MEMO #46

To: Bill Bruckman, Colin Masson, Ray Blundell

From: Heinrich Foltz

Date: April 7, 1991

Subject: ZERO-ORDER GAUSSIAN BEAM CALCULATIONS FOR ALL-FLAT OPTICAL SYSTEM

This memo and the accompanying figures summarize calculations, based on zero-order Gaussian beams, for the bent Nasmyth configuration with all flat mirrors between the subreflector and the receiver diplexers.

Summary The positions of the mirrors and the total path length from the subreflector to the receivers is fixed by mechanical considerations. The free parameters are the subreflector diameter and focal length. In an all flat system directly feeding diplexer-front-end receivers, the subreflector focal length is also roughly fixed by the need to place the secondary waist at the diplexer, so that the main choice in the system is the subreflector diameter. The trade-off in the diameter selection is between truncation loss at the receiver/diplexer aperture at low frequencies, if the subreflector is made too small, versus overlap loss in the diplexer at high frequencies and increased blocking, if the subreflector is made too large.

With a 4-GHz IF and a 5-cm aperture a suitable diameter can be chosen. For lower IF frequencies (e.g. 1.5 GHz), bringing the 230 GHz loss within the reasonable range requires sacrificing perfomance at the higher frequencies unless curved mirrors are used.

For all the path lengths considered, the "best" systems have an f-ratio of about 16.1 to 16.4 if all frequencies (230-810) are treated equally, 18.5 to 19.5 if the loss at 230 GHz is allowed to be twice that at 810 GHz. Allowing a higher loss at 230 lets the subreflector be smaller and reduces the loss at the other frequencies. Because of the narrow range of f-ratios, the subreflector diameter can be treated as proportional to the path length; it would be best to keep this length short if you want to wobble the secondary.

Since the all flat system is not frequency independent, the focused position for each receiver will be different, and the change with frequency will be enough to require focusing as the frequency is tuned within each band, at least for the low frequency receivers.

Range of Parameters Since the distance from the subreflector vertex to the receivers is still not exactly fixed, I carried out the calculations over a range of parameters:

Path length, subreflector to receivers:	5.75 to 7.25 meters, 0.25 steps
Subreflector diameter:	0.25 to 0.60 meters, 0.01 steps
Frequencies:	230, 350, 490, 690, 810

The IF was fixed at 4 GHz, the diplexer aperture at 5 cm, although a few calculations were done with other values and the path length fixed at 6.50 meters as described below.

Total Loss versus Subreflector Diameter Figures 1A through 1G give the combined overlap loss (due to path length difference in the diplexers), truncation loss (due to finite diplexer/receiver aperture), and blockage loss versus subreflector size. Each of the plots is for a different length from the receiver to the subreflector. The diplexers were assumed to have a 5 cm aperture and be tuned for the first order operation at 4 GHz.

For smaller subreflectors, there is a sharp increase in the loss at 230 GHz due to truncation effects, even if 230 GHz is used only for calibration and testing this will set the lower limit to subreflector size. For larger subreflectors, the combined effects of blocking and overlap increase gradually, with the loss at 810 GHz increasing fastest. This sets the upper limit to subreflector size.

Optimum Subreflector Diameter Based on plots 1A through 1G, one can find the "best" subreflector size versus path length using various criteria. I have used two different criteria. The first one is minimization of the maximum loss at any frequency 230 through 810. The second one is minimization of the maximum loss, but counting loss at 230 half as much as at the other frequencies. The results are in Figure 1H. Treating all frequencies equally results in optimum sizes varying from 36 to 44 cm; allowing double the loss at 230 results in optimum sizes from 31 to 37 cm.

Effect of IF frequency Lowering the IF frequency drives the optimum subreflector size downward, with higher overall losses since the increase in overlap loss overcomes the decrease in blocking. However, raising the IF frequency has relatively little effect since at high IF frequencies the overlap loss becomes negligible compared to the aperture blocking loss. This is illustrated by the series of figures 2A, 1D, 2B, showing the IF frequency changing from 1.5 to 4.0 to 10.0 GHz.

Operating the diplexer at its third-order null (3/2 IF wavelength separation instead of 1/2 IF wavelength), in addition to reducing the instantaneous bandwidth, would be equivalent to operating at one third the IF frequency as far as overlap losses are concerned.

Effect of Diplexer Aperture Decreasing the aperture size rapidly increases the truncation loss at 230 and eventually at 350 GHz, thus increasing the optimum subreflector size, and giving higher overall losses at the optimum. Increasing the aperture size would reduce the truncation loss at lower frequencies and would additionally reduce the overlap and blocking loss at high frequencies by allowing a smaller optimum subreflector and higher f-number. These effects are illustrated by the series of figures 3A, 1D, 3B, showing the aperture changing from 4 cm to 5 cm to 7.5 cm.

Waist Shift Figure 6 shows the shift in the waist position with respect to the geometric focus, as a function of frequency. The shift is up to 10 cm at the low end of the frequency range, and thus would definitely need to be taken into account. Over the 210-270 band a shift of a few centimeters occurs, so that some focusing may be necessary as the receiver is tuned.

Other Calculations Figures 4A through 4C and 5A through 5E show the truncation and overlap losses respectively, separated from the other losses.

Summary of Figures

Figure	Path length	IF Freq	Aperture	RF Freq	Quantity
1A	5.75 m	4.0 GHz	5.0 cm	varies	combined loss
1B	6.00 m	4.0 GHz	5.0 cm	varies	combined loss
1C	6.25 m	4.0 GHz	5.0 cm	varies	combined loss
1D	6.50 m	4.0 GHz	5.0 cm	varies	combined loss
1E	6.75 m	4.0 GHz	5.0 cm	varies	combined loss
1F	7.00 m	4.0 GHz	5.0 cm	varies	combined loss
1G	7.25 m	4.0 GHz	5.0 cm	varies	combined loss
1H	varies	4.0 GHz	5.0 cm	-	optimum size
2A	6.50 m	1.5 GHz	5.0 cm	varies	combined loss
2B	6.50 m	10.0 GHz	5.0 cm	varies	combined loss
3A	6.50 m	4.0 GHz	4.0 cm	varies	combined loss

3B	6.50 m	4.0 GHz	7.5 cm	varies	combined loss
4A	varies	4.0 GHz	5.0 cm	230 GHz	truncation
4B	varies	4.0 GHz	5.0 cm	350 GHz	truncation
4C	varies	4.0 GHz	5.0 cm	490 GHz	truncation
5A	varies	4.0 GHz	5.0 cm	230 GHz	overlap
5B	varies	4.0 GHz	5.0 cm	350 GHz	overlap
5C	varies	4.0 GHz	5.0 cm	490 GHz	overlap
5D	varies	4.0 GHz	5.0 cm	690 GHz	overlap
5E	varies	4.0 GHz	5.0 cm	810 GHz	overlap
6	6.50 m	-	-	varies	waist shift

Figure 1A

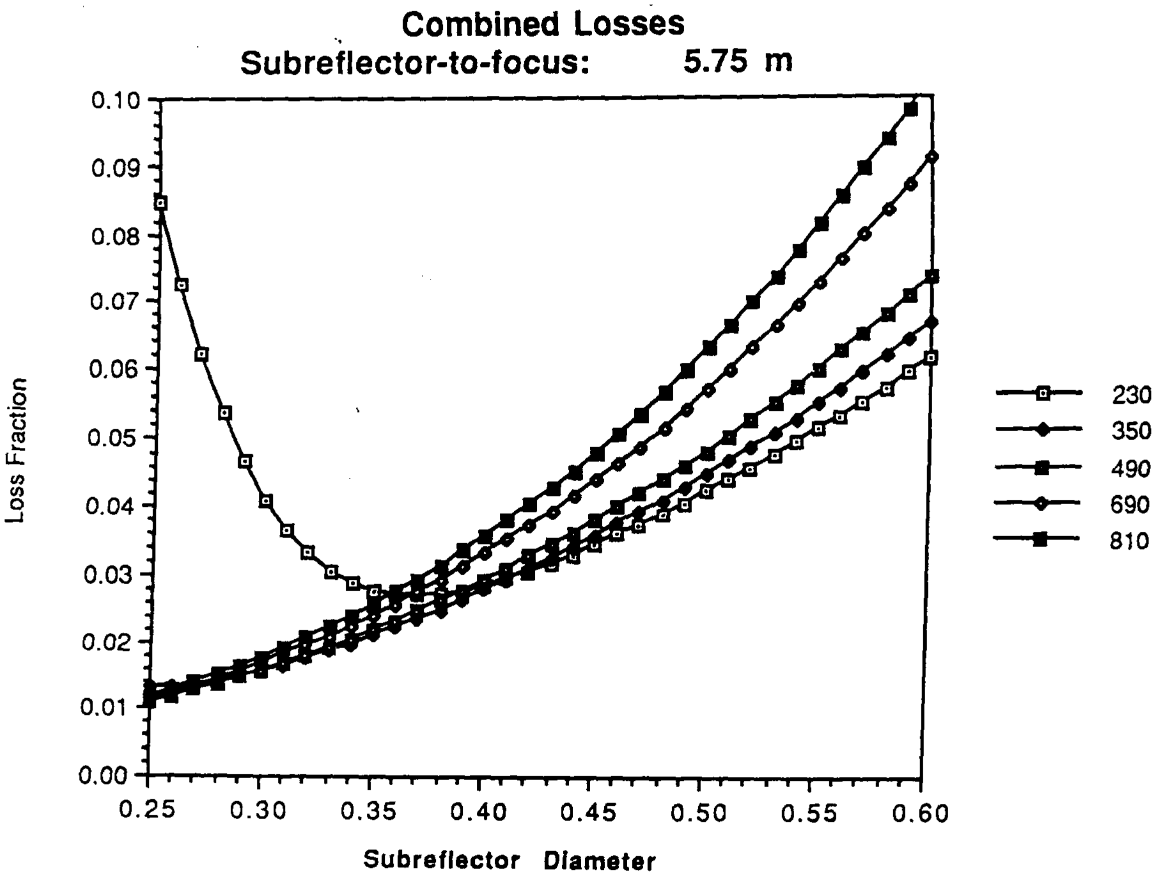

Combined Losses
Subreflector-to-focus: 5.75 m
Loss Fraction
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 1B

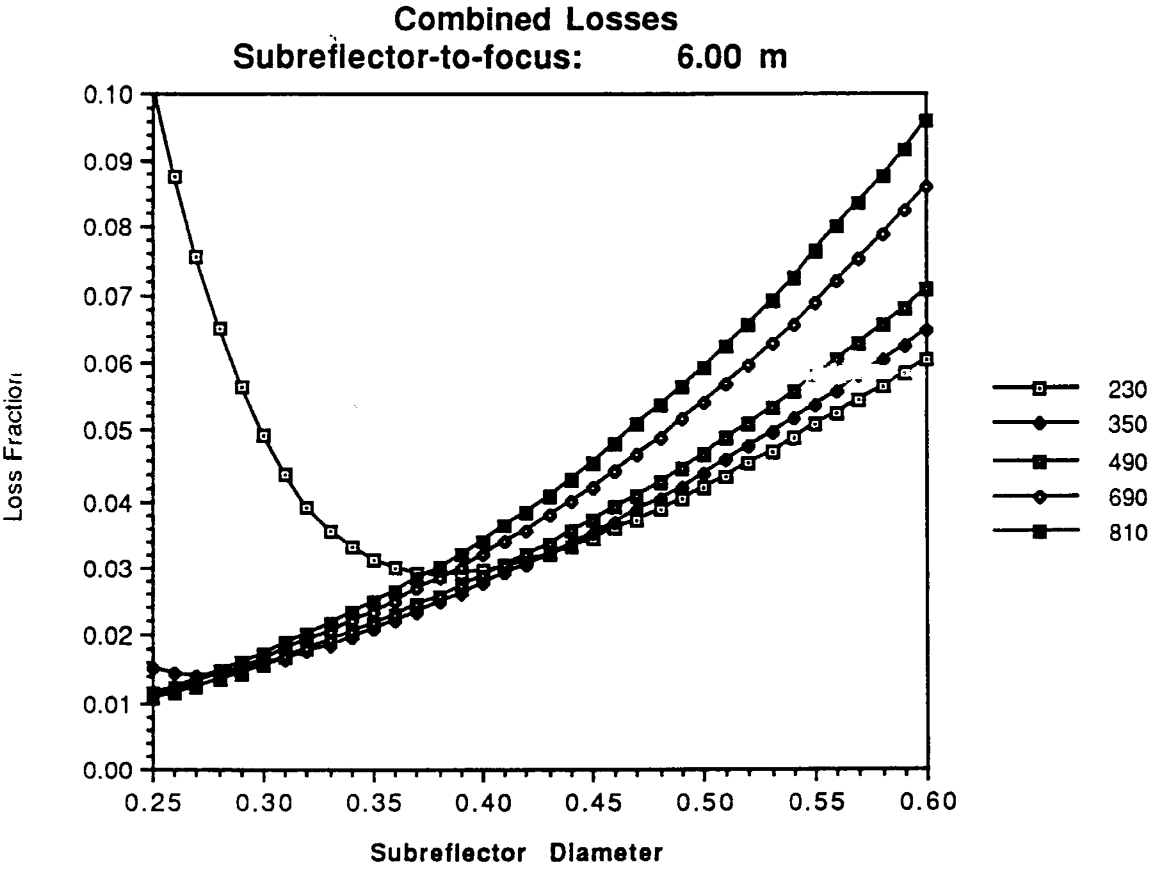

Combined Losses
Subreflector-to-focus: 6.00 m
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 1C

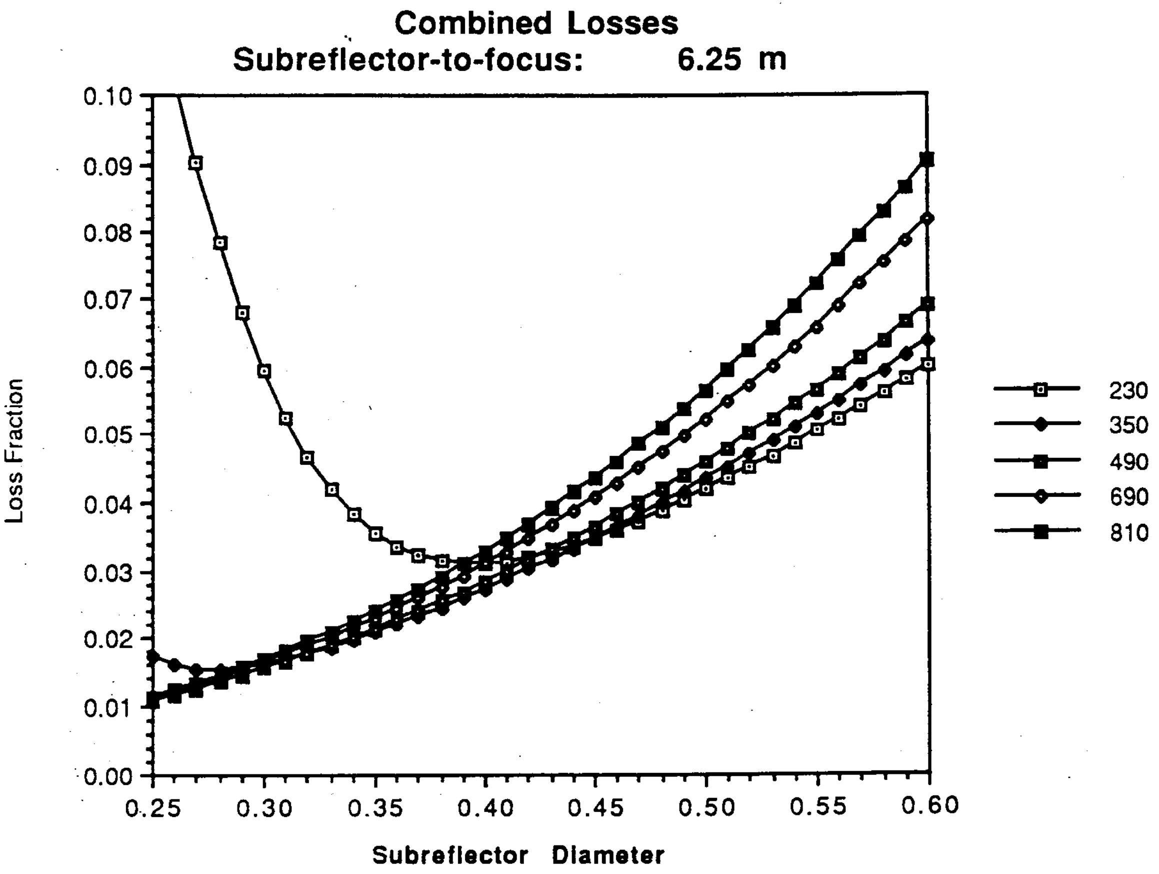
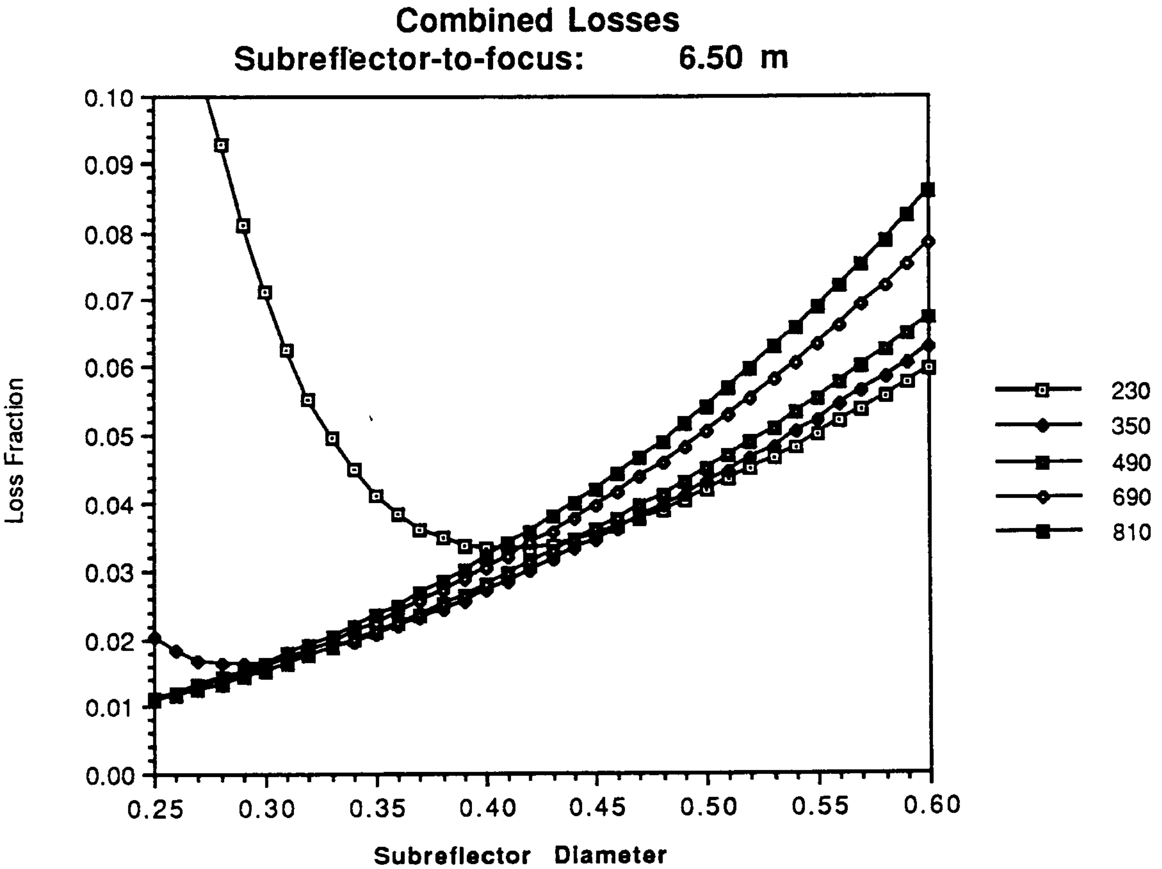
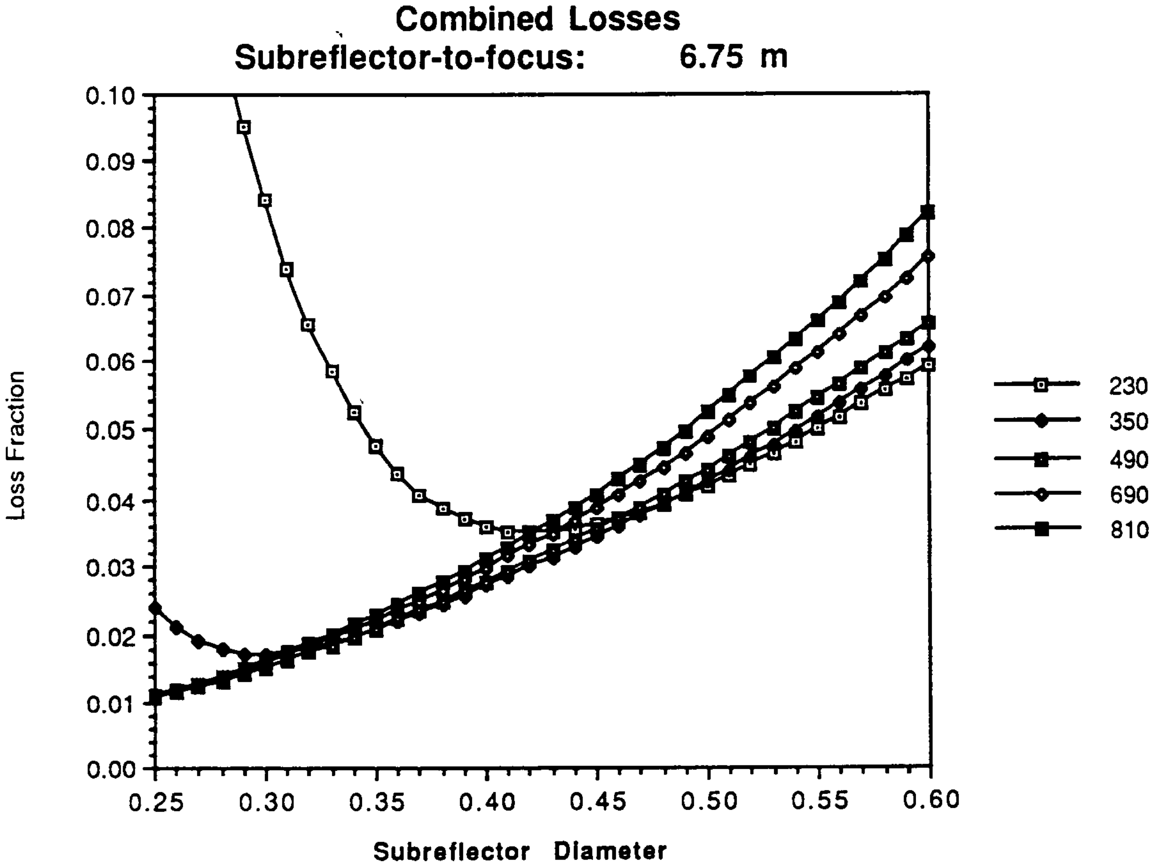

Combined Losses
Subreflector-to-focus: 6.25 m
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 1D



Combined Losses
Subreflector-to-focus: 6.50 m
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 1E


Combined Losses
Subreflector-to-focus: 6.75 m
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

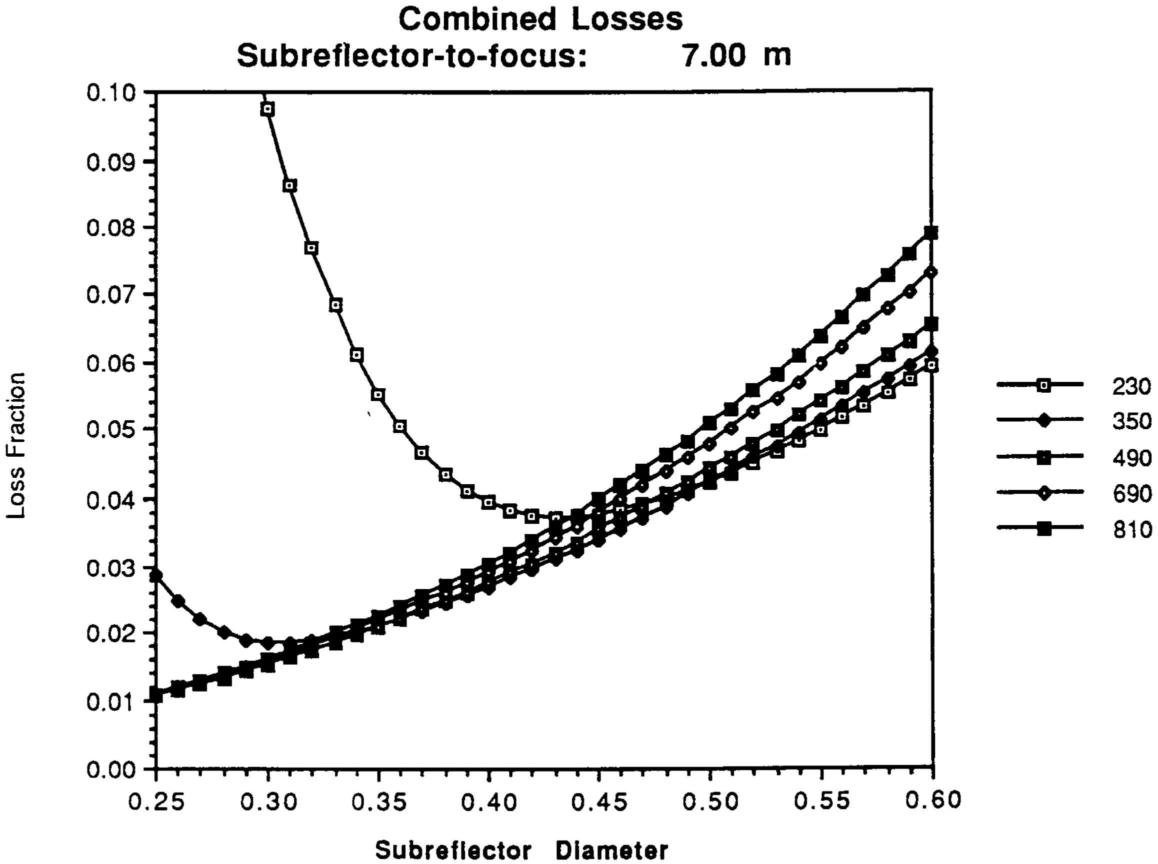

Combined Losses
Subreflector-to-focus: 7.00 m
Loss Fraction
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 1G

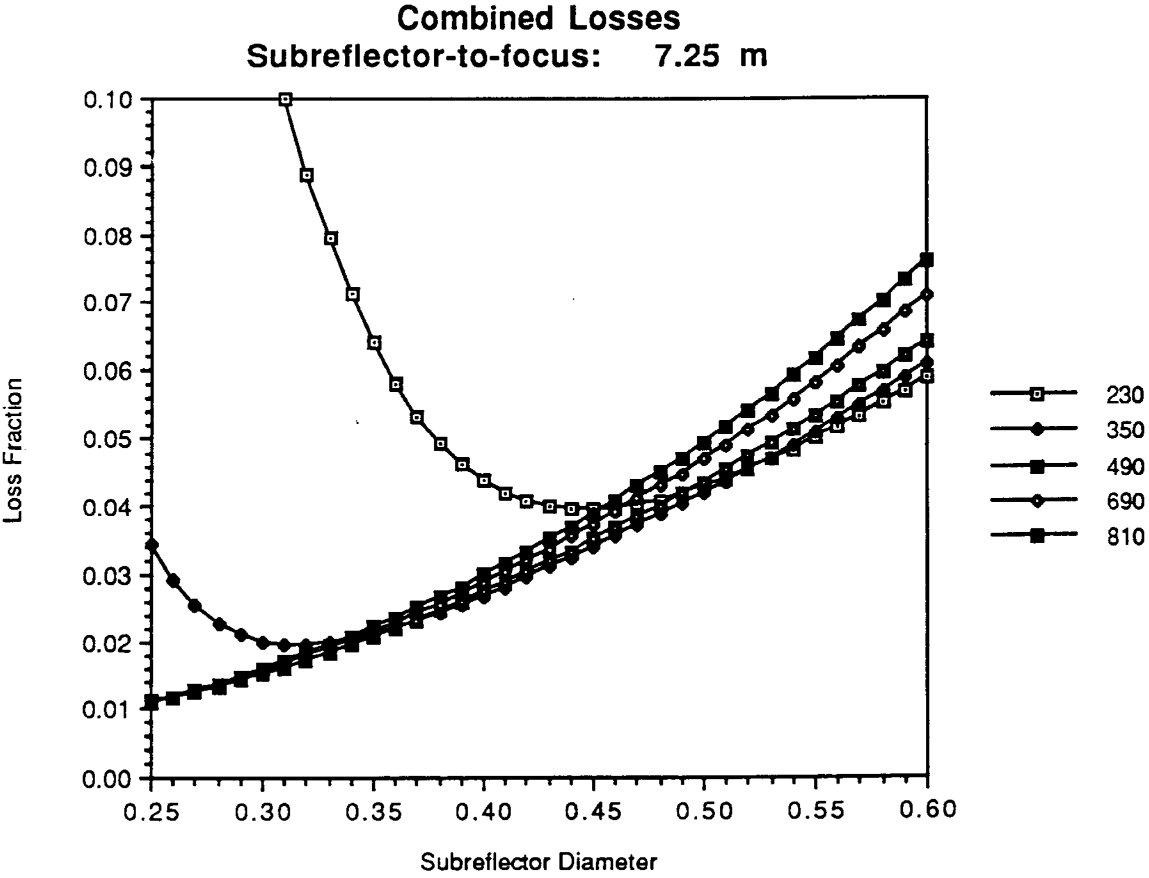
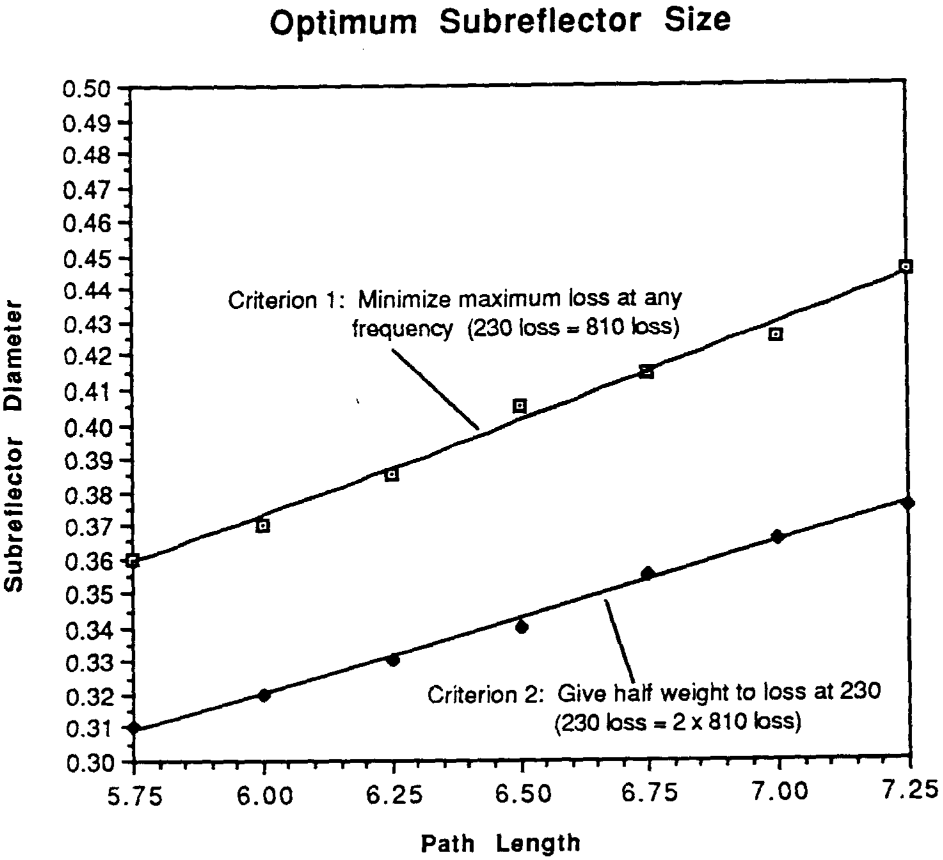

Combined Losses
Subreflector-to-focus: 7.25 m
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 1H


Optimum Subreflector Size
Subreflector Diameter
0.50
0.49
0.48
0.47
0.46
0.45
0.44
0.43
0.42
0.41
0.40
0.39
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.30
5.75
6.00
6.25
6.50
6.75
7.00
7.25
Path Length
Criterion 1: Minimize maximum loss at any frequency (230 loss = 810 loss)
Criterion 2: Give half weight to loss at 230 (230 loss = 2 x 810 loss)

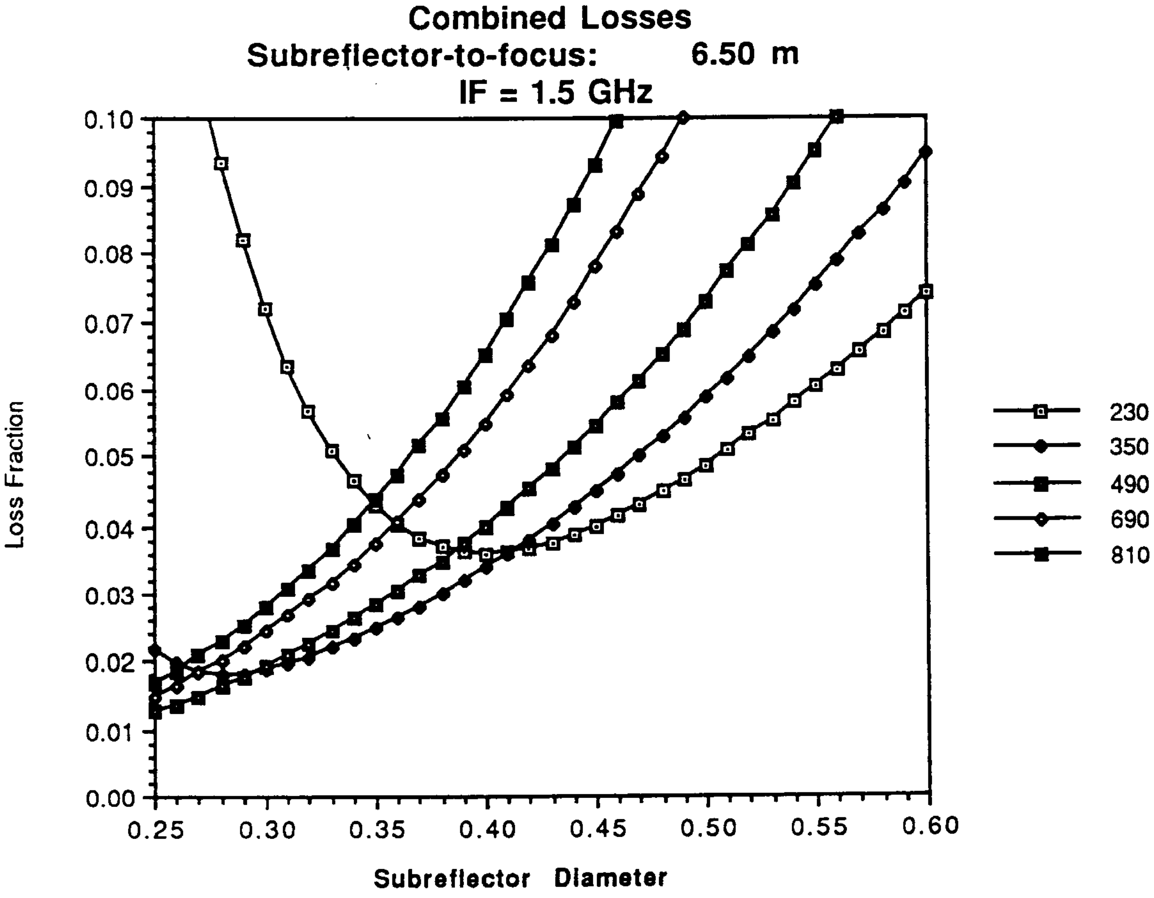
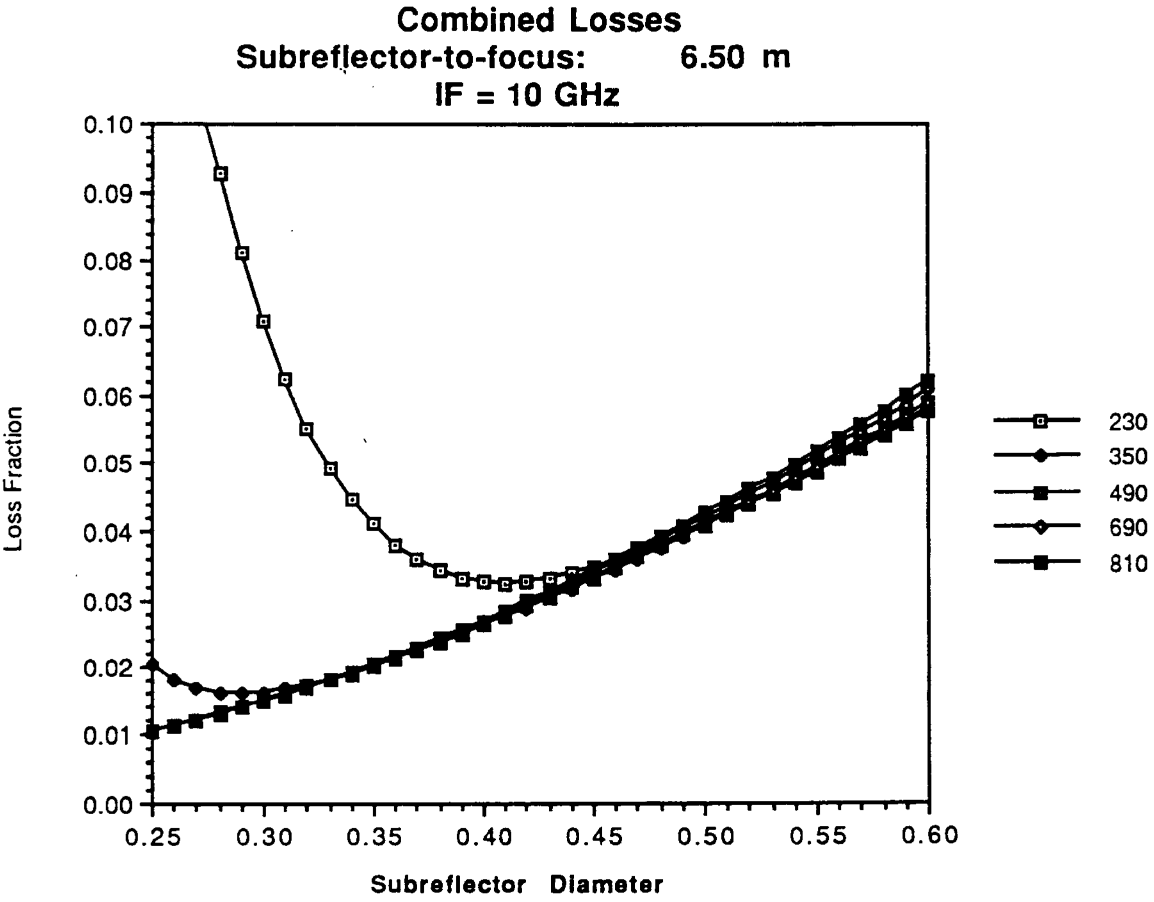

Combined Losses
Subreflector-to-focus: 6.50 m
IF = 1.5 GHz
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 2B


Combined Losses
Subreflector-to-focus: 6.50 m
IF = 10 GHz
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

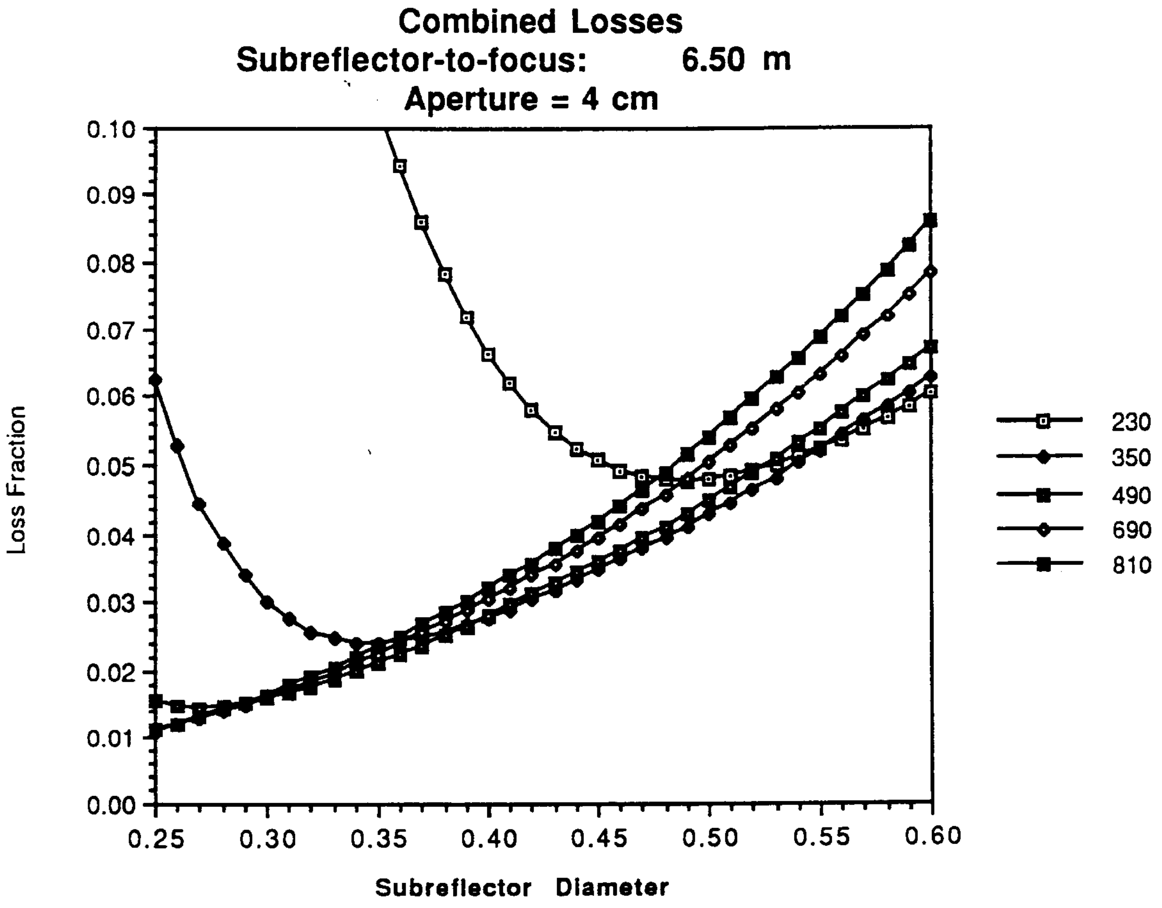
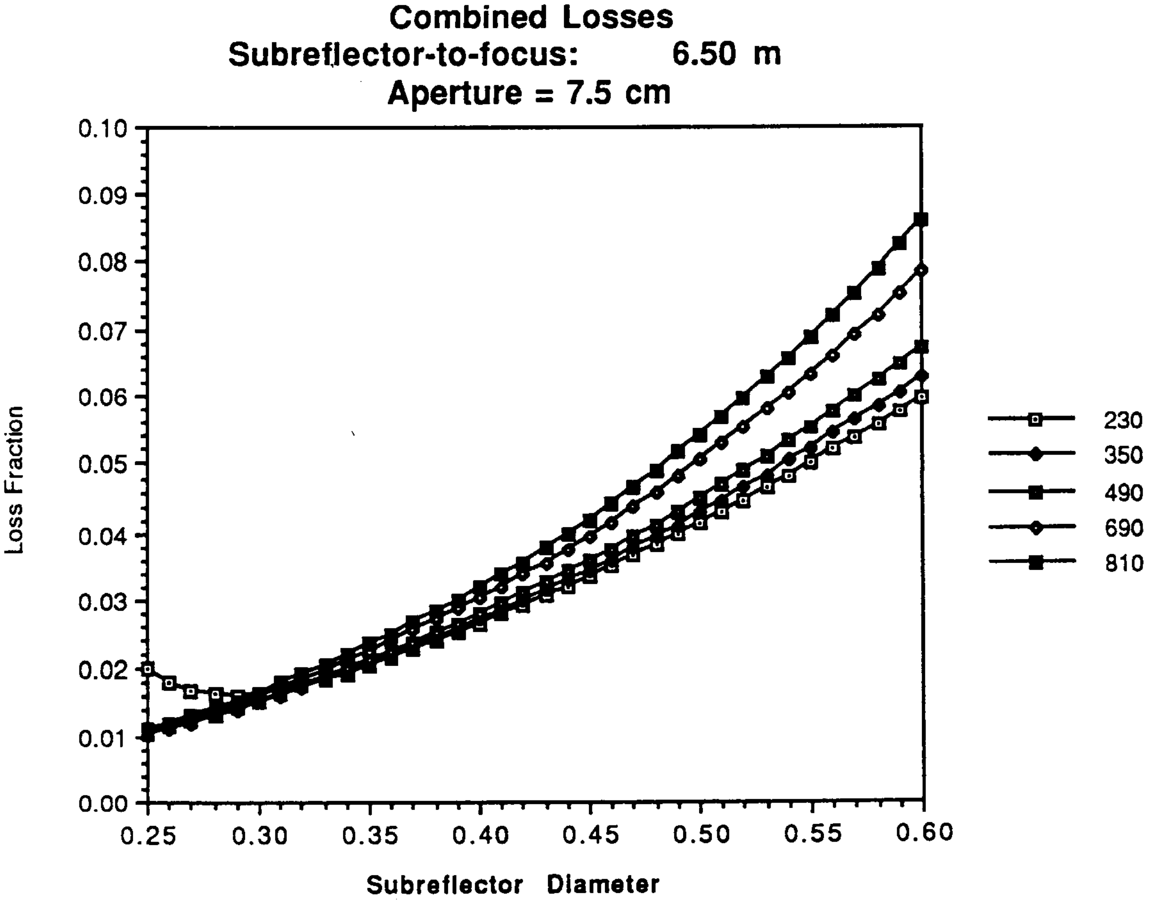
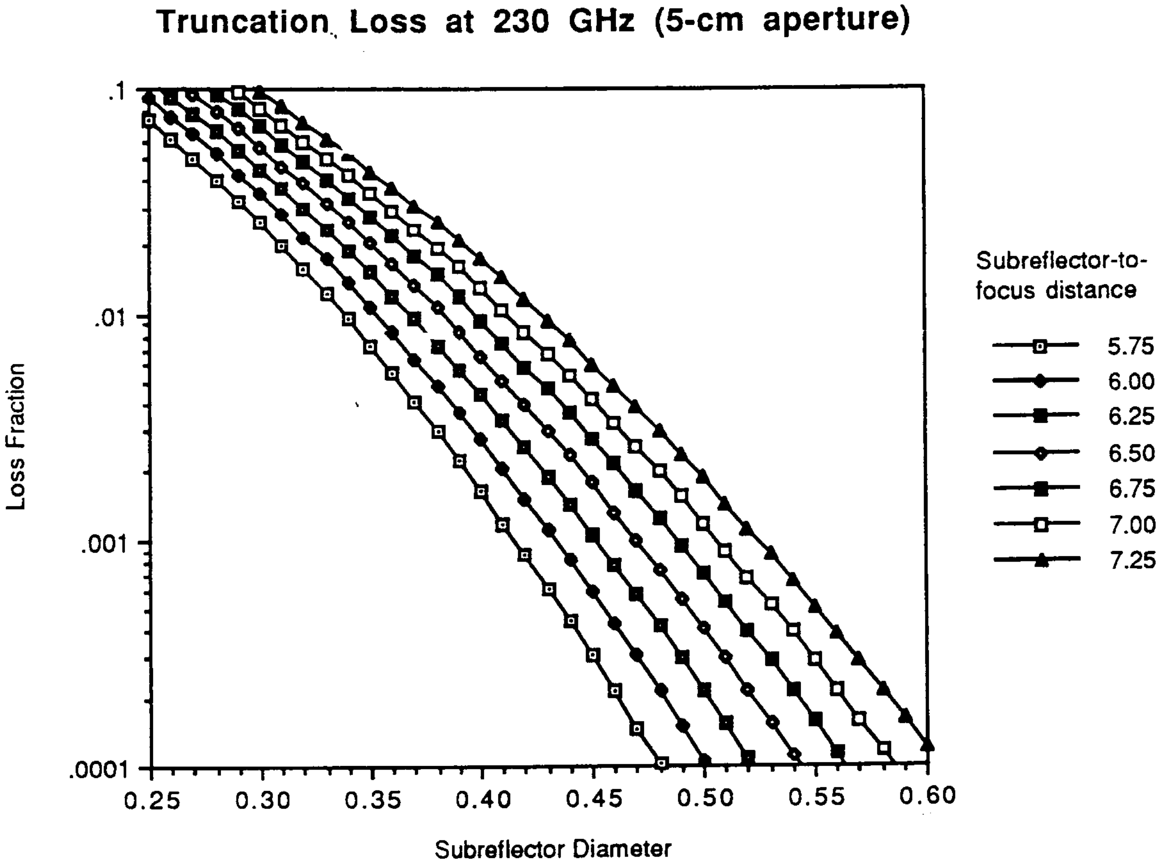

Combined Losses
Subreflector-to-focus: 6.50 m
Aperture = 4 cm
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810

Figure 3B



Combined Losses
Subreflector-to-focus: 6.50 m
Aperture = 7.5 cm
Loss Fraction
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
230
350
490
690
810


Truncation Loss at 230 GHz (5-cm aperture)
Loss Fraction
.1
.01
.001
.0001
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25

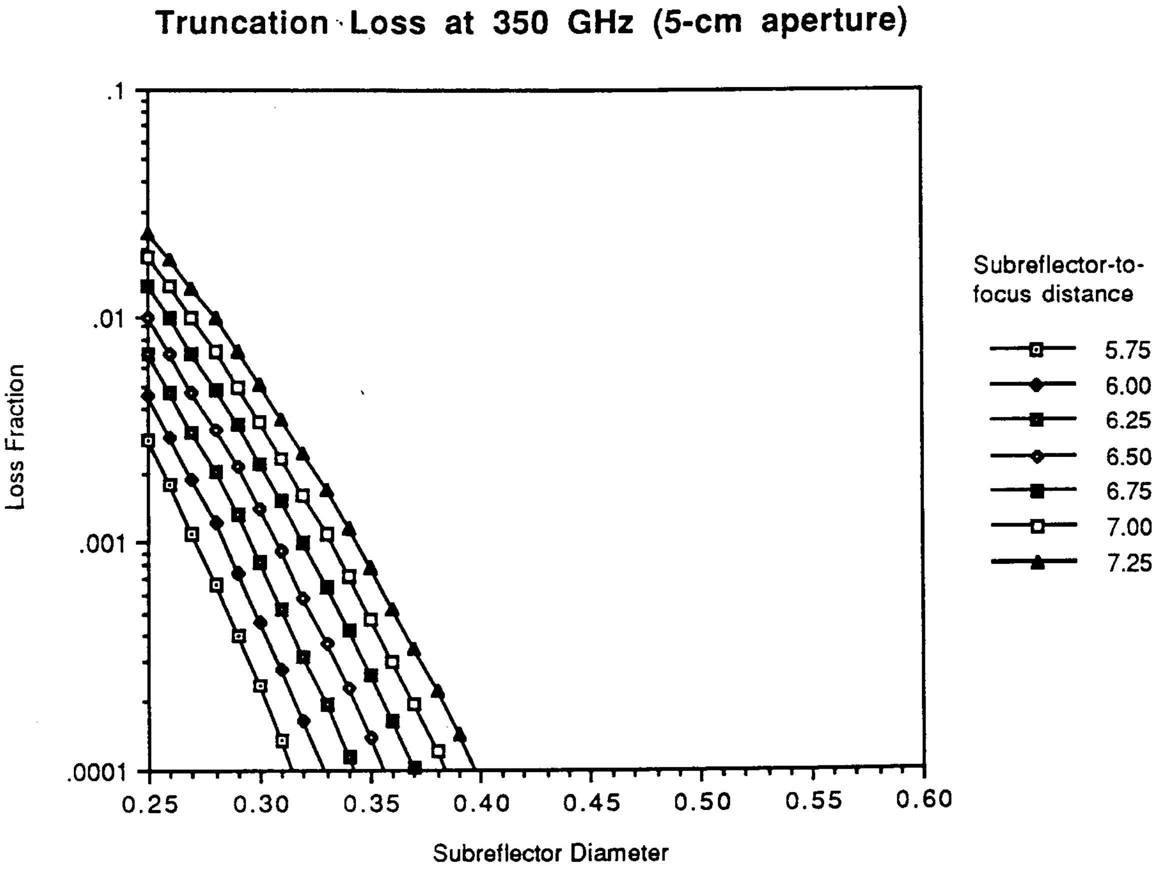

Truncation Loss at 350 GHz (5-cm aperture)
Loss Fraction
.1
.01
.001
.0001
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25

Figure 4C

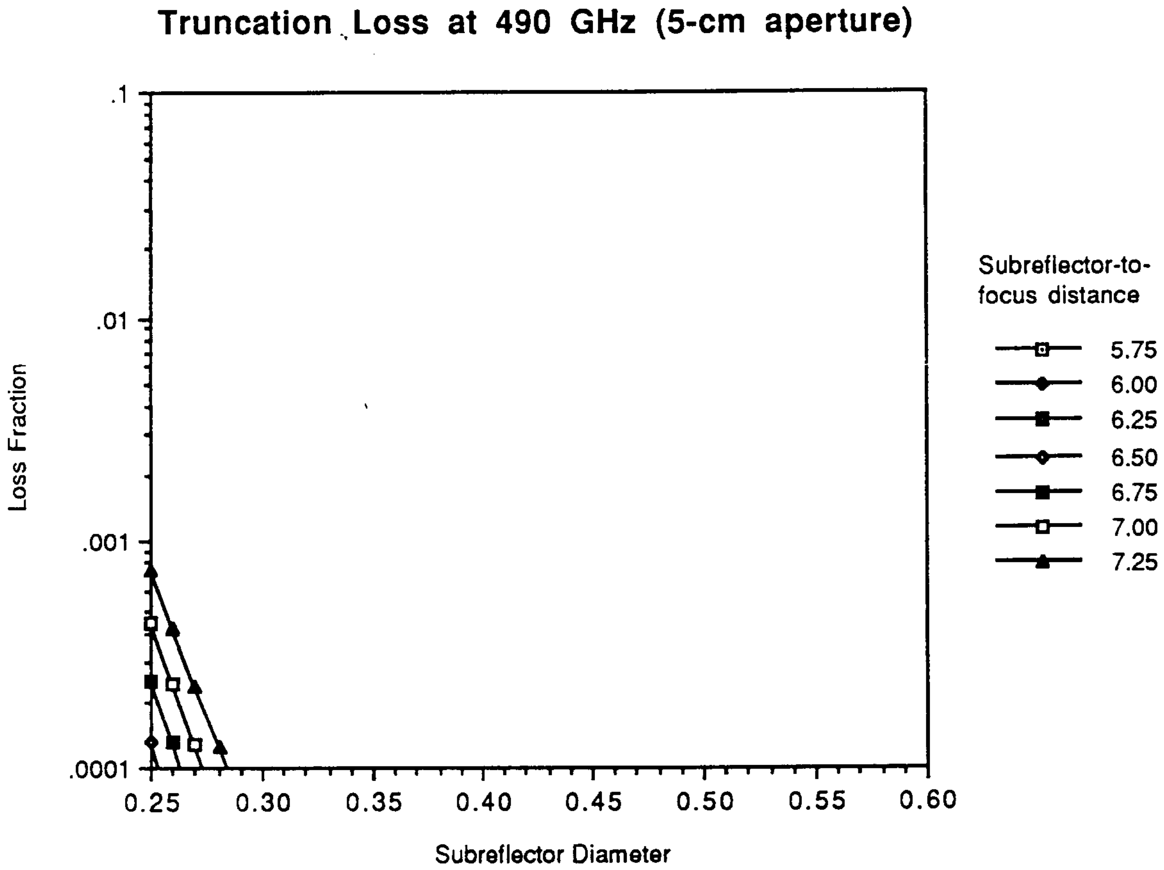

Truncation Loss at 490 GHz (5-cm aperture)
.1
.01
.001
.0001
Loss Fraction
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25

Figure 5A

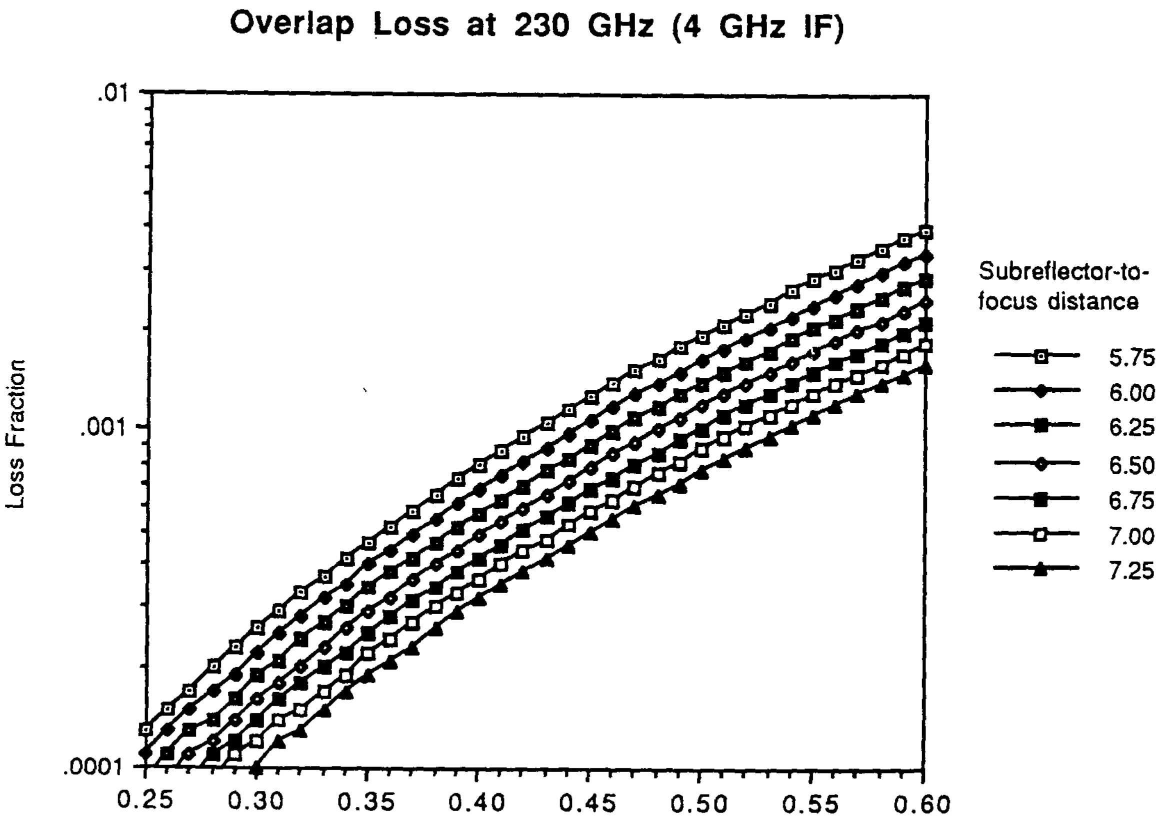
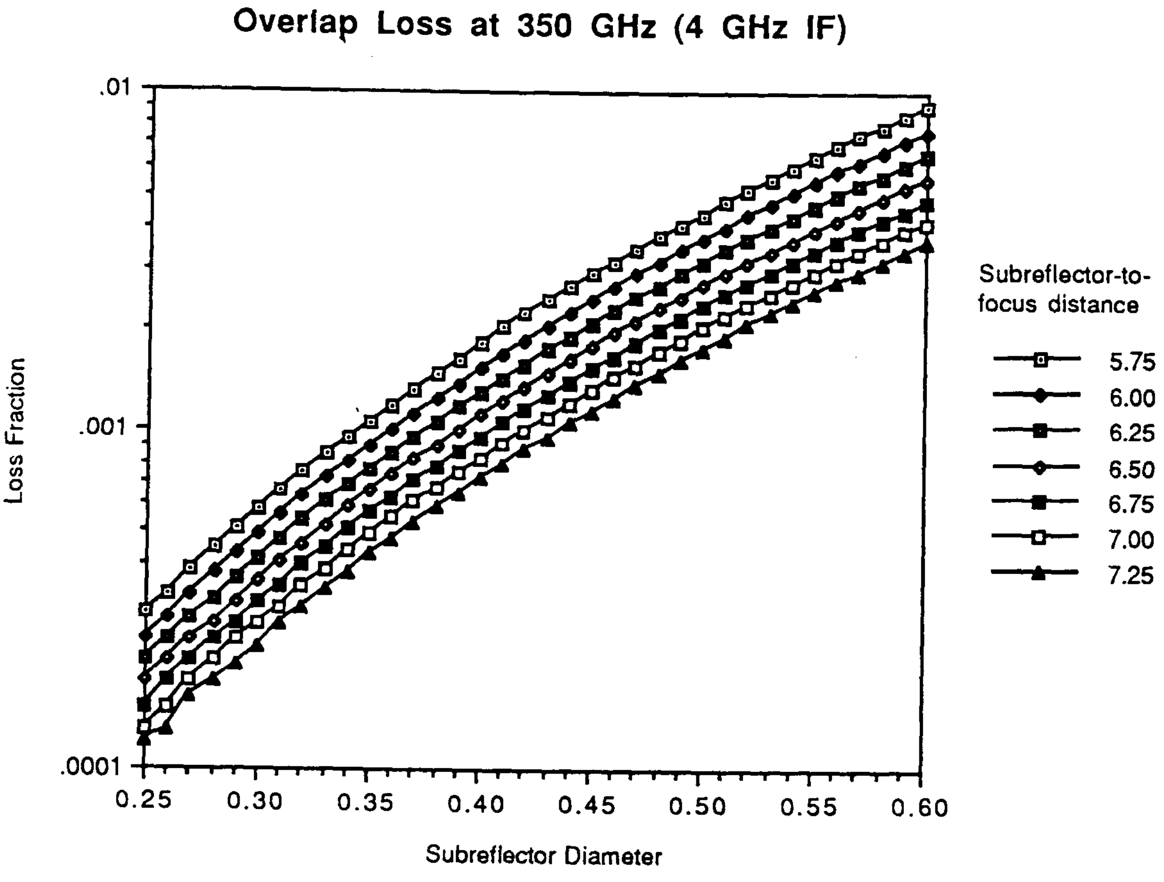
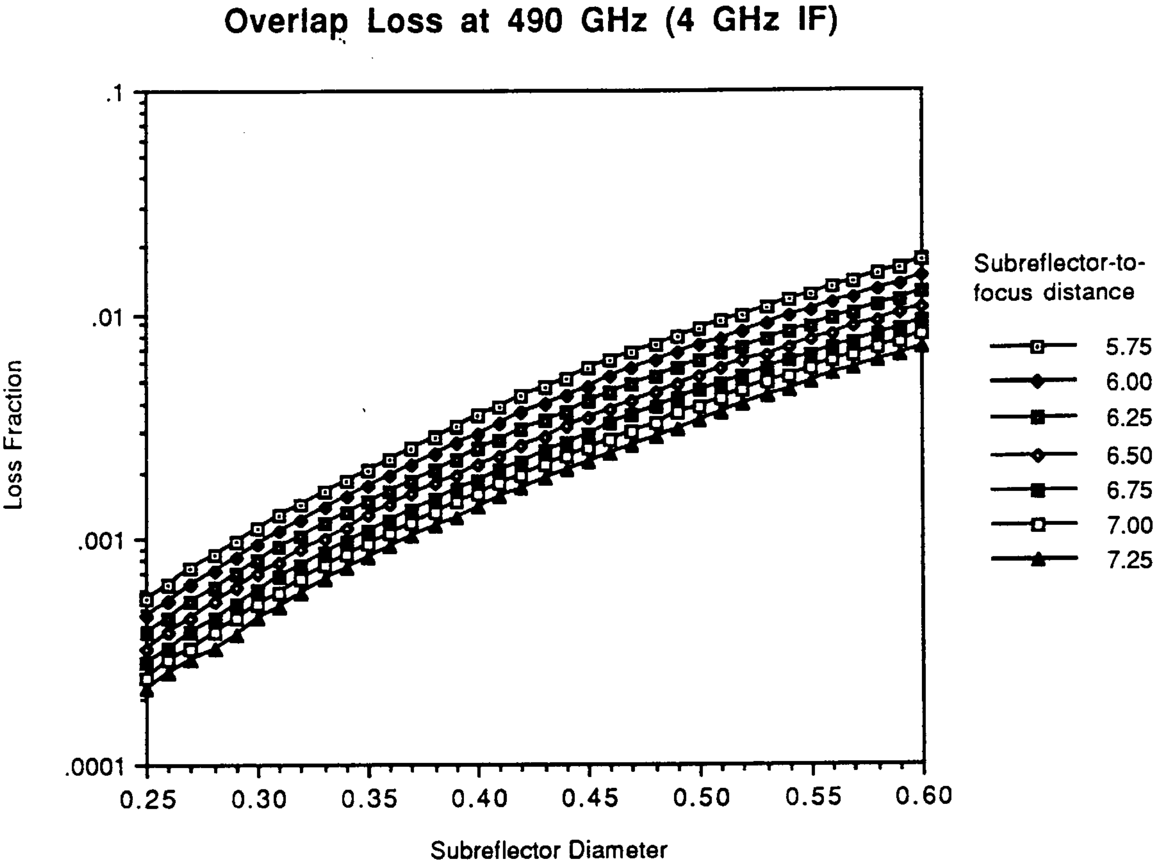

Overlap Loss at 230 GHz (4 GHz IF)
Loss Fraction
.01
.001
.0001
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25

Figure 5B


Overlap Loss at 350 GHz (4 GHz IF)
Loss Fraction
.01
.001
.0001
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25


Overlap Loss at 490 GHz (4 GHz IF)
.1
.01
.001
.0001
Loss Fraction
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25

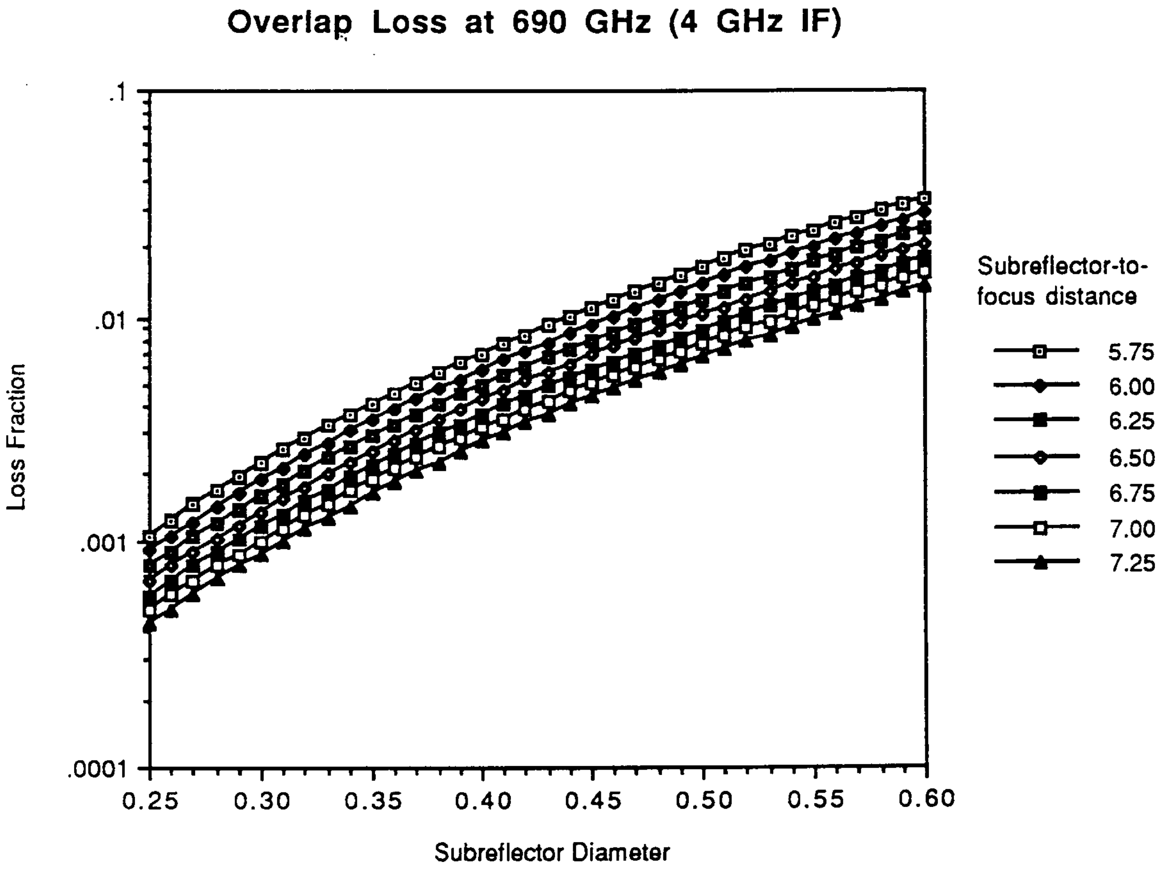

Overlap Loss at 690 GHz (4 GHz IF)
Loss Fraction
.1
.01
.001
.0001
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25

Figure 5E

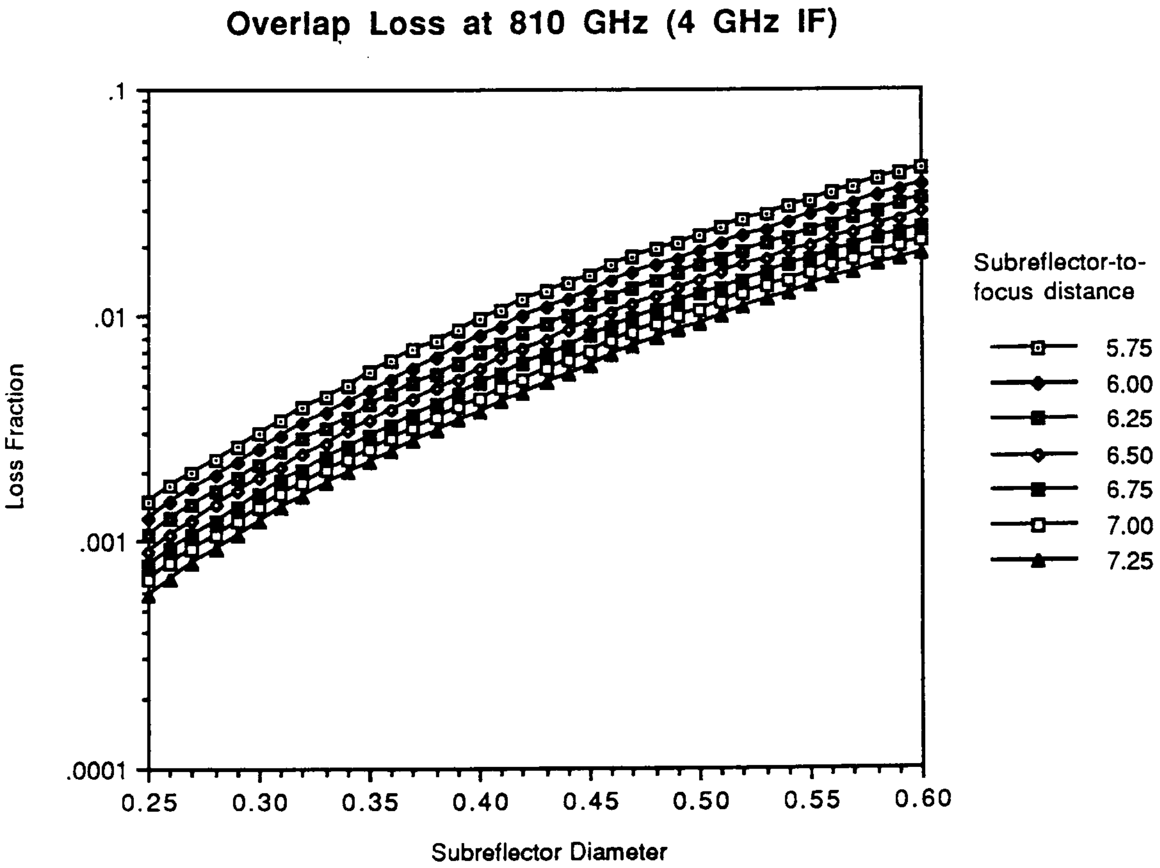
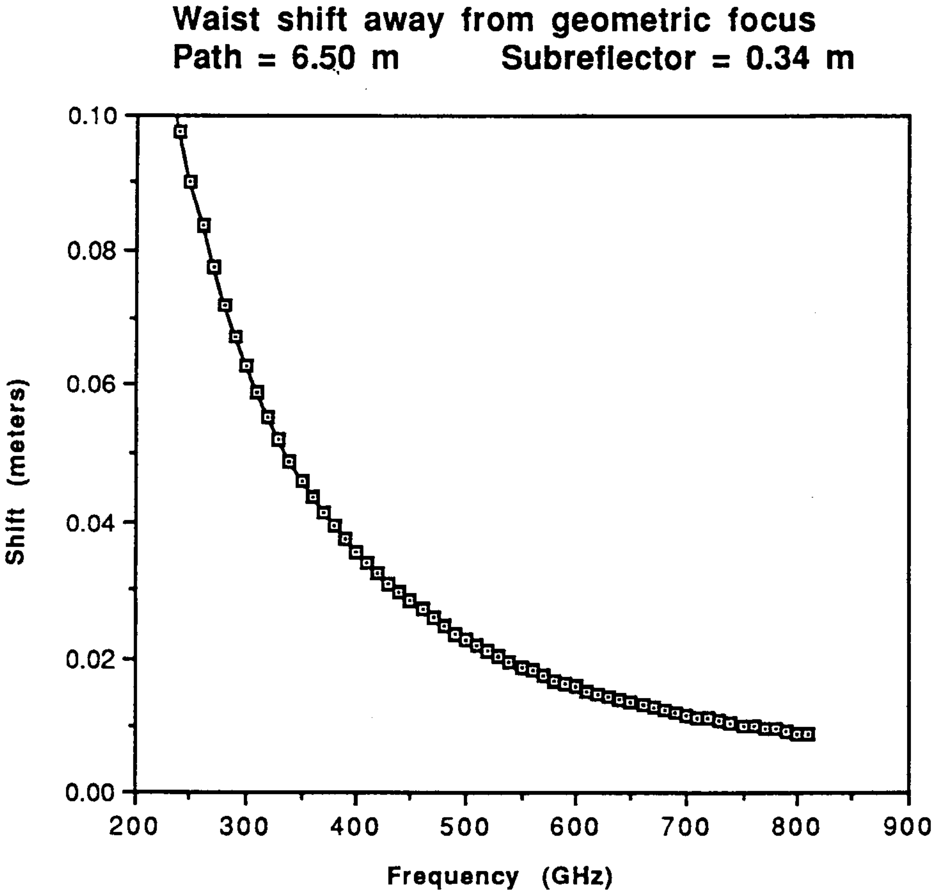

Overlap Loss at 810 GHz (4 GHz IF)
.1
.01
.001
.0001
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Loss Fraction
Subreflector Diameter
Subreflector-to-focus distance
5.75
6.00
6.25
6.50
6.75
7.00
7.25

Figure 6


Waist shift away from geometric focus
Path = 6.50 m
Subreflector = 0.34 m
Shift (meters)
0.10
0.08
0.06
0.04
0.02
0.00
200
300
400
500
600
700
800
900
Frequency (GHz)