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## France

### INTERFERENCE AND SIDELOBE LEVELS OF MILLIMETER WAVELENGTH RADIOTELESCOPES.

#### SUMMARY

The following text is a first attempt to compare the expected sidelobe levels of millimeter wavelength radiotelescopes with those of telescopes operating at longer wavelength.

Good quality telescopes are expected to have comparable far-field sidelobe levels in both wavelength ranges. In the near field, outside the ray optics beam, the sidelobes of large millimeter telescopes are expected to be somewhat smaller.

The ITU reference sidelobe pattern (Recommendation ITU-R SA.509-1) is intended for cm wavelength antennas. It may be difficult for large millimeter telescopes to conform to this ITU standard which seems to underestimate the effects of blockage due to subreflector supports. A new reference pattern may be needed for telescopes operating at millimeter wavelengths.

#### INTRODUCTION

The ITU limits for harmful interference are given in Recommendation ITU-R. RA.769 as flux density or spectral flux density, calculated on the assumption that the interference is received in sidelobes of gain 0 dBi (with respect to isotropic). Such a gain corresponds to a collecting area of  $(\text{wavelength})^2/4 \pi$ . This leads, other things being equal, to larger tolerable flux density limits at shorter wavelengths. The speed with which sidelobe levels decrease to the 0 dBi level away from the main beam direction determines the area of sky lost to observations. Although the sidelobe levels of a telescope are often given relative to the maximum on boresight, for interference calculations using Recommendation ITU-R. RA.769 it is preferable to specify the gain relative to that of an isotropic radiator. In the following we adopt this custom and express the sidelobe levels in decibels (dBi) relative to an isotropic antenna. For interference calculations the ITU has recommended (Recommendation ITU-R SA.509-1) the adoption of a standard "reference radiation diagram" for Space Research Station antennas. It is to be used in the absence of measured data. The sidelobe response is defined, between 1 and 48 degrees off boresight as

$$\text{"Gain (dBi) = } 32 - 25 \log(\text{angle in degrees})\text{"}$$

This is intended to be a mask which gives the envelope of the sidelobes and which is not exceeded by any existing ground station at any "frequency between 2 GHz and about 30 GHz". It is

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\* This document has already been published as Doc. 7B/8.

applicable to antennas with diameters greater than 100 wavelengths and for angles exceeding 1 degree from the main beam axis. Beyond 48 degrees from boresight the response is specified to be -10 dBi. An alternative reference radiation pattern (Recommendation ITU-R S.580), intended for large antennas of the Fixed Satellite Service predicts very similar sidelobe levels.

It is at first sight surprising that such a universal mask can be devised which is valid for such a large range of wavelengths and telescope designs and diameters ! In fact such a sidelobe pattern cannot be valid at all wavelengths - for this to be the case the coefficient of the logarithm must be 20. The Report 677-2 indicates that the adopted sidelobe pattern is based on measurements of a 600 wavelength diameter symmetrical Cassegrain antenna. It is pointed out that offset designs will have smaller sidelobes by between 10 and 20 dB. Existing millimeter wavelength telescopes have diameters in the tens of thousands of wavelengths range and one wonders if this large difference in scale will lead to significantly differences from the reference radiation pattern.

The mask is divided into 3 regions which can be summarized and perhaps interpreted physically as:-

- 1) The main beam region, within 1 degree of boresight, which will depend critically on telescope dimensions and wavelength, is ignored. This implies that the telescope must have a diameter greater than about 100 wavelengths.
- 2) The sidelobe level at the edge of this main beam region is 32 dBi and falls thereafter as angle to a power 2.5. This index is midway between the values expected for diffraction from a uniformly illuminated circular aperture (3) and a strip (2). This might then take account of blocking by a circular subreflector and its supports (modelled as strips). Furthermore, the level of 32 dBi may be intended to allow for the gain in the spillover region around the subreflector of a Cassegrain system.
- 3) Beyond 48 degrees from boresight the sidelobe response is dominated at a level of -10 dBi by incoherent scattering which accounts for less than 10% of the total energy.

In consequence the excluded zone around the main beam, where the gain exceeds 0 dBi, has a radius of 19 degrees ,so about 5% of the sky is inaccessible under the assumptions of Recommendation ITU-R RA.769. Physically, conservation of energy dictates that the mean gain of any loss free antenna is 0 dBi. If we exclude the main beam region, then the mean gain outside the main beam becomes  $10\log(1-\eta)$ , where  $\eta$  is the main beam efficiency. For example for a telescope with main beam efficiency of 0.5, the mean gain outside the main beam is -3 dBi and for 0.9 efficiency, the mean gain becomes -10 dBi. This simple conservation of energy argument tells us only the mean gain in the sidelobes. Of more interest for interference estimations are the peak levels of the sidelobes or their envelope. These may well exceed the average value by 10 dB - if for example 100 scattering centers are contributing incoherently to the average. In the future, for use in Monte Carlo calculations for example, the probability of a given sidelobe level as a function of angle off boresight may be of more interest.

Will the sidelobe properties of millimeter wavelength telescopes be in any way different from those of telescopes operating at longer wavelengths? Often the interfering sources of emission at millimeter wavelengths are in the near field of the telescope. Do these considerations require a modification of the specifications of the "reference antenna"? If the sidelobes of millimeter radiotelescopes exceed those of the reference then excessive interference will be experienced and a revised reference radiation pattern will be needed. As the physical basis for the ITU reference antenna characteristics is unknown it is difficult to answer these questions but in any case it is not intended for millimeter wavelengths. Nevertheless the above questions may perhaps be answered empirically by measurements of a number of typical telescopes, or from theoretical calculations. However since no or few measurements of the far sidelobes of large millimeter radiotelescopes are readily available we must fall back on theory. Software tools are now becoming available for the

detailed prediction of the full sidelobe pattern of simple telescopes. For example the GRASP8 program developed by the Tica Institute in Denmark can treat multimirror telescopes and even take into account the effect of secondary mirror support struts, if of small diameter with respect to the wavelength and circular cross section. (Assumptions most unlikely to be valid at mm wavelengths.) The program is expensive however ! In the time available it is hardly possible to enter into such detail and we must rely on order of magnitude estimates.

### THEORETICAL ORDER OF MAGNITUDE ESTIMATES

At millimeter wavelengths it may be permissible to treat several of the scattering mechanisms in the geometrical optics approximation since the subreflector supports for example will normally be many wavelengths in thickness. The equivalent gain in such scattered beams is then wavelength independent. This approximation should of course overestimate the peak intensity of the scattered radiation, since diffraction and construction errors can only reduce the peak and scatter radiation over a wider angle. The various mechanisms for the production of sidelobes are summarised in Table 1, together with an estimate of their wavelength variation at a fixed angle off boresight I.E. in the sidelobe region.

TABLE 1

MECHANISM	WAVELENGTH VARIATION			
	Angular Position	Angular Width	Gain offaxis	Notes
<b>Diffraction at main mirror</b>				1
Blockage	0°	+1	≥ -0.2	2
Error lobe	0°	+1	>-0.0	3
Panel gaps	≤ 90°		-24 dBi	4
<b>Spillover</b>				
At subreflector	few degrees	few degrees	+16 dBi	5
At main mirror	> 90°	+1	-19 dBi	6
<b>Blockage (circular section)</b>				
Plane wave	~ 60°	0	< -14 dBi	7
Spherical wave	few tens	few tens	< +24 dBi	8
<b>Blockage</b>				
Subreflector+ (vertex cone)+ main apex	?	?	?	9
<b>Blockage by radome</b>				
	> 90°	0	-9 dBi	10
	< 90°		+6 dBi	10
<b>Higher order</b>	up to	tens	?	11

**edge  
diffractions**

180°

This is given as the power to which the wavelength must be raised. With the exception of the peak of the main beam on boresight, the sidelobe gain varies little with wavelength (or telescope diameter). This is because the sidelobe level is expected to fall faster than  $\text{angle}^{-2}$  at any given wavelength. The estimates are meant to apply to a symmetric Cassegrain telescope.

**NOTES**

- 1) The main beam and close in sidelobes can be calculated using the physical optics approximation.
- 2) The near in sidelobes can be estimated from the diffraction pattern of the aperture plane, suitable masked to zero in the areas geometrically blocked. This approximation can be expected to be good out to angles from boresight of about a radian. In the extreme case of blocking by a strip the sidelobe gain will fall with angular distance from boresight as  $\text{angle}^{-2}$  since the radiation pattern is of the form  $(\sin(x)/x)^2$ . Such sidelobes have their maxima in planes perpendicular to the struts and represent the worst case and may cover only a small area of sky. Simulations with a simple model for the 30m telescope, described below, suggest an index of about -1.8, hence the sidelobe gain at a fixed angle may vary as  $\text{wavelength}^{-0.2}$  in the worst case and thus be slightly larger at millimeter wavelengths. The energy blocked is reflected or scattered far from the boresight and is considered in 7,8 and 9 below.
- 3) The "error lobe" is due to the surface errors of the mirrors. From the Ruze formula the peak gain of the error lobe varies to a first approximation as  $\text{wavelength}^{-2}$ . Depending on the smoothness of the mirror surfaces the error lobe is usually confined near boresight. However for "good quality" telescopes this loss will be approximately the same for all telescopes if the telescope efficiency is to be reasonable at the operating wavelength.
- 4) The effect of panel gaps may be estimated from Babinet's principle. However one can not calculate by diffraction from the aperture plane as for 2 since the aperture plane is no longer in the near field of the gaps - normally of the order of some mm's in width. The gaps thus scatter into a large fraction of the forward hemisphere. The listed gain has been calculated on the basis of a uniform scattering into a hemisphere, and gaps 0.001 of a panel diameter.
- 5) The maximum spillover gain, at the edges of subreflector and main mirror is just the gain of the equivalent feed at this angle, reduced by a factor 4 to account for the edge diffraction. The feed gain at the subreflector edge will be invariant - it is normally chosen for the desired aperture taper (we assume -13 dBi) using a Gaussian illumination. For a typical angle subtended by the subreflector of about 1 degree (radius) we calculate a gain of +22 dBi. When an extra -6 dB diffraction loss is applied then the sidelobe gain becomes +16 dBi.
- 6) Spillover past the main mirror will probably cause the largest amplitude "back lobe". The maximum sidelobe gain is that of the effective prime focus feed at the mirror rim (about -7 dBi) reduced by diffraction loss of -6 dB. So typically -13 dBi at 120 degrees to boresight. The width of this ring of emission will be a few beamwidths of an aperture the size of the subreflector.
- 7) The plane wave scattered by the secondary mirror supports will typically be directed at a large angle to the boresight - determined by the angle the supports make with the telescope axis. For support struts of circular cross section the maxima lie on cones centered on the axis of the struts. Their gain varies around the cone as  $\sin(\psi/2)$ , where  $\psi$  is the azimuth angle measured around the strut from the boresight direction. In the case of accurately made struts the width of the cone is given by diffraction as wavelength divided by the length of the strut projected onto the aperture

plane. The maximum gain will then be proportional to the product of the length of the strut and the Fresnel radius of the circular section. In practice at millimeter wavelengths the strut will probably be rough in terms of wavelengths and the intercepted energy can be considered to be incoherently scattered over a large angle. In this approximation the gain will be that of the effective prime focus feed (say 6 dBi), reduced by scattering by the subreflector supports - at least radius/focal length say -20 dB. This leads to a peak gain of about -14 dBi. If the support struts are of rectangular cross section then the peak gain will tend to be larger. However at millimeter wavelengths these struts will block the radiation from each other and after multiple reflections the resulting radiation pattern will be very complex and difficult to predict in any detail.

8) The spherical wave scattered by the focus supports falls mainly on the main mirror and is thus directed and concentrated in the forward direction, within a few degrees of boresight. As for 7 above, the gain is that of the effective prime focus feed (in this case about 0 dBi) reduced by scattering by the subreflector supports but further increased after reflection from the main mirror. We give as a preliminary upper limit a gain of +24 dBi with angular spread given by the angle subtended by the strut at the focus. This value may need revision downwards after a detailed raytracing study.

9) The energy directed from the subreflector towards the apex of the main mirror is either absorbed or scattered at the apex, or scattered at the secondary mirror. The fate of this energy is not clear as it depends greatly on the details of the telescope structure at the apex of the main mirror. In extreme cases multiple reflections can give rise to Newton's ring phenomena.

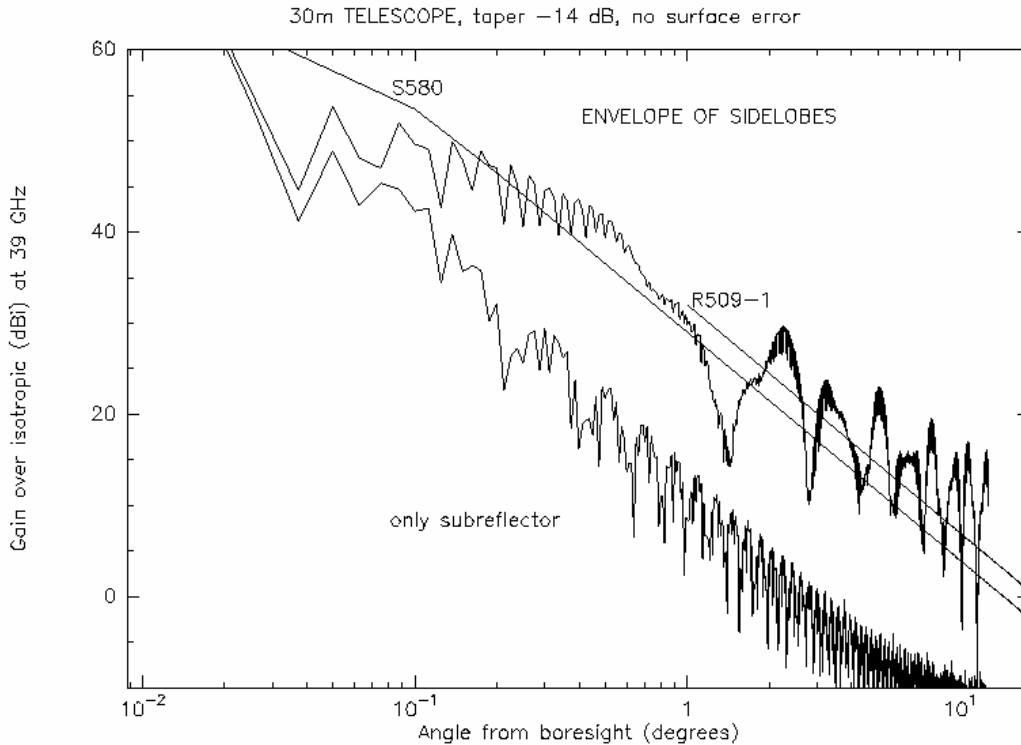
10) Several mm wavelength telescopes are in protective spaceframe radomes which add additional blockage and sidelobes. Typically half the energy scattered by the radome falls in the forward direction near boresight and enhances the sidelobes there by 6 dB or more. The remaining half of the blocked energy is scattered almost isotropically so that for a typical 1dB blockage, the mean backlobe gain due to this cause may be -9dBi or so. This contribution can easily double the magnitude of the backlobes. Since these terms are due to the incoherent addition of several hundred independent contributions, the peak sidelobes may even exceed the average by 10-20 dB.

11) Multiple scattering from the various edges of the mirrors contributes to the far sidelobes. The diffraction coefficients for the scattered field vary with the square root of wavelength and become progressively less important for millimeter wavelength telescopes. Edge diffraction at the rim of the main mirror will give rise to a "Poisson Spot" in the anti-boresight direction.

## **MODELLING RESULTS**

The radiation pattern of the 30m telescope has been calculated close to boresight (<6 degrees) by Fourier transform of a model aperture plane field distribution. This was taken to be Gaussian with taper -14 dB, and was masked to zero in the geometric shadows of the subreflector and its supports. The aperture phase was taken as constant - no surface errors. The envelope of the maxima was then calculated as a function of angular distance from boresight. That is the maximum sidelobe level at each radial distance from boresight was selected. The results are given in Figure 1 where gain relative to that of an isotropic antenna (in dBi) is plotted against logarithm of the angle from boresight for a radio frequency of 39 GHz (7.7mm wavelength). Two curves are displayed, with and without blockage by the subreflector support legs. The slopes of their tangents are indicated. Only in the case of no leg blockage does the slope agree with that assumed in the ITU model (-2.5). With leg blockage taken into account the slope is close to -2 (about -1.8 actually) the value expected from diffraction from a uniformly illuminated strip source. At 1 degree off axis the gain is close to the 32 dBi standard of Recommendation ITU-R SA. 509-1 but at larger angles it significantly higher (by 5 to 10 dB). Taken at face value Figure 1 implies, by extrapolation, that the

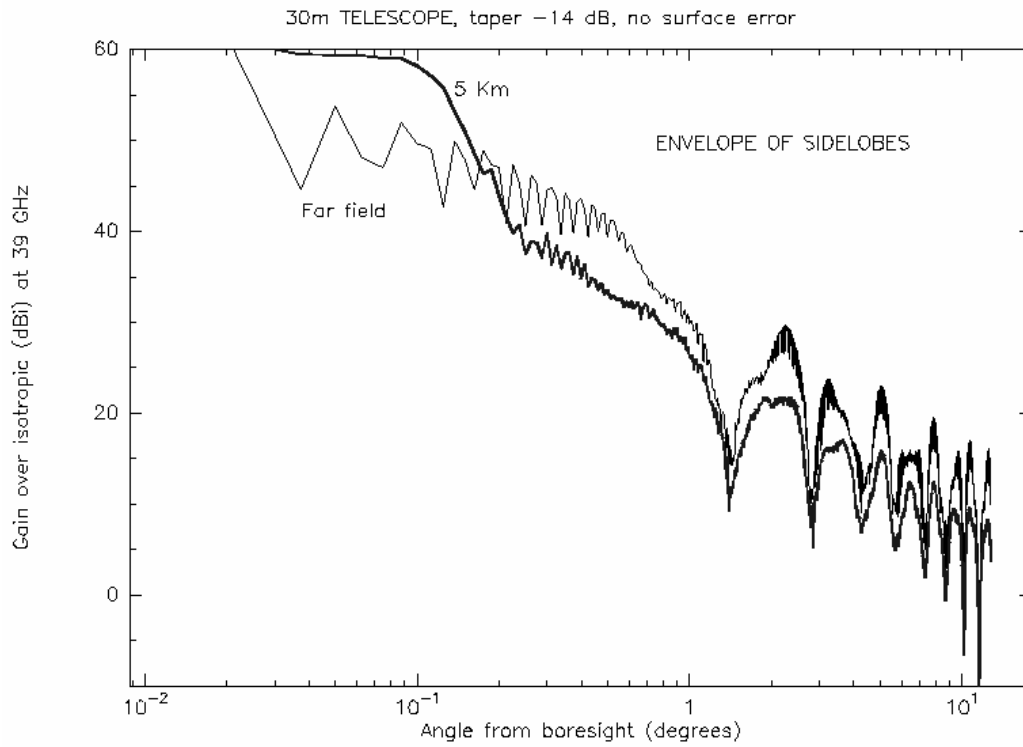
0 dBi level is only attained near 90 degrees from boresight so that in the presence of interference at the Recommendation ITU-R RA.769 levels, a large fraction of the sky would be closed to observations. It would therefore seem that this reference pattern does not give an accurate representation of at least one large millimeter telescope. In consequence the standard radiation pattern may need revision for mm wavelengths.



**Figure 1:** The calculated envelope for the far field sidelobes of the 30m telescope at 39 GHz (7mm wavelength). The lower curve is for a telescope without any blockage due to the subreflector support legs. The straight lines show the prediction of the reference patterns Recommendations ITU-R SA.509-1 and S.580.

### NEAR FIELD EFFECTS

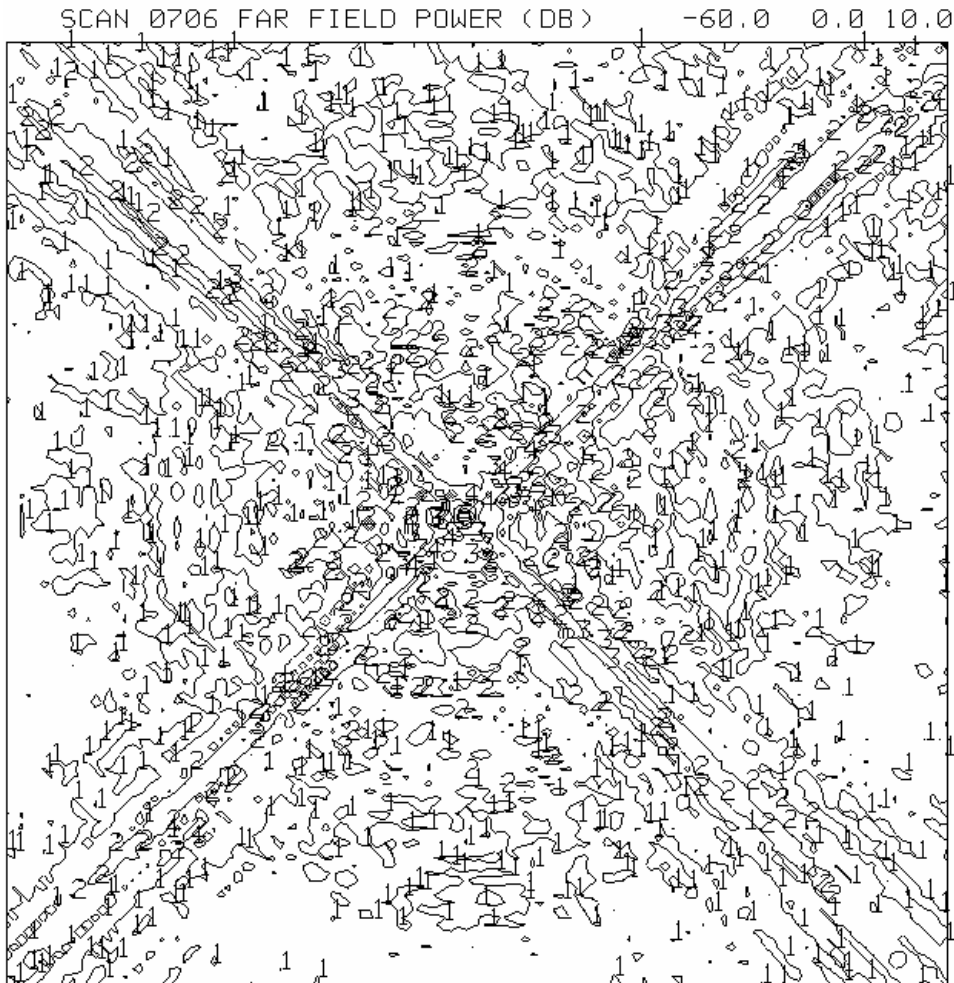
Although the near field main beam and close-in sidelobes, due to diffraction at the aperture plane (1 to 3 above) will be defocussed in the near field, the more distant sidelobes are unlikely to change significantly in the near field since in general they are generated by structures whose Rayleigh distance is quite small. This behavior is confirmed by the modelling results shown in Figure 2. There the sidelobe envelope at a distance 5 Km is compared with the far field result of Figure 1. The power in the far field main beam appears in the ray optics beam out to a radius of about 500 arc seconds from boresight. In fact the sidelobes at about 1 degree and further from boresight have decreased by about 5 dB.



**Figure 2:** Comparison of the calculated far field and near field sidelobes of the 30m telescope at 39 GHz. The heavy curve is the envelope of the sidelobes calculated for a distance of 5 Km.

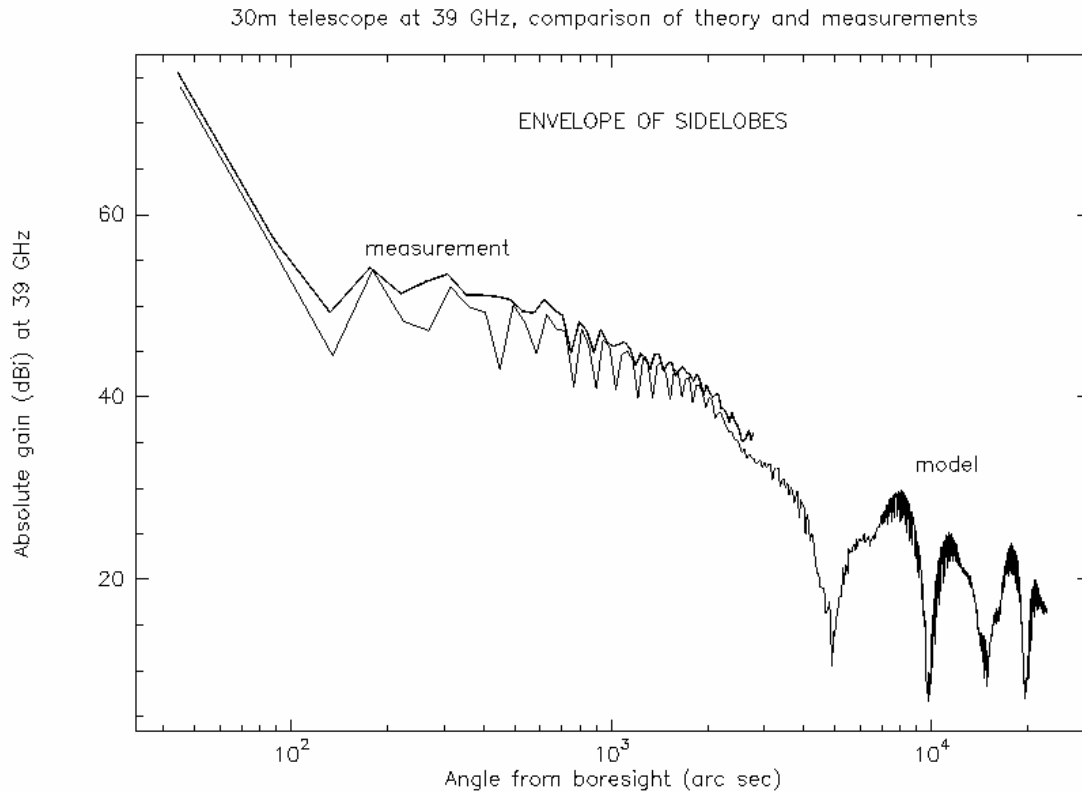
### COMPARISON WITH DATA FOR THE 30M TELESCOPE AT 39 GHz.

Very limited measurements of the sidelobes of the 30m telescope are available at 39 GHz from holographic measurements of the surface quality. They extend out to about 0.6 degrees from boresight. Figure 3 is a contour plot of such a radiation pattern. The pattern is dominated by the cross system of sidelobes due to blocking by the secondary mirror supports. The sidelobe envelope has been found as for the model considered above and is compared with the model predictions in Figure 4.



**Figure 3:** The measured far field radiation pattern of the 30m telescope at 39 GHz - using the ITALSAT satellite. Contours are plotted at 10 dB intervals from -60 dB to 0 dB, numbered 1 to 7. Values are in decibels relative to the on-boresight maximum.





**Figure 4:** A comparison of measured (thick line) and predicted envelope of the sidelobes of the 30m telescope at 39 GHz. The envelope value has been derived by selecting the maximum level at each radial distance from boresight.

## CONCLUSIONS

There should only be marginal differences between the sidelobe levels, expressed with respect to isotropic, of good quality cm and good quality mm wave telescopes. Although the main contributions to sidelobe radiation remain substantially unchanged the sidelobe levels of millimeter wavelength radiotelescopes may be marginally smaller than at longer wavelengths. Terms due to aperture diffraction will of course contract towards the boresight so that with the exception of terms due to strut blockage, the sidelobe response at a fixed angle will drop. Some spillover effects will be smaller, scattered blocked radiation may be distributed over larger areas and far sidelobes due to edge scattering will be smaller. The main sidelobe maxima due to blockage and spillover will remain of similar magnitude. Offset designs avoid the terms due to blockage of course but are still limited by spillover. On the other hand telescopes in spaceframe radomes will probably have sidelobe levels higher by at least 6 dB. The ITU reference patterns of Recommendations ITU-R SA.509-1 and S.580, applicable at cm wavelengths, underestimate the effects of strut blockage and may need revision for mm wavelengths.

## **FUTURE WORK**

- 1) Take more measurements of far sidelobes along a few radii to large distance.
  - 2) Some information on statistics of sidelobes, not just their envelope.
  - 3) Additional information on radomes ?
  - 4) Incorporate the effects of panel errors into the model.
  - 5) Estimate the sidelobes due to strut scattering by raytracing.
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