Near-Field Characterization of 2-D Beam Patterns of Submillimeter Superconducting Receivers

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Abstract

In order to reap the maximum benefit from the low noise temperature of submillimeter superconducting receivers in submillimeter systems, it is important to optimize the illumination of the primary reflector by the receiver feed antennas. Therefore, we have developed a two-dimensional near-field measurement system which probes the beam pattern of submillimeter receiver feed antennas *in situ*, in both amplitude and phase. This system is basically an extension of well-established near-field techniques employed at microwave frequencies and is appropriate for probing paraxial beams where probe correction is not very important. The system has been used to about 500 GHz. The measured near-field data agree well with theoretical models. This system is currently used to characterize feed antennas developed for the Sub-Millimeter Array and is used as a tool in developing an SIS receiver with an integrated planar feed antenna.

I. Introduction

There is increasing interest in measuring the radiation patterns of antennas at submillimeter wavelengths [1,2], particularly for optimizing the illumination of primary reflectors of submillimeter systems. The incentive is particularly strong for the development of planar feed antennas [3-5] because, unlike the more popular waveguide horn antennas, their radiation patterns are not well documented and their open structure nature renders them more susceptible to influence from surrounding mounting structures.

Far field measurements are traditionally used to characterize antenna patterns. At millimeter and submillimeter wavelengths, this is the preferred method because only amplitude measurement is required. However, far field techniques suffer from two main disadvantages:

(1) For measurement of a feed antenna with its associated receiver optics, the far field criterion of $2R^2/\lambda_0$ may impose an unreasonably long range for measurement [1].

(2) Far field techniques require that the antenna under test be rotated. This proves to be difficult for measuring cryogenic receivers *in situ*. In most cases, the measurement is only convenient in a single plane.

In most submillimeter radio-telescopes, the receivers and the primary and secondary reflectors are coupled through a beam waveguide designed using Gaussian beam modes [6,7]. Consequently, the far field patterns of the feed antennas are not very relevent because the overall efficency of the feed is dictated by the coupling of the beam emerging from the receiver to the beam waveguide, and this coupling takes place in the near-field [8].

We have developed a near-field scanning system that measures the 2-D beam profile of submillimeter Superconductor-Insulator-Superconductor (SIS) receivers *in situ*. The system is basically an extension of well established near field techniques employed at microwave frequencies [9]. Both amplitude and phase patterns are measured in our system. We believe that this is the first full vectorial near field measurement performed at submillimeter wavelengths.

II. Measurement Set Up

A block diagram of our set-up is given in Fig. 1. For convenience and in order not to saturate the sensitive SIS receiver, we use a harmonic mixer pumped by an HP83620A frequency synthesizer running in the Ku band as the transmitting source. Typical harmonic output power is less than 1 nW above 200 GHz. The probe is an open waveguide with its front wall chamfered to reduce cross-sectional area. The smallest probe available is in WR-3 waveguide. Consequently some over-moding is inevitable above 350 GHz.

The probe and the harmonic generator are mounted on a stepper motor controlled XY scanner that has a resolution of $5\mu m$ and covers a span of 150 mm in each axis. A low phase distortion flexible cable bent in a loop connects the synthesizer to the harmonic generator. A wide dynamic range is obtained by down converting the IF output of the SIS mixer to 21.7 MHz where it is passed through a narrow band filter before its amplitude and phase are measured by a vector voltmeter against a reference signal.

The master reference of the entire system is the 10 MHz internal reference of the synthesizer. An RF frequency multiplier unit is locked to this reference signal and delivers the frequency reference to the phase lock loop of the Local Oscillator (LO) pumping the SIS mixer. It also provides intermediate LO drives for multiple down conversions in the IF chain and phase lock circuitry, and supplies the reference signal to the vector voltmeter used for the vector measurement.

The measurement set-up is automated by a PC equipped with a GPIB interface controller. The measurement speed is limited at high Signal-to-Noise Ratios (SNR) by the speed of the stepping stages. At low SNR (< 20 dB), integration time is the limiting factor. The total scan time is usually kept to below 1 hour to avoid system drift and temperature fluctuation effects.

III. System Performance and Limitations

One of the major concerns in near-field measurement is the presence of phase errors due to flexible cables and probe positioning [10]. Amplitude error is negligeable in this set-up because the harmonic generator is driven to saturation by the 50 mW of available pumping power.

In our measurement set-up, the only moving cable is a 90 cm low distortion flexible cable linking the synthesizer and the harmonic generator. By maintaining this cable in a loop form, phase errors are minimized because the curvature of the loop stays quite constant except at the corners of the scan plane. In order to quantify the phase error, we have performed a dummy scan in which the moving end of the cable was shorted and the phase of the cable was measured by a network analyzer at 15 GHz. The measured RMS phase fluctuation is about 0.2°. This corresponds to an RMS fluctuation of 4° at 300 GHz. However, it should be noted that the largest phase excursion occurs at the corners of the scan plane and the phase variation over a wide region near the center of the scan plane is significantly less. Therefore, we expect that the impact of phase error introduced by the cable is limited in particular near the center of the scan.

The maximum cumulative positioning error of the XY stages is specified by the manufacturer to be $40\mu m$ over a 100 mm linear scan. While this positioning accuracy is generally adequate for measurement around $\lambda_0 = 1$ mm, higher accuracy is desirable at higher frequencies. Nevertheless, the system works well at least up to 500 GHz for paraxial beams in which transverse phase variation is slow.

Unlike microwave ranges, the waveguide probes used have very thick walls. In fact, the smallest probe is made from a piece of electroformed waveguide section with walls much thicker than the dimensions of the waveguide itself. Chamfering of the open end helps to reduce probe scatter and improves the probe pattern. Absorbers are also carefully placed so as to out metal structures that might give rise to spurious reflections. Probe correction may be introduced using a generalized electromagnetic solver to enhance the measured data [11]. In our measurements so far, we have limited ourselves to paraxial beams where probe correction is less important.

As an initial test of the system, we probed the beam emerging from a plano-convex lens illuminated by a W-band 25 dB standard gain pyramidal horn. The experiment was carried out at room temperature using a commercial Schottky diode mixer receiver operating at 85 GHz. The measured amplitude pattern is given in Fig. 2. The two-dimensional complex data set was then Fourier transformed to derive the far-field beam pattern. This is compared to experimentally measured far-field data in Fig. 3. Clearly a reasonable match exists between the two data sets to the −20 dB level. This indicates that the near field data is reliable to about the −25 dB level and the total RMS phase error is less than a few degrees. Some of the amplitude and phase deviations are due to insufficient electromagnetic shielding as the measurements were performed on an optical bench and not in an anaechoic chamber.

IV. Measured Patterns

The system has been used to measure a number of feed antennas developed for the Smithsonian Astrophysical Observatory Sub-Millimeter Array (SMA). Fig. 4 displays the measured amplitude and phase profiles at 240 GHz of the corrugated feed horn developed for the lowest frequency band of the array [13]. Also shown in the figure are the theoretical profiles derived from a scalar model that assumes axial symmetry. Excellent agreement between the theoretical and measured data is obtained for the H-Plane cut. The E-palne cut differs slightly from the H-plane but the overall beam eccentricity is small.

The horn measured above was then used to illuminate a lens of focal length 55 mm. The lens was positioned 50 mm in front of the aperture of the feed horn. The measured 2-D amplitude and phase patterns at 211 GHz are given in Fig. 5. An SNR in excess of 50 dB was attained during the measurement. In Fig. 6, we compare the measured profile of Fig. 5 to the theoretical model for both the E and H plane cuts. While an excellent match exists around the center of the beam, the match to the theoretical data is pooer at lower power levels. This is attributed to insufficient electromagnetic shielding. This is reflected in the fact that the -25 dB contour in Fig. 5a shows some irregularity in contrast to other contours. We expect a higher beam symmetry if the LO injector and mounting structure of the dewar have larger clear apertures and improved shielding.

The system works well up to 500 GHz. Fig. 7 shows the 2-D amplitude pattern measured at 465 GHz of a corrugated feed horn designed to operate in the band 400 - 520 GHz. In this experiment, the SNR achieved was about 25 dB and the SIS receiver noise temperature was around 150 K. Once again the measured pattern and the theoretical model are seen to be in good agreement, particularly for the phase profile (see Fig. 8). This indicates that systematic phase errors are sufficiently small to allow measurement to frequencies probably in excess of 500 GHz.

The near-field range was also used to characterize an SIS receiver with integrated feed antenna. Fig. 9 shows the 2-D amplitude pattern of a twin dipole antenna on an ellipsoidal immersion lens measured at 255 GHz. The pattern shows a beam with an elliptical cross-section. This is probably due to undesirable radiation from the coplanar strip feed lines feeding the dipoles.

V. Conclusion

A near-field probing system has successfully been implemented to characterize the 2-D complex beam profile of SIS receivers. This system performs well up to about 500 GHz. We believe that this is the first near-field range operating in the sub-millimeter frequency band. The system is currently used to characterize feed antennas developed for the Sub-Millimeter Arrray to allow optimization of the illumination of the telescope. It has also been used as a tool in developing an SIS receiver with an integrated planar feed antenna.

References

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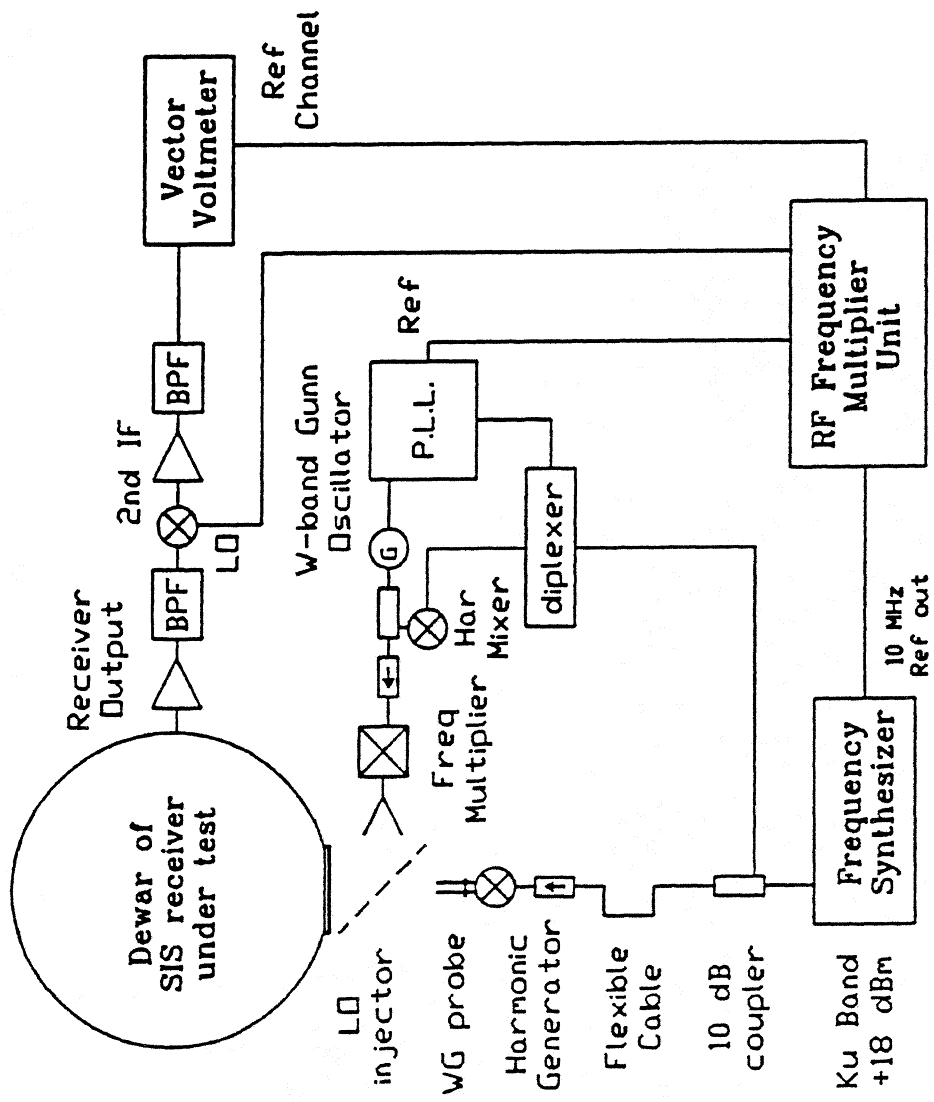


Fig. 1 Block Diagram of Near Field System

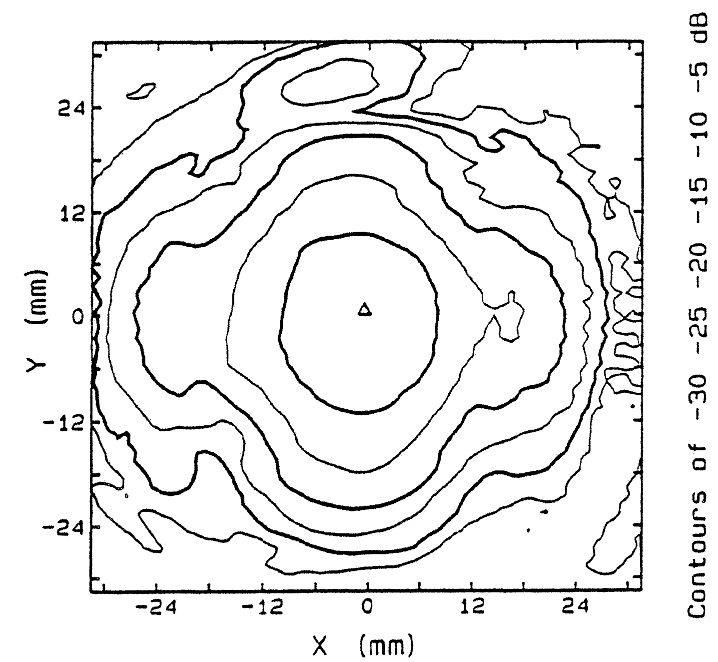


Fig. 2 Near Field Amplitude Data at 85 GHz of a Horn-Lens Combination

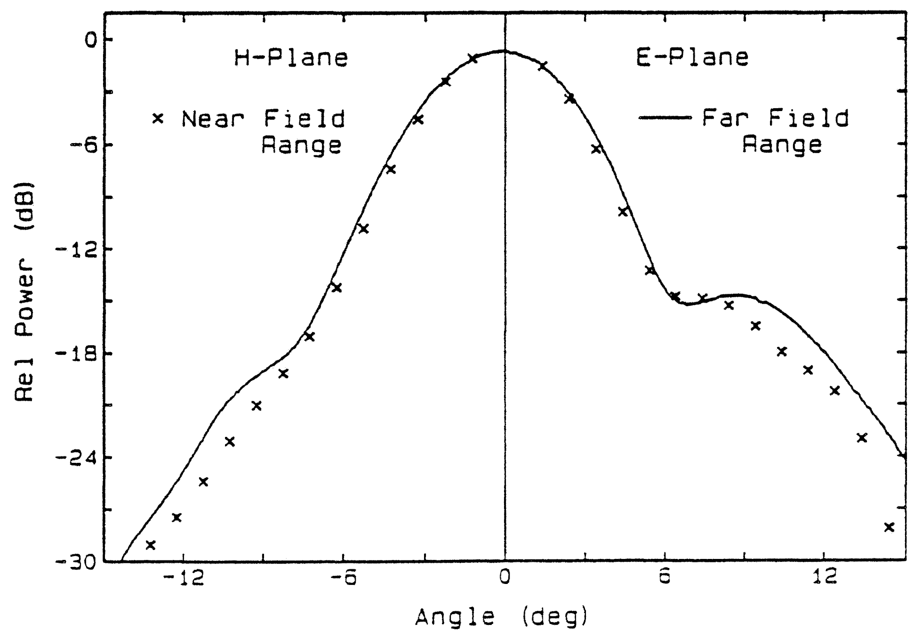


Fig. 3 Comparison of Transformed Near Field Data and Measured Far Field Pattern

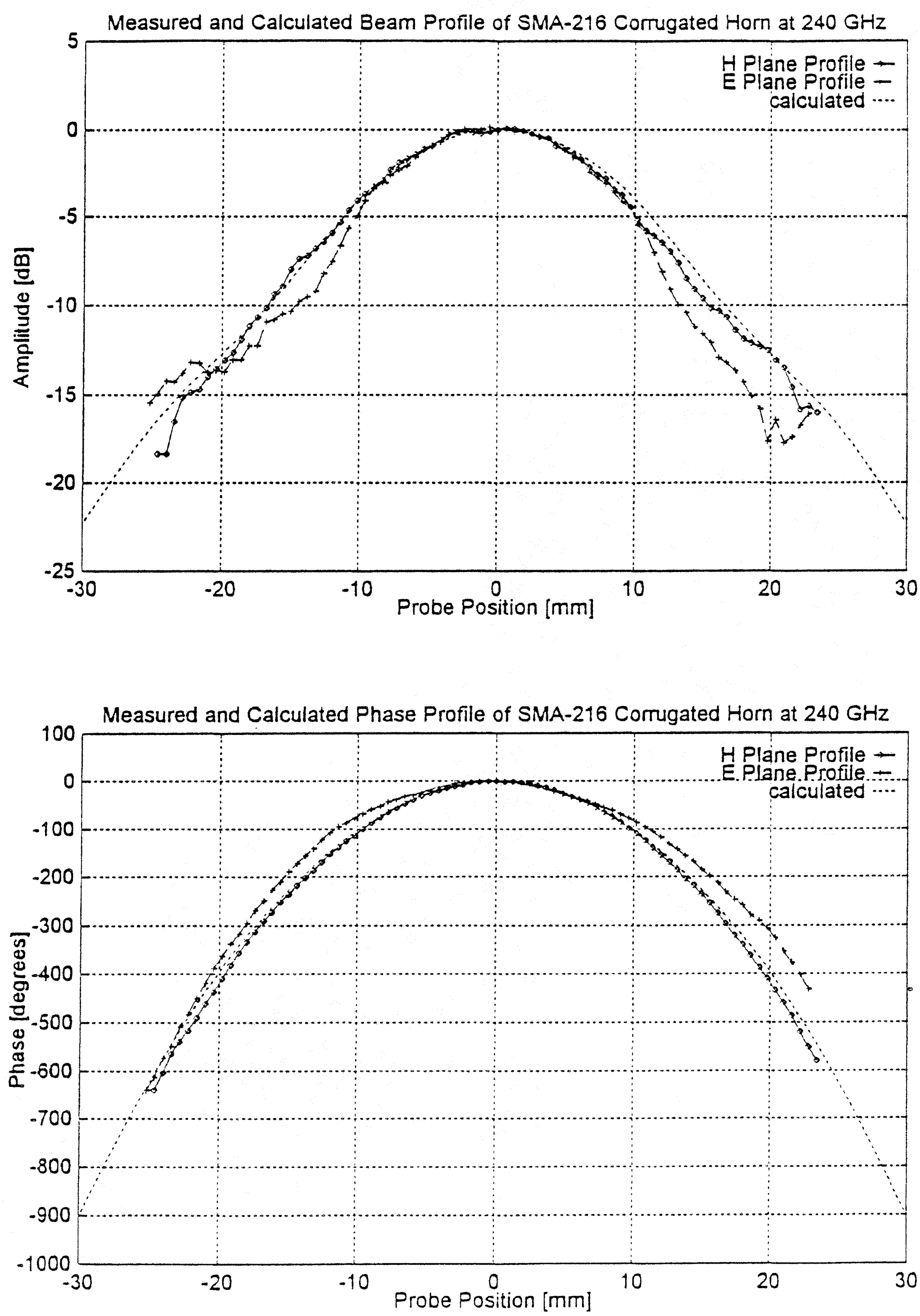

Measured and Calculated Beam Profile of SMA-216 Corrugated Horn at 240 GHz
H Plane Profile
E Plane Profile
calculated
Amplitude [dB]
5
0
-5
-10
-15
-20
-25
-30
-20
-10
0
10
20
30
Probe Position [mm]
Measured and Calculated Phase Profile of SMA-216 Corrugated Horn at 240 GHz
H Plane Profile
E Plane Profile
calculated
Phase [degrees]
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-30
-20
-10
0
10
20
30
Probe Position [mm]

Fig. 4

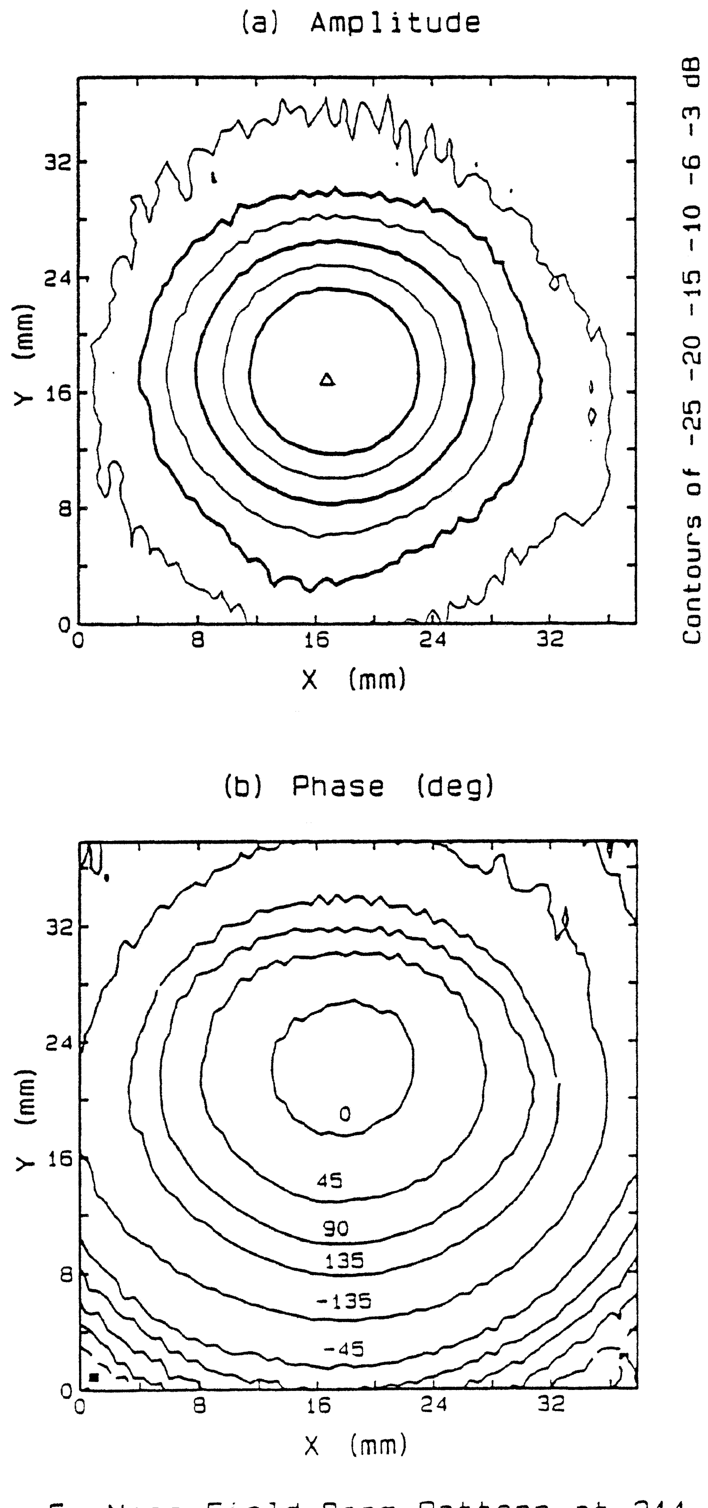
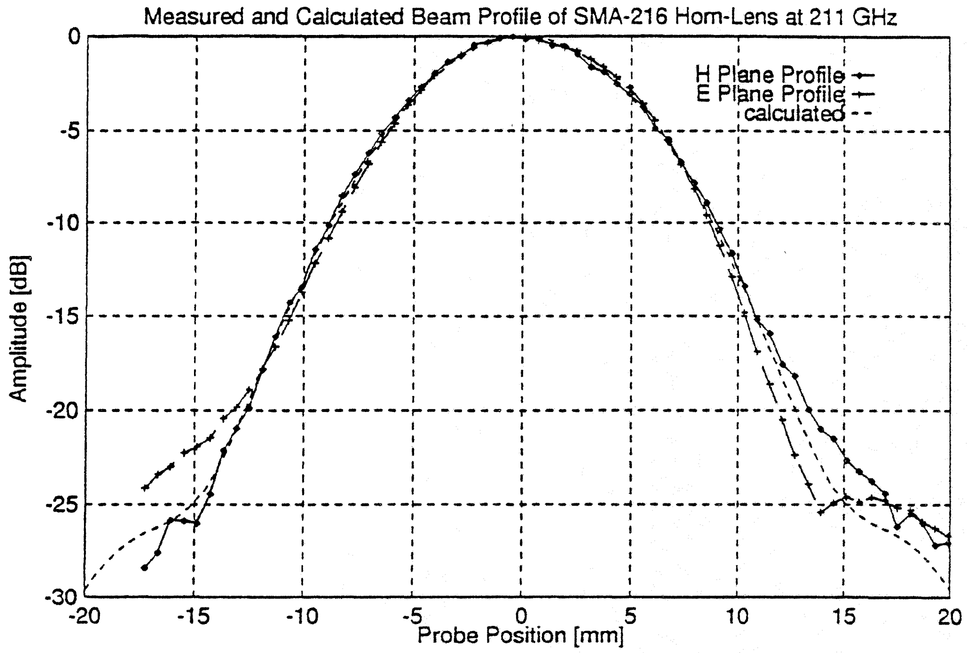
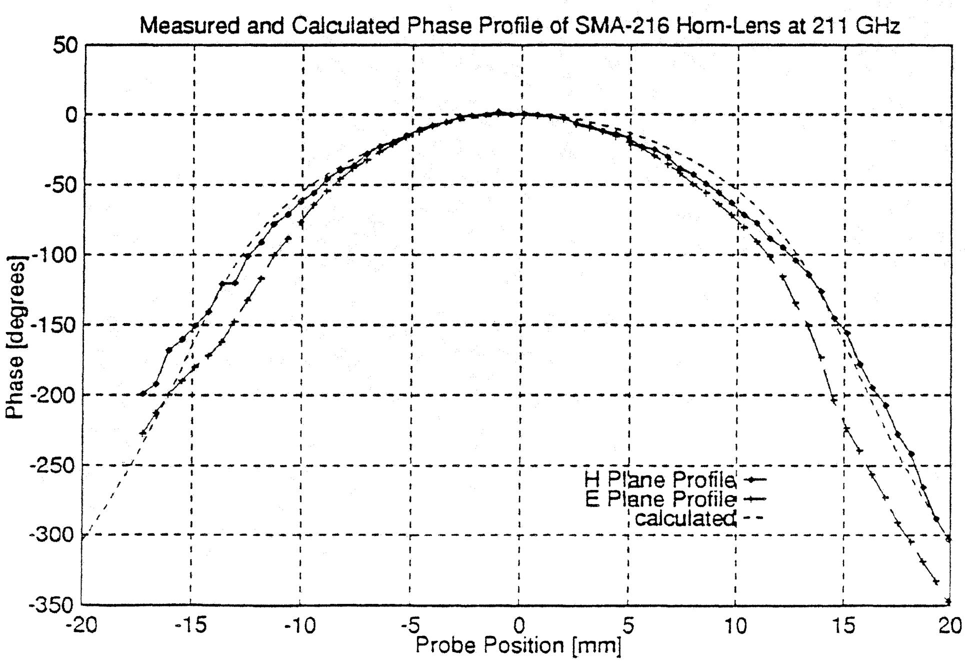


Fig. 5 Near-Field Beam Pattern at 211 GHz
of SMA-216 Horn - Lens Combination



Measured and Calculated Beam Profile of SMA-216 Horn-Lens at 211 GHz
H Plane Profile
E Plane Profile
calculated
Amplitude [dB]
0
-5
-10
-15
-20
-25
-30
-20
-15
-10
-5
0
5
10
15
20
Probe Position [mm]



Measured and Calculated Phase Profile of SMA-216 Horn-Lens at 211 GHz
H Plane Profile
E Plane Profile
calculated
Phase [degrees]
50
0
-50
-100
-150
-200
-250
-300
-350
-20
-15
-10
-5
0
5
10
15
20
Probe Position [mm]

Fig. 6

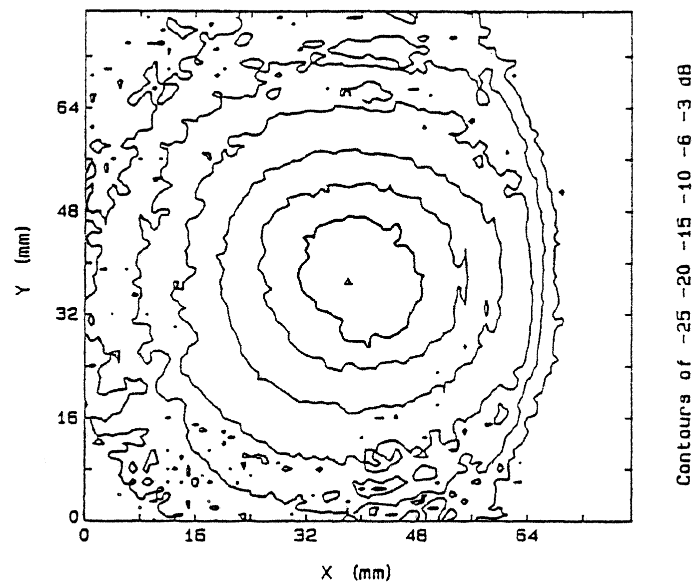


Fig. 7 Near Field Amplitude Data at 465 GHz of SMA-460 Horn-Lens Combination

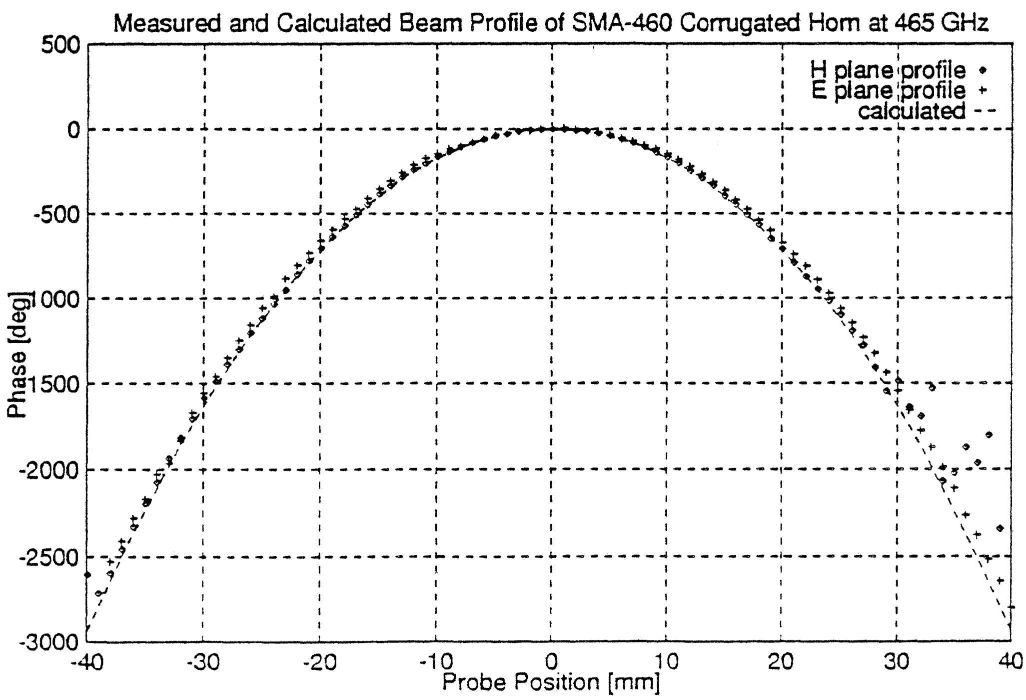


Fig. 8

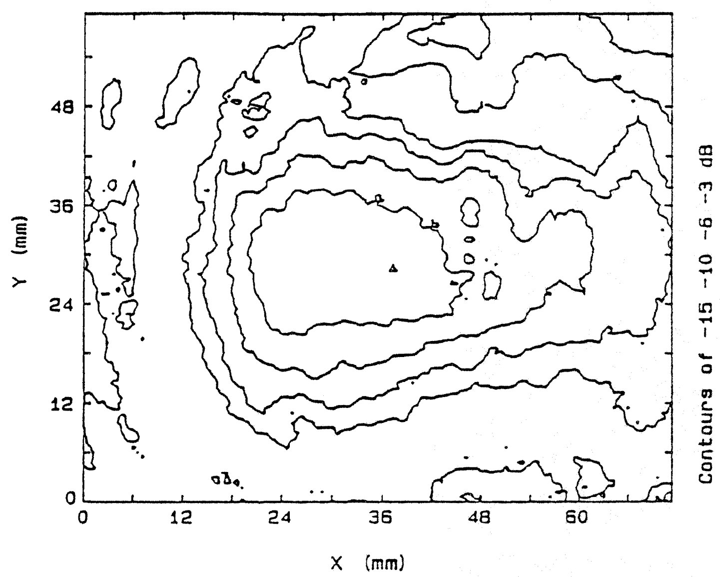


Fig. 9 Near Field Amplitude Data at 254 GHz of Twin Dipole Receiver on Ellipsoidal Lens