On Orbit Measurement of TOPEX/POSEIDON Altimeter Antenna Pattern

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ABSTRACT

The NASA and CNES altimeters on the TOPEX/POSEIDON satellite share a 1.5 m antenna. Early data from the NASA altimeter suggested that the beam was broader than measured preflight. An altimeter transponder was modified to output a relative measurement of received power. The instrument is briefly described. The instrument was deployed on the TOPEX ground track at the coast near Los Angeles, California. Measurements from three of the these deployments are presented to show the on-orbit antenna pattern. The measured pattern is effectively broader than preflight in the central region, particularly the part of the pattern which corresponds to the tail of the altimeter waveform where the attitude is determined. This result is consistent with the general shape of both the TOPEX and POSEIDON waveforms. As the TOPEX corrections which depend on values from the tail of the waveform have been compensated for deviations from the preflight measurements, no appreciable effect on the final data is expected.

1. INTRODUCTION

Satellite altimeters make extremely precise and accurate measurements of the range to the sea surface. In order to achieve an altimeter's ultimate accuracy, many effects must be accounted for. One important effect is error in the range caused by differences between the waveform observed by the altimeter and the simplified model waveform used to design the range tracking algorithms. The difference between the observations and the model is a mainly a function of satellite attitude and significant wave height (SWH). SWH is measured by the altimeter as part of the range tracking process. The apparent satellite attitude can be determined from the "tail" of the waveform (See *Brown* (1978), *Rodriguez* (1988), *Chelton et al.* (1989)). Unfortunately, the TOPEX waveforms have a number of instrumental features which complicate this determination (*Hayne, et al.* (1994)). In addition, during early attempts to determine the satellite attitude from waveform data it appeared that there was more energy than expected in the tail. While this could be part of the other waveform features, it could also arise from the altimeter antenna pattern being broader than was measured on the ground preflight.

From other verification activities planned for TOPEX/POSEIDON (*Christensen and Menard* (1992)), an altimeter transponder was available that could be modified to make measurements of the on orbit antenna pattern. The instrumentation, data acquisition and reduction, and results of those measurements are presented here. We find that the on orbit antenna pattern has a 5 to 15 % enhancement between 0.2 and 0.7 degrees from the center compared to the preflight ground measurements. These differences are comparable to other waveform features described by *Hayne et al.* (1994).

2. EXPERIMENTAL SETUP

2.1 *Instrumentation*

The altimeter transponder was modified by disabling the transmitter section and running the receiver output to power measuring circuitry as shown in Figure 1. A 35 cm dish antenna collects the signal which is immediately amplified at the feed in order to reduce system noise. After passing through the transponder amplifiers, a tunnel diode detector and logarithmic amplifier convert the RF input to a 0 to 2 volt signal at the pulse repetition frequency (PRF). An active bandpass filter and integrator produce a voltage proportional to the received power. This output drives a voltage to frequency converter operating in the audio range. The resulting tone is recorded on an analog tape recorder. It should be noted that the transponder antenna beam width (approximately 5 deg) does not affect the measurements since we are in the far field of the TOPEX antenna. Also, the gain of the transponder antenna is important only to the extent of determining the measurement system SNR.

The measurement system was redesigned after several of the early measurements (not reported here) in order to be less sensitive to the exact altimeter PRF. The system was slightly temperature sensitive, but this was accounted for both by temperature stabilization at 45°C and calibration. The system was calibrated over a range of 25 dB of input at 45°C and room temperature (approximately 25°C) in the laboratory. The calibration was repeated twice during December and three times in January and showed no significant changes. These calibration curves are shown in Figure 2. The curves separate the most at the highest power levels/frequencies. The maximum observed frequency was about 5200 Hz and the minimum used in the analysis was 120 Hz. While the curves differ by up to 0.6 dB, even with temperature calibration considered, the difference between the extreme calibration curves gives a difference of about 3% in the retrieved relative power used here for frequencies between about 3 and 5.2 kHz. Calibration induced differences are less at lower frequencies (lower relative power). Typical observation fluctuations of 50 Hz at 5 kHz and 10 to 20 Hz at low frequencies correspond to less than 2% variations in the final pattern.

Calculations indicated that the system would have an 18 dB signal to noise ratio. The observations showed a sidelobe at -16 dB basically confirming the calculations. The observations show a noise floor of about 1 to 2% (see Figures 5-7). Overall we believe that the measurement system was able to measure the relative power received from TOPEX over a range of about 16 dB to 3 to 4% at worst and 1 to 2% if appropriate calibration curves are available.

2.2 *Data Collection*

TOPEX/POSEIDON is in a 10 day exact repeat orbit which is maintained within +/- 1 km. Pass 119 strikes the southern California coast near San Pedro (Los Angeles). We located a suitable site about 1 km east of the ground track on a bluff approximately 30 m above the ocean (latitude= 33° 42', east longitude= 241° 22'). The altimeter was in lock over the water as it approached the coast, but lost lock over land. We do not believe that the change in signal modulation affected our measurements.

Observations were made on every repeat cycle from November 6, 1992 to February 3, 1993 (except Christmas). Various problems with the early measurements (PRF sensitivity and inadequate calibration) and some later measurements (a failing temperature controller introduced audio frequency noise and also sent the system outside of the calibrated range) resulted in the three apparently complete and reliable cuts through the antenna pattern reported here.

2.3 *Data Reduction*

The audio tone representing the received power was extracted from the tape using an analog to digital converter with MathLab software running on a Macintosh computer. A plot of the frequency versus time output for January 24, 1993 is shown in Figure 3. As can be seen in Figure 3, the output has rapid variations at high received frequencies. This occurs because the Mathlab digitizing interval depends on input frequency. The resulting frequency versus time data were converted to power using the calibration curves described above and to angle using satellite orbit geometry. All observations have been normalized to unity at the maximum and interpolated to equal angular intervals (0.05 deg). The discussion below is carried out in per cent of the maximum ("power", not dB).

The preflight ground antenna measurements made by the Johns Hopkins Applied Physics Laboratory were supplied as strip chart output by C. Purdy of Wallops Flight Facility, Goddard Space Flight Center. Four cuts were made through the antenna pattern. These measurements were hand digitized at an angular interval of 0.05 deg and are shown in Figure 4. The strip charts appear to have noise of about 0.2 dB (5%).

The orientation of the antenna relative to the satellite is known, and the satellite attitude (yaw) during the on orbit measurements has been reconstructed (*Kubitschek*, Private communication). The preflight measurements were linearly interpolated to the cuts observed in the on orbit measurements.

3. RESULTS

The measurements from December 5, 1992; January 14, 1993; and January 24, 1993 are shown in Figures 5-7. Each figure shows the on orbit measurement, the interpolation of the preflight measurements, and the difference between them. The full patterns as well as blow ups of the peak and residual are shown. Figures 5-7 show that the on orbit patterns are broader or "squarer" around the peak than the preflight pattern. This results in differences of 5 to 15% in the regions from 0.2 to 0.7 deg. The difference is approximately 10% near 0.45 deg where the attitude determination gates fall. The position of the on orbit nulls is similar (approximately ± 1.2 deg) to the preflight values. Except for December 5, the on orbit patterns are fairly smooth and symmetrical and generally similar to the preflight patterns.

Figure 4 shows that the E-cut is noticeably wider than the others in addition to having a high sidelobe near -1.8 deg. Of the preflight measurements, the E-cut is the closest in angle to the observed cuts for January 14 and January 24. Direct comparisons of the on orbit measurements (not shown) with the E-cut, rather than the interpolated values, give slightly smaller residuals than shown in Figures 6 and 7.

Fluctuations in the residuals support the contention that the measurements have noise of 3 to 4% at worst and typically only about 2% . Nonetheless, the patterns of the residuals show a clear difference between the on orbit antenna pattern and that measured preflight.

In order to quantify further the difference in width between the ground and on orbit measurements two simple functions often used to describe antenna patterns were fit: the Gaussian and the Jinc = $(J_1(x)/x)^2$, where J_1 is the Bessel function of the first kind and x is the off axis distance. While a Gaussian can describe the central part of an antenna pattern (only approximately the central 0.6 deg is used in the processed signal (*Chelton, et al. (1989)*)), it cannot reproduce the nulls and sidelobes of a real pattern as a Jinc (the theoretical function for a circular aperture) can. However, a Gaussian is used in altimeter waveform models in order to simplify the calculations. A Gaussian and a Jinc were fit to the average ground pattern and to the data from the on orbit measurements. For the ground data the fit parameters were a noise floor, a center offset, and a width scale. For the on orbit data, the patterns were found to be asymmetric enough that it was necessary to fit

separate widths and noise floors to each side. The best fit values as estimated jointly from bias and RMS are listed in Table 1.

For a Gaussian, the width scale can be recovered from the derivative. For a model pattern of

$$G(\Theta) = \exp(-\Theta^2/\Theta_o^2),$$

one can obtain Θ_o by

$$\Theta_o = \mathrm{SQRT}(G * \Theta / (-dG/d\Theta)).$$

This function can be carried out numerically on the antenna measurements to obtain Θ_o as a function of Θ. Plots of Θ_o for the average on orbit and ground and the E-cut patterns are shown in Figure 8. The technique was carried out on the averages in order to reduce noise in the derivative. This method provides numerically reliable values between about 0.1 and 1.0 deg. The scale is fairly constant for the average of the ground measurements at 0.42. The E-cut and on orbit data are somewhat noisier and give wider values: about 0.46 for the E-cut and 0.47 for the on orbit data. As seen in the other analysis, the on orbit data are better represented by a broader function than the ground measurements in the central region.

4. DISCUSSION and CONCLUSIONS

The excess antenna gain in the 0.7 to 0.2 deg area will result in excess waveform power in gates 54 to 128 (128 is the maximum, i.e., the altimeter only uses the center of the antenna beam) which will appear in telemetry waveform samples 43 to 64 (*Hayne et al.* (1994)). Angles between ± 0.17 deg are used in the altimeter AGC determination which sets the overall scale for the waveform. Angles around 0.45 deg affect the waveform signal used for attitude determination and for pointing angle/sea state corrections to other measured quantities. The residuals here show typical differences of about 5-7% between the relative power in the 0-0.2 deg region and the 0.45 deg region. This is similar to other features reported by *Hayne et al.* (1994). CNES altimeter (POSEIDON) data are also consistent with the results reported here (O-Z. Zanife, Private communication).

For processing of TOPEX waveform data the important parameter is the Gaussian antenna width used. Data from Table 1 give a value for Θ_o in a Gaussian of 0.47 (full width at half maximum of 1.11 deg) from the on orbit measurements. A similar value is deduced from the numerical derivative in Figure 8. The value originally used by Hayne and Rodriguez (Private communication) in computing waveform effects was 0.44 (FWHM = 1.04 deg). Later, the value used by them was increased to 0.46 based on early results from these measurements. This difference could change polynomial corrections for pointing angle/sea state effects

depending on how the waveform correction factors are computed. Waveform corrections now largely absorb the excess power from the antenna factor into that for other features. Thus, the attitude angle and pointing angle/sea state corrections for TOPEX data produced on the Geophysical Data Records do not suffer from the apparent broadening of the antenna pattern. In future altimeters, on orbit measurement of the antenna pattern should be carried out to provide confidence in quantities based on the altimeter waveform.

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References

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Table 1: Parameters of Fits to Observations

Pattern	Gaussian Scale	Jinc Scale 1	Jinc Scale 2	On Orbit Yaw*
Average Preflight	0.43	0.322	N/A	
Preflight E-Cut	0.46	0.339	N/A	
On Orbit 92/12/05	0.47	0.340	0.320	70.9
On Orbit 93/01/14	0.50	0.330	0.327	326.8
On Orbit 93/01/24	0.45	0.340	0.323	303.4

* Angle between velocity vector and satellite +X (roll) axis measured clockwise

Figure Captions

Figure 1: Measurement system block diagram.

Figure 2: Calibration curves from December 1992 and January 1993 showing variations with time and temperature. RT indicates room temperature calibration. The other calibrations were done with heaters maintaining the electronics at 45°C.

Figure 3: Frequency versus time as retrieved from measurement tape for observation of January 24, 1993.

Figure 4: Four cuts of the antenna pattern as measured on the ground.

Figure 5: Measurements for December 5, 1992: On orbit antenna pattern measurements compared to the interpolated ground measurement: (a) Overall pattern; (b) Center to half power point; (c) Lowest 10%.

Figure 6: Measurements for January 14, 1993: On orbit antenna pattern measurements compared to the interpolated ground measurement: (a) Overall pattern; (b) Center to half power point; (c) Lowest 10%.

Figure 7: Measurements for January 24, 1993: On orbit antenna pattern measurements compared to the interpolated ground measurement: (a) Overall pattern; (b) Center to half power point; (c) Lowest 10%.

Figure 8: The scale of a Gaussian, Θ_o, from the numerical derivative of the pattern for the average on orbit and ground and the E-cut patterns.

Receiver to Record Topex Antenna Pattern

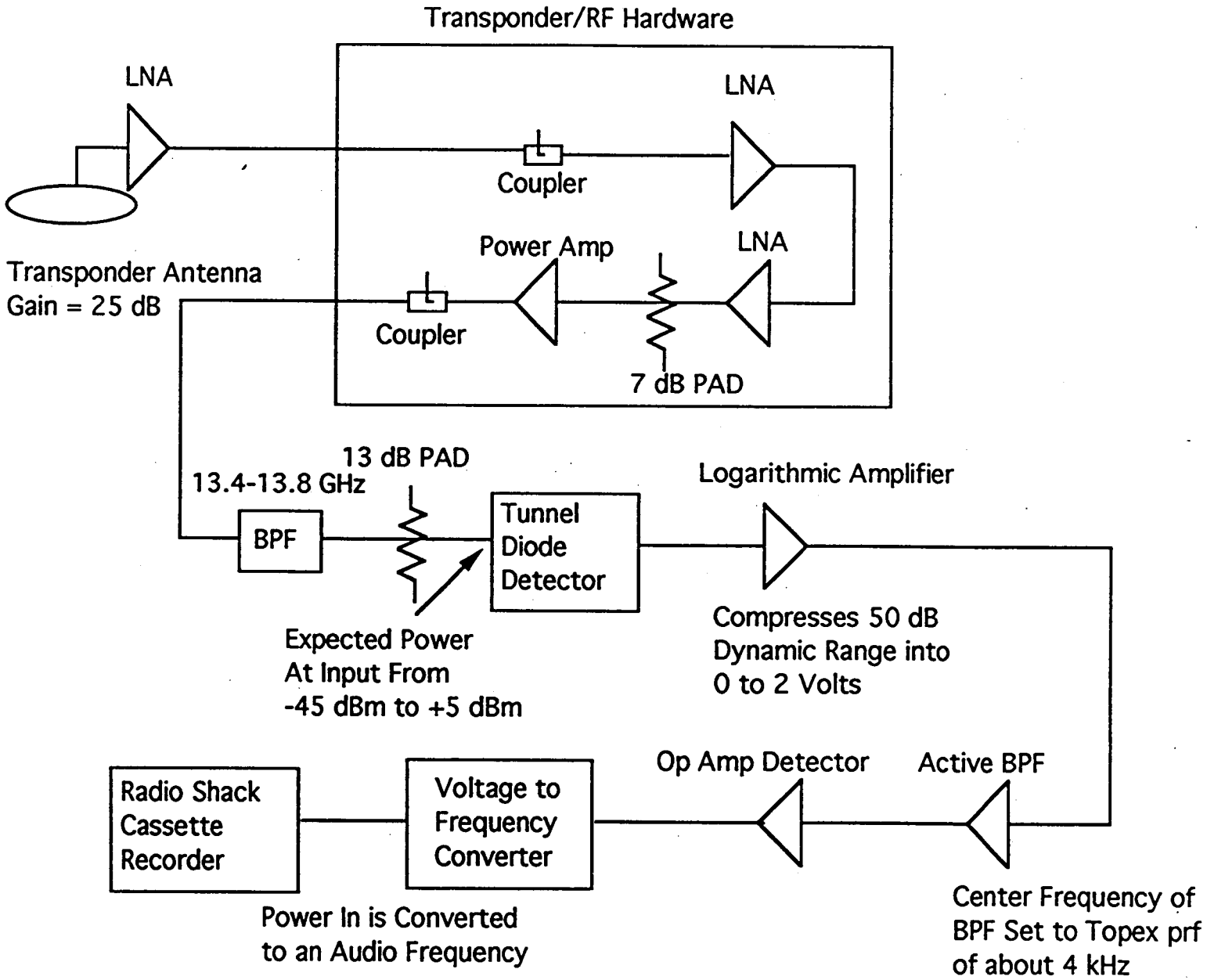
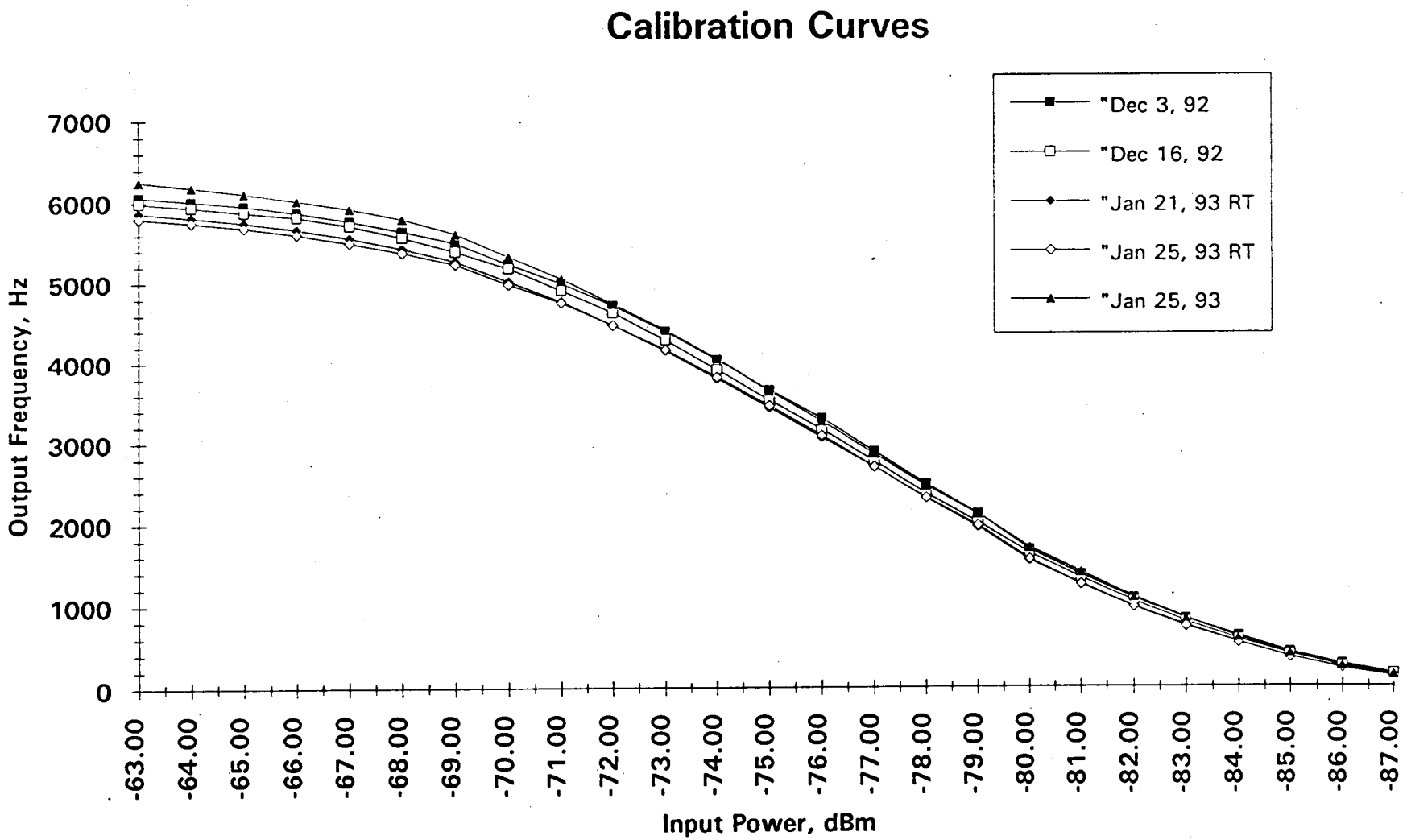


Figure 1


Calibration Curves
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"Dec 16, 92
"Jan 21, 93 RT
"Jan 25, 93 RT
"Jan 25, 93
Output Frequency, Hz
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6000
5000
4000
3000
2000
1000
0
-63.00
-64.00
-65.00
-66.00
-67.00
-68.00
-69.00
-70.00
-71.00
-72.00
-73.00
-74.00
-75.00
-76.00
-77.00
-78.00
-79.00
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-86.00
-87.00
Input Power, dBm

Figure 2

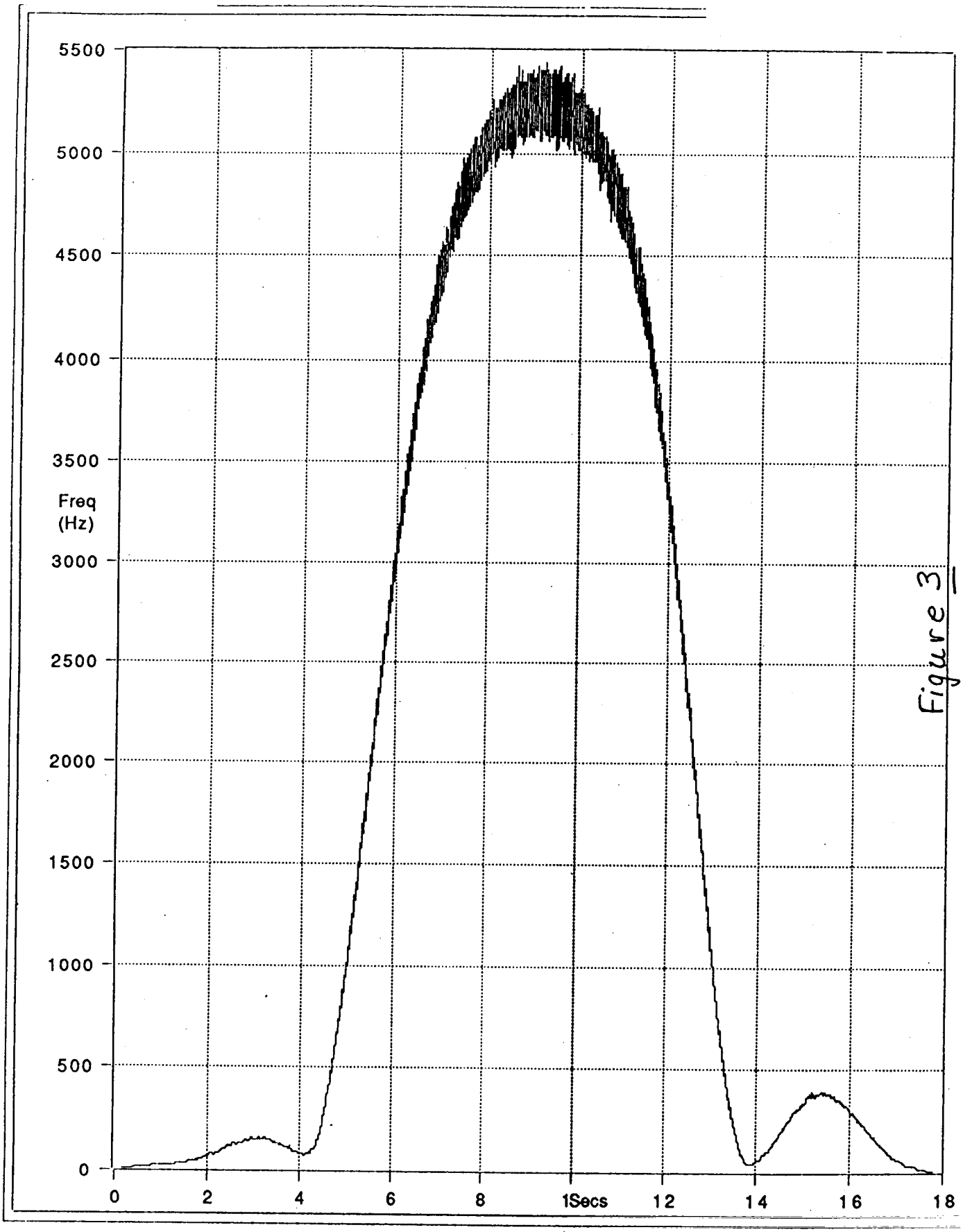
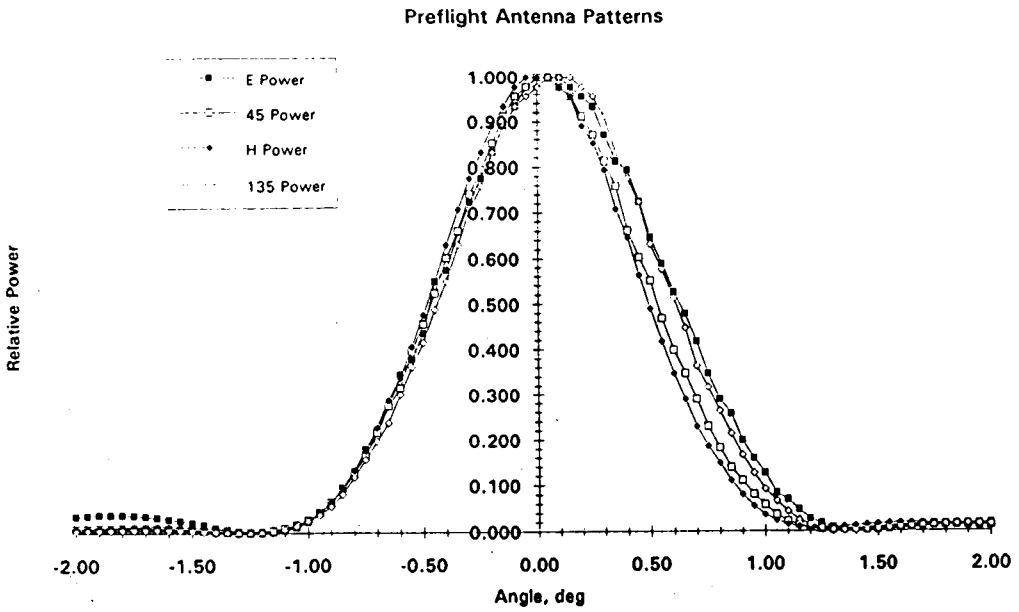

5500
5000
4500
4000
3500
Freq
(Hz)
3000
2500
2000
1500
1000
500
0
0
2
4
6
8
1Secs
12
14
16
18

Figure 3


Preflight Antenna Patterns
E Power
45 Power
H Power
135 Power
Relative Power
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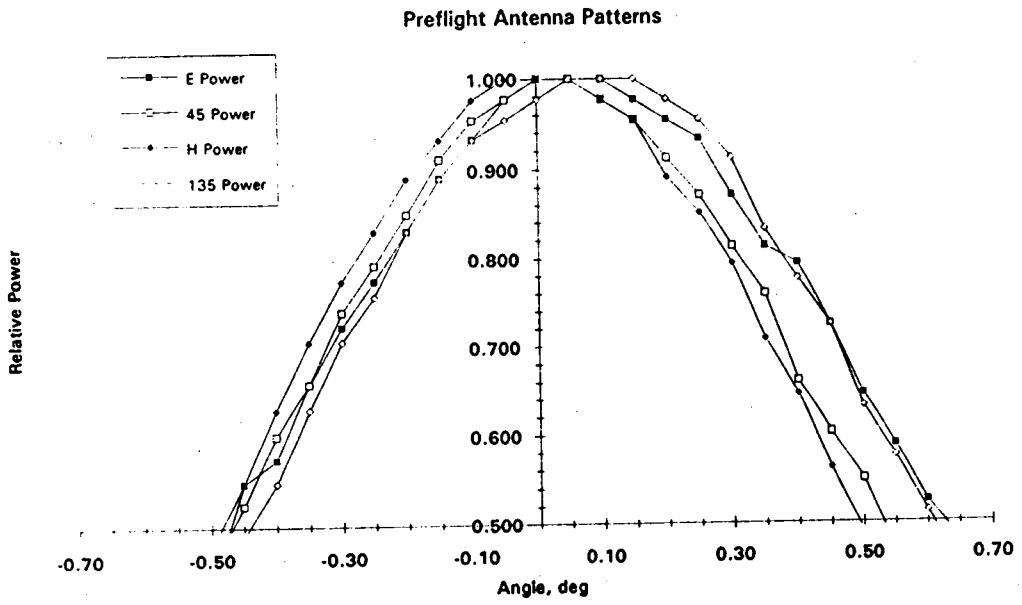
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
Angle, deg


Preflight Antenna Patterns
E Power
45 Power
H Power
135 Power
Relative Power
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0.800
0.700
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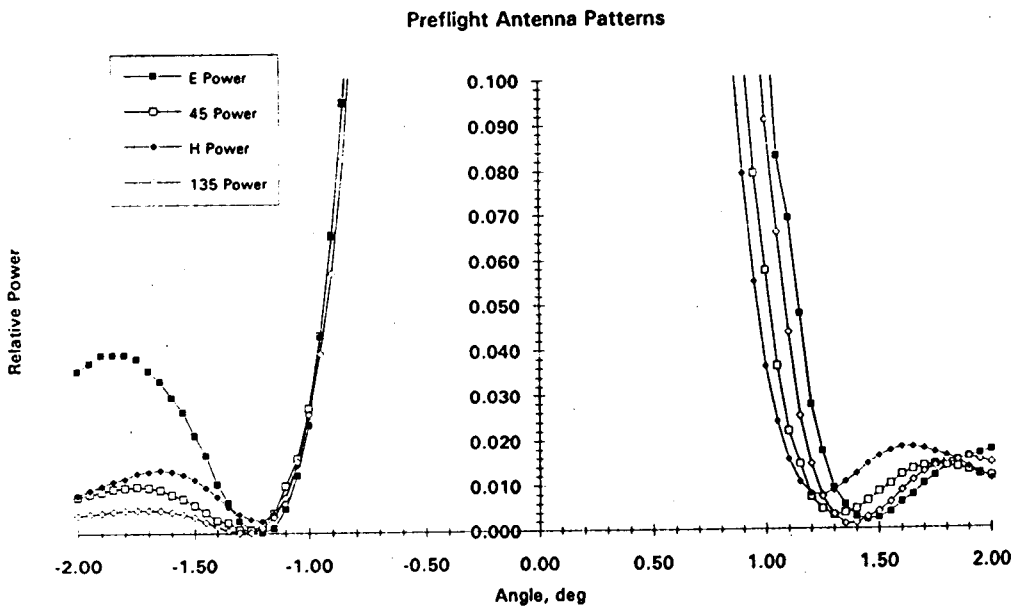
-0.50
-0.30
-0.10
0.10
0.30
0.50
0.70
Angle, deg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E Power
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H Power
135 Power
Relative Power
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0.080
0.070
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0.050
0.040
0.030
0.020
0.010
0.000
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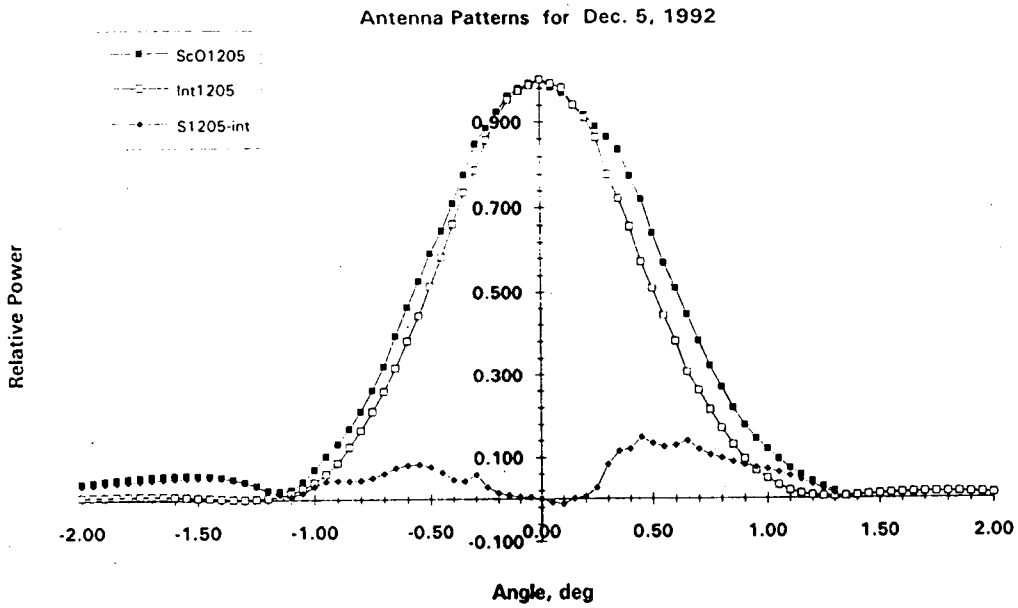
0.00
0.50
1.00
1.50
2.00
Angle, deg

Figure 4


Antenna Patterns for Dec. 5, 1992
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Int1205
S1205-int
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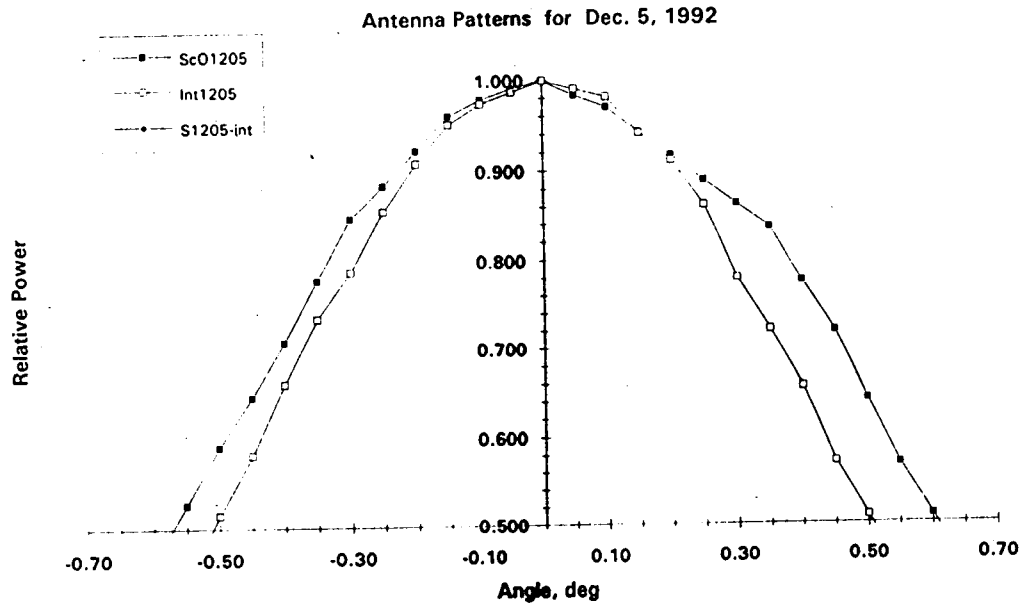
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
Angle, deg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Int1205
S1205-int
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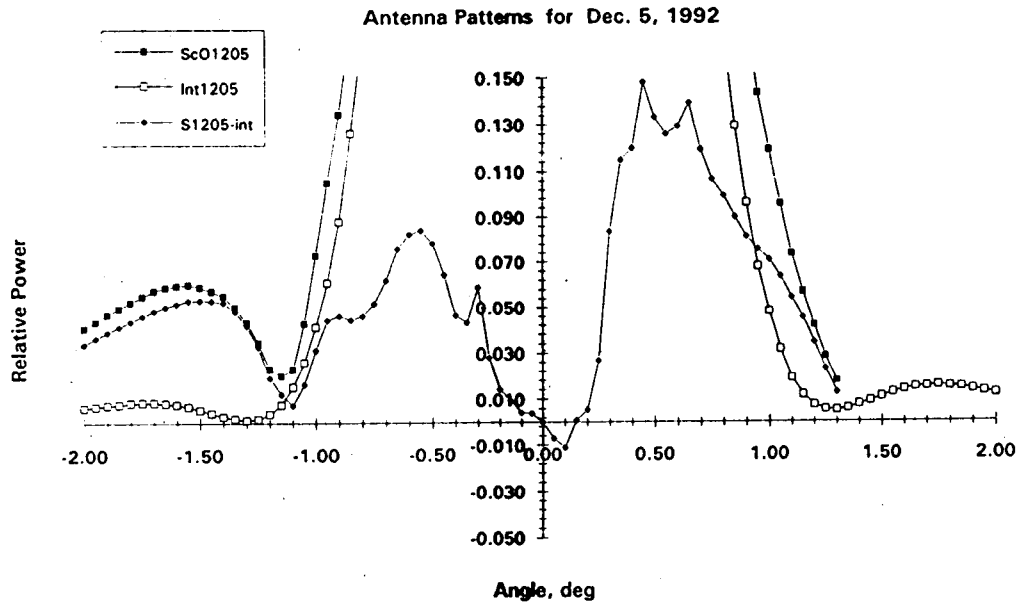
-0.10
0.10
0.30
0.50
0.70
Angle, deg


Antenna Patterns for Dec. 5, 1992
ScO1205
Int1205
S1205-int
Relative Power
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0.110
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0.050
0.030
0.010
-0.010
-0.030
-0.050
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-1.00
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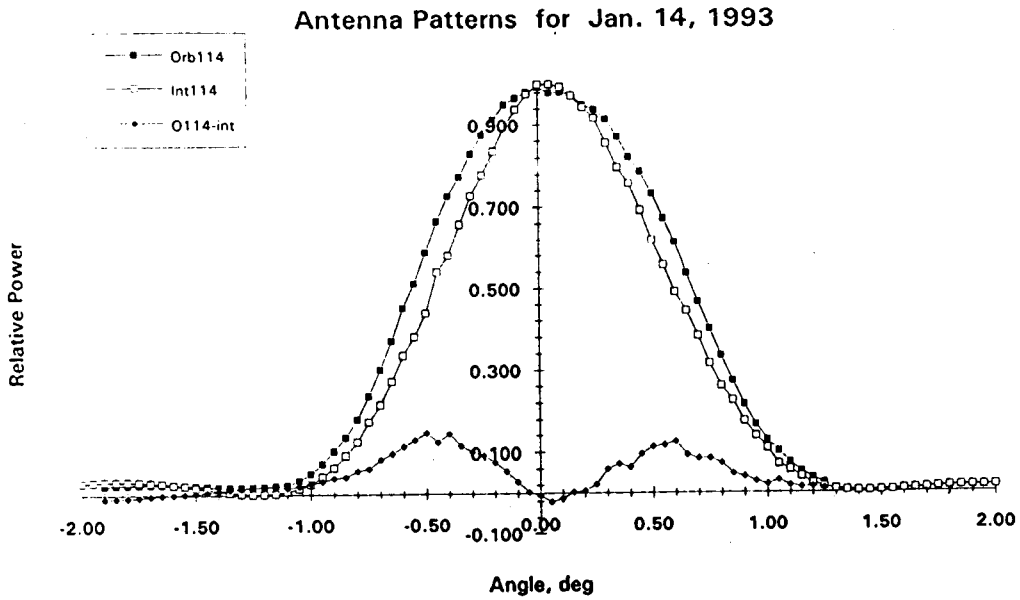
0.00
0.50
1.00
1.50
2.00
Angle, deg

Figure 5


Antenna Patterns for Jan. 14, 1993
Orb114
Int114
O114-int
Relative Power
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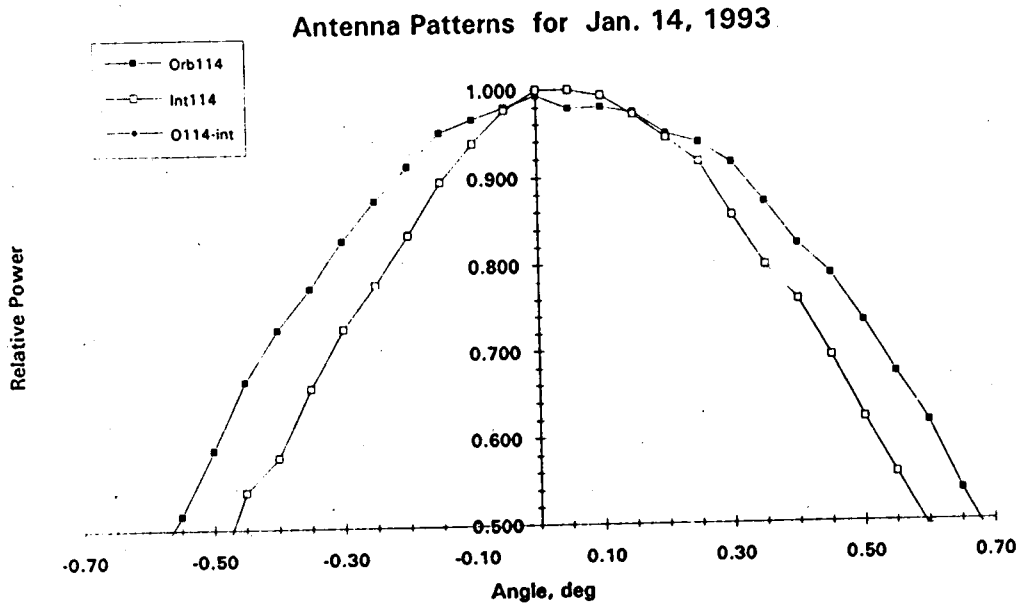
0.700
0.500
0.300
0.100
-0.100
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
Angle, deg


Antenna Patterns for Jan. 14, 1993
Orb114
Int114
O114-int
Relative Power
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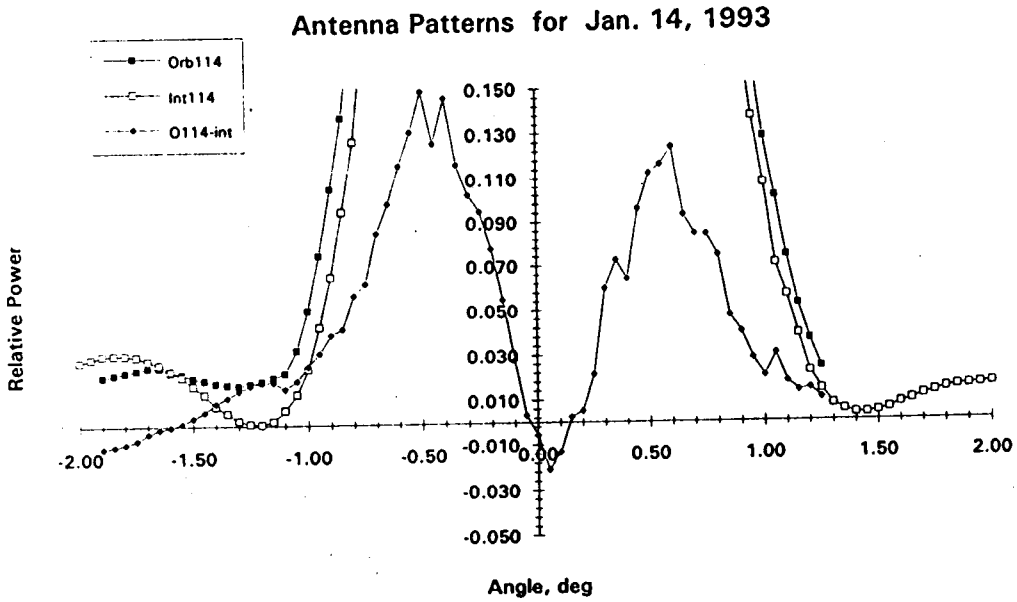
-0.30
-0.10
0.10
0.30
0.50
0.70
Angle, deg


Antenna Patterns for Jan. 14, 1993
Orb114
Int114
O114-int
Relative Power
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0.030
0.010
-0.010
-0.030
-0.050
-2.00
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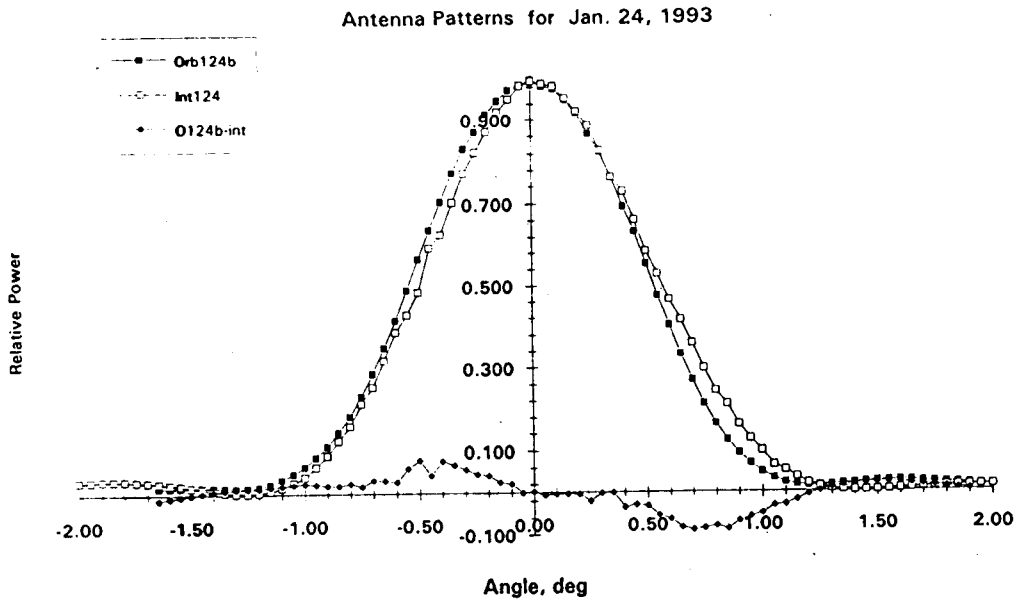
-0.50
0.00
0.50
1.00
1.50
2.00
Angle, deg

Figure 6


Antenna Patterns for Jan. 24, 1993
Orb124b
Int124
O124b-int
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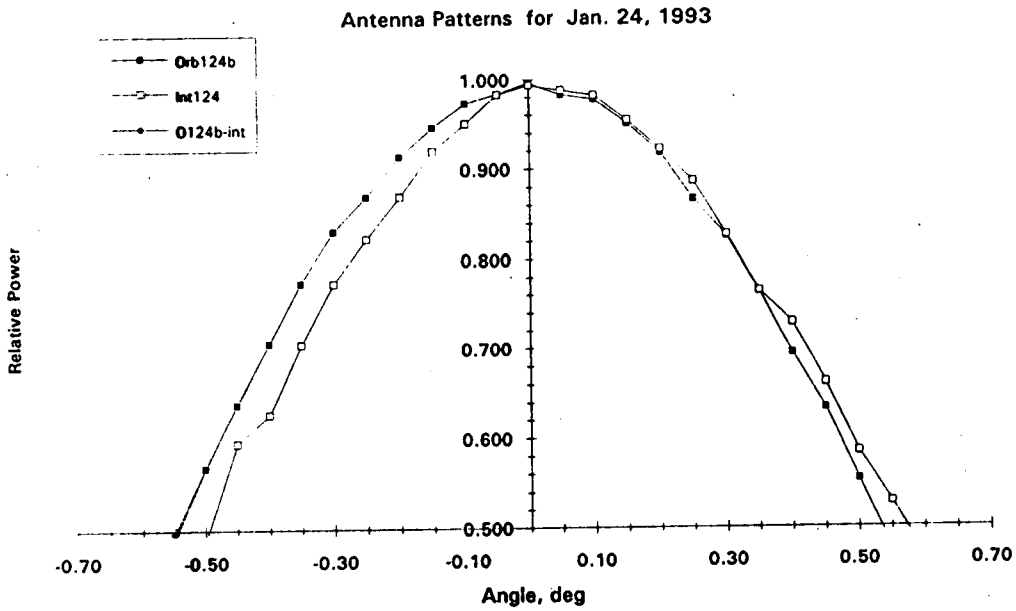
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
Angle, deg


Antenna Patterns for Jan. 24, 1993
Orb124b
Int124
O124b-int
Relative Power
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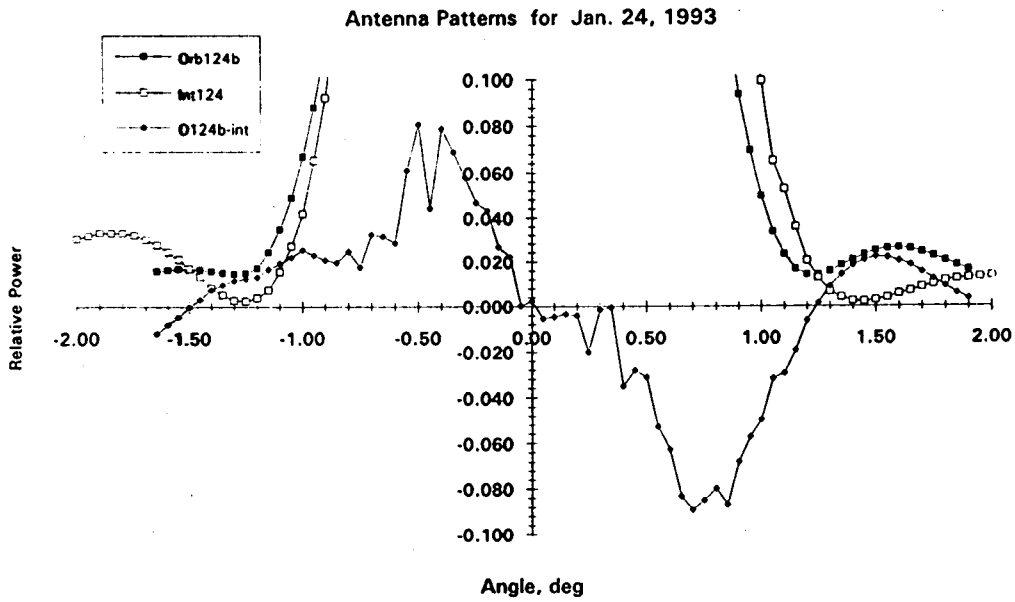
0.30
0.50
0.70
Angle, deg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-0.020
-0.040
-0.060
-0.080
-0.100
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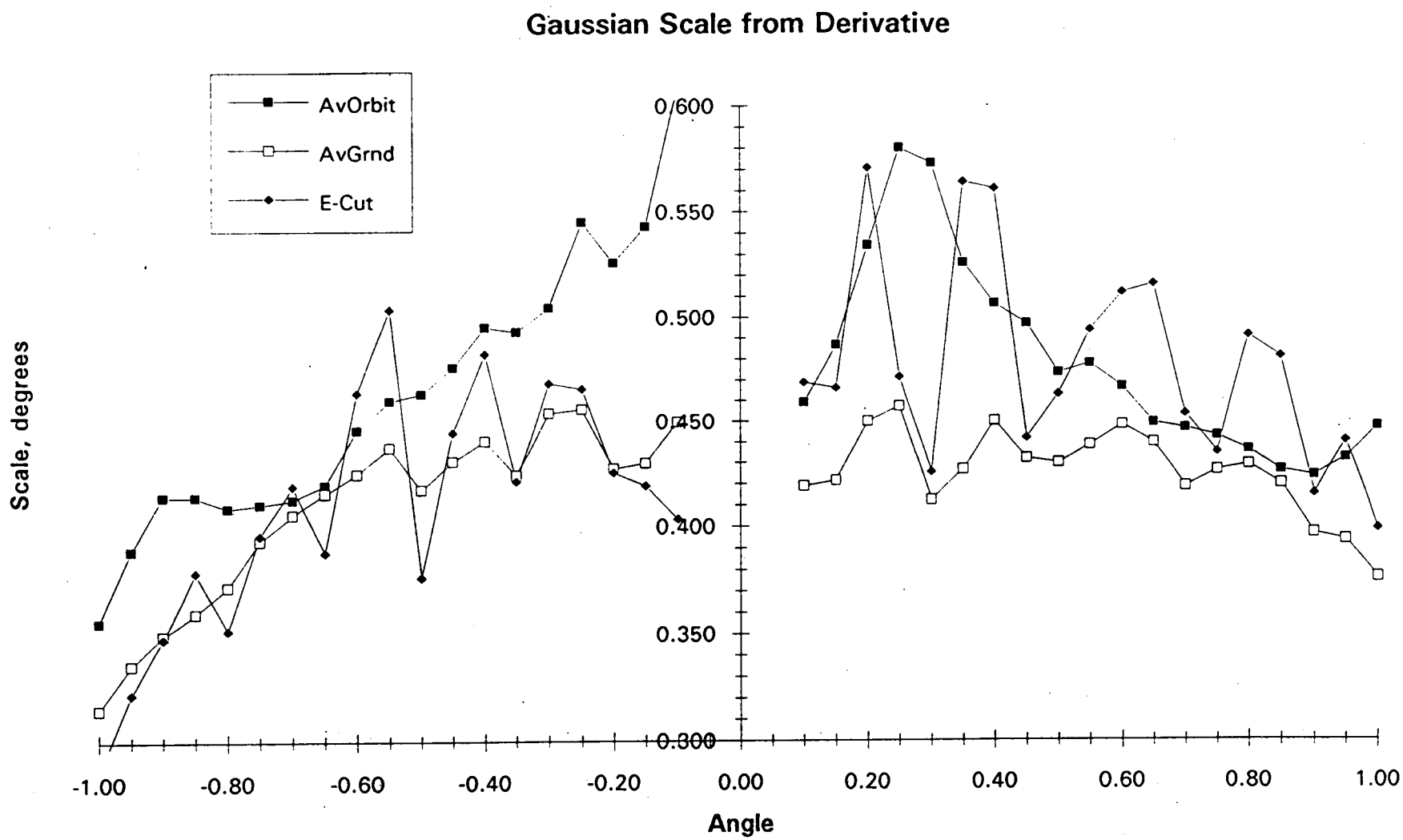
0.00
0.50
1.00
1.50
2.00
Angle, deg

Figure 7


Gaussian Scale from Derivative
AvOrbit
AvGrnd
E-Cut
Scale, degrees
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0.550
0.500
0.450
0.400
0.350
0.300
-1.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
Angle

Figure 8