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Measurements of the ATCA primary beam

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Summary

We have made a systematic set of measurements of the primary beam response of the ATCA dishes using a new mosaic-like observing mode. Observations were made at 3, 6, 13 and 20cm, both aligned with and at 45 degrees to the support legs for the secondary. Out to the 10% level we find the beam to be highly symmetric (< 1.5% variation) and essentially equal for the XX and YY polarizations (< 0.5% difference in response). We derive fits to the beam for use in the AIPS task PBCOR and approximate gaussian fits.

Observations and Reduction

The observations were made on the 12th of April 1992 with the array in the 6C-configuration. The technique we used was to offset all antennas except the reference antenna in azimuth and elevation by amounts specified in a mosaic file. In a single scan the antennas stepped radially outwards, spending 3 integration cycles at each point. The 3 and 6 cm observations were done simultaneously, using dual frequency measurements at 4740 MHz and 8640 MHz of 3C286. Thirty radial steps of 0.008 degrees were made before returning on-source. We obtained scans in 8 directions in 45 degree steps, starting in the positive elevation direction. We similarly observed 1934-638 at 13 and 20cm (observing frequencies 2358 MHz and 1420 MHz), stepping by 0.045 degrees. Each observation took about 2.5 hours to complete.

The baselines containing the reference antenna give the voltage response of the primary beam, while those between other antennas give a power response. We only made use of the voltage responses in our analysis, because these have much higher signal to noise in the outer parts. For the 13/20cm data we used data from three baselines (1-5,3-5,4-5) and for the 3/6cm data we used four baselines (1-5,2-5,3-5,4-5).

The data were edited and calibrated using the on-source measurements between radial scans. We then extracted the central integration cycle on each position for further processing.

In Fig. 1 we show the 8 radial scans at 20cm. Out to the first null all scans lie close together, but beyond 40 arcmin the scans aligned with the support legs for the secondary have a significantly higher response. Also the second null is absent in these directions. Note that the plot shows the voltage power response, the values have to be squared to obtain the power response. The highest first sidelobe reaches about 4% in power.

In Fig. 2 and 3 shows the average of the 20cm scans aligned with the legs and those at 45 degrees.

Figure 4 shows the beam voltage response at 13cm, measured on the same grid as the 20cm beam, and thus more sparsely sampled.

Figure 5 shows the 8 radial scans obtained at 6cm. There are clear systematic differences between the scans. These are due to pointing errors.

The difference between the two polarisations (XX and YY) was found to be negligible, therefore all subsequent analysis was done using Stokes I.

Pointing errors

Especially at the higher frequencies, it is clear that significant pointing errors are present in the data. These affect the derived responses even when averaged over 4 or 8 directions and a number of antennas. We therefore used the primary beam data to iteratively solve for the peak height and offsets in Az. and El. of a fixed width circular gaussian using data out to the 30% power level. (The peak had to be fitted because the data had been normalized to 1.0 at the 'on-source' points). Using the corrected data a new gaussian width was derived, this procedure was repeated 2 or 3 times till the values converged. The pointing errors thus found ranged from 0. to 45. arcseconds, with typical errors of 15 arcseconds. An independent check on the results was made by comparing the offsets found for each of the two simultaneous frequencies. The largest difference at 3/6cm was 9 arcseconds, at 13/20cm (where the fit is much less accurate) it was 24 arcseconds. We averaged the corrections for each set of frequencies and applied them to data for the two individual frequencies. Note that the effect of these pointing errors is much bigger than the differences between the detailed fits derived for each frequency. Therefore, before trying to accurately correct for primary beam effects one should make sure the pointing errors in the direction of interest are small enough.

At 3cm the average correction factor for the peak value was 1.04. This value should be taken into account in (systematic) errors on flux densities at high frequency if absolute flux calibrator and program source are far apart. At the other frequencies the correction factors were 1.01–1.02.

In Fig. 6 we show the 3cm data before and after correction for pointing errors (and scale errors).

Primary Beam fits

We fitted the pointing corrected data with 3 functions. Firstly a gaussian was fitted to the data out to a normalized distance of x=35. The distance x is the distance in arcminutes times the frequency in GHz. The point x=35 corresponds roughly to the 20% (power) level. Figure 7 shows the resulting fits together with the pointing corrected data. From the plots it is clear that the gaussian fit gives a reasonable fit to the beam out to about the 30% level. Fit parameters are given in Table 1. When the data from directions aligned with the legs and those at 45° are fitted separately, the beam is found to be 1-2% wider in the directions aligned with the support legs, the values in the table are based on all data. For high dynamic range mosaicing new data will be needed to investigate the relative contributions of these two directions for data taken over a range of hour angles. However, pointing errors will probably limit the accuracy of the corrections before these effects come into play.

Secondly, fits based on the formula used in the AIPS task PBCOR were made. These fits are of the form

$$A(x) = \frac{1}{1 + a_1x^2 + a_2x^4 + a_3x^6 + a_4x^8},$$

where A(x) is the beam power response. For these fits the data out to $x = 50$ (about the 3% level) were used. The results are shown in Figure 8, the fits are reasonable out to the 5% level. The coefficients are listed in Table 2.

Finally, for completeness, a higher order fit was made to the data out to larger distances (70–110). These fits were done for the two principal directions separately because of the distinctly different sidelobe behaviour. This fit was a standard polynomial fit with only even powers of x (a justification for this is that these are the terms present in the theoretical beam response $J_1(r)/r$) :

$$A(x) = 1 + a_1x^2 + a_2x^4 + \cdots$$

The results are shown in Figure 9, note that these fits must be strictly limited to the range used for the fit (or 10% less) because they 'explode'. Table 3 lists the coefficients for these fits, the two directions are distinguished by '+' for aligned and '×' for 45° with the support legs.

In Figure 10 we compare the PBCOR fits for the 4 frequencies. It can be seen that the 13cm beam is wider than the 20cm beam, this is probably related to the fact that the focus at 13cm is worse than at 20cm. The focus at 6cm is much better, at 3cm the effects of focus and dish accuracy might be responsible for the relatively wide beam, some residual pointing errors could also still affect these data. Finally, note that all these measurements were made at a fixed focus setting of the subreflector and that the beam shapes will change if these settings are changed.

Table 1. Gaussian primary beam fits: $e^{-4\log(2)(x/fwhm)^2}$

Band	fwhm [arcsec GHz]	range [arcsec GHz]
20cm	47.9	0–35
13cm	49.7	0–35
6cm	48.3	0–35
3cm	50.6	0–35

Table 2. PBCOR primary beam fits: $1/(1 + a_1x^2 + a_2x^4 + a_3x^6 + a_4x^8)$

Band	a_1	a_2	a_3	a_4	range [arcsec GHz]
20cm	8.99E-04	2.15E-06	-2.23E-09	1.56E-12	0–50
13cm	1.02E-03	9.48E-07	-3.68E-10	4.88E-13	0–50
6cm	1.08E-03	1.31E-06	-1.17E-09	1.07E-12	0–50
3cm	1.04E-03	8.36E-07	-4.68E-10	5.50E-13	0–50

Table 3. Polynomial primary beam fits: $1 + a_1x^2 + a_2x^4 + a_3x^6 + \cdots$

Band	dir.	a_1	a_2	a_3	a_4	a_5	a_6	range [arcsec GHz]
20cm	+	-1.049E-02	4.238E-06	-8.473E-11	9.073E-15	-5.004E-19	1.118E-23	0–110
20cm	×	-1.078E-03	4.618E-07	-1.011E-10	1.207E-14	-7.513E-19	1.908E-23	0–100
13cm	+	-9.942E-04	3.932E-07	-7.772E-11	8.239E-15	-4.492E-19	9.899E-24	0–110
13cm	×	-1.032E-03	4.340E-07	-9.337E-11	1.088E-14	-6.553E-19	1.598E-23	0–105
6cm	+	-1.075E-03	4.651E-07	-1.035E-10	1.227E-14	-6.215E-19		0–70
6cm	×	-1.096E-03	4.922E-07	-1.148E-10	1.410E-14	-7.262E-19		0–70
3cm	+	-9.778E-04	3.876E-07	-8.068E-11	9.414E-15	-5.841E-19	1.499E-23	0–100
3cm	×	-9.903E-04	4.016E-07	-8.589E-11	1.027E-14	-6.505E-19	1.698E-23	0–100

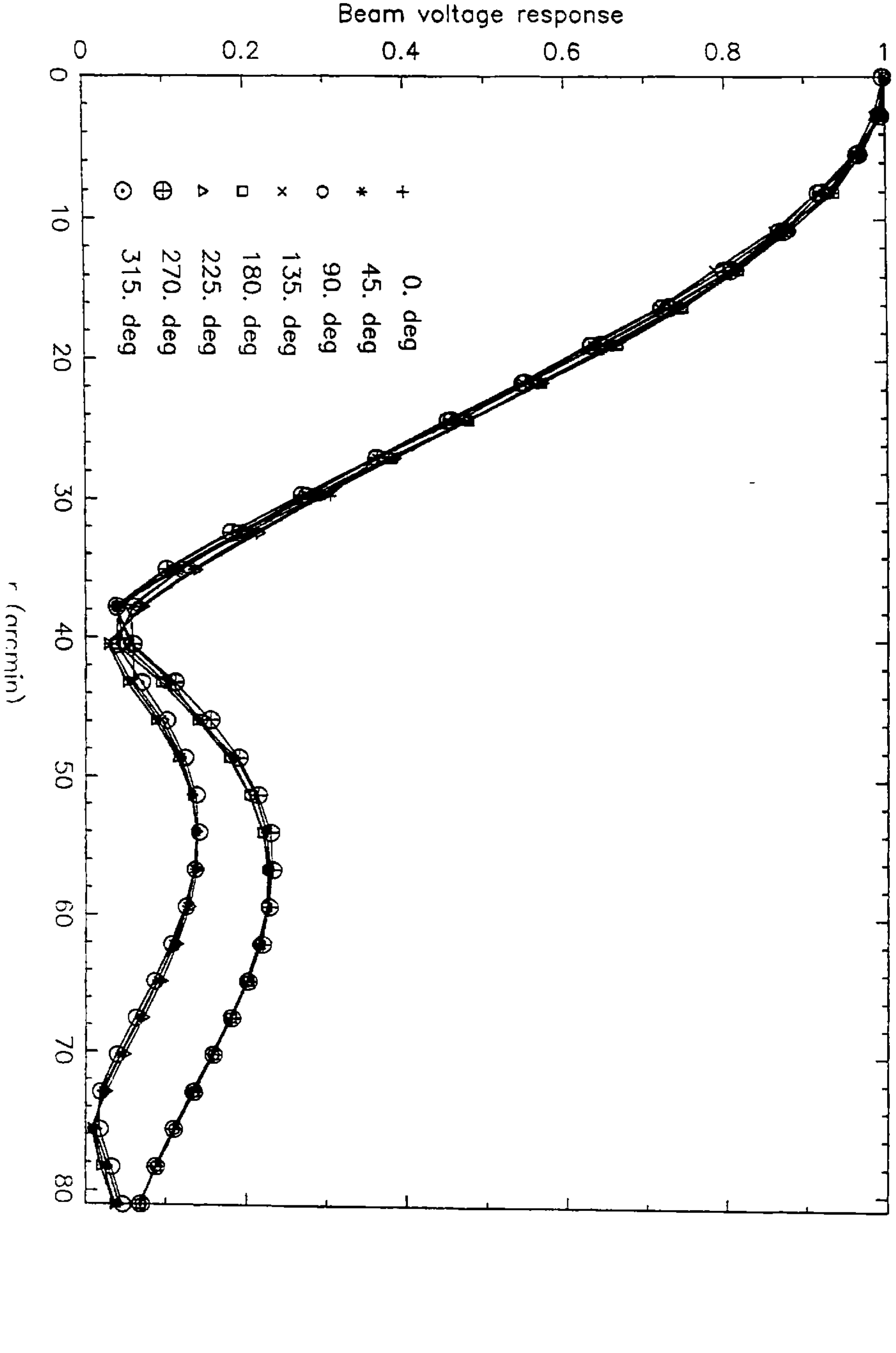


Figure 1. Primary beam 20cm, Stokes I

Figure 2. Primary beam 20cm, Stokes I

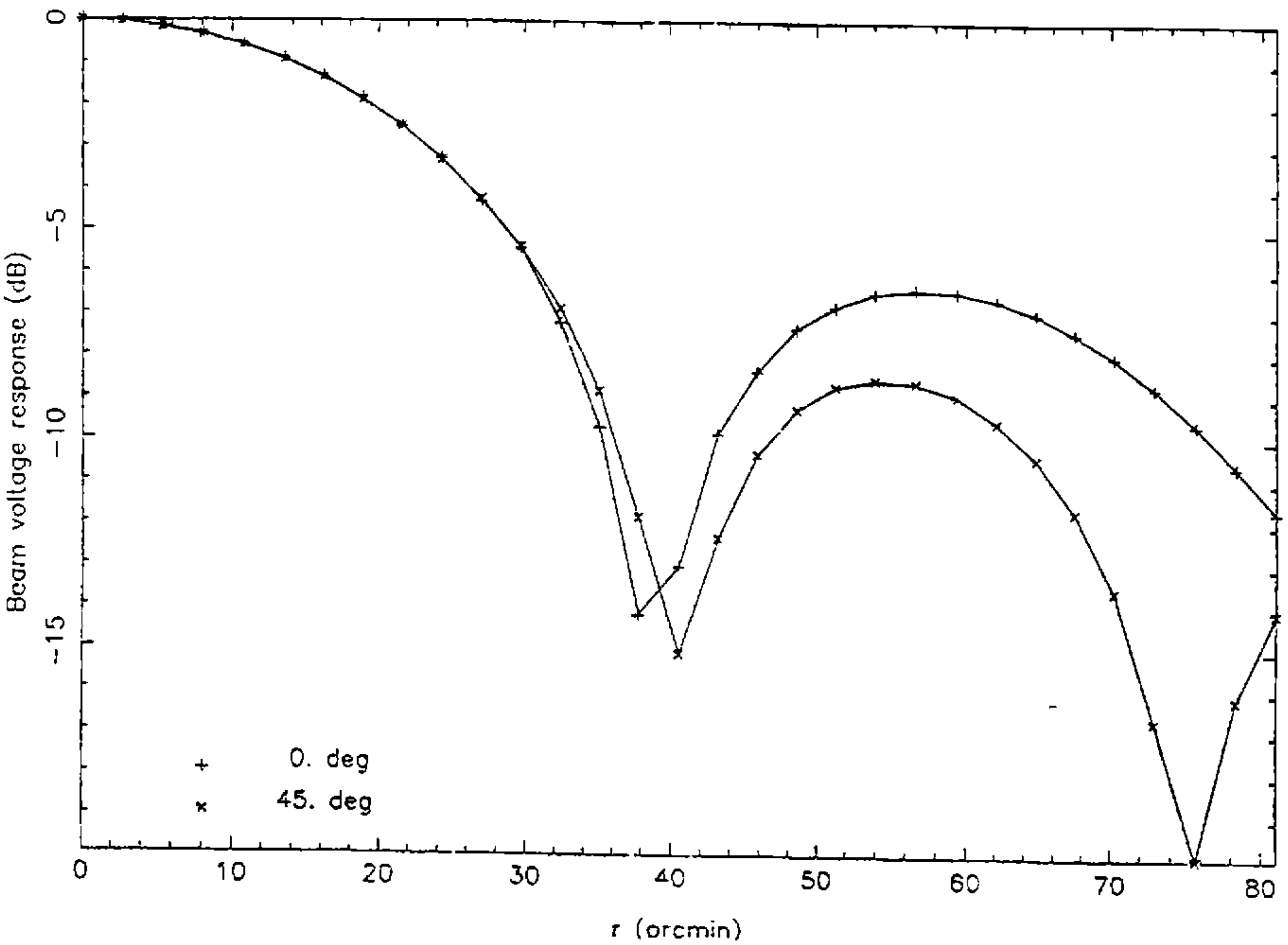
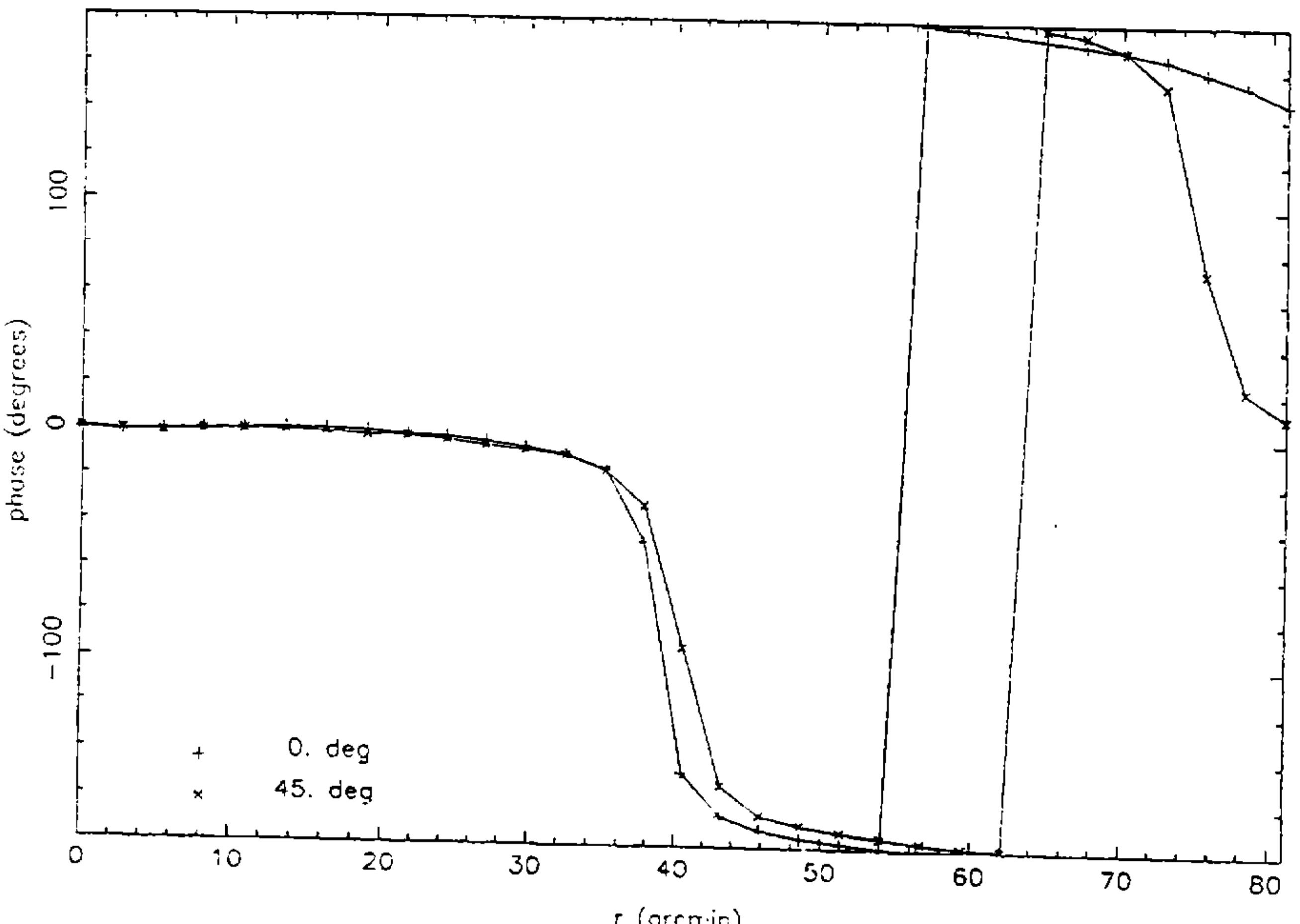


Figure 3. Primary beam 20cm, Stokes I



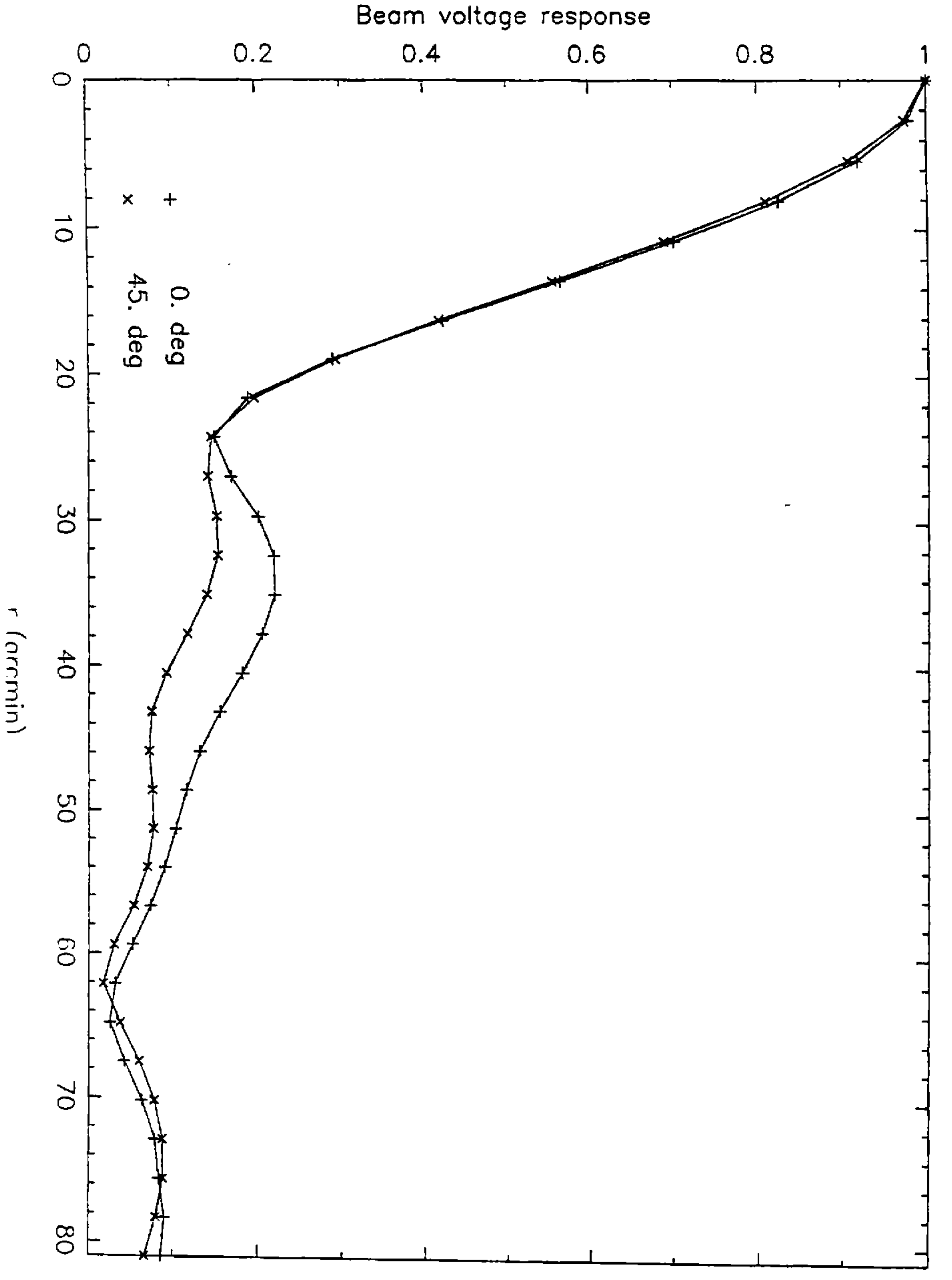


Figure 4. Primary beam 13cm, Stokes I

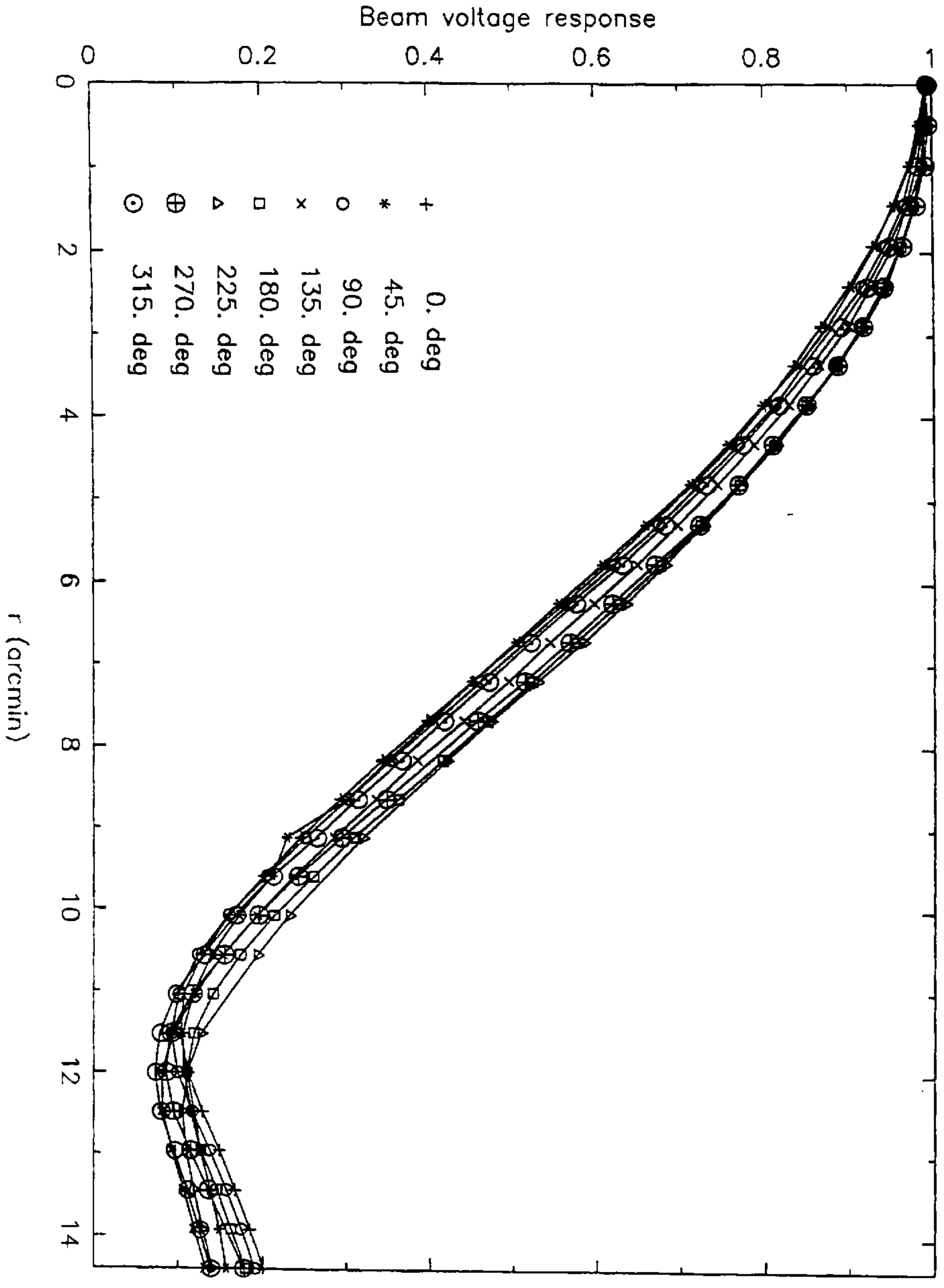


Figure 5. Primary beam 6cm, Stokes I

Figure 6a. 3cm, raw Primary Beam data

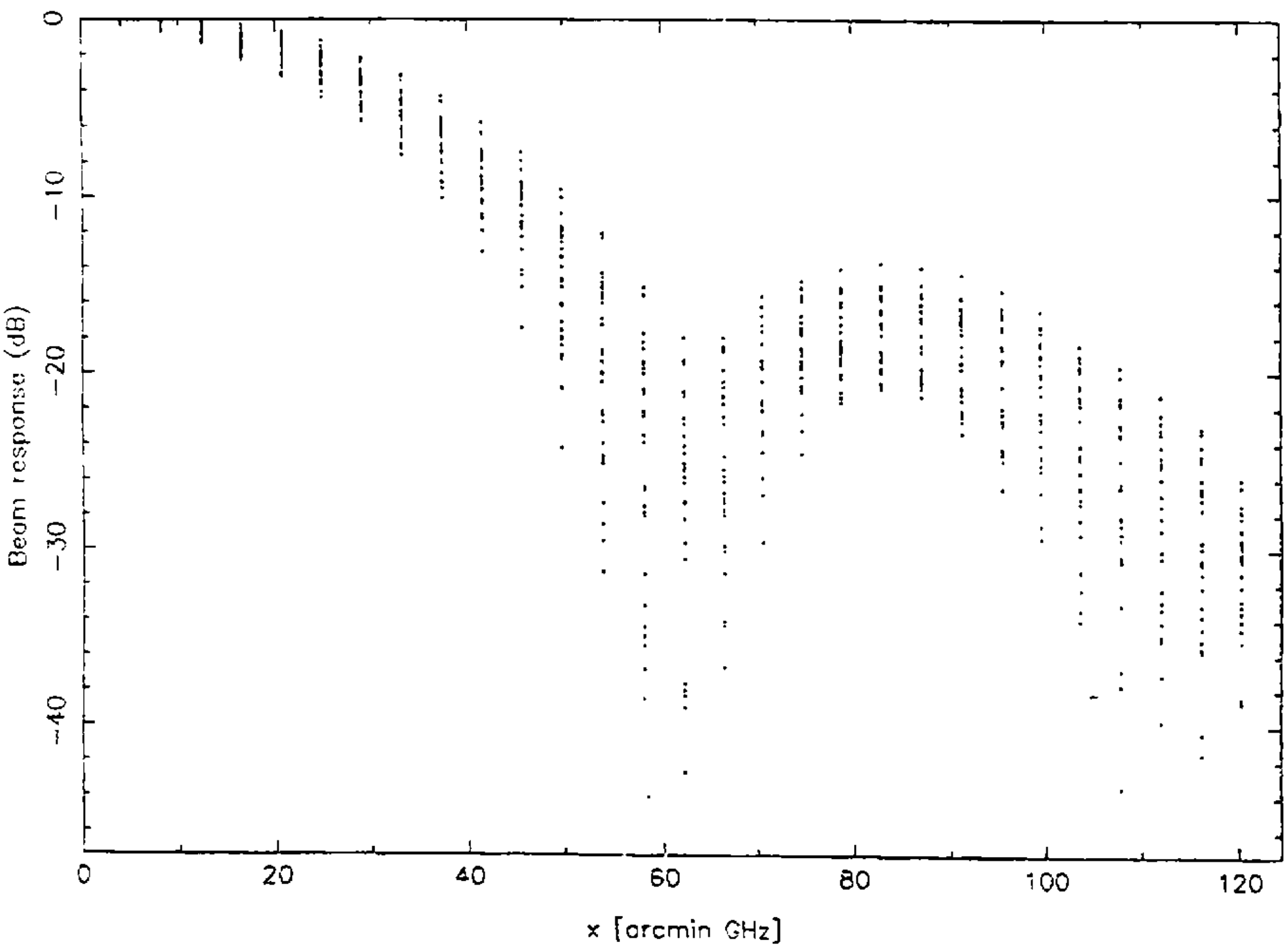
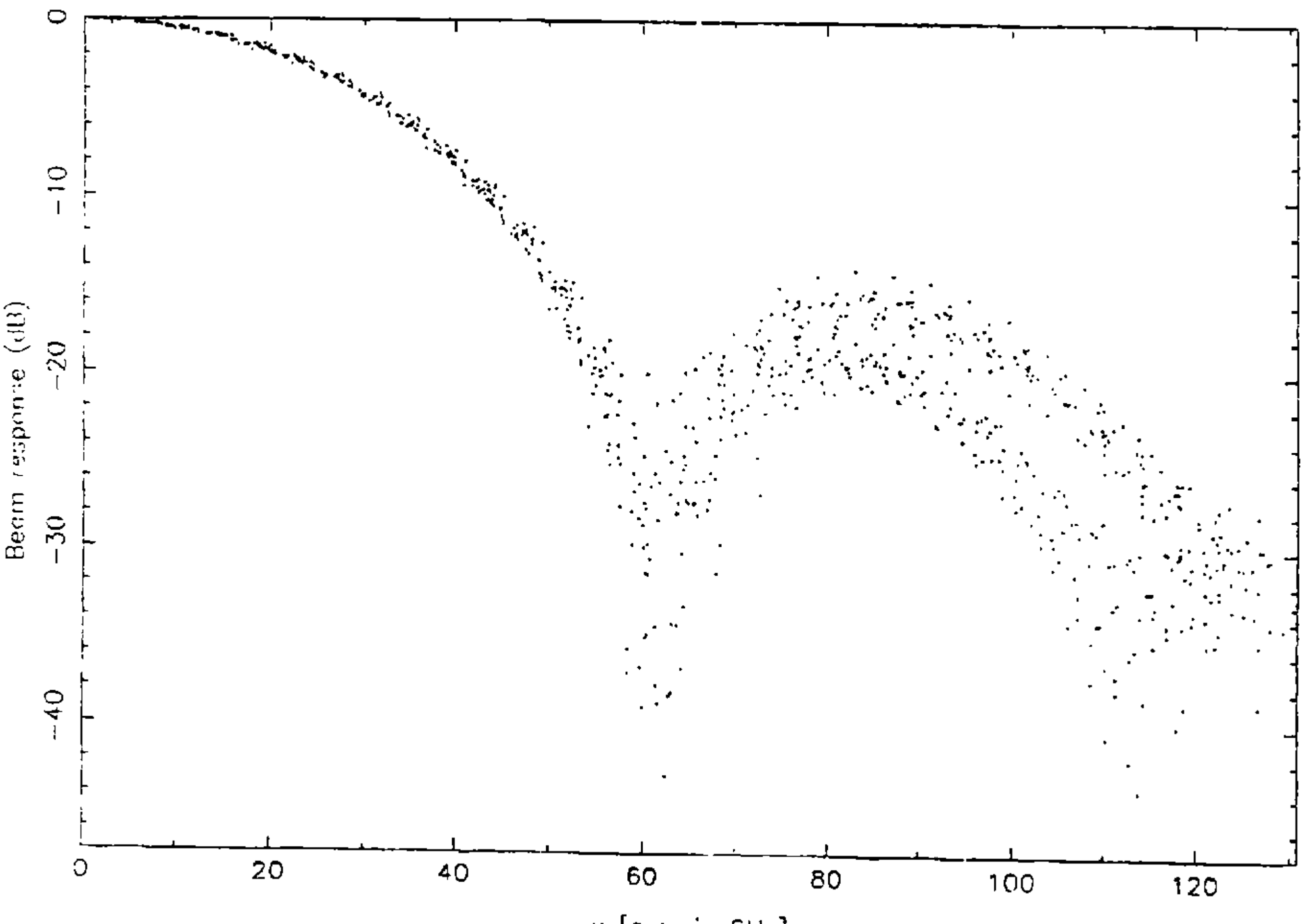


Figure 6b. 3cm, pointing corrected Primary Beam data



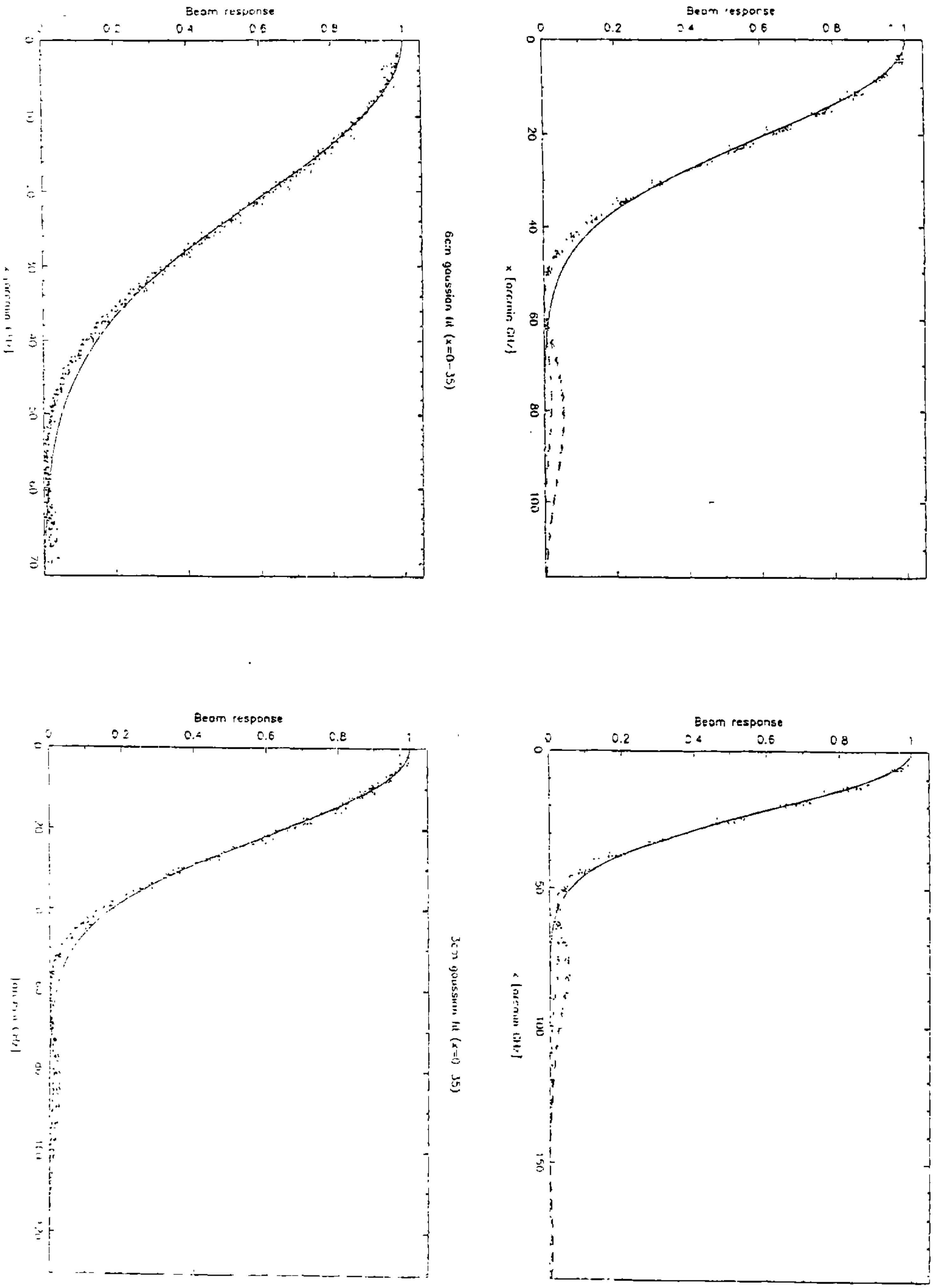

Beam response
20cm gaussian fit (x=0–35)
x [arcmin GHz]
6cm gaussian fit (x=0–35)
3cm gaussian fit (x=0–35)
x [arcmin GHz]

Figure 7

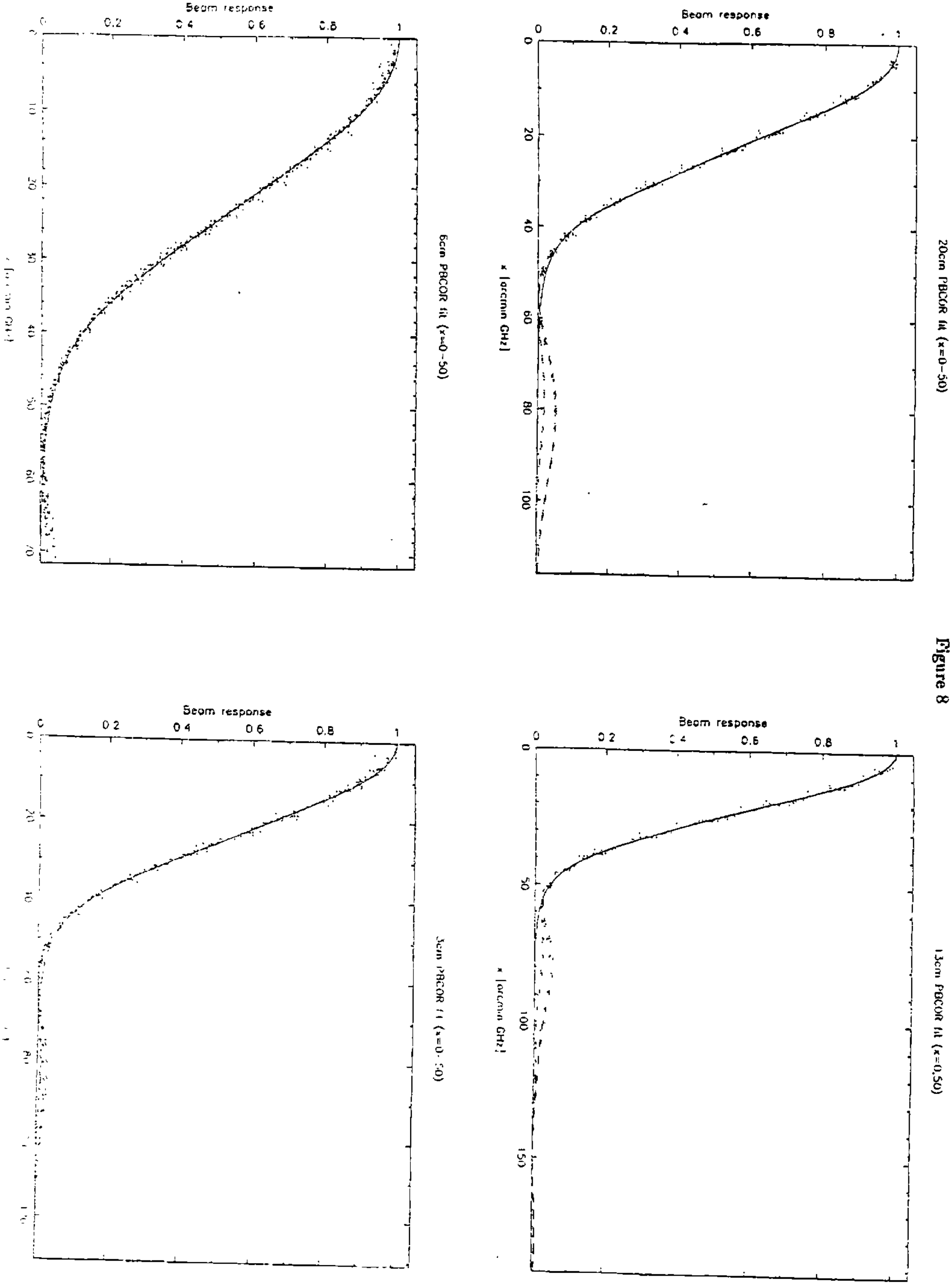
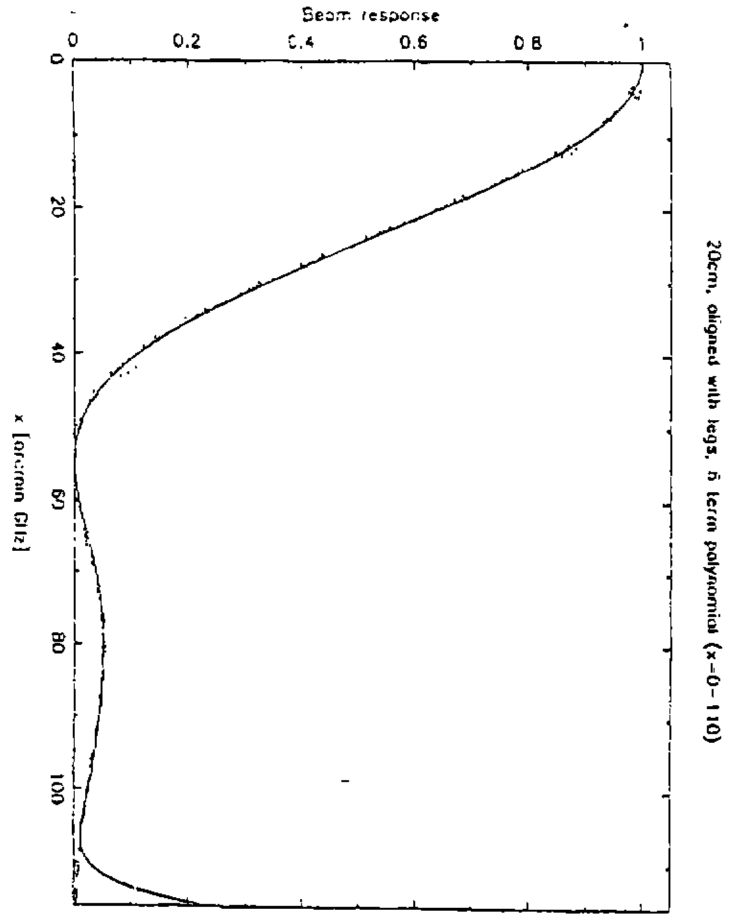
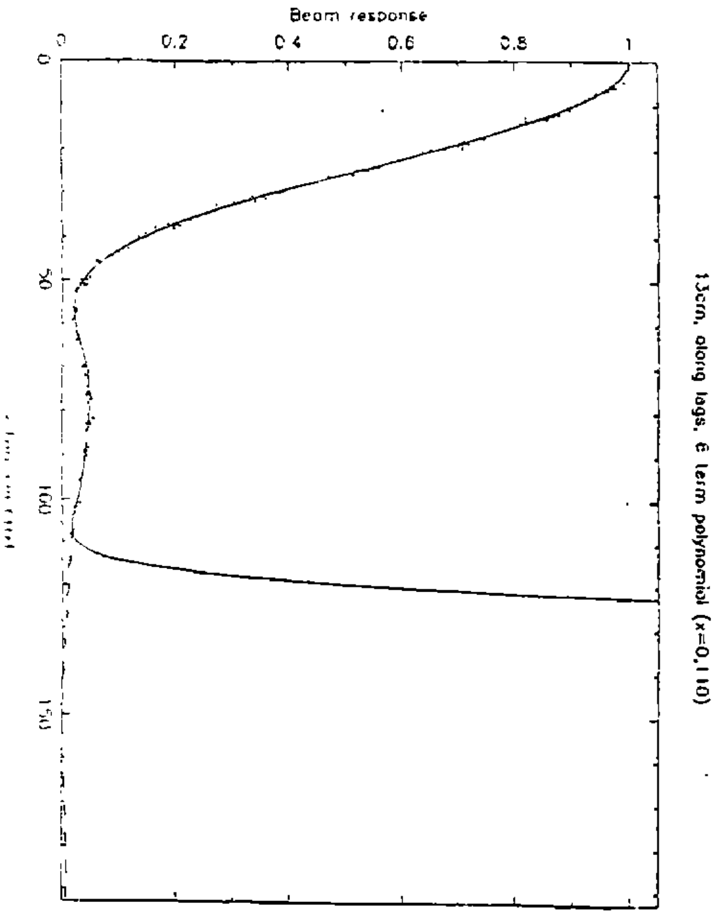
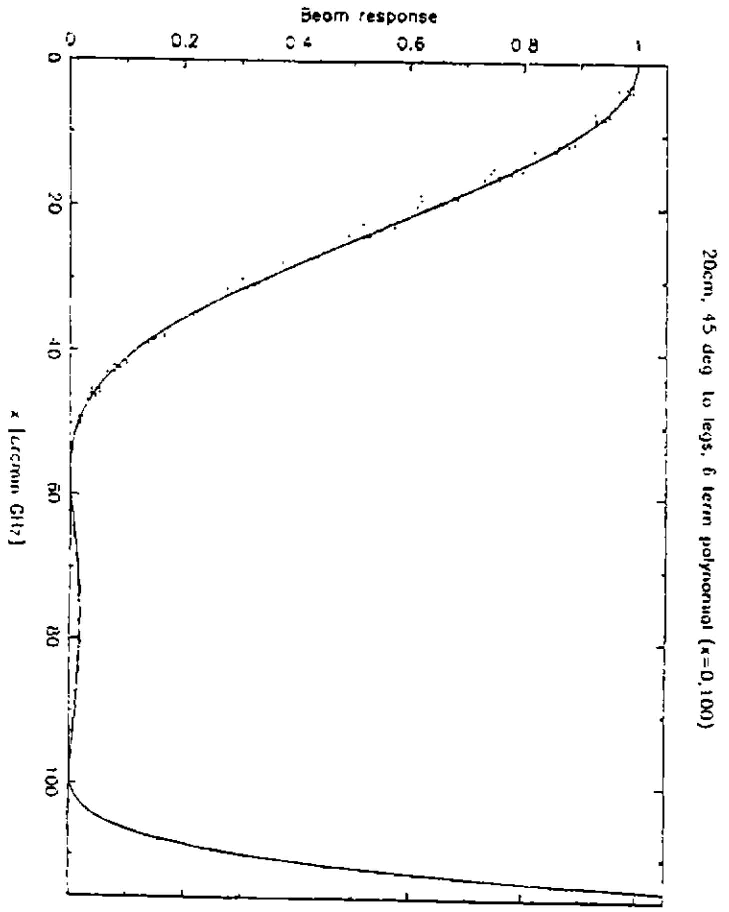

20cm PBCOR fit (x=0-50)
6cm PBCOR fit (x=0-50)
13cm PBCOR fit (x=0-50)
3cm PBCOR fit (x=0-50)
Beam response
x [arcmin GHz]

Figure 8


20cm, aligned with legs, 6 term polynomial (x=0-110)
Beam response
x [arcmin GHz]


13cm, along legs, 6 term polynomial (x=0,110)
Beam response


20cm, 45 deg to legs, 6 term polynomial (x=0,100)
Beam response
x [arcmin GHz]

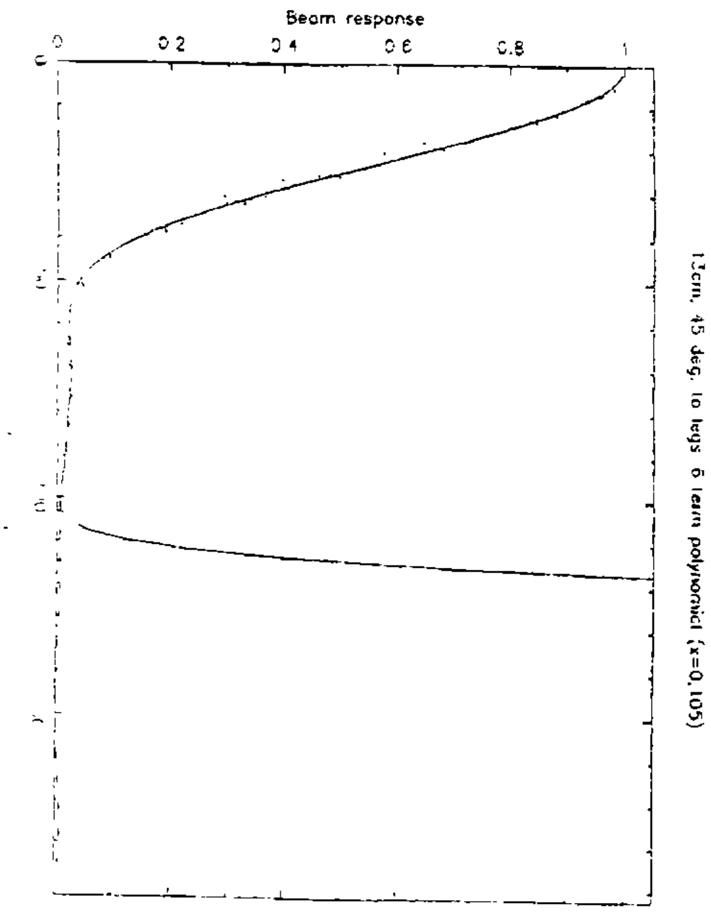
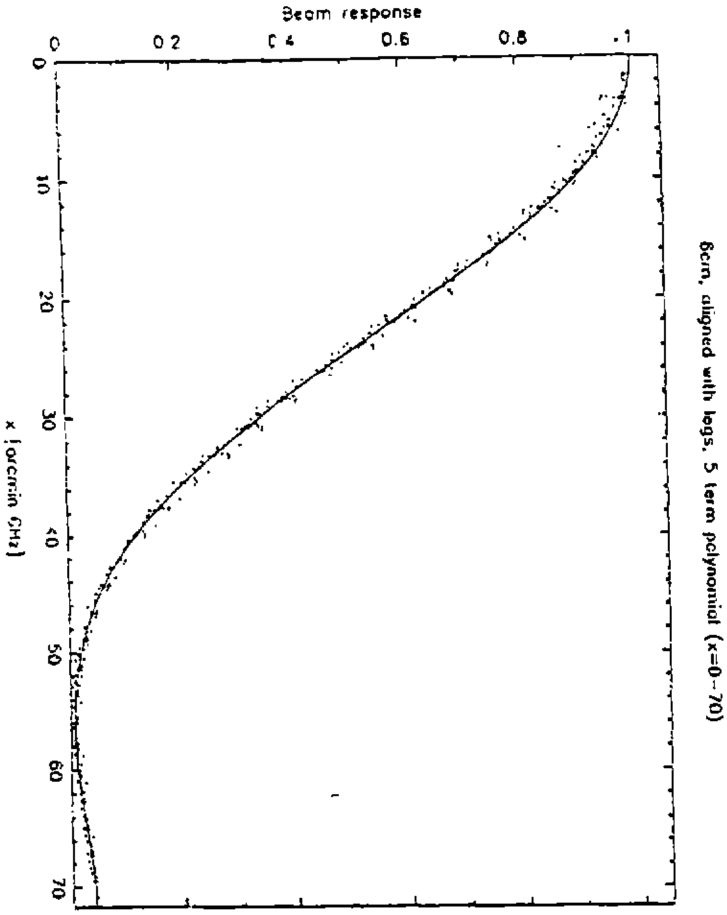
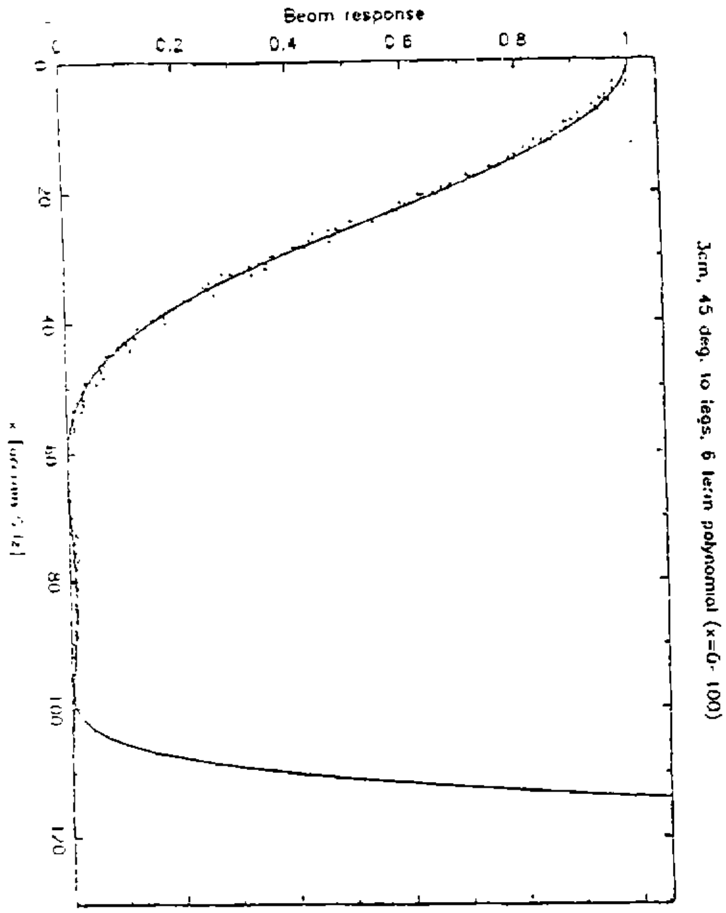
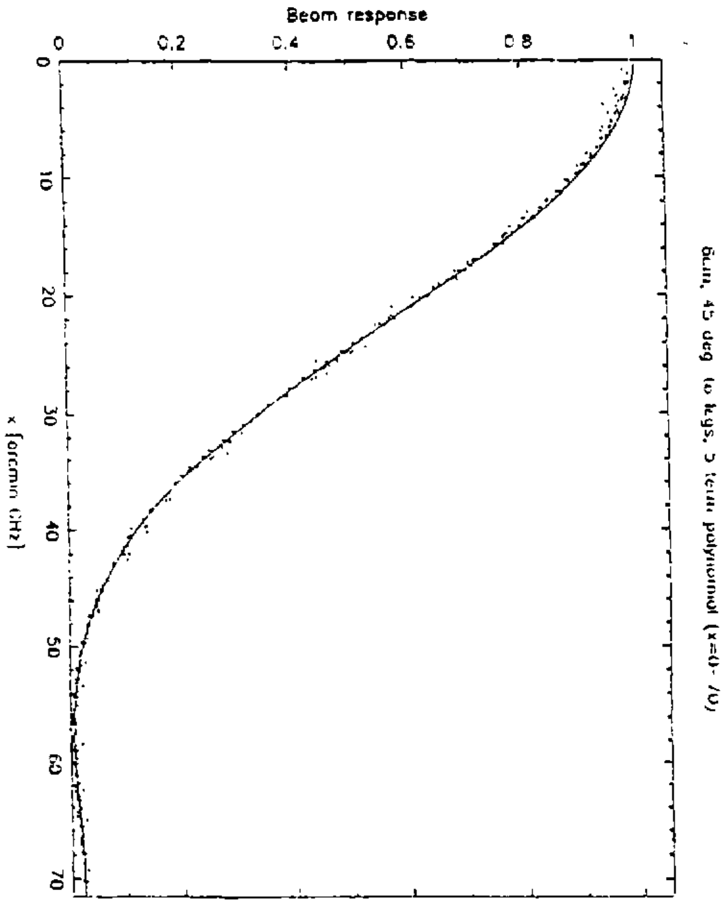

13cm, 45 deg, to legs 6 term polynomial (x=0,105)
Beam response

Figure 9a


Beam response
x [arcmin 6GHz]
6cm, aligned with legs, 5 term polynomial (x=0-70)


Beam response
3cm, 45 deg. to legs, 6 term polynomial (x=0-100)


Beam response
x [arcmin GHz]
6cm, 45 deg. to legs, 5 term polynomial (x=0-70)

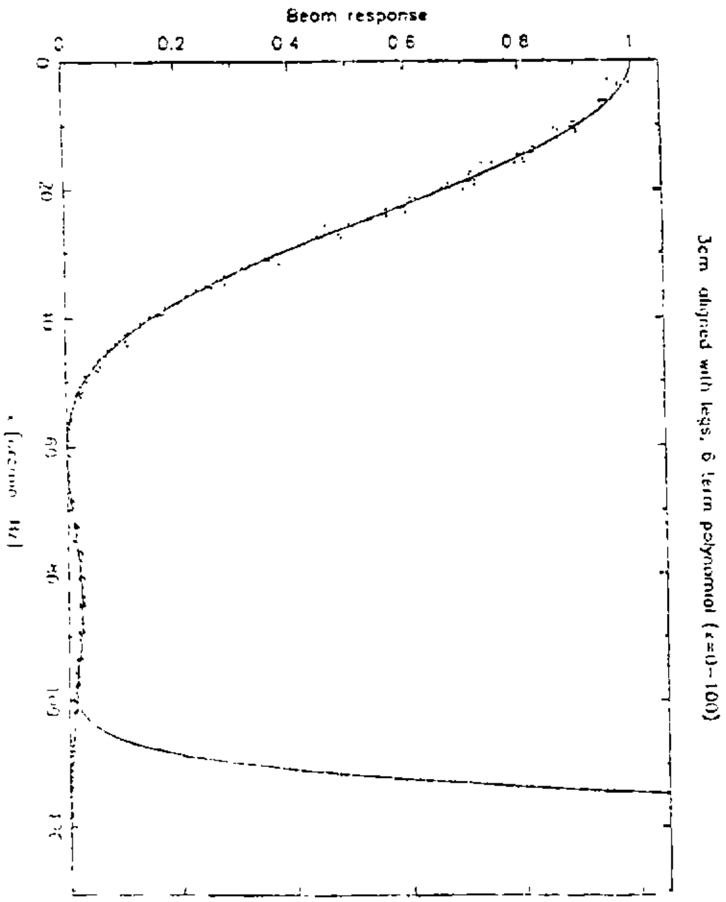

Beam response
3cm, aligned with legs, 6 term polynomial (x=0-100)

Figure 5b

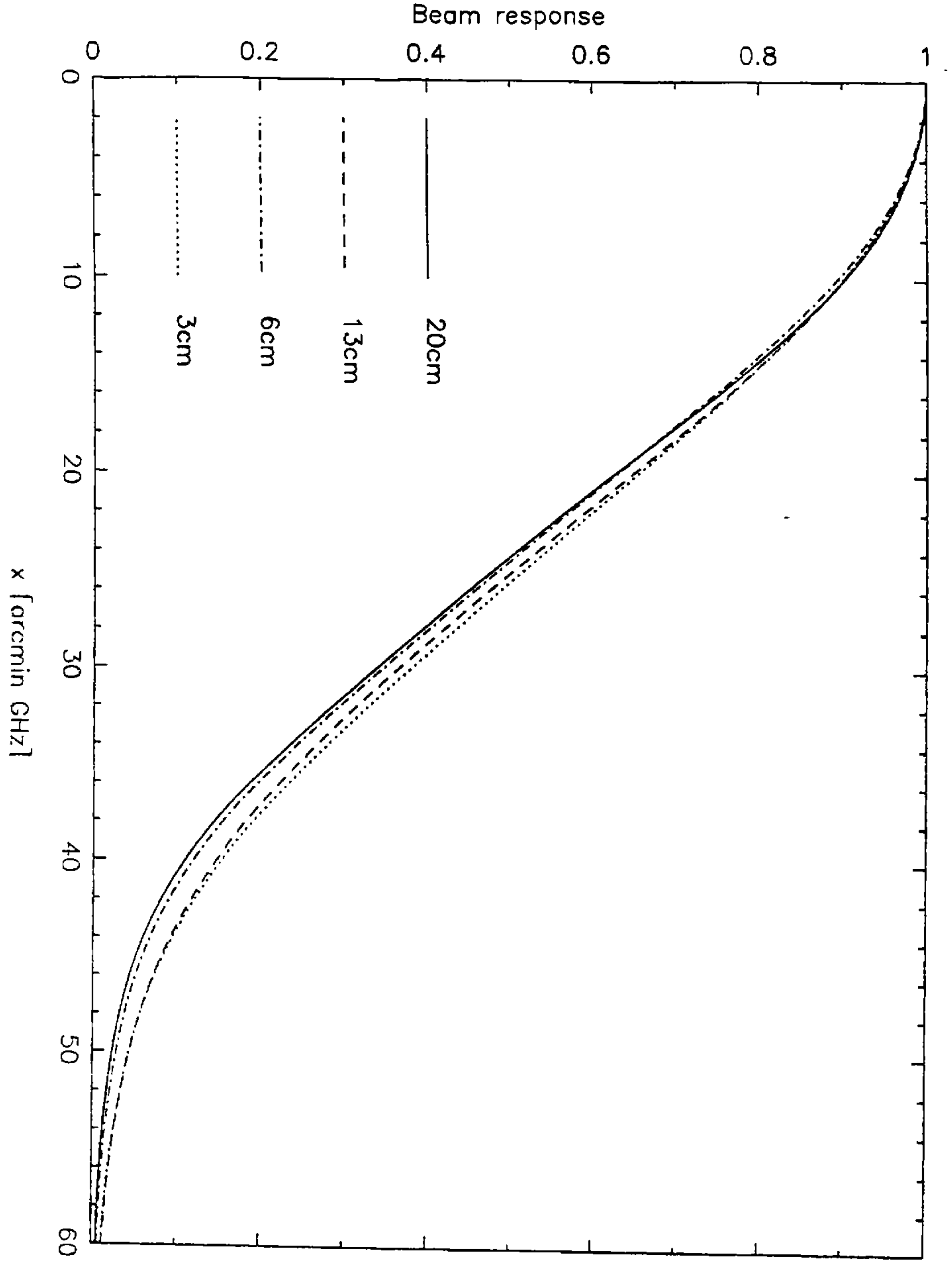


Figure 10. Comparison of PBCOR fits