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Document Title: Practical Measurements of Side-lobe Levels of Radio Telescopes – Work in Progress.

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Objective: To provide preliminary results, and a report on work in progress, on measurements of far-out side-lobe levels of radio telescopes, for comparison with existing ITU models.

Abstract: In calculations of the interference potential between the active services and radio astronomy stations, it is customary to use patterns defined in established ITU antenna models. The applicability of the ITU models to radio telescopes, whose design criteria may be somewhat different from those of communications systems, needs to be examined. This document presents an analysis of existing detailed measurements, for comparison with the ITU models.

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PRACTICAL MEASUREMENTS OF SIDE-LOBE LEVELS OF RADIO TELSCOPES:

WORK IN PROGRESS

1. Introduction

Radio Astronomy installations use state-of-the-art equipment in order to approach the highest possible level of sensitivity. As a result, they are particularly susceptible to what might, in other services, be considered very low levels of interference. The derivation of detrimental interference thresholds for Radio Astronomy is given in Recommendation ITU-R RA.769; the interference is presumed to reach the radio astronomy receiver through the side-lobe response of the radio astronomy antenna. A far-out side-lobe response of 0 dBi is taken to derive the level of detrimental interference. A model of the typical side-lobe levels for large paraboloid antennas is given in Recommendation ITU-R SA.509; in that model, the side-lobe response reaches 0 dBi at 19 degrees from the main beam axis. In computing the likely interference to RA stations from non-GSO satellites, the epfd method is used (see Recommendations ITU-R(epfd)) ; these recommendations assume ~~temporarily~~ provisionally that the average far-out side-lobe level of the radio astronomy antenna is as given in Recommendation ITU-R S.1428.

The models in Recommendations ITU-R S.465, SA.509, S 580, and ITU-R S.1428 are representative of large antennas used in space communications; there has been little data available until now to compare these models with the large reflector antennas generally used in radio astronomy. This document begins to address the comparison of the models with measurements of an operational radio telescope.

2. Available data

There is surprisingly little data available on the far-out side-lobe pattern of practical radio telescope antennas. The main reason for this scarcity of data is that such measurements, if carried out in a proper fashion, are extremely time-consuming. All major radio

telescopes in the world are heavily oversubscribed; and unless absolutely necessary, limited telescope time is maximally used for astronomical observations. As an example, a 100-meter diameter telescope, operating at a wavelength of 2 cm, has a main beam size of about 0.014 degrees. The Nyquist sampling interval for mapping the beam pattern would be less than 0.006 degrees; this corresponds to a mapping cell size of 0.000036 square degrees. Given that the entire beam pattern consists of more than 41,000 square degrees, this means that some $1.1*10^9$ independent measurements must be made to define the antenna beam pattern over all angles. If only one millisecond is spent at each point, some one million seconds would still be required to make a full response map at a single frequency, corresponding to about two weeks of continuous measurement, even ignoring the required additional overhead of telescope slew time and calibration. Most radio telescopes are designed for longer integrations, such as 2000 seconds; special data logging apparatus would have to be built to accommodate such measurements. Also, most radio telescopes are designed for precision tracking at sidereal speeds, rather than the approximately 500 beamwidths per second that would be entailed if only 1 millisecond is to be spent per measurement point. Further, the side-lobe measurement may have to be made on the strongest celestial sources, where integration times measured in hundreds of seconds, rather than a thousandth of a second, may be necessary in order to achieve adequate sensitivity and dynamic range. In practice, such factors mean that very large expenditures of time and human resources, as well as additional special-purpose hardware or software would be required in order to make a properly sampled map of the full side-lobe pattern of a large radio telescope.

One technique commonly used to measure the surface of a modern radio telescope dish antenna is radio holography. If sufficiently precise measurements are made of the antenna beam pattern, in both amplitude and phase, then a Fourier inversion of the beam map allows antenna surface errors to be computed. However, antenna beam maps made for this purpose only need to extend a few tens of beamwidths from the main beam, covering perhaps one square degree in total. Such measurements provide no information about the far-out side-lobe response. Even to measure just this inner ~one square degree of the beam pattern of a large antenna, many hours of observing time are usually required, so for the reasons already outlined above, it is hardly practical to make beam maps to measure the far-out sidelobes with an angular resolution equal to the width of the main beam.

3. Side-lobe Structure, Feedleg Diffraction and other Dish Features

Sometimes a single cut in azimuth at fixed antenna elevation, and a single cut in the elevation response, at fixed azimuth, are used to obtain a representative measure of the side-lobe levels of an antenna. There are however problems with this approach:

a. The dominant side-lobe from the usual symmetric paraboloid is often the diffraction pattern of the feed-legs that support either the prime focus feed, or the sub-reflector. Depending on the geometry of the feed-legs, the azimuth and elevation cuts may run exactly along the diffraction pattern of the feed-legs, so giving a significant over-estimate of the real side-lobe level.

b. Alternately, the azimuth or elevation cut may completely miss the feed-leg diffraction pattern – for example, if the feed supports are offset at an angle of 45 degrees to the horizontal or vertical, as is the case with some antennas. In this case, the estimate of side-lobe levels for the antenna may be a severe under-estimate.
c. The dominant side-lobe may arise -from some- feature of the telescope, such a periodic- irregularity caused by the surface panels. This can put significant side-lobe power into discrete directions at seemingly arbitrary offset angles from the main beam. A single azimuth and elevation cut may miss such side-lobe responses.
d. Antennas with Cassegrain optics are often used in radio astronomy. The optimum illumination of the subreflector is a compromise between best efficiency (high illumination at the edges) and low spillover past the subreflector. Depending on details of the antenna optics, the sidelobes resulting from spillover past the subreflector may or may not be circularly symmetric. Features apparent from the data shown in Figures 3 and 4 include diffraction past the subreflector edge, sidelobes of the horn which illuminates the subreflector, and spillover beyond the main reflector edge, with a diffraction peak just before the dropoff.

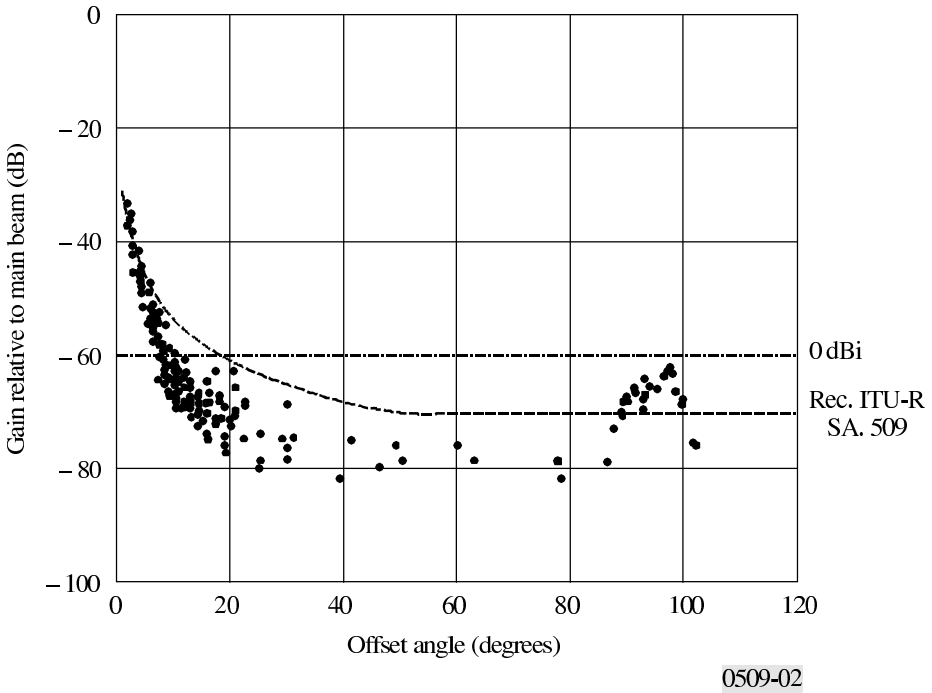
This, measuring just a cut in azimuth and/or a cut in elevation may not yield a representative measure of an antenna side-lobe response. Nevertheless, it often may be the best that can be done in practice.

4. Existing ITU-R Recommendations

A number of existing ITU-R recommendations address the question of side-lobes of large antennas. Note that the S series of recommendations apply to the Fixed-satellite Service, and the SA series to Space Applications and Meterology.

ITU-R SA.509 is **"Generalized Space Research Earth Station and Radio Astronomy Antenna Radiation Pattern for Use in Interference Calculations, incouding Coordination Procedures."** It applies to antennas with diameter greater than 100 wavelengths, between 1 and 30 GHz. It recommends that for offset angles φ (in degrees from the main axis) from 1 to 48°, the gain should be taken as assumed to be 32-25log(φ), and beyond 48° the gain should be taken as –10 dBi. This pattern reaches a gain of 0 dBi at 19° from the main axis, as quoted in ITU_R RA.769. Figure 1 is taken from ITU-R SA.509, and shows the comparison of this model with measurements on the Lovell Mk1A Radio Telescope, a 76-meter paraboloid, which uses a prime-focus feed on a tower and thus has no feed-leg blockage. The vertical axis is calibrated in dB with respect to boresight gain, which in this case is 60 dBi. The 0 dBi level is marked by the horizontal dashed line. The measurements shown in Figure 1 are from a cut across the beam, not from a full mapping of the sidelobes. However, this telescope is unusual in that, with its single prime-focus feed tower, the usual feed-

Measured side-lobe pattern at 1 420 MHz



leg diffraction pattern is not present, and the antenna beam pattern is expected to be more circularly symmetric than more conventional reflectors.

Figure 1

ITU-R S.465 is **"Reference Earth-station Radiation Pattern for use in Coordination and Interference Assessment in the Frequency Range from 2 to about 30 GHz."** It specifies the same side-lobe pattern as SA.509 above.

ITU-R S.580 is **"Radiation Diagrams for Use as Design Objectives for Antennas of Earth Stations operating with Geostationary Satellites."** It recommends, that for antennas greater than 150 wavelengths, the ***design objective*** should be that at least 90% of the side-lobes do not exceed $G=29-25\log(\varphi)$ out to $\varphi=20°$. From 20 to 26.3 degrees the side-lobe gain is taken as –3.5 dBi, and beyond that is taken from ITU-R S.465, which in this respect is identical to SA.509 – see above.

ITU-R SA.1428 is **"Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 GHz and 30 GHz."** It recommends that for calculations involving

moving interfering sources, and for antennas greater than 100 wavelengths, the side-lobe level be taken as G=29 - 25log(φ) from φ_r to 10°, as 34 - 30log(φ) from 10° to 34.1°, as –12 dBi from 34.1° to 80°, as –7 dBi from 80° to 120°, and –12 dBi from 120° to 180°.

φ_r is given by $15.85\left(\frac{D}{\lambda}\right)^{-0.6}$ degrees. For a 25-meter antenna at a wavelength of 18 cm, φ_r would be 0.8°.

Figure 2 below shows a comparison of the above models.

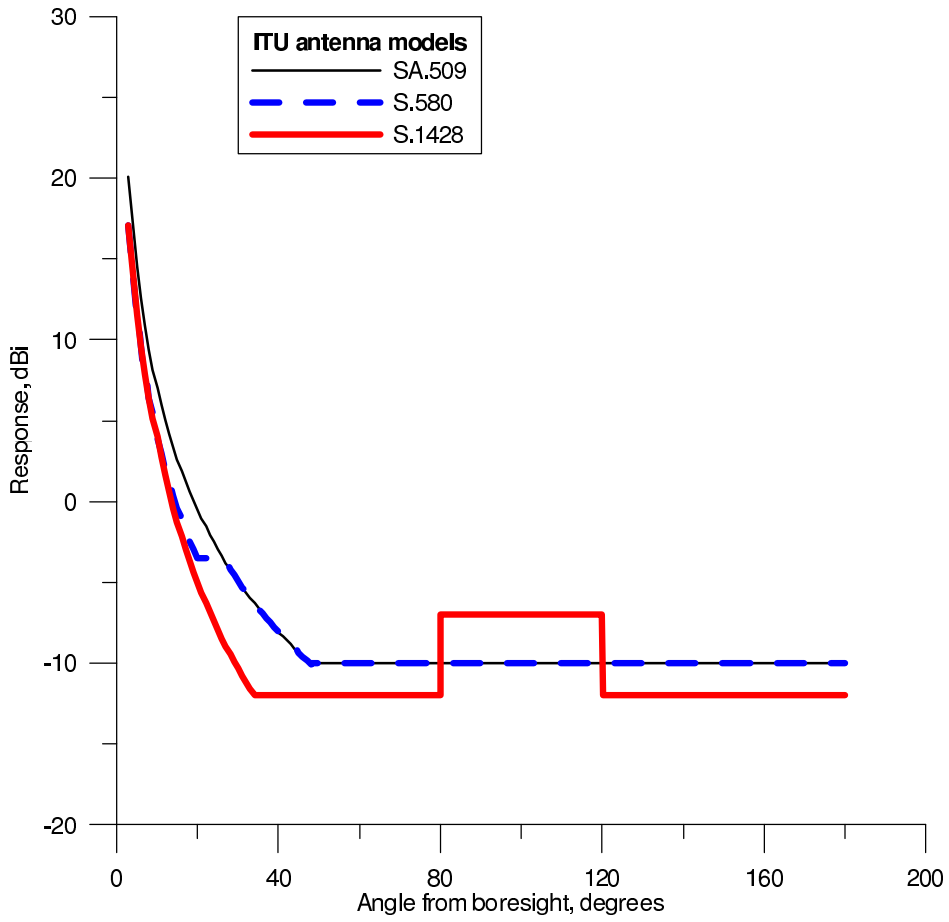


Figure 2

5. The Measurements

The data presented in this document were measured on two 25-meter antennas of different design, at frequencies of 1620 MHz and 1720 MHz. One of these is a single antenna of the Very Large Array (VLA), and the other one is one of the antennas of the Very Long Baseline Array (VLBA). Both arrays are operated by the National Radio Astronomy Observatory (NRAO) as user facilities; the VLA is a connected-element interferometer consisting of twenty-seven 25-meter antennas, while the VLBA consists of ten 25-meter antennas, spread over the continental US, Hawaii and St. Croix (US Virgin Islands). It is possible for the arrays to continue operations, albeit at reduced efficiency, if one of the antennas is removed from normal observations ; this fact, and the lower frequency compared to the example used in Section 2 (1.6 and 1.7 GHz, respectively), , made a full side-lobe pattern measurement possible over a period of time without bringing scientific operations to a standstill. However, in the interests of minimizing the measurement period, somewhat~~slightly~~ coarser sampling than desirable was used, and some beam smearing also occurred from the continued scanning of the telescopes while data was being integrated. We estimate that these effects may have caused us to underestimate isolated side-lobe peaks by up to 2 dB. Nevertheless, the measurements are among the most comprehensive available of the far-out side-lobe pattern of a modern radio-telescope antenna. The VLA is described in detail in *The Very Large Array, P.J. Napier, et al., IEEE Trans. MTT, April 1977, p.244.* The VLBA is described in *The Very Long Baseline Array, P.J. Napier, et al., Proc. IEEE, November 1993. (Special issue on the Design and Instrumentation of Antennas for Deep Space Communications and Radio Astronomy.)*

The VLA antenna number 17 was used, and the VLBA antenna is that situated at Los Alamos. For these measurements the data received at the antenna with right circular polarization (RCP) was recorded; the transmitter was linearly polarized, so effectively transmitting simultaneously RCP and LCP radiation.

6. The Results

Figures 3 and 4 below show azimuthal averages of the side-lobes measured on an antenna from, respectively, the NRAO VLA and the NRAO VLBA radio telescopes. Both antennas are 25-meter paraboloids with Cassegrain feed systems, and the measurements were made at frequencies of, 1620 MHz and 1720 MHz for theVLA and VLBA antennas, respectively. The measurements are analysed to determine two sets of values: first the peak sidelobe in each azimuthal ring, and second the average side-lobe level in each azimuthal ring. The peak values are representative of the side-lobe envelope, and can be compared with Recommendations S.509 and S.580, while the averaged values are in line with Recommendation SA.1428, for use in calculations for rapidly moving sources of interference.

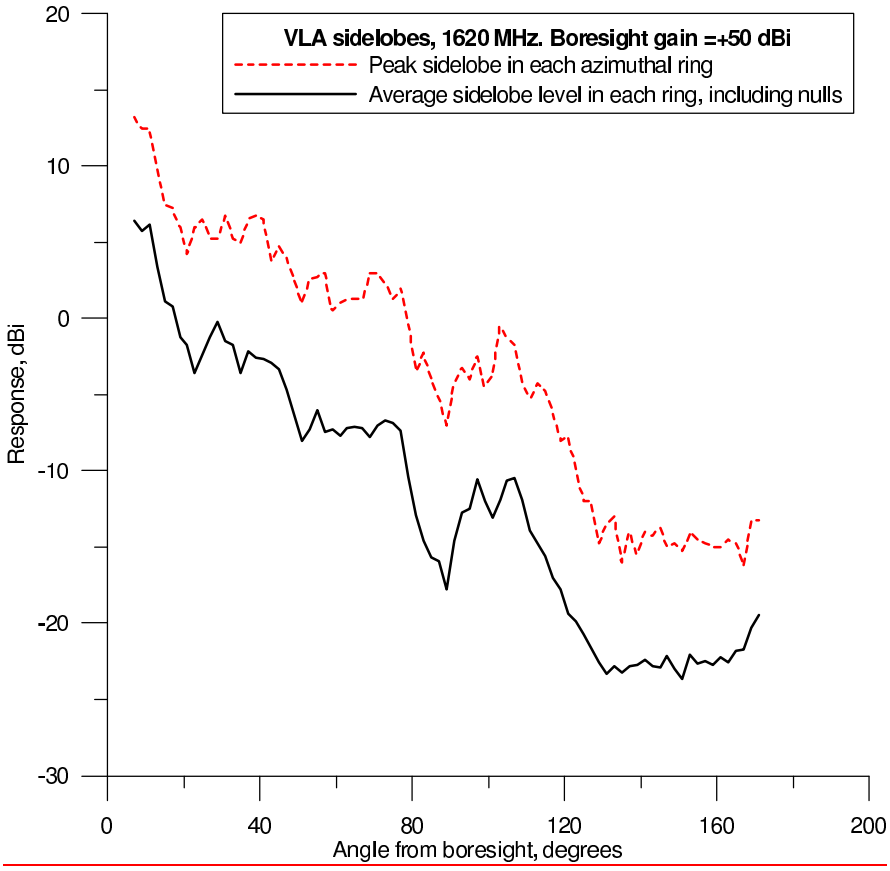

VLA sidelobes, 1620 MHz. Boresight gain =+50 dBi
Peak sidelobe in each azimuthal ring
Average sidelobe level in each ring, including nulls
Response, dBi
20
10
0
-10
-20
-30
0
40
80
120
160
200
Angle from boresight, degrees

Figure 3

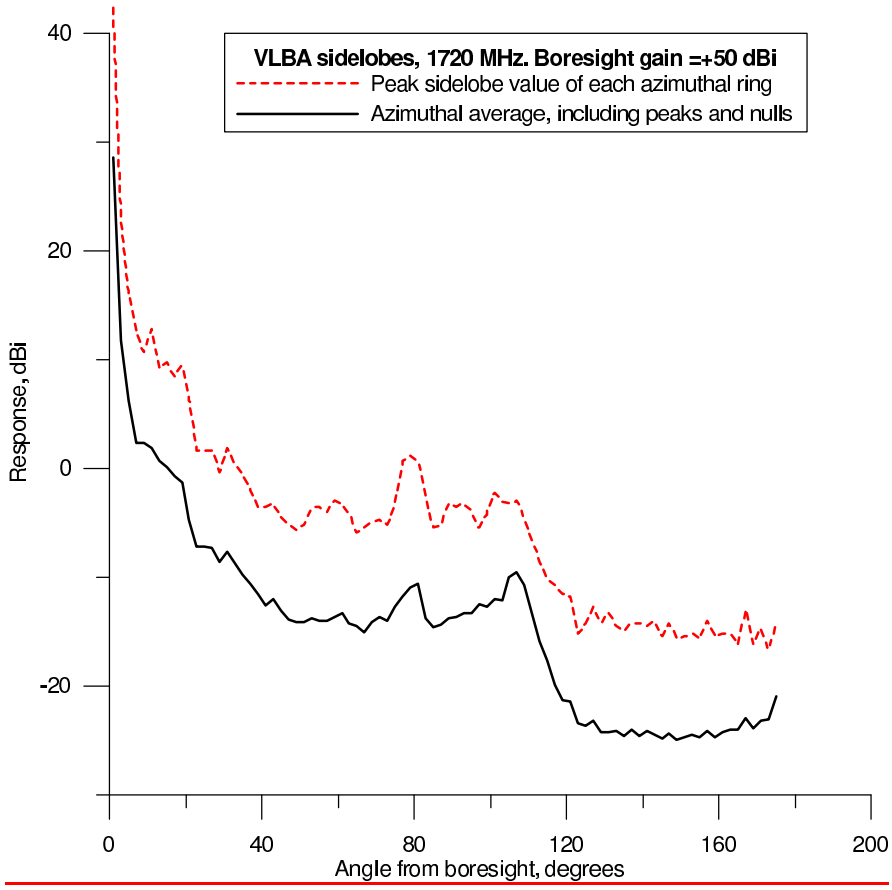


Figure 4

Figure 5 shows a superposition of the measured data and of the ITU models described above. Several conclusions can be drawn from this:

1. All ITU models underestimate the peak side-lobe envelope within about 110 degrees of the main axis. Conversely, the models slightly overestimate the side-lobe envelope beyond 110 degrees – but note that a radio telescope is always pointing towards the sky. The side-lobes beyond 90 degrees are more likely to be in the direction of the ground, and thus susceptible to thermal radiation from the ground rather than to interference.
2. The model SA.1428 is a reasonable fit to the average side-lobe level out to approximately 80 degrees from the main beam. Beyond 80 degrees, the model overestimates the mean side-lobe level – but again, as mentioned above, that part of the telescope beam is usually directed towards the ground.

7. Conclusions.

A measurement of the complete far-out side-lobe pattern of a radio telescope is extremely time consuming and expensive in terms of lost scientific observing time. Inadequately sampled data can be misleading, in that major side-lobe responses can easily be missed.

Presented here are fairly comprehensive measurements, at a wavelength of 18 cm, of two 25-meter antennas from, respectively, the VLA and VLBA systems – two of the world's premier radio-telescope arrays. Based on these two antennas, the relevant ITU models of side-lobe envelope and of average side-lobe response are surprisingly representative.

There is a need for more data on radio telescope side-lobe responses. However, based on the data currently available, the validity of the models used in ITU recommendations is confirmed.

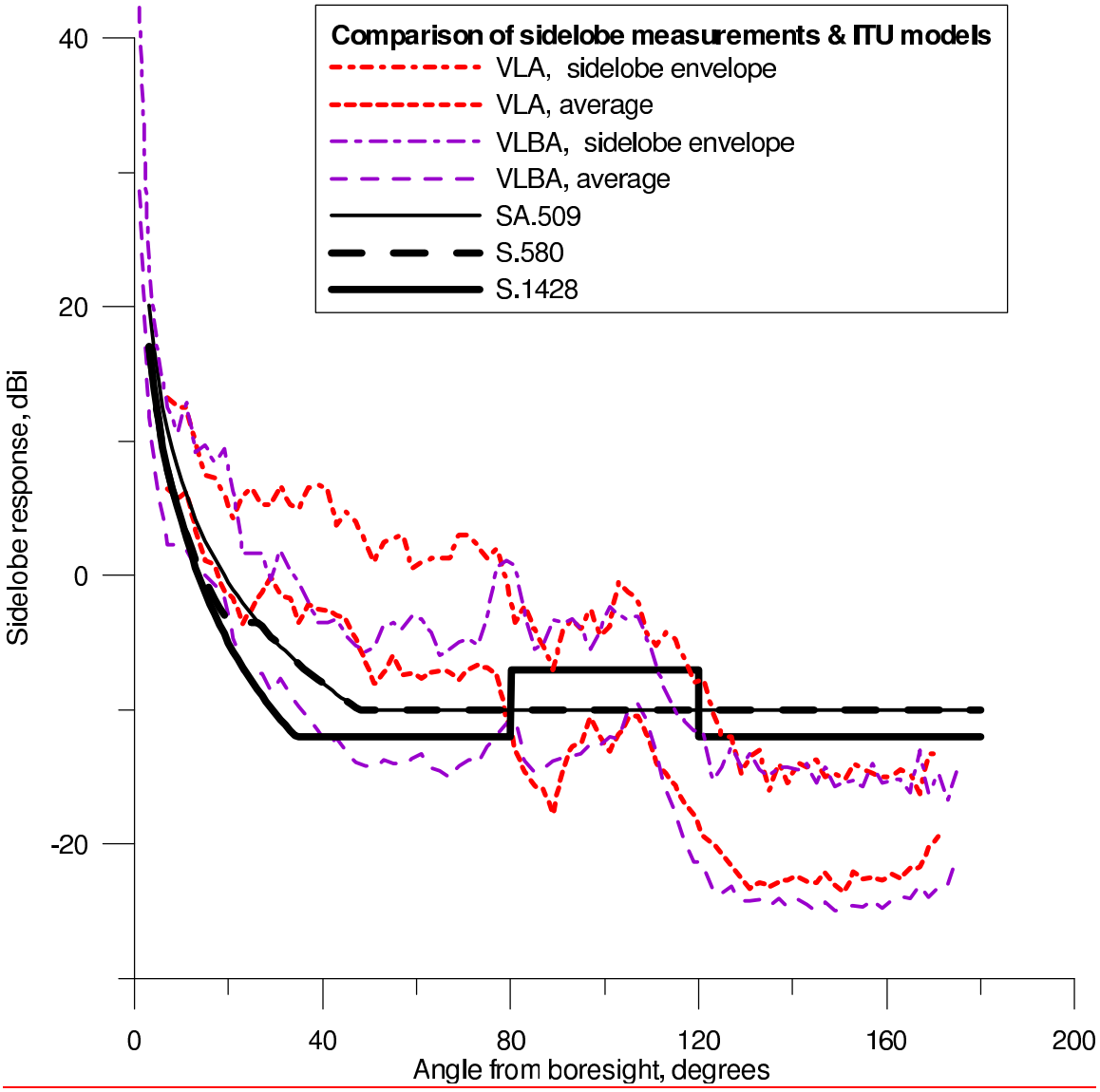


Figure 5