Interoffice

NATIONAL RADIO ASTRONOMY OBSERVATORY

TUCSON, ARIZONA

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25 Meter Millimeter Wave Telescope
Memo #63

To: 25-M Working Group

From: B. L. Ulich

Subject: Radome study

The 25-M Telescope will be enclosed in an astrodome with a removeable door which is, for all practical purposes, identical to a section of a spherical radome. A dielectric membrane will cover the triangular openings of the metal space frame. The constraints on the support members are principally structural: we want a door strong enough to survive high winds but yet with as small a cross-sectional area as possible to minimize aperture blockage. For millimeter wavelengths the blockage is simply the geometrical area projected onto the telescope aperture and weighted by the illumination function. The smallest blocked area that can be achieved using conventional techniques is about 5% and the gain of the telescope is therefore reduced by 10%. Possible boresight errors can be minimized by utilizing a random icosahedral geometry for the triangular panels.

The second and more critical element in the radome is the dielectric membrane. Generally thin, low-loss dielectric sandwich materials are used to achieve the necessary mechanical strength and weathering resistance with the least degradation of the telescope performance. In general the deleterious effects due to a metal space frame radome fall into the following categories:

(1) loss of telescope gain due to scattering from the metal space frame and to reflection, absorption, and phase errors in the dielectric panels,

(2) increase in sidelobe levels due to aperture blockage and phase errors,

(3) increase in system noise temperature due to scattered ground radiation and to emission from the panels,

(4) boresight pointing error,

(5) standing waves between the telescope and radome, and

(6) diffraction lobes due to periodic space frame and membrane structure.

Extensive tests on the Haystack radome have shown that boresight pointing errors, polarization effects, and gain and noise granularity are all negligibly small for the type of radome we are considering. The increase in the system noise temperature should be about 20K. To my knowledge no measurements of radome standing waves have been reported for radio astronomy telescopes, but some observers at the NRAO 36-foot telescope claim that observing through the side of the astrodome accentuates baseline problems. The most serious effect of radomes is the significant signal attenuation at millimeter wavelengths. Figure 1 is a plot of the transmissivity of a dielectric fabric (which covers the NRAO astrodome on Kitt Peak) versus the angle of incidence for both perpendicular and parallel linear polarizations. The solid line is a homogeneous dielectric model fit to the measurements by least squares. One can see that the loss is small at normal incidence and is polarization dependent. At large incidence angles the average loss increases rapidly. The net effect is to artificially taper the amplitude illumination function. This tapering is more severe when the radome diameter approaches the telescope aperture size and will produce slightly larger telescope beamwidths and reduced gain. Figure 2 is a plot of transmissivity at normal incidence versus frequency using the same model fit to the polarization data in Figure 1. The agreement between the model and the measurements is excellent at the lower frequencies, but not particularly good above 100 GHz.

Figure 3 separates the different loss components of a dielectric covered, metal space frame radome (using the ESSCO Esscolam V design) into blockage, absorption, and reflection losses. Generally the reflection loss predominates, with resonances visible at wavelength intervals of quarter-wave electrical thickness. One should adjust either the dielectric constant or the material thickness in order to obtain low-loss at the frequencies of interest. Note that the NRAO astrodome material has an effective electrical thickness of 1.6 mm while Esscolam V is 1.5 mm. Thus the transmission curves are quite similar. For radio astronomy it is advantageous to match the transmission peaks to the atmospheric windows defined by the absorption lines of H_2O and O_2. By making the dielectric quite thin the first resonance can be shifted to shorter wavelengths. Figure 4 is the transmissivity/frequency plot for black sailcloth. This material is strong enough for radome uses but has a short expected lifetime (∿1 year) due to breakdown of the Dacron yarn by ultraviolet radiation. In addition, about 17% of the available solar energy is transmitted, which will cause thermal distortions in the antenna. As can be seen in Figure 4, the low transmissivity from 200-400 GHz seriously hampers the telescope performance in this critical range. Thus black sailcloth of the type tested (Bainbridge 3.8 ounce Dacron) does not appear to offer significant advantages over the thicker, sandwich materials now in general use.

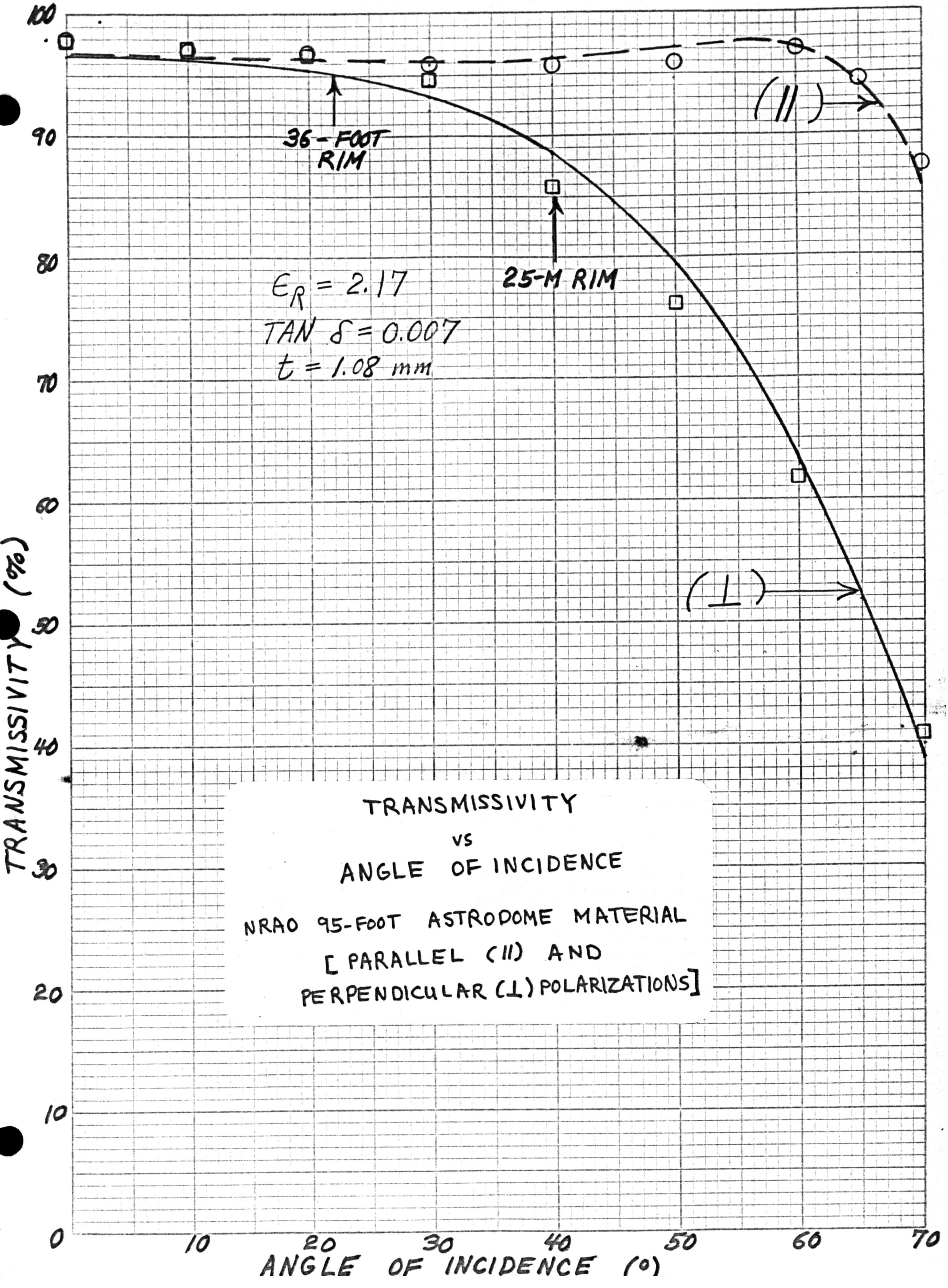
The only radome for which full-scale loss measurements have been made is the NRAO 95-foot astrodome, and the results are presented in Figure 5 along with the model calculations. The area blocked by the metal space frame is 7.8% which results in a transmissivity of 85%. Observations made in 1973 when the fabric was removed for replacement indicate a transmissivity of 0.84±0.02 at 3.5 mm wavelength, in excellent agreement with calculation. The large scatter in the measurements is probably due to the fact that the dome loss is somewhat elevation angle dependent because of the large arch beams and the non-spherical geometry. The measurements plotted in Figure 5 were made using an extended source (the Sun) and refer to blockage, absorption, and reflection losses. In Figure 6 I have plotted the radome transmissivity versus frequency when observing a point source. The agreement with the simple (planar) dome model is reasonable at long wavelengths but worsens at high frequencies. The cause of the observed extra loss is phase errors. Periodic and random variations in the insert phase of the dielectric material will distort the planar phase front of the signal, reduce the peak gain, and produce an error pattern. Figure 7 is a plot of the ratio of the dome transmissivity for a point source to that for an extended source. This extra loss in gain is due to phase errors which have an RMS of about 0.13 mm if the correlation length is small compared to the telescope aperture. Variations in the electrical thickness of the radome cover of up to 0.05 mm are expected from the scalloped curve of the radome wall. In addition, variations in the mechanical thickness of up to 0.08 mm have been measured on different material samples. At 230 GHz scans of the Sun through the dome indicate a significant enhancement of the error pattern with a width corresponding to a short correlation length (<1 m). Observations of Jupiter at 90 GHz show that the dome produces astigmatism of the main lobe. Thus the radome also introduces some phase errors which are correlated over the entire aperture (this component may be due to the spherical curvature of the radome wall).

In general the performance of the NRAO 95-foot astrodome will be poorer than a well-designed metal space frame radome. However, the poor phase efficiency of the astrodome points out one area in which problems might arise for the 25-M astrodome door. Observations at longer wavelengths (such as at Haystack) will not reveal the presence of phase errors which could severely hamper radome performance at very short wavelengths. Care must be taken to assure uniformity in the electrical thickness of dielectric panels in order to minimize insert phase variations.

The only feasible method of significantly reducing the overall dome loss is to reduce the reflection component by matching the outer dielectric surfaces. This can be done in several ways at one frequency, but good matching over a decade in frequency is very difficult to achieve in practice. One must somehow vary the effective dielectric constant from near unity at the surfaces to a higher value in the center of the panel.

This could be done by layering very thin homogeneous sheets of varying dielectric constant, but no structurally strong,durable, and waterproof materials have dielectric constants below about 2.0. One alternative is to artifically create a graded dielectric interface by cutting grooves in a rigid, flat, homogeneous dielectric panel. The groove spacing determines the high-frequency cutoff and the groove depth sets the low frequency limit. It may be possible to construct thick (and strong) grooved panels with less than 10% loss over a 10:1 bandwidth in frequency. I plan to investigate the performance, manufacturing methods, and cost of large panels with matching grooves.

FIGURE 1



100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
ANGLE OF INCIDENCE (°)
TRANSMISSIVITY (%)
36-FOOT RIM
25-M RIM
(//)
(⊥)
$\epsilon_R = 2.17$
$TAN\ \delta = 0.007$
$t = 1.08\ mm$
TRANSMISSIVITY
VS
ANGLE OF INCIDENCE
NRAO 95-FOOT ASTRODOME MATERIAL
[PARALLEL (//) AND
PERPENDICULAR (⊥) POLARIZATIONS]

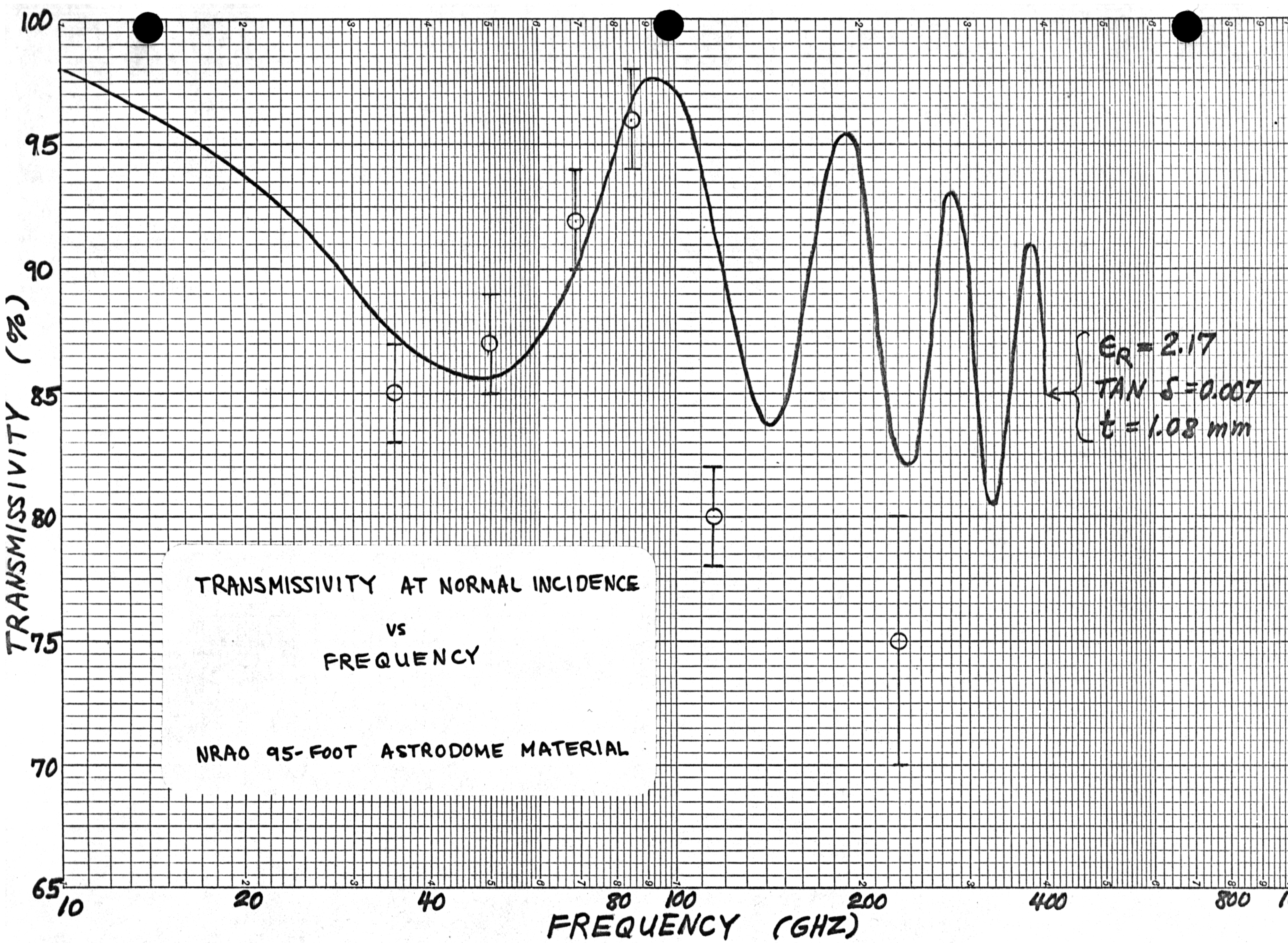

TRANSMISSIVITY AT NORMAL INCIDENCE
VS
FREQUENCY
NRAO 95-FOOT ASTRODOME MATERIAL
TRANSMISSIVITY (%)
FREQUENCY (GHZ)
100
95
90
85
80
75
70
65
10
20
40
80
100
200
400
800
1000
$\epsilon_R = 2.17$
$\tan\delta = 0.007$
$t = 1.08$ mm

FIGURE 2

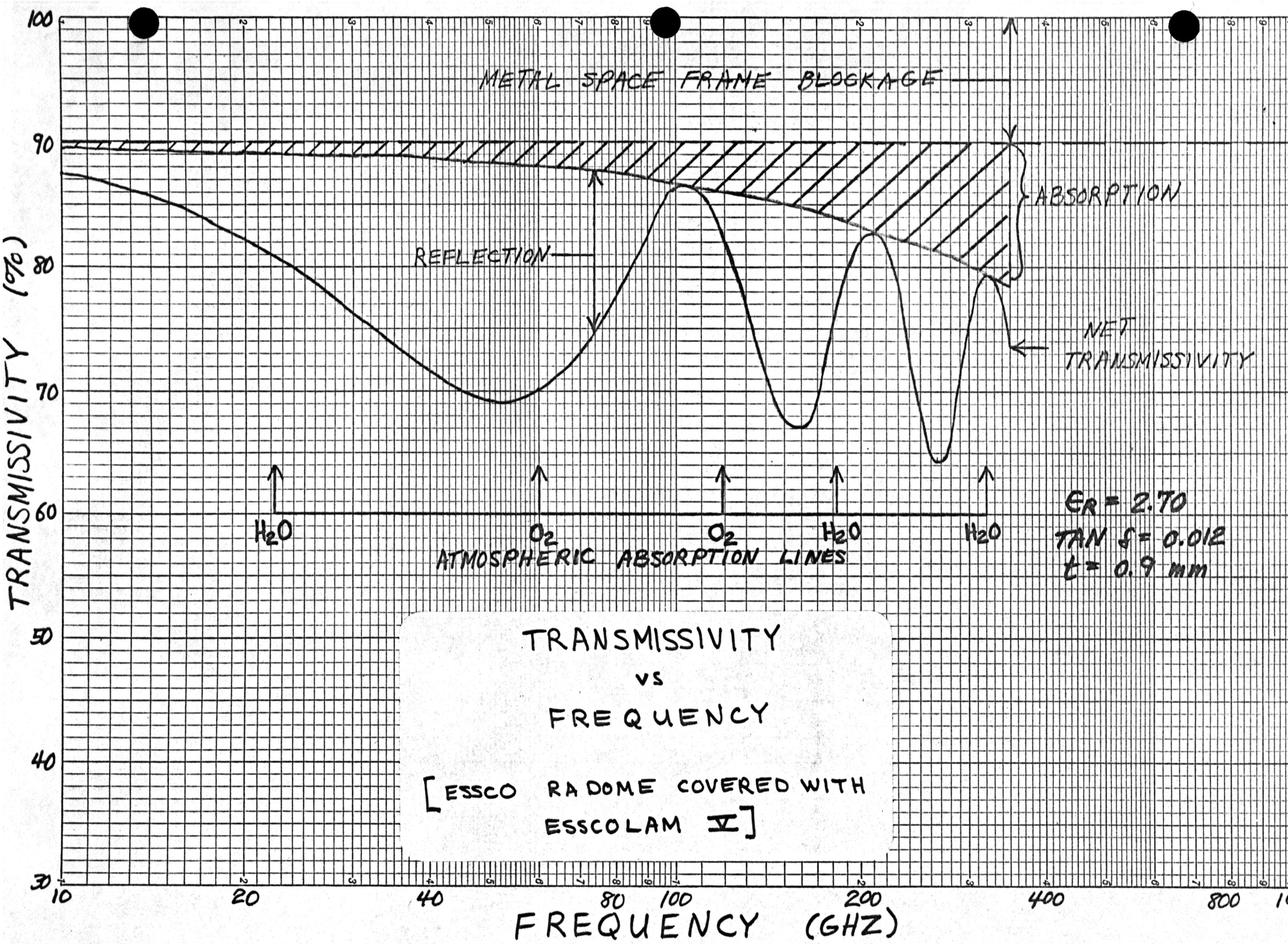
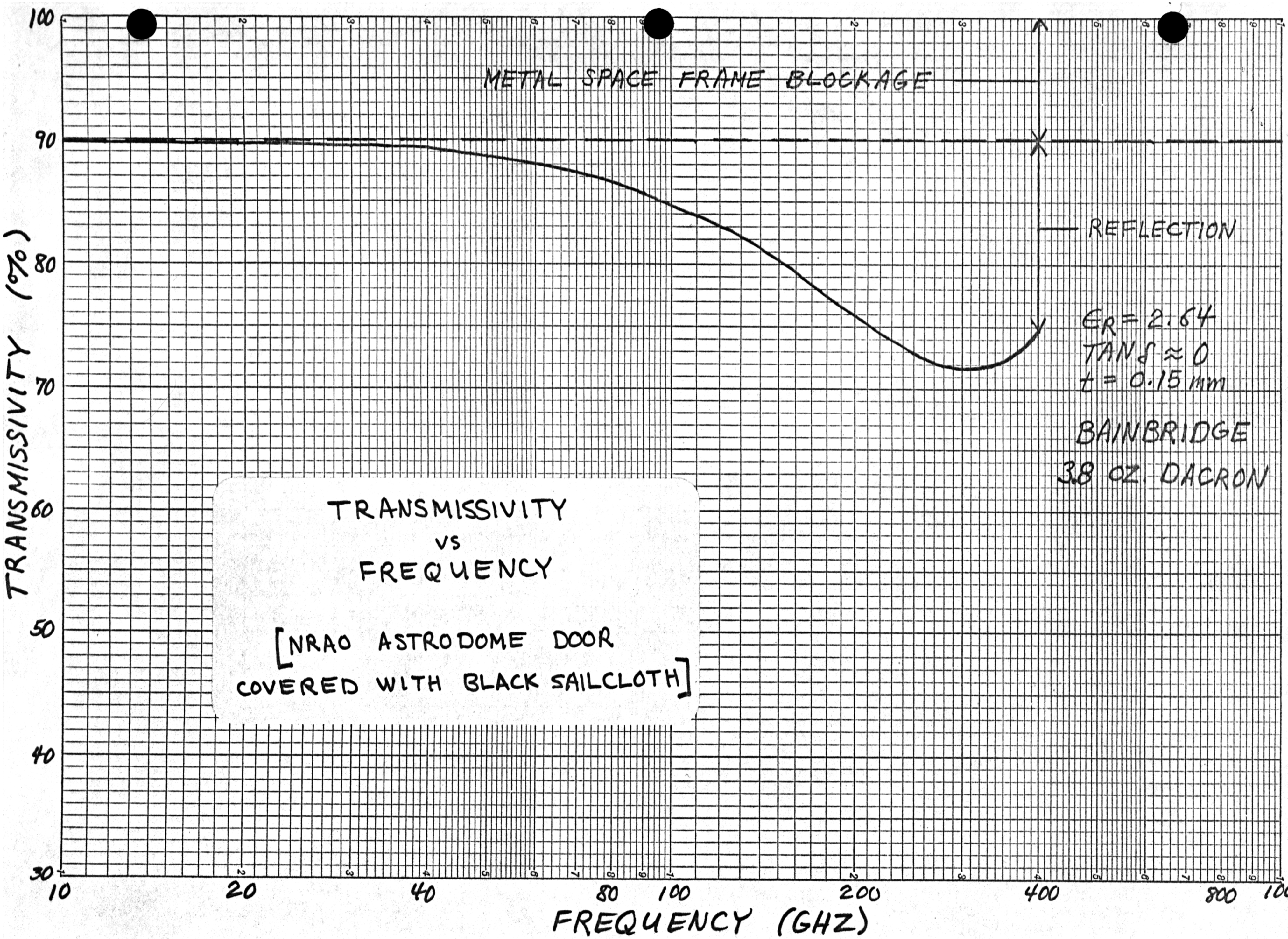
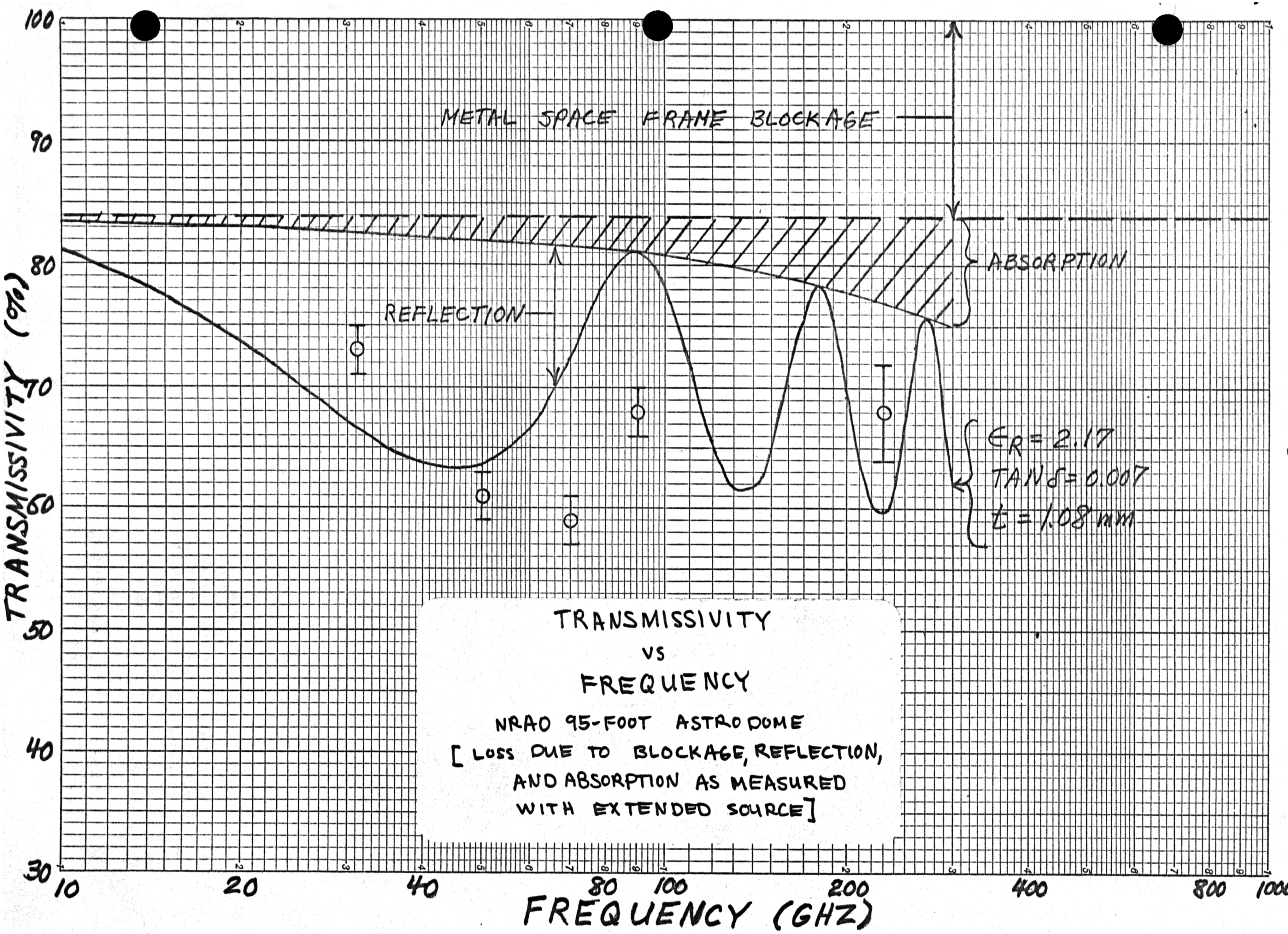

TRANSMISSIVITY
vs
FREQUENCY
[ESSCO RADOME COVERED WITH ESSCOLAM V]
METAL SPACE FRAME BLOCKAGE
ABSORPTION
REFLECTION
NET TRANSMISSIVITY
$\epsilon_R = 2.70$
$TAN\ \delta = 0.012$
$t = 0.9$ mm
H_2O
O_2
O_2
H_2O
H_2O
ATMOSPHERIC ABSORPTION LINES
TRANSMISSIVITY (%)
100
90
80
70
60
50
40
30
FREQUENCY (GHZ)
10
20
40
80
100
200
400
800
1000

FIGURE 3



METAL SPACE FRAME BLOCKAGE
REFLECTION
$\epsilon_R = 2.64$
$\tan\delta \approx 0$
$t = 0.15$ mm
BAINBRIDGE
3.8 OZ. DACRON
TRANSMISSIVITY
VS
FREQUENCY
[NRAO ASTRODOME DOOR
COVERED WITH BLACK SAILCLOTH]
TRANSMISSIVITY (%)
100
90
80
70
60
50
40
30
10
20
40
80
100
200
400
800
1000
FREQUENCY (GHZ)

FIGURE 4



TRANSMISSIVITY
VS
FREQUENCY
NRAO 95-FOOT ASTRODOME
[LOSS DUE TO BLOCKAGE, REFLECTION,
AND ABSORPTION AS MEASURED
WITH EXTENDED SOURCE]

FIGURE 5

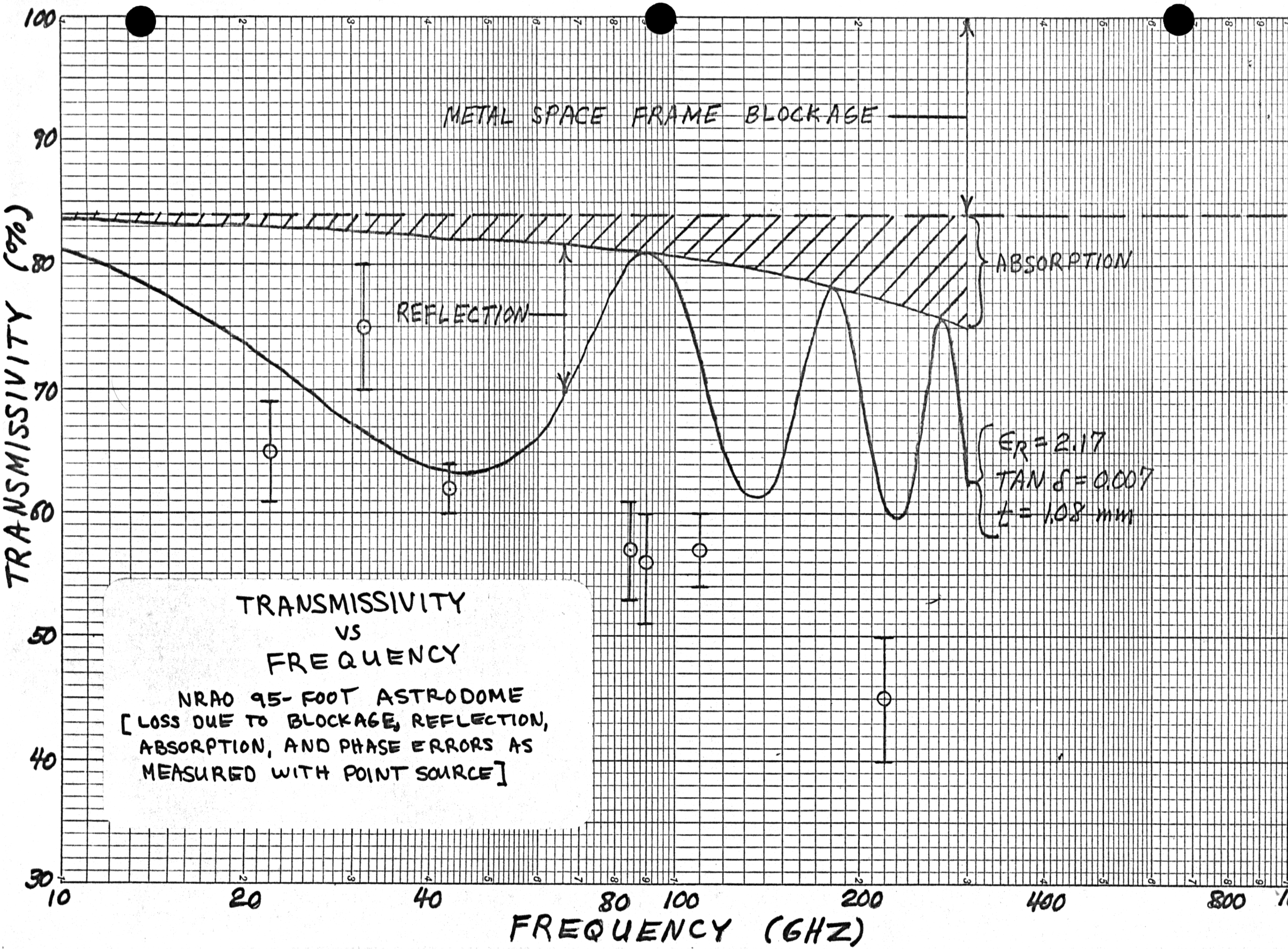

TRANSMISSIVITY VS FREQUENCY
NRAO 95-FOOT ASTRODOME
[LOSS DUE TO BLOCKAGE, REFLECTION, ABSORPTION, AND PHASE ERRORS AS MEASURED WITH POINT SOURCE]
METAL SPACE FRAME BLOCKAGE
ABSORPTION
REFLECTION
$\epsilon_R = 2.17$
$TAN\ \delta = 0.007$
$t = 1.08$ mm
TRANSMISSIVITY (%)
FREQUENCY (GHZ)
100
90
80
70
60
50
40
30
10
20
40
80
100
200
400
800
1000

FIGURE 6

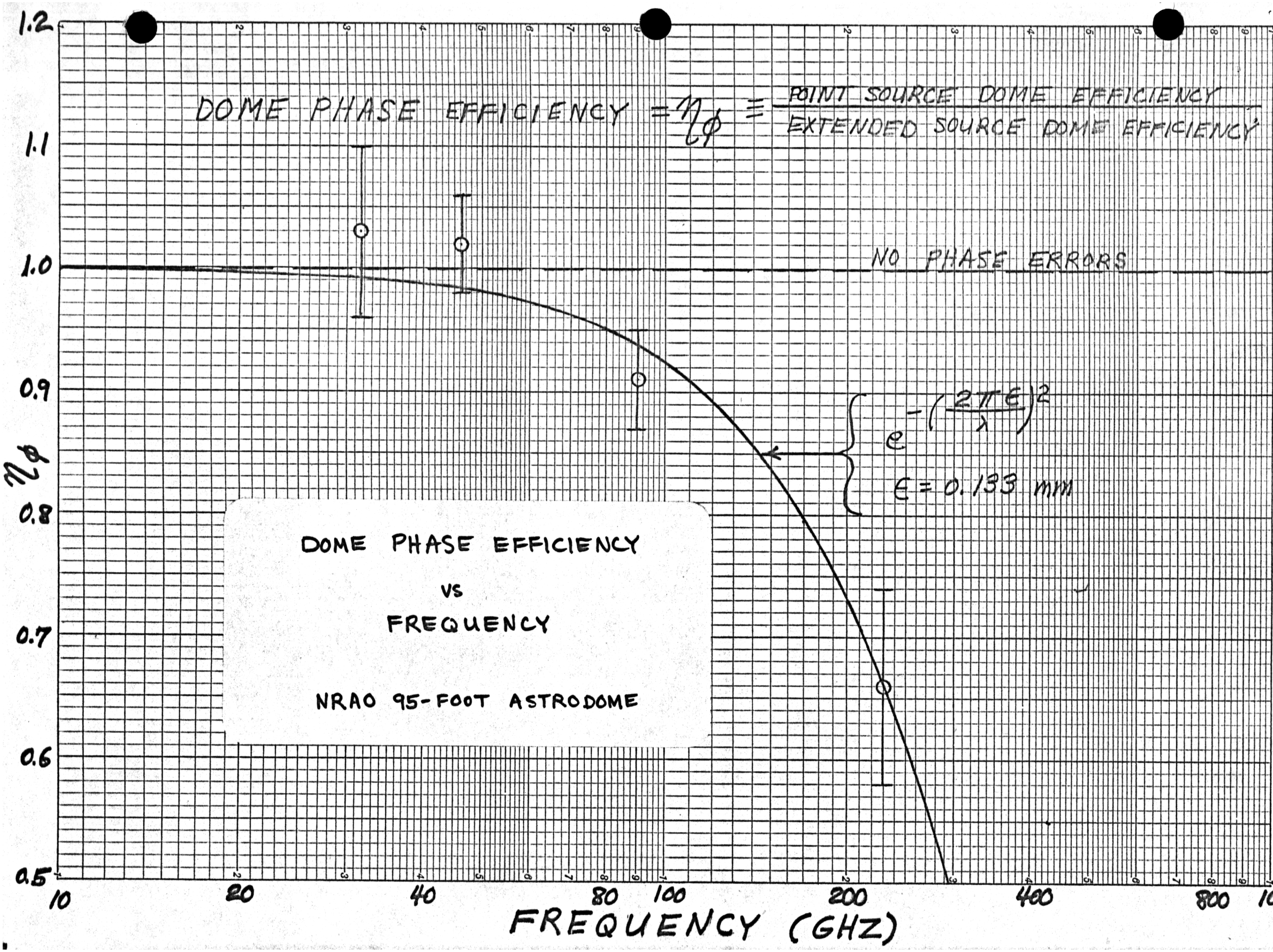

DOME PHASE EFFICIENCY $= \eta_\phi \equiv \frac{\text{POINT SOURCE DOME EFFICIENCY}}{\text{EXTENDED SOURCE DOME EFFICIENCY}}$
NO PHASE ERRORS
$e^{-\left(\frac{2\pi\epsilon}{\lambda}\right)^2}$
$\epsilon = 0.133$ mm
DOME PHASE EFFICIENCY
VS
FREQUENCY
NRAO 95-FOOT ASTRODOME
η_ϕ
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
10
20
40
80
100
200
400
800
1000
FREQUENCY (GHZ)

FIGURE 7