On Aperture Blockage and Its Consequences for Astronomical Observations

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I. Blocked vs. Unblocked

The D'Addario committee study [1] of technical issues in the design of the new Green Bank Telescope (GBT) concludes that a telescope properly illuminated from an offset position works just as well (e.g. in polarization purity, beam-scanning, etc.) as a telescope illuminated from the axis of symmetry. Others who have considered this issue have reached a similar conclusion [2,3]. The structural symmetries of a center-fed design (i.e. the traditional parabolic radio telescope as first built by Reber) make it cheaper to construct by $\sim$ 20% than an offset unblocked parabolic telescope of similar geometric area [1]. The monetary savings, however, come with their own cost: a center-fed system has aperture blockage from feed support legs, from the subreflector and its housing, and so on, that degrades the performance of the telescope.

It is important to realize that aperture blockage does not enhance a telescope in any respect. At best, blockage is a mildly negative factor; at worst, it can cause serious corruption of the astronomical observations.

This memo presents a compilation of information (such as there is) about the effects of aperture blockage on astronomical observations. Many of the consequences of blockage (e.g., the location and amplitude of telescope sidelobes or the spectral baselines caused by standing waves) are difficult to measure and are known poorly, if at all, for most radio telescopes. Many of the consequences are even difficult to calculate theoretically (see section III). But there is enough information to gauge the impact of blockage and compare that to the savings in cost.

The topic divides into two general categories: the effect of blockage on the reception of the desired signals, and its effect on rejection of undesired signals. The second is vastly more important than the first.

II. Reduction of Gain

Any structure that blocks the telescope aperture will scatter radiation out of the main beam and thus reduce the gain of the telescope. The reduction in gain is about twice the fractional blockage. Thus, the gain of a 100m GBT with $\sim$ 4%

effective blockage (3% from the feed support legs and 1% from the subreflector and everything else) is 0.92 that of an unblocked aperture[1]. This reduces the difference in cost between the competing telescope designs when gain is held constant. If a telescope's total cost is proportional to its diameter to the 2.7 power, an unblocked telescope costs only $\sim$ 10% more than a blocked one of equal gain. This topic is discussed in more detail by Norrod [3].

III. Creation of Sidelobes

Any power scattered out of the main beam goes into sidelobes that are spread across the sky. There are at least three sources of sidelobes: the aperture edge, surface irregularities, and blockage. This section summarizes the properties of the sidelobes; their consequences are given in later sections.

"Aperture" sidelobes result from the termination of the illumination pattern at the sharp edge of the dish. They are exactly the same as the Airy rings, and can occur in all telescopes, blocked or unblocked. Their amplitude and shape depends on the aperture and its illumination, but the amplitude always decreases with offset from the main beam, and the angular separation of these sidelobes from the main beam scales with λ/Diameter. Aperture sidelobes can be controlled by proper choice of the illumination pattern.

An example of aperture sidelobes is given in Figure 1. These measurements were made on the horn-reflector of Bell Labs at Crawford Hill [5]. This antenna has been used occasionally for radio astronomy [6]. Its aperture is 28 m^2 and its main beam efficiency is 91.7%. Figure 1 covers an area $\sim 4 \times 7$ half-power beam-widths and includes more than 99% of the total antenna response. The illumination pattern that was used for these measurements was essentially constant in the elevation direction (vertically in this figure) producing noticable $\sim$ sinc^2 sidelobes.

A second kind of sidelobe arises when scattering by irregularities in the dish surface forms a broad, low-level "error beam" around the main beam. This sidelobe is familiar to users of the old 36 ft. mm-wave telescope [7;20] and is important near the high frequency limit of every telescope. "Surface" sidelobes can be reduced only by improving the surface accuracy. They are common to blocked and unblocked telescopes, do not affect the question of aperture blockage, and will not be discussed further.

The remaining sidelobes – in many ways the most important ones – arise from aperture blockage. "Blockage" sidelobes do not depend strongly on the precise

[1] The geometric blockage of existing open air radio telescopes ranges from 4% to 7%. The effective blockage varies with frequency and is larger than the geometric value by a factor that can be 1.2 or 1.5 [4].

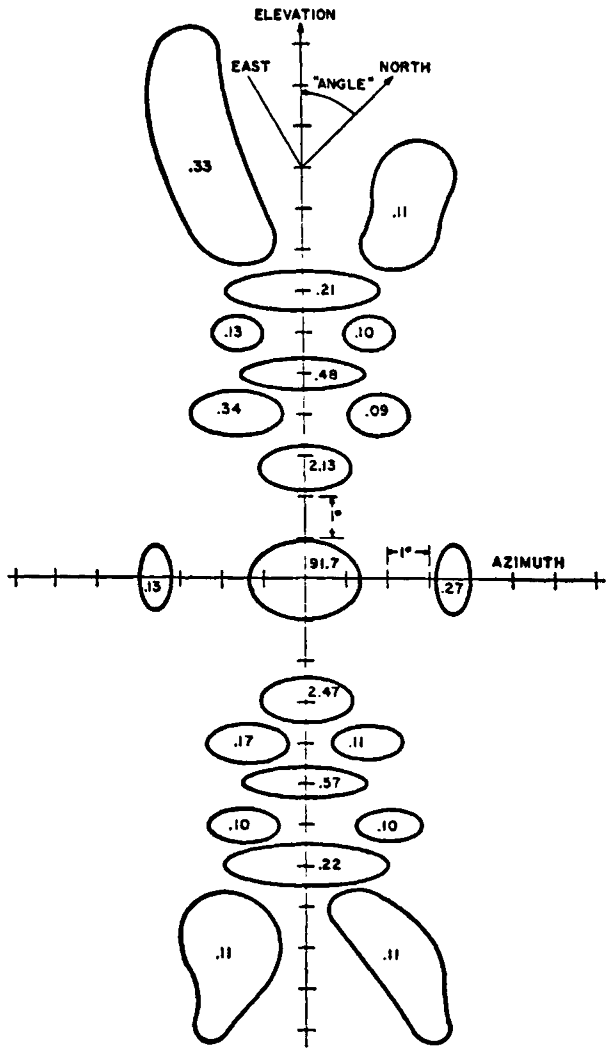

FIG. 1. Schematicized antenna pattern in the transverse polarization (i.e., E vector parallel to the elevation axis in the figure): All measurements were made in this polarization to avoid difficulties with the spillover lobe (Crawford *et al.* 1961). The contours indicate the approximate half-power extent of the lobes. The normalized response of each lobe is indicated.

Figure 1: Beam pattern for the Crawford Hill horn-reflector of Bell Labs. The percentage of the total antenna response is given for each lobe. More than 99% of the antenna's total response is included in this figure (from Penzias et al. [5]).

illumination pattern because blockage is usually distributed over the aperture[2]. These sidelobes arise from diffraction and scattering by fixed structural elements, so their general angular structure tends to be independent of wavelength. Because the scatterers typically have a modest size, their sidelobes are usually broad and have low amplitude, though the power in them can be appreciable. The sidelobes can be highly polarized (see section VI). It may be useful to think of the blocking elements as small antennas that systematically deflect some part of the total power out of the main beam while also leaving a gap in the aperture. The precise form of blockage sidelobes is difficult to calculate because the obstructions are often comparable to or smaller than the wavelength, and because they can be illuminated not only by the plane wave from the aperture but also by the spherical wave from the feed [15].

Examples of blockage sidelobes are given in Figures 2, 3 and 4. Figure 2 shows portions of sidelobes caused by scattering off the three feed support legs of the Dwingeloo 25m telescope [8,9][3].

A feed support leg produces a ring sidelobe that is centered at the projected position of the leg on the sky. The ring has a radius equal to the angle of the leg to the vertical, and a width that is roughly equal to the wavelength divided by the length of the leg projected into the aperture [22].

Each of the feed support legs at Dwingeloo thus produces a scattering ring with a diameter of 60° which passes through the main beam, and is centered symmetrically opposite the leg on the sky, (i.e. the sidelobe from the *north* leg is centered 30° *south* of the main beam). These particular ring sidelobes are about 3° to 6° wide. In all, they contain 4.1% of the telescope's total response.

Although the rings are the most prominent signature of feed support leg blockage, the legs also create lower-level, broad sidelobes that are visible as three-fold symmetries in the antenna response pattern up to 90° off axis [9]. Feed support legs also produce back-lobes, as will be discussed in section IV.

Figure 3 shows the response pattern of the Effelsberg 100m telescope near the main beam [10]. It is clear that the feed support sidelobes (here from a quadrapod) dominate the near sidelobes as well as the far. The intersection of the four rings distorts the main beam into a rectangular shape at the −12.5 dB level. The four-fold symmetry of the "blockage" sidelobes swamps the weaker, circularly-symmetric "aperture" sidelobes.

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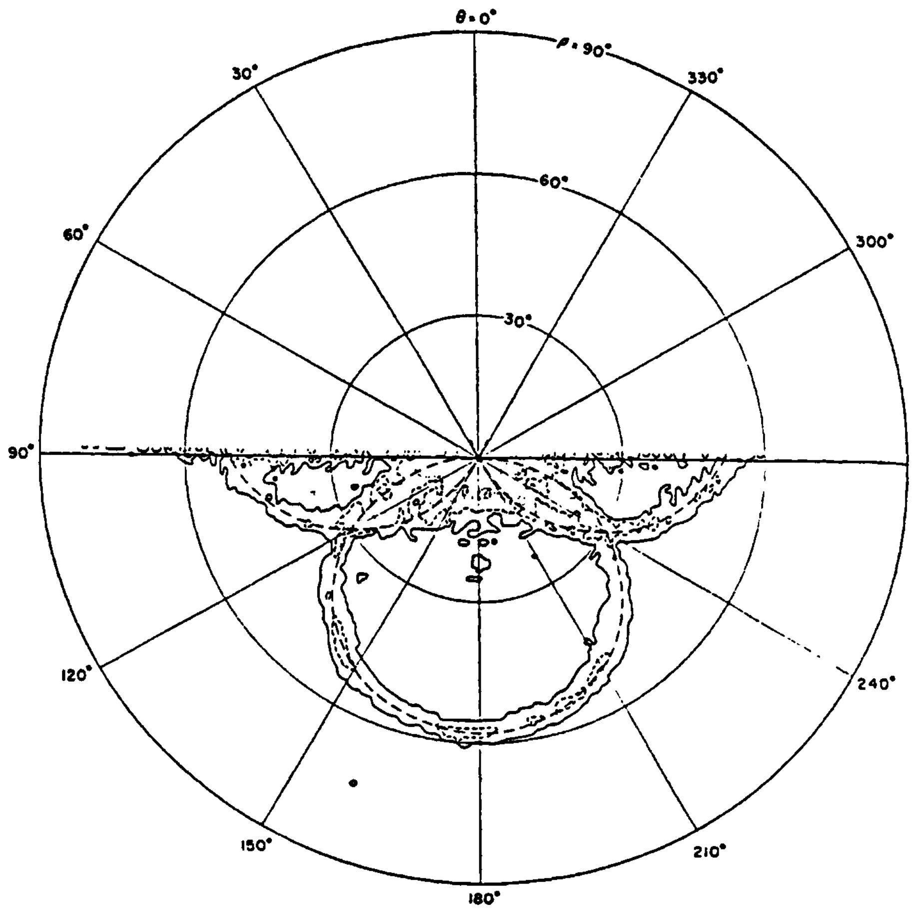
[2]It may be possible, in theory, to illuminate an aperture with nulls at every feed support leg, etc., but I do not know of any instance where it has been attempted, and it may not be practical with currently available low noise feeds.

[3]These measurements from Higgs [8] were made using a transmitter on a nearby TV tower. The missing upper half of the antenna pattern corresponds to negative telescope elevations. It is much more difficult to use celestial radio sources to map these sidelobes and the results are not as accurate, mainly because of confusion (cf. this figure with Figure 5 in [9]).



FRONT

Figure 2. Principal features of the antenna pattern, as observed at 1° intervals in azimuth and elevation. No corrections for observational errors have been made. The solid contour denotes a level of - 50 db with respect to the main beam; the dashed contour, - 45 db; and the dotted contour, - 40 db. In the "front" hemisphere, the dashed circles show the position of the predicted feed-leg scattering cones. In the "rear" hemisphere (see opposite page), the dashed circle denotes the projected position of the rim of the antenna as seen from the feed.

Figure 2: Sidelobes of the Dwingeloo 25m telescope caused by feed support leg scattering (from Higgs [8]).

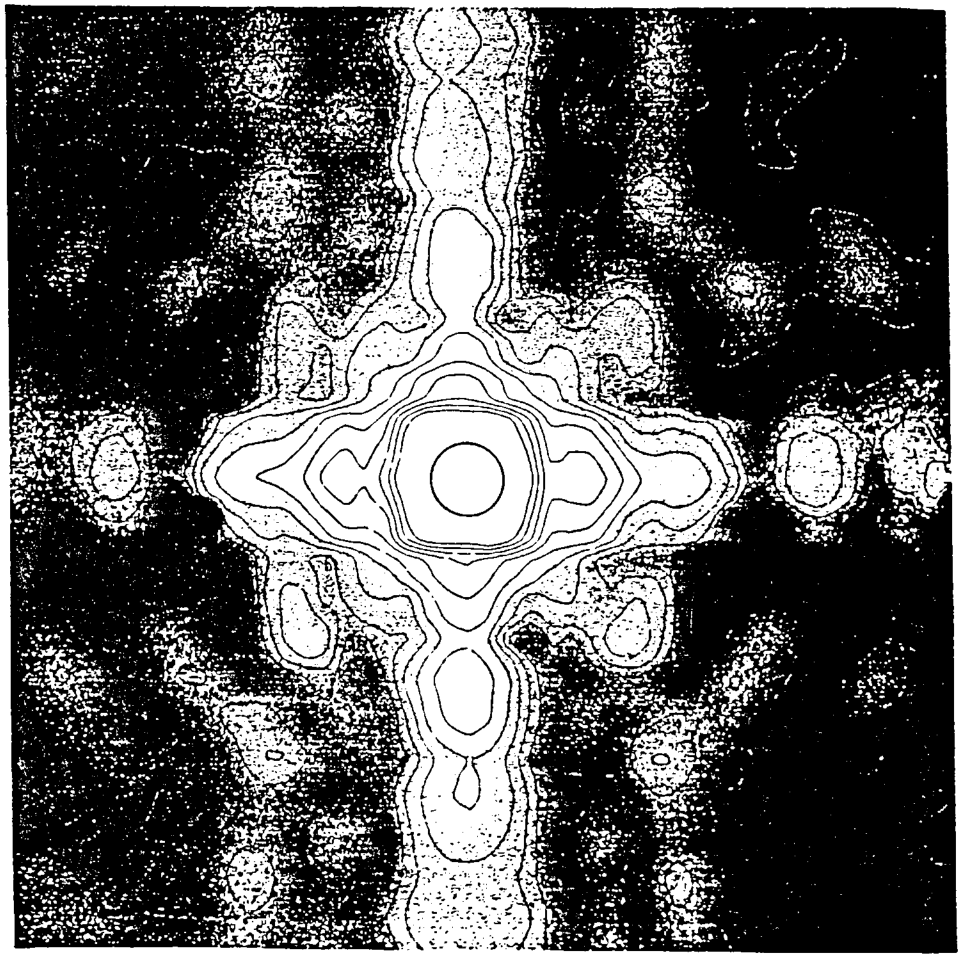


Fig. 1. Antenna pattern of the 100 m telescope at $\lambda = 21$ cm. The field size is $2^\circ \times 2^\circ$, north is at the top, west at the left. The **−3 dB** level for the main beam is indicated by a circle. The levels from −12.5 dB to −40 dB are shown by isophotes separated by **2.5 dB**. Sidelobe levels between −25 dB and −47 dB are indicated by the gray scale

Figure 3: Sidelobes near the main beam of the Effelsberg 100m telescope. The radial lobes are the intersection of the four feed leg ring sidelobes (from Kalberla et al. [10]).

Every structural element that blocks the aperture contributes its own sidelobes. An example is given in Figure 4, which shows a measurement of the antenna response of the 100m telescope in a quadrant adjacent to the main beam [10]. The extended minimum in the pattern about 2° from the main beam, and the sidelobe about 3° away, arise from the diffraction pattern of the 6.5m secondary reflector which was located above (behind) the prime focus receiver when these measurements were made.

A factor that is useful in characterizing the performance of a radio telescope is the beam efficiency

$$\eta_b = \lambda^{-2} \int A_e d\Omega$$

where A_e is the effective area, and the integral is taken out to some angle θ from the direction of the main beam. Integrated over the entire sky $\eta_b = 1$ if resistive losses are small (as they most often are). The beam efficiency shows how much of the telescope's response is where it should be (in the direction the telescope is pointing) and how much of it is elsewhere.

Measurements from the literature usually give η_b only over some rather arbitrary area defined by the limits of the observer's patience in taking the required data. To compare several telescopes Table 1 lists the measured efficiencies against angle from the main beam in units of the telescope's HPBW, although from the above discussion it is clear that the scaling is only appropriate for the horn-reflector. The notes to the table contain enough information to recover the original data.

TABLE I

Beam Efficiencies η_b

θ[1]	Dwingeloo[2]	Effelsberg[3]	Crawford Hill[4]
0.8			0.92
1.25	0.76		
1.7		0.70	0.97
5.0			>0.99
8.5	0.81[5]		
27.		0.82	

1) Angle in units of the telescope's HPBW at 21cm except for (5).
2) 25 meter with tripod. HPBW=35'. Blockage 5.4% (Geometric).
3) 100 meter with quadrapod. HPBW=9'. Blockage 7% (Geometric).
4) Bell Labs horn-reflector ∿5 meter. HPBW=3°x2°. No blockage.
5) Measurement made at 820 MHz. HPBW=62'.

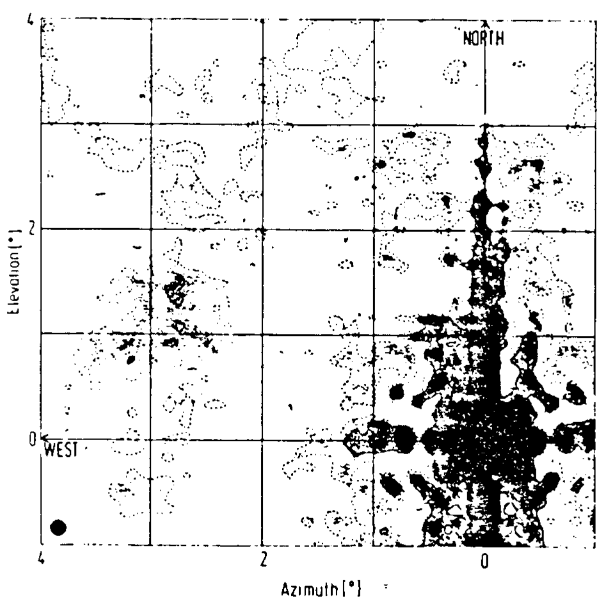


Fig. 2. Antenna pattern of the 100 m telescope for the NW quadrant. The field size is 5° × 5°. The levels between −30 dB and −45 dB are indicated by isophotes separated by 5 dB. The shaded areas are above −45 dB

Figure 4: Antenna response in a quadrant near the main beam of the 100m telescope. The sidelobe 3° from the main beam is caused by diffraction at the subreflector edge (from Kalberla et al. [10]).

The two telescopes with aperture blockage have $\sim$ 20% of their total response more than 5 HPBW away from the main beam. A small amount of the "missing" η_b is in spillover lobes, which are stimated to contain perhaps as much as 3% of the response of the 25m and 100m telescopes [8,10]. But the main loss of efficiency is due to aperture blockage. The Bell Labs data show just how good an antenna can be, and calculations for an offset parabaloid with f/D = 0.6 predict that it will have a η_b = 0.97 in an area of radius 1.25 HPBW [14], similar to the measured values for the horn-reflector.

To summarize the material in Table 1, aperture blockage typically increases a telescope's off-axis (and hence unwanted) response by a factor $\sim$ 20 compared to the response over a similar area of an unblocked aperture. The Dwingeloo and Effelsberg telescopes have nearly 20% of their response at angular displacements greater than 5 HPBWs from the main beam.

IV. Increase of System Temperature[4]

Sidelobes can pick up radiation from the ground, increasing the total system temperature and reducing the sensitivity of the radio telescope.

The effect is shown quite dramatically in Figure 5. These measurements were made at 6 cm on the 300 ft. telescope using a special purpose feed designed by S. Srikanth that illuminated only a patch about 130 ft. in diameter offset towards the dish edge (this is shown schematically in the top panel). Because the 300 ft. telescope had only two feed support legs, the feed could be rotated to illuminate an almost completely unblocked aperture (near angles of 90° and 270°) or an aperture partially blocked by the feed support legs (at angles of 0° and ±180°). The variation in total power with rotation angle is due entirely to scattered ground radiation. Measurements were made with the telescope pointed at the zenith (elevation 90°) and at declination −12° (elevation 40°). At the zenith the ground radiation picked up through the legs' sidelobes was as high as 18 K; averaged over all rotation angles it contributed about 3.8 K to the total system temperature. Note that at the zenith all scattered ground radiation must come in through back lobes (in addition to whatever spillover there might be) and not through the main ring lobes. On the 300 ft. telescope these feed support back lobes must have contained at least 1% of the total antenna response. These measurements agree quite well with calculations of the average expected feed-leg scattering [21].

At lower telescope elevations more of the antenna's sidelobes intersected the ground and the scattered power was larger. When the telescope was pointed south,

[4]The 300 ft. measurements described in this section were made in August 1987 with S. Srikanth, and H. Payne. I am indebted to J.R. Fisher and S. Srikanth for many discussions about feeds and sidelobes.

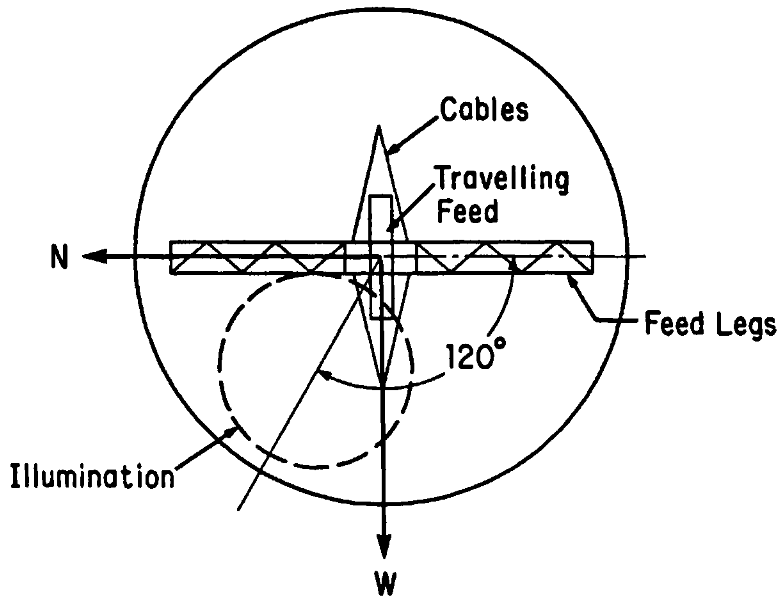


Figure 5a: Schematic of the 300 ft. telescope and the location of the illumination pattern made by Srikanth's special purpose feed at a rotation angle of 120°.

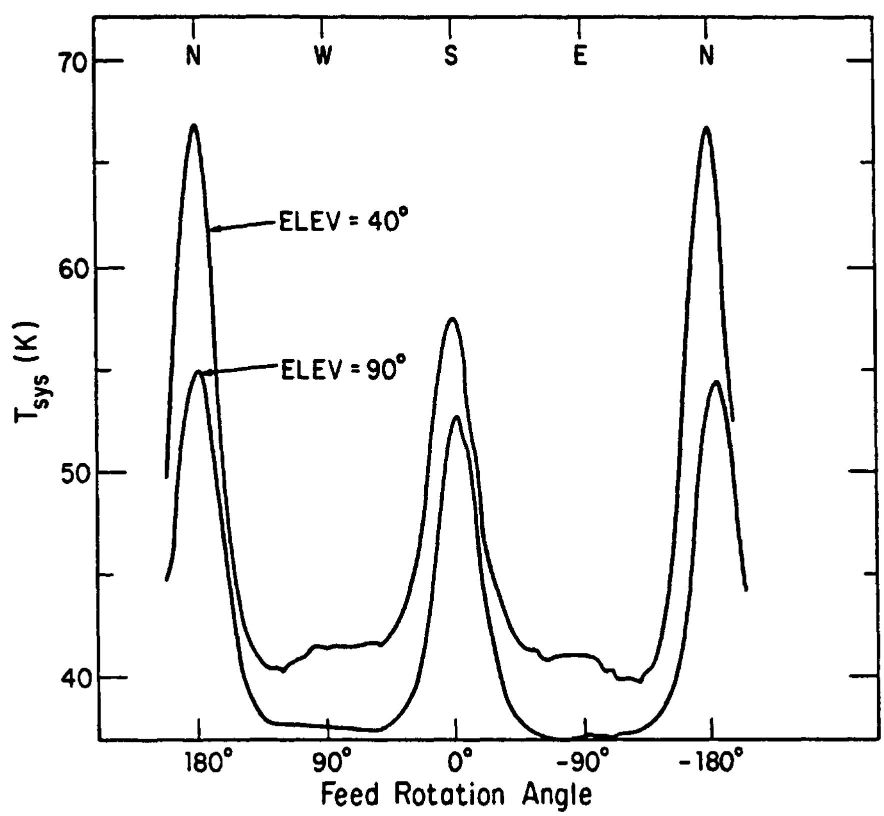


Figure 5b: Variation in 300 ft. system temperature with feed rotation at two elevations. This is for the special feed whose illumination pattern is illustrated schematically in Figure 5a. The telescope's two feed support legs are located North and South.

the northern feed support leg, whose ring sidelobe was to the south of the main beam, was more than 8 K "hotter" than the southern leg. Averaged over all feed angles, the system temperature at 40° elevation was about 4.5 K greater than at the zenith.

Figure 6 shows the system temperature variation with elevation on the 140 ft. telescope at 1425 MHz using the standard hybrid-mode feed which illuminates the entire dish. I have tried to remove the effect of continuum sources (and the galactic plane) from these data, but the bump at declinations 60° to 70° may be the Sun in one of the ring sidelobes (the Sun was at $\delta \sim 0°$ when these measurements were made). Radiation from the ground entering scattering sidelobes accounts for almost all of the increase in Tsys away from the zenith because spillover should be approximately constant (or even decreasing away from the zenith), and the variation that can be attributed to the atmosphere (shown by the dashed line) is not significant.

Scattering and spillover now contribute 7 to 9 K of the zenith Tsys on the 140 ft. (this is ~ 30% of the total Tsys at L band and C band; see Norrod [3]). In contrast, antenna losses, scattering and spillover contribute only ~ 1 K to the C band system temperature of the Crawford Hill horn-reflector [6]. Ground radiation in blockage sidelobes will soon be the single largest source of noise in L band systems at NRAO. Reduction of this noise requires that aperture blockage be reduced significantly.

V. Stray Radiation

Radio emission from the Sun, Milky Way, or other celestial radio sources in the sidelobes of an antenna can affect an astronomical experiment to varying degrees. At its most benign, the radiation simply increases the overall system temperature.

A more serious circumstance is when the signal entering the sidelobe has the same characteristics as the source under study. A prime example of this occurs in galactic HI observations of the 21cm line. Figure 7 shows the magnitude of this effect at the 100m Effelsberg telescope [10]. The spectra on the left side of the figure (labelled 770308, 760116, etc.) are the raw observations. Under each is the portion of the signal which is calculated to be coming in through sidelobes. Spectra on the right of the figure show the "main beam" component, i.e. the 21 cm emission that is coming through the main beam. This is the desired signal. It was derived by subtracting the calculated stray component from each observed spectrum. In this example most of the "observed" emission has come to the receiver through blockage sidelobes.

Similar figures have been made for measurements of HI at the 140 ft.: when that telescope is pointed toward the North Galactic Pole, roughly equal amounts

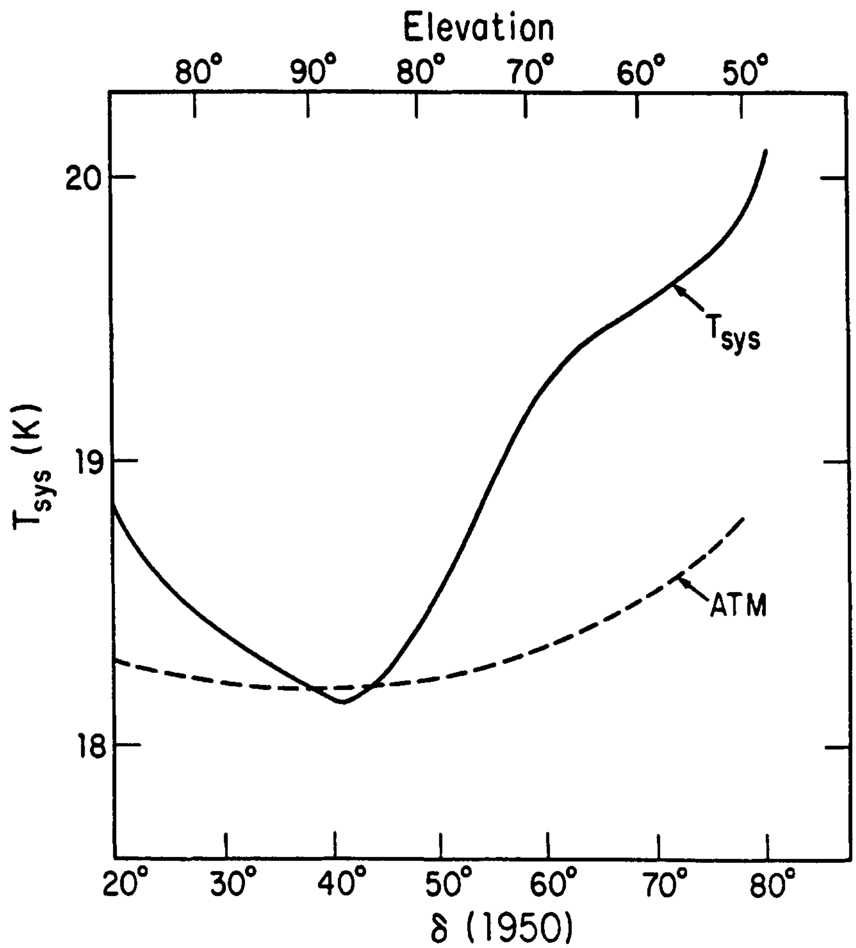


Figure 6: Variation of system temperature with elevation on the 140 ft. telescope. The atmosphere contributes slightly to the increase at lower elevations (dashed curve labeled ATM), but most of the variation is from ground radiation entering the telescope's sidelobes.

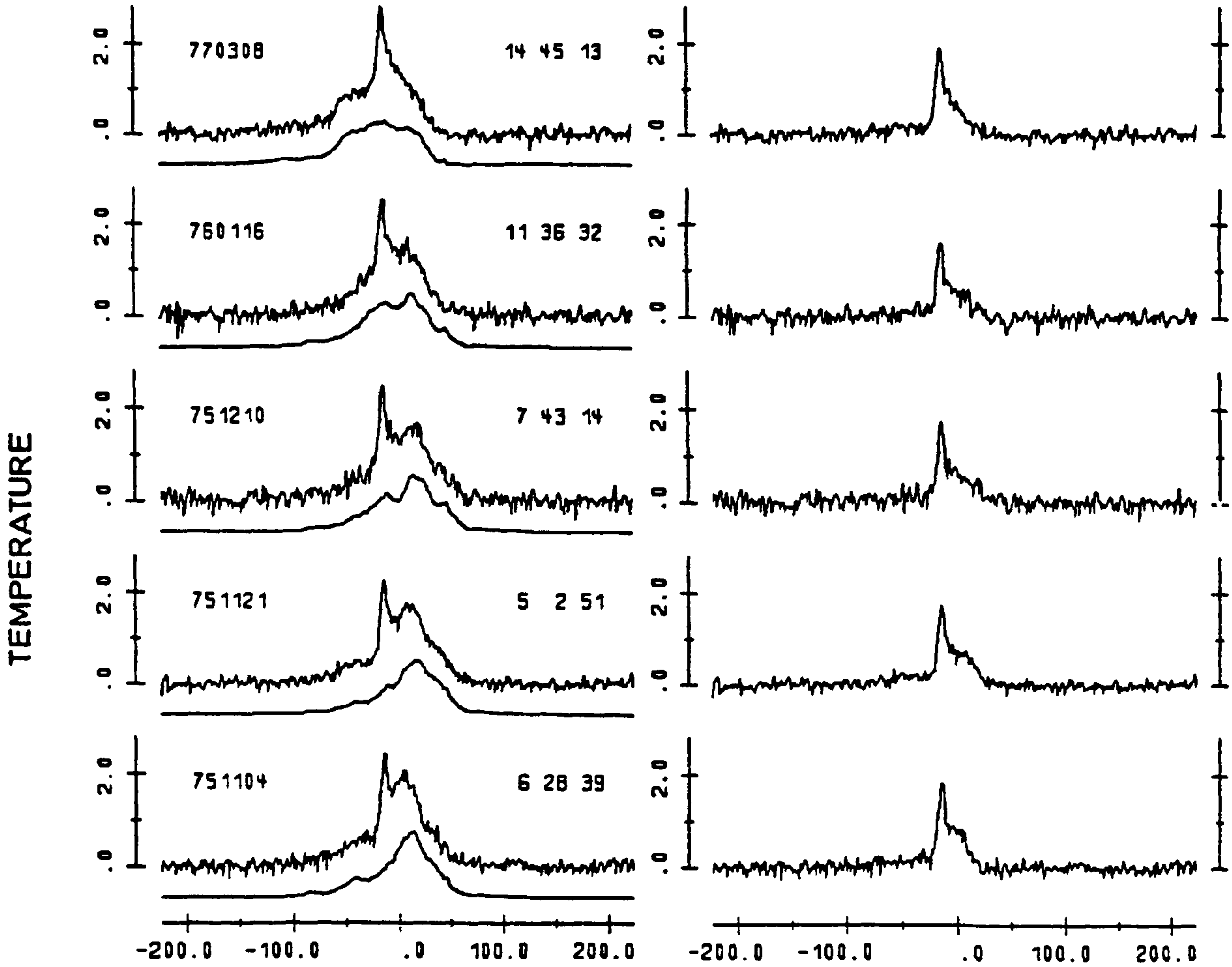


Figure 7: Stray 21cm HI radiation in the sidelobes of the 100m telescope (from Kalberla et al. [10]). The spectra on the left show the raw observations and, below each, the portion of the signal which is calculated to be stray. The spectra on the right show the signal which is actually comming through the main beam. An unblocked telescope (that also had small aperture sidelobes) would detect only the signals shown on the right. All these spectra were taken in the same direction on the sky (i.e. at the same α and δ). The motion of the sidelobes across the sky produces a diurnal and seasonal variation in the stray radiation, and thus in the observed spectra.

of 21cm emission are received from the galactic plane in far sidelobes $\sim 90°$ off axis, as from the main beam [11]. "Stray" signals of order 1 K in brightness temperature are often observed[5].

Scattered ground radiation is also a form of stray radiation that confuses observations of celestial continuum emission (see the discussion of observing technique in [23]). It is no accident that the microwave background was discovered with an unblocked telescope [6]! Accurate total power continuum measurements require an extremely clean telescope beam, and thus very low aperture blockage.

VI. Polarized Sidelobes and the Zeeman Effect[6]

The sidelobes of blocked telescopes can be strongly polarized. Figure 8 shows the circularly polarized beam pattern of the Hat Creek 26m telescope over a large area around the main beam. There is an irregular region near the main beam and long arcs of polarized response. All these sidelobes are due to the feed legs [16].

Polarized sidelobes can interfere with many astronomical observations, especially measurement of Zeeman splitting in HI. The Zeeman effect is a small frequency shift between the two circularly polarized components of a 21cm HI line emitted from a magnetized region. The difference is usually $< 10^{-3}$ of the 21cm signal. Measurement of the shift gives the amplitude of the magnetic field. From a scientific point of view, this experiment is extremely important, but it is very difficult to perform because of instrumental polarization.

Beam squint (beam displacement) is the most well-known instrumental problem that must be overcome. It is a slight angular separation between the two oppositely polarized beams that can produce HI spectral features that mimic Zeeman splitting. Beam squint can occur in any telescope, and can be controlled through use of special feeds and feed alignment mechanisms [16]. It is often said that beam squint is an intrinsic, intractable problem for offset parabolids, but this is now known not to be the case if a correcting subreflector or special feed is used [1,2,3,14]. Beam squint thus may not be a significant factor in the competition between telescope designs.

Blockage, however, creates instrumental polarization that cannot be ameliorated by an adjustment of the optics. It now limits the accuracy of 21 cm Zeeman measurements and causes systematic errors in polarization measurements of any

[5] The magnitude of this effect may be understood by remembering that the Milky Way is very bright in the 21cm line and subtends a large angle. A sidelobe that contains 1% of the telescope's total response will produce a 1 K line at the receiver if it lies fully on the 100 K HI in the galactic plane, even if the amplitude of the sidelobe is tens of dB below the main beam response.

[6] This is a complex topic that I will only summarize here. Most of this section is based on the 1982 paper of Troland and Heiles [16] to which interested readers should refer.

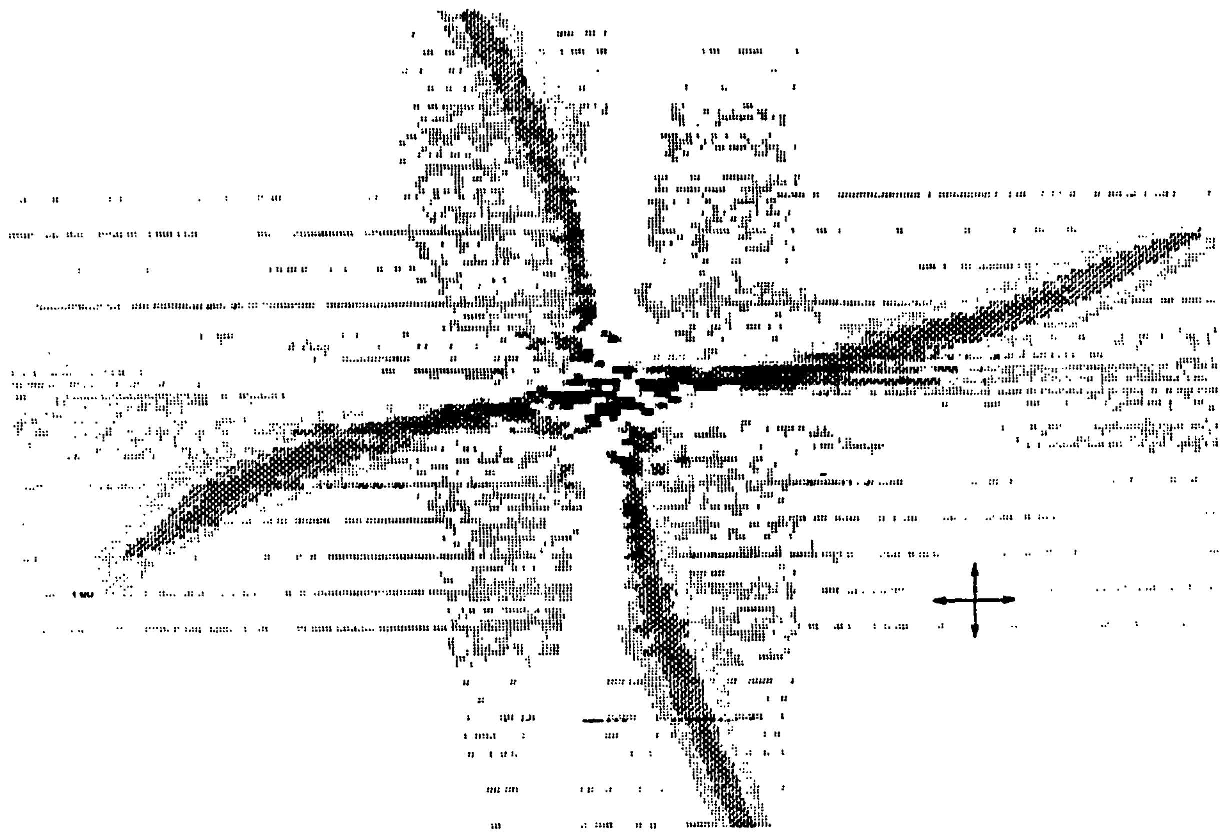


FIG. 1 --Circularly polarized beam pattern of the Hat Creek 26 m telescope within 24° of beam center. Arrows represent 4° in each direction. Only the positive values of the pattern are shown (*dark areas*). Negative values appear in the figure as blank areas.

Figure 8: The circularly polarized beam pattern of the Hat Creek 26m telescope within 24° of the beam center. Only positive values of the pattern are shown (dark areas). Negative values appear in the figure as blank areas. All polarized features are caused by the quadrapod blockage (from Troland and Heiles [16]).

source which subtends an angle larger than the main beam (e.g., the galactic continuum background). The large-scale, small-amplitude feed leg rings in the polarized beam pattern produce stray signals in polarization-switched HI spectra. The only way to remove them is to calculate the "expected" spurious component (taking into account the polarized sidelobes up to 90° off axis) and subtract it from the observed spectra [16]. Contamination of spectra by signals from the polarized blockage sidelobes is now a far more important source of error in Zeeman measurements than receiver noise is [16].

VII. Interference

Virtually all RFI is picked up in sidelobes, not in the main beam. It is a mistake to think of interference as either absent, or strong enough to ruin observations completely; at Green Bank a lot of interference is relatively weak (this is stressed by Norrod [3]). A good example of merely "pesky" interference, which affected a recombination line observation made near 10.5 GHz on the 140 ft. telescope, is shown in Figure 9. The "notch" near the peak of the stronger line results from an interfering signal that has not cancelled perfectly in the difference between the "on" and "off" source spectra[7]. The interference had an antenna temperature which varied between Kelvins and milli-Kelvins, depending on which far sidelobe was pointed at the transmitter. Needless to say, the 140 ft. main beam was always pointed well away from it.

RFI at Green Bank comes from cars, planes, airports, satellites, meat grinders and so on. Reduction of telescope sidelobes (by reducing or eliminating blockage) is the best way to reduce a telescope's response to these proliferating signals.

VIII. Spectral Baselines

The factor which now limits the sensitivity of most spectral line observations is the instrumental baseline of the telescope. This arises mainly from standing waves caused by reflections from structures that block the aperture [12,13,1,3]. Reflections can be single or multiple: at the Effelsberg 100m telescope it has been demonstrated that feed-to-leg-to-surface-to-feed paths are significant (quoted in [13]).

Observers learned long ago that spectral baselines could be improved by taking the "reference" spectrum over the same azimuth and elevation as the "signal"

[7] The source of this particular interference was tentatively identified by W. Brundage as a "microwave intrusion alarm", of the type which is available at home electronics stores for a few tens of dollars.

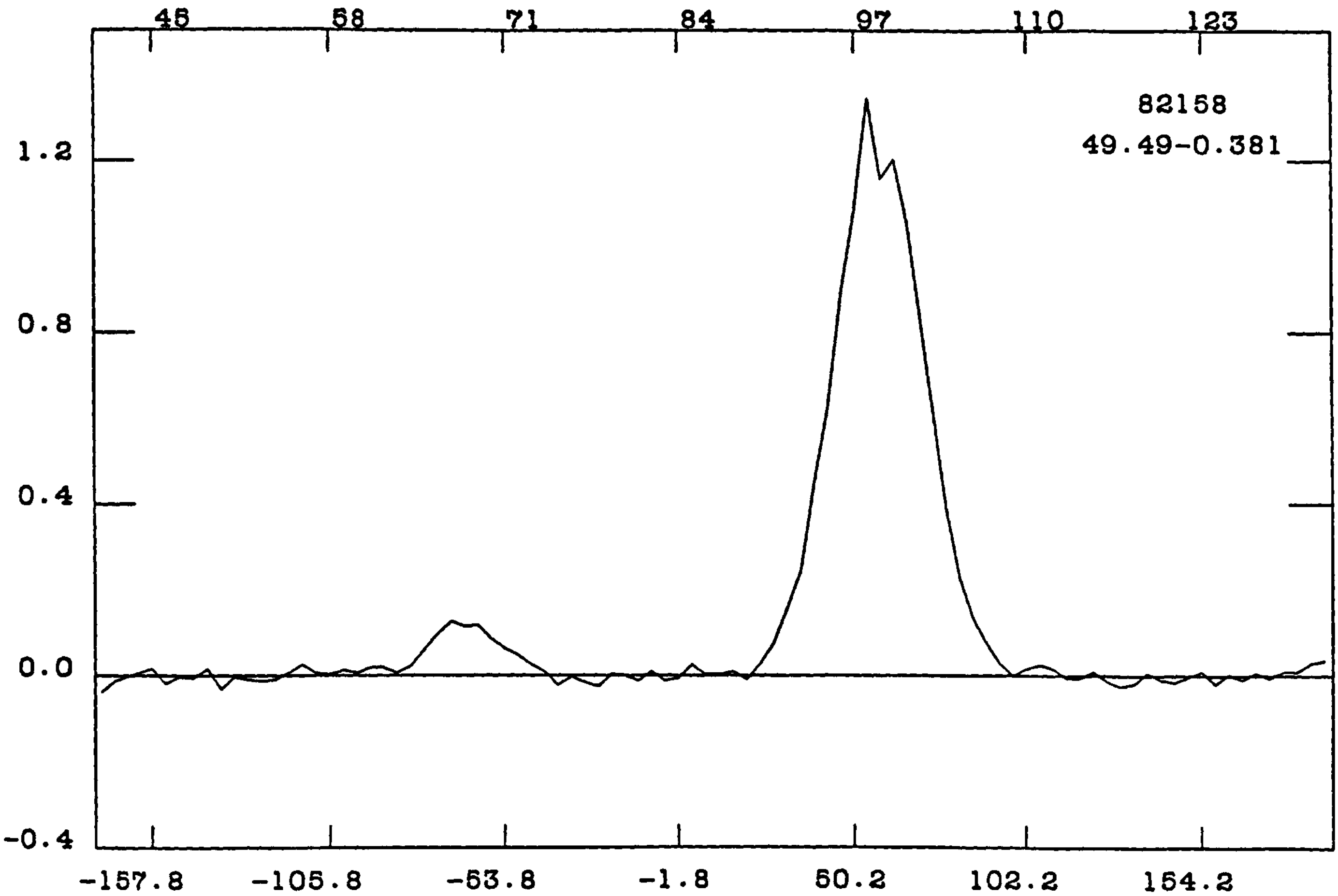


Figure 9: The "notch" in the larger line near channel 100 is an example of the weak interference often encountered at Green Bank. These observations were at 10.5 GHz.

spectrum so that ground radiation entering the telescope's sidelobes would cancel in the difference [18]. Aperture blockage effects spectra twice, for it not only sets up the sites where reflection occurs (see Fisher's analysis [12;13]), but it also creates sidelobes which transmit a changing amount of ground (or solar) radiation to these sites as the telescope tracks a celestial object. This is why sensitive spectral observations are often difficult to make during the day. The Sun does not move at the sidereal rate, and thus passes through the far sidelobe pattern as observations are being made. It is not possible to cancel the standing waves induced by both the Sun and the ground simultaneously. Blocked apertures have about 20 dB more reflected power from the vertex back into the feed than unblocked apertures [3].

The extent to which spectral baselines compromise research is not widely appreciated. In order to improve baseline stability observers have used multiple switching schemes which unfortunately also greatly reduce the efficiency of the observations. Some observers have to switch not only between source and nearby blank sky, but also between a reference, lineless, continuum source and blank sky nearby it, thus spending less than 25% of the observing time actually measuring the line in the direction of interest. A good description of baseline vageries and partial solutions is given in [17]. Elimination of blockage, and hence of the major source of standing waves, would easily double the effective sensitivity of the new telescope for spectroscopy.

IX. Summary and Editorial

Blockage reduces a telescope's gain. It creates sidelobes that pick up ground radiation, inteference and stray or confusing signals. It distorts the main beam. It confuses measurements of polarization. Blocked telescopes are noisier than unblocked telescopes. As receivers improve and become less of a factor in the total system temperature, blockage will emerge (as it already has at L band) as a main culprit in the noise budget. Blocked telescopes have instrumental baselines which limit the sensitivity of line measurements. Blockage makes a telescope susceptible to interference and also difficult to calibrate. The effects of blockage are entirely negative. No astronomical experiment benefits from it. This is why participants at the scientific workshop on the new telescope stated, frequently and strongly, their preference for an unblocked aperture [19].

The principal difference between the performance of blocked and unblocked telescopes for radio astronomy is not in the ability to receive the desired signals, but in the power to reject undesired signals. Compared to this, other differences between the two competing designs (e.g. the amount of room at the prime focus) seem minor. If the new Green Bank Telescope were to be operated in an ideal environment – free from unwanted signals from the ground and Sun, free from terrestrial and satellite interference, and if standing waves could be supressed magically (or spectroscopy was forbidden) – then aperture blockage would be a minor issue. But the reality is that blockage now compromises **every** observation if only through increased system temperature. As the interference environment worsens, as it certainly will, interference rejection will become an increasingly necessary property of every radio telescope.

I conclude that blocking the aperture is not worth the savings in cost. Twenty years from now the extra bit spent to build the best possible (unblocked) telescope will be forgotten, but any sidelobe that we design into the telescope will still be there, and will have been there for every observation made throughout the years. It will be certainly more harmful then than we can imagine now.

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