MILLIMETER ARRAY
MEMO NO. 58

Millimeter-Wave Atmospheric Opacity and Transparency Curves

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In earlier work pertaining to site surveys and characterization of telescope sites (see MMA Memo. No. 51 and NLSRT Memo. No. 52) we used radiosonde measurements, together with H. J. Liebe's millimeter-wave propagation model [2,3], to estimate millimeter-wave zenith opacity, at selected wavelengths, under the meteorological conditions typical (at a given locale) of particular dates or seasons of the year. By analyzing, in detail, a few selected portions of the radiosonde data archive we can also generate estimates of millimeter-wave opacity and transmittivity across all the radio continuum between 1 and 1000 GHz, for atmospheric conditions ranging from excellent to poor. Here we give the results of such an analysis, in the hope that this will provide useful perspective for the Millimeter Array studies and that millimeter-wave observers (at the NRAO 12-Meter Telescope, for example) might also benefit.

This work supplements an earlier study [4] by Martin and Ulich, who used the AFCRL (1973) compilation of molecular line data, in conjunction with the U.S. Standard Model Atmosphere of 1976, to generate curves showing estimates of atmospheric transmission vs. frequency for varied atmospheric conditions, the latter characterized by the zenith-path integral of precipitable water vapor (PWV). Like Martin and Ulich, we have chosen to use the column density of water vapor as the key variable characterizing the observing conditions.

Liebe's propagation model, which we have been using, is simpler than the AFCRL model, in that it incorporates a reduced set of lines (44 O_2 and 30 H_2O lines) in the 20–1000 GHz range, complemented by empirical models of the water vapor continuum (including far-wing contributions from lines above 1 THz) and the non-resonant dry air spectrum. The AFCRL model includes a large number of molecular transitions due to water vapor, oxygen, and ozone (2314, counting O_3 lines), ranging as high in frequency as 3 THz. Because ozone and a model of the upper atmosphere are included in their work, Martin and Ulich's transmission curves show fine structure due to this trace gas; these features, of course, are absent from our curves—but otherwise, the overall forms are similar.

For the present study, we have chosen to analyze radiosonde data from Tucson, Arizona, because of its proximity to the 12-Meter Telescope and because some of the most interesting of the possible sites for the MMA are located in Arizona. We selected radiosonde launches and base-altitudes for numerical integration of the atmospheric profiles such that the zenith column-density of water vapor (which in our plots we label 'PWV') was close (within ±5%) to some nominal value, say 1 mm. In the attached figures we present results for radiosonde launches corresponding to nominal PWV values of 0.5, 1, 2, 3, 4, 8, and 16 mm.

Parenthetical remark: In this memorandum we follow the custom of atmospheric physics and define the opacity $\tau(\nu)$ at frequency ν in such a way that the zenith-path atmospheric transmission, or transparency, is given by $e^{-\tau(\nu)}$. In this definition, the attenuation of a signal passing through an atmosphere of opacity τ is $1 - e^{-\tau}$.

Figure 1 shows plots of the atmospheric opacity $\tau(\nu)$, over the frequency range 1 to 1000 GHz, for nominal PWV values of 0.5, 1, 2, 3, 4, 8, and 16 mm. Opacity and transparency were computed over this frequency range in steps of one gigahertz; if we had chosen a smaller frequency increment, then some of the peaks in the opacity curves would have been noticeably higher, but, since it is the atmospheric windows that are of primary interest to astronomers, we felt that this frequency resolution would suffice. In order to easily find a radiosonde launch with the selected PWV level, we chose base altitudes of 13750 ft for PWV = 0.5 mm, 12000 ft for PWV = 1 mm, 10500 ft for PWV = 2 mm, and 6275 ft (the Kitt Peak altitude) for the other cases.

In order to get an idea whether the data we selected might be atypical—and to estimate how much scatter we might have observed, had we chosen to analyze more radiosonde launches—we selected ten additional launches with a nominal PWV value of 3 mm. The corresponding ten opacity curves are shown in Figure 2, together with the 2 mm and 4 mm curves that were shown in Figure 1. Within each of the atmospheric 'window' regions, the 2 mm and 4 mm PWV curves bracket the ten 3 mm curves.

Figures 3 through 9 are separate plots of the same data as were shown in Figure 1. Figures 10 through 16 show the corresponding atmospheric transparency curves $e^{-\tau(\nu)}$.

Figures 17 through 21 show typical curves of the atmospheric opacity across five 'windows' of the millimeter-wave spectrum: 24–56 GHz, 64–118 GHz, 120–180 GHz, 185–320 GHz, and 326–366 GHz, respectively. Seven curves are shown in each of these plots, corresponding to nominal PWV values, from bottom to top, of 0.5, 1, 2, 3, 4, 8, and 16 mm, respectively. Figures 22 through 26 show the corresponding atmospheric transmission curves; here the seven curves shown in each plot correspond, from top to bottom, to nominal PWV values of 0.5, 1, 2, 3, 4, 8, and 16 mm.

ACKNOWLEDGMENTS

Our computer program for analysis of radiosonde data is based in large part on a program furnished us by Harry Lehto, and used in Lehto's thesis work [1]. R. N. Martin, of Steward Observatory, provided helpful suggestions and furnished Arizona radiosonde data that he had previously analyzed.

REFERENCES

[1] H. J. Lehto (1989), *High Sensitivity Searches for Short Timescale Variability in Extragalactic Objects*, Ph. D. Thesis, University of Virginia; see Appendix A.

[2] H. J. Liebe (1989),"MPM—An atmospheric millimeter-wave propagation model", *Int. J. Infrared & Millimeter Waves*, 10, 631–650.

[3] H. J. Liebe and D. H. Layton, "Millimeter-wave properties of the atmosphere: Laboratory studies and propagation modeling", National Telecommunications and Information Administration Report 87-224, Boulder CO (October 1987).

[4] R. Martin and B. Ulich, "Atmospheric transmission spectra", SMT Technical Memo. UA-83-19, Steward Observatory, Tucson AZ (October 1983).

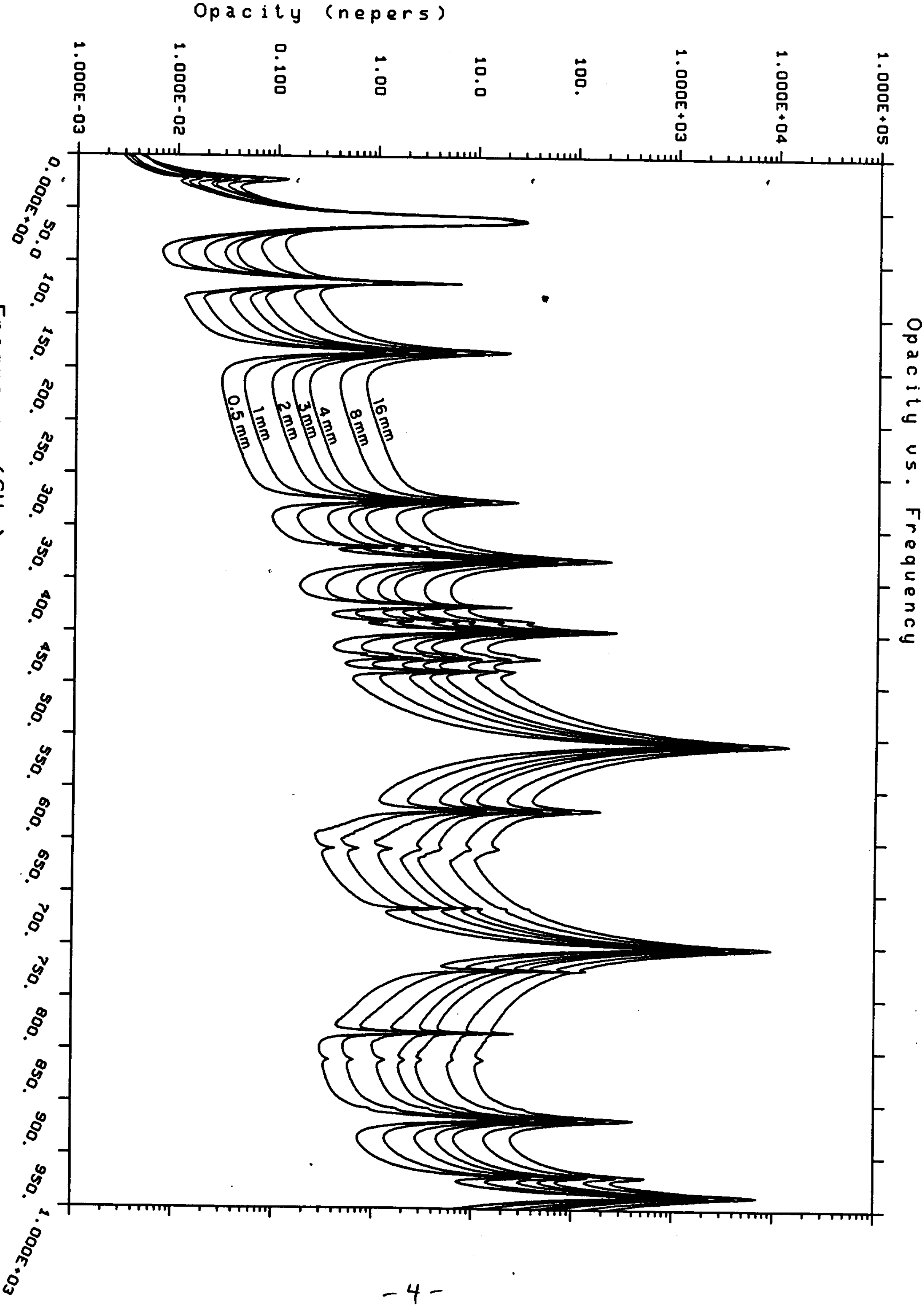

Opacity vs. Frequency
Opacity (nepers)
1.000E-03
1.000E-02
0.100
1.00
10.0
100.
1.000E+03
1.000E+04
1.000E+05
Frequency (GHz)
0.0000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.0000E+03
16 mm
8 mm
4 mm
3 mm
2 mm
1 mm
0.5 mm

Figure 1.

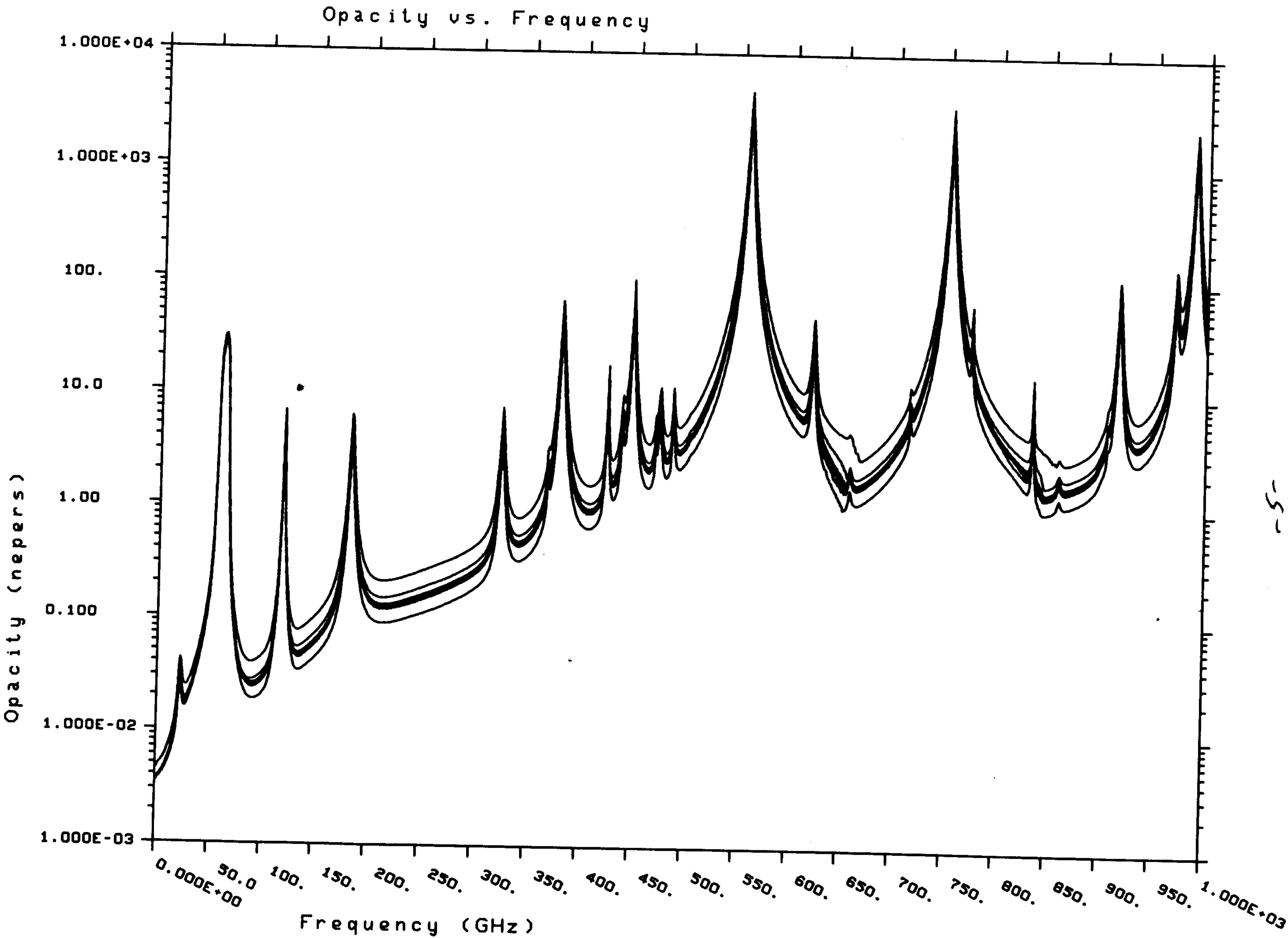

Opacity vs. Frequency
Opacity (nepers)
1.000E+04
1.000E+03
100.
10.0
1.00
0.100
1.000E-02
1.000E-03
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03
Frequency (GHz)

Figure 2.

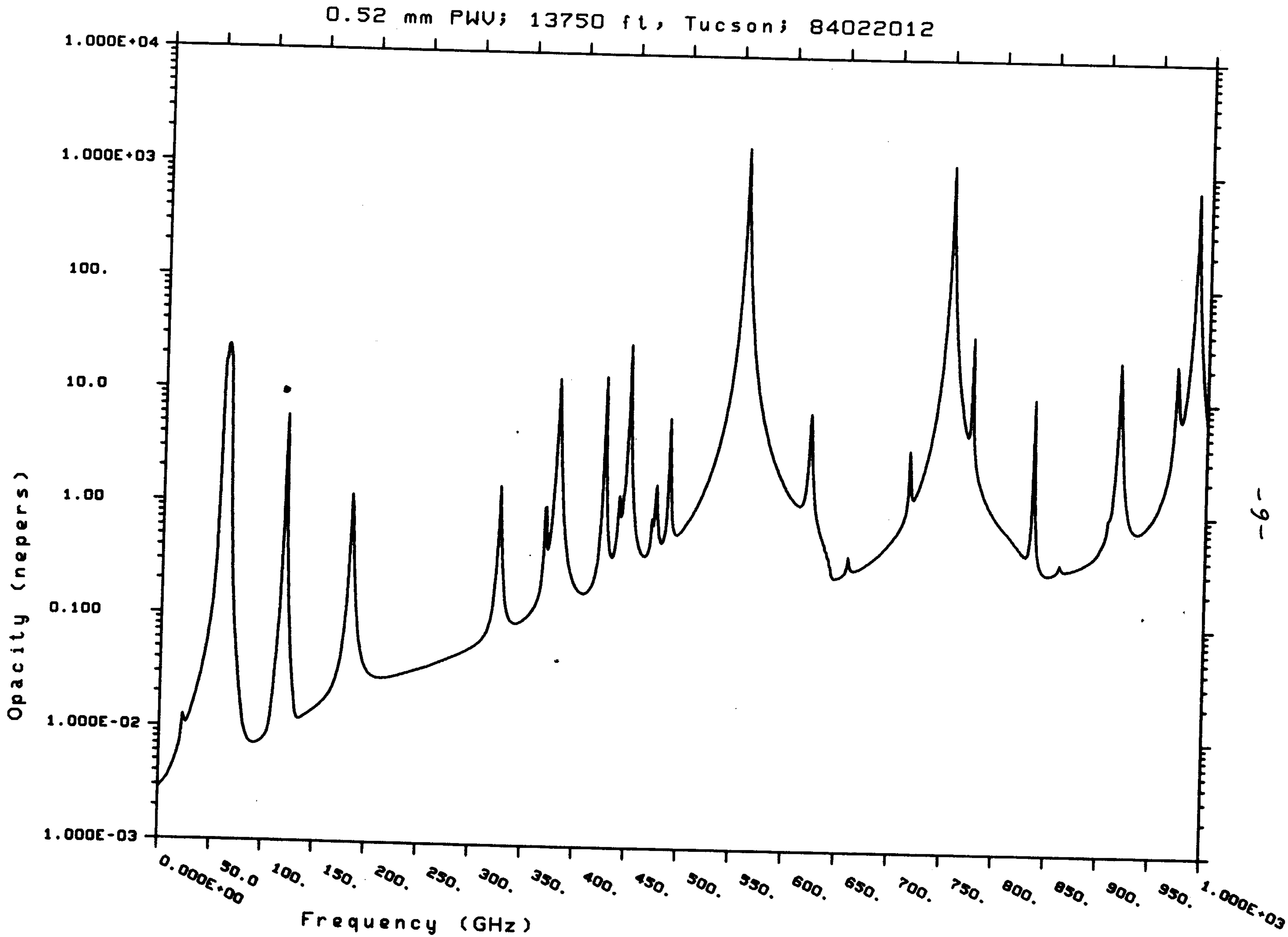

0.52 mm PWV; 13750 ft, Tucson; 84022012
Opacity (nepers)
1.000E+04
1.000E+03
100.
10.0
1.00
0.100
1.000E-02
1.000E-03
Frequency (GHz)
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03

Figure 3.

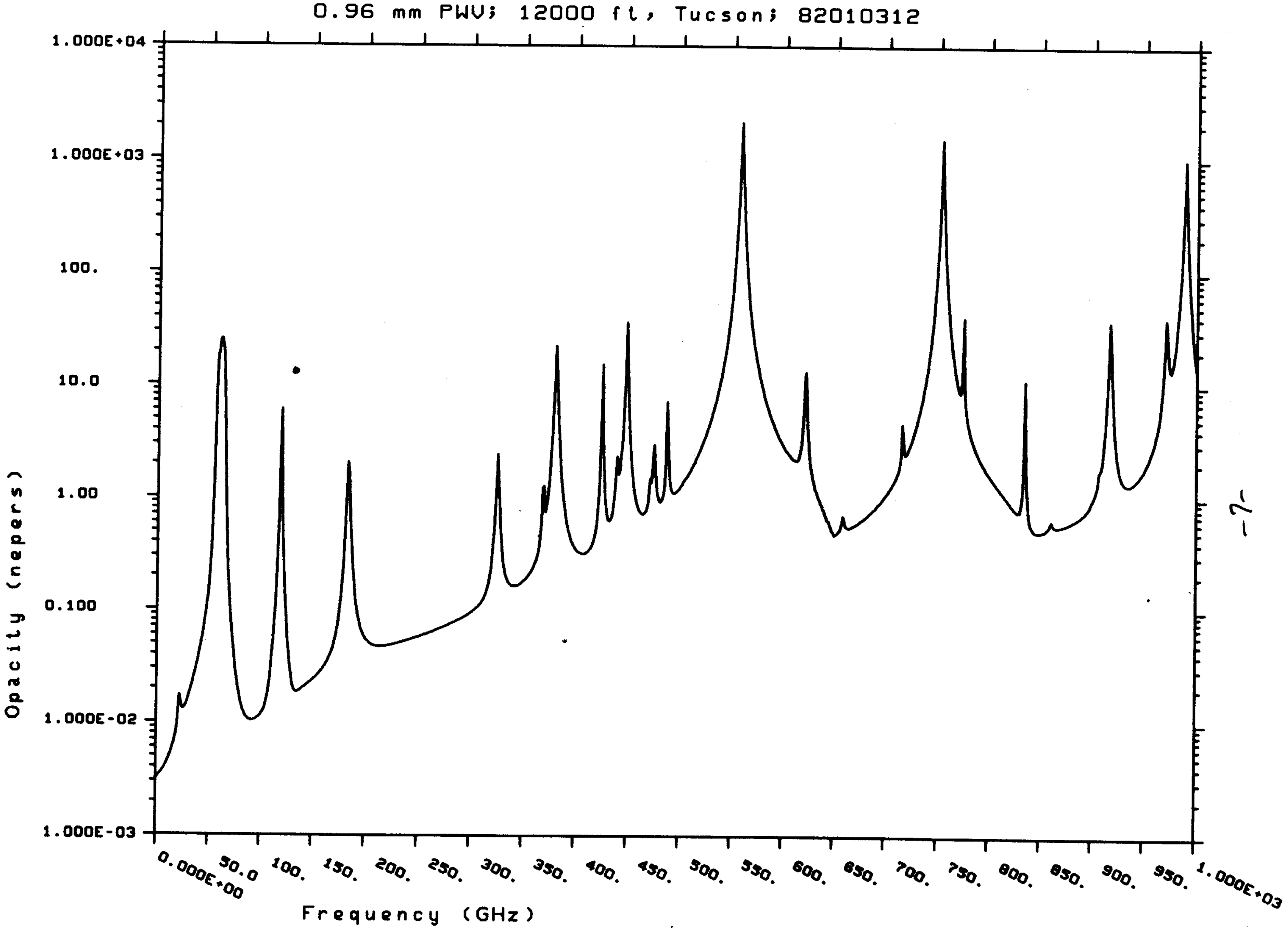

0.96 mm PWV; 12000 ft, Tucson; 82010312
Opacity (nepers)
1.000E+04
1.000E+03
100.
10.0
1.00
0.100
1.000E-02
1.000E-03
Frequency (GHz)
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03

Figure 4.

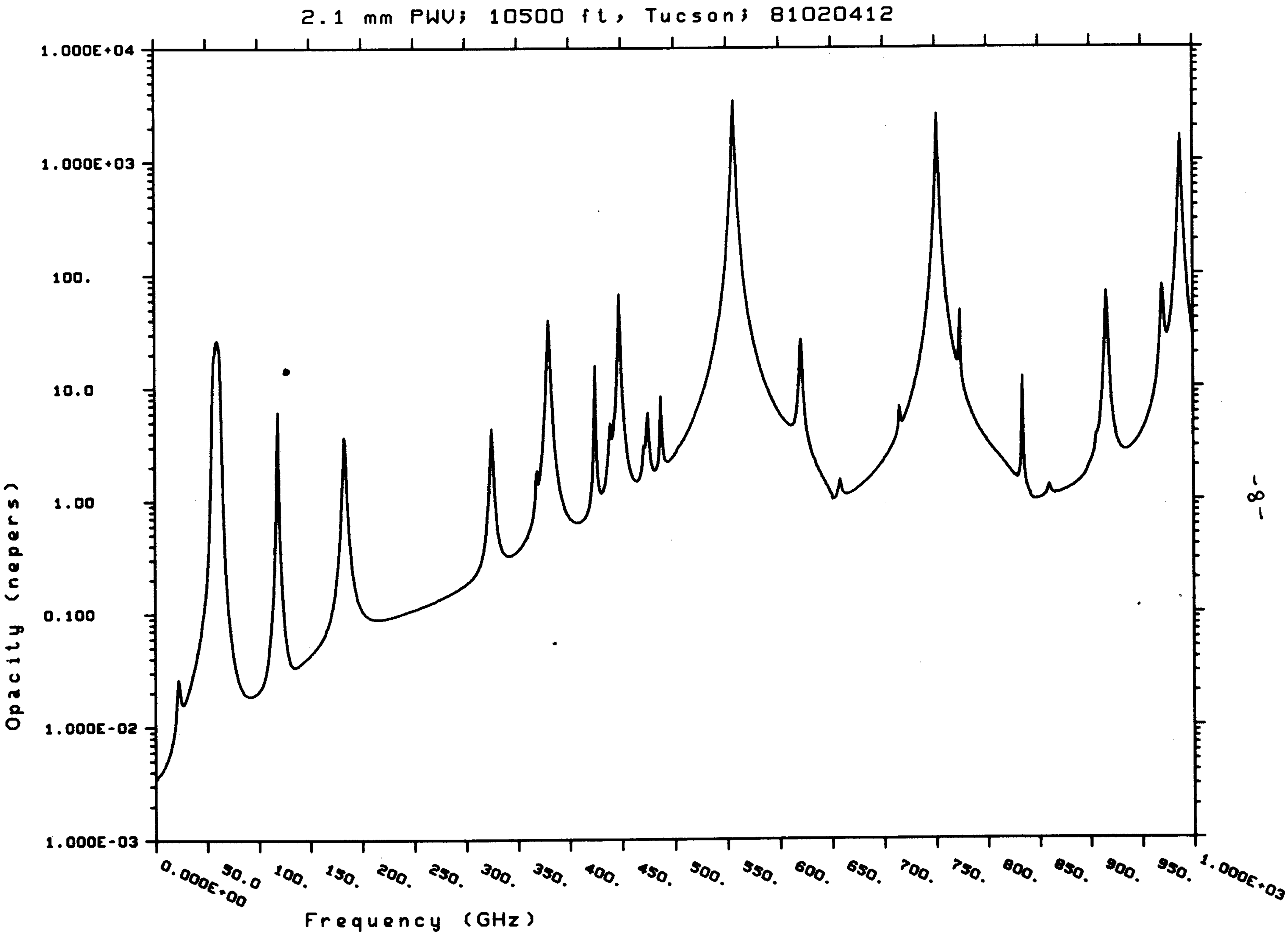

2.1 mm PWV; 10500 ft, Tucson; 81020412
Opacity (nepers)
1.000E+04
1.000E+03
100.
10.0
1.00
0.100
1.000E-02
1.000E-03
Frequency (GHz)
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03

Figure 5.

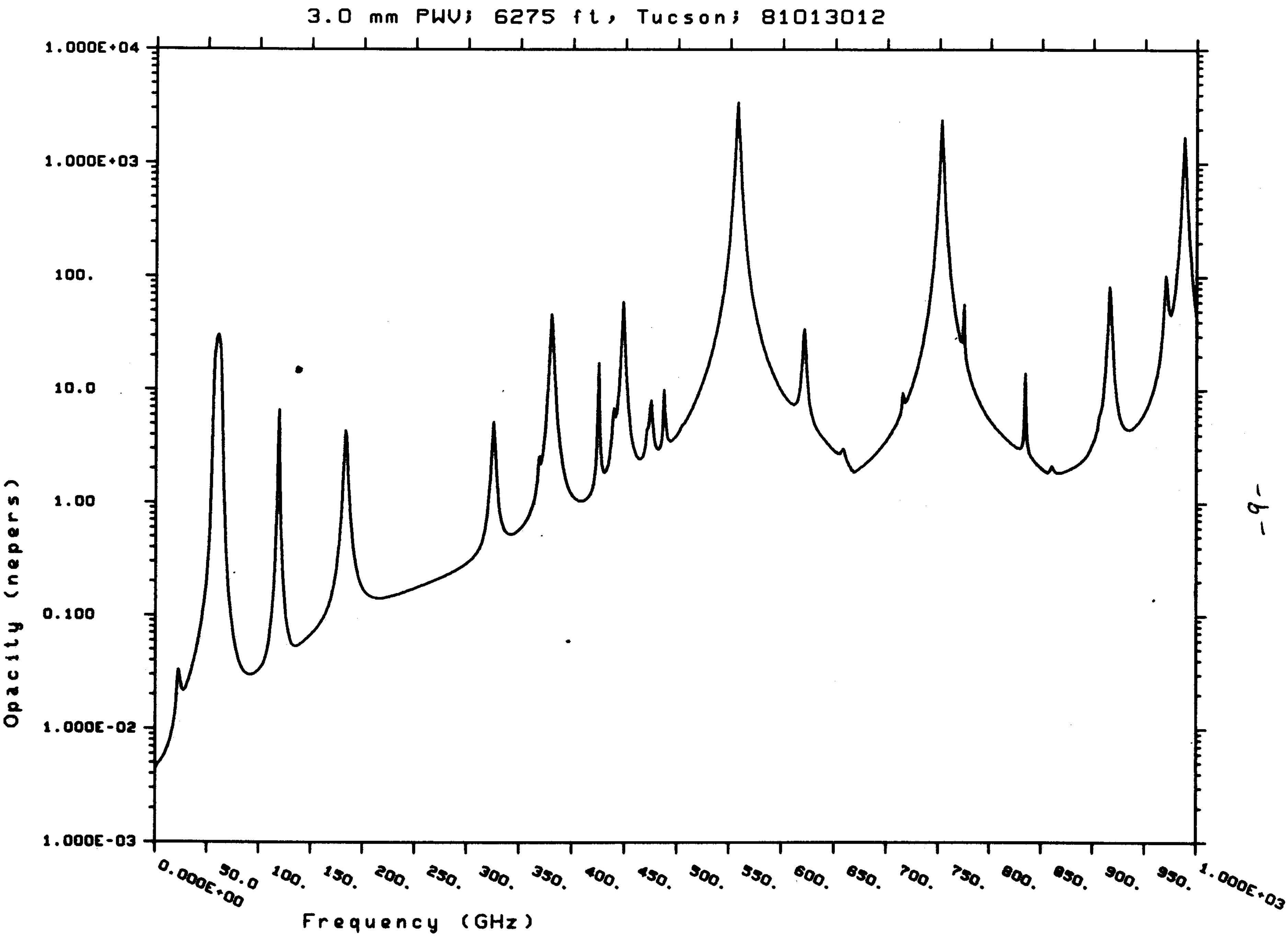

3.0 mm PWV; 6275 ft, Tucson; 81013012
Opacity (nepers)
1.000E+04
1.000E+03
100.
10.0
1.00
0.100
1.000E-02
1.000E-03
Frequency (GHz)
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03

Figure 6.

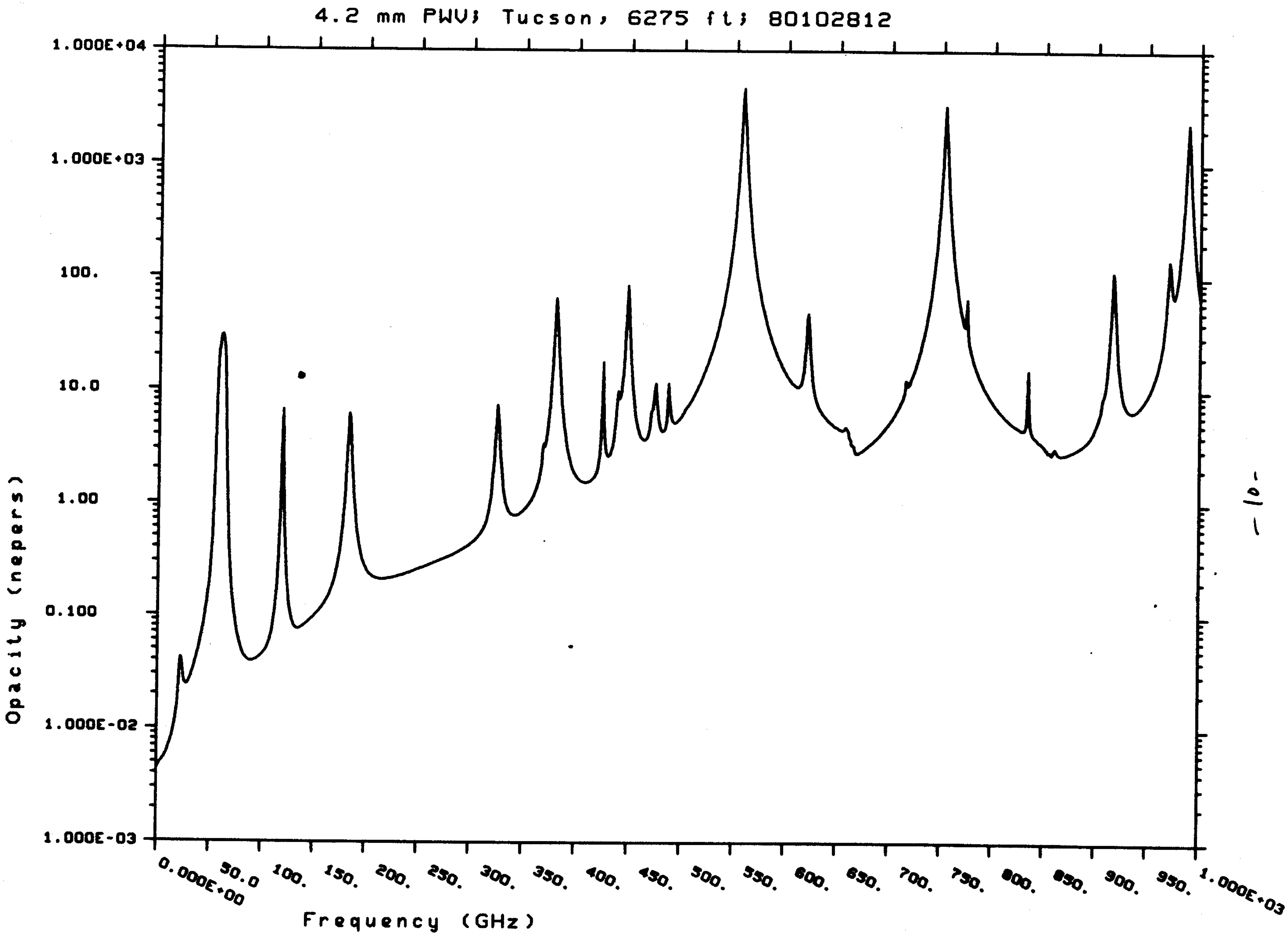

4.2 mm PWV; Tucson, 6275 ft; 80102812
Opacity (nepers)
1.000E+04
1.000E+03
100.
10.0
1.00
0.100
1.000E-02
1.000E-03
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03
Frequency (GHz)

Figure 7.

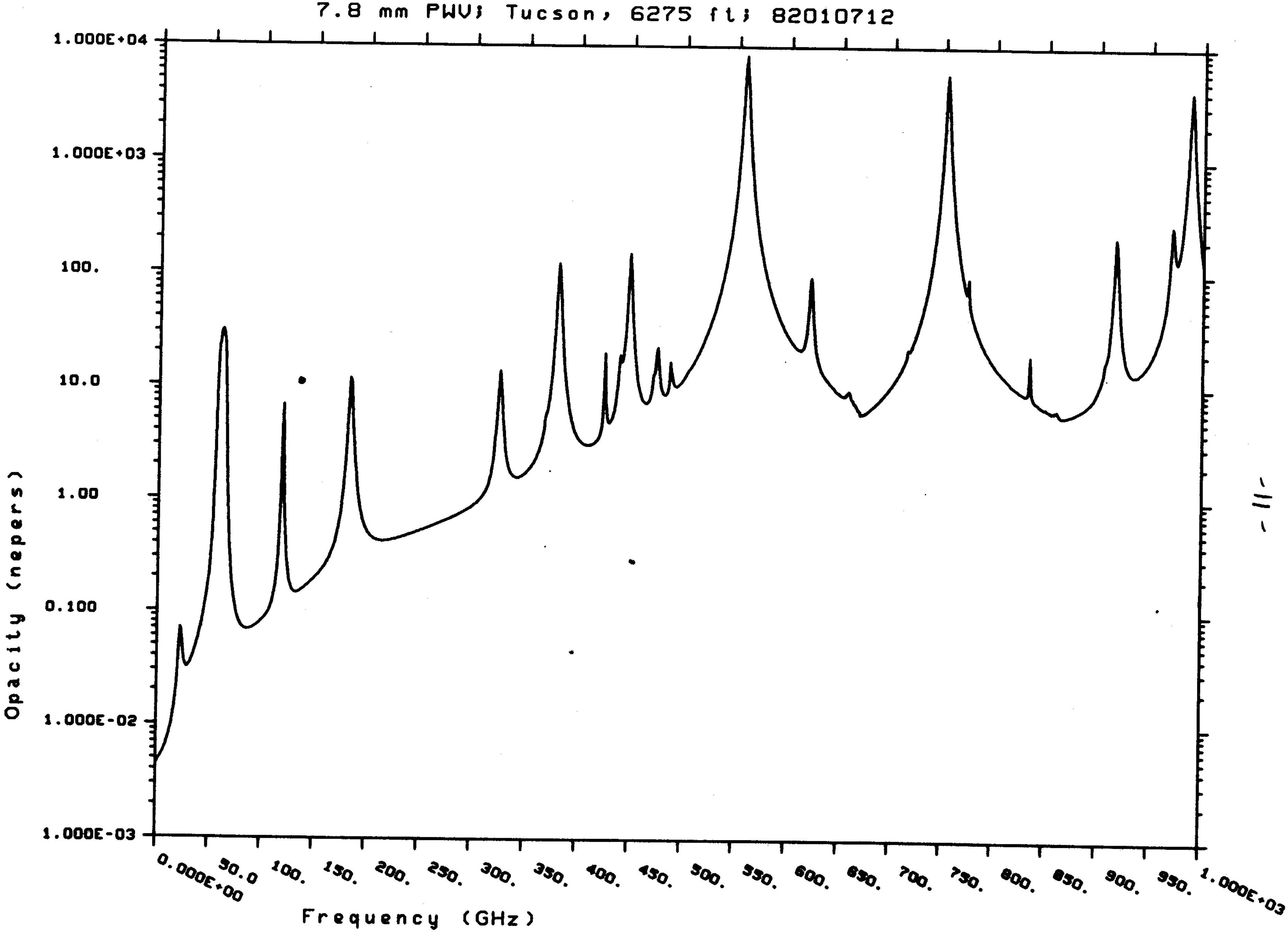
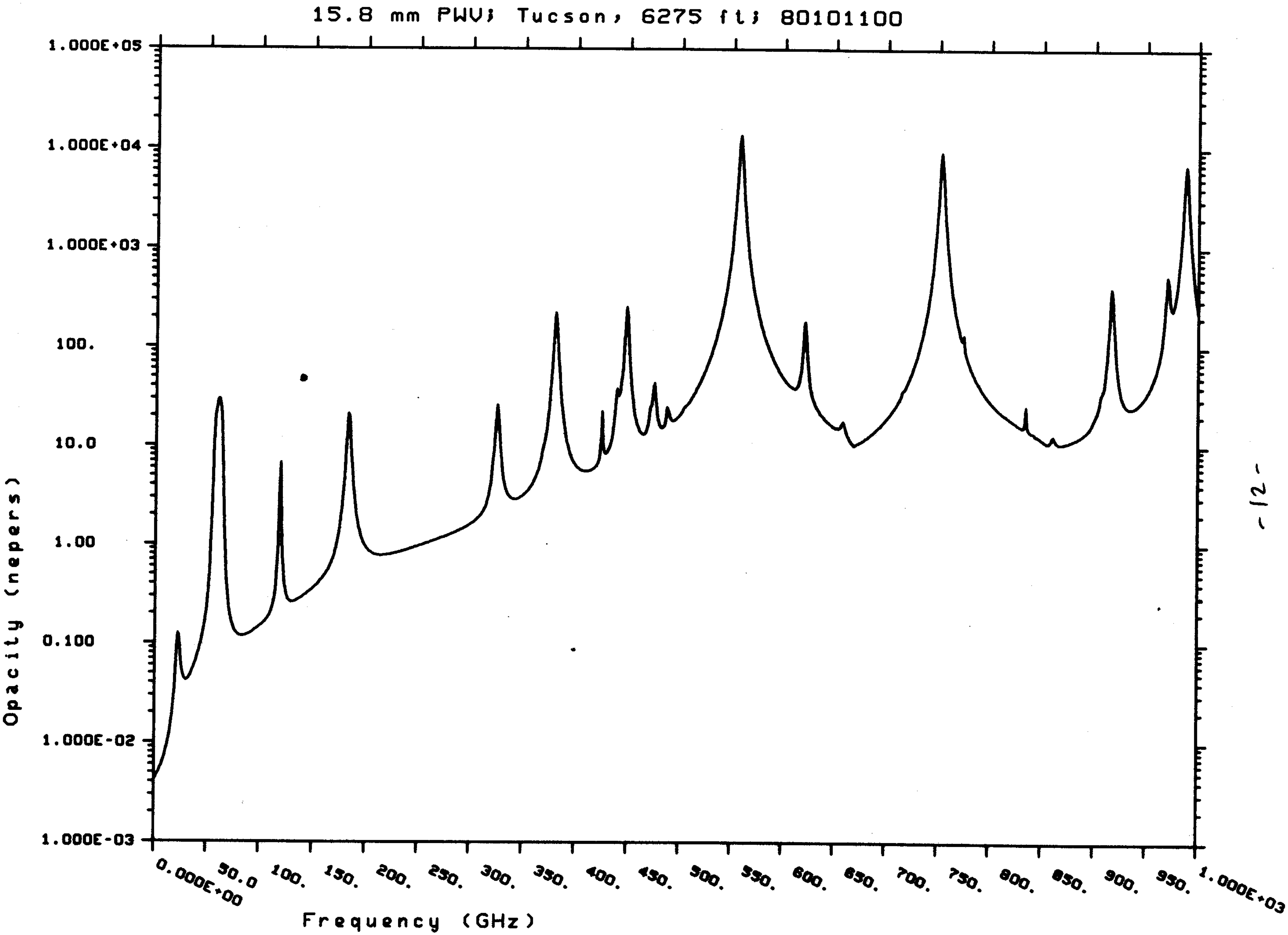

7.8 mm PWV; Tucson, 6275 ft; 82010712
Opacity (nepers)
1.000E+04
1.000E+03
100.
10.0
1.00
0.100
1.000E-02
1.000E-03
Frequency (GHz)
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03

Figure 8.



15.8 mm PWV; Tucson, 6275 ft; 80101100

Figure 9.

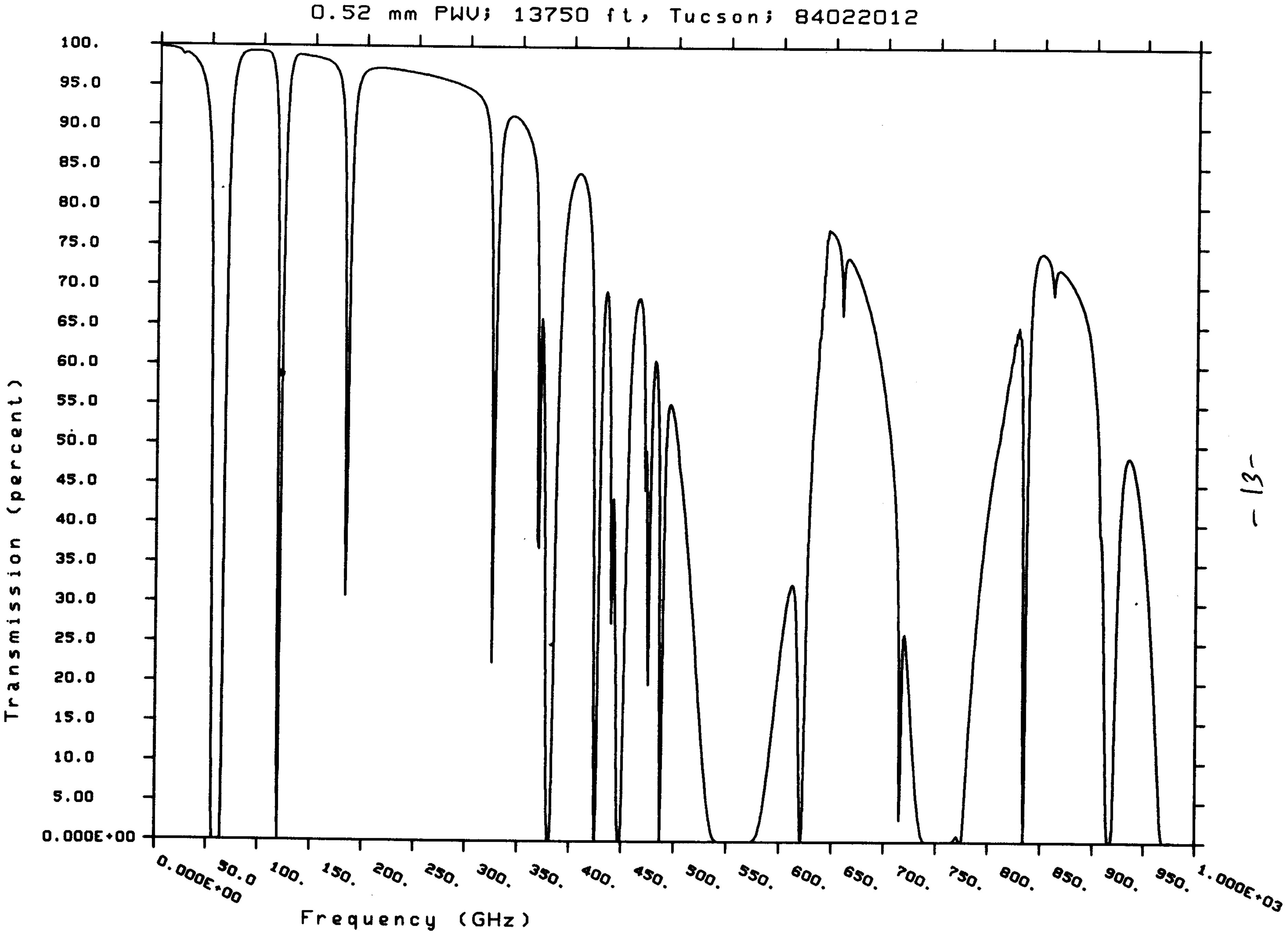

0.52 mm PWV; 13750 ft, Tucson; 84022012
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03
Frequency (GHz)

Figure 10.

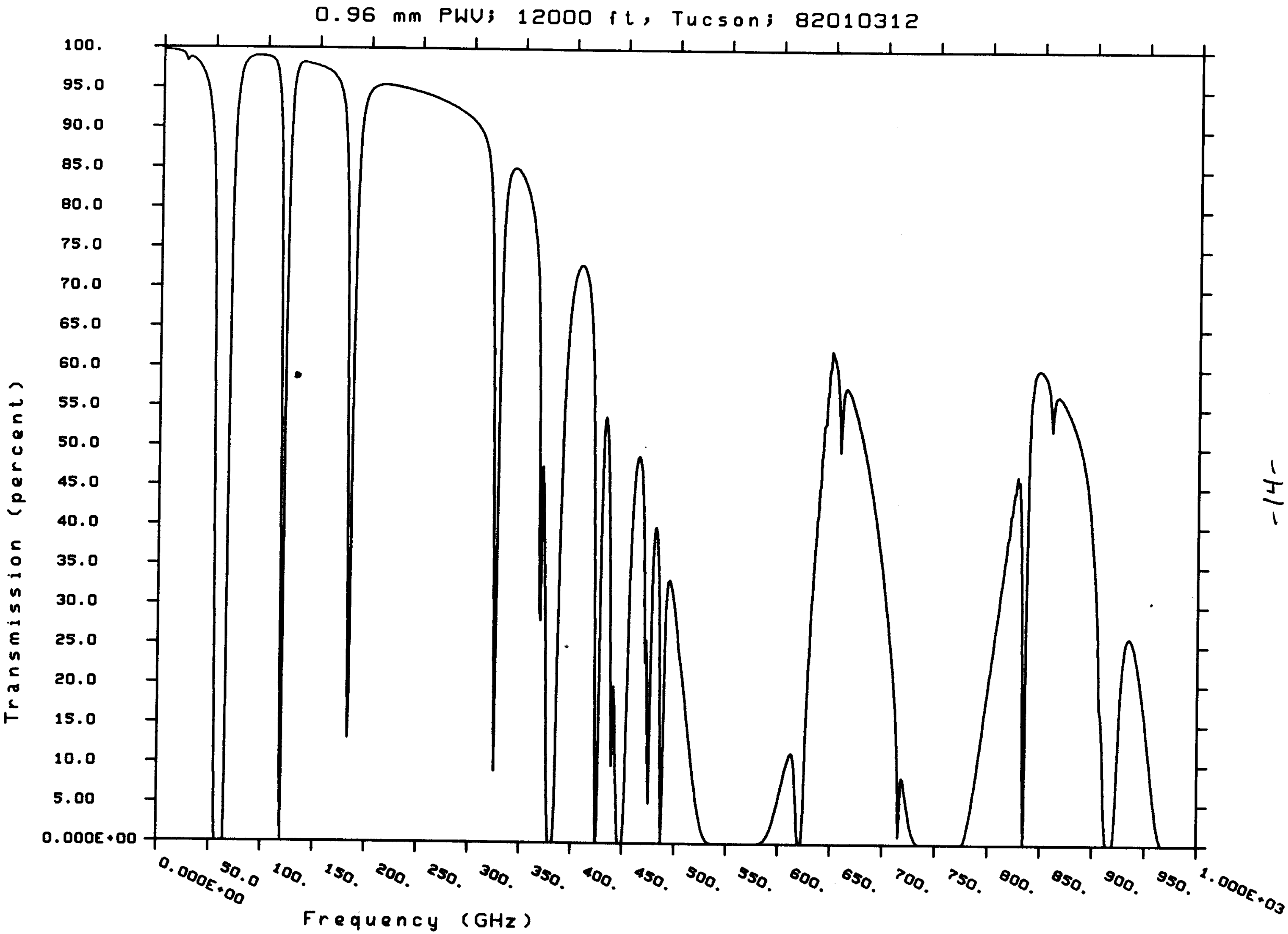

0.96 mm PWV; 12000 ft, Tucson; 82010312
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03
Frequency (GHz)

Figure 11.

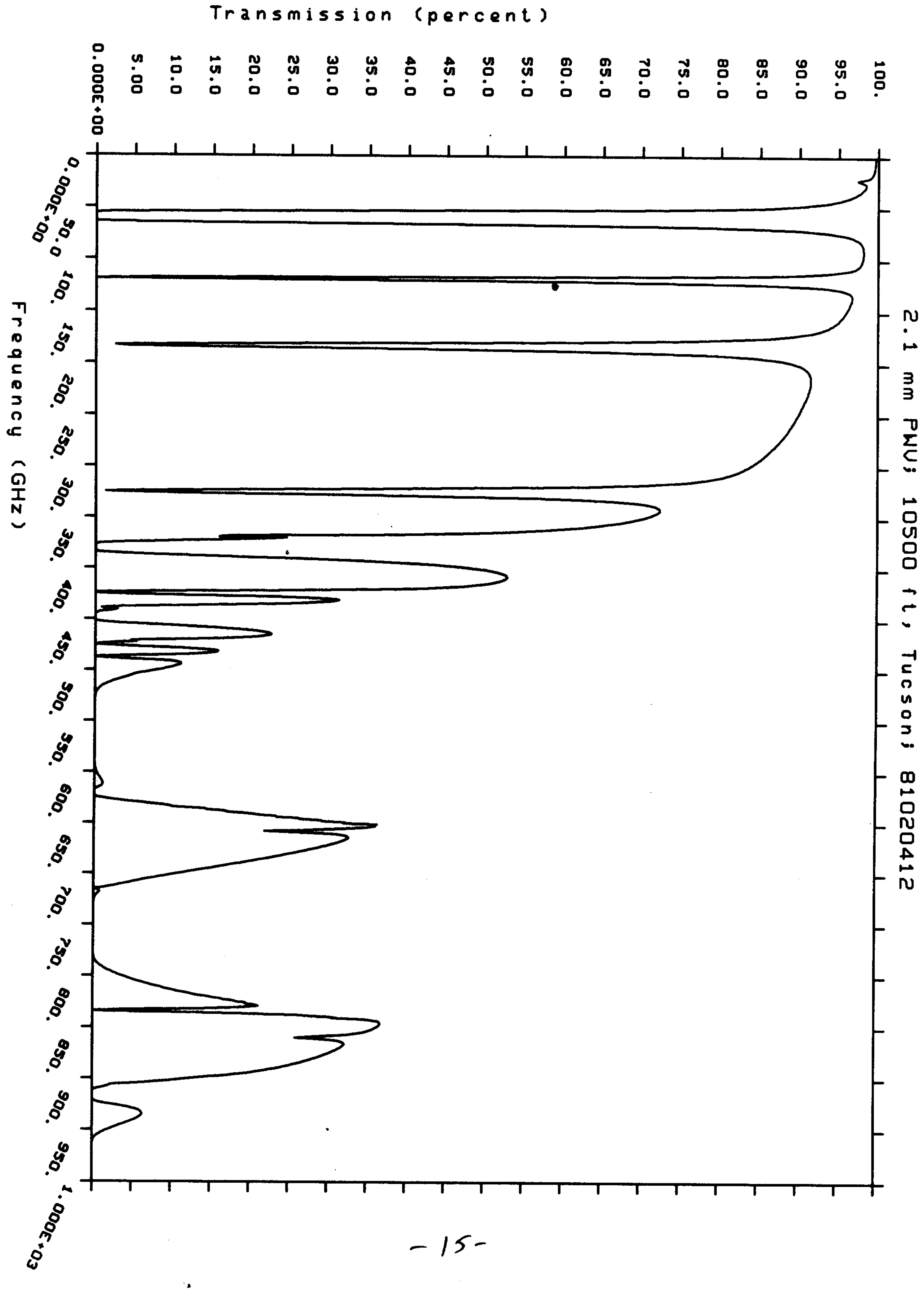
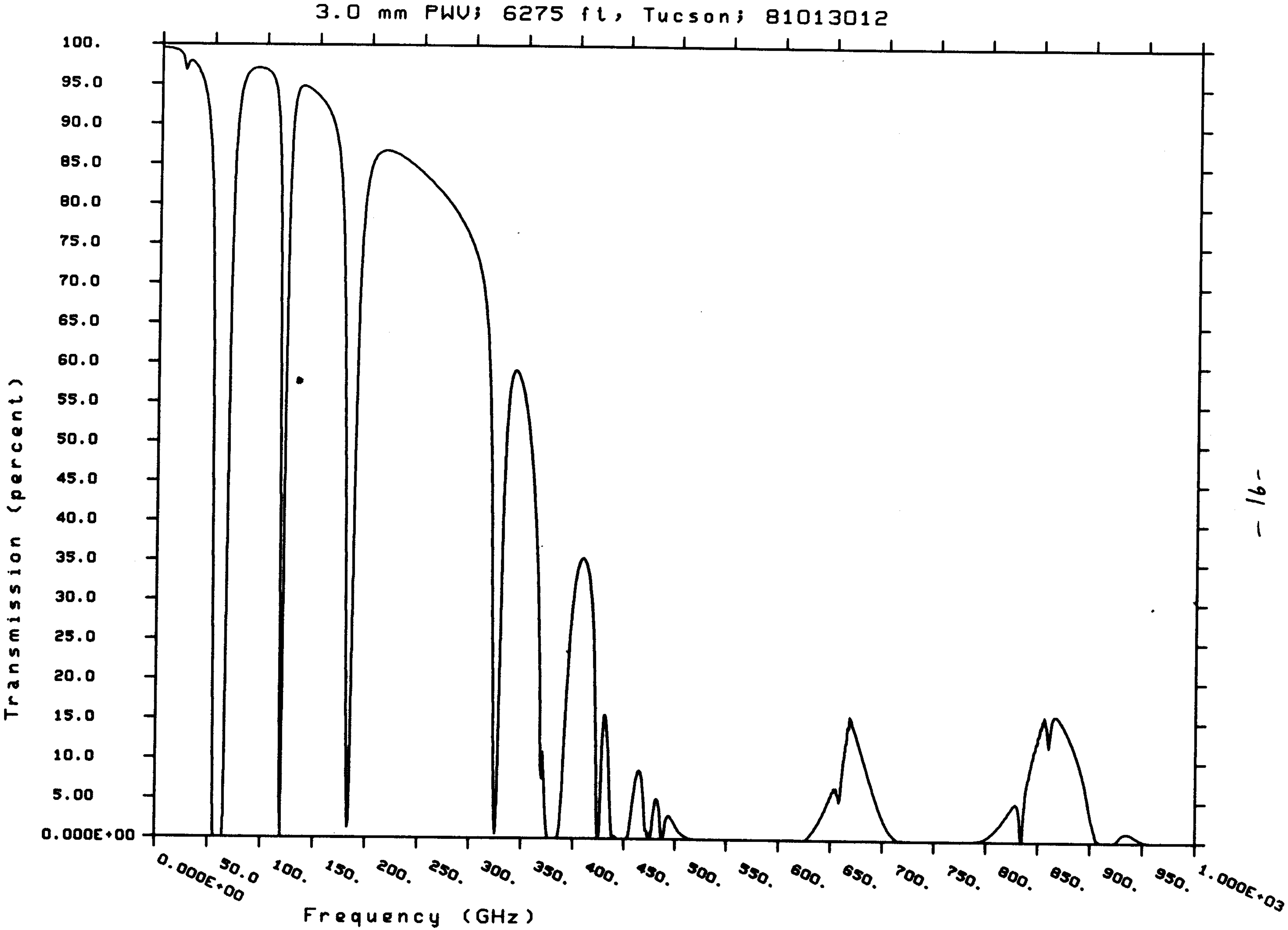

2.1 mm PWV; 10500 ft, Tucson; 81020412
Transmission (percent)
0.000E+00
5.00
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
80.0
85.0
90.0
95.0
100.
Frequency (GHz)
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03

Figure 12.


3.0 mm PWV; 6275 ft, Tucson; 81013012
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
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650.
700.
750.
800.
850.
900.
950.
1.000E+03
Frequency (GHz)

Figure 13.

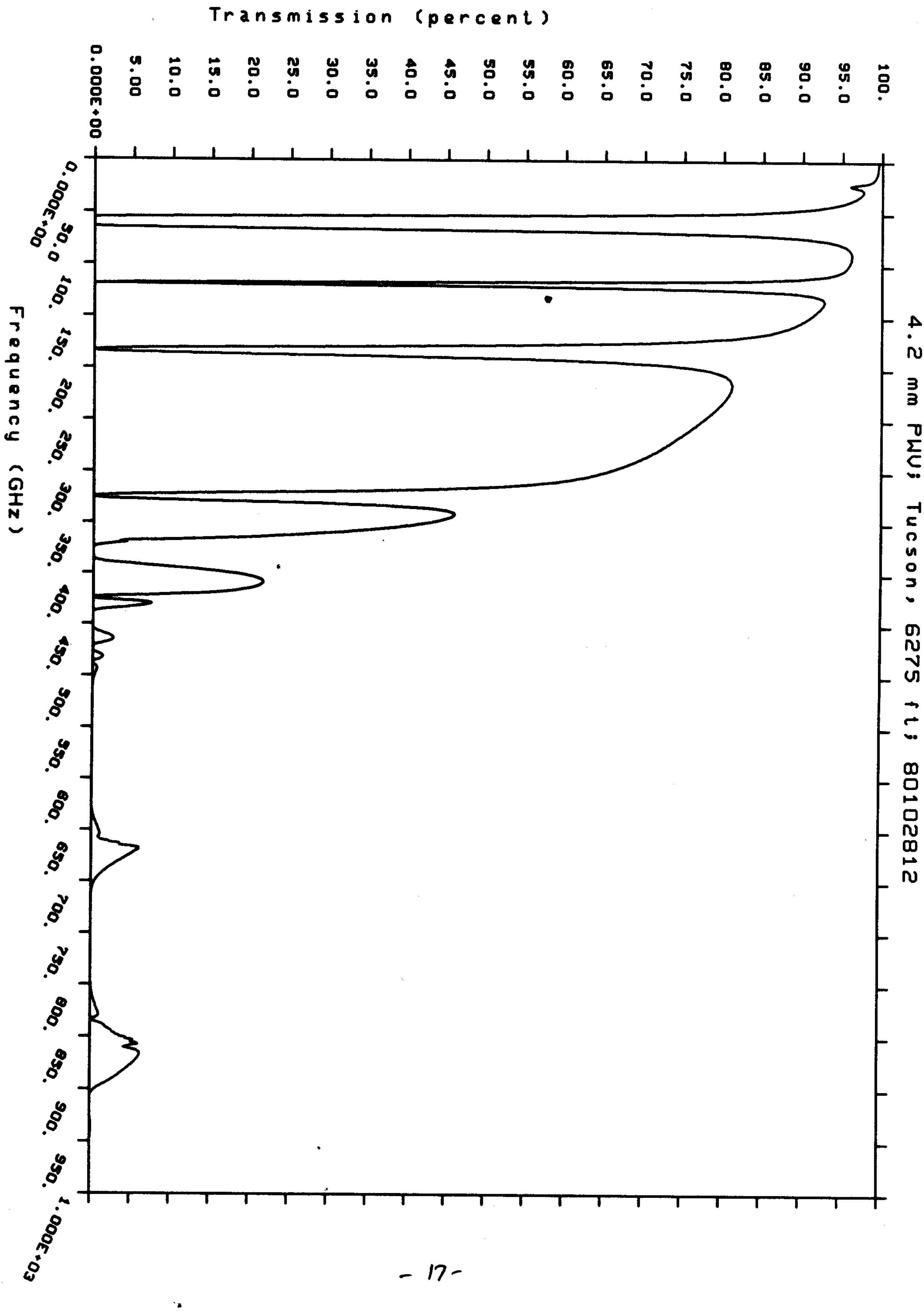
4.2 mm PWV; Tucson, 6275 ft; 80102812
Transmission (percent)
0.000E+00
5.00
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
80.0
85.0
90.0
95.0
100.
Frequency (GHz)
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03

Figure 14.

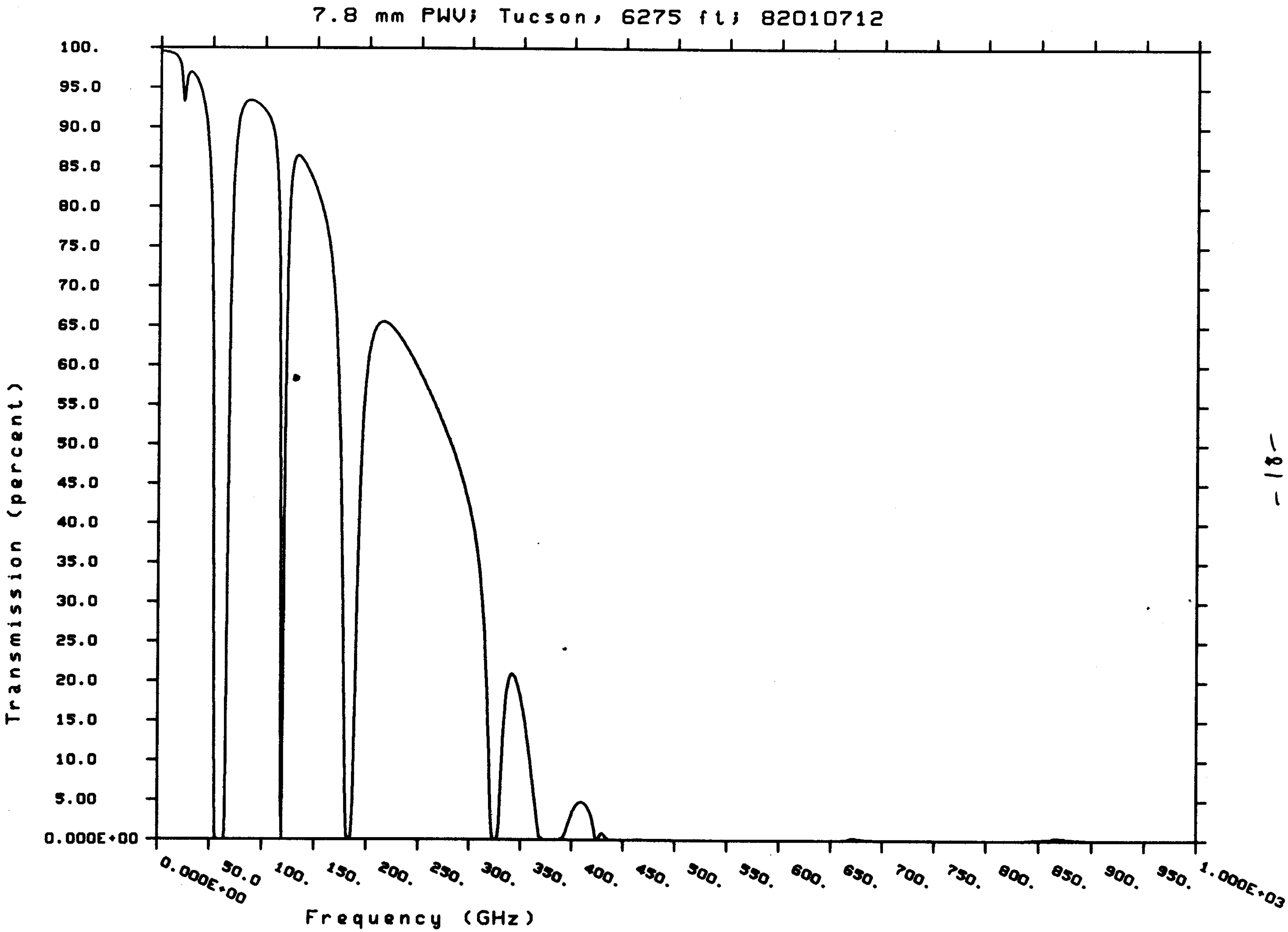
7.8 mm PWV; Tucson, 6275 ft; 82010712
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03
Frequency (GHz)

Figure 15.

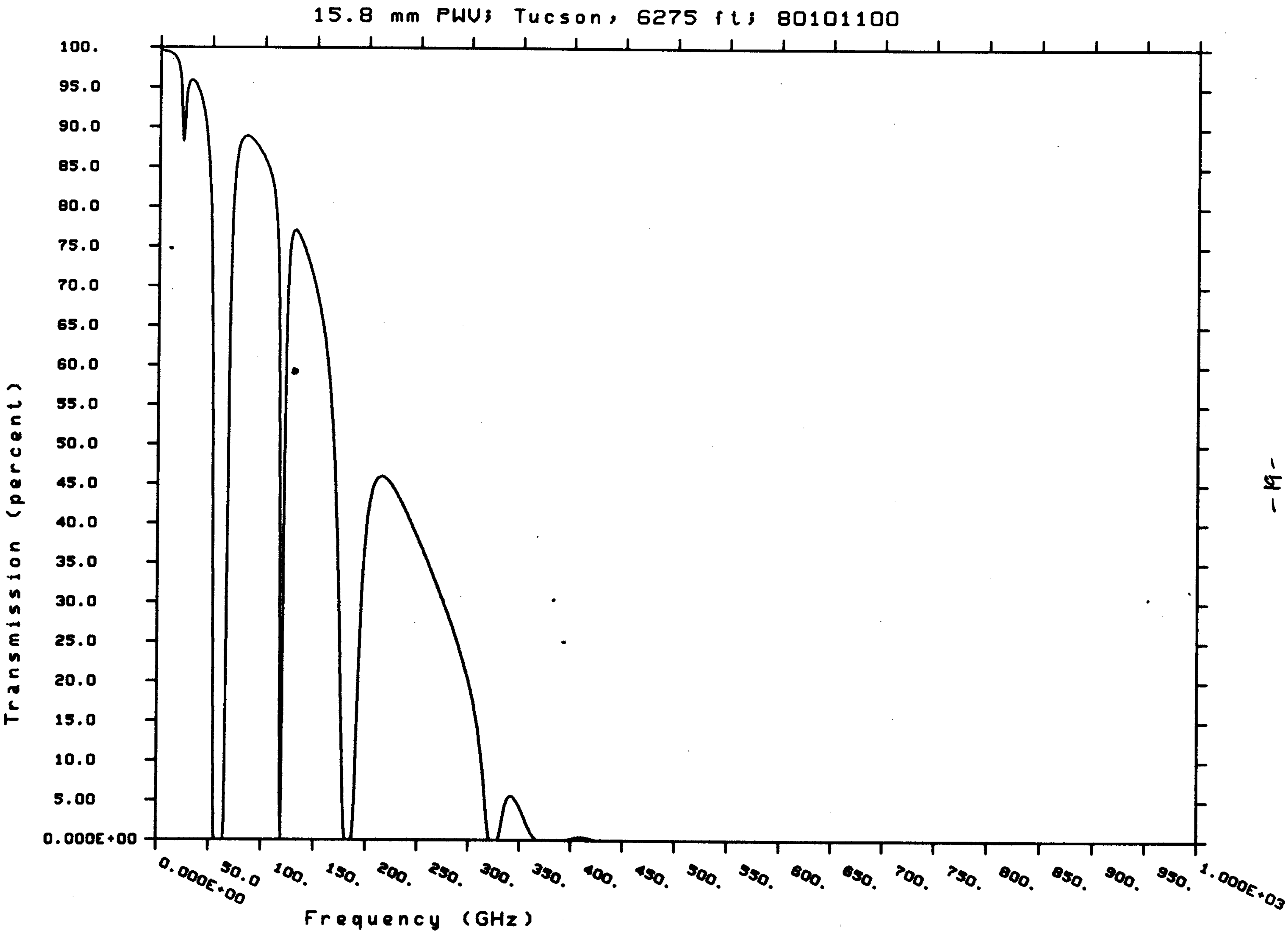
15.8 mm PWV; Tucson, 6275 ft; 80101100
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
0.000E+00
50.0
100.
150.
200.
250.
300.
350.
400.
450.
500.
550.
600.
650.
700.
750.
800.
850.
900.
950.
1.000E+03
Frequency (GHz)

Figure 16.

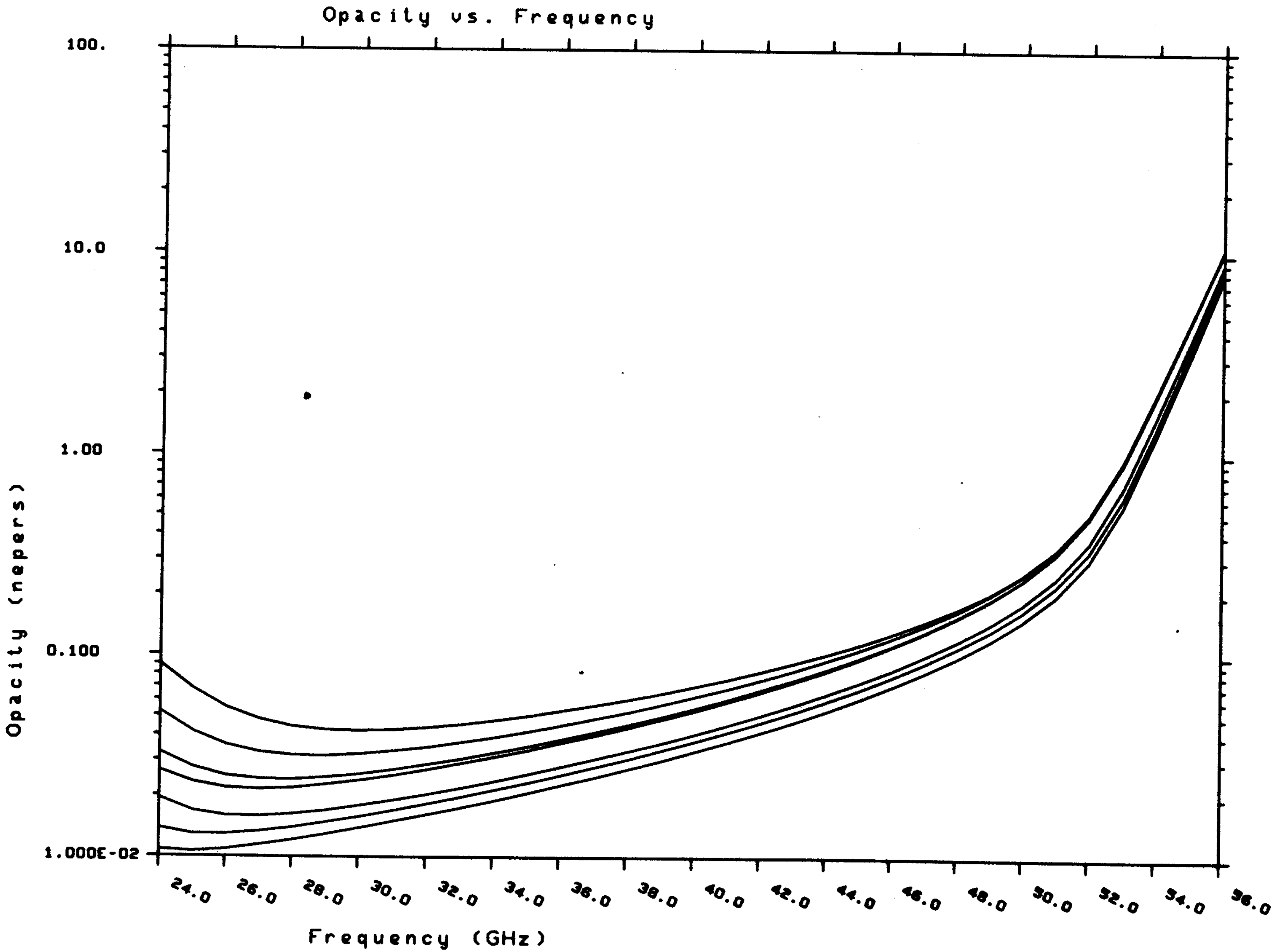
Opacity vs. Frequency
Opacity (nepers)
100.
10.0
1.00
0.100
1.000E-02
24.0
26.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0
50.0
52.0
54.0
56.0
Frequency (GHz)

Figure 17.

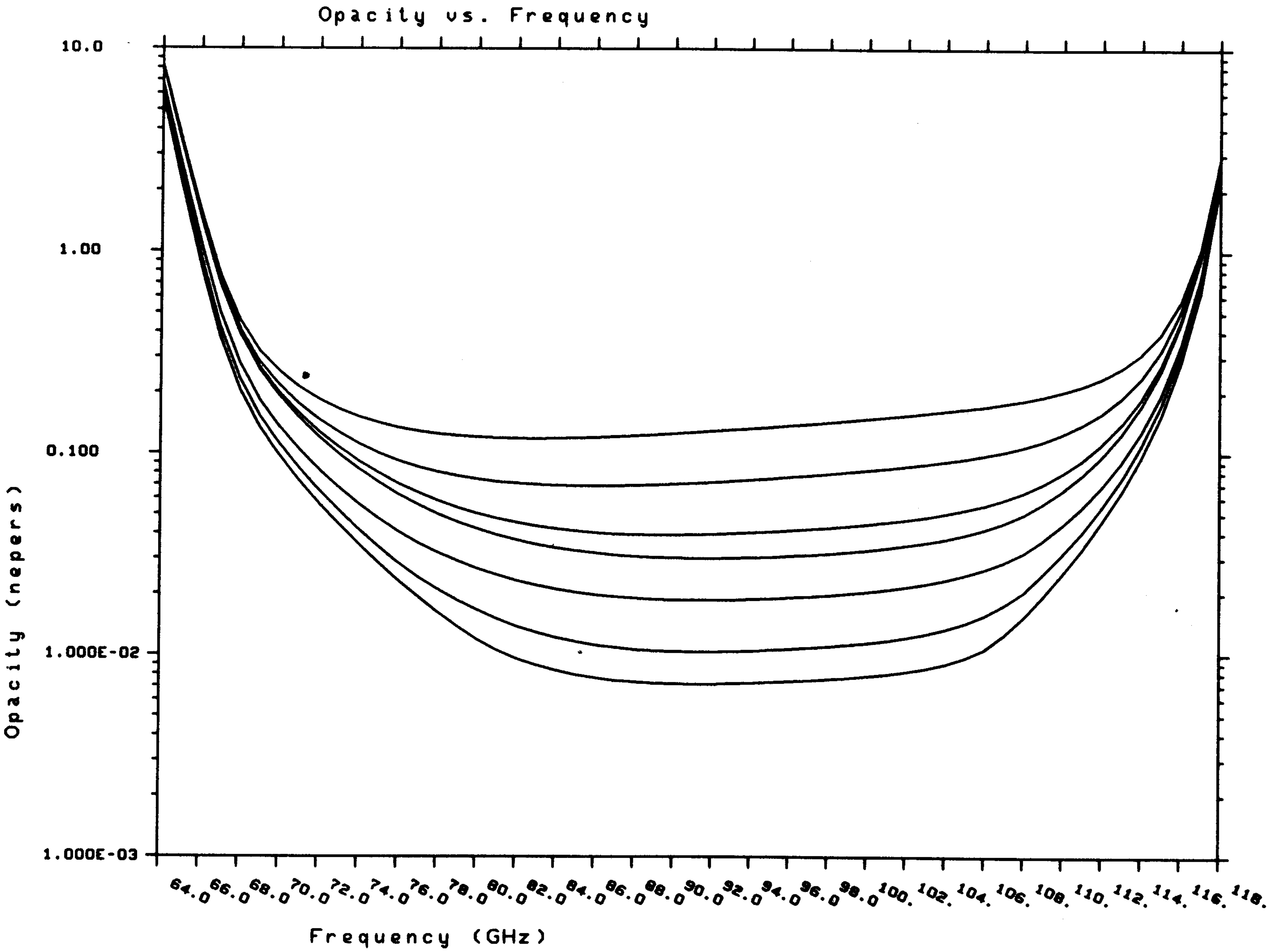
Opacity vs. Frequency
Opacity (nepers)
10.0
1.00
0.100
1.000E-02
1.000E-03
Frequency (GHz)
64.0
66.0
68.0
70.0
72.0
74.0
76.0
78.0
80.0
82.0
84.0
86.0
88.0
90.0
92.0
94.0
96.0
98.0
100.
102.
104.
106.
108.
110.
112.
114.
116.
118.

Figure 18.

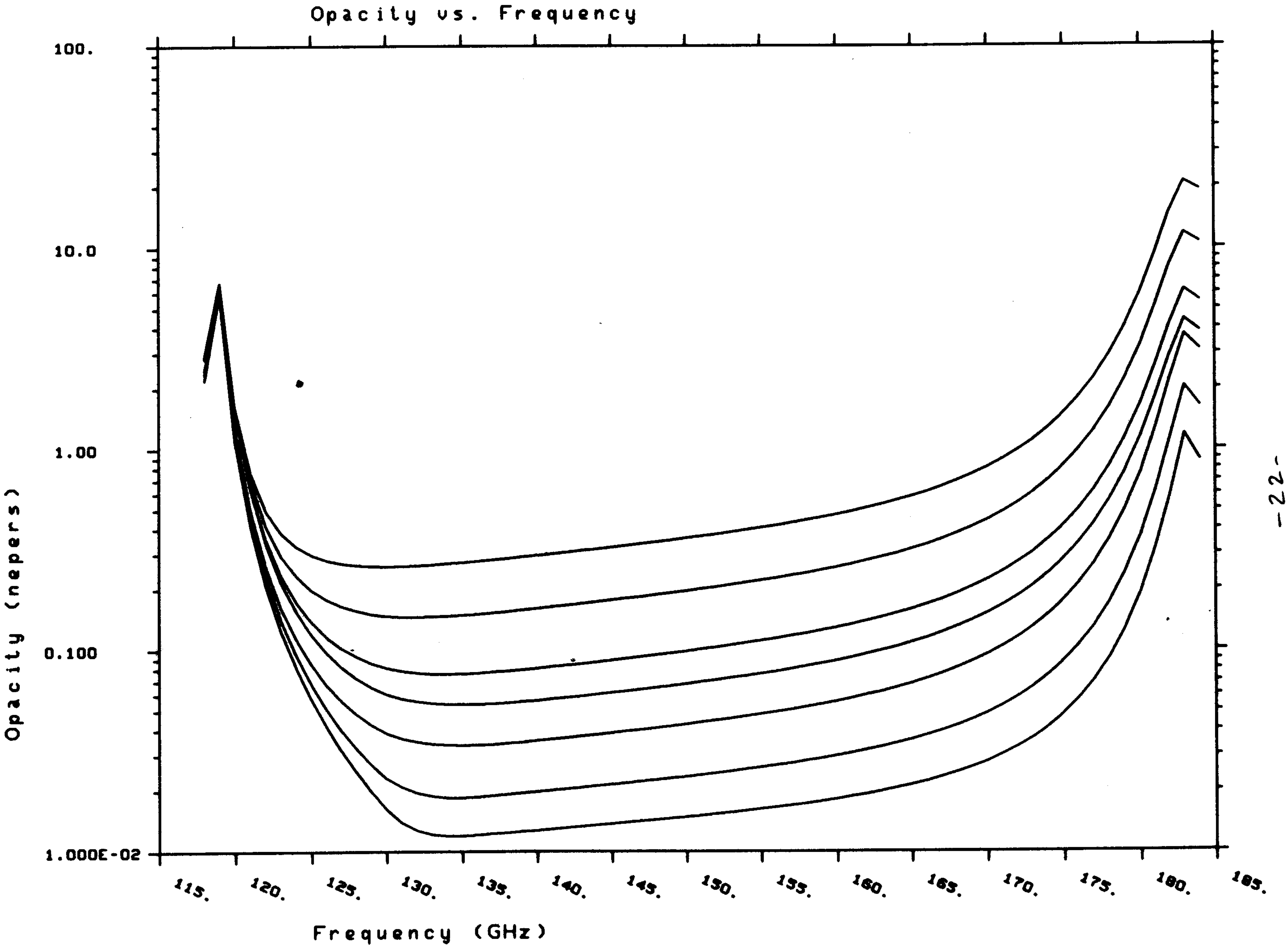
Opacity vs. Frequency
Opacity (nepers)
100.
10.0
1.00
0.100
1.000E-02
115.
120.
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
175.
180.
185.
Frequency (GHz)

Figure 19.

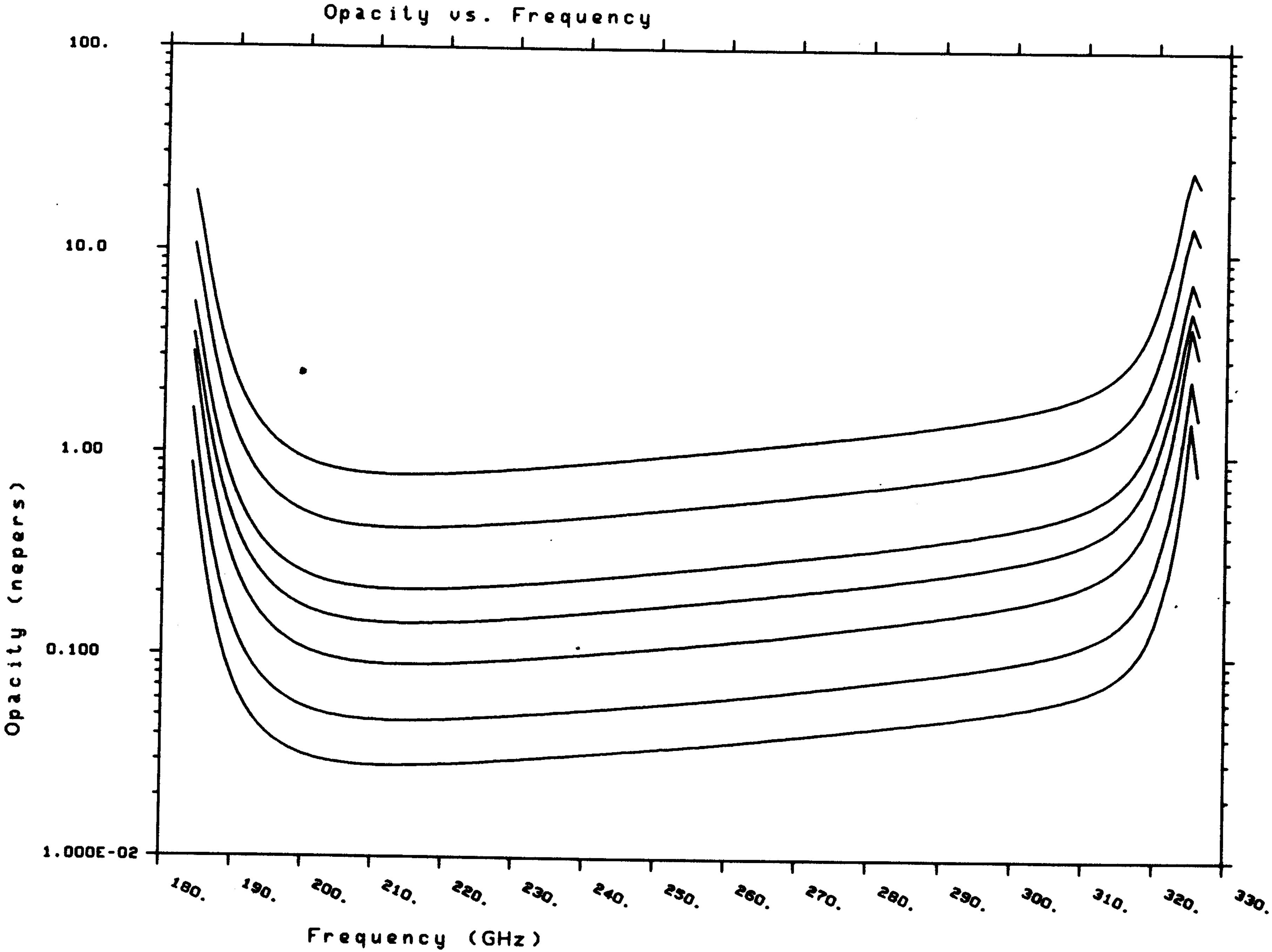
Opacity vs. Frequency
Opacity (nepers)
100.
10.0
1.00
0.100
1.000E-02
180.
190.
200.
210.
220.
230.
240.
250.
260.
270.
280.
290.
300.
310.
320.
330.
Frequency (GHz)

Figure 20.

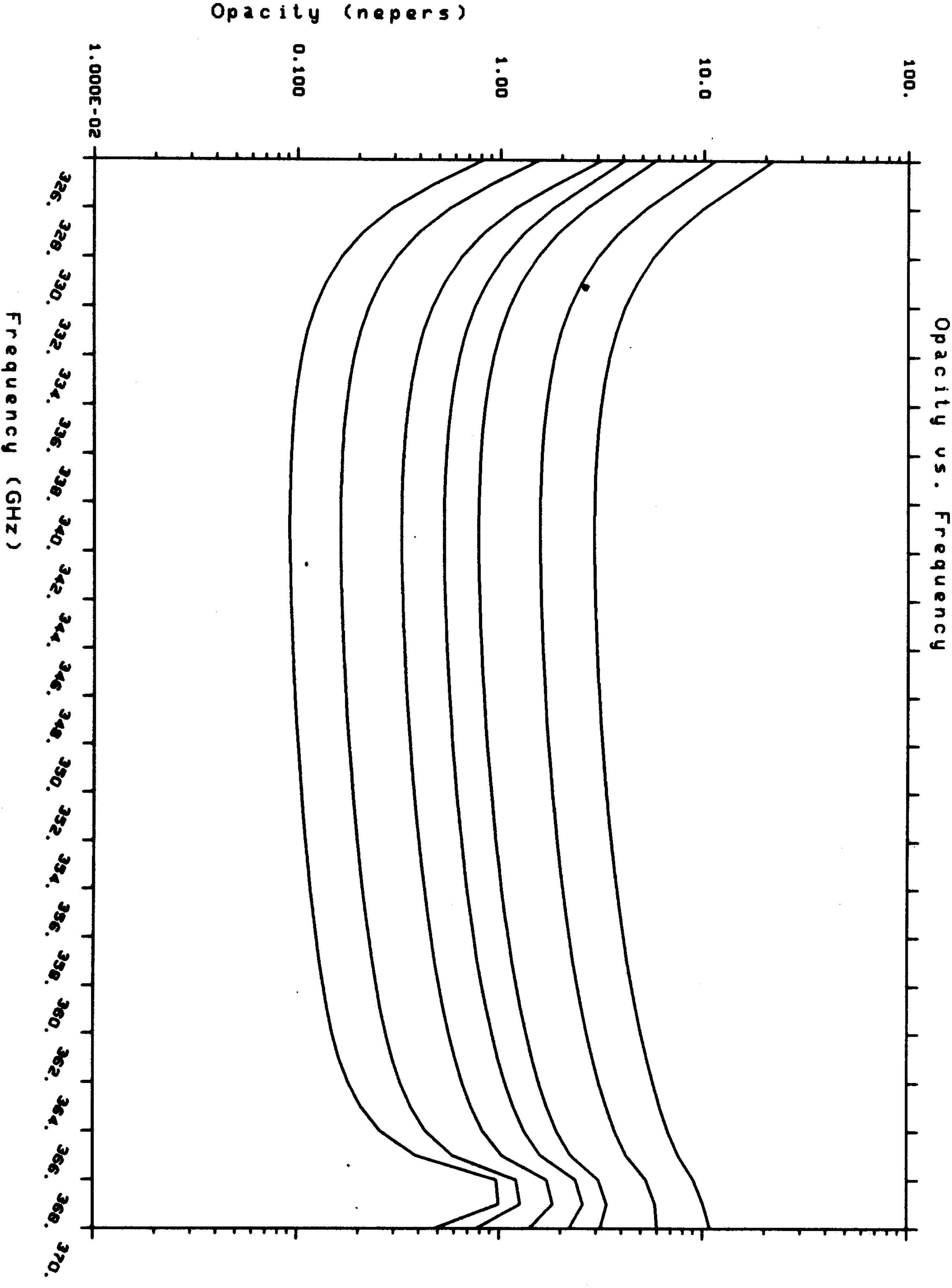
Opacity vs. Frequency
Opacity (nepers)
1.000E-02
0.100
1.00
10.0
100.
Frequency (GHz)
326.
328.
330.
332.
334.
336.
338.
340.
342.
344.
346.
348.
350.
352.
354.
356.
358.
360.
362.
364.
366.
368.
370.

Figure 21.

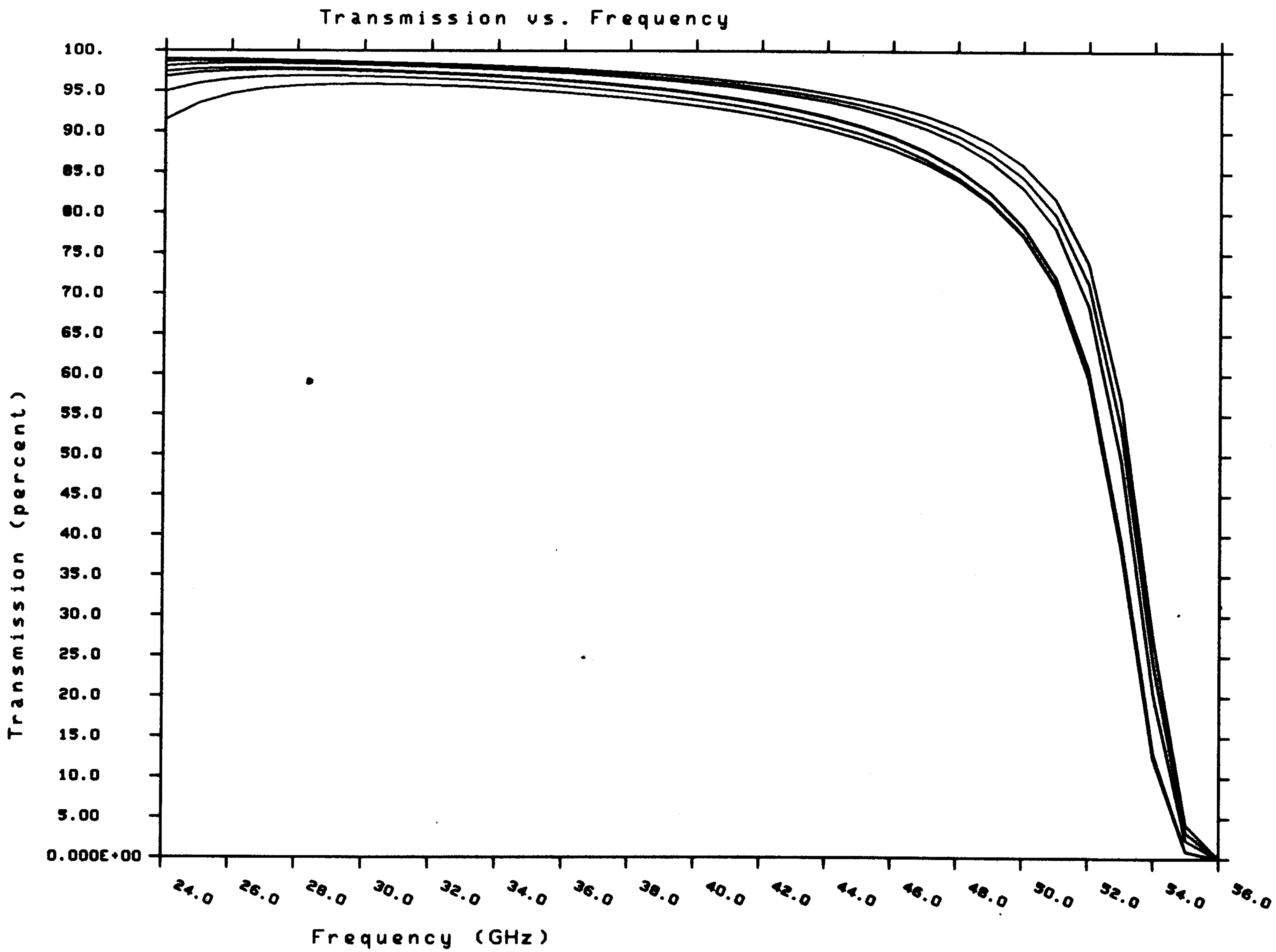
Transmission vs. Frequency
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
24.0
26.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0
50.0
52.0
54.0
56.0
Frequency (GHz)

Figure 22.

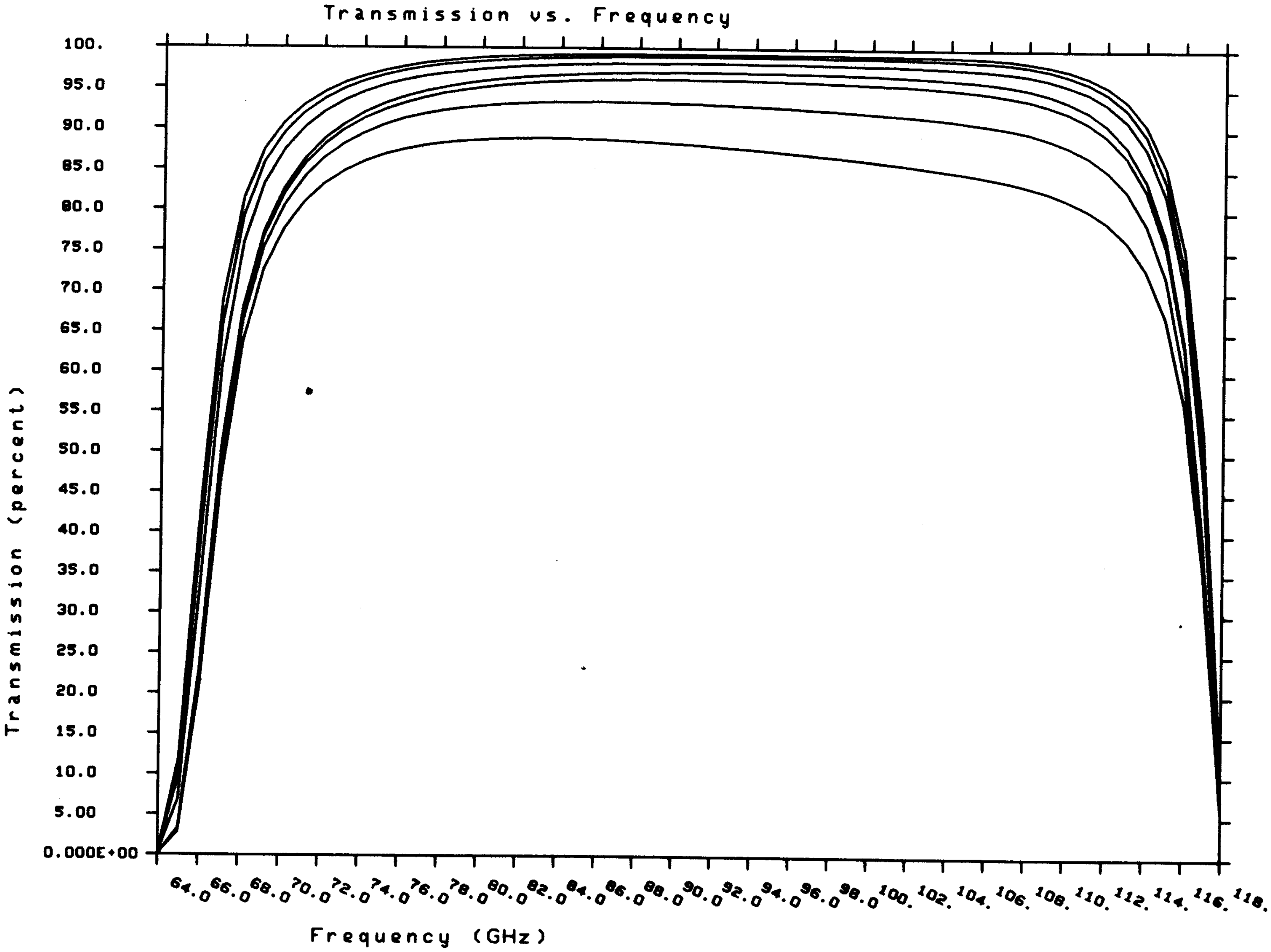
Transmission vs. Frequency
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
64.0
66.0
68.0
70.0
72.0
74.0
76.0
78.0
80.0
82.0
84.0
86.0
88.0
90.0
92.0
94.0
96.0
98.0
100.
102.
104.
106.
108.
110.
112.
114.
116.
118.
Frequency (GHz)

Figure 23.

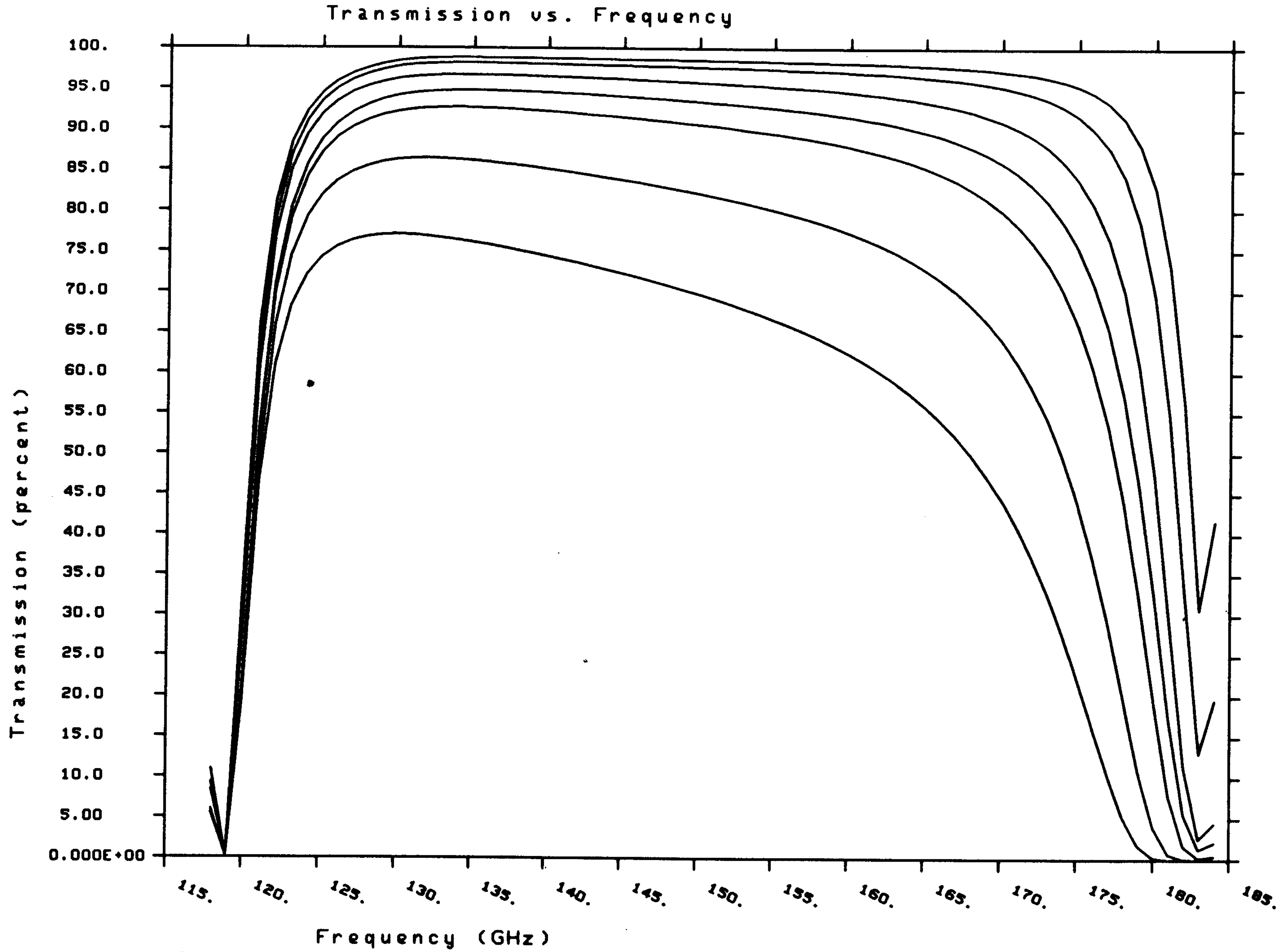
Transmission vs. Frequency
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
115.
120.
125.
130.
135.
140.
145.
150.
155.
160.
165.
170.
175.
180.
185.
Frequency (GHz)

Figure 24.

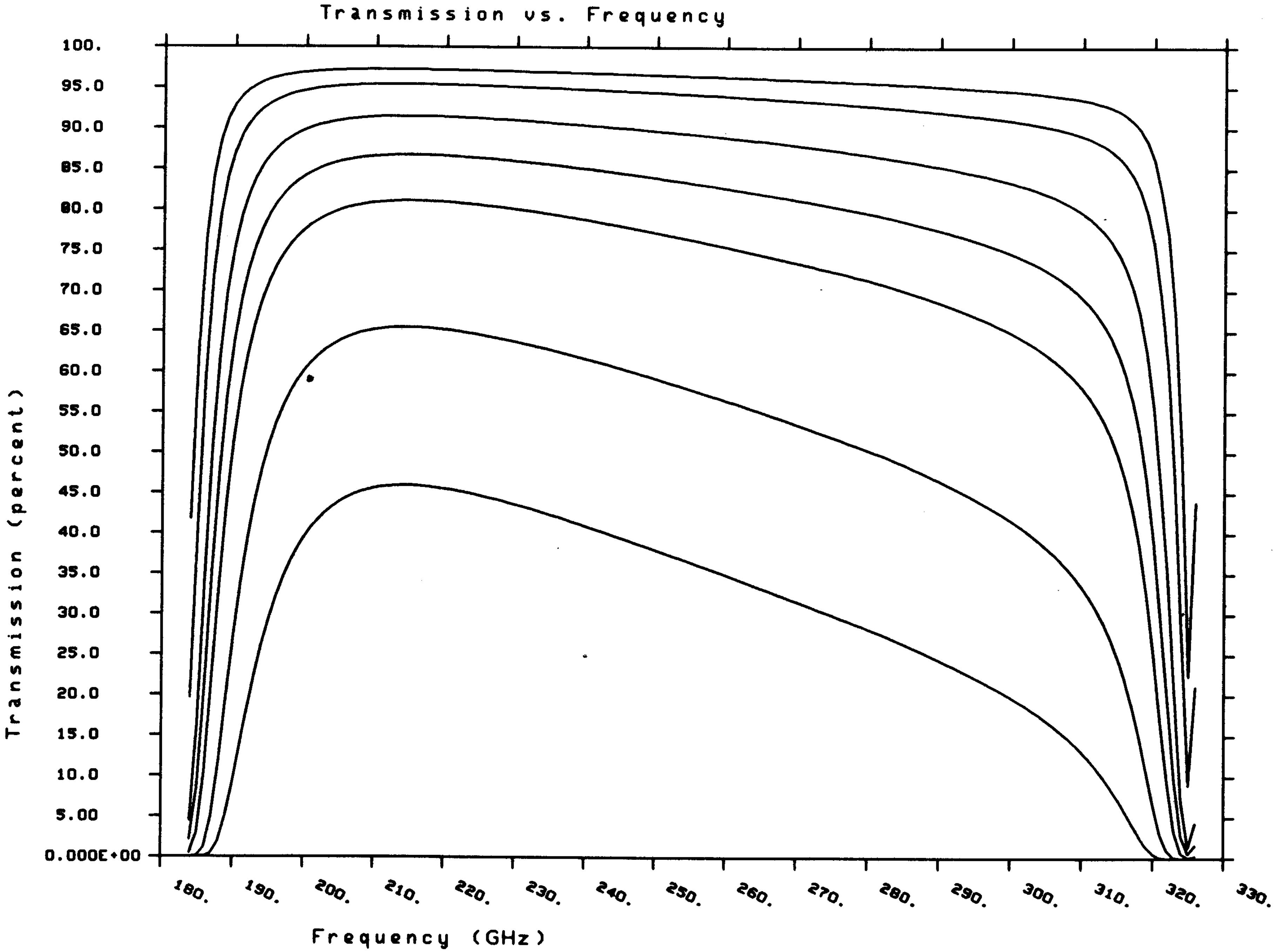
Transmission vs. Frequency
Transmission (percent)
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
180.
190.
200.
210.
220.
230.
240.
250.
260.
270.
280.
290.
300.
310.
320.
330.
Frequency (GHz)

Figure 25.

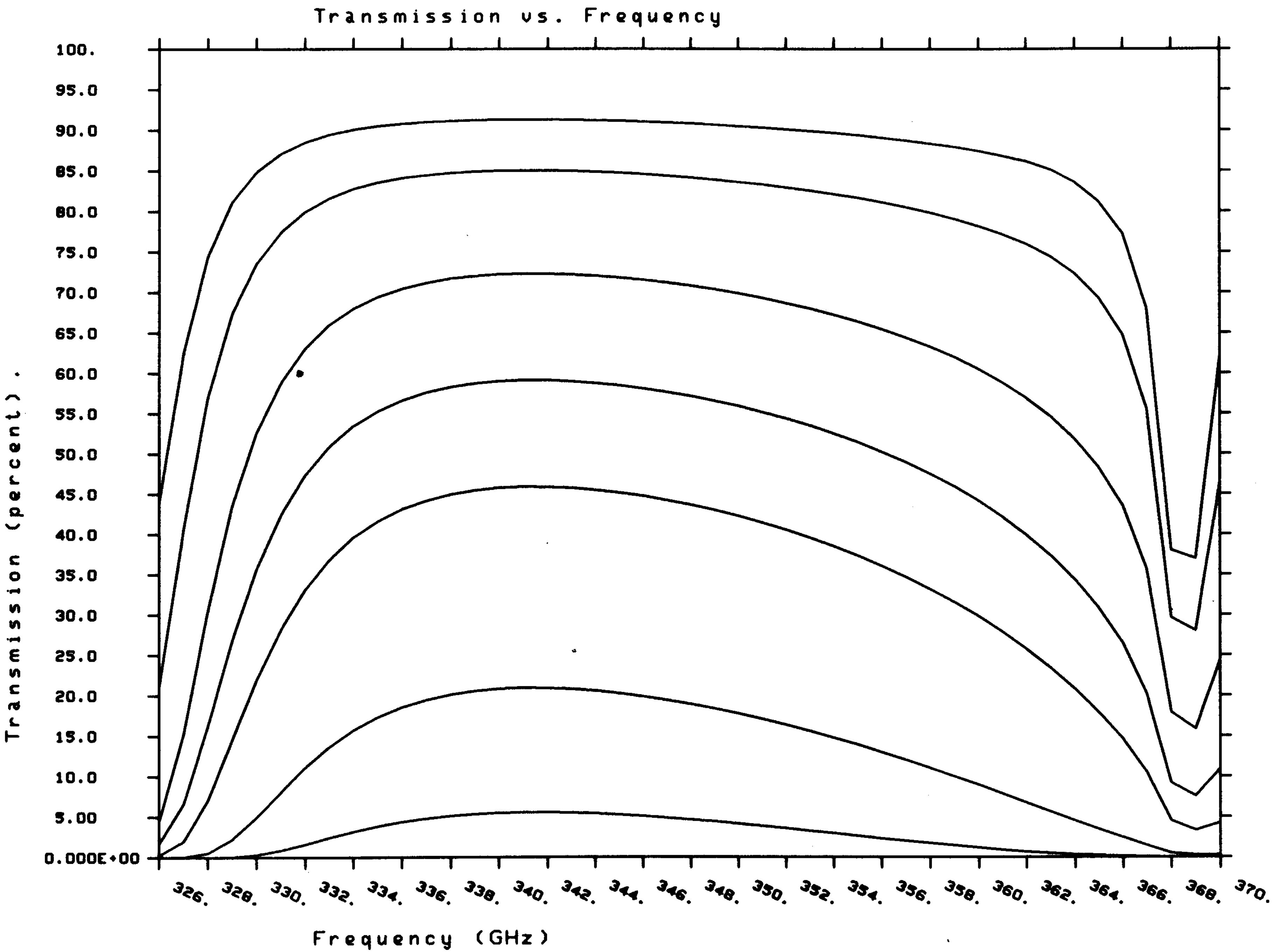
Transmission vs. Frequency
Transmission (percent).
100.
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.00
0.000E+00
326.
328.
330.
332.
334.
336.
338.
340.
342.
344.
346.
348.
350.
352.
354.
356.
358.
360.
362.
364.
366.
368.
370.
Frequency (GHz)

Figure 26.