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ABSTRACT

The microwave attenuation and noise temperature effects of clouds can result in serious degradation of telecommunications link performance, especially for low-noise systems presently used in deep-space communications. Although cloud effects are generally less than rain effects, the frequent presence of clouds will cause some amount of link degradation a large portion of the time.

This report presents a general review of cloud types, water particle densities, radiative transfer, attenuation and noise temperature calculations, and examples of basic link signal-to-noise ratio calculations. The results of calculations for twelve different cloud models are presented for frequencies of from 1 to 50 GHz and elevation angles of 30-degrees and 90-degrees. These case results may be used as a handbook to predict noise temperature and attenuation values for known or forecast cloud conditions.

CONTENTS

INTRODUCTION

Microwave propagation through the earth's atmosphere is affected adversely by the presence of rain and clouds. As communications systems operate at higher and higher frequencies (greater than 30 GHz), attenuation and noise temperature effects become increasingly severe. Although rain effects are generally greater than those of clouds, rain occurs less than about five-percent of the time. Clouds, on the other hand, may be present fifty-percent of the time as a yearly-average or continuously for periods of weeks on end. Thus, the integrated cloud effects (dB-hours or Kelvin-hours) may be much larger than those for rain.

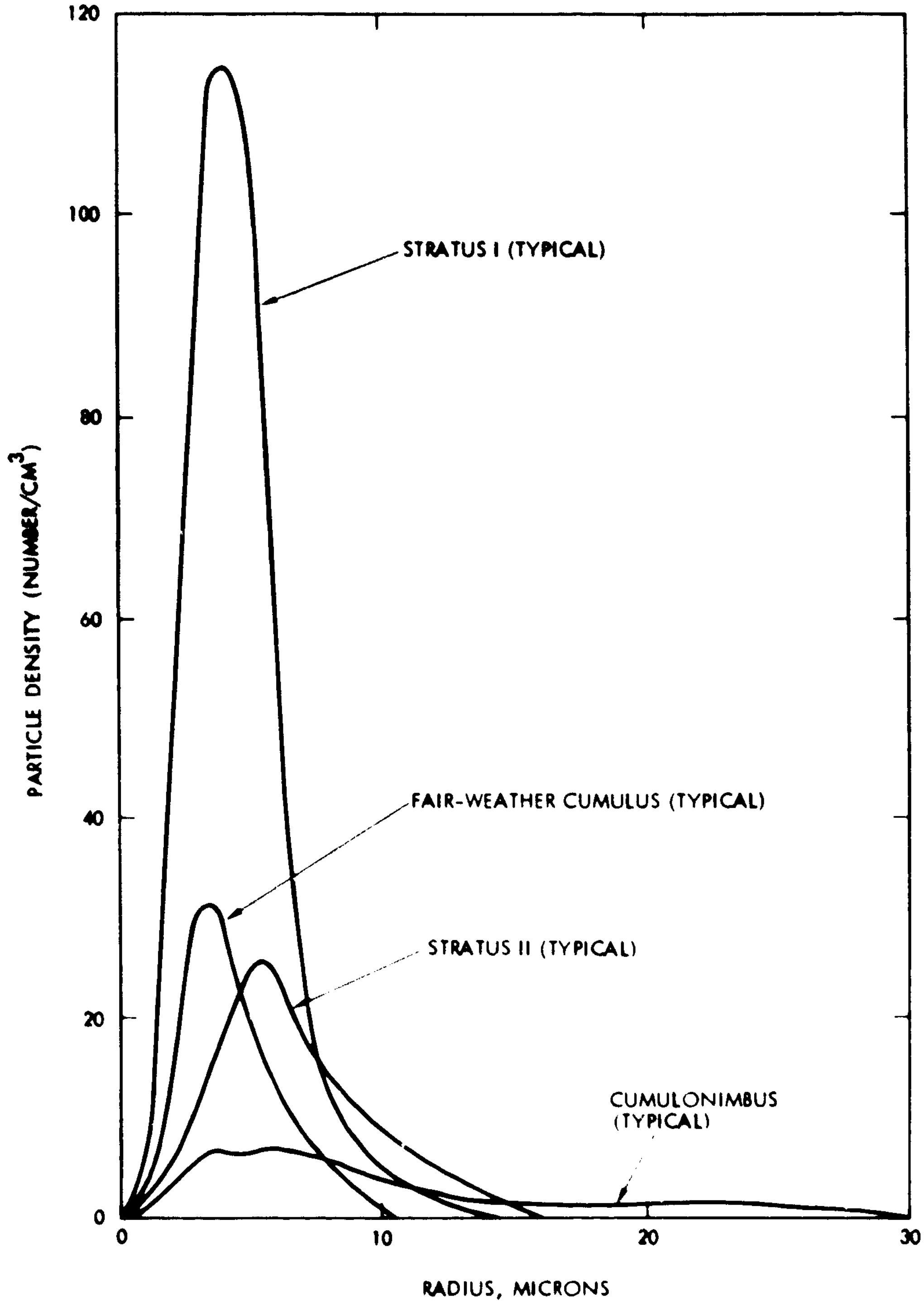
Compared to rain studies, little has been done to characterize the statistics of cloud effects. Clearly, the best method of determining noise temperature statistics is to go out and measure noise temperature! Lacking the resources and equipment to do this, an alternative method is to draw upon the vast amount of historical weather data (surface observations, radiosonde profiles, pilot reports, etc.) and turn this real weather data into estimates of noise temperature and attenuation. To this end, a cloud model and computational scheme have been developed to calculate attenuation and noise temperature using real weather observations as program inputs. Forecasts of real weather parameters can also be used to give <u>forecasted</u> cloud effects, using this model.

This report presents a general discussion of cloud characteristics and the computational model. Sample case calculations for twelve specific cloud cases are given for a frequency range of 1 to 50 GHz. Future work will involve calculation of cloud effect statistics based on real weather observations at numerous locations throughout the United States.

I. CLOUD DESCRIPTIONS

A cloud may be described as a random distribution of liquid water particles above the ground having diameters of from 0 to 100 microns (μm). For comparison, raindrops have a size distribution of approximately 100 microns (0.1 mm) to 3 mm (Refs. 1 and 2). Rare cases will be found where particle sizes will be outside the ranges stated. Clouds are not water vapor, which is a clear, colorless gas, like oxygen and nitrogen, although the relative humidity is usually 100% within the cloud. Clouds can exist at high temperatures (+20°C) as well as at temperatures below freezing (-10°C) where they remain liquid (supercooled) and pose a great icing threat to aircraft penetrating them. High-level clouds, such as cirrus, are composed of ice crystals and will not generally be found at temperatures above -12°C. (Ref. 2)

Figure 1 (Ref. 3) and Table 1 (Ref. 3) show typical model cloud drop spectra for different cloud types. These spectra may be integrated over the range of cloud drop radii (~0 to 30 microns) to determine the average cloud density and average drop diameter for the various cloud types. Table 2 gives the results of these calculations for the cloud types of Ref. 3. The spectra in Figure 1 are for illustrative purposes only.



<u>FIGURE 1. MODEL CLOUD DROP SPECTRA</u>

(after Carrier, et al, Ref. 3)

TABLE 1. MODEL CLOUD DROP SIZE AND CONCENTRATION

(after Carrier, et al, Ref. 3)

CLOUD TYPE	N	r_{mode}	r_{min}	r_{max}	Δr
Stratus I	464	3.5	0	16.0	3.0
Altostratus	450	4.5	0	13.0	4.5
Stratocumulus	350	3.5	0	11.2	4.4
Nimbostratus	330	3.5	0	19.8	9.5
Fair-weather cumulus	300	3.5	0.5	10.0	3.0
Stratus II	260	4.5	0	20.0	5.7
Cumulus congestus	207	3.5	0	16.2	6.7
Cumulonimbus	72	5.0	0	30.0	7.0

N = total concentration, no./cm^3

r_{mode} = radius corresponding to the maximum number of droplets, microns

r_{min} = minimum radius, microns

r_{max} = maximum radius, microns

Δr = bandwidth of the drop-size distribution at half-value points, microns

TABLE 2

SUMMARY OF CLOUD MODEL DENSITIES AND AVERAGE RADII

#	CLOUD TYPE	CONCENTRATION (no/cm^3)	DENSITY (g/m^3)	AVERAGE RADIUS (microns)
1	STRATUS I	464	0.27	5.2
2	STRATOCUMULUS	350	0.16	4.8
3	FAIR-WEATHER CUMULUS	300	0.15	4.9
4	STRATUS II	260	0.49	7.6
5	CUMULONIMBUS	72	0.98	14.8
6	CUMULUS CONGESTUS	207	0.67	9.2
7	NIMBOSTRATUS	330	0.99	9.0
8	ALTOSTRATUS	450	0.46	6.2

The stratus I cloud is based on observations taken off the coast of California. Stratus II is found over land. The altostratus and stratocumulus clouds observed had bases approximately 2000 meters above ground and tops up to 4000 meters above ground, with a typical thickness of 1800 meters. For reference, the standard temperature at 4000 meters above sea level is about -5°C. It is suggested in Ref. 2 that the drop size spectra for nimbostratus and fair-weather cumulus be used for altocumulus clouds. A standard pictorial listing of cloud types is given in the U.S. National Weather Service Cloud Code Chart (Ref. 4). The clouds portrayed on the chart conform to the standard types approved by the World Meteorological Organization and serve as a common point of reference for use in cloud observations and predictions.

Although Table 2 shows cloud densities of less than 1 g/m^3, several investigators (Ref. 2) have observed cloud densities of up to 10 g/m^3. Convective type clouds (cumulus, cumulonimbus) in the summer have maximum water contents of 3 (cumulus humilis) to 10 (cumulonimbus) g/m^3, although for clouds with large vertical development (cumulonimbus exceeding 10 km in height), there is some question as to the relative proportions of actual cloud particles and suspended precipitation particles.

Four cloud models used by other investigators (Ref. 5) are summarized in Table 3. These models are consistent with descriptions above, except in the case of altostratus clouds.

TABLE 3

CLOUD MODELS USED IN REFERENCE 5

	MODEL 1	MODEL 2	MODEL 3	MODEL 4
TYPE	COASTAL STRATUS	STRATO-CUMULUS	STRATO-CUMULUS	ALTO-STRATUS
BASES*	0.500 km	1.000 km	1.000 km	2.500 km
TOPS*	1.030 km	2.000 km	2.500 km	4.500 km
WATER DENSITY	0.33 g/m^3	0.33 g/m^3	0.20 g/m^3	0.15 g/m^3

*above ground level

Table 4 (Ref. 6) gives typical fog and cloud models which are representative of midlatitude conditions. This table is of particular interest because of its listing of cloud bottom and top heights.

The term "precipitable water" is used to describe the total amount of water through which one looks along a path through the entire atmosphere. Precipitable water has the units g/cm^2, or simply cm (i.e., 1 cm^3 of water weighs 1 g.). For a cloud with a density of 1 g/m^3, 1 km thick, the precipitable water (vertically) is 0.1 g/cm^2 or 0.1 cm. By comparison, a typical value of precipitable water vapor is 1.5 g/cm^2 along a vertical path through the entire atmosphere.

TABLE 4. TYPICAL FOG AND CLOUD MODELS

(Ref. 6)

Cloud Type	Density (g/m^3)	Heights above ground (m) Bottom	Top
Heavy Fog 1	0.37	0	150
Heavy Fog 2	0.19	0	150
Moderate Fog 1	0.06	0	75
Moderate Fog 2	0.02	0	75
Cumulus	1.00	660	2700
Altostratus	0.41	2400	2900
Stratocumulus	0.55	660	1320
Nimbostratus	0.61	160	1000
Stratus	0.42	160	660
Stratus	0.29	330	1000
Stratus-Stratocumulus	0.15	660	2000
Stratocumulus	0.30	160	660
Nimbostratus	0.65	660	2700
Cumulus-Cumulus Congestus	0.57	660	3400

II. ABSORPTION AND SCATTERING EFFECTS

The total attenuation (or extinction) of a radio wave by a cloud is the sum of the absorption and scattering by particles in the cloud. Absorption of microwave energy by a cloud particle heats it up slightly, and it then re-radiates isotropically (equally in all directions) with an emissivity less than 1.0 at its particular physical temperature. Scattering results in a re-direction of the incident energy so that it does not arrive at its "straight line" destination. Scattering in certain directions is enhanced depending on the wavelength of incident energy, particle size distribution, and dielectric constant of the scattering particles. Scattering may be advantageous for some applications, such as in troposcatter communication systems.

The absorbed energy is lost and does not contribute to the noise temperature (power) received by a radiometer. The absorbing medium itself does radiate power into the receiver and contributes to the total system noise temperature. This is discussed further in Sections III and IV.

A good general description of scattering by water and ice particles is found in Battan (Ref. 7), who draws on the original work of Mie (Ref. 8). A detailed discussion of scattering theory is beyond the scope of this survey article, but for the case of microwave radiation (1 to 50 GHz for communications bands) and cloud particles (diameters 1 to 100 microns) certain computational simplifications become possible.

A common parameter used in scattering calculations is

$$\alpha = 2\pi a/\lambda$$

where a = drop radius

λ = wavelength of incident radiation

For the case $\alpha \ll 1$, the scattered component of the incident radiation is small compared to the absorptive component; and the total attenuation (extinction) is due to absorption. For the shortest wavelength (0.6 cm for 50 GHz) and the largest cloud drop diameter (100 microns), $\alpha = 0.052$, which satifies the relationship $\alpha \ll 1$. Using the cloud drop spectrum suggested by Diermendjian (Ref. 9), Dutton and Dougherty (Ref. 10) make the argument that even for frequencies as high as 350 GHz(λ = 0.086 cm) "Rayleigh" approximations are valid (see Battan, Ref. 7) and extinction of microwave energy is almost entirely due to absorption.

The attenuation of cloud drops is given by (Ref. 7, Eqn. 6.14):

$$k_c = [0.4343\ 6\pi/\lambda\ \mathrm{Im}\{-(m^2-1)/(m^2+2)\}]M$$

$$= K_1 M$$

where m = complex index of refraction of water, function of temperature and wavelength

M = density of cloud water particles, g/m^3 (range ~ 0 to 10 g/m^3)

Values of K_1, taken from Gunn and East (Ref. 11) are given in Table 5. Bean and Dutton (Ref. 12) also use these values in their discussion of cloud attenuation.

TABLE 5

One-Way Attenuation Coefficient, K_1, in Clouds, $dB/km/g/m^3$ (from Gunn and East, Ref. 11)

TEMPERATURE (°C.)		WAVELENGTH (Cm.)			
		0.9(33.31GHz)	1.24(24.18GHz)	1.8(16.66GHz)	3.2(9.37GHz)
Water Cloud	20....	0.647	0.311	0.128	0.0483
	10....	0.681	0.406	0.179	0.0630
	0....	0.99	0.532	0.267	0.0858
	- 8....	1.25	0.684	0.34(extrapolated)	0.112(extrapolated)
Ice Cloud	0....	8.74×10^{-3}	6.35×10^{-3}	4.36×10^{-3}	2.46×10^{-3}
	-10....	2.93×10^{-3}	2.11×10^{-3}	1.46×10^{-3}	8.19×10^{-4}
	-20....	2.0×10^{-3}	1.45×10^{-3}	1.0×10^{-3}	5.63×10^{-4}

Note that ice clouds have attenuation coefficients about two orders of magnitude less than water clouds. Their attenuation (absorption) effects may be neglected as long as the ice particles continue to satisfy the relationship $\alpha \ll 1$. In the absence of liquid water clouds, scattering by ice clouds will be the only contribution to signal attenuation.

Rather than using the tabulated cloud attenuation values (Table 5), a convenient expression to use for cloud absorption (in the region 1 to 50 GHz) is (following Staelin, Ref. 13):

$$A_{cloud} = \frac{4.343 \times M \times 10^{0.0122(291-T)-1}}{\lambda^2} \times 1.16 \quad \text{dB/Km}$$

where

M = cloud water particle density, g/m^3

T = cloud particle temperature, Kelvins

λ = wavelength, cm.

4.343 = changes nepers* to dB

1.16 = factor to match the Staelin expression to the Gunn and East values, within 10%

For use in radiative transfer calculations, an absorption coefficient α (nepers/km) must be used where

$$\alpha \text{ (nepers/km)} = A \text{ (dB/km)}/4.343$$

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*The neper is used here in the "power" sense (1 neper = 4.343 dB) rather than the traditional "voltage" sense (1 neper = 8.686 dB).

$$P_2 = P_1 e^{-\alpha x}$$

$$P_2/P_1 \text{ (dB)} = 10 \log_{10} e^{-\alpha x}$$

$$= -10\, \alpha \log_{10} e \quad (x = 1 \text{ km})$$

$$= -4.343\, \alpha$$

III. EQUATION OF RADIATIVE TRANSFER

The description and use of the equation of radiative transfer is given by numerous authors (Refs. 14-20, et al). The noise temperature at a given frequency received by an ideal antenna with infinitely narrow beamwidth looking upward at a source outside the atmosphere and ignoring scattering is given by (See Figure 2):

$$T_a = T_a' e^{-\tau} + \int_0^{\infty} T(s)\, \alpha(s) e^{-\int_0^{s} \alpha(s')ds'} ds$$

where T_a = effective antenna temperature, Kelvins.

T_a' = noise temperature of source outside the atmosphere (e.g., black body disc temperature of the moon), Kelvins

$T(s)$ = physical temperature of a point s in the atmosphere, Kelvins.

τ = total atmosphere attenuation (optical depth), nepers

$\alpha(s)$ = total absorption coefficient at a point s in the atmosphere, nepers/km (neglecting scattering)*

s = distance from antenna to a point in the atmosphere, km

---

* In the case of scattering (attenuation = scattering + absorption), simple first-order considerations will show that $\alpha(s)$ will be the absorption coefficient and $\alpha(s')$ will be the total attenuation coefficient. This condition is not considered for this cloud survey, but scattering must be considered for propagation through rain, particularly at frequencies greater than 10 GHz.

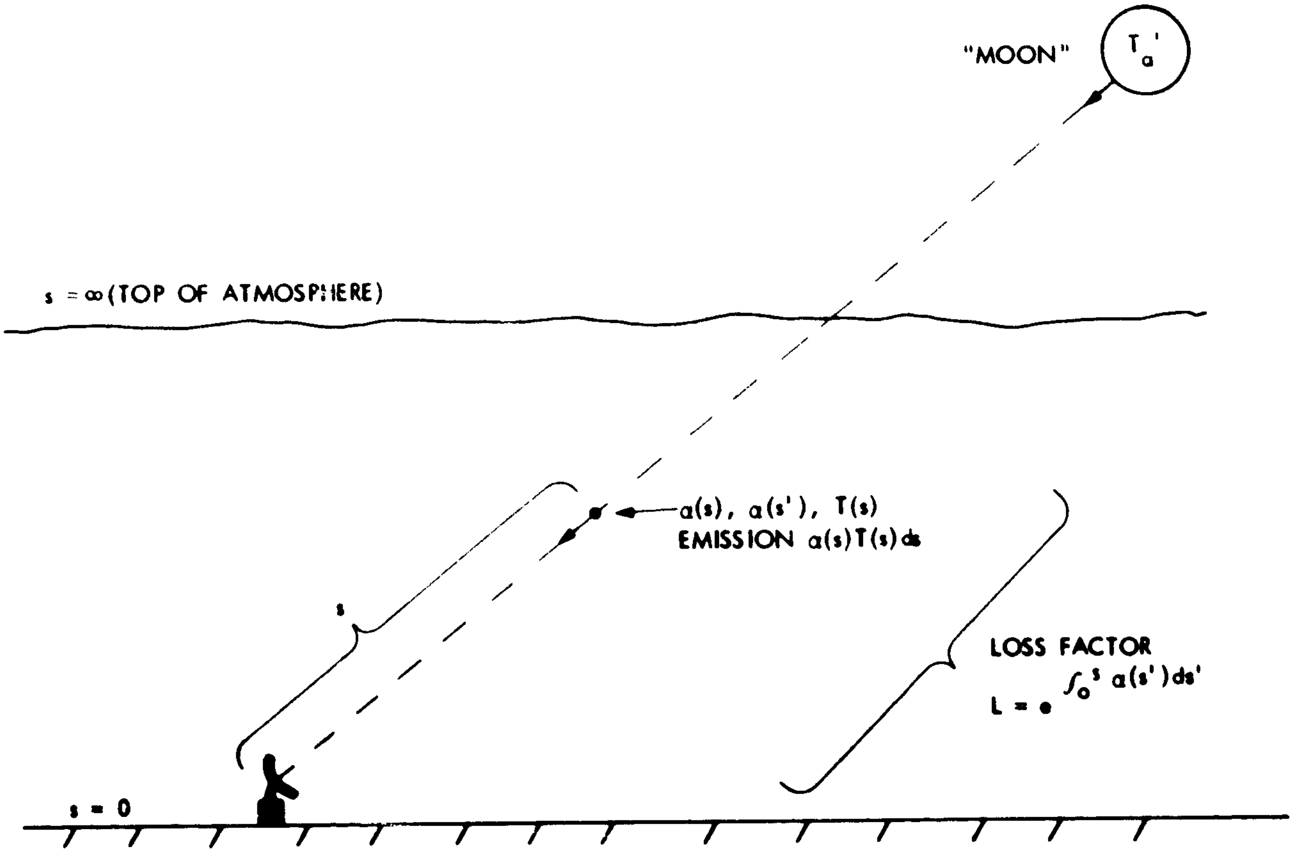

FIGURE 2. ELEMENTS OF RADIATIVE TRANSFER EQUATION

The total absorption coefficient ($\alpha(s)$ nepers/km) is the sum of the individual absorption coefficients of all atmospheric constituents (water vapor, oxygen, clouds, rain). If any component is absent, its individual absorption coefficient equals zero. The loss ("loss factor") through the entire atmosphere is:

$$L(\text{ratio}) = e^{\tau} = e^{\int_0^\infty \alpha(s')ds'} > 1.0$$

where $\int_0^\infty$ represents the total path through the atmosphere, approximately 30 km at zenith, and τ is the optical depth (nepers).

The "transmissivity" of the atmosphere is defined as:

$$T = 1/L = e^{-\tau} \quad , \quad 0 < T < 1$$

The "absorptivity" or "opacity" is defined as:

$$A = 1-T = 1 - e^{-\tau} = 1-1/L \quad , \quad 0 < A < 1$$

The first term of the radiative transfer equation gives the net brightness temperature of a source located outside the atmosphere after transmissivity reduction 1/L. The second term represents the sum of infinitesimal brightness temperature contributions [$T(s)\ \alpha(s)\ ds'$], each attenuated by the atmosphere between it and the receiving antenna (path length s). For atmospheric studies using passive radiometry only, and no source in or outside of the atmosphere, the term ($T_a'\ e^{-\tau}$) is equal to zero.

Sun- and moon-tracker studies (sources outside the atmosphere) enable one to determine space diversity improvement and various atmospheric parameters (Refs. 21-25).

The total atmospheric absorption, A(dB), through the atmosphere, can be derived from the loss factor L by:

$$A(dB) = 10 \log_{10}(L)$$
$$= 10 \, \tau \log_{10} e = 4.343 \, \tau$$

where $\tau = \int_0^\infty \alpha(s) ds$ along a path through the entire atmosphere (nepers)

An effective mean physical temperature, T_p, of the atmosphere may be derived from the relationship*

$$T_a = T_p \times (\text{Absorptivity})$$
$$= T_p (1 - e^{-\tau})$$
$$= T_p (1 - 1/L)$$

where T_a = antenna temperature due to emission from the absorptive ("lossy") atmosphere, Kelvins

T_p = mean physical temperature, Kelvins

L = loss factor, ≥ 1.0

* This equation is strictly true only for an isothermal atmosphere, but is a good practical approximation for the earth's atmosphere, where the bulk of attenuation occurs in regions whose temperatures are within 10% of 273 K.

A more rigorous derivation of this expression begins with the equation of radiative transfer:

$$T_a = \int_0^{\infty} T(s)\alpha(s)\, e^{-\int_0^{s} \alpha(s')ds'} ds$$

For an isothermal, homogeneous atmosphere

$\alpha(s) = \alpha$, the mean absorption coefficient

$T(s) = T_p$, the mean physical temperature

Then,

$$T_a = \alpha T_p \int_0^{\ell} e^{-\alpha s} ds, \text{ where } \ell = \text{top of atmosphere}$$

$$= T_p \left(1-e^{-\alpha\ell}\right)$$

$$= T_p \left(1-1/L\right)$$

This relationship is discussed in more detail by Waters (Ref. 14).

As a specific example (based on an actual calculation using the equation of radiative transfer) consider an atmosphere (heavy clouds, at 32 GHz) whose antenna temperature and attenuation at zenith are:

$$T_a = 99.04636 \text{ Kelvins}$$

$$A = 1.93854 \text{ dB } (L = 1.56262)$$

T_p is found to be

$$T_p = T_a \left[L/(L-1)\right] = 275.091 \text{ Kelvins}$$

This physical temperature corresponds to a region in the atmosphere where the "bulk" of the attenuating material lies (in this case, clouds at an altitude of approximately 3 km). The surface temperature for this case was 293.16 Kelvins and the lapse rate was 6.3 K/km down to a minimum temperature of 220 K.

It should be noted that T_p is an artifact and not a "constant" of the atmosphere. It is found after performing the radiative transfer calculation. For the case of temperature and/or attenuation gradients in the atmosphere, the T_p found will depend on whether the atmosphere is "viewed" (integrated) from below or above.

A further discussion of atmospheric modelling and noise temperature errors is given by Stelzried and Slobin (Ref. 26).

Using these simplified formulae, it is instructive to attempt to predict the antenna temperature for this cloud model at an elevation angle of 30°. To a good approximation, the attenuation at 30°-elevation is twice the zenith attenuation. Thus,

$$A(dB) = 3.87708 \text{ dB } (L = 2.44179)$$

Using T_p = 275.091 K, the antenna temperature is calculated to be:

$$T_a = 162.431 \text{ K}$$

Actual radiative transfer integration at 30°-elevation yields:

$$T_a = 161.660 \text{ K}$$

a difference of 0.771 K.

Using

$$T_a = 161.660 \text{ K}$$

and

$$A = 3.87708 \text{ dB } (L = 2.44179)$$

the 30°-elevation mean physical temperature is calculated as

$$T_p = 273.785 \text{ K}$$

which is different by 1.306 K from the zenith mean physical temperature.

These one-Kelvin differences reflect an equivalent resolution well within present ability to measure or forecast cloud parameters. Thus, elevation angle modelling of attenuation and noise temperature is adequate for stratified atmospheres. For the case of scattered clouds, non-simple geometries, or low elevation angles, complete radiative transfer calculations should be carried out.

IV. SAMPLE CASE CALCULATIONS OF CLOUD ATTENUATION AND NOISE TEMPERATURE

A computer program has been written to calculate the atmospheric noise temperature and absorption of water vapor, oxygen, clouds, and rain, (using the equation of radiative transfer) along various paths in the atmosphere. For computational purposes, the atmosphere is divided into 300 layers, each 100 meters thick, up to a height of 30 km above the ground. For specific cloud/rain models and/or frequencies at which the attenuation coefficient is very large ($\alpha \sim 1$ neper/km (4.34 dB/km)), the 100 meter step size must be reduced (~ 10m) and the number of steps increased (~ 3000) in order to avoid large computational errors. The effect of these errors is to calculate a value of noise temperature that is too low (for the case of very dense clouds, at least). The present version of the program is not "smart" (or self-adjusting); but the calculations appear to be adequate for all cloud cases, excluding rain, except very near the peak of the oxygen absorption band (60 GHz), or for very heavy clouds at high frequencies (> 60 GHz). The presentation here is restricted to frequencies less than 50 GHz.

Since clouds do not exist independent of water vapor and oxygen, the effects of these two species must be included in any calculation of cloud noise temperature and attenuation.

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The particular constituent models are described as follows:

WATER VAPOR

1. CCIR Profile (Ref. 27)
2. 7.5 g/m^3 at surface
3. 2 km scale height
4. 20°C at surface
5. 6.3 K/km temperature lapse rate
6. 220 K minimum temperature
7. Bean and Dutton absorption coefficient (Ref. 12), modified slightly to yield agreement with values calculated by the JPL Radiative Transfer Program (Ref. 28)

OXYGEN

1. CCIR Profile (Ref. 27)
2. 1013.6 mb at surface
3. Pressure profile curve-fit $P=P_0e^{-0.116h}$, h in km (pressure scale height = 8.62 km)
4. 20°C at surface
5. 6.3 K/km temperature lapse rate
6. 220 K minimum temperature
7. Bean and Dutton absorption coefficient (Ref. 12) modified slightly to yield agreement with values calculated by the JPL Radiative Transfer Program (Ref. 28)

CLOUD

1. Absorption model from Staelin (Ref. 13)
2. Modified to fit Gunn and East values (Ref. 11)
3. Water particle densities derived from drop size distribution in Carrier, Cato, and von Essen (Ref. 3)

Figure 3 shows a schematic view of the cloud and clear air models used in the calculations. In these models, h is the height (km) above the ground; h_o is the height of the ground above sea level.

The cloud model has up to two layers, base and top heights specified, and water particle density determined by specification of cloud type as defined by the World Meteorological Organization Cloud Code Chart (Ref. 4). The relative humidity is not adjusted to be 100% within the cloud layer; the absolute humidity is defined by an exponential decrease with a 2 km scale height.

A number of specific weather cases were considered for calculation using the equation of radiative transfer to determine noise temperature and attenuation. Table 6 lists the 12 cases (1 clear, 11 cloudy); they represent increasingly dense and thick cloud layers.

This table will be discussed further with respect to S, X, and K_A-Band noise temperature and attenuation effects of clouds.

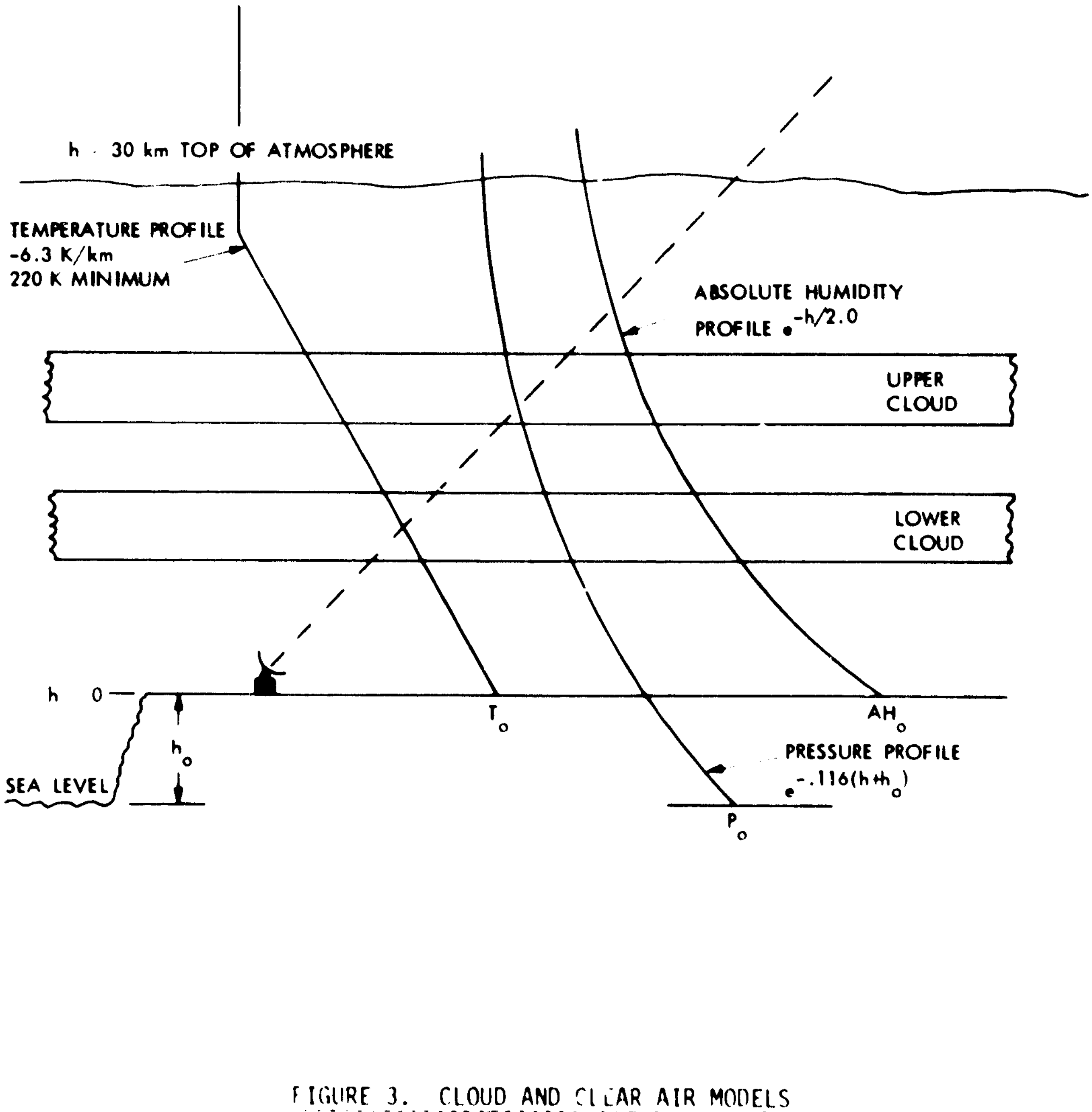

FIGURE 3. CLOUD AND CLEAR AIR MODELS

TABLE 6. SAMPLE CLOUD MODELS AND S-, X-, K_A-BAND ZENITH EFFECTS

CASE	LOWER CLOUD				UPPER CLOUD				REMARKS	S-BAND (2.3 GHZ) ZENITH		X-BAND (8.5 GHZ) ZENITH		K_A-BAND (32 GHZ) ZENITH	
	DENSITY g/m^3	BASE km	TOP km	THICK-NESS km	DENSITY g/m^3	BASE km	TOP km	THICK-NESS km		T(K)	A(dB)	T(K)	A(dB)	T(K)	A(dB)
1	-	-	-	-	-	-	-	-	Clear Air	2.15	.035	2.78	.045	14.29	.228
2	0.2	1.0	1.2	0.2	-	-	-	-	Light, Thin Clouds	2.16	.036	2.90	.047	15.92	.255
3	-	-	-	-	0.2	3.0	3.2	0.2		2.16	.036	2.94	.048	16.51	.266
4	0.5	1.0	1.5	0.5	-	-	-	-		2.20	.036	3.55	.057	24.56	.397
5	-	-	-	-	0.5	3.0	3.5	0.5		2.22	.037	3.83	.062	28.14	.468
6	0.5	1.0	2.0	1.0	-	-	-	-	Medium Clouds	2.27	.037	4.38	.070	35.22	.581
7	-	-	-	-	0.5	3.0	4.0	1.0		2.31	.038	4.96	.081	42.25	.731
8	0.5	1.0	2.0	1.0	0.5	3.0	4.0	1.0		2.43	.040	6.55	.105	61.00	1.083
9	0.7	1.0	2.0	1.0	0.7	3.0	4.0	1.0		2.54	.042	8.04	.130	77.16	1.425
10	1.0	1.0	2.0	1.0	1.0	3.0	4.0	1.0	Heavy Clouds	2.70	.044	10.27	.166	99.05	1.939
11	1.0	1.0	2.5	1.5	1.0	3.5	5.0	1.5		3.06	.050	14.89	.245	137.50	3.060
12	1.0	1.0	3.0	2.0	1.0	4.0	6.0	2.0	Very Heavy Clouds	3.47	.057	20.20	.340	171.38	4.407

Notes: 1) Clear and cloud models as described in text
2) Cases 2-12 are clear air and clouds combined
3) Antenna located at sea level
4) Heights are above ground
5) No cosmic background or ground contribution considered
6) T(K) is atmospheric noise temperature at zenith
7) A(dB) is atmospheric attenuation along vertical path from ground to 30 km above ground

Table 7 shows a printout of the temperature, pressure, and absolute humidity profiles used in the calculations up to a height of 10 km above the ground. The values are given at the center of the 0.1 km-thick layers. The receiving antenna is considered to be located at sea level and the clouds are horizontally stratified. The specific case shown in Table 7 is for clouds plus rain (10 mm/hr at the ground). The columns labeled ALPHT1 and ALPHT2 are the extinction (total attenuation) and absorption coefficients (nepers/km) at 32 GHz, respectively, for the case where scattering from rain is considered. The clouds are not considered to scatter at frequencies below 100 GHz for the purpose of these calculations. DENC is the cloud water particle density, 1.00 g/m^3 for the lower cloud and 1.00 g/m^3 for the upper cloud. The rainrate (mm/hr) is given in the last column, based on a specific model. The rain is considered to start at 3.5 km above the ground and the rate increases in a downward direction.

Returning to Table 6, the last columns show the S-, X-, and K_A-Band zenith noise temperature and attenuation effects for the cloud models shown. The notes at the bottom of the table describe the models used and will clarify the tabulated values.

Table 6 shows the increasingly severe effects of clouds as the frequency changes from S-thru K_A-Band. S-Band is affected only slightly by even the heaviest clouds, whereas K_A-Band shows very large effects, which are quite severe for the case of low-noise receiving systems.

TABLE 7

PROFILES USED IN CLOUD CALCULATIONS

HEIGHT	TEMP	PRESS.	ABS HUM.	ALPHT1	ALPHT2	DENC	RNRT	
.05000	292.84500	1007.62124	7.31482	.46616	.34339	.00000	9.99500	
.15000	292.21500	996.50037	6.95868	.46335	.33817	.00000	9.95510	
.25000	291.58500	984.51351	6.61873	.45880	.33478	.00000	9.87578	
.35000	290.95500	973.15914	6.29593	.45255	.33026	.00000	9.75798	
.45000	290.32500	961.93571	5.98887	.44465	.32465	.00000	9.60339	
.55000	289.69500	950.84174	5.69679	.43521	.31799	.00000	9.41294	
.65000	289.06500	939.87569	5.41896	.42430	.31034	.00000	9.18972	
.75000	288.43500	929.03613	5.15467	.41206	.30178	.00000	8.93597	
.85000	287.80500	918.32157	4.90327	.39861	.29240	.00000	8.65455	
.95000	287.17500	907.73059	4.66414	.38408	.28227	.00000	8.34853	
1.05000	286.54500	897.26175	4.43667	.51843	.42128	1.00000	8.02118	
1.15000	285.91500	886.91365	4.22029	.50490	.41264	1.00000	7.67590	
1.25000	285.28500	876.68489	4.01446	.49080	.40361	1.00000	7.31616	
1.35000	284.65500	866.57410	3.81867	.47631	.39428	1.00000	6.94544	
1.45000	284.02500	856.57992	3.63243	.46158	.38477	1.00000	6.56718	CLOUD
1.55000	283.39500	846.70100	3.45528	.44676	.37517	1.00000	6.18474	
1.65000	282.76500	836.93602	3.28676	.43200	.36559	1.00000	5.80132	
1.75000	282.13500	827.28365	3.12647	.41743	.35612	1.00000	5.41994	
1.85000	281.50500	817.74261	2.97399	.40318	.34684	1.00000	5.04342	
1.95000	280.87500	808.31159	2.82894	.38937	.33784	1.00000	4.67433	
2.05000	280.24500	798.98936	2.69097	.19731	.15040	.00000	4.31495	
2.15000	279.61500	789.77463	2.55973	.18148	.13898	.00000	3.96730	
2.25000	278.98500	780.66618	2.43489	.16629	.12796	.00000	3.63310	
2.35000	278.35500	771.66277	2.31614	.15182	.11741	.00000	3.31377	
2.45000	277.72500	762.76320	2.20318	.13809	.10735	.00000	3.01044	
2.55000	277.09500	753.96626	2.09573	.12516	.09783	.00000	2.72396	
2.65000	276.46500	745.27078	1.99352	.11304	.08885	.00000	2.45490	
2.75000	275.83500	736.67560	1.89630	.10175	.08044	.00000	2.20358	
2.85000	275.20500	728.17953	1.80381	.09128	.07259	.00000	1.97010	
2.95000	274.57500	719.78145	1.71584	.08162	.06531	.00000	1.75433	
3.05000	273.94500	711.48022	1.63216	.28615	.27199	1.00000	1.55595	
3.15000	273.31500	703.27473	1.55256	.28187	.26963	1.00000	1.37449	
3.25000	272.68500	695.16389	1.47684	.27840	.26786	1.00000	1.20935	
3.35000	272.05500	687.14658	1.40481	.27570	.26667	1.00000	1.05981	
3.45000	271.42500	679.22173	1.33630	.27373	.26604	1.00000	.92504	CLOUD
3.55000	270.79500	671.38828	1.27113	.23891	.23891	1.00000	.00000	
3.65000	270.16500	663.64517	1.20913	.24290	.24290	1.00000	.00000	
3.75000	269.53500	655.99136	1.15016	.24697	.24697	1.00000	.00000	
3.85000	268.90500	648.42583	1.09407	.25113	.25113	1.00000	.00000	
3.95000	268.27500	640.94754	1.04071	.25537	.25537	1.00000	.00000	
4.05000	267.64500	633.55551	.98995	.00497	.00497	.00000	.00000	
4.15000	267.01500	626.24873	.94167	.00483	.00483	.00000	.00000	
4.25000	266.38500	619.02621	.89575	.00470	.00470	.00000	.00000	
4.35000	265.75500	611.88700	.85206	.00457	.00457	.00000	.00000	
4.45000	265.12500	604.83012	.81051	.00445	.00445	.00000	.00000	
4.55000	264.49500	597.85462	.77098	.00433	.00433	.00000	.00000	
4.65000	263.86500	590.95958	.73338	.00421	.00421	.00000	.00000	
4.75000	263.23500	584.14436	.69761	.00410	.00410	.00000	.00000	
4.85000	262.60500	577.40713	.66359	.00400	.00400	.00000	.00000	
4.95000	261.97500	570.74791	.63122	.00390	.00390	.00000	.00000	

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TABLE 7 (cont.)

5.05000	261.34500	564.16549	.60044	.00380	.00380	.00000	.00000
5.15000	260.71500	557.65898	.57115	.00371	.00371	.00000	.00000
5.25000	260.08500	551.22751	.54333	.00361	.00361	.00000	.00000
5.35000	259.45500	544.87021	.51689	.00353	.00353	.00000	.00000
5.45000	258.82500	538.58624	.49163	.00344	.00344	.00000	.00000
5.55000	258.15500	532.37473	.46762	.00336	.00336	.00000	.00000
5.65000	257.56500	526.23487	.44481	.00328	.00328	.00000	.00000
5.75000	256.93500	520.16581	.42312	.00321	.00321	.00000	.00000
5.85000	256.30500	514.16675	.40249	.00313	.00313	.00000	.00000
5.95000	255.67500	508.23688	.38286	.00306	.00306	.00000	.00000
6.05000	255.04500	502.37539	.36418	.00299	.00299	.00000	.00000
6.15000	254.41500	496.58150	.34642	.00293	.00293	.00000	.00000
6.25000	253.78500	490.85444	.32953	.00286	.00286	.00000	.00000
6.35000	253.15500	485.19342	.31346	.00280	.00280	.00000	.00000
6.45000	252.52500	479.59770	.29817	.00274	.00274	.00000	.00000
6.55000	251.89500	474.06651	.28363	.00268	.00268	.00000	.00000
6.65000	251.26500	468.59911	.26979	.00262	.00262	.00000	.00000
6.75000	250.63500	463.19476	.25664	.00257	.00257	.00000	.00000
6.85000	250.00500	457.85275	.24412	.00252	.00252	.00000	.00000
6.95000	249.37500	452.57235	.23221	.00246	.00246	.00000	.00000
7.05000	248.74500	447.35284	.22089	.00241	.00241	.00000	.00000
7.15000	248.11500	442.19353	.21012	.00237	.00237	.00000	.00000
7.25000	247.48500	437.09372	.19987	.00232	.00232	.00000	.00000
7.35000	246.85500	432.05273	.19012	.00227	.00227	.00000	.00000
7.45000	246.22500	427.06987	.18085	.00223	.00223	.00000	.00000
7.55000	245.59500	422.14448	.17203	.00218	.00218	.00000	.00000
7.65000	244.96500	417.27590	.16364	.00214	.00214	.00000	.00000
7.75000	244.33500	412.46346	.15566	.00210	.00210	.00000	.00000
7.85000	243.70500	407.70653	.14807	.00206	.00206	.00000	.00000
7.95000	243.07500	403.00446	.14084	.00202	.00202	.00000	.00000
8.05000	242.44500	398.35662	.13398	.00198	.00198	.00000	.00000
8.15000	241.81500	393.76238	.12744	.00195	.00195	.00000	.00000
8.25000	241.18500	389.22112	.12123	.00191	.00191	.00000	.00000
8.35000	240.55500	384.73225	.11531	.00187	.00187	.00000	.00000
8.45000	239.92500	380.29514	.10969	.00184	.00184	.00000	.00000
8.55000	239.29500	375.90921	.10434	.00181	.00181	.00000	.00000
8.65000	238.66500	371.57385	.09925	.00177	.00177	.00000	.00000
8.75000	238.03500	367.28849	.09441	.00174	.00174	.00000	.00000
8.85000	237.40500	363.05257	.08981	.00171	.00171	.00000	.00000
8.95000	236.77500	358.86549	.08543	.00168	.00168	.00000	.00000
9.05000	236.14500	354.72670	.08126	.00165	.00165	.00000	.00000
9.15000	235.51500	350.63565	.07730	.00162	.00162	.00000	.00000
9.25000	234.88500	346.59177	.07353	.00159	.00159	.00000	.00000
9.35000	234.25500	342.59454	.06994	.00157	.00157	.00000	.00000
9.45000	233.62500	338.64340	.06653	.00154	.00154	.00000	.00000
9.55000	232.99500	334.73783	.06329	.00151	.00151	.00000	.00000
9.65000	232.36500	330.87731	.06020	.00149	.00149	.00000	.00000
9.75000	231.73500	327.06131	.05726	.00146	.00146	.00000	.00000
9.85000	231.10500	323.28932	.05447	.00144	.00144	.00000	.00000
9.95000	230.47500	319.56083	.05181	.00141	.00141	.00000	.00000
10.05000	229.84500	315.87534	.04929	.00139	.00139	.00000	.00000
10.15000	229.21500	312.23236	.04688	.00136	.00136	.00000	.00000
10.25000	228.58500	308.63139	.04460	.00134	.00134	.00000	.00000
10.35000	227.95500	305.07195	.04242	.00132	.00132	.00000	.00000

The change in signal-to-noise ratio (ΔSNR, dB) is given by:

$$\Delta SNR = \Delta dB + 10 \log_{10}(T_{op}/T_{base})$$

where ΔdB = change in attenuation, relative to clear air baseline

T_{op} = system noise temperature with clouds, Kelvins

T_{base} = baseline system noise temperature, including ground, waveguide horn, clear air, and cosmic background contributions, Kelvins

As an example, consider a low-noise receiving system at K_A-Band with a baseline zenith system noise temperature of 35 Kelvins. Using Case 10 (Table 6), it is seen that the zenith attenuation increases from 0.228 dB to 1.939 dB. The atmospheric noise temperature increases from 14.29 Kelvins to 99.05 Kelvins. The 2.7 Kelvin cosmic background effect decreases from 2.56 Kelvin (2.7 attenuated by .228 dB) to 1.73 Kelvin (2.7 K attenuated by 1.939 dB). The new T_{op} is 35 + (99.05-14.29) + (1.73-2.56) = 118.93 Kelvins. Thus,

$$\Delta SNR = (1.939-0.228) + 10 \log_{10} (118.93/35.) = 1.711 + 5.312$$
$$= 7.021 \text{ dB, at zenith}$$

Most of the signal-to-noise degradation in low noise receiving systems comes from the noise temperature increase. For high noise receiving systems (> 500 Kelvins), the atmospheric attenuation will cause the greatest SNR degradation.

The Appendix of this report contains numerous curves of total atmospheric attenuation coefficients, atmospheric noise temperature, and atmospheric attenuation for the cloud models in Table 6. The curves are in sets of five, one set for each of the twelve cases listed. The five curves of each set are:

1) Total atmospheric attenuation coefficient at 32 GHz, vs. height, all constituents, no scattering because clouds only (labelled -1)

2) Atmospheric noise temperature at zenith vs. frequency (labelled -2)

3) Atmospheric attenuation at zenith vs. frequency (labelled -3)

4) Atmospheric noise temperature at 30°-elevation vs. frequency (labelled -4)

5) Atmospheric attenuation at 30°-elevation vs. frequency (labelled -5)

The eight parameters of each plot are printed at the bottom. They are:

1) ELEV = elevation angle from horizontal, degrees

2) LAST LOOP = counting loop, internal use only

3) DENCLOW = density of lower cloud, g/m^3

4) LOWCLDTHK = thickness of lower cloud, km

5) DENCLMID = density of upper cloud, g/m^3

6) MIDCLDTHK = thickness of upper cloud, km

7) RAINRATE = rainrate at the ground, mm/hr

8) RAINTHICK = thickness of the rain, km

Table 8 shows results of tests of integration step size on the determination of atmospheric noise temperature and attenuation for the "worst-case" cloud, Case 12, at five different frequencies. NL is the number of layers in the atmosphere up to 30 km above the ground. For NL=300, layer thickness = 100 meters; NL=1000, 30 meters; NL=3000, 10 meters. Assuming the NL=3000 case to give the "correct" answer, noise temperatures at the same frequency but different step sizes are compared to that value. At all frequencies shown, the errors at zenith are less than two percent. However, at higher frequencies or for cases including rain (where the attenuation coefficient exceeds approximately 1 neper/km), care must be exercised in choosing an optimum number of tropospheric layers. Carrying out all calculations at NL=3000 makes computation of even a few cloud cases prohibitively expensive. Future work will involve the development of computational methods which strike an acceptable balance between accuracy and cost.

TABLE 8

"WORST CLOUD"* TEST CASE OF INTEGRATION STEP SIZE

** NL	FREQ GHz	90°-ELEV			30°-ELEV		
		T(K)	A(dB)	*** % ERROR	T(K)	A(dB)	*** % ERROR
300	10	26.84	0.457	-0.11	51.01	0.915	-0.20
(100 m)	20	94.35	1.864	-0.33	155.97	3.729	-0.62
RC=1	30	159.18	3.891	-0.83	224.41	7.782	-1.54
	40	214.08	6.912	-1.44	258.09	13.823	-2.53
	50	251.92	11.682	-1.92	269.91	23.364	-3.17
1000	10	26.96	0.460	+0.33	51.26	0.919	+0.29
(30 m)	20	94.88	1.875	+0.23	157.11	3.749	+0.11
RC=3.4	30	160.64	3.910	+0.07	227.50	7.819	-0.19
	40	216.89	6.943	-0.15	263.50	13.887	-0.49
	50	255.98	11.737	-0.34	276.86	23.473	-0.68
3000	10	26.87	0.458	0.00	51.11	0.916	0.00
(10 m)	20	94.66	1.869	0.00	156.94	3.738	0.00
RC=38.3	30	160.52	3.895	0.00	227.93	7.790	0.00
	40	217.21	6.917	0.00	264.80	13.835	0.00
	50	256.85	11.697	0.00	278.75	23.395	0.00

* CASE NO. 12, TABLE 6

** NUMBER OF LAYERS IN 30-KM-THICK ATMOSPHERE, THICKNESS OF LAYER AND RELATIVE COST
NOTE THE ANOMALOUS BEHAVIOR OF ATTENUATION AT NL=1000 AND 3000, FREQUENCY=50 GHz, WHERE NOISE TEMPERATURE INCREASES AND ATTENUATION DECREASES; ALSO OSCILLATORY BEHAVIOR OF ERROR

*** TEMPERATURE ERROR COMPARED TO VALUE AT SAME FREQUENCY WITH NL=3000; VALUE AT NL=3000 ASSUMED TO BE CORRECT

REFERENCES

1. R. R. Rogers, "Statistical Rainstorm Models", IEEE Trans. Ant. and Prop., July 1976, pp. 547-566.

2. S. L. Valley, editor, Handbook of Geophysics and Space Environments, 1965 edition, McGraw-Hill Book Co., New York, 1965.

3. L. W. Carrier, G. A. Cato, K. J. von Essen, "The Backscattering and Extinction of Visible and Infrared Radiation by Selected Major Cloud Models", Applied Optics, Vol. 6, page 1209, July 1967.

4. Cloud Code Chart, National Weather Service, U. S. Dept. of Commerce, Supt. of Documents, U. S. Govt. Printing Office, Washington, D.C.

5. N. E. Gaut, E. C. Reifenstein, "Degradation by the Atmosphere of Passive Microwave Observations from Space in the Frequency Range 0.5 to 20 GHz", Environmental Research and Technology, Inc., Stamford, Connecticut.

6. V. J. Falcone, L. W. Abreu, "Atmospheric Attenuation of Millimeter and Submillimeter Waves", EASCON '79 Record, IEEE Publication 79CH 1476-1 AES.

7. L. J. Battan, Radar Meteorology, Univ. of Chicago Press, Chicago, Illinois, 1959.

8. G. Mie, "Beitrage zur Optik ...", Ann. Phys., XXV (1908), p. 377.

9. D. Deirmendjian, "Complete Microwave Scattering and Extinction Properties of Polydispersed Cloud and Rain Elements", Report R-422-PR, The Rand Corporation, Santa Monica, Calif., 1963.

10. E. J. Dutton, H. T. Dougherty, "Estimates of the Atmospheric Transfer Function at SHF and EHF", NTIA Report 78-8, U. S. Dept. of Commerce, Washington, D.C., August 1978.

11. K. L. S. Gunn and T. W. R. East, "The Microwave Properties of Precipitation Particles", Quart. Jour. Roy. Meteorol. Soc., LXXX (1954), pp. 522-545.

12. B. R. Bean, E. J. Dutton, Radio Meteorology, Dover Publications, New York, 1968.

13. D. H. Staelin, "Measurements and Interpretation of the Microwave Spectrum of the Terrestrial Atmosphere near 1-Centimeter Wavelength", Journal of Geophysical Research, Vol. 71, No. 12, June 15, 1966, pp. 2875-2881.

14. J. W. Waters, "Absorption and Emission by Atmospheric Gases", in Methods of Experimental Physics, Vol. 12, Academic Press, New York, 1976.

15. E. D. Damosso, S. de Padova, "Some Considerations about Sky Noise Temperature at Frequencies above 10 GHz.". Alta Frequenza, Vol. XLV, No. 2, Feb. 1976, pp. 98-10E to 106-18E.

16. A. W. Straiton, "The Absorption and Reradiation of Radio Waves by Oxygen and Water Vapor in the Atmosphere", IEEE Trans. Ant. and Prop., July 1975,, pp. 595-597.

17. L. Tsang, J. A. Kong, E. Njoku, D. H. Staelin, J. W. Waters, "Theory of Microwave Thermal Emission from a Layer of Cloud or Rain", IEEE Trans. Ant. and Prop., Sept. 1977, pp. 650-657.

18. D. C. Hogg, "Ground-Based Remote Sensing and Profiling of the Lower Atmosphere Using Radio Wavelengths", IEEE Trans. Ant. and Prop., March 1980, pp. 281-283.

19. V. J. Falcone, K. N. Wulfsberg, S. Gitelson, "Atmospheric Emission and Absorption at Millimeter Wavelengths", Radio Science, Vol. 6, No. 3, pp. 347-355, March 1971.

20. A. T. C. Chang, T. T. Wilheit, "Remote Sensing of Atmospheric Water Vapor, Liquid Water ...", Radio Science, Vol. 14, No. 5, pp. 793-802, Sept-Oct 1979.

21. M. T. Decker, Millimeter and Submillimeter Waves; Scatter, Absorption, and Radiation, ERL/ESSA (Boulder) Radio Propagation Course, Lecture VII-5.

22. R. J. Coates, "Measurements of Solar Radiation and Atmospheric Attenuation at 4.3-millimeters Wavelength", Proc. IRE, Vol. 46, No. 1, pp. 122-126, January 1958.

23. R. W. Wilson, "A Three-Radiometer Path-Diversity Experiment", Bell System Technical Journal, July-August 1970, pp. 1239-1242.

24. R. W. Wilson, "Sun Tracker Measurements of Attenuation by Rain at 16 and 30 GHz", Bell System Technical Journal, May-June 1969, pp. 1383-1404.

25. W. V. T. Rusch, S. D. Slobin, C. T. Stelzried, T. Sato, "Observations of the Total Lunar Eclipse of October 18, 1967, at a Wavelength of 3.33 Millimeters", Astrophysical Journal, Vol. 155, March 1969, pp. 1017-1021.

26. C. T. Stelzried, S. D. Slobin, "Calculations of Atmospheric Loss from Microwave Radiometric Noise Temperature Measurements", TDA Progress Report 42-62, Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1981.

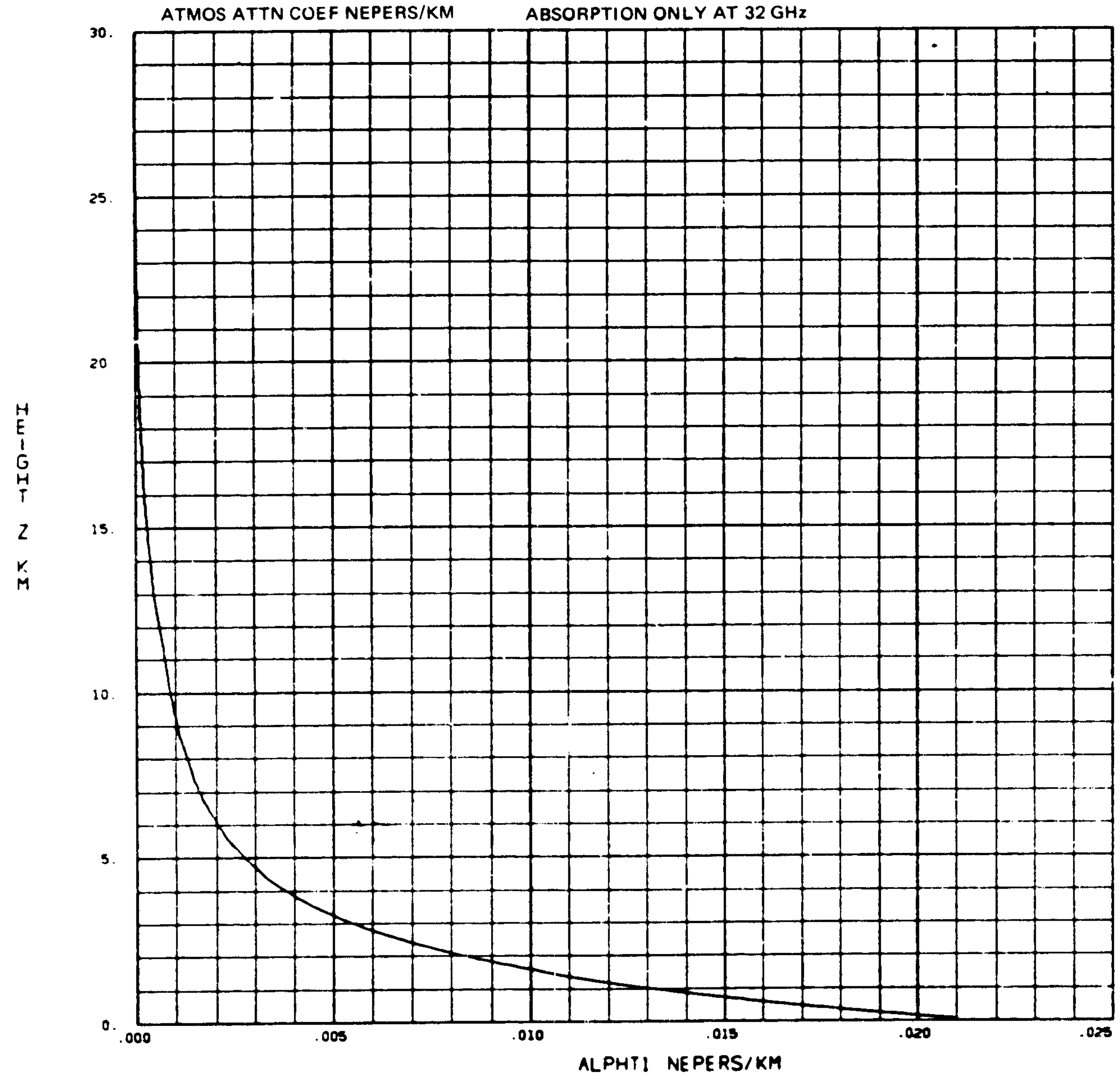
27. CCIR, Recommendations and Reports of the CCIR, 1978, Volume V, Repts. 719 & 720, Propagation in Non-Ionized Media, International Telecommunication Union, Geneva, 1978.

28. E. K. Smith and J. W. Waters, "A Comparison of CCIR Values of Slant Path Attenuation and Sky Noise Temperature With Those From the JPL Radiative Transfer Program", presented at URSI National Radio Science Meeting, Boulder, Colorado, January 12-16, 1981.

APPENDIX

SAMPLE CASE CALCULATIONS OF CLOUD ATTENUATION AND NOISE TEMPERATURE

CASE 1-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
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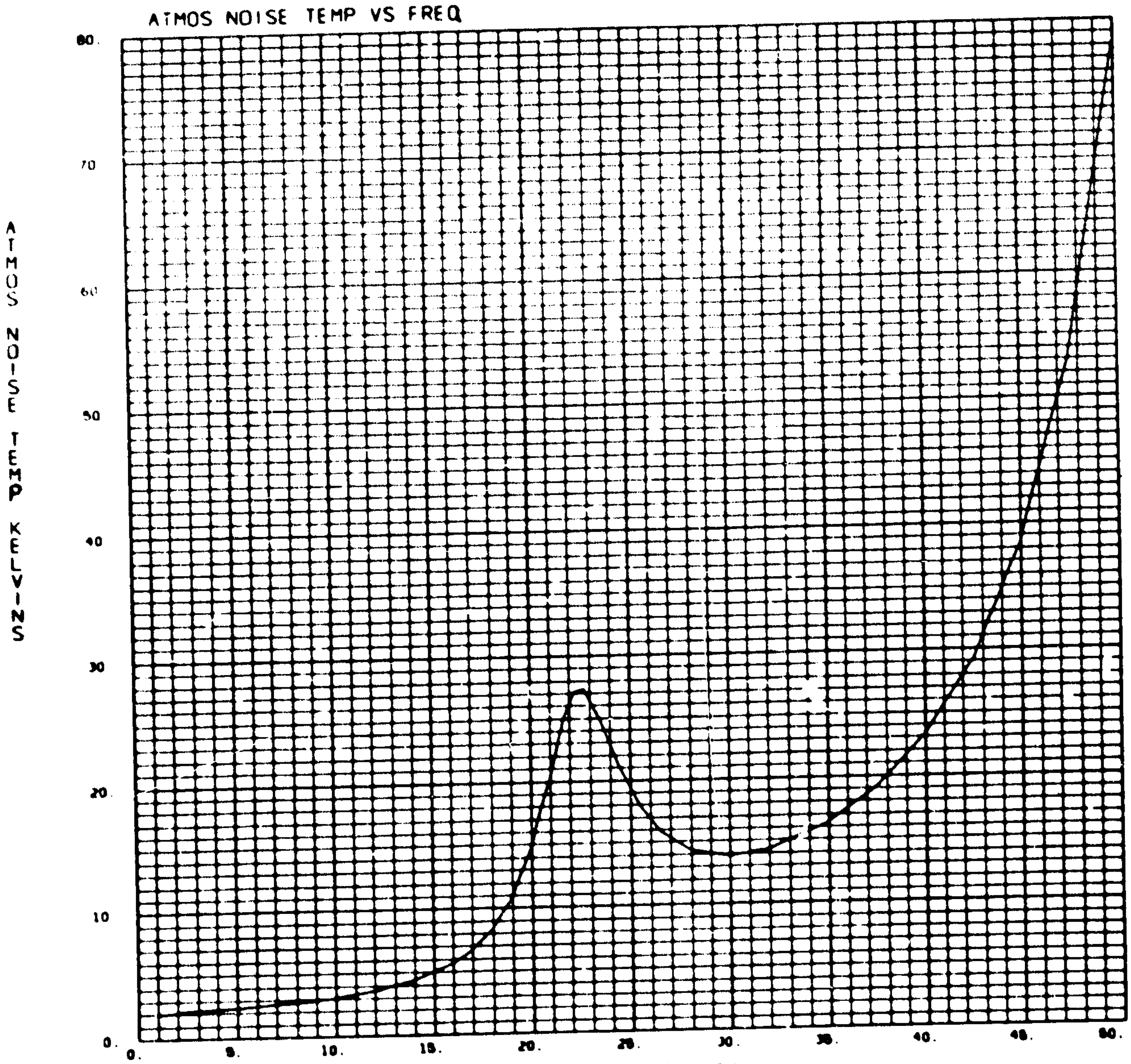
CASE 1-2



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
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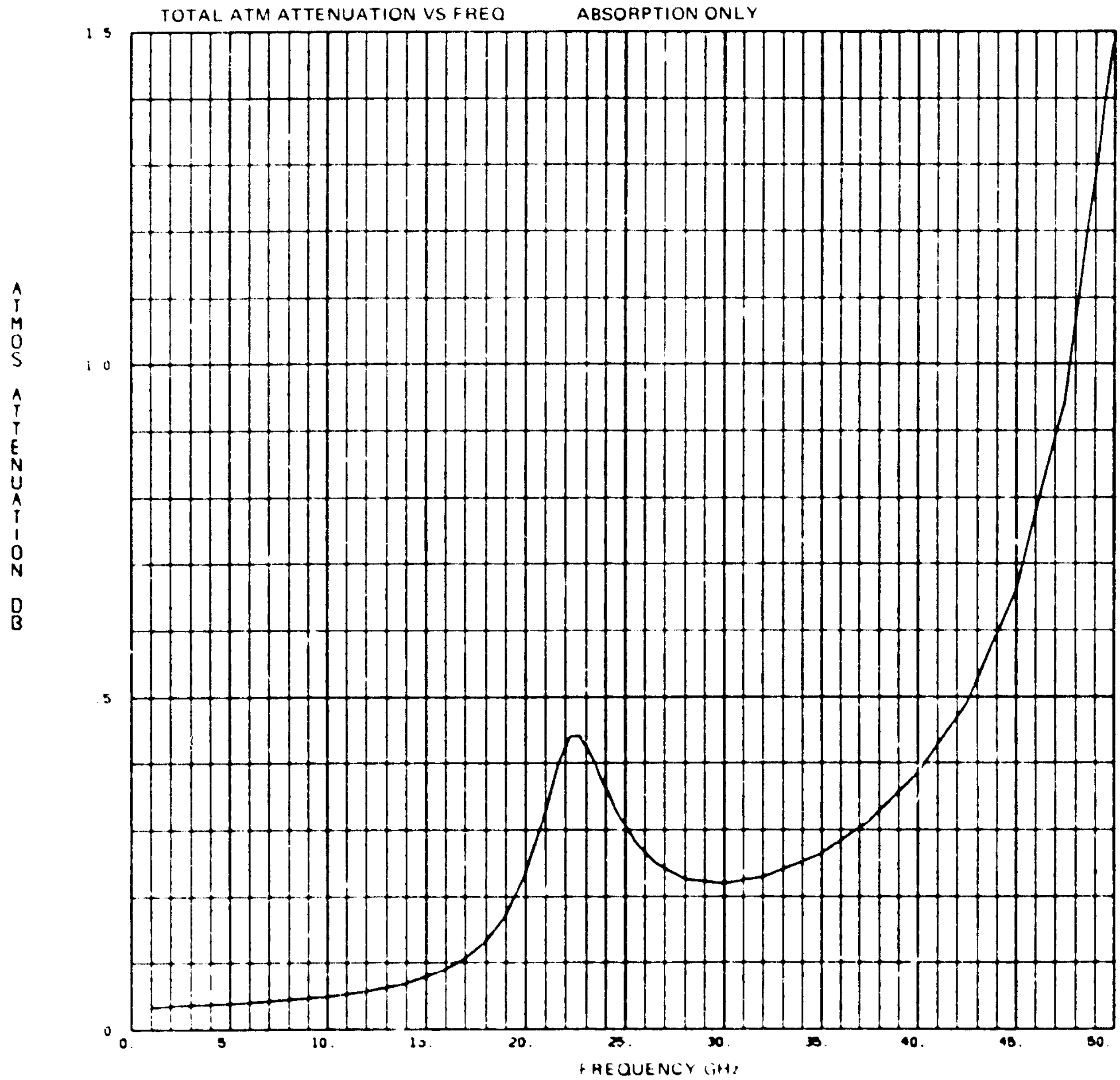
CASE 1-3



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
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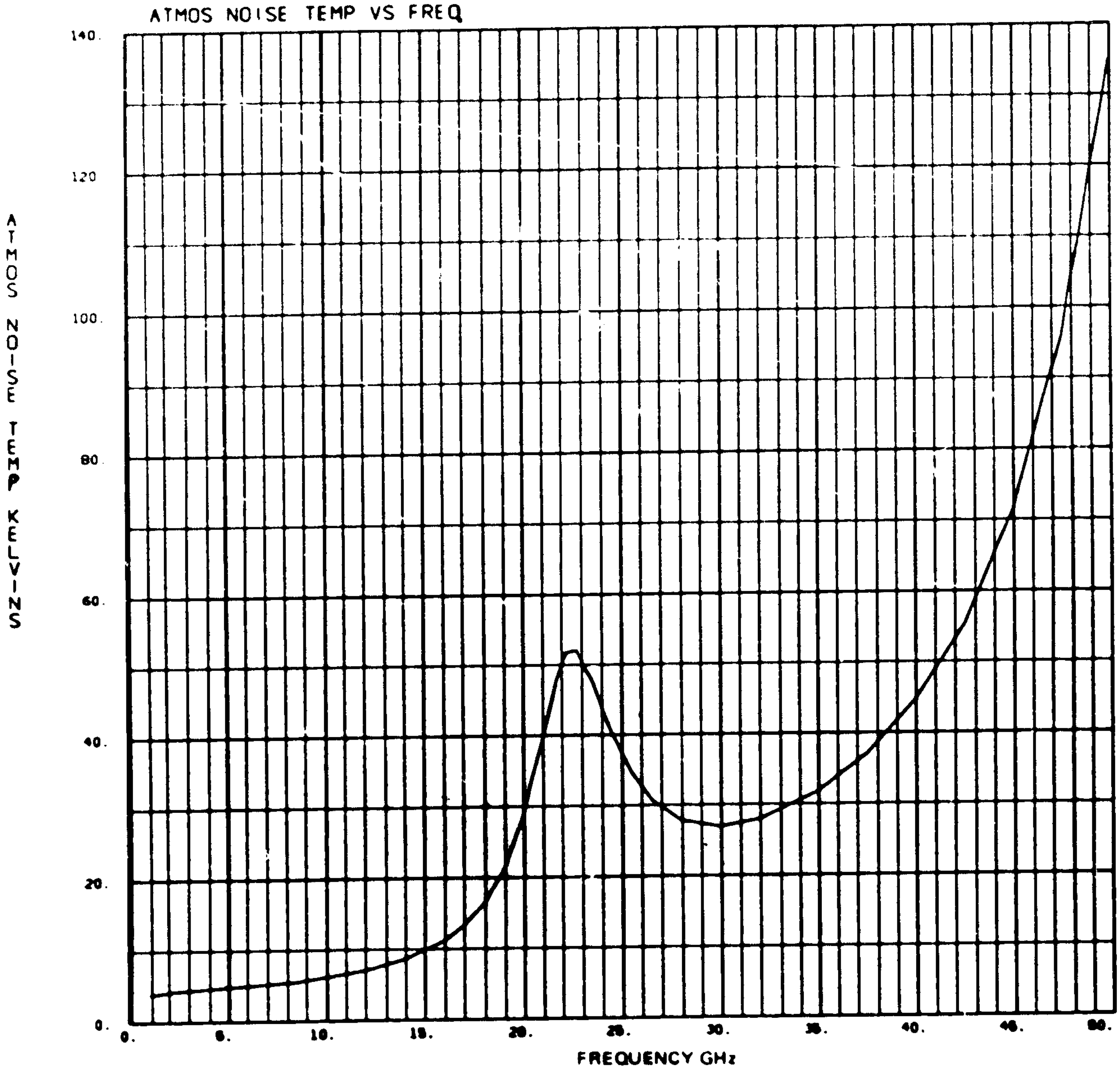
CASE 1-4



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
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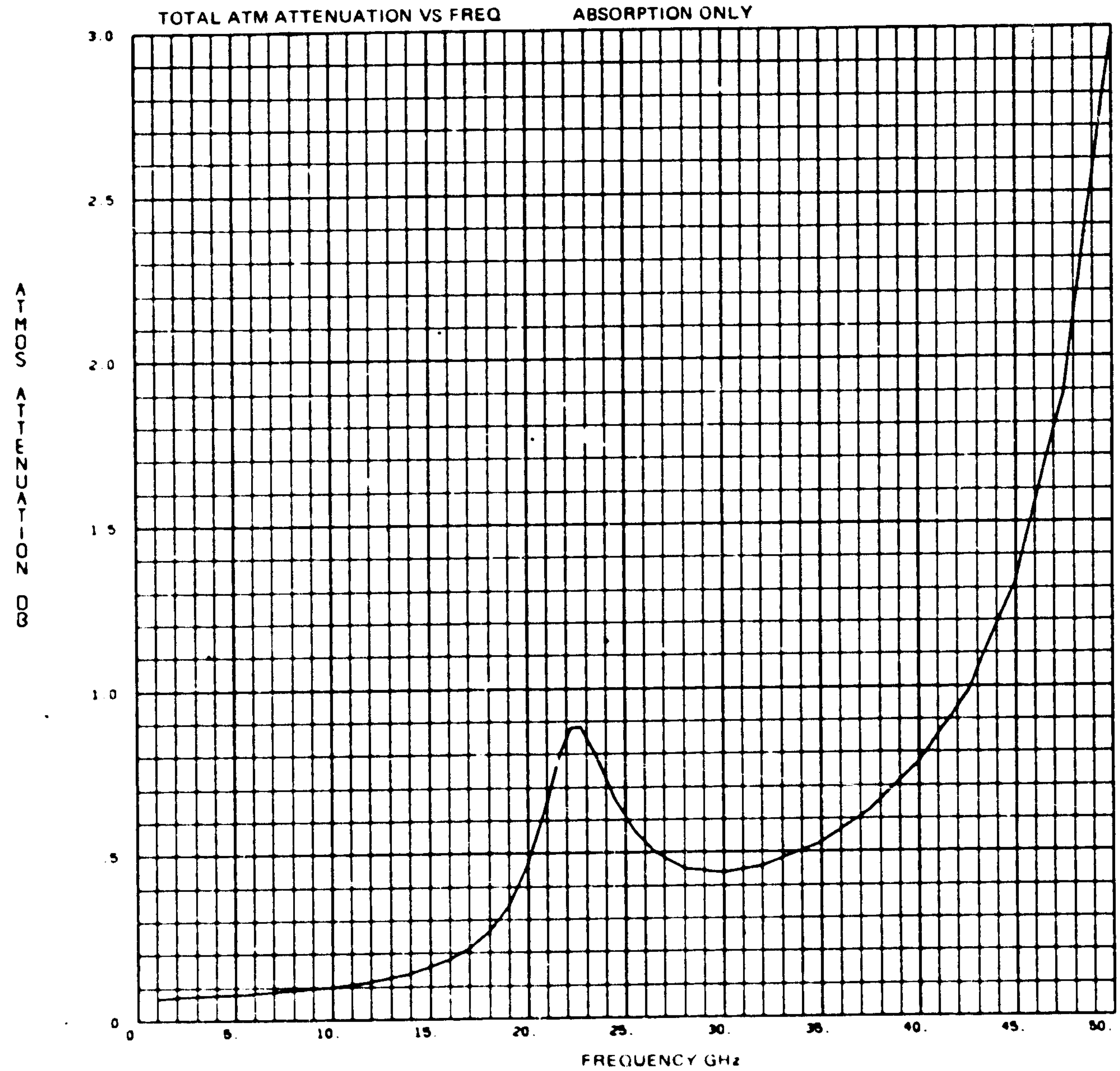
CASE 1-5



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
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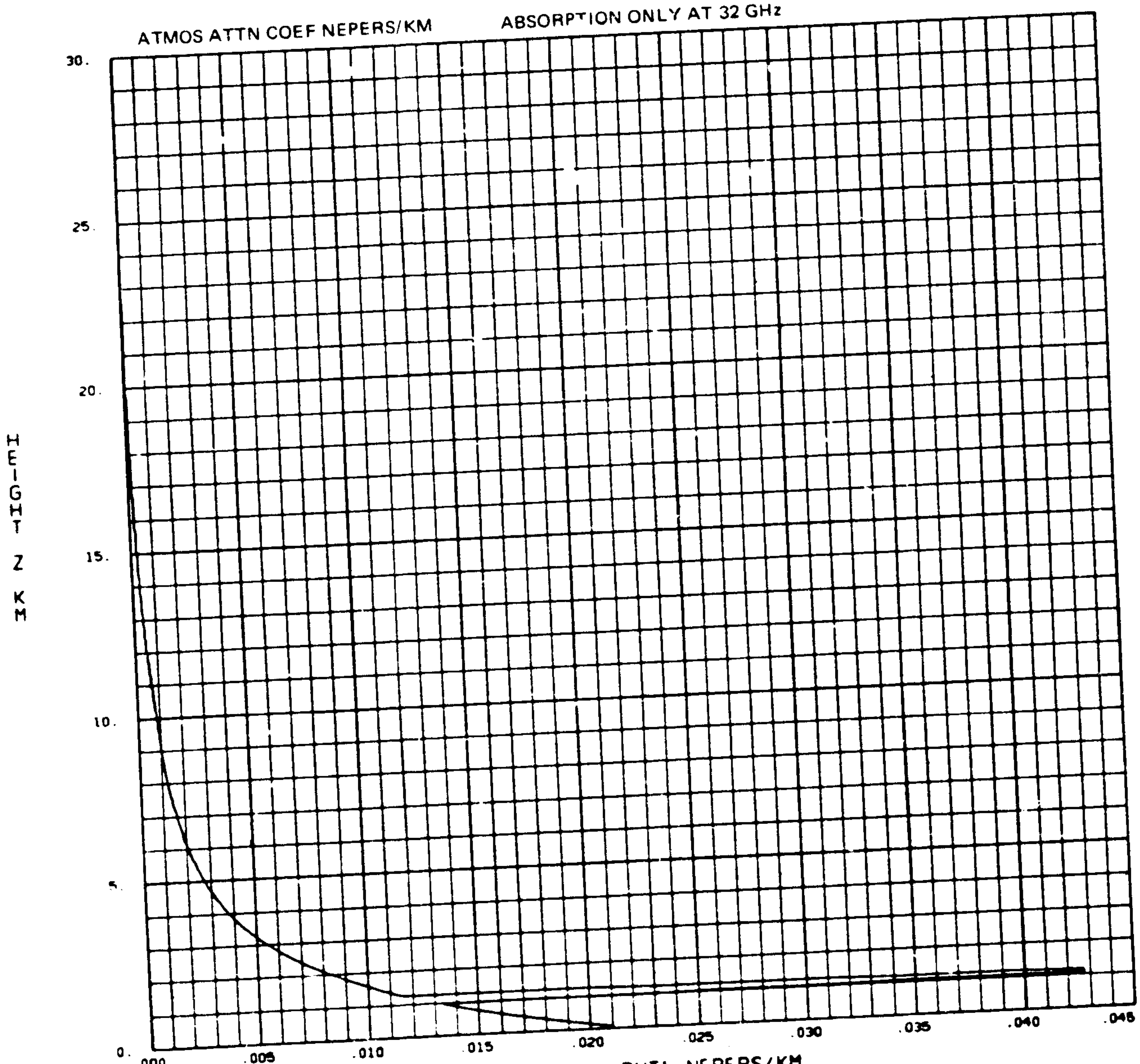
CASE 2-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	8.3000000+01	2.0000000-01	2.0000000-01	0.0000000	0.0000000	0.0000000	0.0000000

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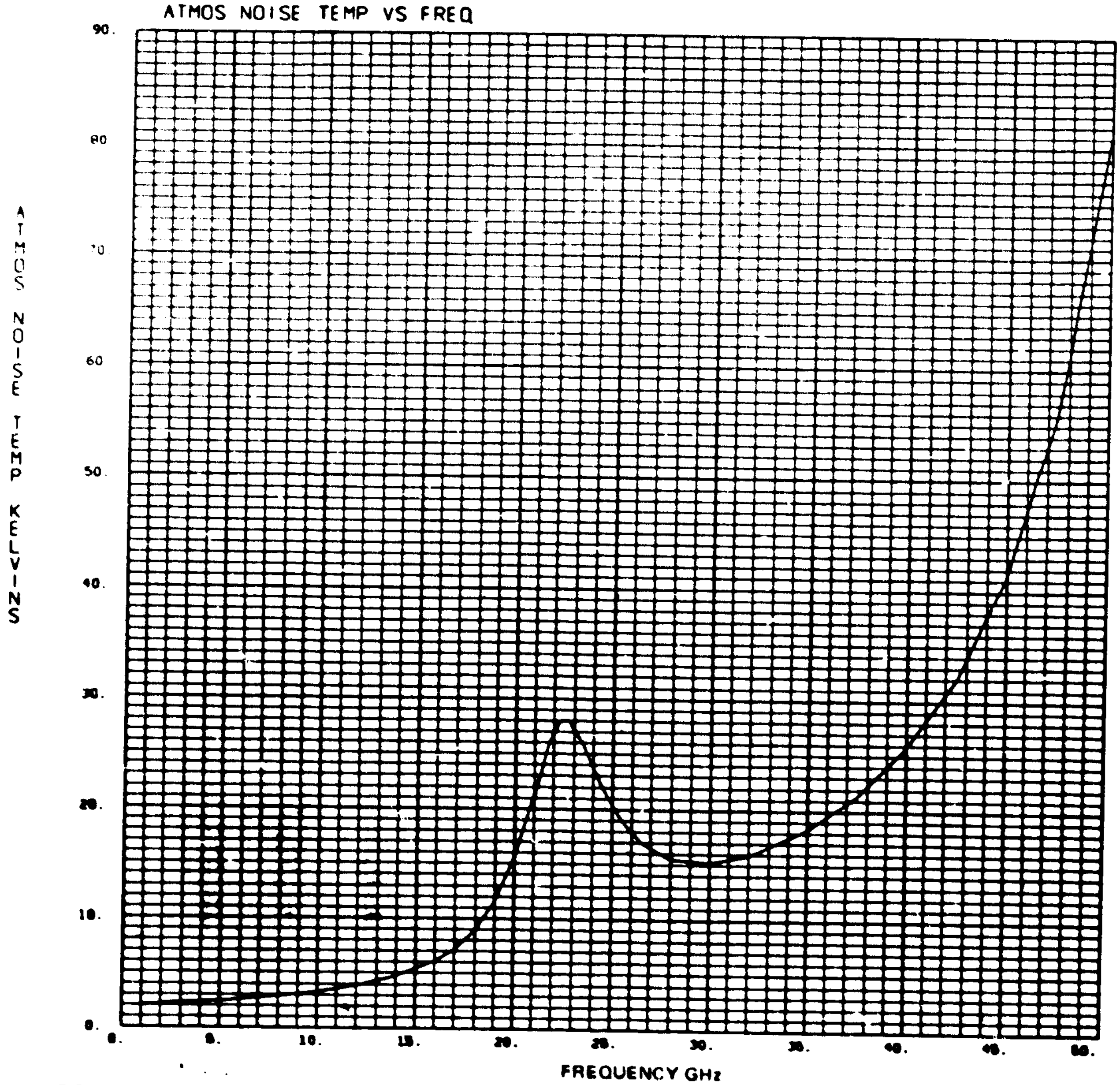
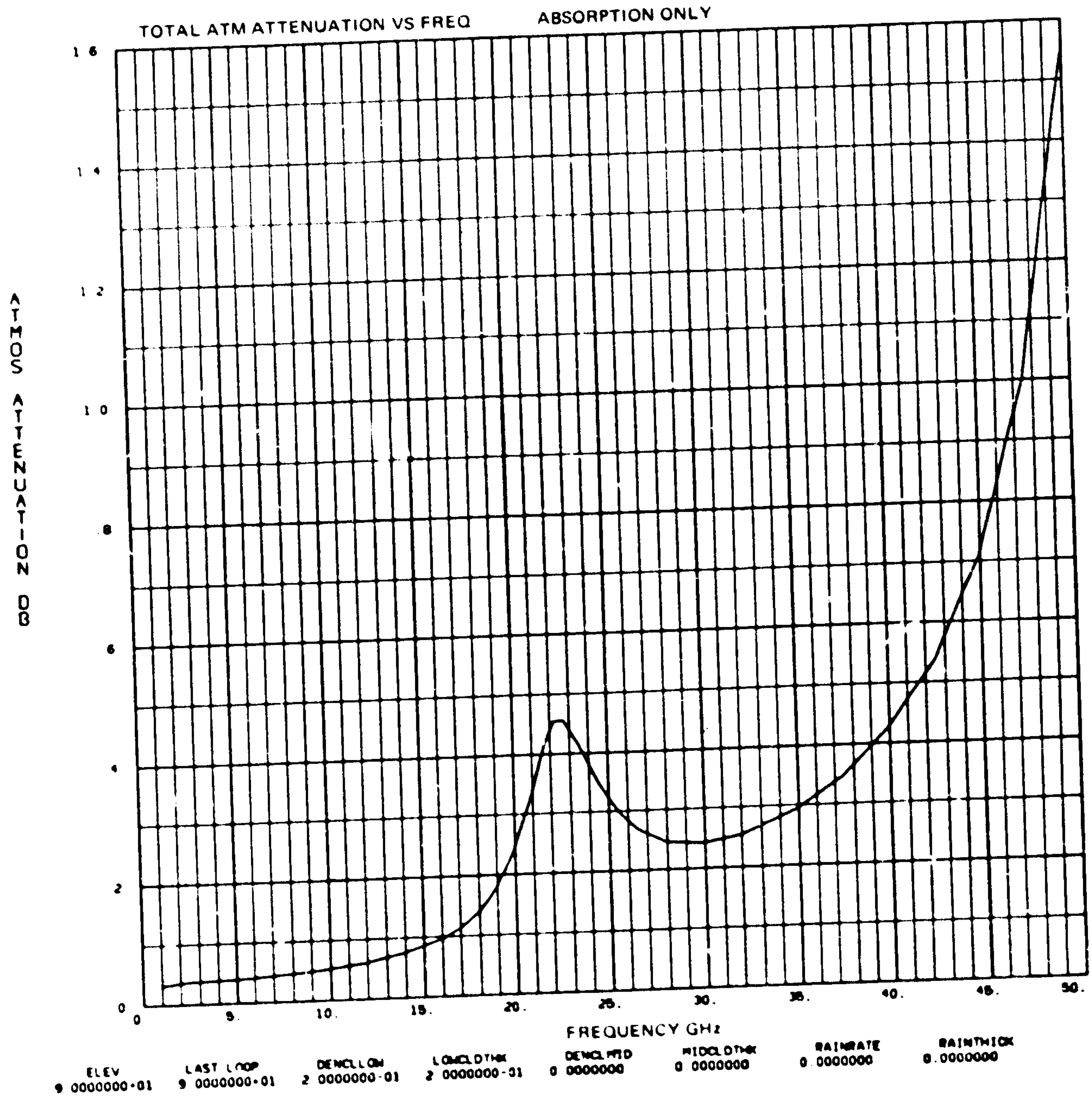
CASE 2-2

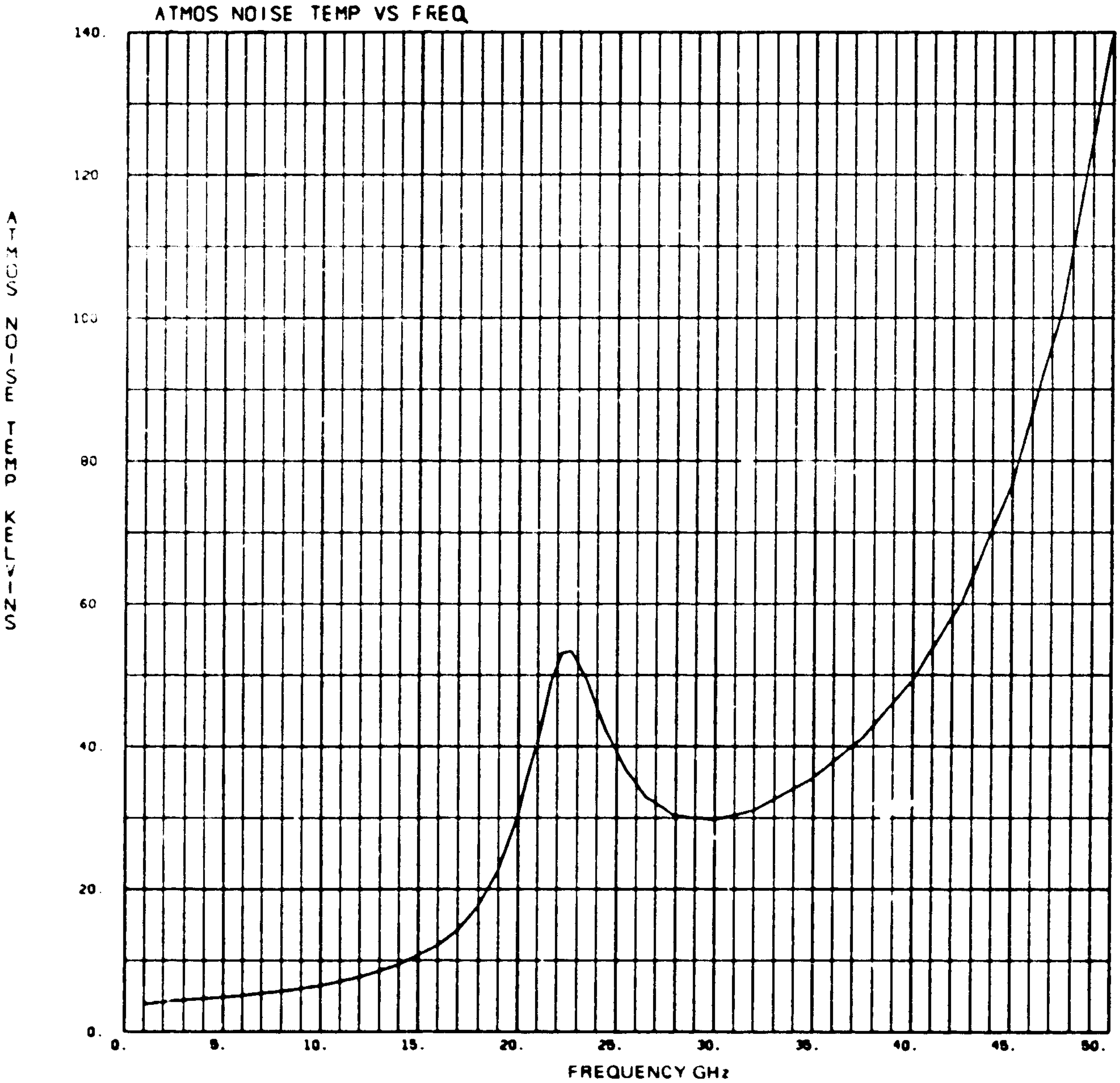


ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	9.0000000+01	2.0000000-01	2.0000000-01	0.0000000	0.0000000	0.0000000	0.0000000

CASE 2-3

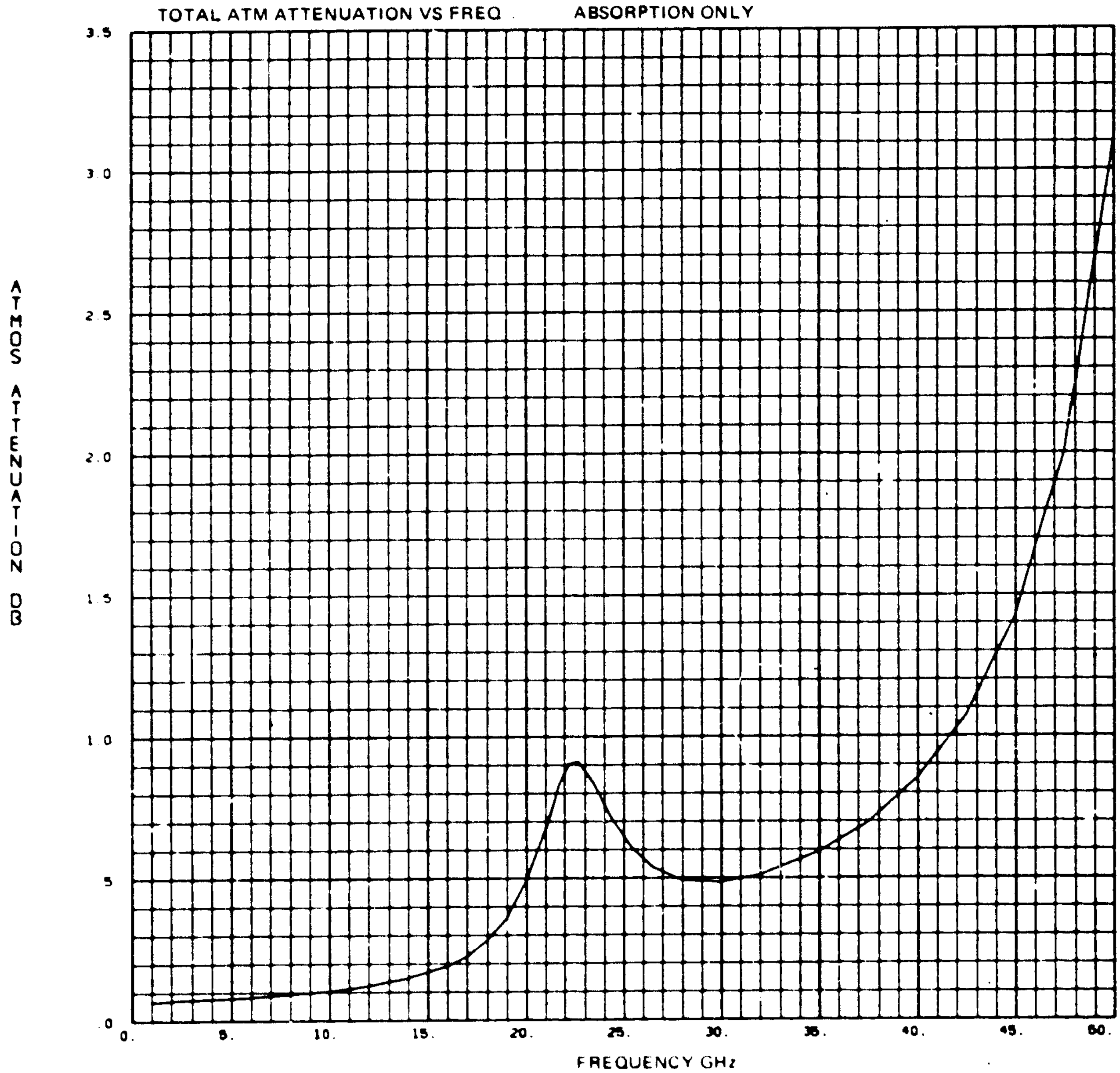

TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV
9.0000000-01
LAST LOOP
9.0000000-01
DENCLLOW
2.0000000-01
LOWCLDTHK
2.0000000-01
DENCLMID
0.0000000
MIDCLDTHK
0.0000000
RAINRATE
0.0000000
RAINTHICK
0.0000000

CASE 2-4



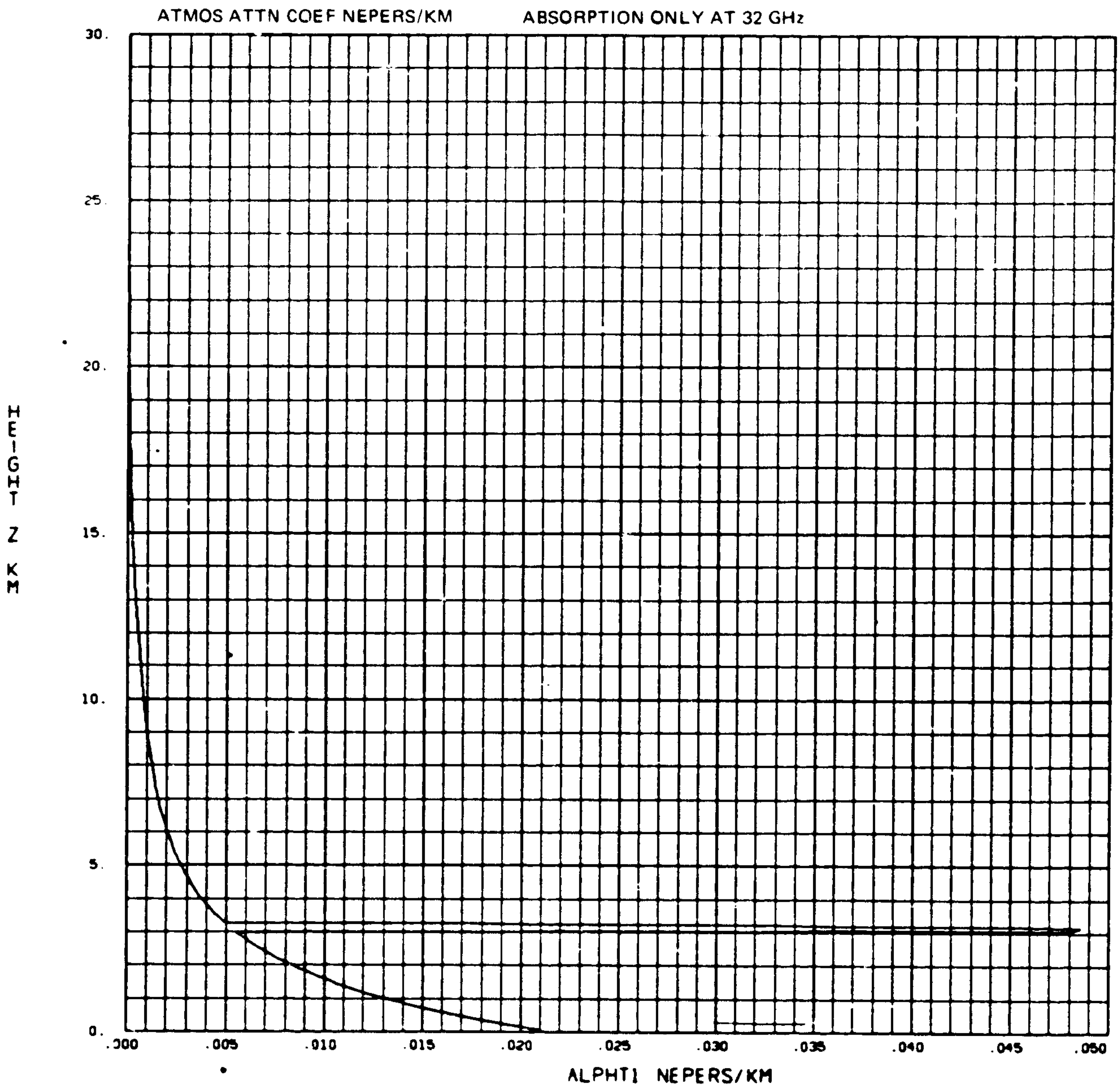
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000-01	1.2000000-02	2.0000000 01	2.0000000-01	0.0000000	0.0000000	0.0000000	0.0000000

CASE 2-5



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	1.2000000+02	2.0000000-01	2.0000000-01	0.0000000	0.0000000	0.0000000	0.0000000

CASE 3-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	1.4300000+02	0.0000000	0.0000000	2.0000000-01	1.9999999-01	0.0000000	0.0000000

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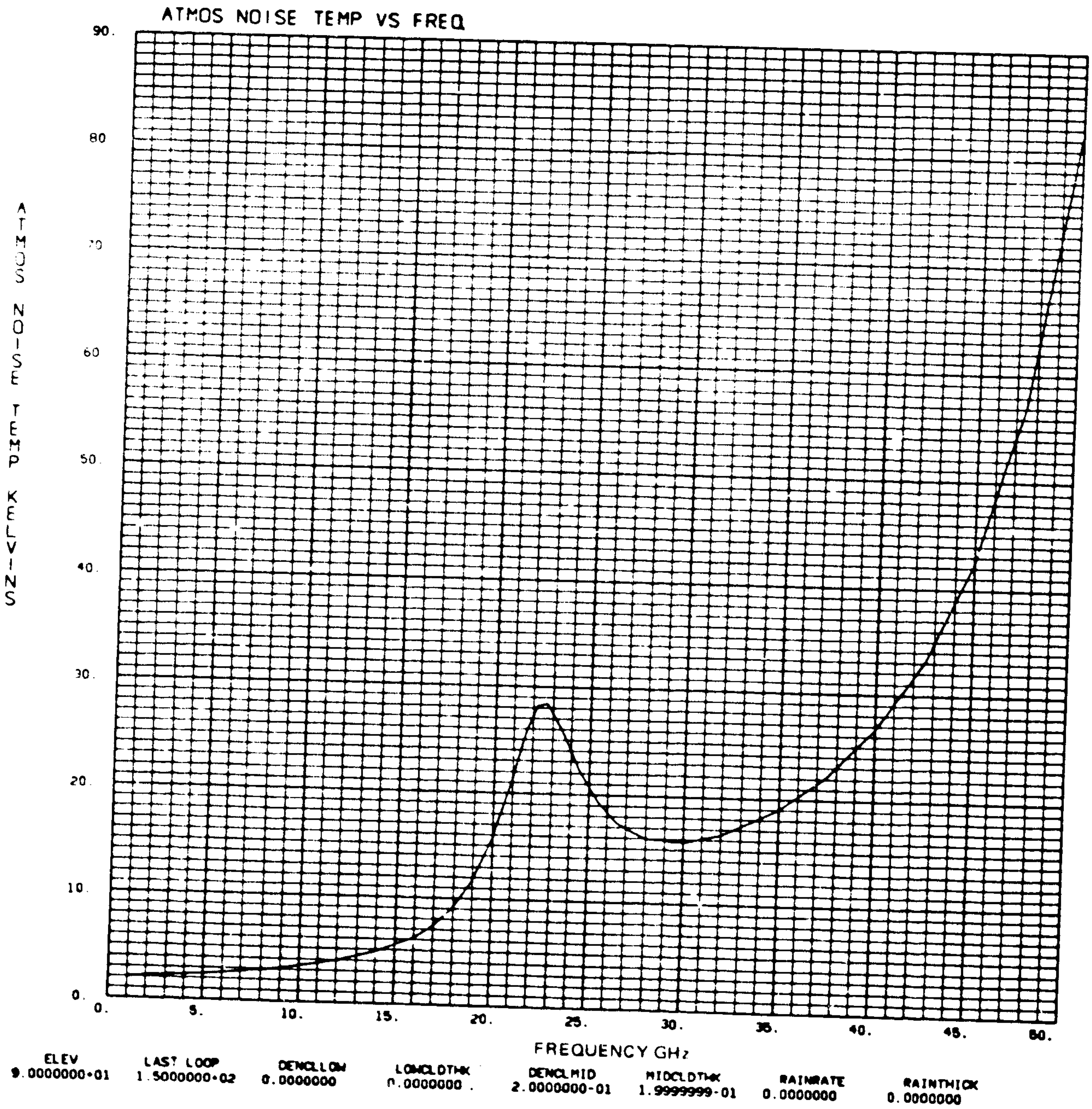
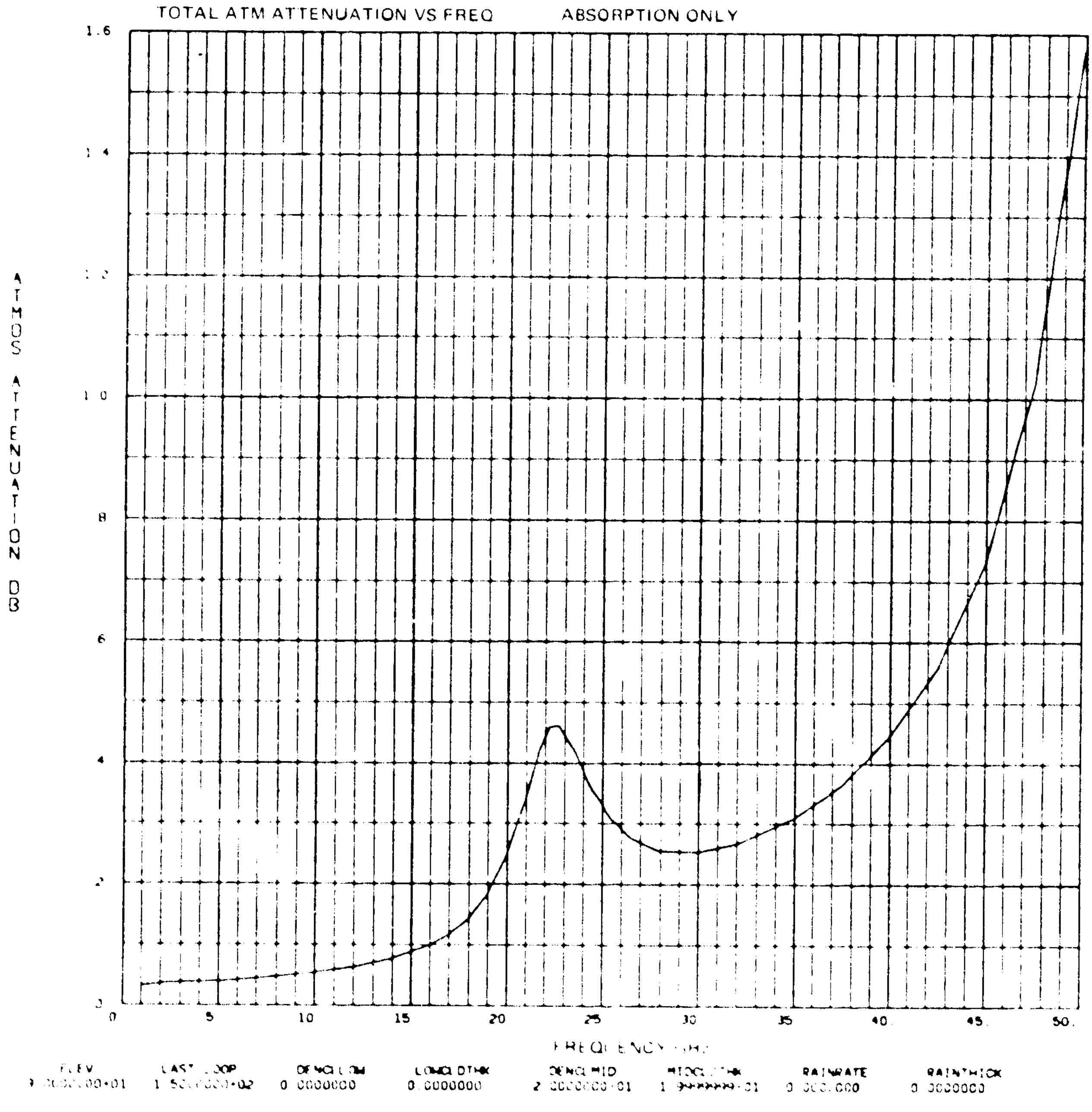
CASE 3-2

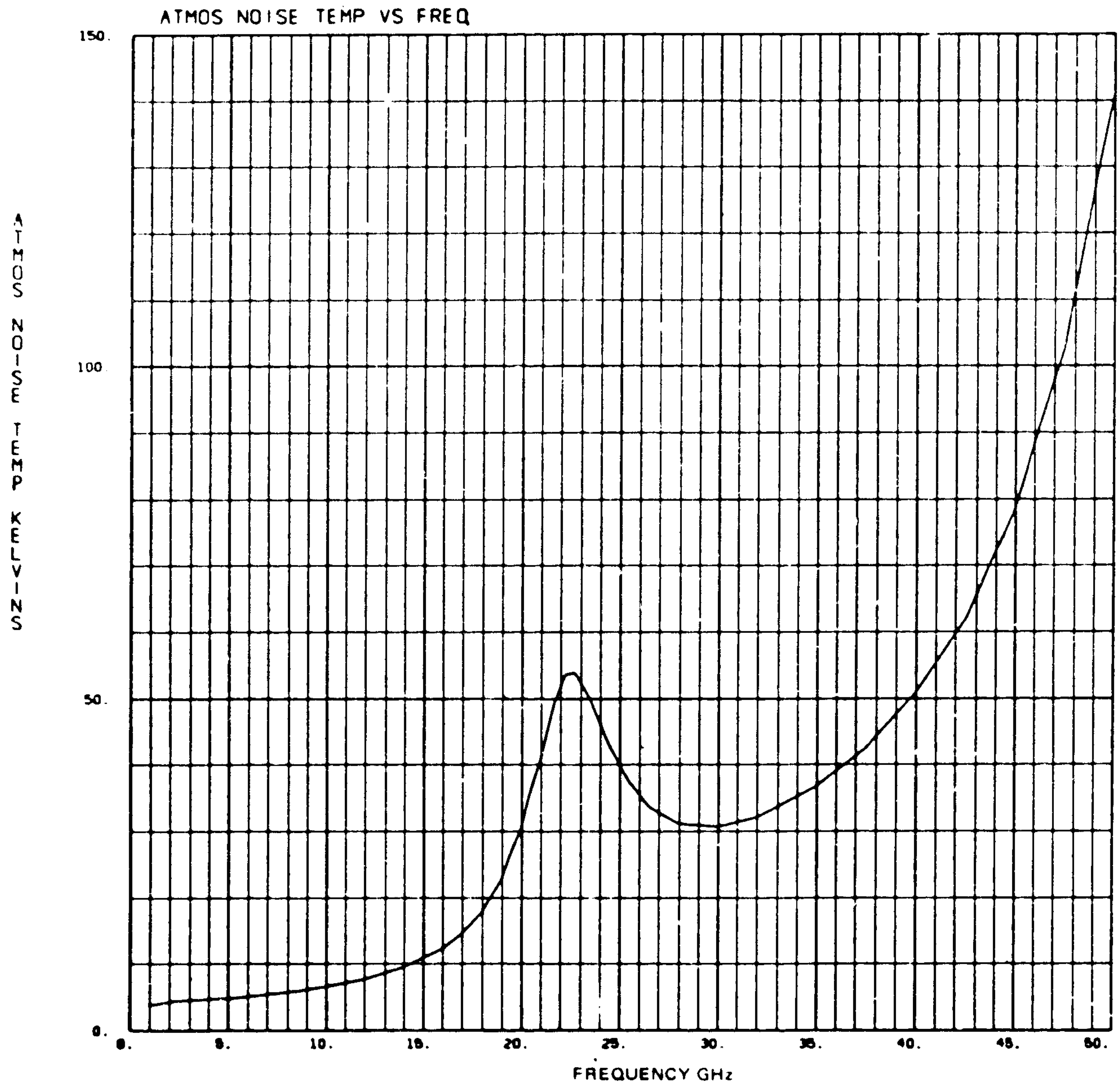

ATMOS NOISE TEMP VS FREQ
ATMOS NOISE TEMP KELVINS
90.
80
70
60
50.
40.
30.
20.
10.
0.
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV 9.0000000+01
LAST LOOP 1.5000000+02
DENCLLOW 0.0000000
LOWCLDTHK 0.0000000
DENCLMID 2.0000000-01
MIDCLDTHK 1.9999999-01
RAINRATE 0.0000000
RAINTHICK 0.0000000

CASE 3-3



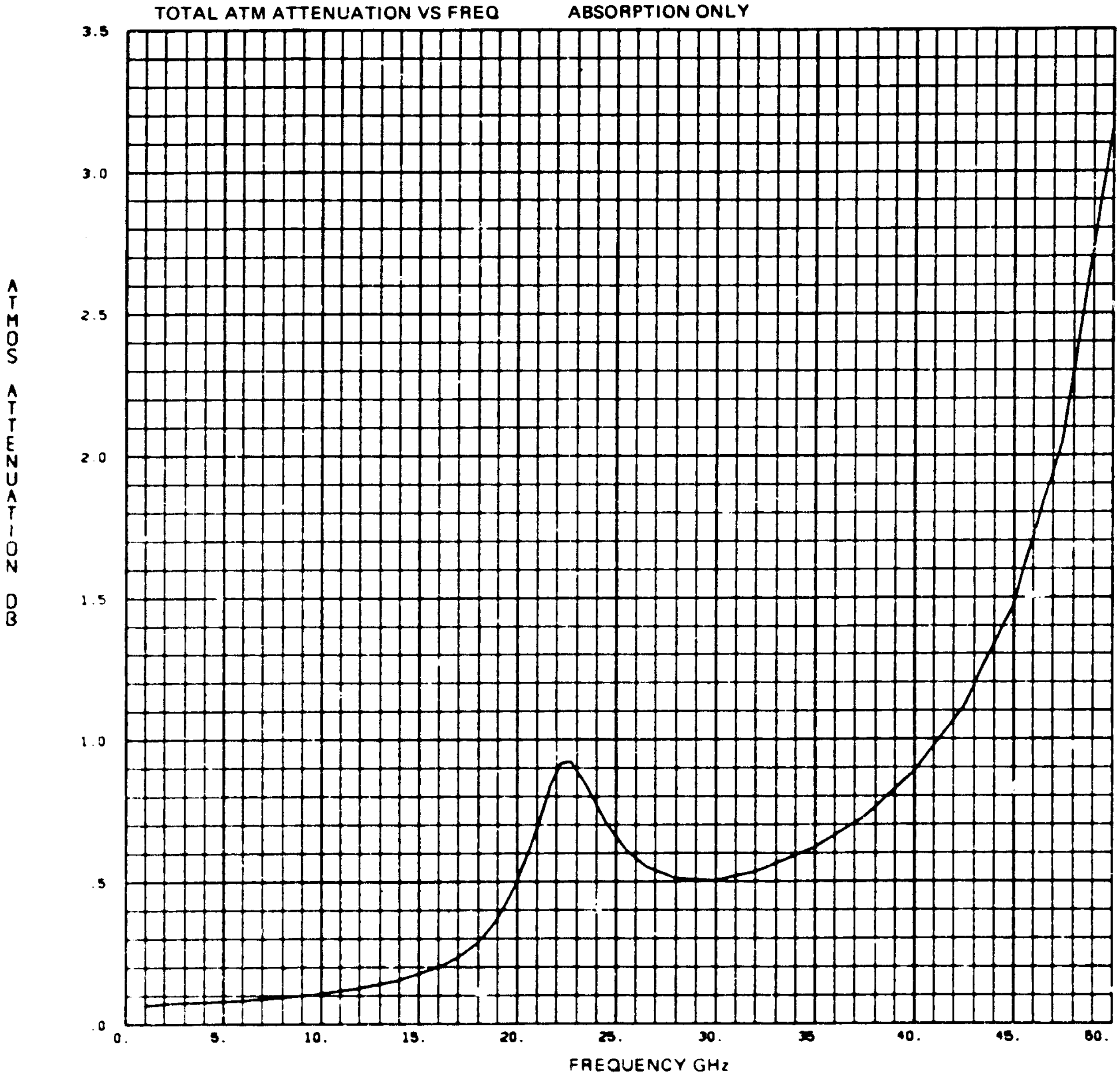
TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
FREQUENCY

CASE 3-4



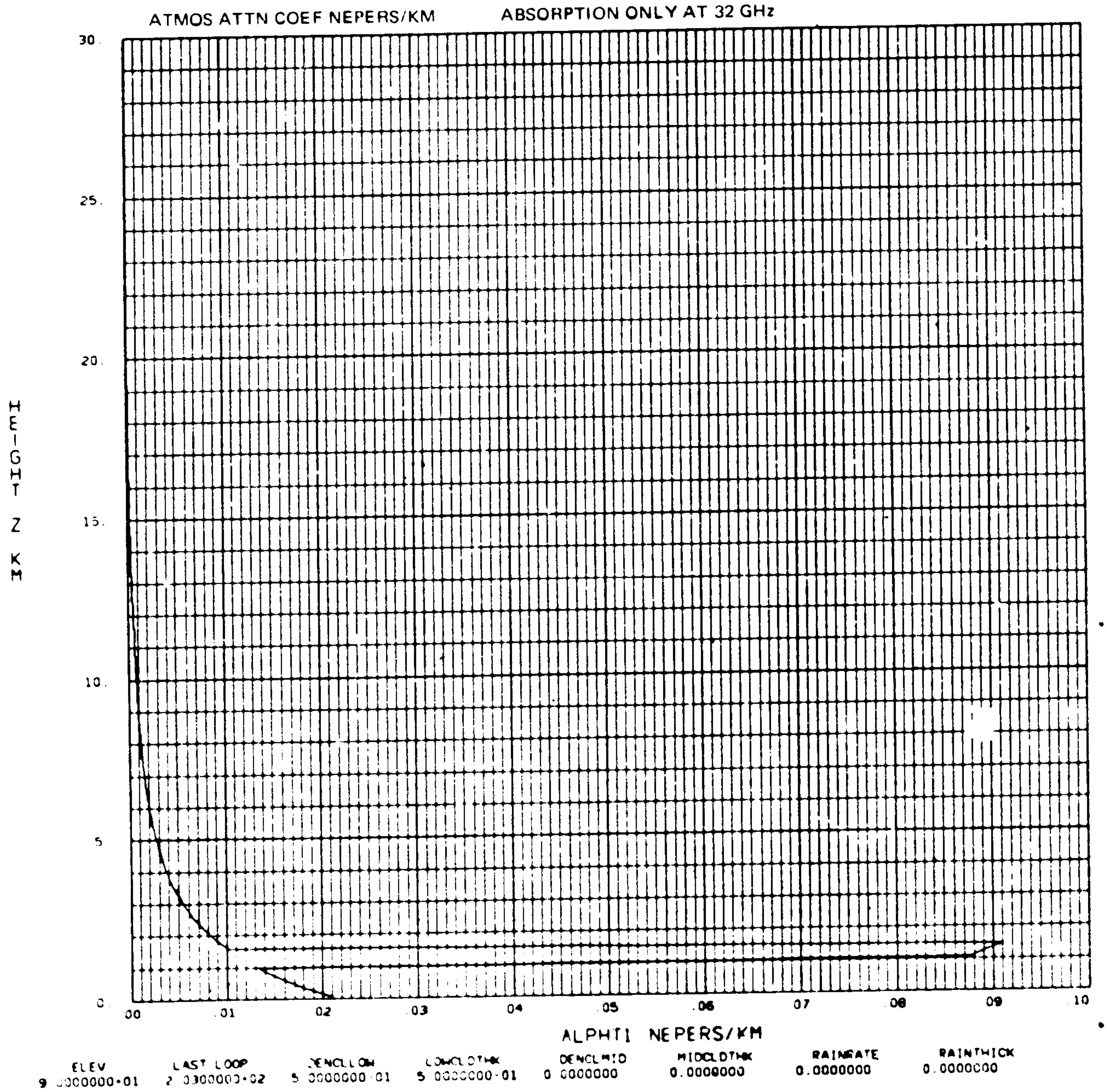
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	1.0000000+02	0.0000000	0.0000000	2.0000000-01	1.9999999-01	0.0000000	0.0000000

CASE 3-5



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	1.8000000+02	0.0000000	0.0000000	2.0000000-01	1.9999999-01	0.0000000	0.0000000

CASE 4-1



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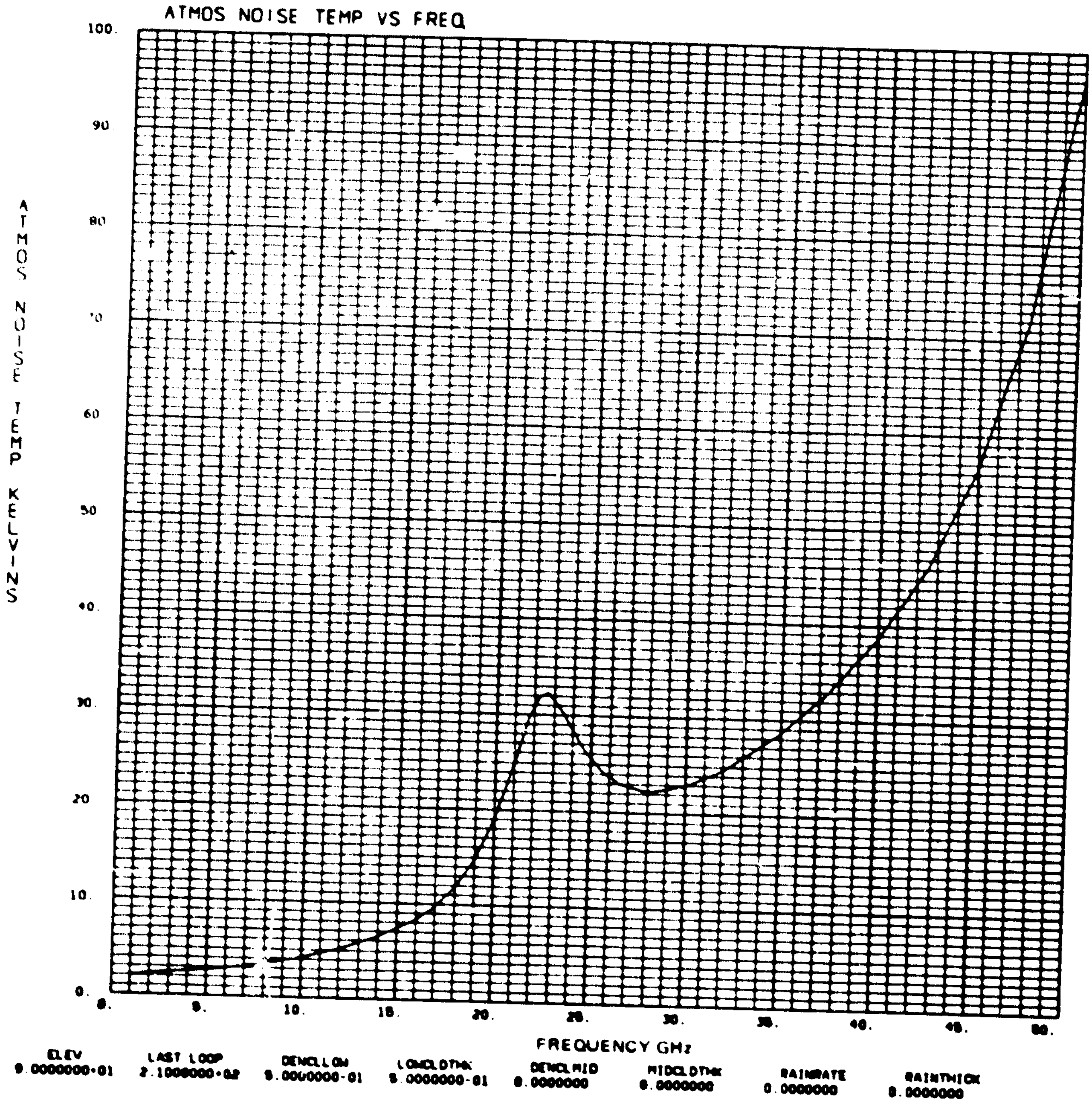
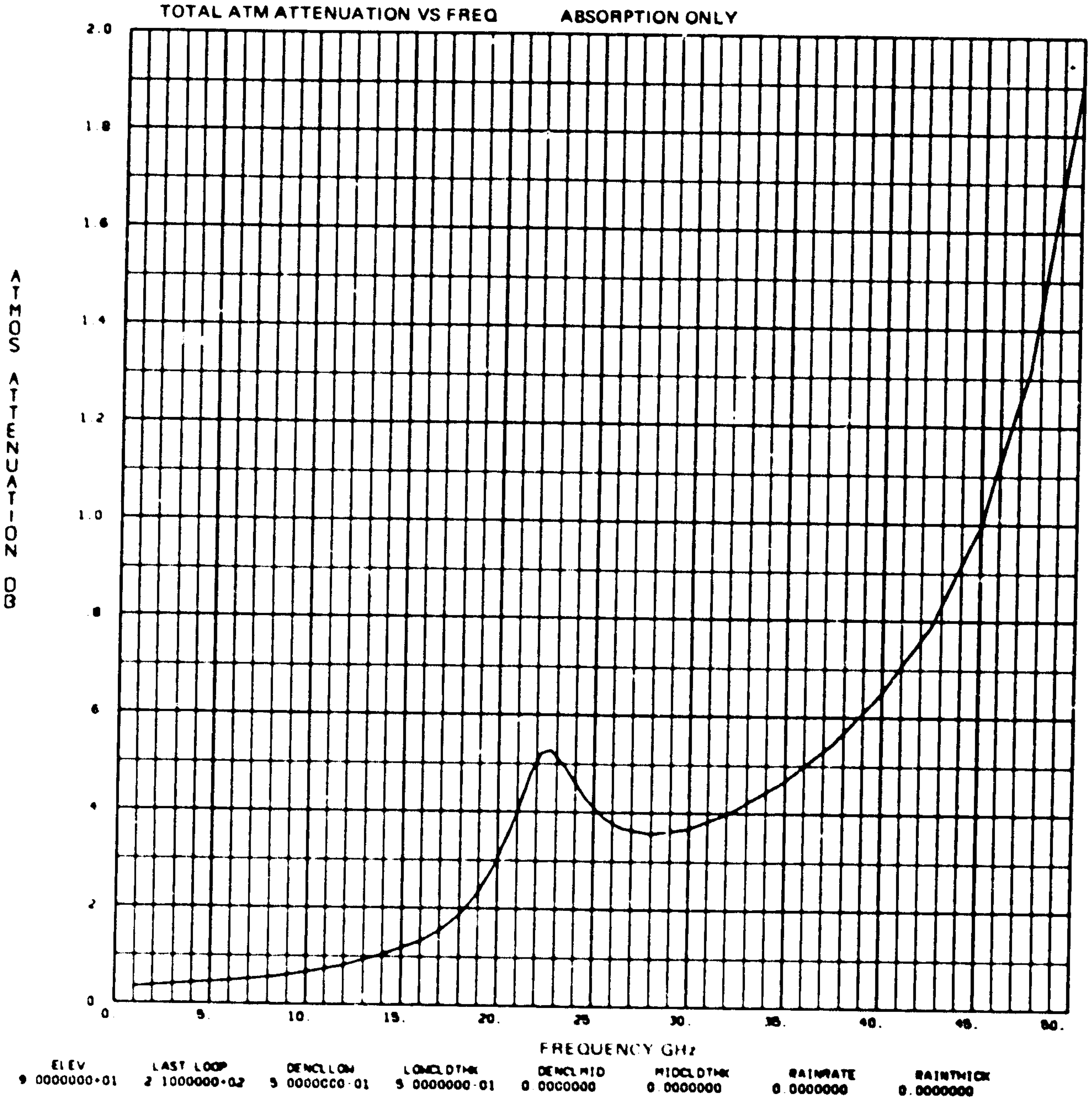
CASE 4-2

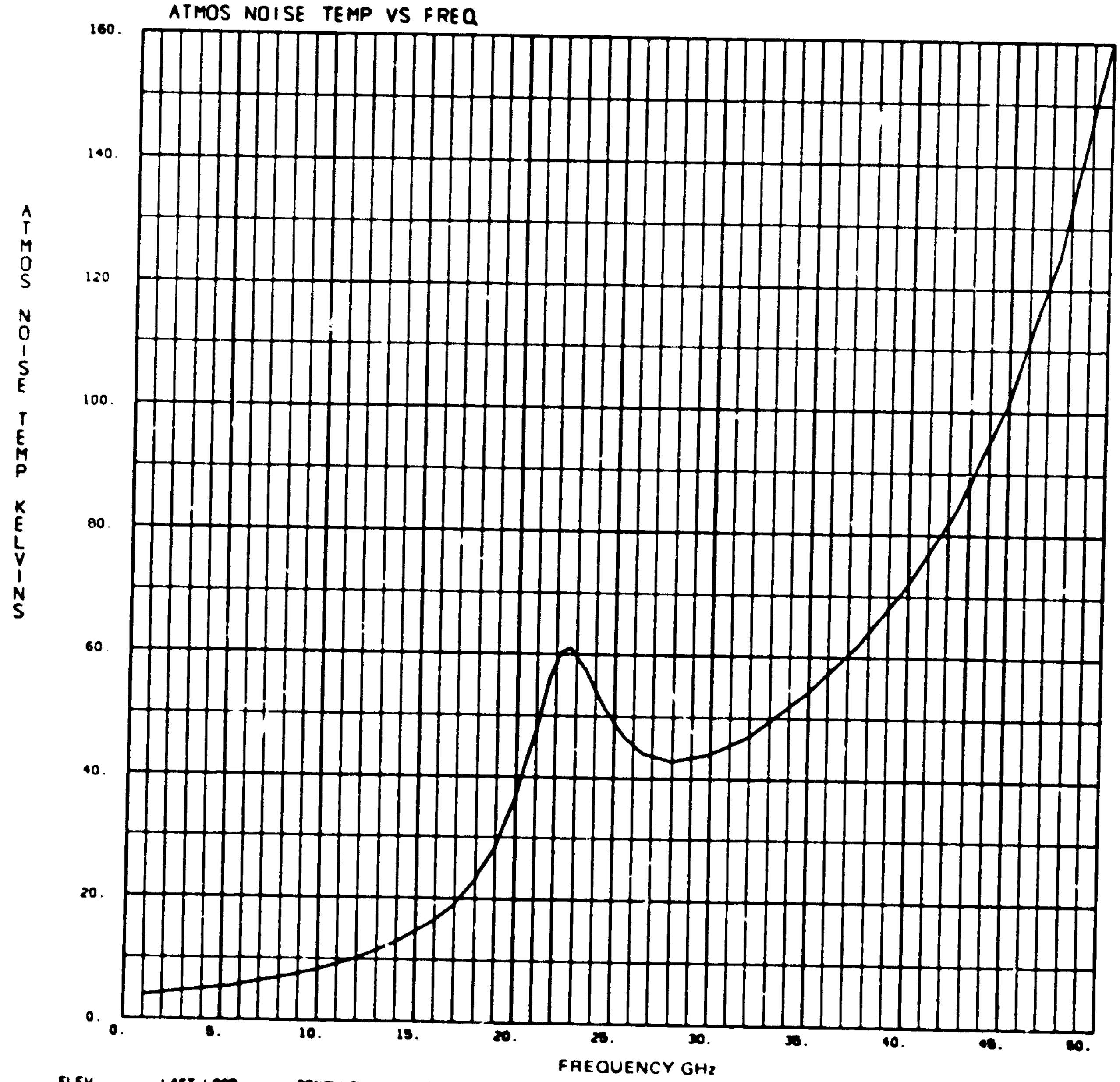


ATMOS NOISE TEMP VS FREQ
ATMOS NOISE TEMP KELVINS
FREQUENCY GHz
ELEV
LAST LOOP
DENCLLOW
LOWCLDTHK
DENCLMID
MIDCLDTHK
RAINRATE
RAINTHICK

CASE 4-3

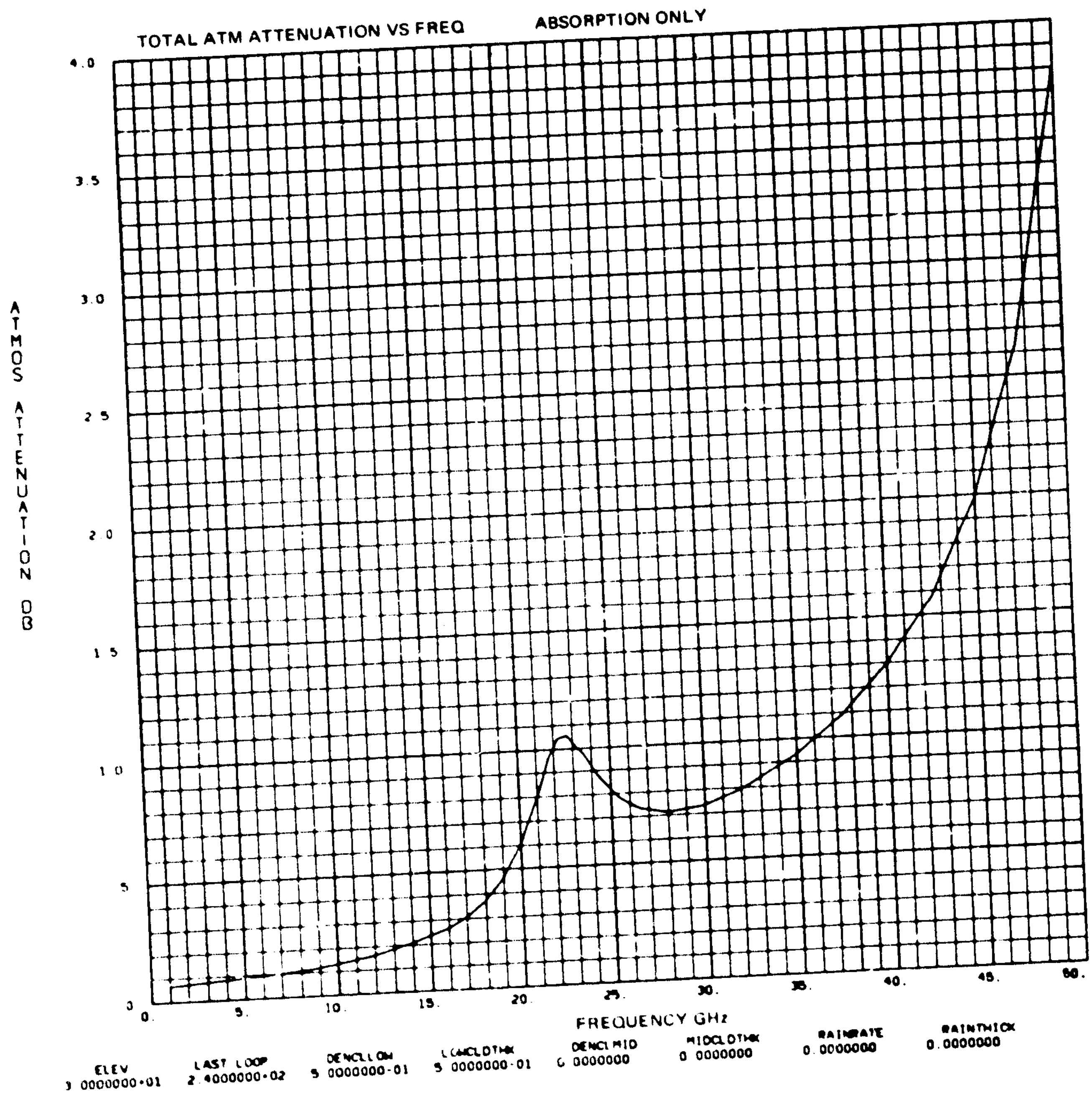

TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV 9.0000000+01
LAST LOOP 2.1000000+02
DENCLLOW 5.0000000-01
LOWCLDTHK 5.0000000-01
DENCLMID 0.0000000
MIDCLDTHK 0.0000000
RAINRATE 0.0000000
RAINTHICK 0.0000000

CASE 4-4

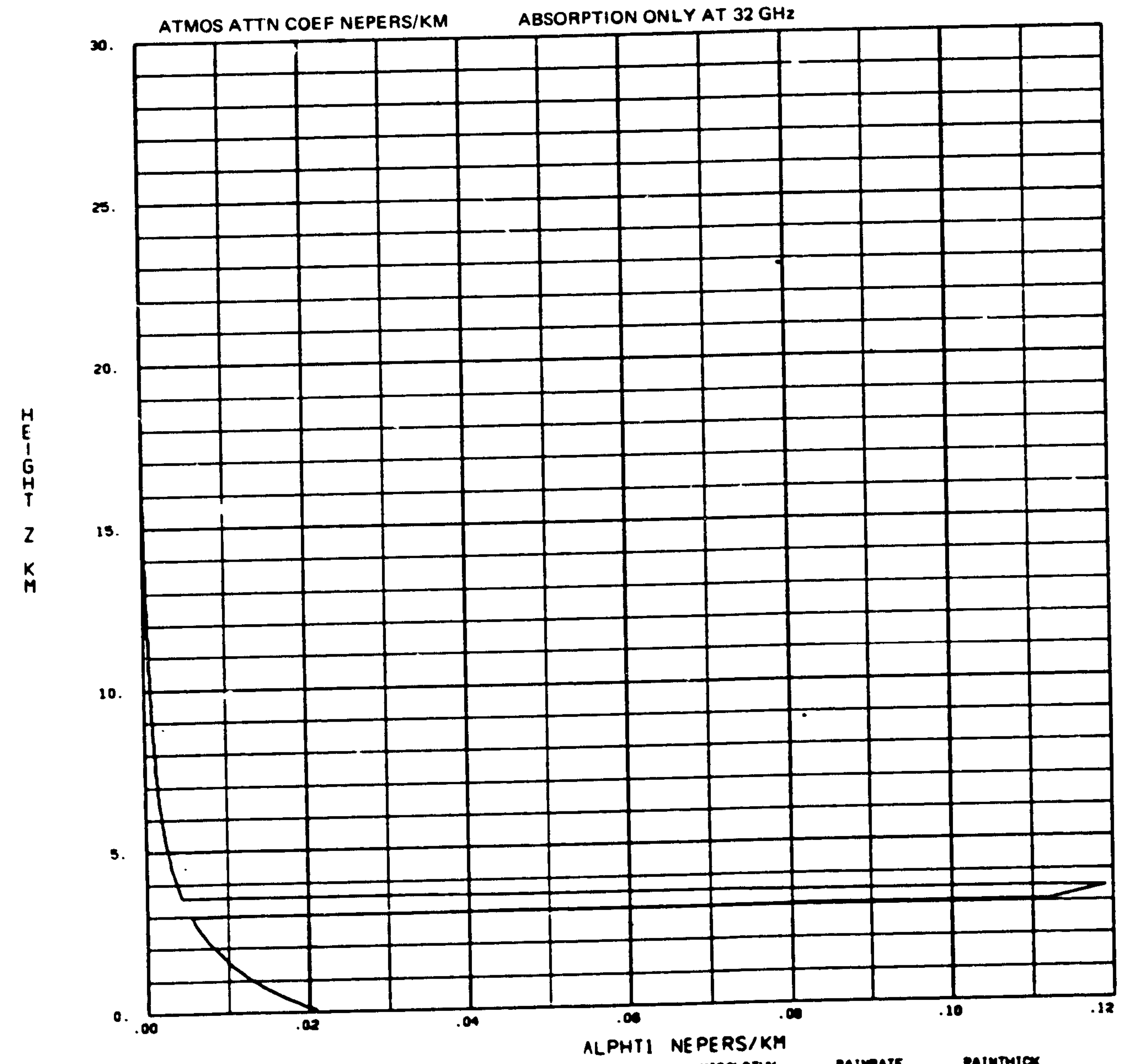


ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	2.4000000+02	5.0000000-01	5.0000000-01	0.0000000	0.0000000	0.0000000	0.0000000

CASE 4-5


TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
0
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV
3.0000000+01
LAST LOOP
2.4000000+02
DENCLLOW
5.0000000-01
LOWCLDTHK
5.0000000-01
DENCLMID
0.0000000
MIDCLDTHK
0.0000000
RAINRATE
0.0000000
RAINTHICK
0.0000000

CASE 5-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	2.6300000-02	0.0000000	0.0000000	5.0000000-01	5.0000000-01	0.0000000	0.0000000

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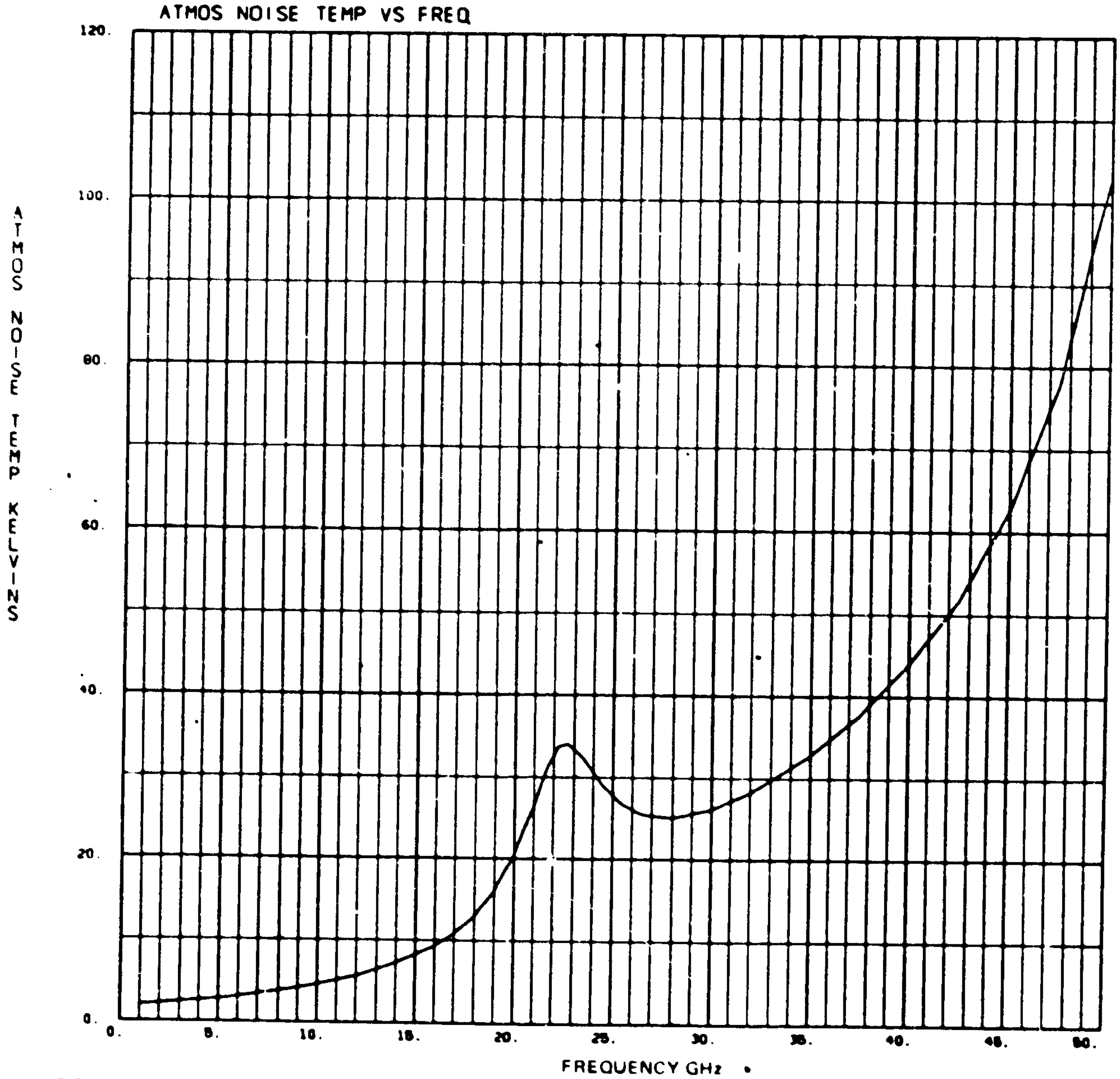
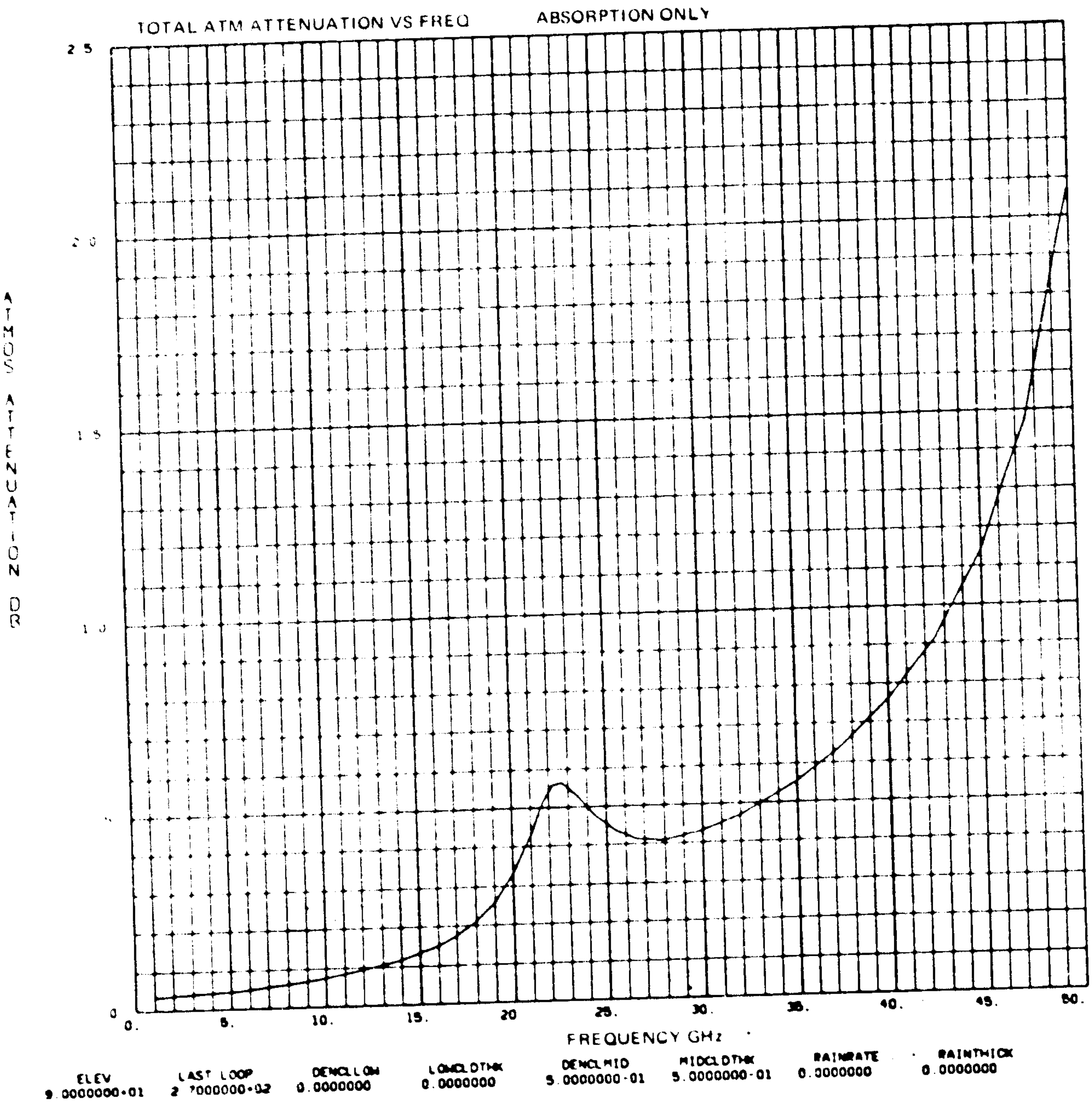
CASE 5-2

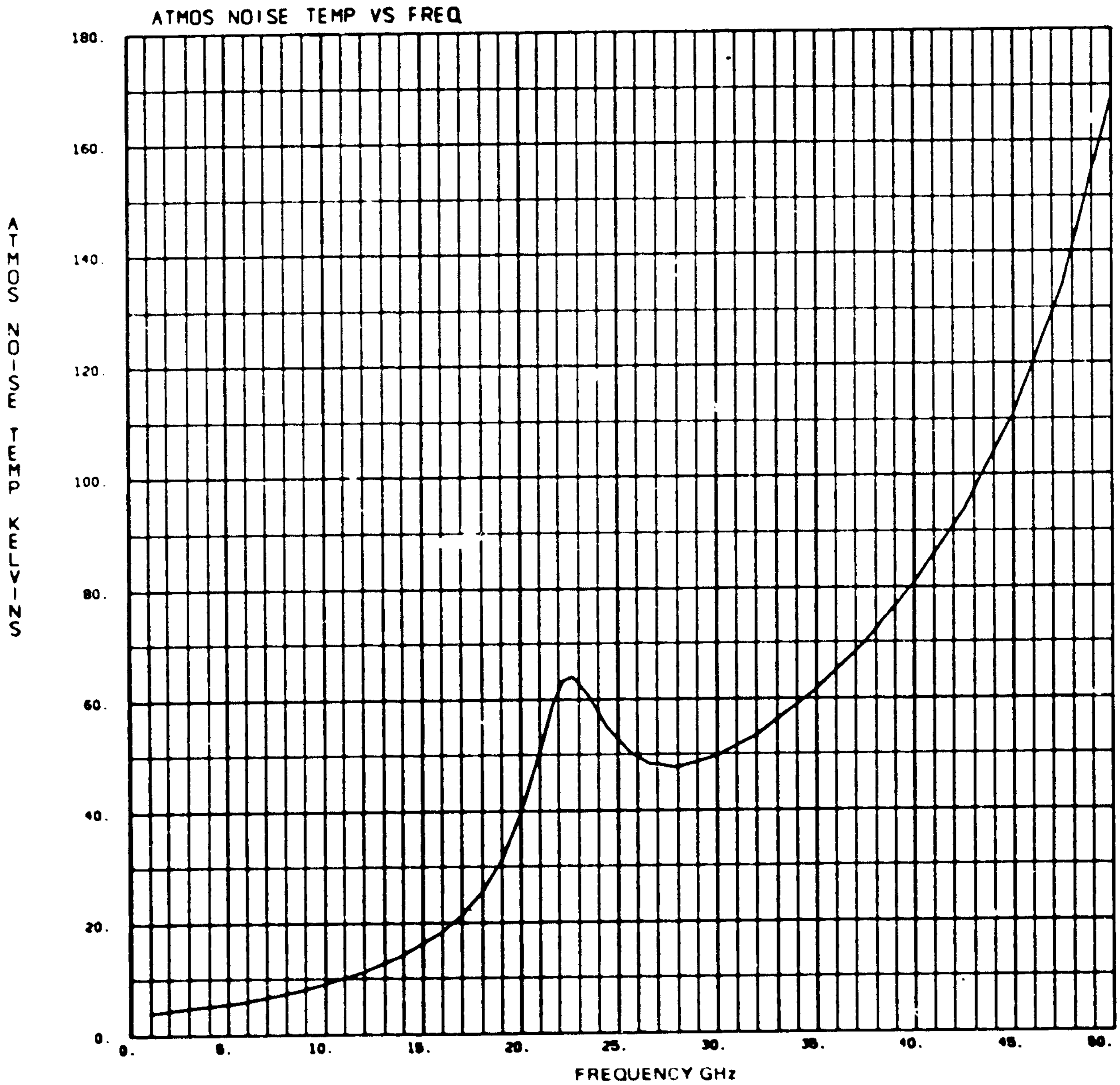


ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	2.7000000+02	0.0000000	0.0000000	5.0000000-01	5.0000000-01	0.0000000	0.0000000

CASE 5-3

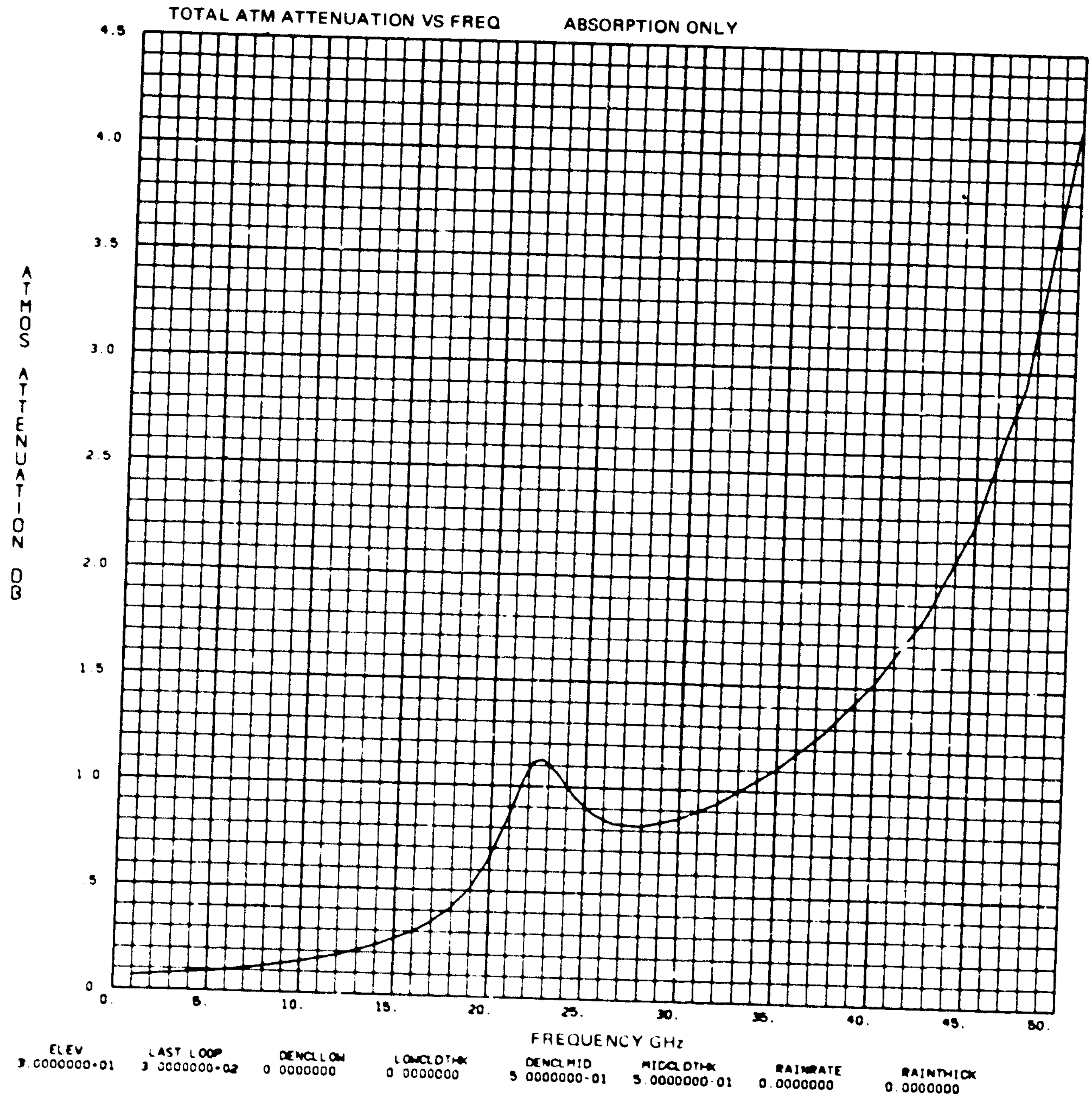

TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
FREQUENCY GHz
0.
5.
10.
15.
20
25.
30.
35.
40.
45.
50.
ELEV
9.0000000-01
LAST LOOP
2.7000000+02
DENCLLOW
0.0000000
LOWCLDTHK
0.0000000
DENCLMID
5.0000000-01
MIDCLDTHK
5.0000000-01
RAINRATE
0.0000000
RAINTHICK
0.0000000

CASE 5-4

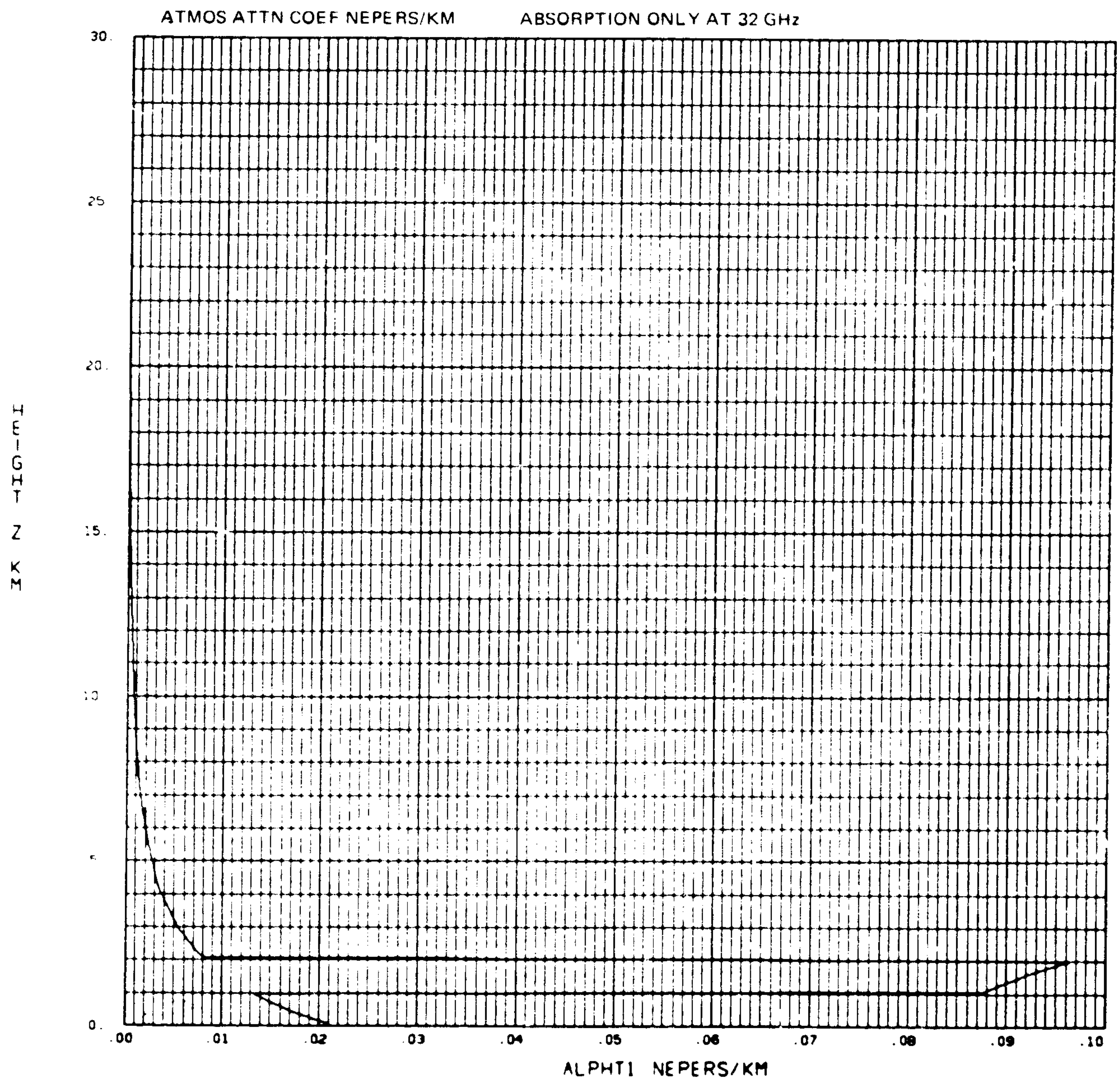


ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	3.0000000+02	0.0000000	0.0000000	5.0000000-01	5.0000000-01	0.0000000	0.0000000

CASE 5-5


TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
0
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV
3.0000000-01
LAST LOOP
3.0000000-02
DENCLLOW
0.0000000
LOWCLDTHK
0.0000000
DENCLMID
5.0000000-01
MIDCLDTHK
5.0000000-01
RAINRATE
0.0000000
RAINTHICK
0.0000000

CASE 6-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	3.2300000+02	5.0000000-01	1.0000000+00	0.0000000	0.0000000	0.0000000	0.0000000

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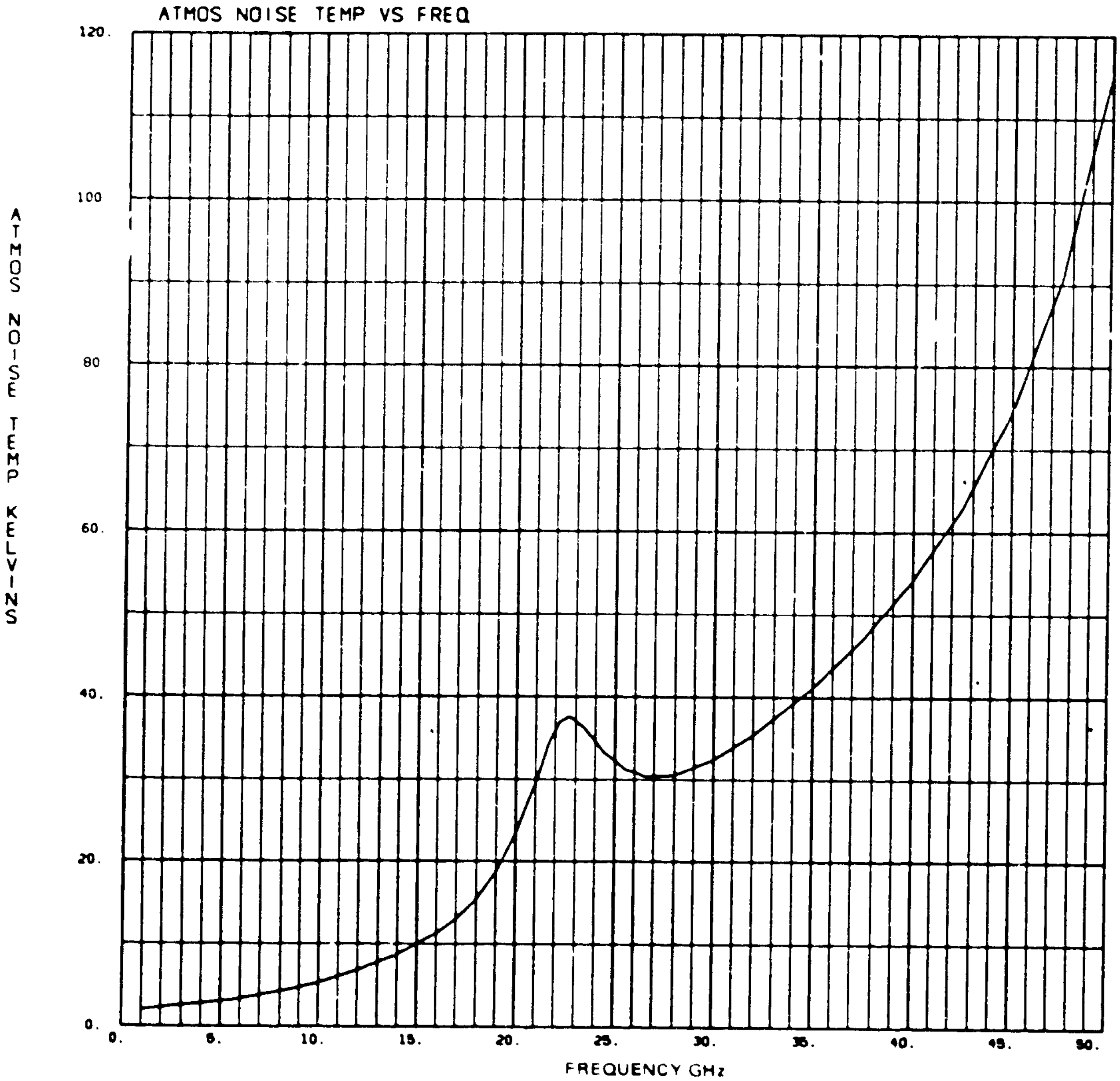
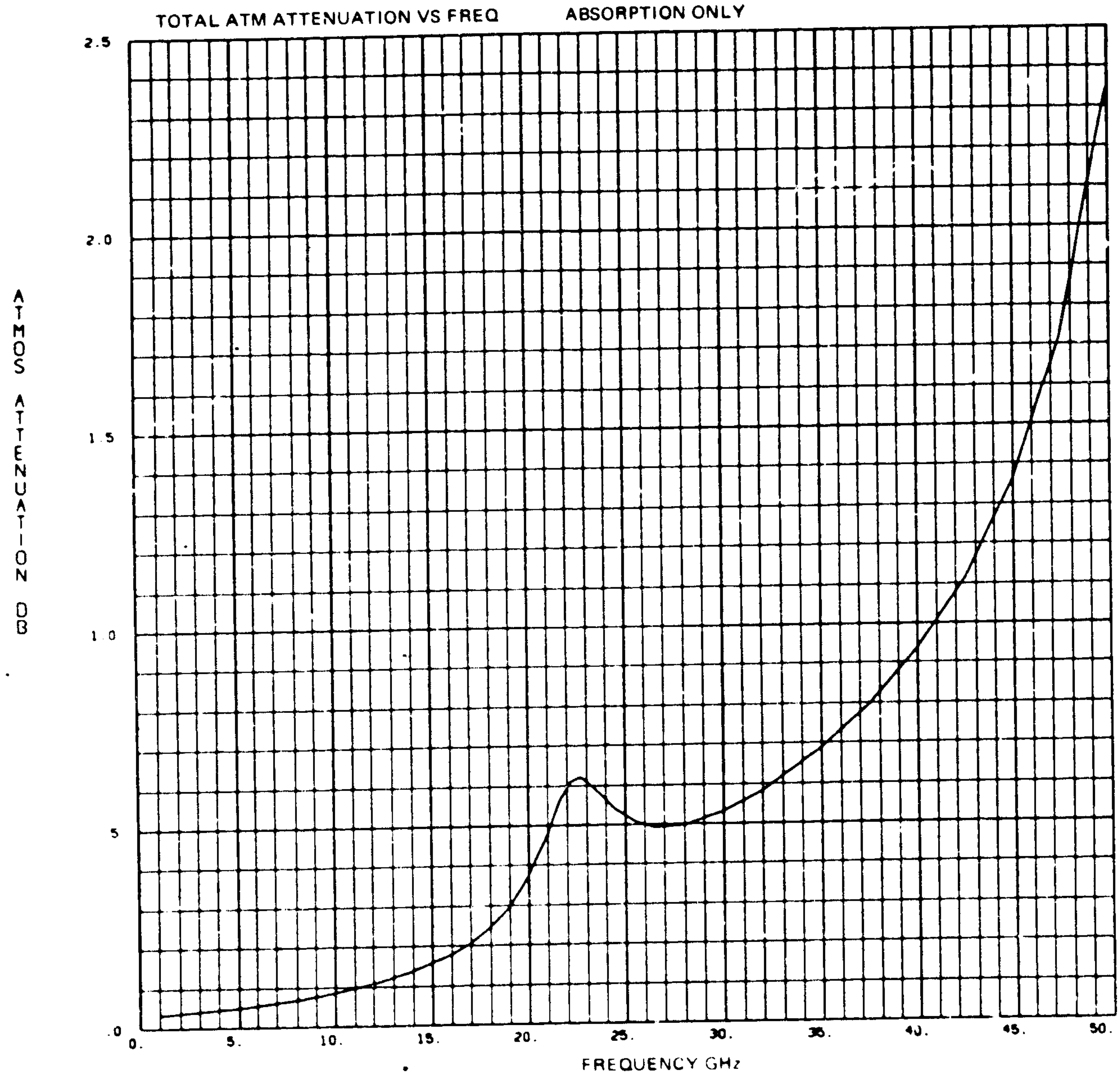
CASE 6-2



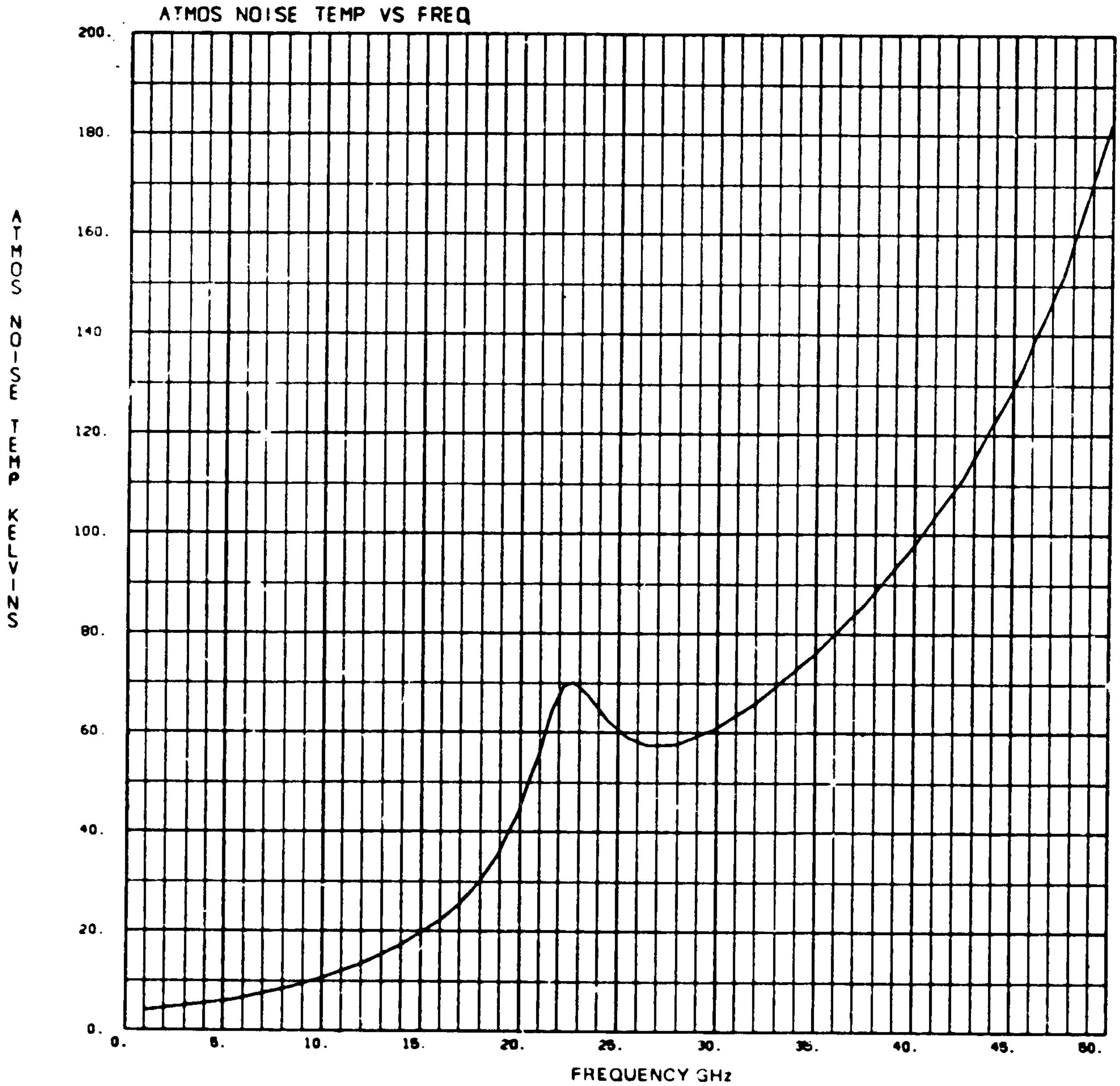
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	3.3000000+02	5.0000000-01	1.0000000+00	0.0000000	0.0000000	0.0000000	0.0000000

CASE 6-3



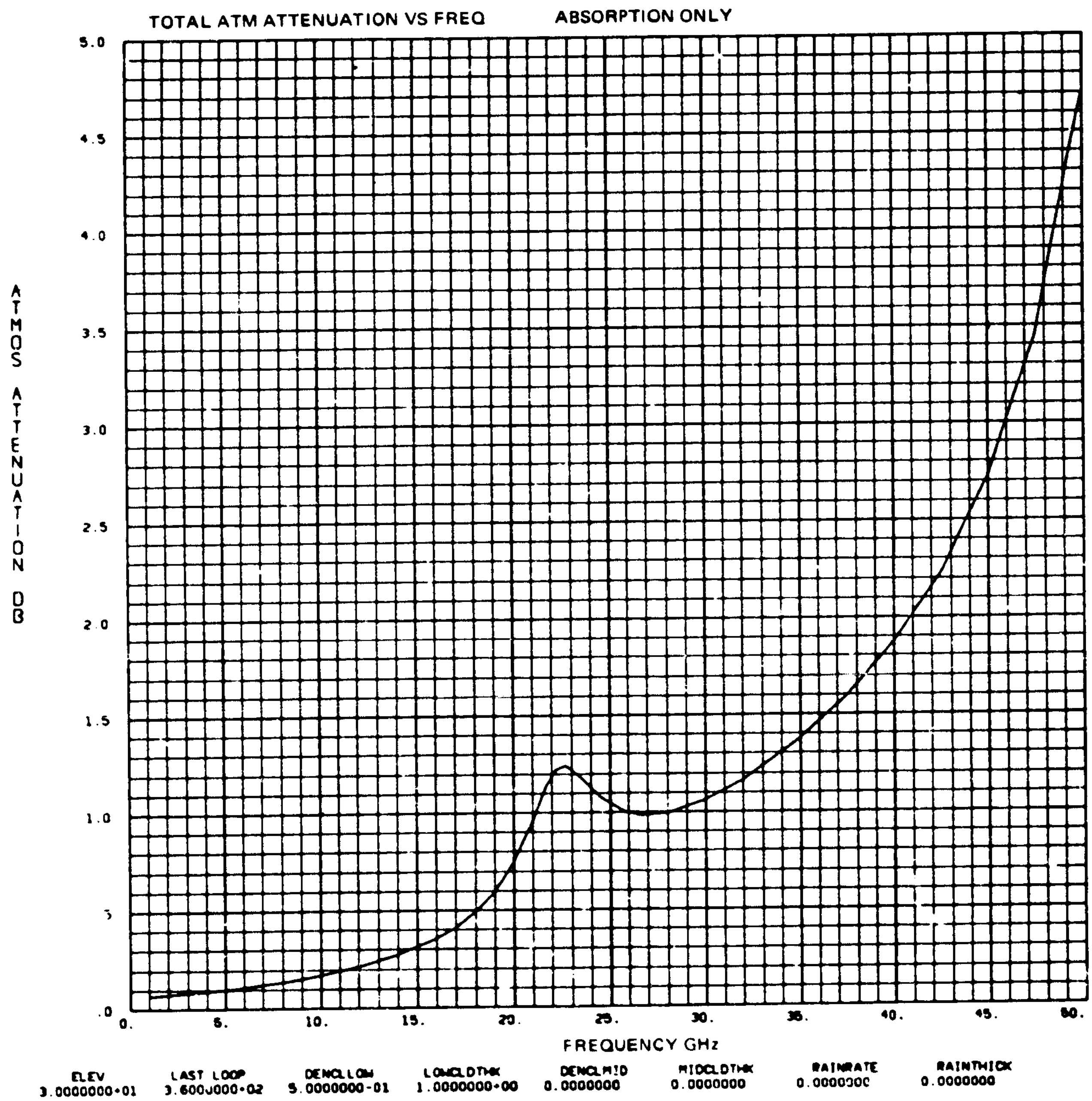
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	3.3000000+02	5.0000000-01	1.0000000+00	0.0000000	0.0000000	0.0000000	0.0000000

CASE 6-4

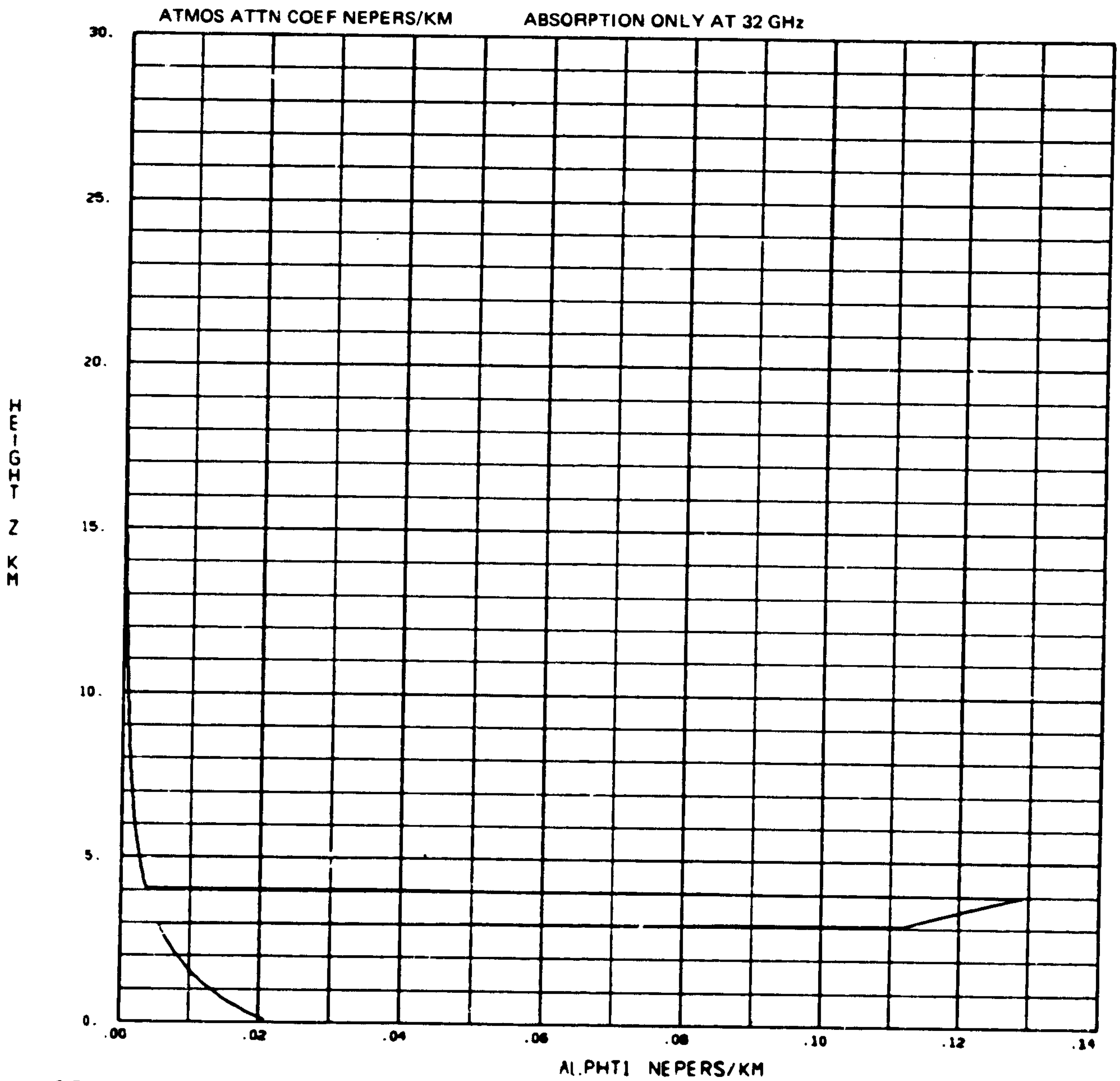


ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	3.6000000+02	5.0000000-01	1.0000000+00	0.0000000	0.0000000	0.0000000	0.0000000

CASE 6-5


TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
.0
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV 3.0000000+01
LAST LOOP 3.6000000+02
DENCLLOW 5.0000000-01
LOWCLDTHK 1.0000000+00
DENCLMID 0.0000000
MIDCLDTHK 0.0000000
RAINRATE 0.0000000
RAINTHICK 0.0000000

CASE 7-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	3.8300000+02	0.0000000	0.0000000	5.0000000-01	1.0000000+00	0.0000000	0.0000000

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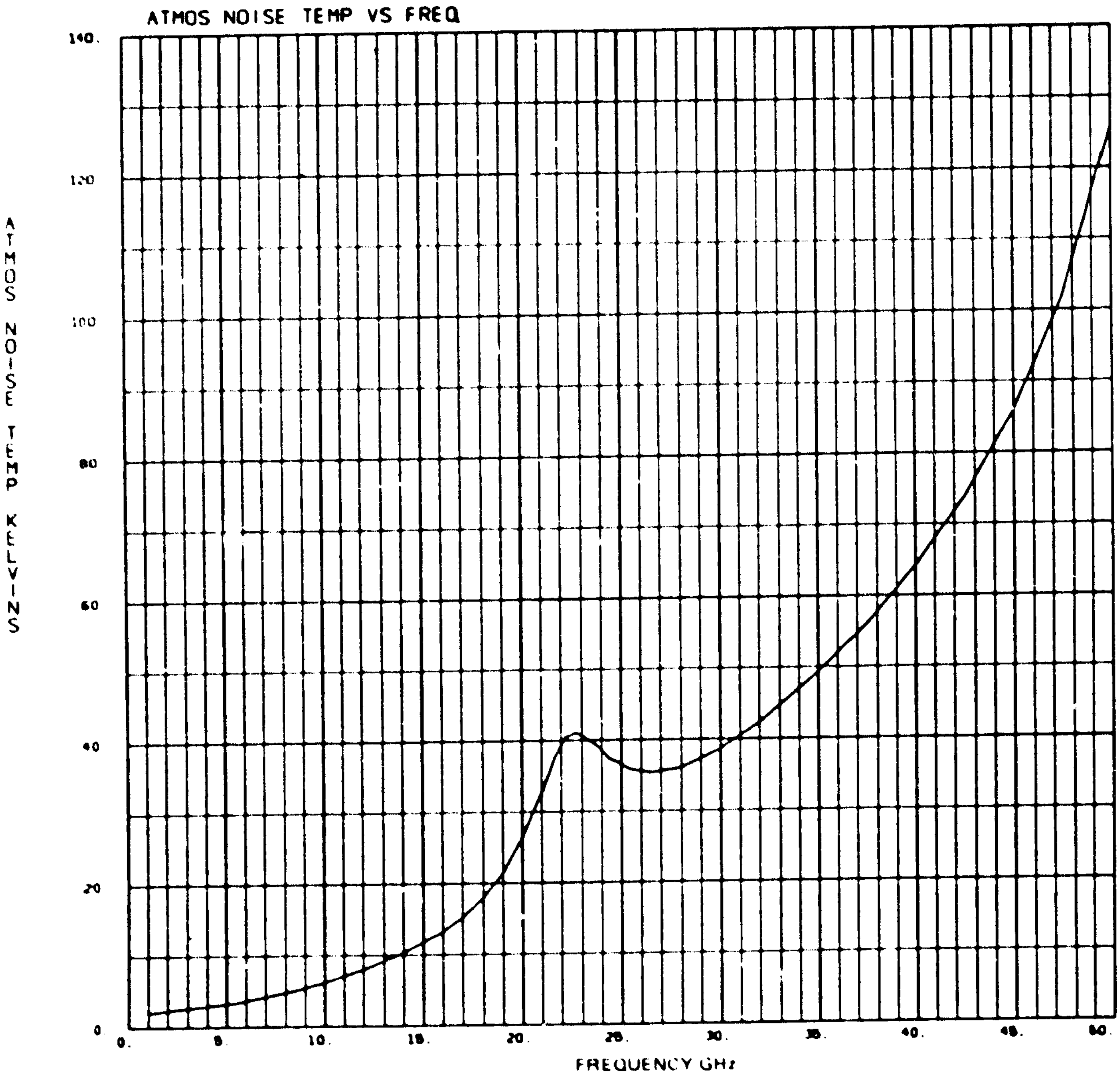
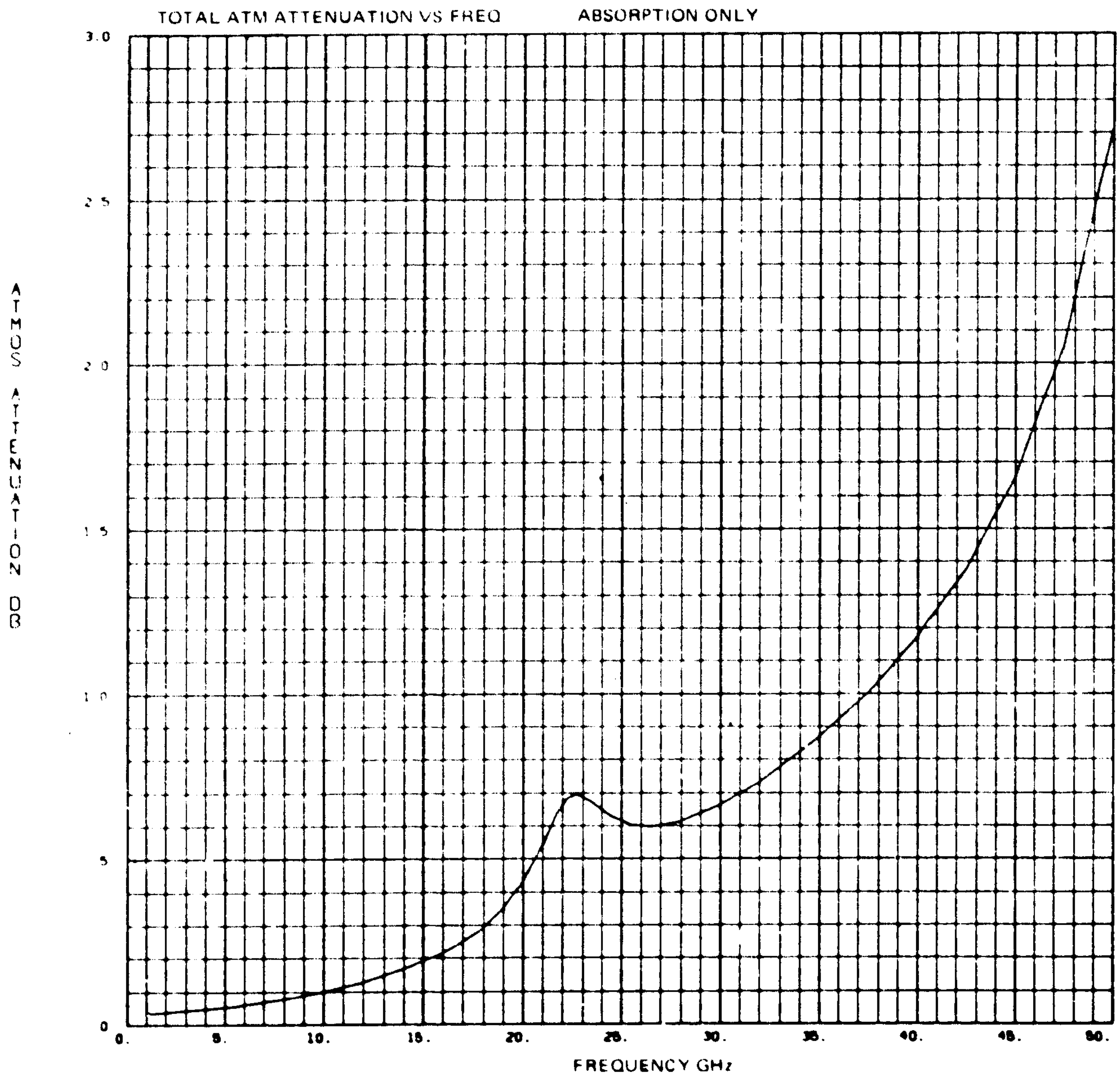
CASE 7-2

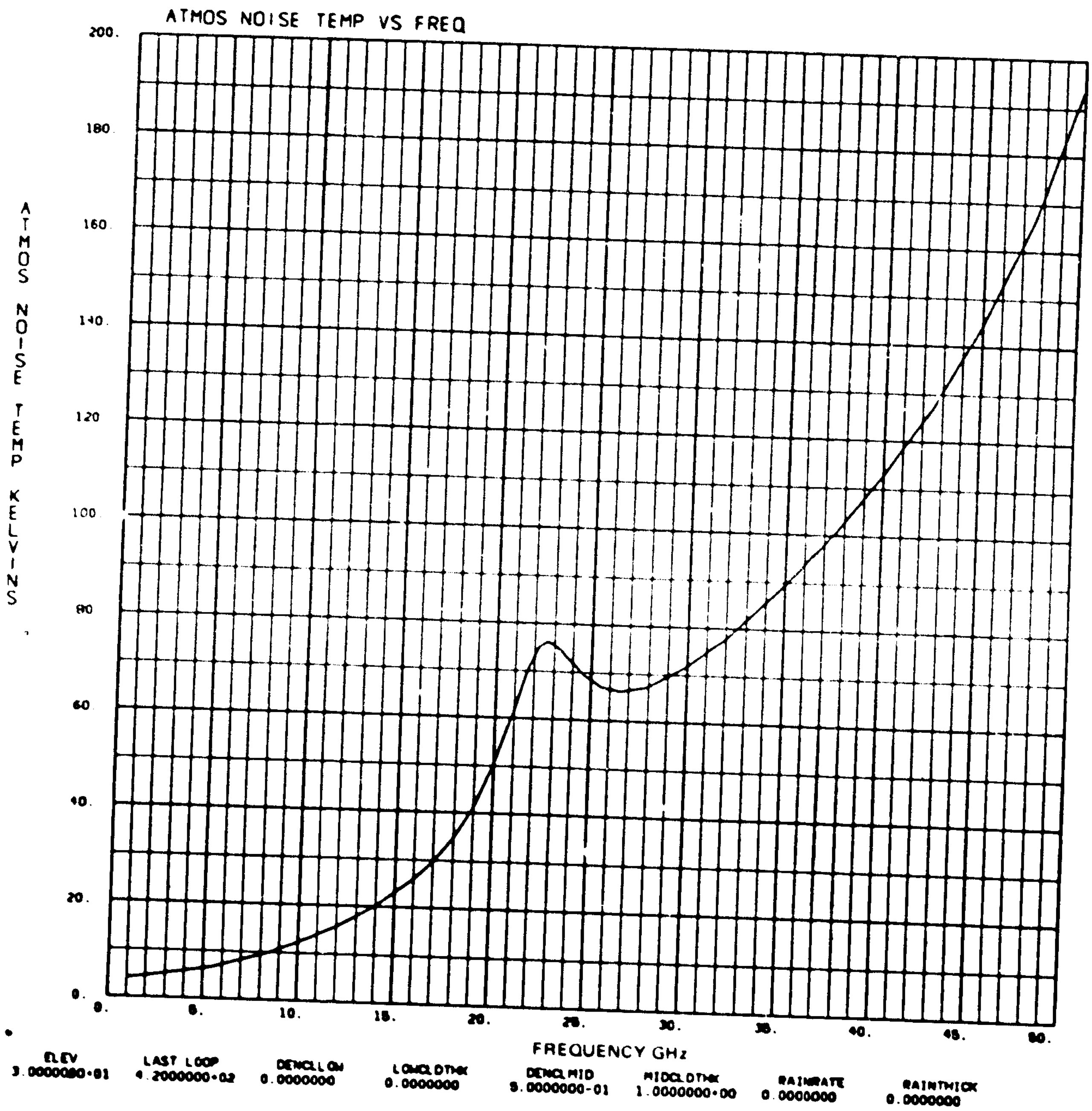


ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	3.9000000+02	0.0000000	0.0000000	5.0000000-01	1.0000000+00	0.0000000	0.0000000

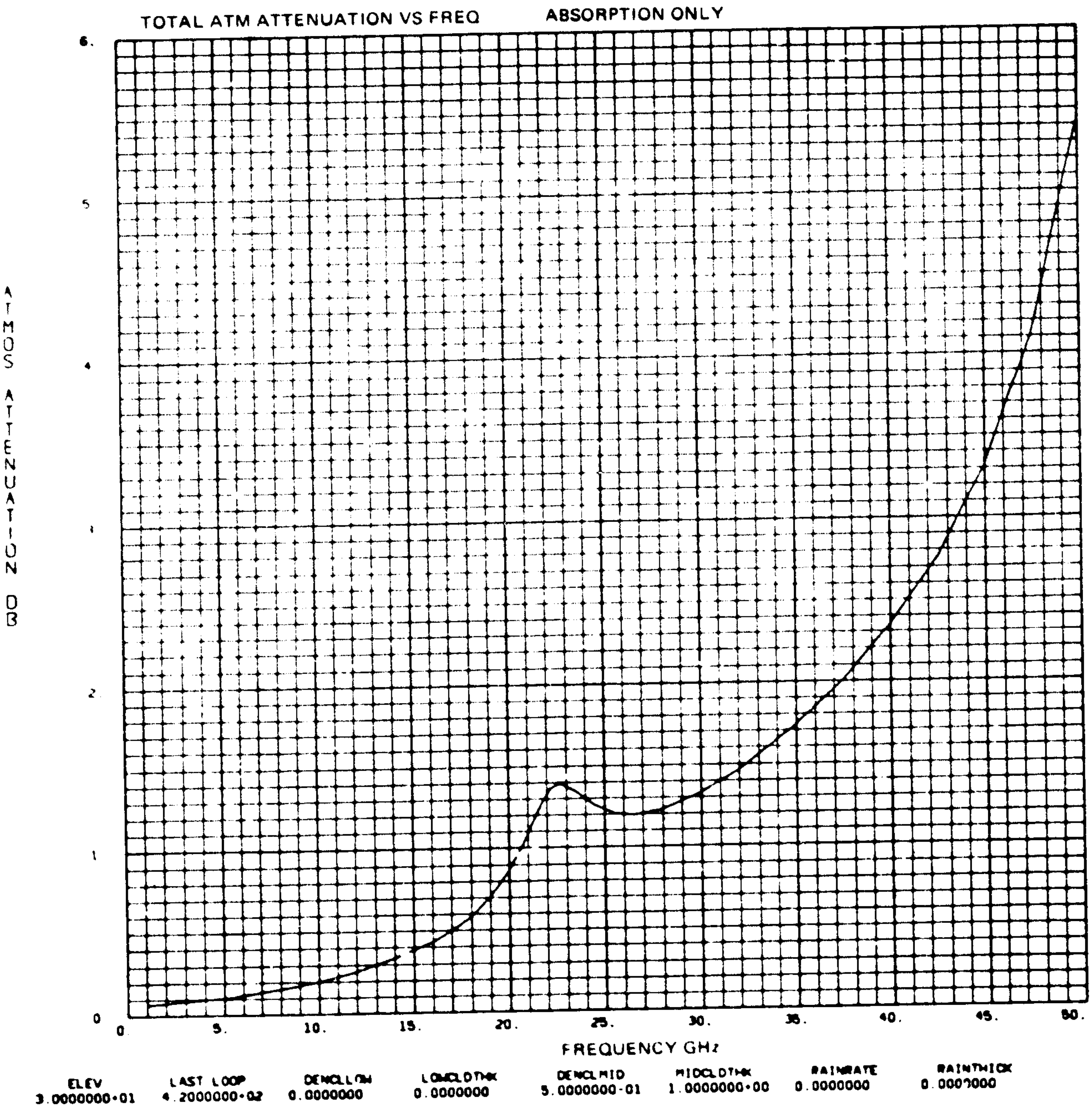
CASE 7-3



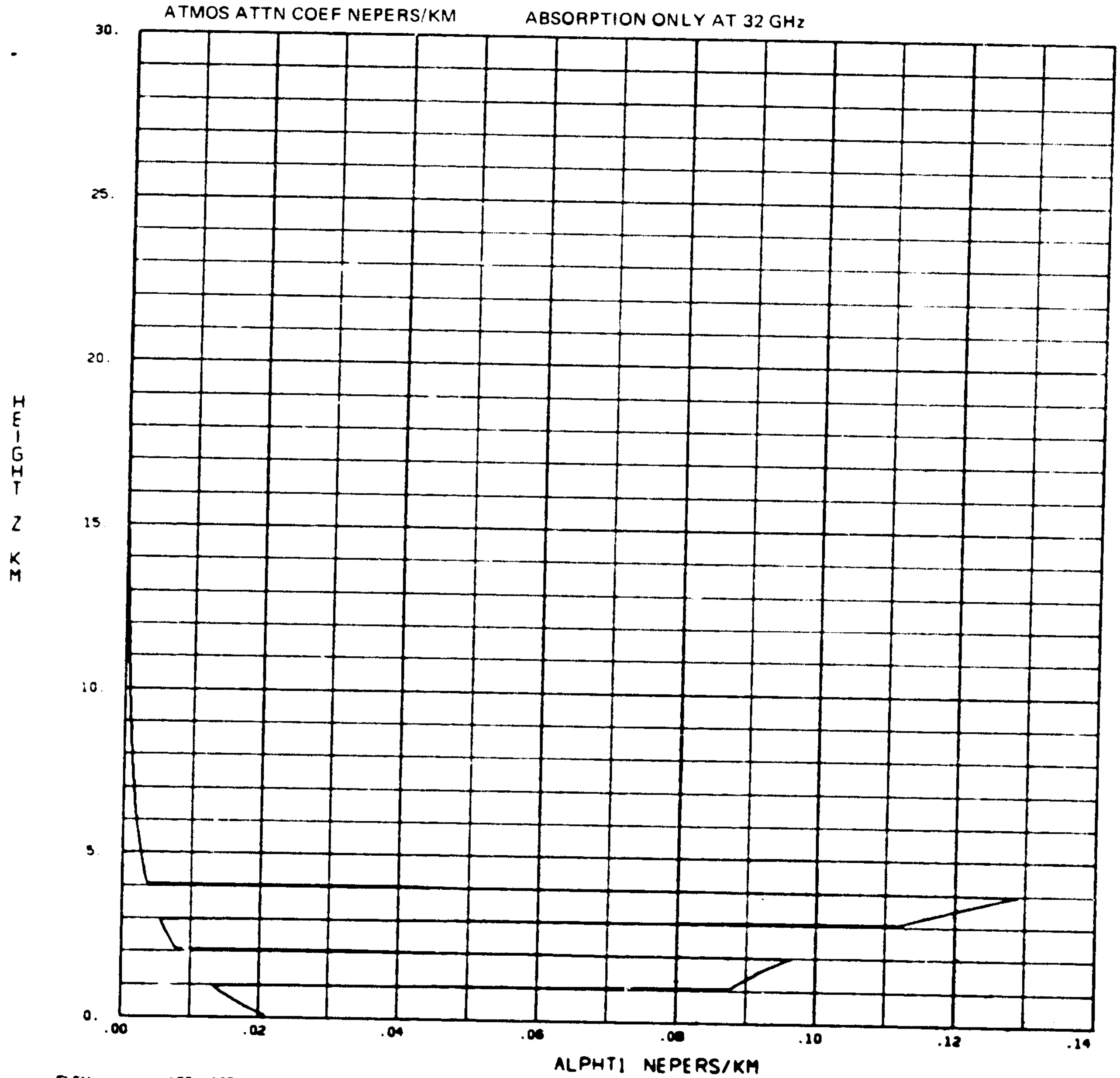
ELEV	LAST LOOP	DENCLLOW	LOWCLDTH	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	3.9000000+02	0.0000000	0.0000000	5.0000000-01	1.0000000+00	0.0000000	0.0000000


ATMOS NOISE TEMP VS FREQ
ATMOS NOISE TEMP KELVINS
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV
3.0000000+01
LAST LOOP
4.2000000+02
DENCLLOW
0.0000000
LOWCLDTHK
0.0000000
DENCLMID
5.0000000-01
MIDCLDTHK
1.0000000+00
RAINRATE
0.0000000
RAINTHICK
0.0000000

CASE 7-5


TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
FREQUENCY GHz
ELEV 3.0000000+01
LAST LOOP 4.2000000+02
DENCLLOW 0.0000000
LOWCLDTHK 0.0000000
DENCLMID 5.0000000-01
MIDCLDTHK 1.0000000+00
RAINRATE 0.0000000
RAINTHICK 0.0000000

CASE 8-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9 0000000+01	4.4300000+02	5.0000000-01	1.0000000+00	5.0000000-01	1.0000000+00	0.0000000	0.0000000

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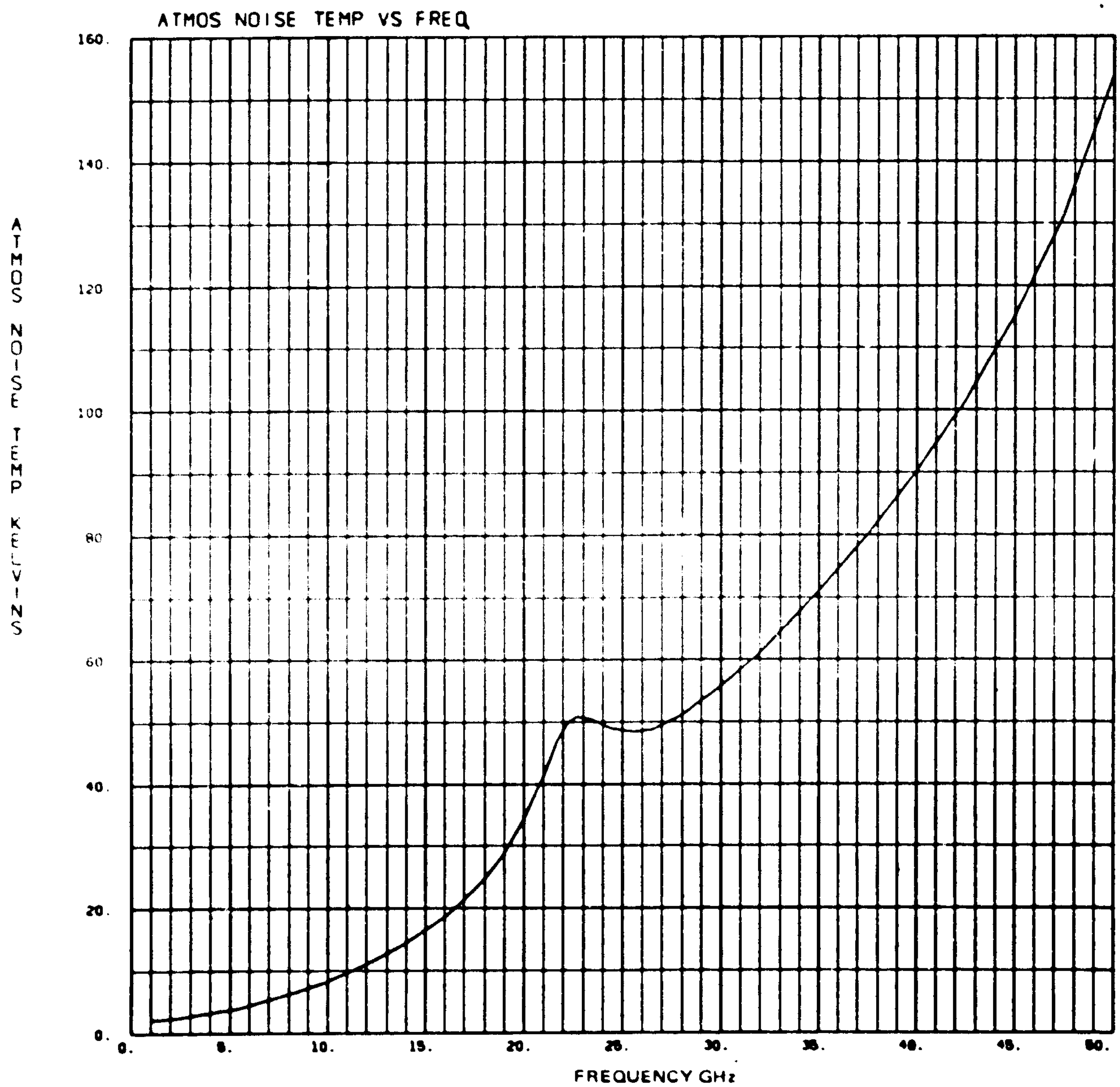
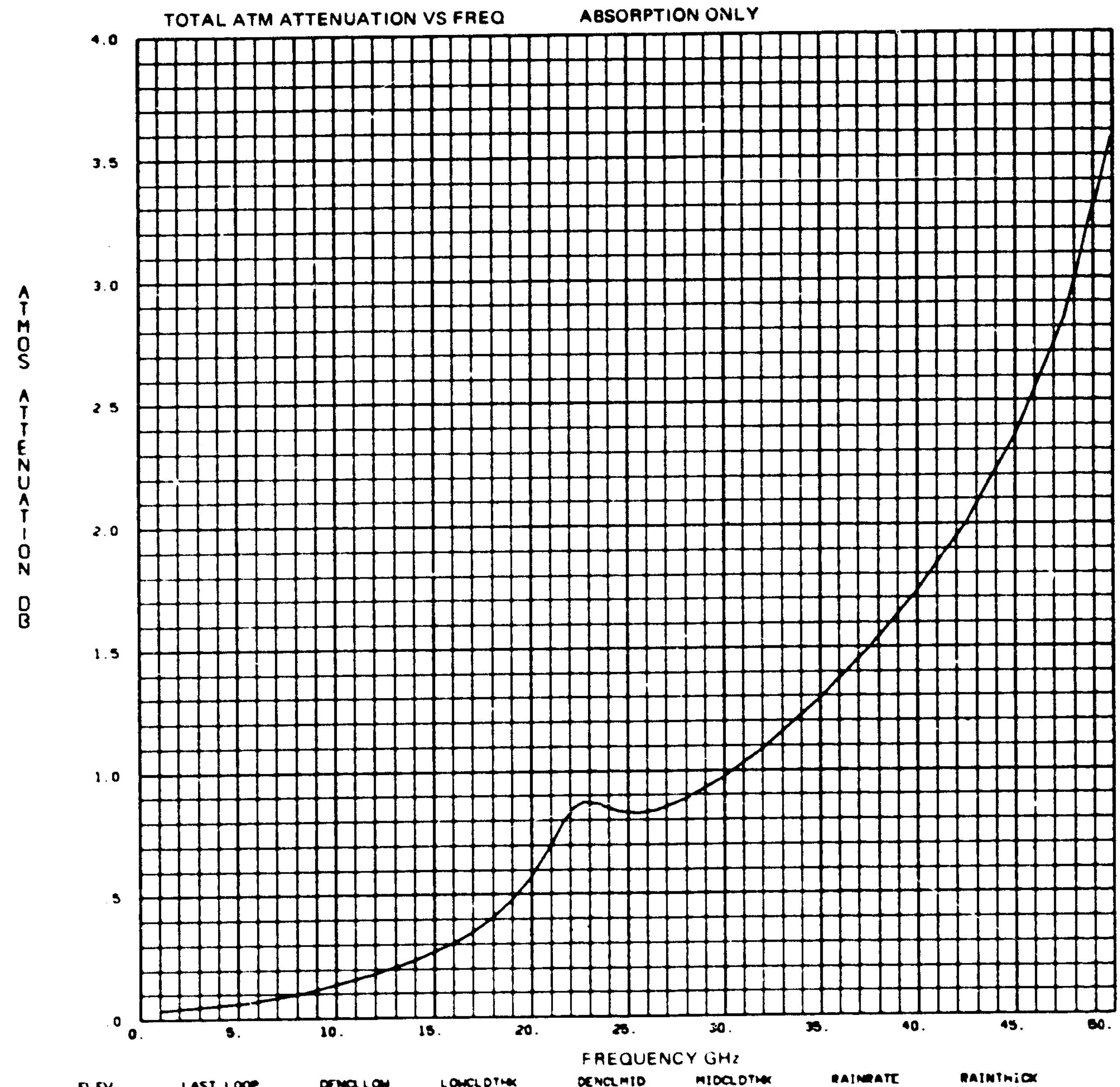
CASE 8-2



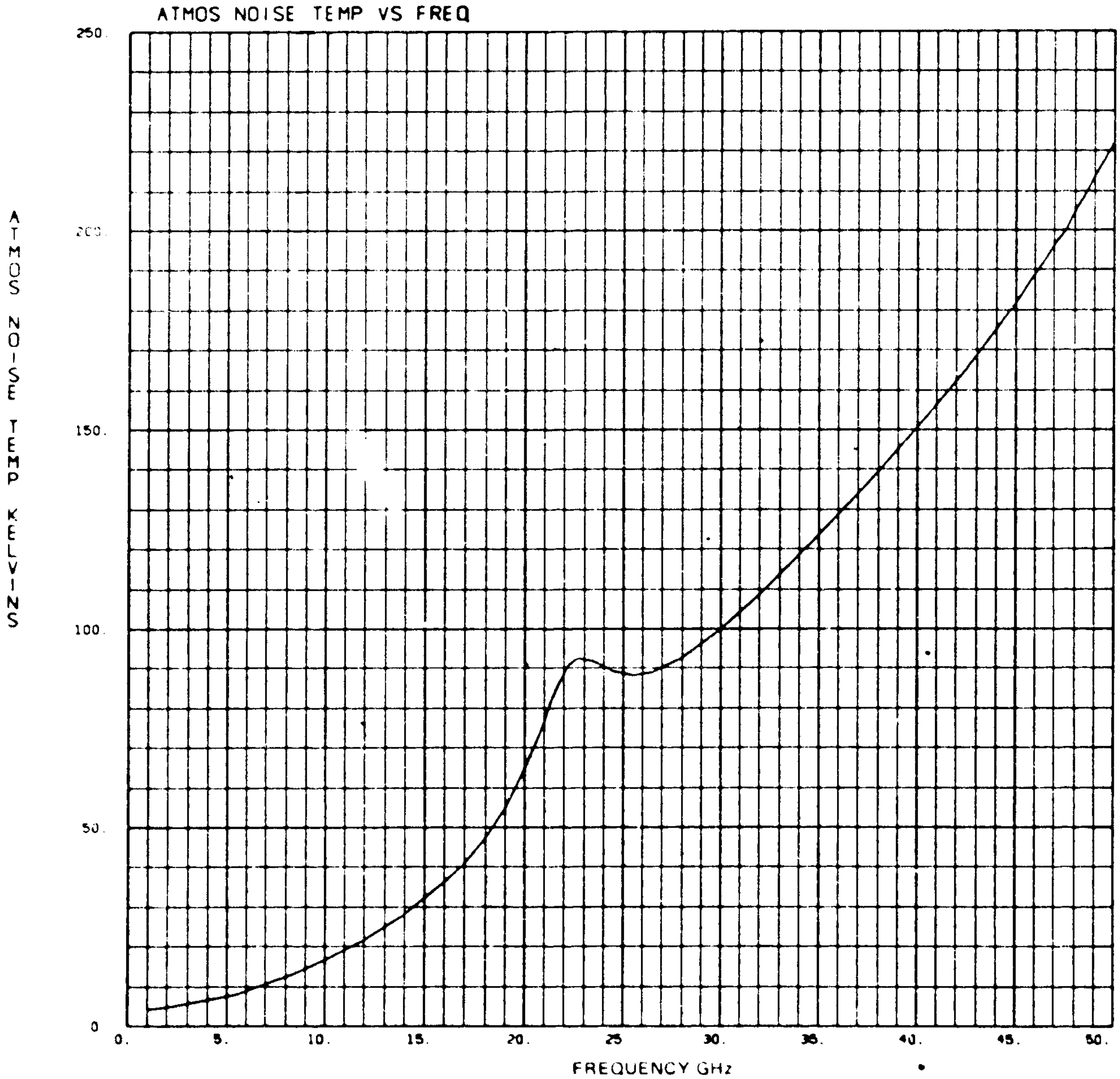
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	4.5000000+02	5.0000000-01	1.0000000+00	5.0000000-01	1.0000000+00	0.0000000	0.0000000

CASE 8-3



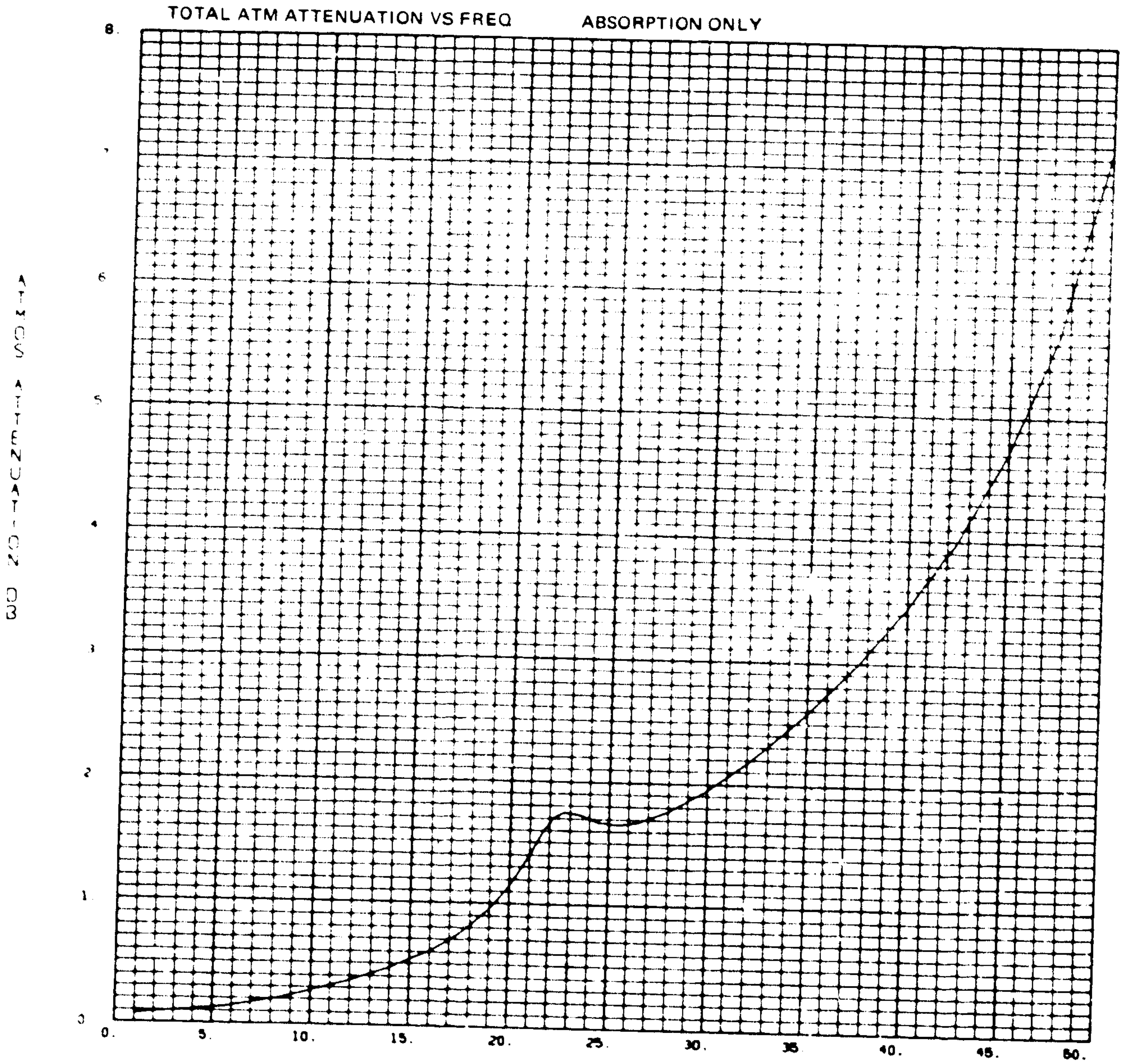
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	4.5000000+02	5.0000000-01	1.0000000+00	5.0000000-01	1.0000000+00	0.0000000	0.0000000

CASE 8-4



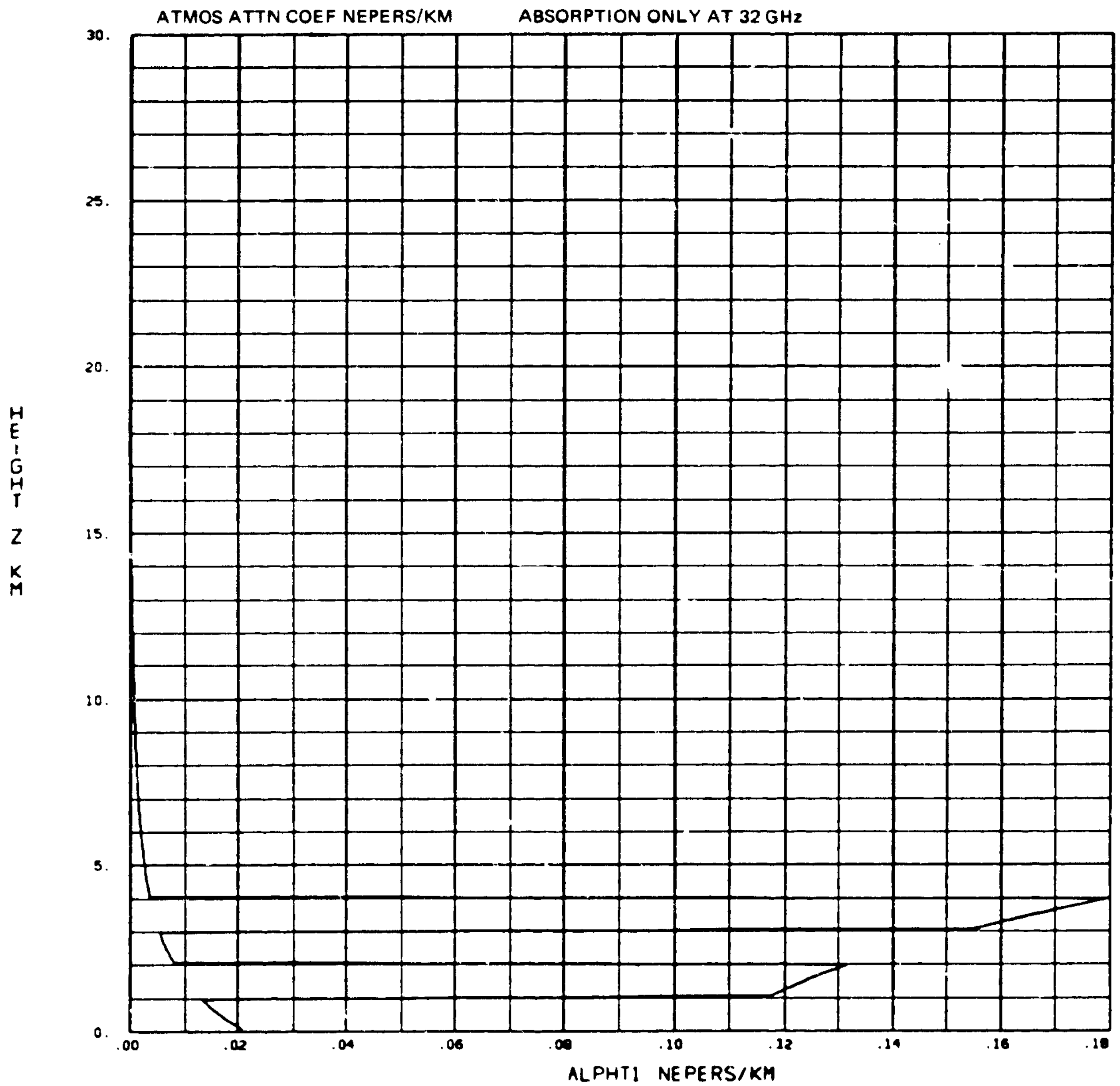
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	4.8030000+02	5.0000000-01	1.0000000+00	5.0000000-01	1.0000000+00	0.0000000	0.0000000

CASE 8-5



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	4.8000000+02	5.0000000-01	1.0000000+00	5.0000000-01	1.0000000+00	0.0000000	0.0000000

CASE 9-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9 0000000+01	5.0300000+02	7.0600000 01	1.0000000+00	7.0000000-01	1.0000000+00	0.0000000	0.0000000

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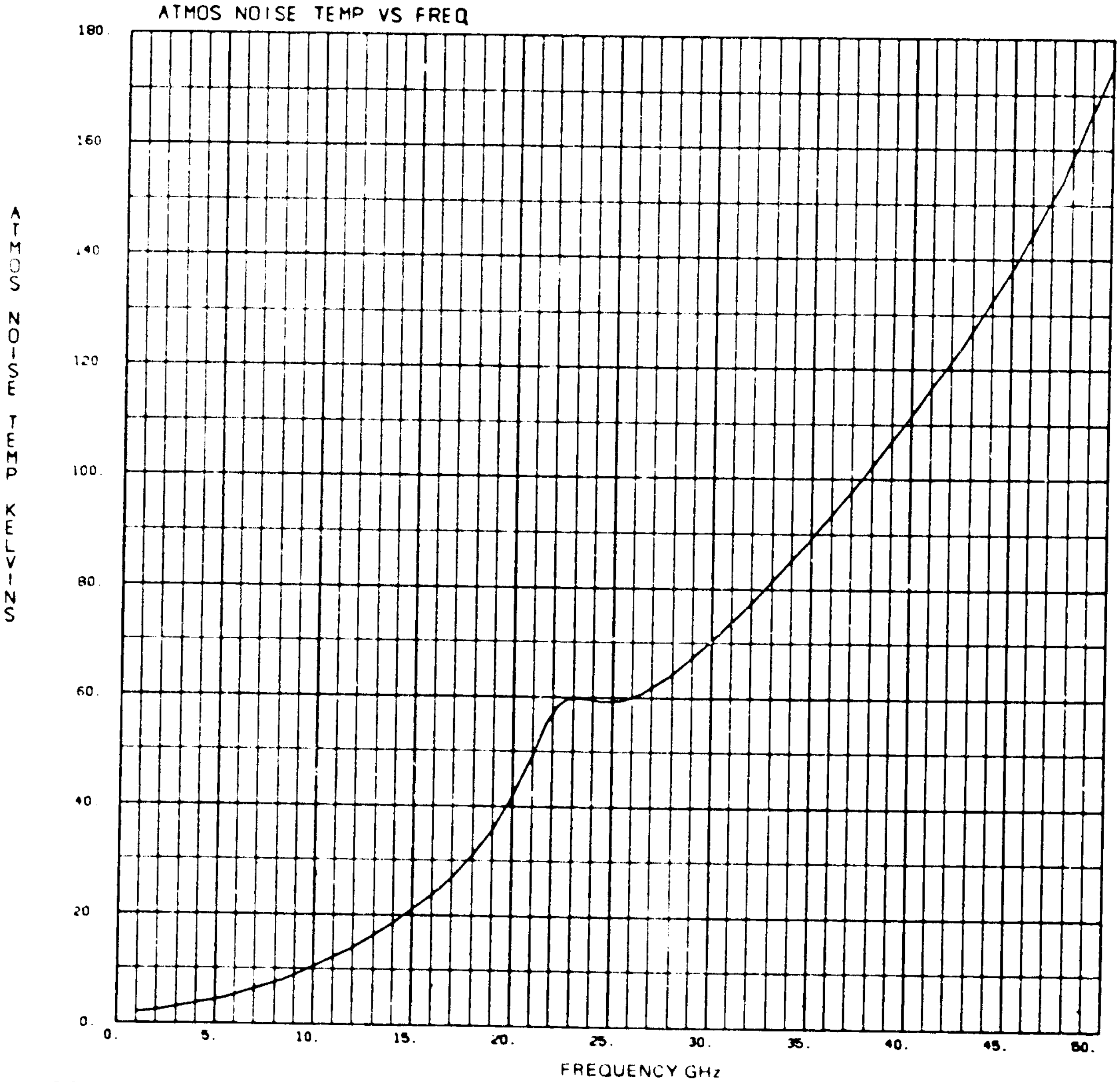
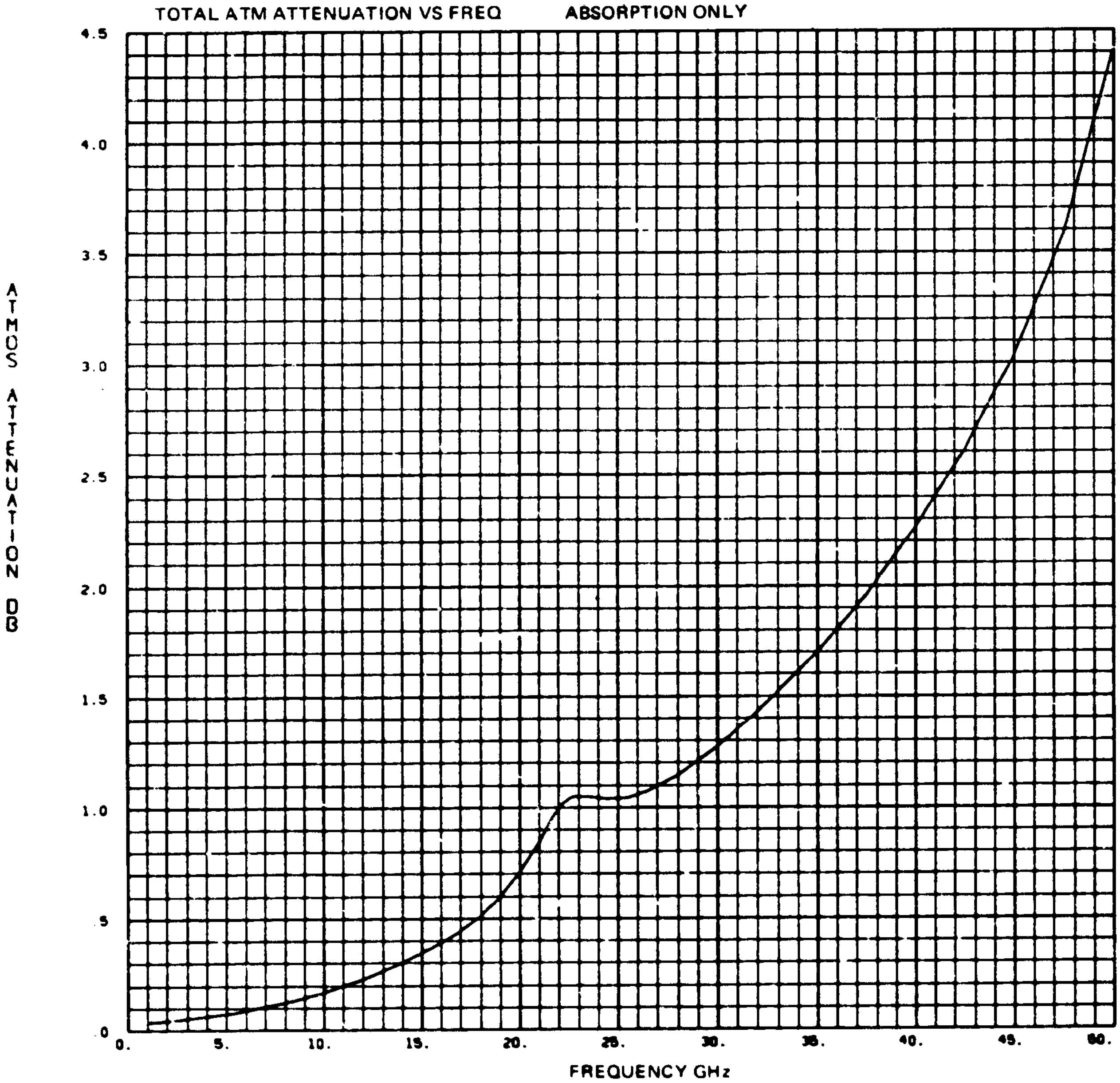
CASE 9-2



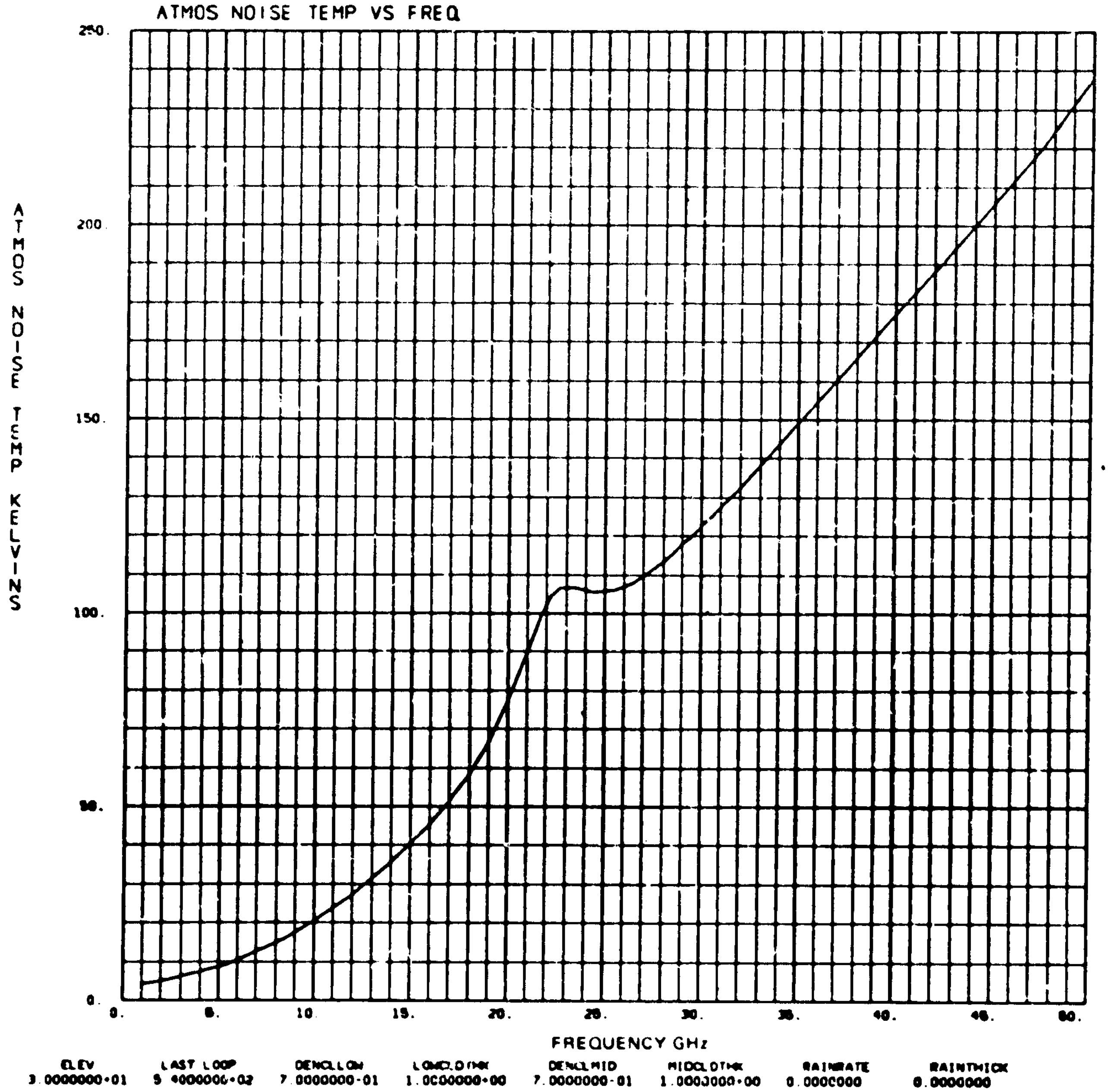
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	5.1000000+02	7.0000000-01	1.0000000+00	7.0000000-01	1.0000000+00	0.0000000	0.0000000

CASE 9-3

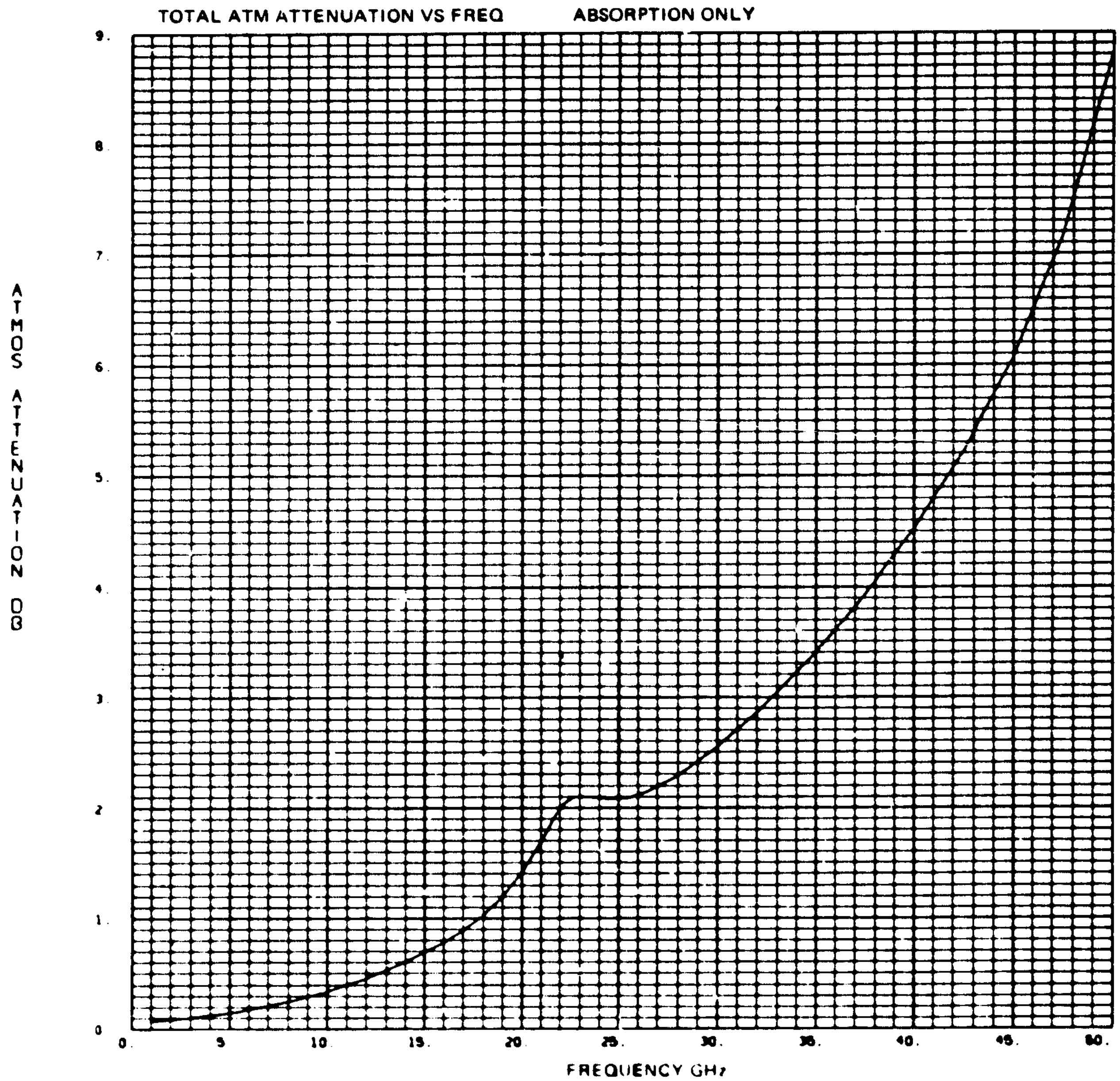


ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000-01	5.1000000+02	7.0000000-01	1.0000000+00	7.0000000-01	1.0000000+00	0.0000000	0.0000000

CASE 9-4

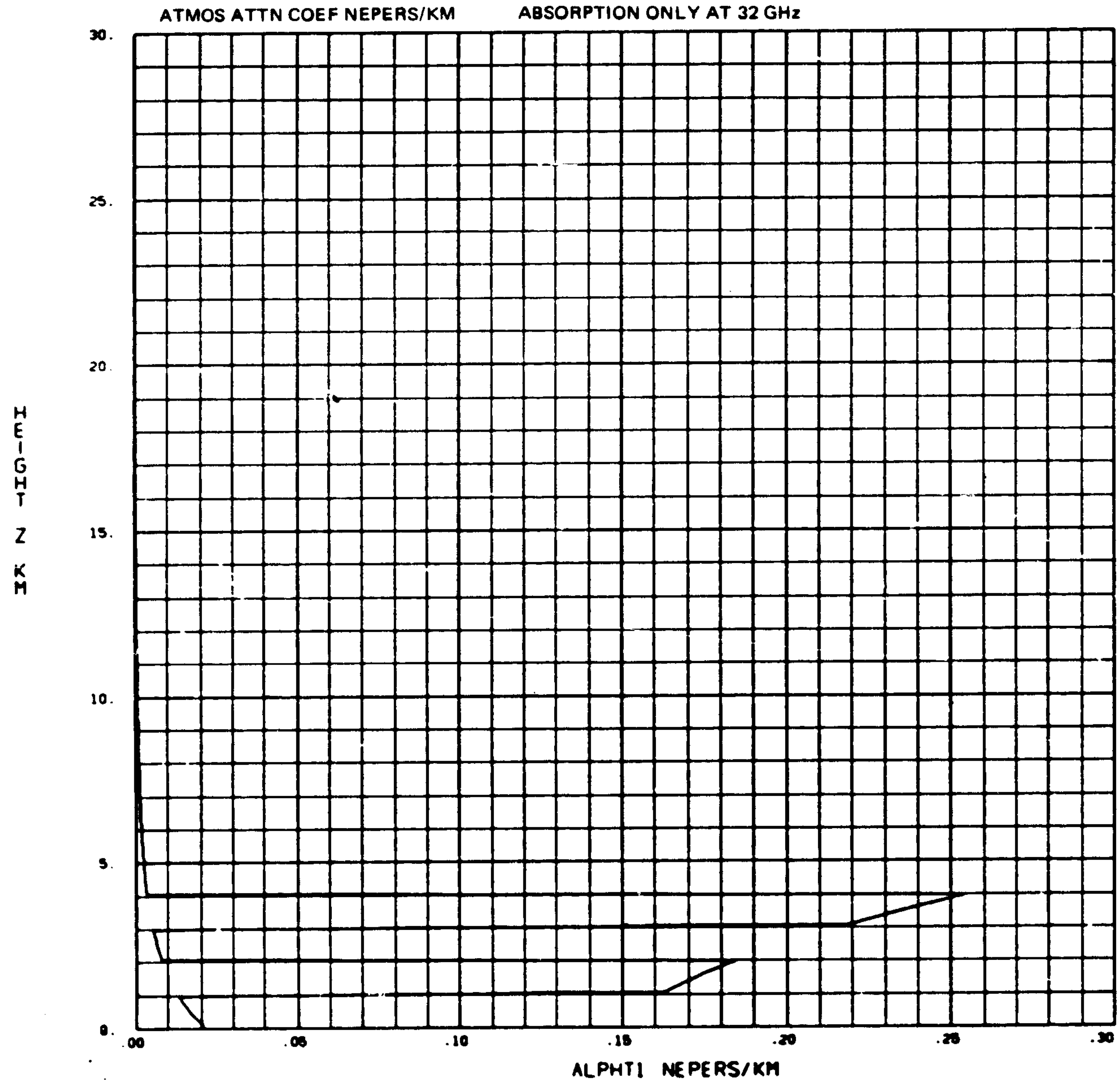

ATMOS NOISE TEMP VS FREQ
ATMOS NOISE TEMP KELVINS
250.
200.
150.
100.
50.
0.
0.
5.
10
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV 3.0000000+01
LAST LOOP 5.4000000+02
DENCLLOW 7.0000000-01
LOWCLDTHK 1.0000000+00
DENCLMID 7.0000000-01
MIDCLDTHK 1.0000000+00
RAINRATE 0.0000000
RAINTHICK 0.0000000

CASE 9-5



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	5.4000000+02	7.0000000-01	1.0000000+00	7.0000000-01	1.0000000+00	0.0000000	0.0000000

CASE 10-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	5.C000000+02	1.0000000+00	1.0000000+00	1.0000000+00	1.0000000+00	0.0000000	0.0000000

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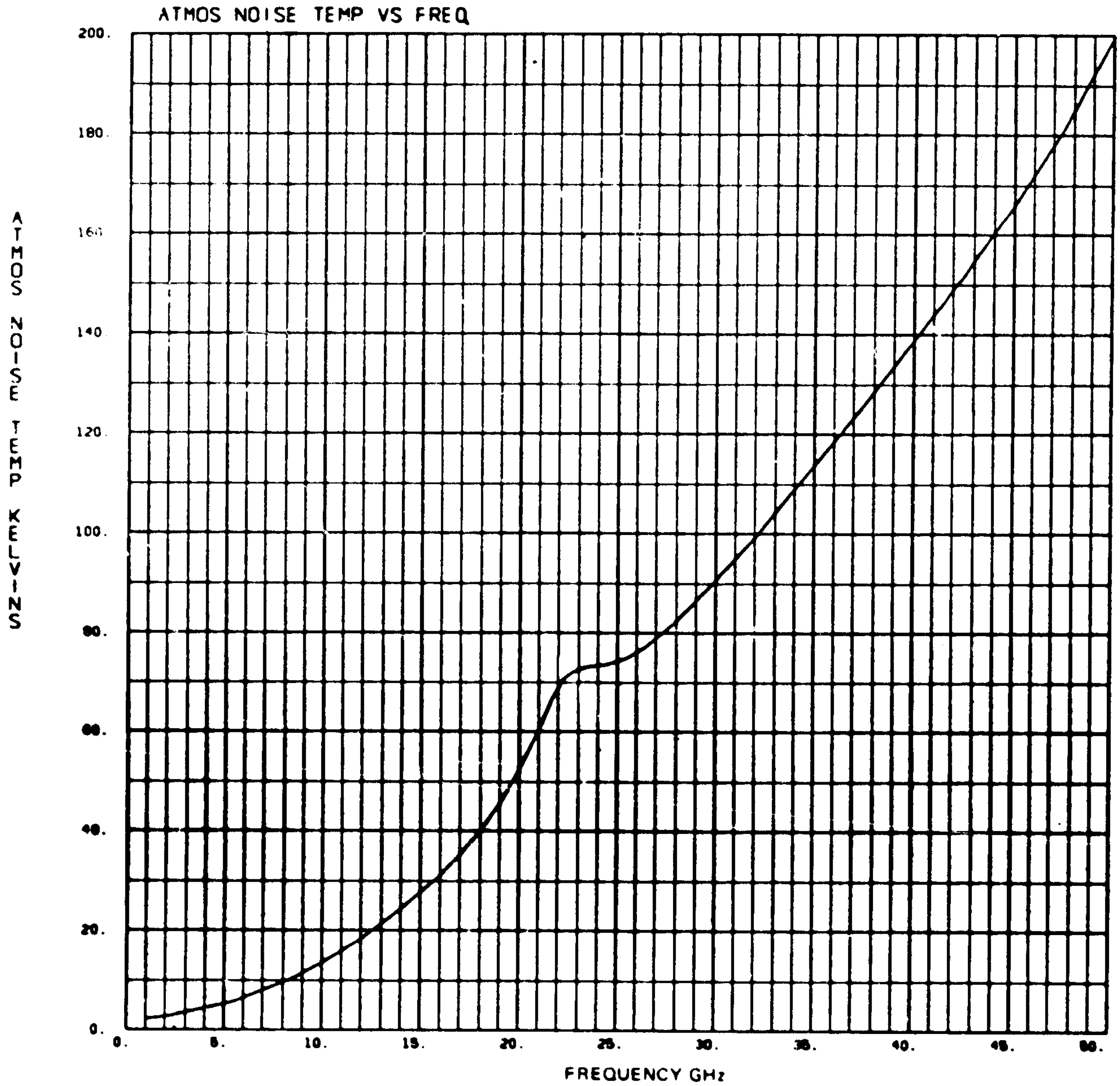
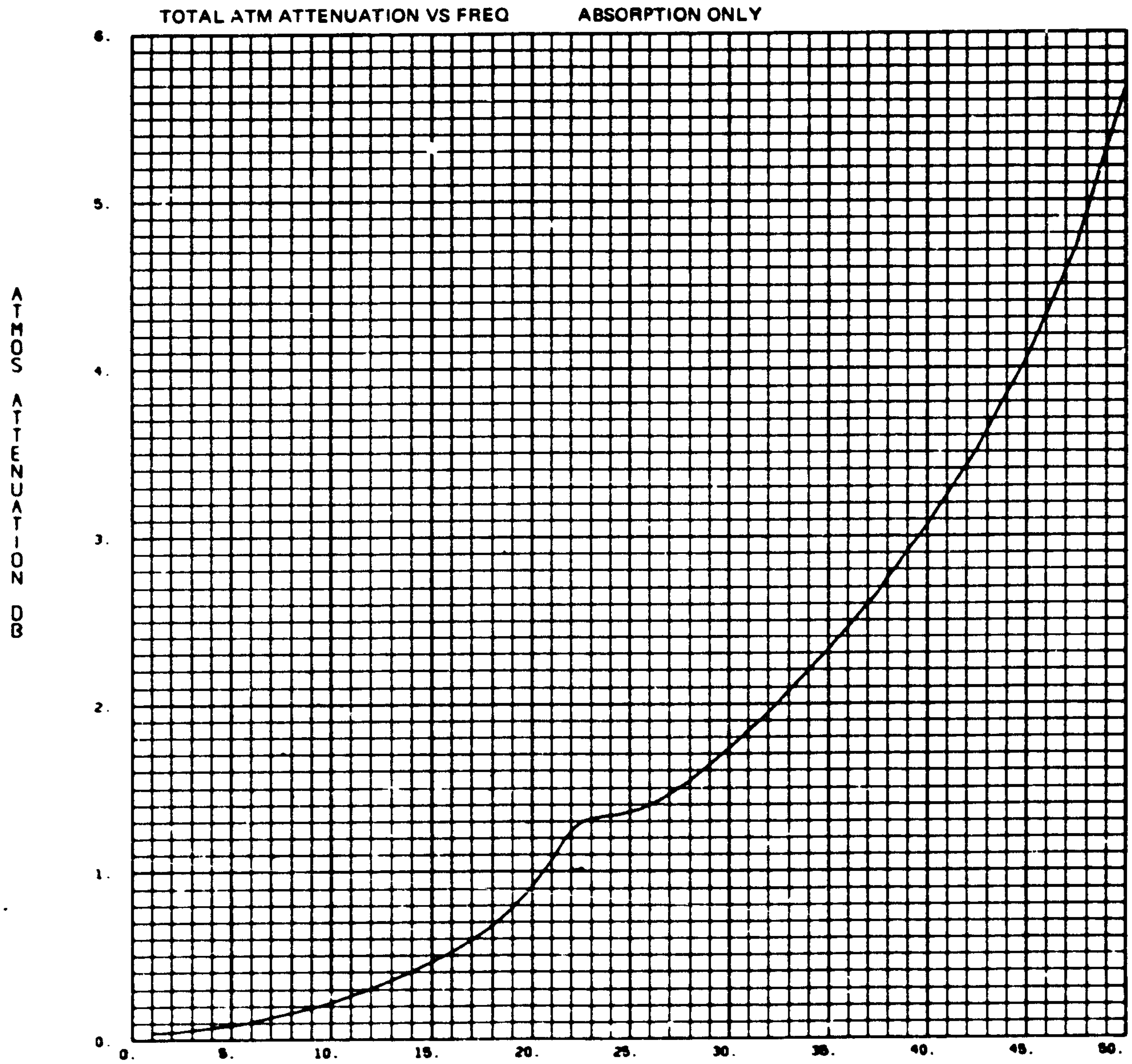
CASE 10-2



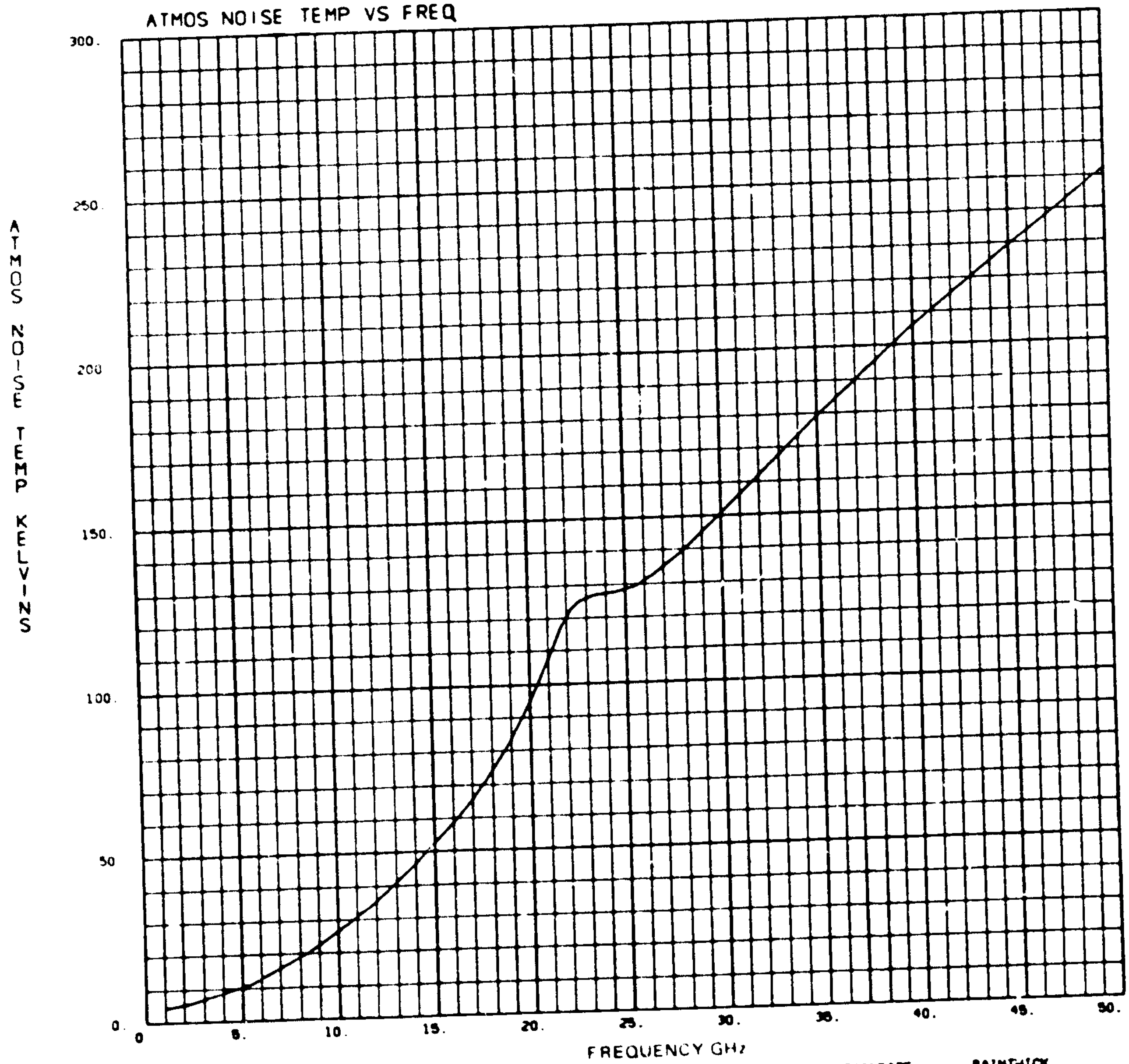
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	5.7000000-02	1.0000000+00	1.0000000+00	1.0000000+00	1.0000000+00	0.0000000	0.0000000

CASE 10-3



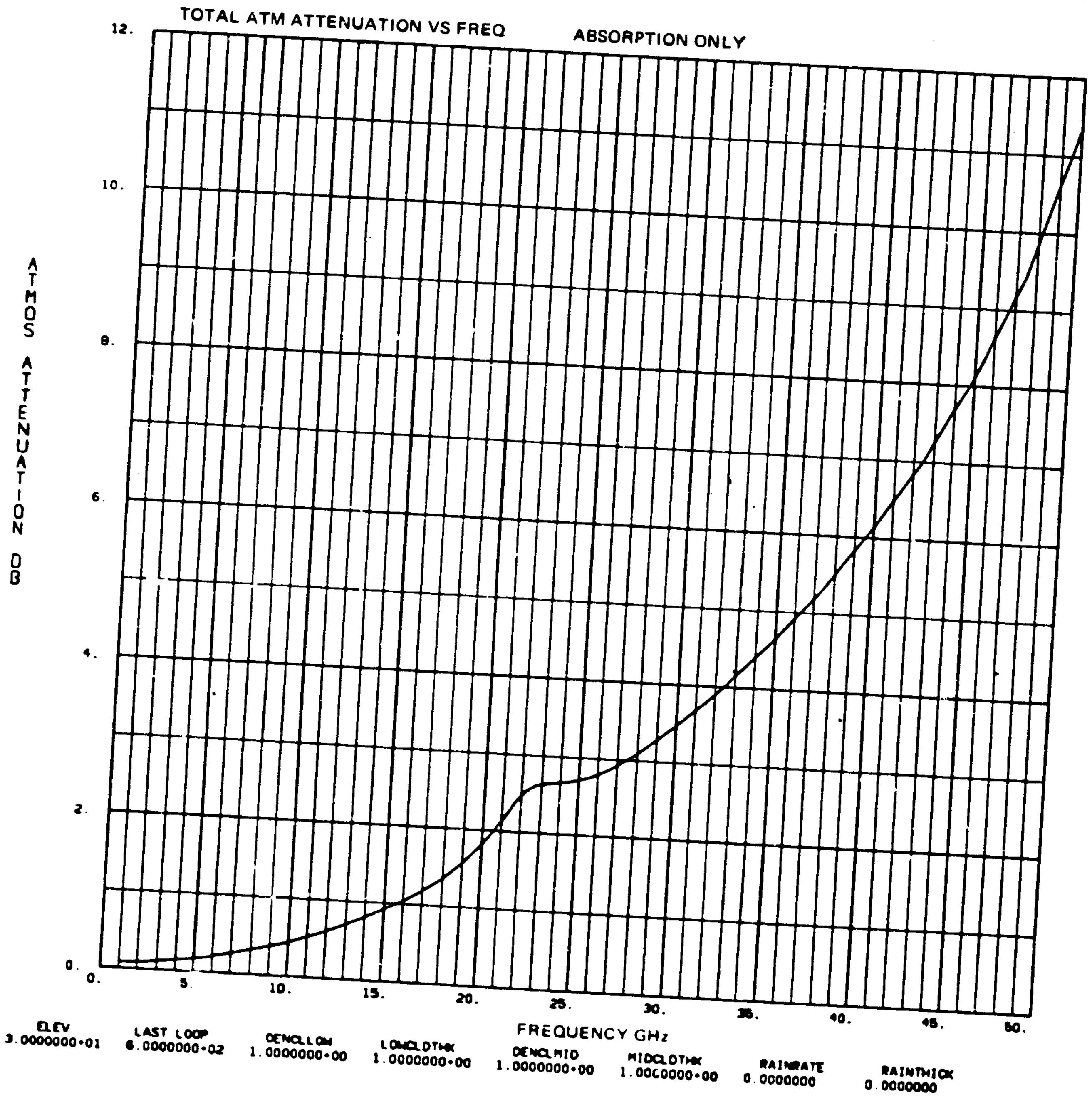
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	5.7000000+02	1.0000000+00	1.0000000+00	1.0000000+00	1.0000000+00	0.0000000	0.0000000

CASE 10-4



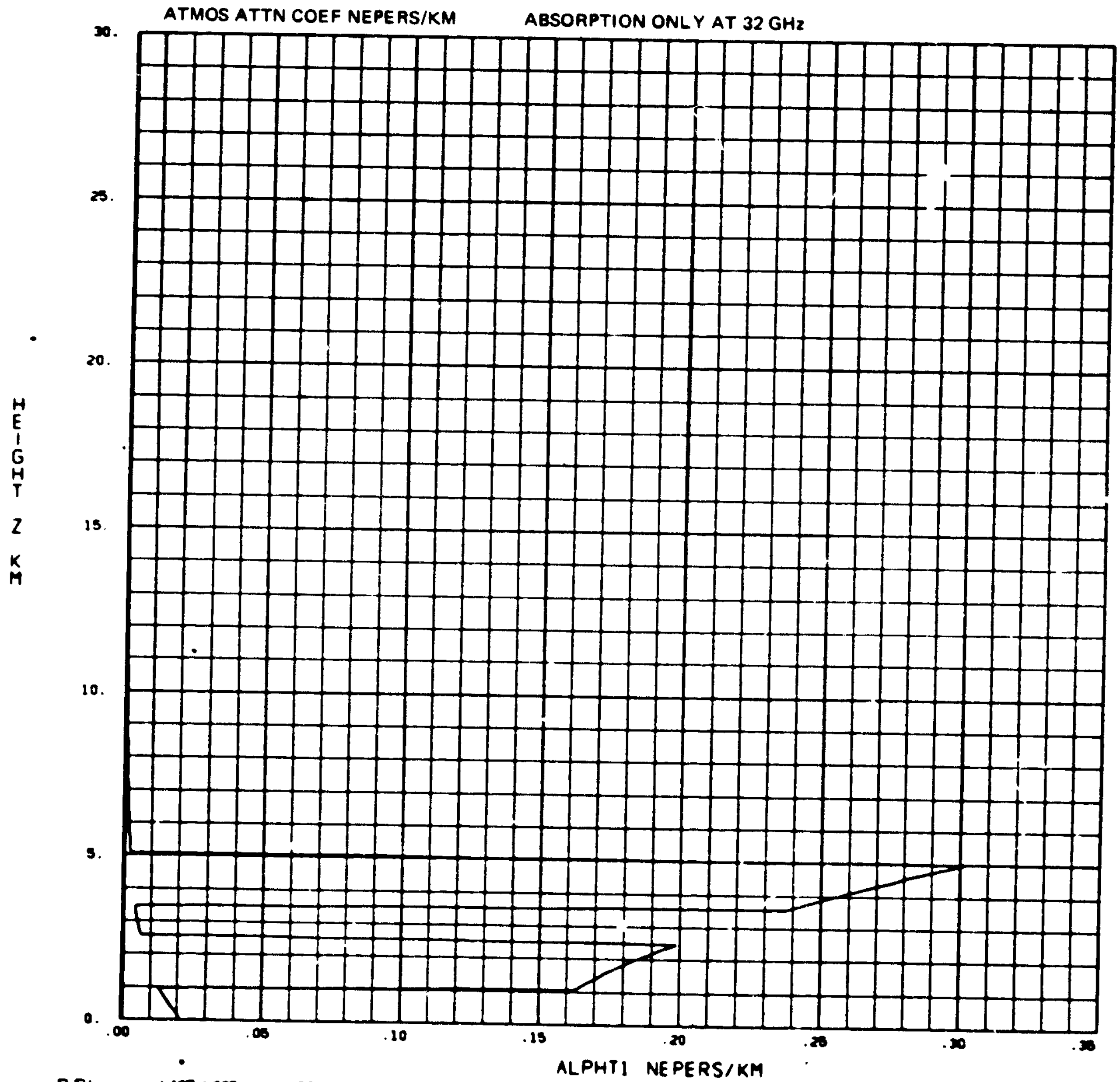
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	6.0000000+02	1.0000000+00	1.0000000+00	1.0000000+00	1.0000000+00	0.0000000	0.0000000

CASE 10-5



TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
FREQUENCY GHz
0.
2.
4.
6.
8.
10.
12.
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
ELEV 3.0000000+01
LAST LOOP 6.0000000+02
DENCLLOW 1.0000000+00
LOWCLDTHK 1.0000000+00
DENCLMID 1.0000000+00
MIDCLDTHK 1.0000000+00
RAINRATE 0.0000000
RAINTHICK 0.0000000

CASE 11-1



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	6.2300000+02	1.0000000+00	1.5000000+00	1.0000000+00	1.5000000+00	0.0000000	0.0000000

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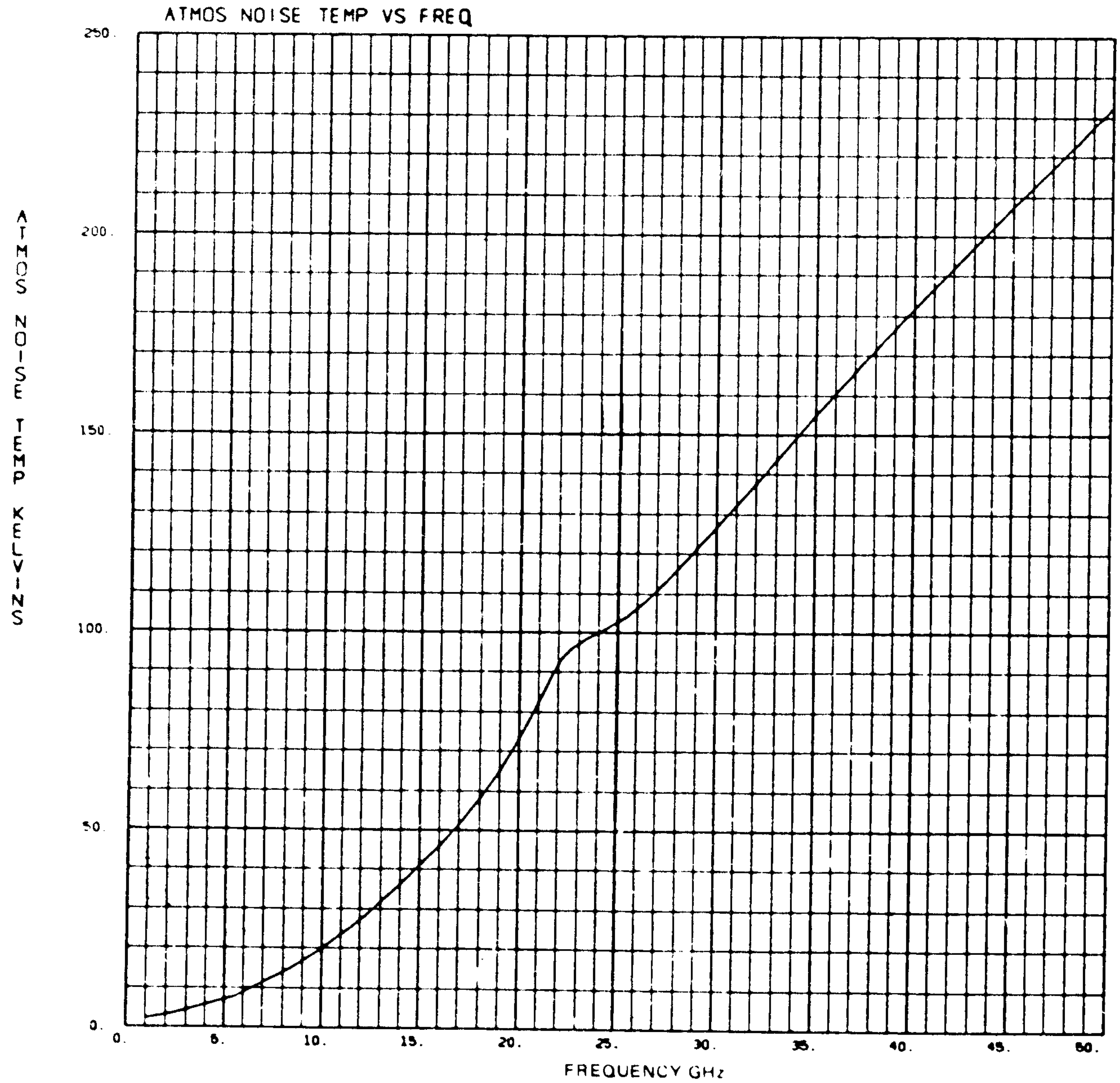
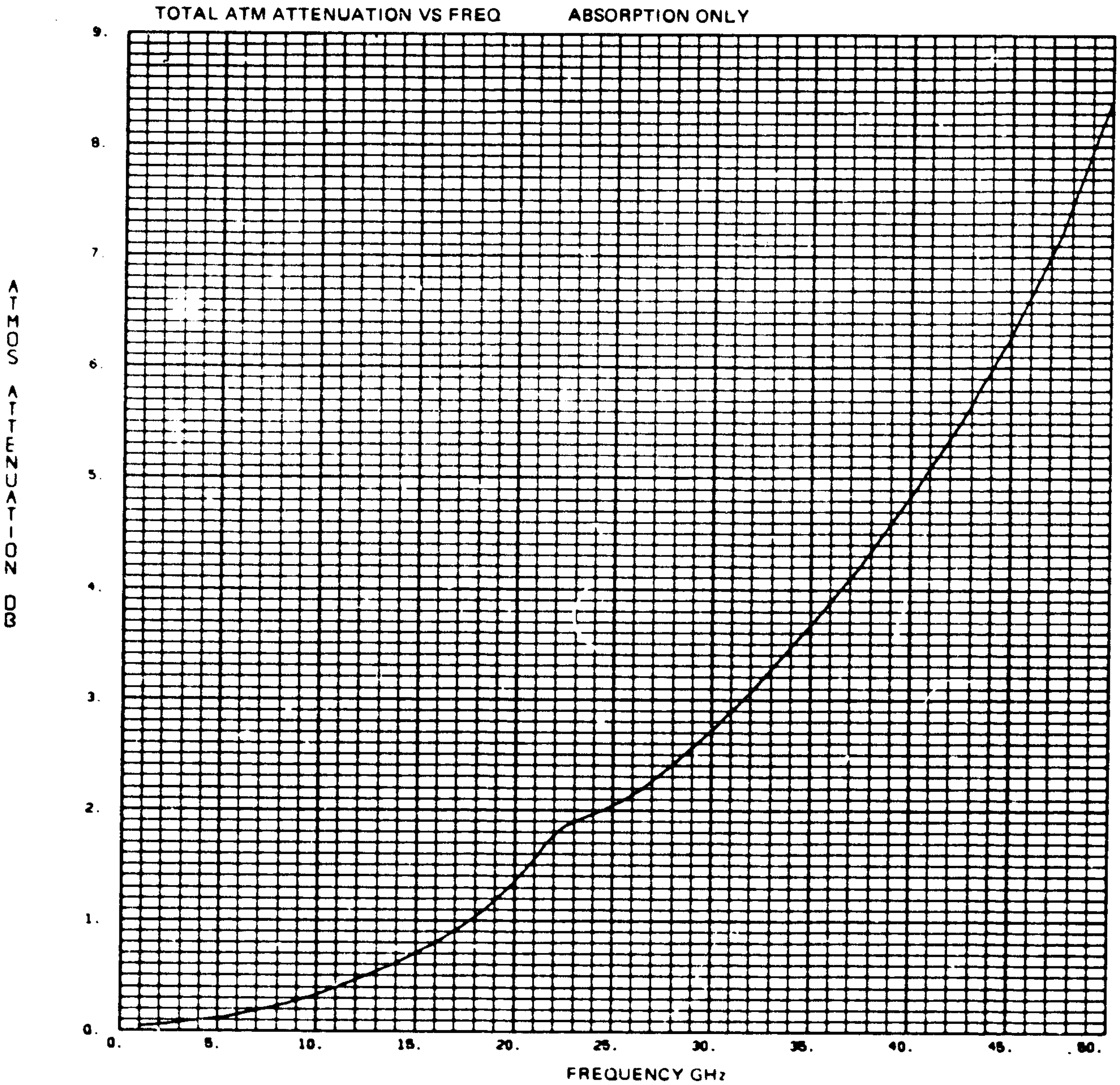
CASE 11-2



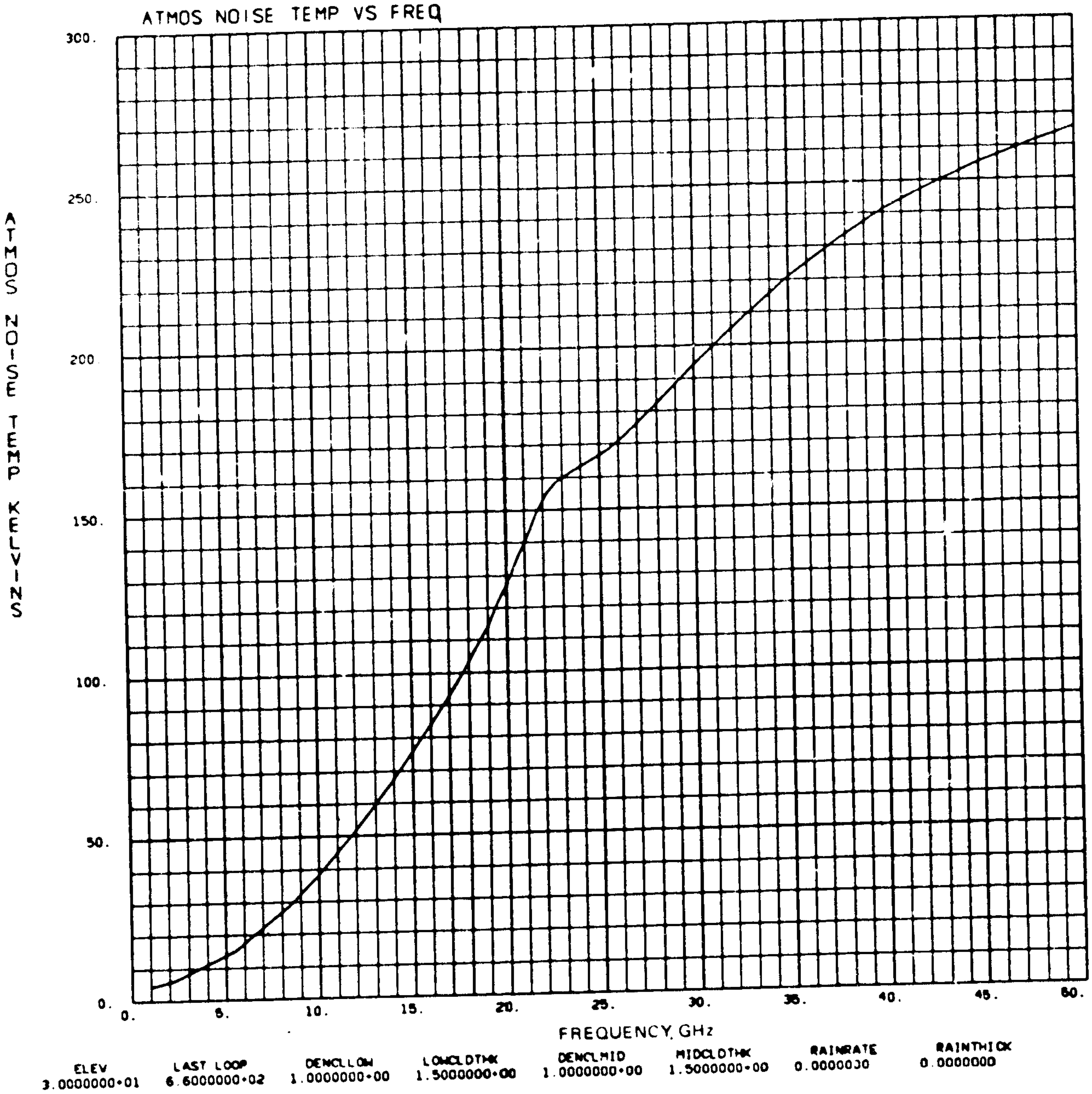
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000-01	6.3000000-02	1.0000000+00	1.5000000+00	1.0000000+00	1.5000000+00	0.0000000	0.0000000

CASE 11-3



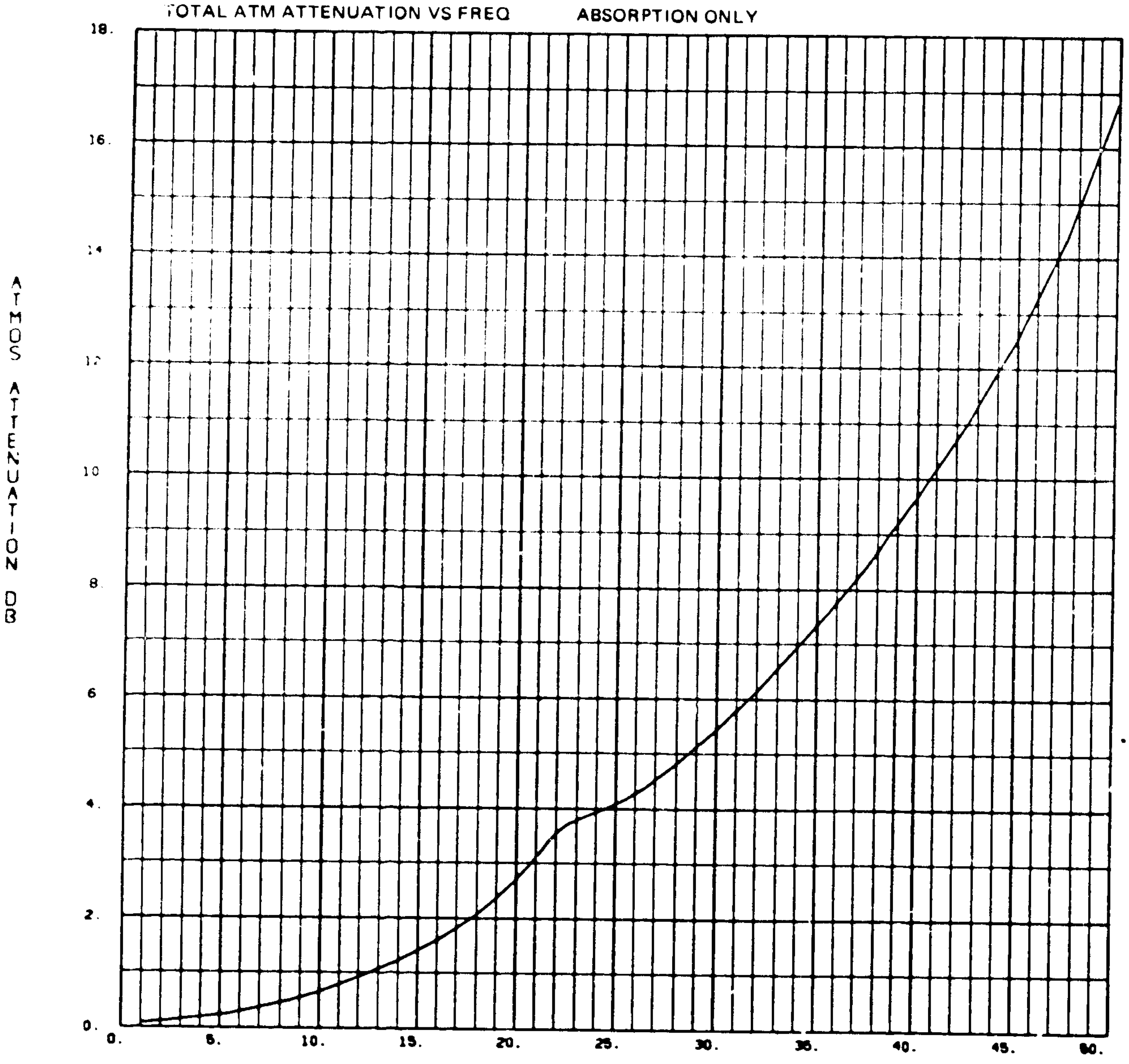
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	6.3000000+02	1.0000000+00	1.5000000+00	1.0000000+00	1.5000000+00	0.0000000	0.0000000

CASE 11-4



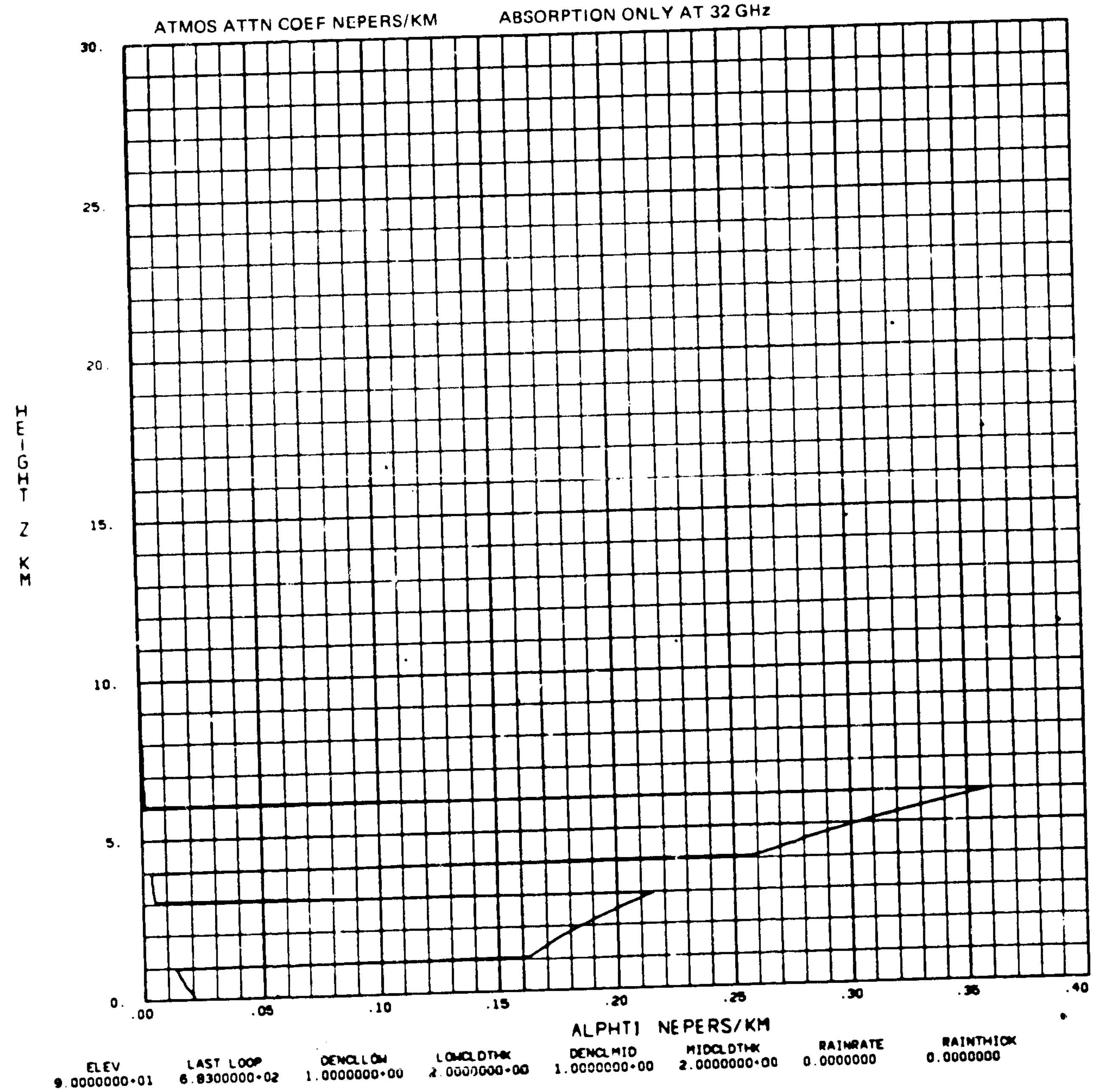
ATMOS NOISE TEMP VS FREQ
ATMOS NOISE TEMP KELVINS
300.
250.
200.
150.
100.
50.
0.
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY, GHz
ELEV 3.0000000+01
LAST LOOP 6.6000000+02
DENCLLOW 1.0000000+00
LOWCLDTHK 1.5000000+00
DENCLMID 1.0000000+00
MIDCLDTHK 1.5000000+00
RAINRATE 0.0000030
RAINTHICK 0.0000000

CASE 11-5



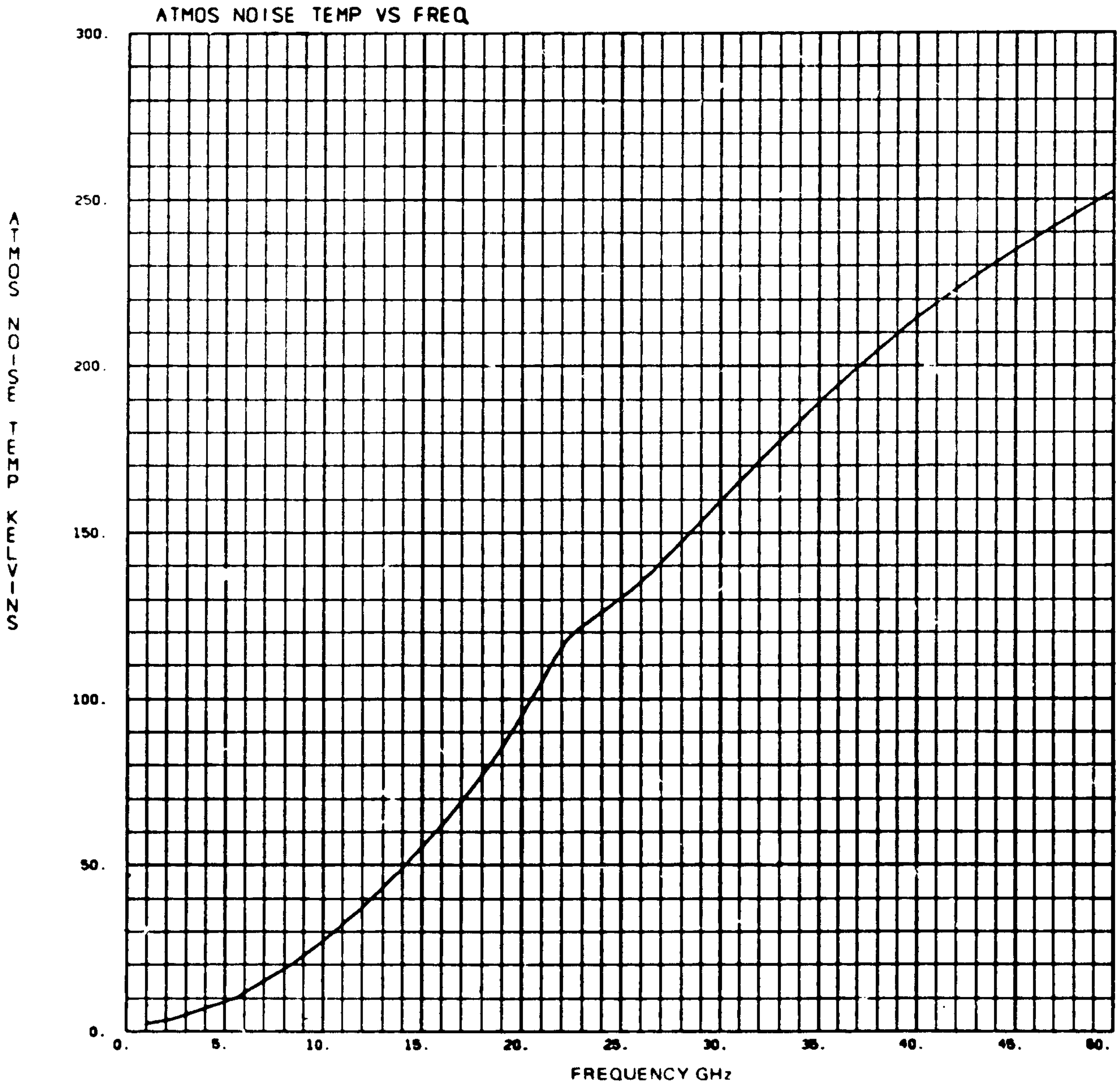
ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	6.6000000+02	1.0000000+00	1.5000000+00	1.0000000+00	1.5000000+00	0.0000000	0.0000000

CASE 12-1



ATMOS ATTN COEF NEPERS/KM
ABSORPTION ONLY AT 32 GHz
HEIGHT Z KM
ALPHT1 NEPERS/KM
0.
5.
10.
15.
20.
25.
30.
.00
.05
.10
.15
.20
.25
.30
.35
.40
ELEV 9.0000000+01
LAST LOOP 6.8300000+02
DENCLLOW 1.0000000+00
LOWCLDTHK 2.0000000+00
DENCLMID 1.0000000+00
MIDCLDTHK 2.0000000+00
RAINRATE 0.0000000
RAINTHICK 0.0000000

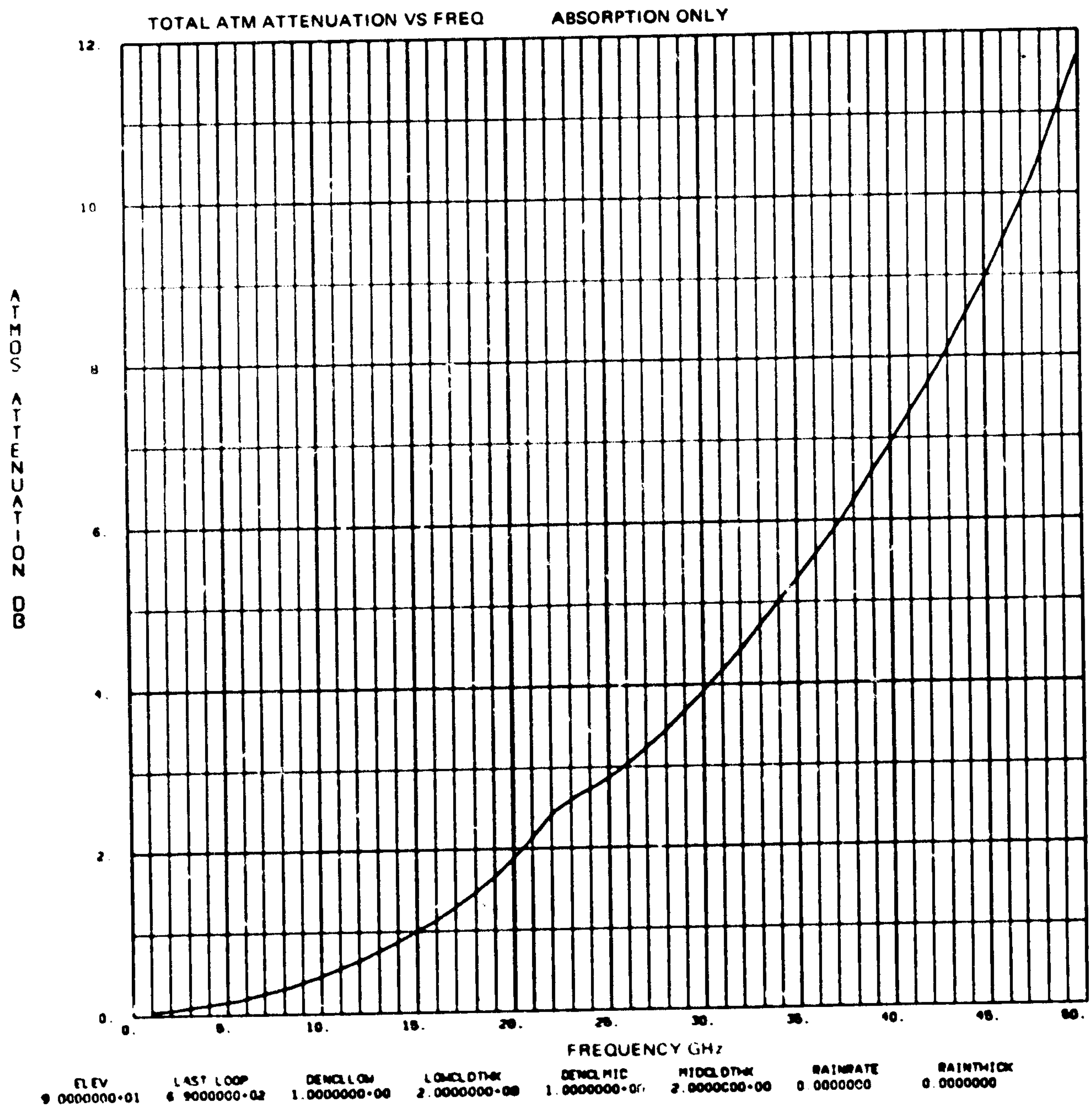
CASE 12-2



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
9.0000000+01	6.9000000+02	1.0000000+00	2.0000000+00	1.0000000+00	2.0000000+00	0.0000000	0.0000000

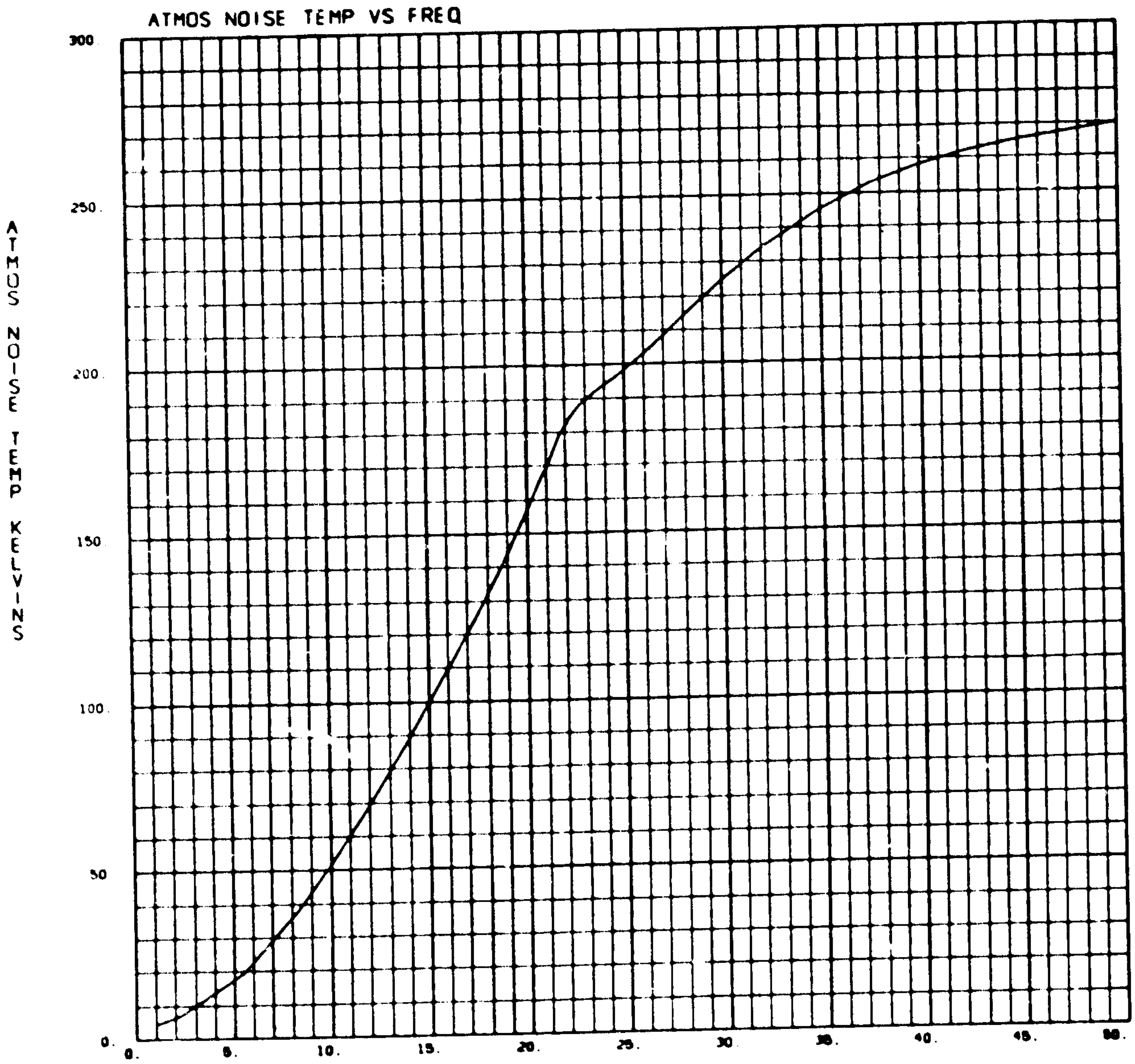
C-2

CASE 12-3



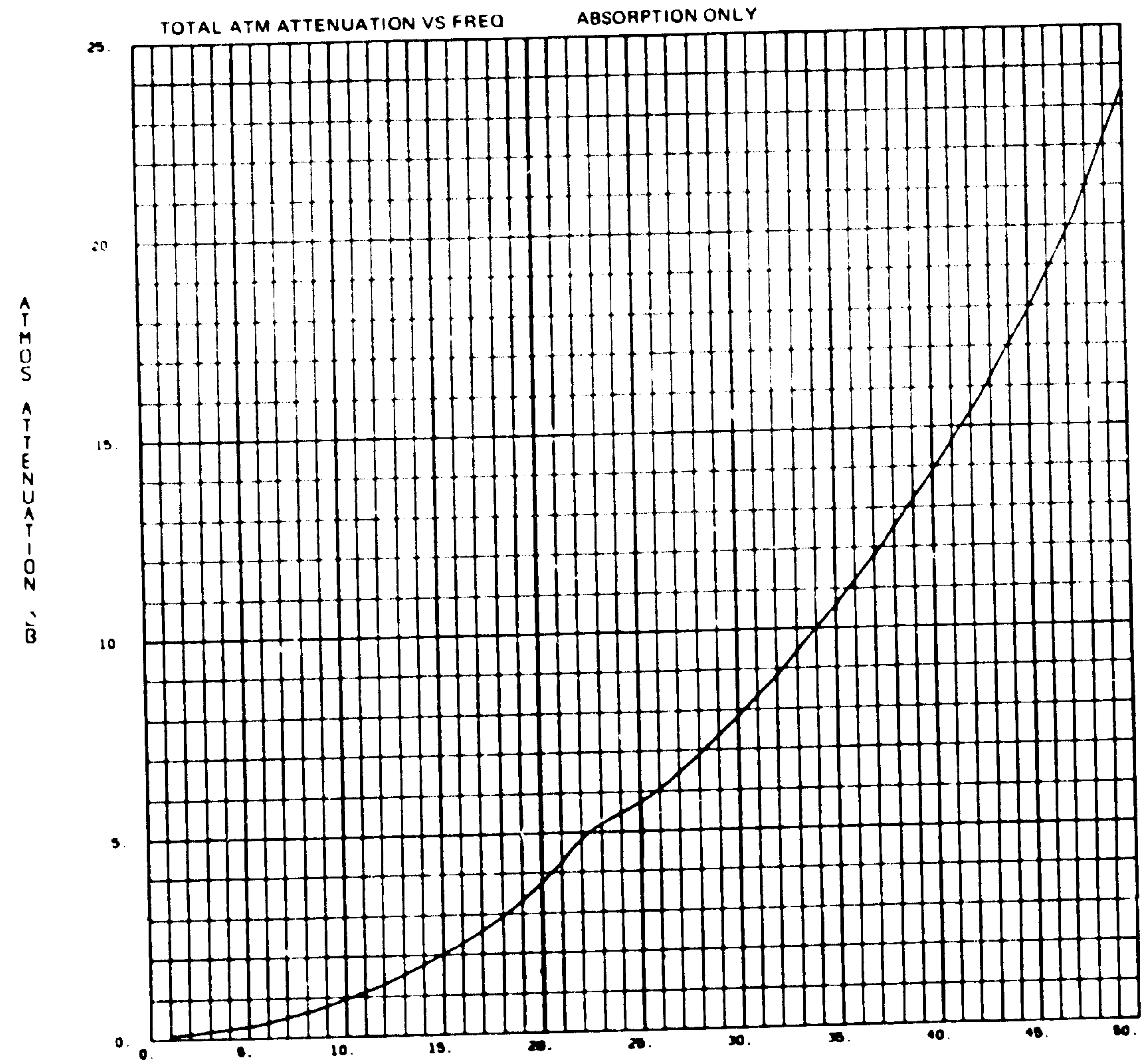
TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY
ATMOS ATTENUATION DB
12.
10
8
6.
4.
2.
0.
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
FREQUENCY GHz
ELEV
9.0000000+01
LAST LOOP
6.9000000+02
DENCLLOW
1.0000000+00
LOWCLDTHK
2.0000000+00
DENCLMID
1.0000000+00
MIDCLDTHK
2.0000000+00
RAINRATE
0.0000000
RAINTHICK
0.0000000

CASE 12-4



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	7.2000000+02	1.0000000+00	2.0000000+00	1.0000000+00	2.0000000+00	0.0000000	0.0000000

CASE 12-5



ELEV	LAST LOOP	DENCLLOW	LOWCLDTHK	DENCLMID	MIDCLDTHK	RAINRATE	RAINTHICK
3.0000000+01	7.2000000+02	1.0000000+00	2.0000000-08	1.0000000+00	2.0000000+00	0.0000000	0.0000000