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MICROWAVE RADIOMETER MEASUREMENT ERRORS DUE TO A LOSSY RADOME

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ABSTRACT

Radiometric brightness temperature measurements taken through non-zero loss radomes will be in error. The magnitude of this error will depend on several factors: radome loss factor, effective background brightness temperature, and the radome physical temperature. Each of these factors is treated and its relative importance given for an airborne radiometer. No attempt is made to account for atmospheric induced errors which are independent from radome induced errors.

INTRODUCTION

The microwave radiometer now under development by Space General Corporation will be used in conjunction with multiple sensors in the MSC Earth Resources Survey Program. The sensors are to be mounted in the MSC P3 aircraft thus requiring an airborne radome enclosure for the radiometer.

The radiometer is a broadband four frequency radio receiver with a sensitivity of 1-degree Kelvin. The four frequencies are 1.42, 10.625, 22.3 and 31.4 gigahertz.

NON-ZERO LOSS RADOME

A non-zero loss radome can be considered an absorbing and emitting medium. This means a source brightness will be attenuated when viewed through a lossy medium. Also, the medium will have some contribution to the observed brightness. Consider a lossy medium situated between an antenna and a source at absolute zero temperature. Without the lossy medium the observed brightness temperature would be zero, however, the lossy medium will give an increase in available antenna power given by $k \Delta f (dT_B)$. A blackbody will generate power $[k \Delta f\, T(x)\, d\delta(x)]e^{-\delta(x)}$ where T(x) is the thermal equilibrium temperature distribution, $d\delta(x)$ is the incremental attenuation distribution and δ(X) is the total attenuation (in nepers) between any source point (X) and the observer.

Thus,
$$k \Delta f (d T_B) = [k \Delta f\, T(x)\, d\delta(x)]\, e^{-\delta(x)}$$

or
$$d T_B = T(x)\, [d\delta(x)]\, e^{-\delta(x)}$$

now
$$d\,\delta(x) = \alpha(x)\, dX$$

and
$$\delta(x) = \int_{X}^{X_2} \alpha(x)\, dX$$

where α (X) is the medium attenuation constant per unit length and dX is the incremental length. Thus, the brightness temperature for the lossy medium alone becomes

Eq. 1
$$T_B = \int_{x=x_1}^{x=x_2} T(x) \exp\left\{-\int_{y=x}^{y=x_2} \alpha(y)\, dy\right\} \alpha(x)\, dx$$

where $X = X_1$ and $X = X_2$ are the boundaries of the lossy medium. (See Figure 1).

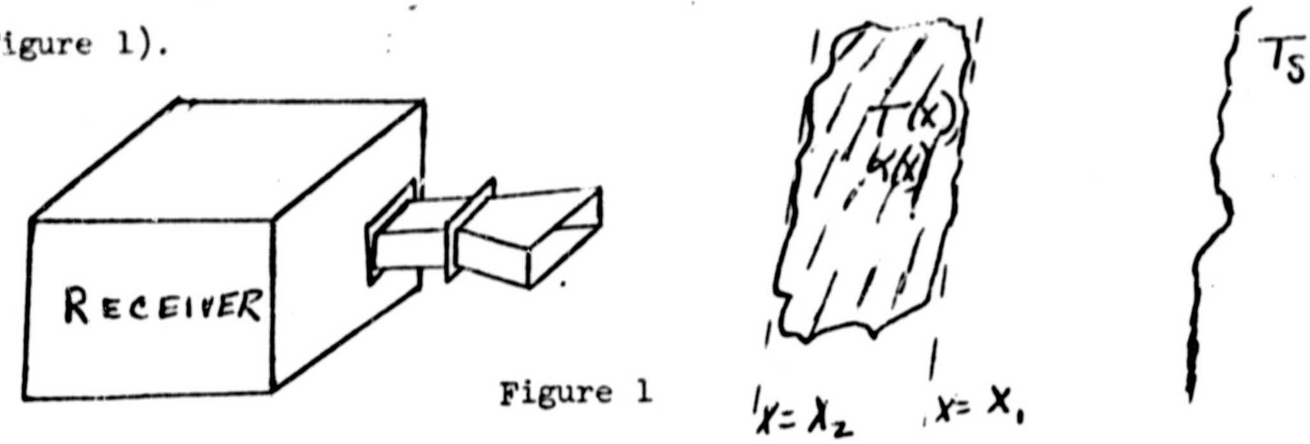


Figure 1

For the case of a lossy radome, two simplifying assumptions are made. It is assumed that T(X) is a constant T_R and that α (X) is a constant at any point in the radome. Now, if $T_s \neq 0$, the effective antenna brightness temperature (T_A) is given by

$$T_A = T_S e^{-\int_{x=x_1}^{x=x_2} \alpha(x)\,dx} + T_R \int_0^{\delta} e^{-\delta}\, d\delta$$

$$= T_S e^{-\delta} + T_R (1 - e^{-\delta})$$

where $\delta =$ total attenuation in nepers

Defining the loss factor (L) as $L = e^{\delta}$

$$T_A = \frac{T_S}{L} + T_R \left(1 - \frac{1}{L}\right)$$

$$T_A = \frac{T_S}{L} + \left(\frac{L-1}{L}\right) T_R \qquad \text{Eq. 2}$$

The simplifying assumptions made that allowed such a clean and simple formulation need a few words of explanation. The radome temperature and attenuation constant per unit length will vary throughout. It would be near impossible to determine and measure the distribution function of these variables and even then it would leave one with a complex integration.

A much simpler approach is to monitor the temperature gradient (which should be fairly constant) and perform effective loss measurements at various radiometer look angles $(L(\theta,\varphi))$. These loss measurements may then be tabulated and inserted into the antenna brightness computations indicated by equation two.

ERRORS

Although a method is established whereby the source brightness temperature may be calculated (solving equation 2 for Ts and using the appropriate L (θ,φ) term), errors will still be present due to measurement errors. It thus remains to establish the range of errors to be expected.

Loss Factor

The loss factor will be greater than 1 (zero-loss) and less than 2 (50 percent loss).

A good (very good) antenna range could achieve one-quarter of a db accurate measurement. Allowing this to be ±one-eighth of a db is about ±3 per cent error. If, however, careful measurements are conducted at a high altitude radio-astronomy site an accuracy of ± 1- to ±2- per cent should be possible.

Radome Temperature

The radome temperature monitor instrumentation will be accurate to 1-degree Kelvin or better. However, in establishing an effective radome temperature function other errors will be involved such as sensor location and actual radiometer look angle, localized heating (or cooling) due to sun, wind currents, etc., original measurements interpretation and extrapolation, etc. If a complete testing and documentation procedure is followed, and assuming the radiometer accuracy is ±1- degree

Kelvin, it should be possible to establish the effective radome temperature to ± 2- degrees Kelvin. The radome temperature range should be from about 220- degrees Kelvin to 325-degrees Kelvin.

To summarize, the following equalities and inequalities can be stated.

$$1 < L < 2 \qquad 0.01 < \left|\frac{\Delta L}{L}\right| < 0.02$$

$$220^\circ K < T_R < 325^\circ K \qquad |\Delta T_R| \simeq 2.0^\circ K$$

$$|\Delta T_A| \simeq 1^\circ K$$ (Radiometer accuracy)

CALCULATIONS

Solving equation 2 for T_s gives

$$T_s = L T_A - (L-1) T_R \qquad \text{Eq. 3}$$

Allowing L, T_A and T_R to become $L + \Delta L$, $T_A + \Delta T_A$ and $T_R + \Delta T_R$ equation 3 becomes

$$T_s + \Delta T_s = (L + \Delta L)(T_A + \Delta T_A) - (L + \Delta L - 1)(T_R + \Delta T_R)$$

$$= L T_A - (L-1) T_R + [\Delta L (T_A - T_R) + L (\Delta T_A - \Delta T_R) + \Delta T_R] + \Delta \cdot \Delta$$

From equation 3 $L T_A - (L-1) T_R$ is the source brightness calculation performed in data reduction and taken as the actual brightness temperature for data purposes. Recognizing this, replacing T_A by equation 2, and neglecting $\Delta \cdot \Delta$ terms results in

$$\Delta T_s = \frac{\Delta L}{L}(T_s - T_R) + L \Delta T_A + (1 - L) \Delta T_R \qquad \text{Eq. 4}$$

Note that as L approaches 1 (equivalent to no radome), $\Delta T_s \rightarrow \Delta T_A$ which is the radiometer accuracy.

Since the interest is in maximum errors, equation 4 is maximized with regard to signs. Thus,

$$\Delta T_s = \left|\frac{\Delta L}{L}\right| |T_s - T_R| + |L \Delta T_A| + |(1-L) \Delta T_R| \qquad \text{Eq. 5}$$

The last two terms are linearly dependent on the loss factor L while the first term is dependent on the accuracy to which L is measured and the difference between the source and radome temperature. Equation 5 is sketched in Figure 2, Figure 3, and Figure 4 for different values of L, $\frac{\Delta L}{L}$ and T_R. Note that Figure 2 and Figure 3 differ only in assumed radome temperature. However, the importance of the radome loss measurement is clearly evident by comparing Figure 3 with Figure 4.

It should be remembered that the above treatment concerned itself with maximum error. In operation ΔL, ΔT_A, and ΔT_R are RMS quantities and will be a somewhat random fluctuations. Consequently, it may be possible to establish the total error as the root-sum-square of all quantities. That is

$$\Delta T_S \,(RSS) = \sqrt{\left[\frac{\Delta L}{L}(T_S - T_R)\right]^2 + (L\,\Delta T_A)^2 + \left[(1-L)\Delta T_R\right]^2} \qquad \text{Eq. 6}$$

Equation 6 is sketched in Figure 5 for $L = 1.1$ and $\frac{\Delta L}{L} = 1/100$ (one-percent) and $\frac{\Delta L}{L} = 2/100$ (two-per cent). For reference equation 5 for L = 1.1 and $\frac{\Delta L}{L} = 1/100$ is the dashed line in Figure 5.

The actual total error will be determined experimentally at a proper test range. The technique for accomplishing this will be to view known brightness temperatures (such as cold sky) with and without the radome.

RADIOMETER SENSITIVITY

The radiometer sensitivity will also suffer due to the radome. To show this consider equation 2. If the background brightness under observation goes from $T_{B1} \rightarrow T_{B2}$, the corresponding change in T_A is $\frac{\partial T_A}{\partial T_B} = \frac{1}{L}$, or $\Delta T_B = L \Delta T_A$ $\Delta T_B = T_{B1} - T_{B2}$.

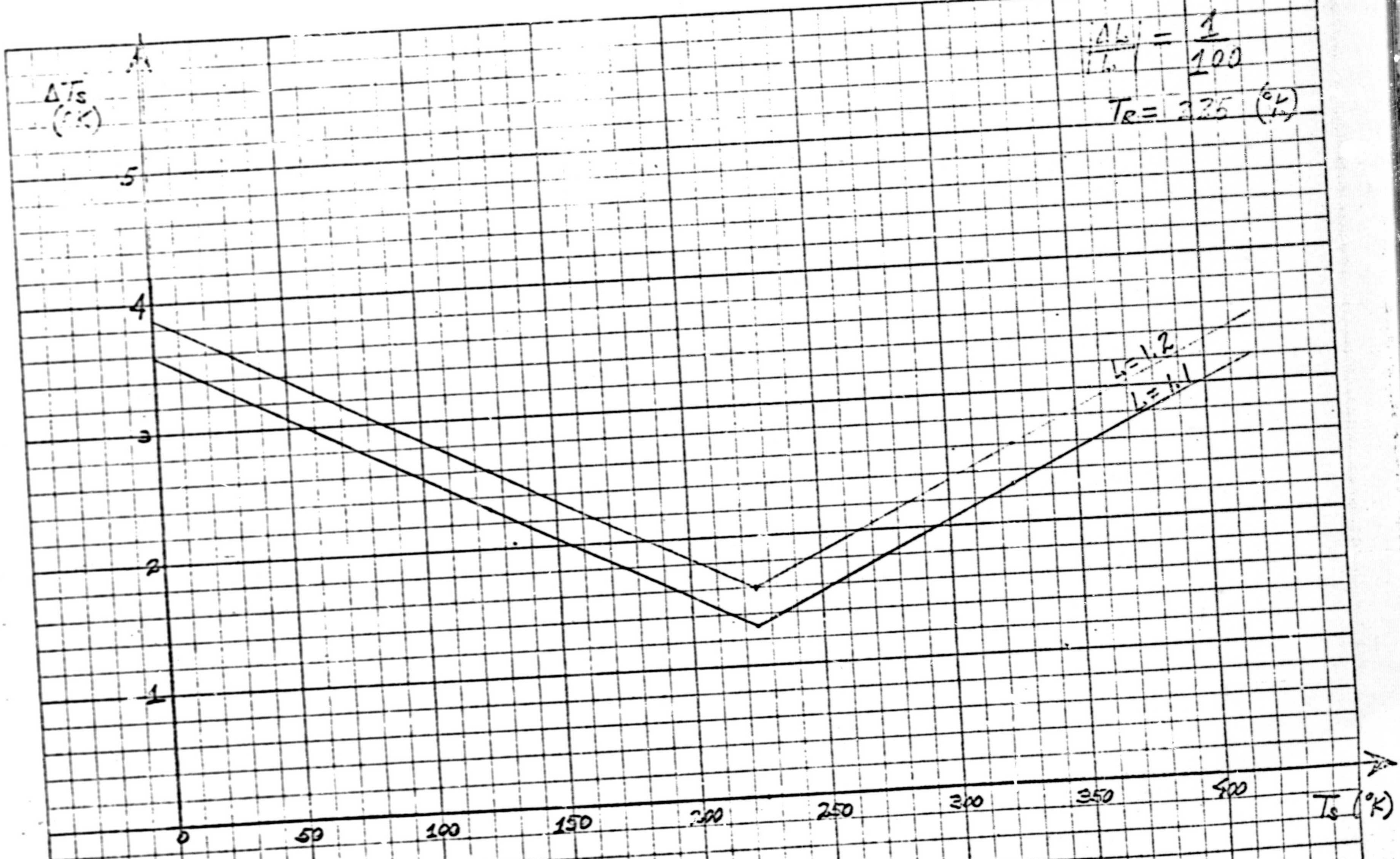
Conversely, for a given (ΔT_A) radiometer sensitivity, the minimum detectable background brightness change is L (ΔT_A).

CONCLUSIONS

Every effort should made to insure the best possible radome. However, for low loss radomes ($L < 1.1$) more important items become the loss factor measurement, beam displacement, etc.

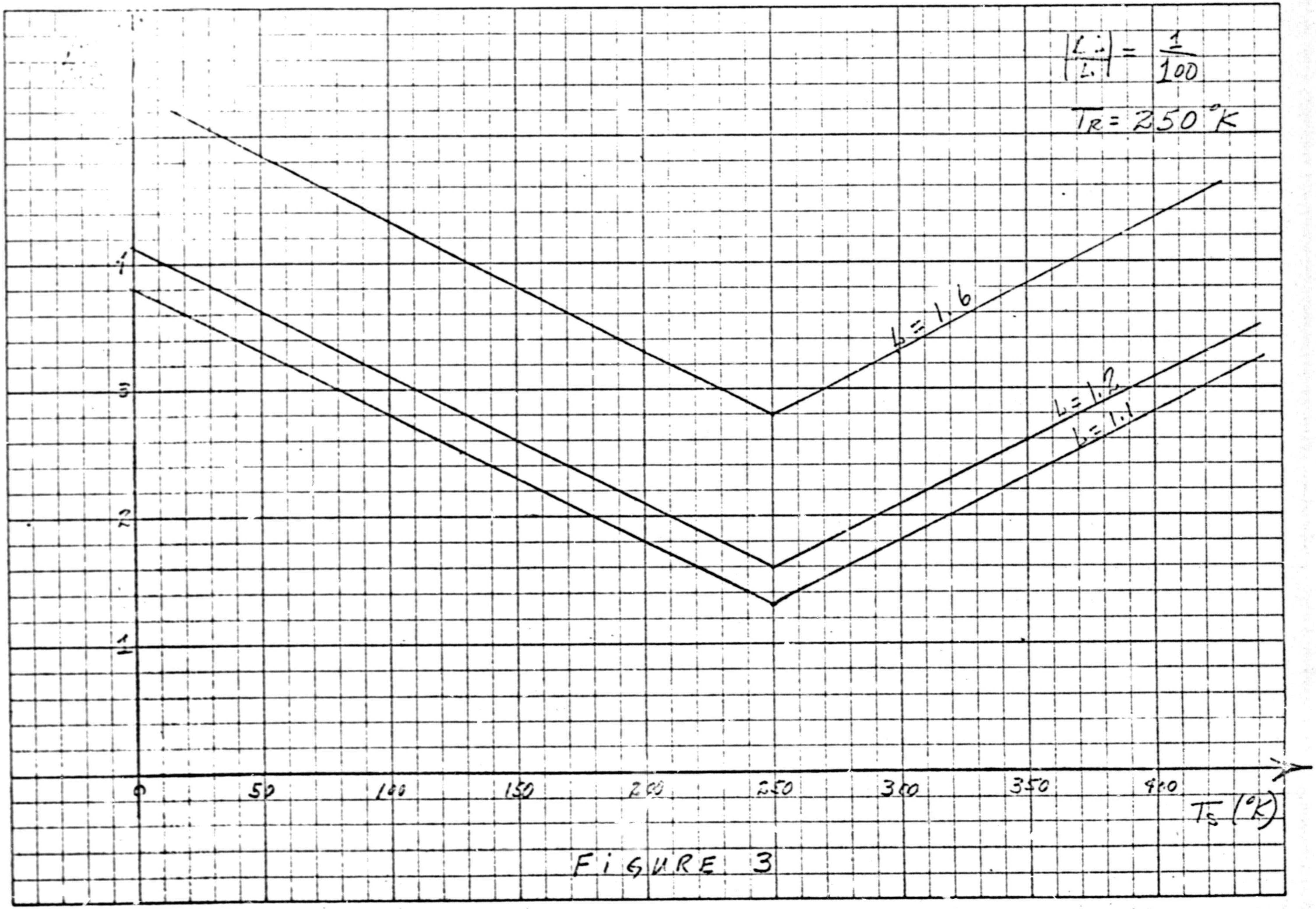
The errors developed in this report should be taken only as an estimate of radiometer system performance when enclosed in an airborne radome. Even low loss radomes will introduce errors of two, three- maybe even ten-degrees Kelvin when viewing very cold (radiometrically) objects, the actual error being dependent on how extensive a calibration and controlled testing program is accomplished.

The radiometer sensitivity will not be seriously degraded for low loss radomes. That is to say a measurement of incremental brightness temperature change between plowed ground and grassy plains should be as good with the radome as without. This assumes the incremental measurement is made on a single flight line.



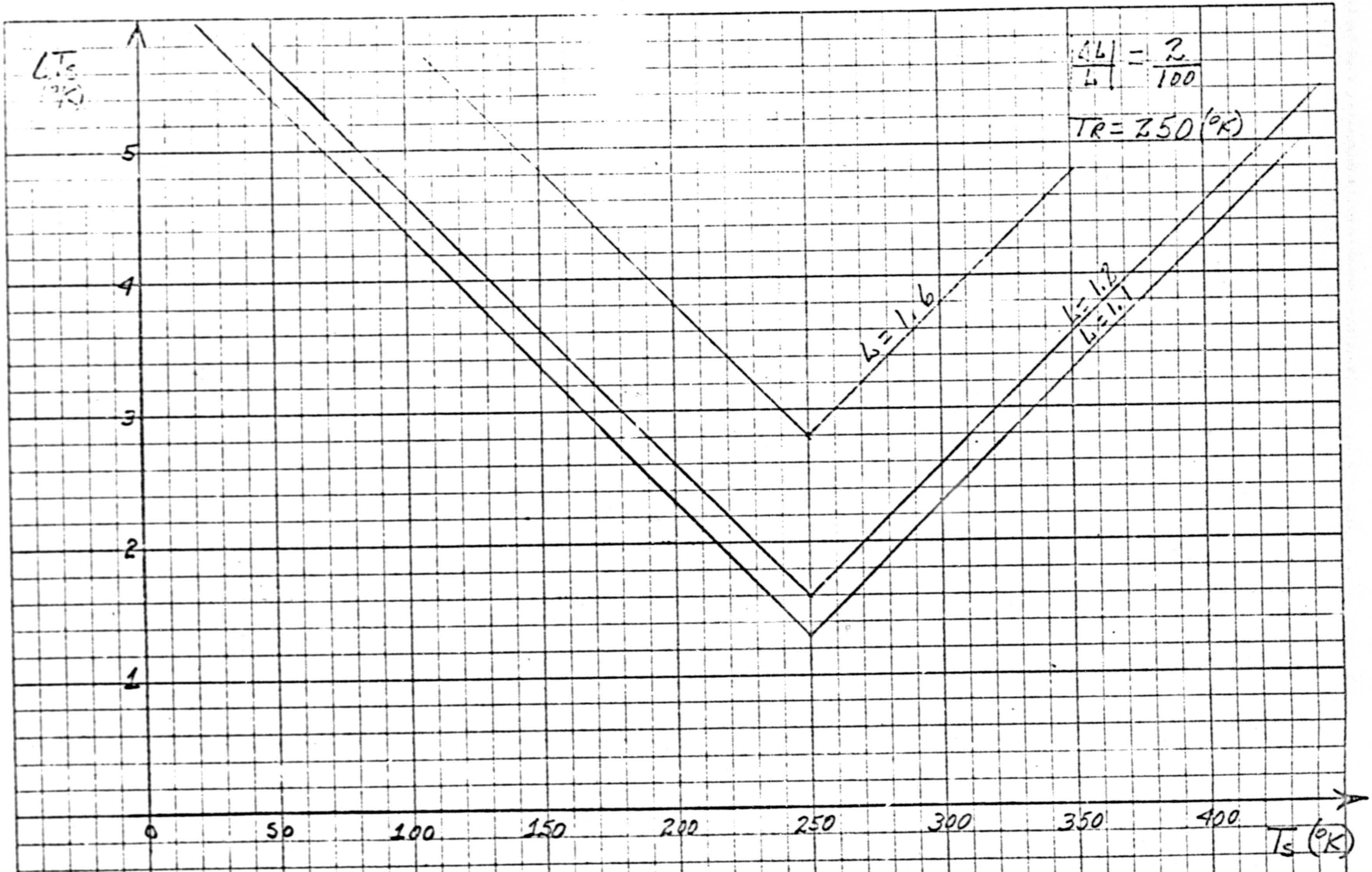
ΔT_s (°K)
$\left|\frac{\Delta L}{L}\right| = \frac{1}{100}$
$T_R = 325$ (°K)
5
4
3
2
1
L = 1.2
L = 1.1
0
50
100
150
200
250
300
350
400
T_s (°K)

FIGURE 2



$\left|\frac{L_i}{L}\right| = \frac{1}{100}$
$T_R = 250\,°K$
L = 1.6
L = 1.2
L = 1.1
0
50
100
150
200
250
300
350
400
T_S (°K)
1
2
3
4

FIGURE 3



ΔT_s (°K)
5
4
3
2
1
0
50
100
150
200
250
300
350
400
T_s (°K)
$\frac{|\Delta L|}{L} = \frac{2}{100}$
$T_R = 250$ (°K)
L = 1.6
L = 1.2
L = 1.1

FIGURE 4

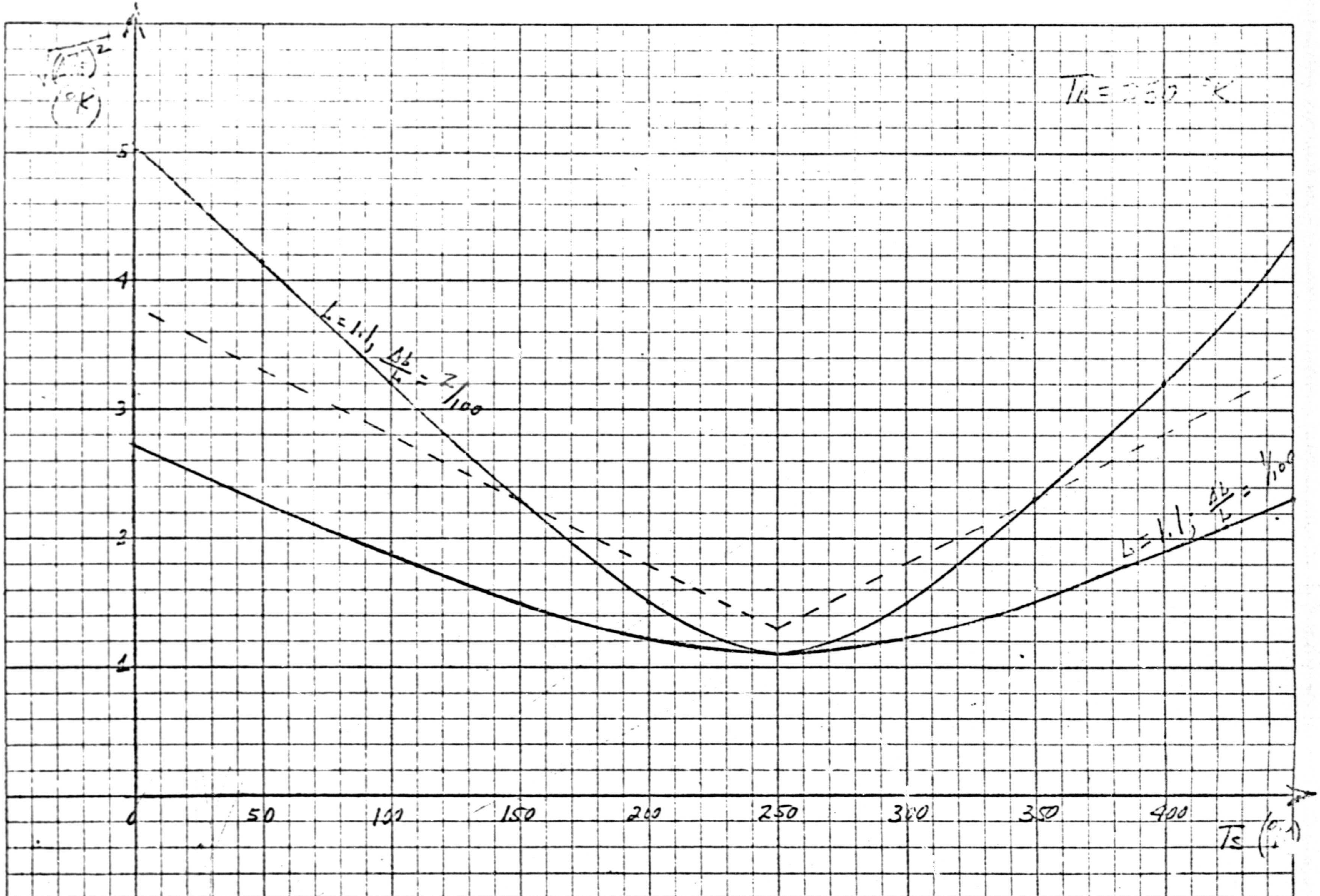

(°K)
5
4
3
2
1
0
50
100
150
200
250
300
350
400
Ts
L = 1.1; ΔL/L = 2/100
L = 1.1; ΔL/L = 1/100

FIGURE 5

List of Symbols

T_A - Antenna Effective Brightness Temperature - ^oK

T_B - Lossy Medium Effective Brightness Temperature - ^oK

T_R - Radome Thermal Equilibrium Temperature - ^oK

T_S - Source Brightness Temperature - ^oK

$T(X)$ - Lossy Medium Thermal Equilibrium Temperature Distribution - ^oK

ΔT_A - RMS Antenna Brightness Temperature Error - ^oK

ΔT_R - RMS Radome Temperature Error - ^oK

ΔT_S - Maximum Source Brightness Temperature Error - ^oK

L - Radome Loss Factor

$\alpha(x)$ - Lossy Medium Attenuation Constant per Unit Length -nepers/length

$\delta(x)$ - Total attenuation between observer and any source point x -nepers

δ - Total Attenuation

k - Boltzmann's Constant - $1.38 \times 10^{-23} \frac{\text{joules}}{^oK}$

Δf - Receiver Bandwidth - H_z

^oK - Degree Kelvin

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