes, about 1.8 m (6ft) in diameter. The beamwidth to half-power points is about 4.5°. Under these conditions it is unimportant as to whether the disc is uniformly bright, or has scattered, bright, localized sources; they all integrate into the total flux without any need for special consideration.

As the antennas get larger and the beamwidth decreases, an antenna with its boresight directed at the centre of the disc starts to "see" the edge of the disc with lower gain than it does the disc centre. Consequently the contribution of the outer areas of the disc are underemphasized compared with the inner parts, and the observed flux density starts to fall compared with integrated flux density, as would be observed using a broader-beam antenna. In principle, if the antenna is pointed precisely at the centre of the disc, and the solar disc is uniformly bright, it should be possible to measure the antenna gain using a simple, boresight measurement. However, no localized sources can be present for this method to work. This condition is met quite often around solar activity minimum, but much more rarely elsewhere in the cycle.

We look at two cases:

- Measuring the flux with a an antenna with a narrow, pencil-beam pointed at the centre of the solar disc.
- Calibrating an antenna with a beamwidth smaller than 4° in one or both planes.

7.1 Looking at the Solar Disc With a Pencil-Beam Antenna

The simplest way to calibrate an antenna is to point it at the Sun, measure the received flux density and compare this with the a measurement of the integrated flux density made using a small antenna. Although this method works for antennas with half-power beamwidths larger than about 4°, it becomes increasingly questionable as the beamwidth decreases below that value. This difficulty arises because the antenna gain varies significantly over the solar disc, so the reulting flux density is weighted, and may be difficult to relate to the unweighted value. Moreover, if there are bright, localized sources located near the solar limb, the position of the apparent maximum will be biassed, and the average further weighted by an unknown factor. In this section we discuss the difficulty encountered when measuring antennas with narrower beams, a possible application of the method, and a more reasonable use of the method to measure the gain of a small antenna.

7.1.1 Background Theory

Consider the case of observing the Sun with an antenna with a pencil-beam. The antenna boresight is directed at the centre of the disc, which is $\simeq 0.5°$ in diameter (0.0087 radians) and subtends a solid angle of 6.8×10^{-5} radians. Expressing the equation in polar coordinates, the observed flux density in $\mathrm{wm^{-2}Hz^{-1}}$ is given by:

$$S = \int_0^{2\pi} \int_0^{\rho_s} \Phi(\rho, \sigma) P(\rho, \sigma) \rho d\rho d\sigma \tag{15}$$

where ρ and σ are respectively the radial and polar angles in a polar coordinate system. The parameter ρ_s is the angular radius of the Sun, and as before, $0 \leq P \leq 1$. If the beamwidth of the antenna is sufficiently large for $P \simeq 1$ over the solar disc, the equation reduces to:

$$S = \int_0^{2\pi} \int_0^{\rho_s} \Phi(\rho, \sigma) \rho d\rho d\sigma \tag{16}$$

which is the equation for S_0, the integrated flux density of the Sun. Thus, small antennas (having a beamwidth greater than about 4° will measure the integrated solar flux density in a single measurement. However, for wider beams this is not the case. To illustrate the problem in terms of tractable calculations, we take the example of the Sun being uniformly bright over the disc and the antenna having an axysymmetric, Gaussian beam. It is assumed that the beamwidth is never so small that sidelobes fall on the solar disc and need to be considered. In this instance, the antenna power function and the solar brightness distribution may be represented respectively by, $P(\rho) = \exp[-(G_0/4)\rho^2]$ and $\Phi = \epsilon$, the average disc emissivity, given by $\epsilon = S_0/\Omega = S_0/(\pi\rho_s^2)$, where Ω is the solid angle subtended by the solar disc. The observed flux density S is then given by:

$$S = 2\pi\epsilon \int_0^{\rho_s} \exp\left(-\frac{G_0}{4}\rho^2\right) \rho d\rho \tag{17}$$

from which we obtain, after integrating and substituting $S_0/(\pi\rho_s^2)$ for η,

$$\zeta = \frac{S}{S_0} = \frac{4}{G_0\rho_s^2}\left[1 - \exp\left(-\frac{G_0}{4}\rho_s^2\right)\right] \tag{18}$$

The quantity ζ is a factor describing how much the observed flux density S falls below the integrated solar flux density S_0 as the antenna gain increases. For antennas with narrower beams, the method becomes more uncertain. In principle one can measure the flux density and calculate ζ, and then obtain from the equation a value for G_0, provided that one either knows the brightness distribution over the solar disc, or can assume that the solar disc is uniformly bright. Unfortunately the equation is transcendental and must be solved numerically. Alternatively it can be obtained from a table or a plot, such as that in Figure 8.

7.1.2 In Practice

For a small antenna, with a beamwidth less than about 4° the method is simple; peak up on the Sun and measure the increase in received power compared to the background sky. A drift scan made by setting the antenna ahead of the Sun and letting the Earth's rotation take it through the beam might be preferable in that the ground noise is not changing. However, this assumes that the gain of the receiver system is sufficiently stable with time. A calibrated noise source is used to inject a known noise power into the system. The antenna gain is obtained by comparing the received signal with the known value for the integrated flux density.

For larger antennas this technique is rather risky, since it is based upon the assumption that the Sun is uniformly bright. This is usually only the case around solar activity minimum. However, this technique is usable when the Moon is used as a calibration source, since for wavelengths longer than about 6 cm, the Moon can be treated as a black body with a uniform temperature of 225 K.

The other shortcoming is that some knowledge of the polar diagram is required, unless the half-power beamwidth is large enough to ensure that the Sun lies entirely in the main beam of the antenna, in which case a Gaussian or $(\sin(\theta)/\theta)^2$ model may be adequate. However, this method is attractive in that it is simple. The observed solar flux density is measured by adjusting the antenna direction to get the strongest solar signal, then calculating ζ, which is the ratio of this measured flux density and the integrated, full-disc flux density derived from small-antenna measurements such as the 10.7 cm solar flux. The boresight gain G_0 is then derived from equation 18. However, the mapping procedure discussed below is superior, although more complex.

To measure a flux density, a known level of noise has to be injected into the front end of the receiver, as close as possible to the antenna. Terminating the input with a load of known temperature is not as good because when it is is connected, all sources of noise from the antenna are switched off. Consequently only the total of the noise contributions coming from the antenna are measured. The solar signal level can only be obtained if all the other contributions, such as that from the ground, are known.

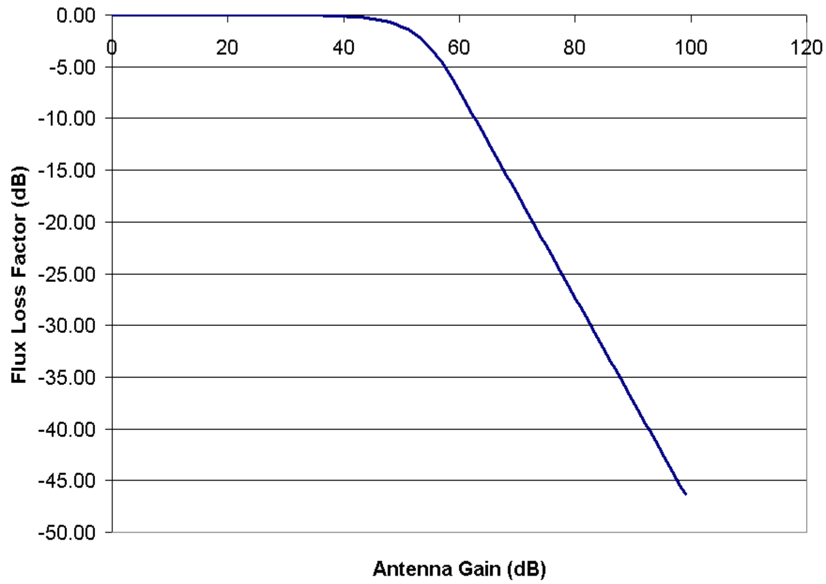

Figure 7: The flux degradation factor ζ plotted against antenna gain for an antenna with a axisymmetric, Gaussian main beam and assuming a uniformly-bright Sun.

The increase in output level when the antenna is moved from empty sky to the centre of the solar disc is noted, and compared with the deflection due to the noise source. A signal generator is not a good alternative, since the receiver passband has then to be known precisely. It is convenient to express the noise injected in terms of temperature. For example a typical solid-state noise source (with noise factor N) produces an output increase of $T_N = (N-1)T_0$ when switched on. If the noise output is given as 30 dB, then $N = 1000$ and the noise output from the source $T_N = 300,000$ K. If this is injected into the main signal line by a (say) 30 dB directional coupler, a calibration noise signal of 300 K is available. This is compared with the increase in signal when the antenna is driven on-source from empty sky. By linear comparison with the calibration signal the solar signal can be expressed in Kelvins. This is the strength of solar radio emission received in terms of antenna temperature, T_a. The observed flux density is given by

$$S = \frac{8\pi k T_a}{G_0 \lambda^2} \tag{19}$$

Assuming that the antenna beam is not much smaller than the angular diameter of the Sun it is reasonable to assume the part of the main beam falling on the solar disc is Gaussian and stable enough to derive ζ. Then we can substitute ζS_0 for S in the above equation, and solve it for G_0:

$$G_0 = \frac{8\pi k T_a}{\zeta S_0 \lambda^2} \tag{20}$$

This does indeed yield an estimate for the antenna gain but the derivation is not very "hygenic" and is based upon the assumption that the solar disc is uniformly bright. However the method is relatively quick and easy, and may be appropriate in some situations. For a serious attempt to estimate the gain of an antenna with a beamwidth smaller than about 4° using the Sun, the mapping method is recommended.

7.2 Calibrating and Antenna Using the Mapping Technique

The method described here is more tedious to apply, but can be used to measure antennas with pencil-beams with half-power widths smaller than 4.5°, or fan beams that are smaller than 4.5° in one plane. Is insensitive to the presence of bright, localized sources on the solar disc, and can be used with any antenna having a beam that is not so broad on one plane that it is not possible to get completely off the Sun for estimating of the background sky level. This method is based upon the property of radio maps that the total flux density in the map is the same as the flux density measured by an antenna that "sees" the source as a point.

7.2.1 Background Theory

Consider the case of a bright patch of radio emission in the sky. It's centre lies at the origin of a sky coordinate frame. Points away from the origin are identified by their coordinates ξ, η, which respectively give the right ascension or declination (preferable) or azimuth and elevation (usable) offsets from that origin. The brightness of the source, in terms of flux density per unit solid angle, is given by the *brightness distribution function* $\Phi(\xi, \eta)$. The antenna boresight is pointed in a direction ξ_0, η_0 from that origin. The antenna beam profile is described by $P(\theta, \phi)$ where $0 \leq P \leq 1$ and the coordinates θ and ϕ are measured in the same direction as ξ and η respectively, but with an origin at the antenna boresight. We have therefore that $\xi = \xi_0 + \theta$ and $\eta = \eta_0 + \phi$. In terms of sky coordinates, the flux density received from an element of sky $\Delta\xi \times \Delta\eta$ the total power received by the antenna is given by (as per equation 21:

$$S(\xi_0, \eta_0) = \int_{-\eta^*}^{+\eta^*} \int_{\xi^*}^{\xi^*} \Phi(\xi, \eta).P(\xi - \xi_0, \eta - \eta_0).d\xi.d\eta \tag{21}$$

where the integration ranges $-\xi^* \rightarrow +\xi^*$ and $-\eta^* \rightarrow +\eta^*$ encompass a sufficient range of azimuth and elevation to cover all the sky occupied by the source. These values are assessed by scanning the antenna until the observed receiver output has fallen to the level obtained when empty sky is being observed. The units of S are w.m^{-2}.Hz^{-1}.

This value is not easily related to the flux density of the whole source, as would be measured by a small antenna, since it requires knowledge of the brightness distribution of the source and the antenna beam. Even if the brightness distribution of the source is known precisely, it is not possible to obtain unambiguously the form of $P(\theta, \phi)$, from which the antenna gain can be calculated. We make use to the property of maps, even those smeared out by the antenna beam, that the total flux density integrated over the map is the flux density that would be measured using a small antenna, which sees the whole source with equal sensitivity. The observing antenna smears the map but does not affect the integrated flux density.

If a raster-scan map of the source area is made, with the scans close enough to one another to adequately sample all the structure in $\Phi(\zeta, \phi)$ the map will be "smeared" out by the limited resolution of the antenna. However, if by interpolation polynomial fitting, the sampled map is made into an estimate of the brightness distribution, the flux density integrated over the map, although smeared out by the antenna, is still equal to the integral of the brightness distribution. The antenna beam just makes the distribution look broader, with finer angular details lost. Therefore

$$S_0 = \int_{\eta_0^*}^{\eta_0^*} \int_{\xi_0^*}^{\xi_0^*} S(\xi_0, \eta_0) d\xi_0 d\eta_0 \tag{22}$$

where the $*$ superscripts indicate positions in the sky that are far enough from the source for none of its emission to be identifiable in the receiver output.

7.2.2 In Practice

How the map is made depends upon the antenna and its control system. If the control system and time available are adequate, a grid of points is set up, centred on the Sun, of spacing not more than a quarter of the half-power beamwidth or the angular diameter of the Sun, whichever is the smaller, and covering an area of the sky big enough for the edges of the map to include a good piece of background sky, so that the solar emission can be determined as an increase over the background sky emission. The total radio emission at each point is then measured.

If this is not possible, a raster scan map may be made by wagging or nodding the antenna. It is however important than the map extends to background sky in all directions. If motion in elevation is the easier option. the antenna should execute a series of nods centred on the angle of elevation of the Sun, and large enough to include empty sky. The antenna can be scanned in azimuth while nodding, or pointed due south and the Sun allowed to move through the antenna beam while the antenna is nodding. The result is a raster-scan map of a patch of sky centred on the Sun. If on the other hand wagging is more feasible, then wags at a range of elevations across the azimuth of the Sun can be used. This method is made more complex by the changing azimuth of the Sun during the measurements.

In general, any map over more than a few degrees of sky, or which involves observing at low angles of elevation, will contain a component due to ground radiation. In the case of drift scans or wags where the antenna is at a constant elevation (for that particular scan at least), the ground radiation will be part of the base level. It should be easy to subtract this constant component from the observation. If it isn't possible, the scan doesn't include enough background sky.

Nodding is a little more difficult to deal with, since the elevation of necessity changes though a large angle. In this case the elevation scans made at the beginning and end of the survey, when there is a negligible solar contribution to the receiver output, can be used as observations of the ground radiation, and subtracted from the elevation scans. This will flatten the baseline but will probably leave a constant residue, which can be subtracted.

Using the grid of measured points or the raster scans, together with whatever interpolation, smoothing and function fitting is needed, a two-dimensional model for the brightness distribution is fitted to the data. At this point the data are uncalibrated.

As in the previous case, a noise calibration signal is necessary, known as precisely as possible and injected as close as possible to the antenna feed. By switching on the calibration signal regularly during the calibration process, it is possible to calibrate the solar signal in terms of the injected noise temperature, yielding a map calibrated in terms of antenna temperature T_a.

The total signal is obtained by integrating the map (after the background is subtracted). The result is the total flux density produced by the Sun at the observing wavelength, expressed in terms of antenna temperature. If T_a is the integrated antenna temperature over the map, the gain of the antenna is given by:

$$G_0 = \frac{8\pi k}{S_0 \lambda^2} T_a \tag{23}$$

Note that in each case described here an accurately-known, noise calibration signal is needed.

7.3 Polarization

For antennas with broad beams ($> 3°$), the Sun can be assumed to be an unpolarized source. When using an antenna with a narrow enough beam to focus on individual active regions, a few percent circular polarization may be observed, although this might cancel out when integrating over the whole region. For antennas having beamwidths of a few arc-minutes or less, compact, highly-circularly polarized sources (up to 80% or so) may be observed. The Sun produces no significant amount of linearly-polarized radio emissions.

Polarization should not be an issue when antennas are being calibrated in the manner described in this paper. Antennas that have sufficiently large beamwidths for them to be calibrated by simply pointing them at the Sun will observe no significant polarization; it will all cancel out. Antennas with narrow beams cannot be calibrated by pointing them at the Sun; the mapping method should be used. When integrating over the map to derive the total flux density, the polarization will integrate out, leaving a signal that can be assumed randomly polarized.

8 Calibration: Signal Generators versus Noise Sources

The Solar radio emissions can, within the passband of a receiving system, be considered as broad-band noise. It is certainly possible to make a flux density calibration using a CW signal generator, but a noise source is better. Consider the case of a receiver operating at a centre frequency of f_0, where the gain variation across the bandwidth is described by $g(f)$, and the antenna collecting area is A_{eff} (so the antenna boresight gain is $G_0 = 4\pi A_{eff}\frac{f_0^2}{c^2}$, which is assumed constant across the receiver bandwidth. If that system is used to observe the Sun, the observed power increase at the output of the receiver is:

$$W_s = \frac{1}{2}G_0\frac{c^2}{4\pi f_0^2}\int_0^\infty S(f)g(f)df \tag{24}$$

If we now move the antenna off-source, and inject a known input at a frequency of f_0 from a signal generator, the output increase is:

$$W_g = P_g g(f_0) \tag{25}$$

where P_g is the injected power from the signal generator. Define a relation $\mathcal{R}$

$$\mathcal{R} = \frac{W_s}{W_g} = \frac{1}{2}G_0\frac{c^2}{4\pi f_0^2 P_g g(f_0)}S(f_0)\int_0^\infty g(f)df \tag{26}$$

since we can assume the solar flux density $S(f_0)$ is constant across the receiver bandwidth and needs only to be measured or calculated for the centre frequency. The antenna gain is given by

$$G_0 = \frac{8\pi\mathcal{R}{f_0}^2 P_g g(f_0)}{S(f_0)c^2}\left[\int_0^\infty g(f)df\right]^{-1} \tag{27}$$

The obvious difficulty with this method is that to calculate the antenna gain one needs values for the centre-band gain, $g(f_0)$, and the integrated gain $\int_0^\infty g(f)df$.

If instead, when the antenna was driven off source, a calibration signal from a noise source is injected, of flux $N(f_0)$ watts per Hz, the output of the receiver increases by the power increment

$$W_N = N(f_0) \int_0^\infty g(f) df \tag{28}$$

The ratio $\mathcal{R}$ in this case is therefore

$$\mathcal{R} = \frac{W_s}{W_N} = \frac{1}{2} G_0 \frac{c^2}{4\pi f_0^2} \frac{S(f_0)}{N(f_0)} \tag{29}$$

so the antenna gain G_0 is now given by:

$$G_0 = \frac{8\pi \mathcal{R} {f_0}^2}{c^2} \frac{N(f_0)}{S(f_0)} \tag{30}$$

This is much simpler, because $\mathcal{R}$ is the only quantity to be measured; the other quantities are known. By comparing the increase in receiver output due to the Sun, with that caused by the noise source, we can calculate the solar power input to the receiver in terms of the calibration noise flux. The ratio of this power and the solar flux density gives the effective collecting area of the antenna, and thence the gain.

If a noise source has an excess noise ratio of (say) 30dB, it has a noise temperature of around 300,000 K. If the mean coupling factor of the directional coupler is (say) 30dB, we are injecting 300K into the receiver. We're assuming the injection point is at the feed. If it is at the receiver end of the waveguide run, the injected power has to be multiplied by the waveguide loss. Spectral density (power per Hz) is related to temperature by kT, so if we're injecting 300 K, this is a spectral density of 4.2×10^{-21} w Hz^{-1}

In using signal generators to measure noise signals, another important consideration is that of linearity and dynamic range. For example, if we add 500 K of noise to a 10 MHz bandwidth receiver with a system noise temperature of 100 K, the noise level across the band increases by about 7 dB, and the total power from the noise source is $kTB = 7 \times 10^{-14}$ W. The power per unit bandwidth is $kT = 10^{-21}$ WHz^{-1}. If the signal generator has a bandwidth of 1 kHz and has to produce the same power level, it has to produce 40 dB more power in that 1 kHz band in order to equal the band-filling noise from the noise source. Instead of a 7 dB increase in noise level across the band, we have to deal with a 40 dB increase concentrated in a spike at band centre. This places a much larger demand on the dynamic range and linearity of the receiver.

9 Where's the Sun?

The average radar antenna knows nothing about celestial coordinates, it is usually on some form of altazimuth mount and has encoders that read its position in terms of azimuth and elevation. Unless an appropriately programmed control computer is available, it is difficult or impossible to track the

Sun across the sky. One practice is to find the Sun by measuring the signal level and peaking on the maximum signal. This is a usable technique for antennas with half-power beamwidths larger than about 2°. However, in general, setting up a gain measurement procedure requires knowing where the Sun is.

An ephemeris provides the position of the Sun in astronomical coordinates. These are *right ascension* which is the time interval between when a particular reference point in the sky known as the *First Point of Aries* crosses the southern meridian and the time the Sun does. The other coordinate is *declination.* Declination is exactly analogous to latitude. An excellent ephemeris program is available from the US Naval Observatory. It is inexpensive, lacks the un-needed frills, and produces output in a convenient format. We use that program to produce an annual listing of the coordinates of the Sun at 0:00UT. The antenna control program then linearly interpolates those values through the day, giving the Sun's right ascension and declination at any moment.

Because the celestial coordinate frame gradually slides round the sky at one revolution a year, deriving where to look in the sky to observe the Sun requires some further computation. Using the ephemeris we obtain the *Julian Day Number* for the current time and then calculate the *Local Sidereal Time* which is the right ascension due south at that time. From this we get the Sun's *hour angle* which is the angle between the Sun and the meridian, or if measured in hours, how many hours the Sun is from crossing the meridian. The hour angle is given by $HA = LST - RA$. Where LST = Local Sidereal Time, which is obtained using the program fragment below:

Constants

$$q_0 = 36525 \quad (31)$$
$$a_0 = 2415020 \quad (32)$$
$$a_1 = 0.276919398 \quad (33)$$
$$a_2 = 100.021359 \quad (34)$$
$$a_3 = 0.000001075 \quad (35)$$
$$a_4 = 1.002737908 \quad (36)$$
$$\quad (37)$$

Calculation

First calculate number of years that have passed since the first Julian Day.

$$T = (JD - a_0)/q_0 \quad (38)$$

Now calculate the Greenwich Sidereal Time at local midnight in days.

$$GST = a_1 + (a_2 + a_3 * T) * T \tag{39}$$

We don't need the whole number, just the fractional part, which we convert to hours.

$$GST = (GST - FIX(GST)) * 24 \tag{40}$$

Now convert it to Local Sidereal Time.

$$LST = GST + UT * a_4 - obslong/15 \tag{41}$$

where UT is the Universal Time and $obslong$ is the observatory longitude. There are 15 degrees of longitude in an hour.

This calculation gives us the coordinates of the Sun in the sky expressed in terms of hour angle and declination.

The formulae below give the Sun's elevation and azimuth.

$$\sin(el) = \sin(obslat)\sin(dec) + \cos(obslat)\cos(dec)\cos(HA) \tag{42}$$

$$\cos(el) = (1 - \sin^2(el))^{1/2} \tag{43}$$

$$\sin(az) = \frac{-\cos(dec)\sin(HA)}{\cos(el)} \tag{44}$$

$$\cos(az) = \frac{\sin(dec) - \sin(el)\sin(obslat)}{\cos(el)\cos(obslat)} \tag{45}$$

Sine and cosine forms of the equations are needed for quadrant management.

Solving the elevation equation for $HA = 0$ gives the elevation of the Sun at noon.

10 Discussion and Summary

The best source for measuring the gain of an antenna is a bright, stationary point source of known intensity in the far field of the antenna. For large antennas, cosmic radio sources such as Cygnus A can be used. For wavelengths longer than about 10 cm, the Moon can be assumed to be a uniformly-bright disc with an average temperature of about 225 K. If however, neither of these options yields a usable signal-to-noise ratio the Sun may be used, with all the provisos discussed earlier in this paper. At the moment the only rapidly-available, absolutely calibrated measurements of the solar radio flux density are made at 10.7 cm wavelength - the 10.7 cm solar flux ($F_{10.7}$).

There are methods that can be used to obtain usable estimates of the flux density at other wavelengths in terms of those 10.7-cm measurements *most of the time*. Antennas with beamwidths larger than about 4° can measure the integrated flux density in a single operation, with the antenna boresight directed at the centre of the solar disc. Antennas with smaller beamwidths can be measured by mapping the solar disc and integrating the total power over the map. In either of these cases, provided that the right option is used for the antenna beamwidth, the Sun can be assumed to be an unpolarized source.

All the calibration methods depend upon a known calibration signal being injected as close as possible to the antenna feed. Signal generators are usable, but relating a CW signal from the signal generator to a noise-like signal from the Sun, which fills the receiver passband is rather difficult. It requires detailed knowledge of the receiver passband. In addition, balancing a narrow band signal to a broadband one makes great demands upon receiver linearity. The best device is a solid-state noise source. These are excellent secondary standards and produce a signal very much like the solar one. In this case the receiver passband need not be known at all.

Unless the solar disc is uniformly bright, a situation that occurs frequently around solar activity minimum but less often at other times, using the "pencil-beam" pointed at disc centre way of measuring the gain (with the gain correction process discussed in Section 7.1) may not be reliable. Mapping (Section 7.2) would be better. However, not all antennas will be able to do this very easily. An oversampled grid map would be best, but not always possible. It is however feasible to map the Sun using wagging or nodding, recording the receiver output and antenna position "on-the-fly". Provided that enough sky is mapped to see down to the background, delays in data flow and the possibility that the antenna beamwidth is large enough to produce a badly-smeared map has no effect on the gain measurement, even if the map looks terrible.

Antennas having beamwidths of 0.5-$\approx$ 1° may be somewhat deceiving in that since no evidence of distorting effects due to localized, bright sources on the solar disc is identified, it might be assumed that there is therefore no error being introduced by their presence. Whether or not this can be regarded as true depends upon how accurately it is required that the antenna gain be measured. Even when an antenna with a 0.5° is used to map a Sun consisting of a uniform disc with a bright source on the edge, that bright source would be observed, unless very bright, as a slight brightening or distortion of one limb. However, the gain estimate, even if corrected for non-uniform observation of the solar disc, will still be significantly degraded. If the antenna is pointed at the Sun by maximizing the received noise, the error could be larger, due to biassing of the antenna pointing direction towards the source.

However, on the whole, the Sun provides a convenient calibration source. It is bright, in the far field, and available to many facilities at the same time. Also, unlike satellites, it crosses the Sun usably slowly and, at a distance of 150 million kilometers, shows no parallax. Consequently, computing its position is relatively simple, and the same ephemeris can be used be everybody. However, the Sun would be a better calibration source if we made absolute measurements over more frequencies.

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