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RM-4760-ARPA
JANUARY 1966

UTILIZATION OF RIOMETERS FOR THE DETECTION OF NUCLEAR EXPLOSIONS IN SPACE

B. C. Potts

PREPARED FOR:
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The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

This Memorandum is part of RAND's continuing VELA Analysis study for the Advanced Research Projects Agency to assess the relative capabilities of various methods of detection of nuclear explosions above the earth's surface. The riometer technique is one possible method for the detection of nuclear explosions at high altitude and in deep space. The maximum range or altitude at which a 1-kT X-ray impulse can be detected by measuring changes in high-frequency cosmic noise absorption utilizing a riometer is determined in the Memorandum. It is shown that the detection range is a function of the riometer time constant.

This Memorandum was submitted to Dr. Robert Frosch, Deputy Director of the Advanced Research Projects Agency, for inclusion in the IEEE special issue on nuclear detection.

SUMMARY

This Memorandum considers the detection of overhead nuclear explosions in space by riometer measurement of the effects of explosion-induced ionization on the absorption of high-frequency cosmic noise. The induced ionization is calculated as a function of height and time for a 1-kT X-ray impulse having temperatures of .5, 1.0, and 2.0 kev and having burst heights from 10^3 to 10^5 km. The absorption at each height due to the induced ionization is then calculated at a radio frequency of 30 Mc. In order to determine the change in the effective antenna temperature as a function of time at the riometer, the total absorption through the ionosphere is then determined. The response of a riometer with several time constants is found for this sharp change in received cosmic noise power. Detection ranges are calculated for each X-ray temperature and several possible riometer time constants based on the criterion that the nuclear burst must produce a 1-db peak response in the diode current of the riometer. These detection ranges are tabulated and compared with those that were found neglecting riometer response time.

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I. INTRODUCTION

The riometer[1] is a very stable receiver used to measure the relative change in cosmic noise arising primarily from synchrotron radiation within our own galaxy. The relative changes in received noise power are measured quite accurately by continuously comparing the antenna noise temperature with the noise temperature of a controlled noise source. In the absence of the earth's ionosphere, the intensity of the cosmic radio noise from any given large sector of the galaxy is constant with only the usual statistical fluctuations. In the presence of the ionosphere, the portion of the noise spectrum below f_oF2 is basically cut off, while the frequency components higher than f_oF2 pass through the ionosphere and are attenuated. The amount of attenuation introduced by the ionosphere is frequency dependent and varies in time with the amount of ionization in the ionosphere. When a high-altitude nuclear burst occurs, the ambient ionization in the ionosphere may be enhanced, causing increased attenuation of the cosmic radiation that may be detected by a riometer on the earth.

A large body of literature is available which calculates and estimates the effects of explosion-produced ionization on radio waves. A few of these papers which have been used extensively for background in this paper are mentioned below. Latter and LeLevier[2] have calculated the vertical absorption applicable to the study of riometer measurements due to X-ray, γ-ray, and β-ray radiation of high-altitude nuclear bursts neglecting any ambient ionization. Crain and Booker[3] developed a simple, but general, relation for the prompt vertical absorption illustrating its dependence on operating frequency, angle of incidence, maximum induced ionization, and the X-ray radiation temperature. The time dependence of the ionization impulse decay was also discussed. This work was extended by Crain[4] in a paper which pointed out the nonlinear effects in the rate of ionization decay that may also occur depending on the intensity of the X-ray impulse. An analytical expression for the decay of the ionization for the special case of equal electron-ion and ion-ion recombination rates was developed by LeLevier.[5]

In this Memorandum, the X-ray induced ionization is calculated for a 1-kT X-ray yield for a range of altitudes and hypothetical X-ray temperatures. The decay of this ionization as a function of time is then computed, as well as the resulting absorption as a function of height. The total one-way absorption through the ionosphere is also calculated as a function of time after the burst, and the riometer response to this attenuation is computed taking into account its hypothetical time constant and antenna pattern.

From the calculation of riometer response to an X-ray impulse, detection ranges are calculated which are used to draw conclusions as to the utility of the riometer in detecting nuclear explosions in space. Explosions at altitudes below about 1000 km are not considered.

II. THEORETICAL X-RAY IONIZATION IMPULSES

Standard procedures[2] exist for obtaining the energy deposited at each altitude due to a given flux of X-ray radiation from a nuclear explosion. Using these procedures, the vertical ionization depositions were calculated for a 1-kT X-ray yield at altitudes from 10^3 to 10^5 km which have (hypothetical X-ray) radiation temperatures of .5, 1.0, and 2.0 kev.

The computed values of the electron density, ΔN, at vertical incidence versus height for a 1-kT X-ray impulse at a height of 1000 km at the instant after the impulse occurs are shown in Fig. 1 for three X-ray temperatures. The curves of Fig. 1 will hold almost equally well for a 100-kT burst at 10,000 km since the initial, or prompt, ionization scales[3] as Y/R^2 where Y is the yield in kT and R is the distance from the burst altitude to the altitude of interest in km. The initial ionization curves of Fig. 1 hold equally well for day or night.

The curves of Fig. 1 demonstrate that the cooler the radiation, the higher the ionization is deposited. To clarify the magnitudes of the ionization impulses under discussion, Table 1 is given to illustrate the peak electron density for each height and temperature of the hypothetical 1-kT X-ray impulse.

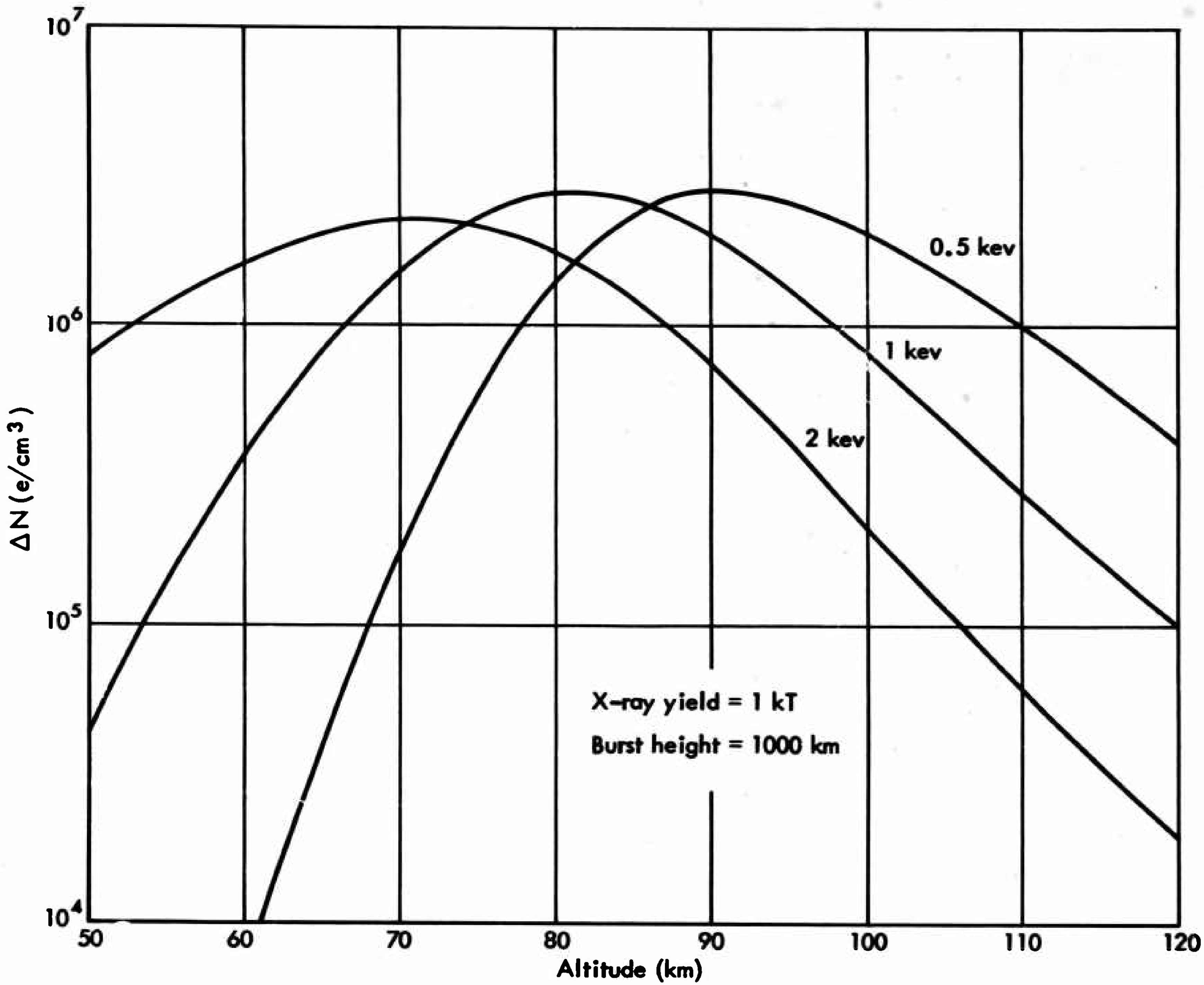
10^7
10^6
10^5
10^4
ΔN (e/cm 3)
0.5 kev
1 kev
2 kev
X-ray yield = 1 kT
Burst height = 1000 km
50
60
70
80
90
100
110
120
Altitude (km)

Table 1

APPROXIMATE PEAK VALUES OF 1-kT X-RAY IMPULSES

Burst height (km)	ΔN (elec/cc)		
	Temperature (kev)		
	0.5 (91 km)[a]	1.0 (82 km)[a]	2.0 (71 km)[a]
10^3	2.9×10^6	2.8×10^6	2.3×10^6
3×10^3	2.9×10^5	2.8×10^5	2.3×10^5
10^4	2.4×10^4	2.4×10^4	2.0×10^4
3×10^4	2.6×10^3	2.6×10^3	2.2×10^4
10^5	2.4×10^2	2.4×10^2	2×10^2

[a] Height of peak

III. DECAY OF AN IONIZATION IMPULSE

Using the standard rate equations[3] for atmospheric ionization and commonly used values of the recombination coefficients[5], the decay of X-ray deposited ionization was computed versus time for heights from 30-140 km. The values obtained are typical, and the final result is relatively independent of reasonable changes in the recombination coefficients such as suggested by Crain[4] or recent laboratory measurements.[6,7] The collision frequency as a function of height was taken from a paper by Nicolet[8] (the lower of his estimated values for each altitude above 85-km altitude).

The set of first-order differential rate equations was solved numerically on the computer using an Adams-Moulton variable step size predictor-corrector procedure. The solutions led to the distribution of enhanced ionization as a function of height and time for the hypothetical nuclear bursts of interest. Figure 2 illustrates the case which demonstrated the most dramatic change with time. In Fig. 2 it is seen that the electrons deposited at $t = 0$ are quickly attached to the neutral particles at altitudes below 65 km. A detailed discussion of the decay results obtained is beyond the scope of this Memorandum. Readers interested in the details of decay and persistance of an impulse of ionization are referred to a paper by Crain.[4]

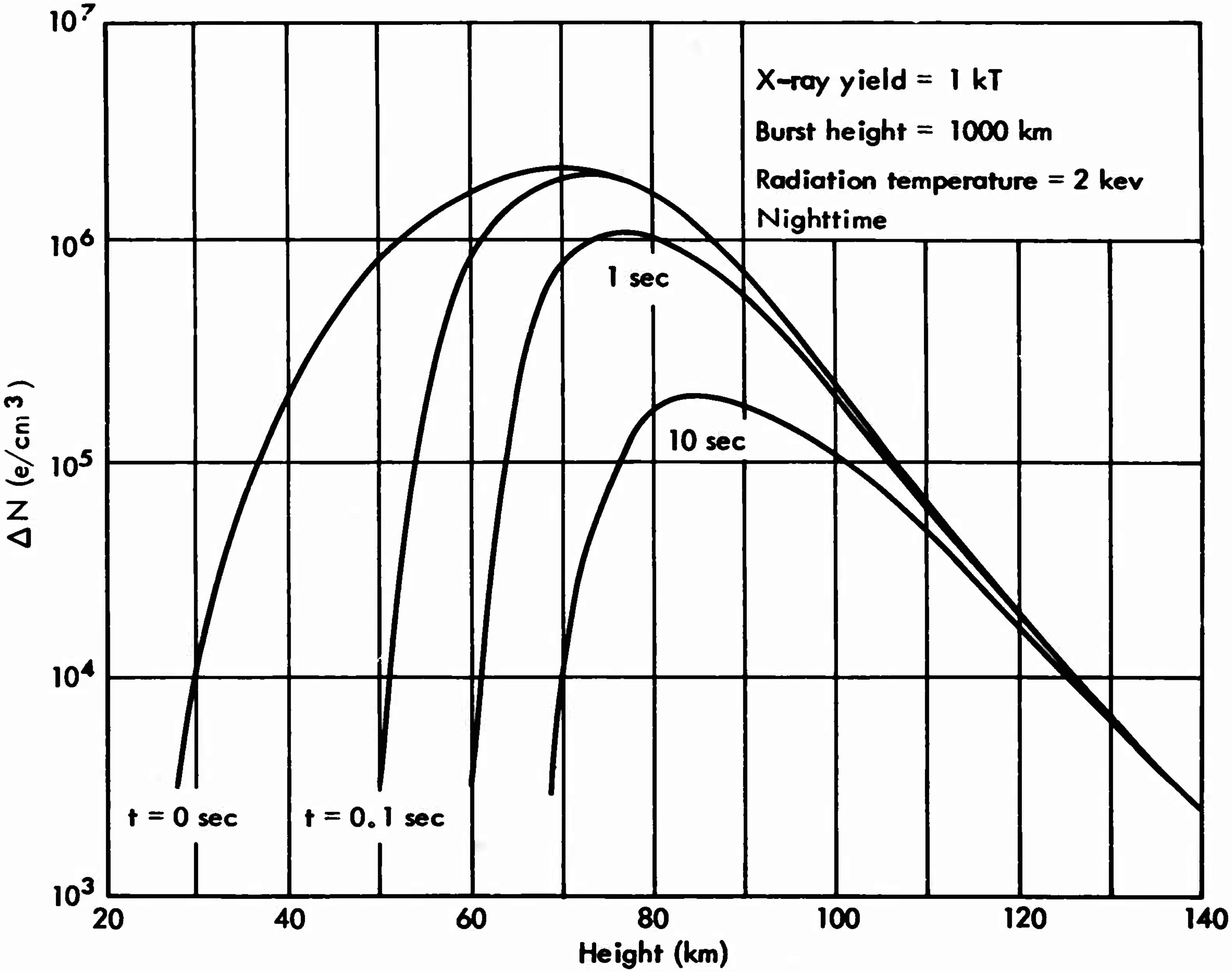

Fig. 2—Decay of ionization deposition versus altitude and time

IV. COSMIC NOISE ABSORPTION

The impulses of ionization produced by a high-altitude X-ray burst will cause increased absorption at a given altitude according to the absorption expression

$$A' = 4.6 \times 10^4 \left[\frac{1}{\mu_i}\left(\frac{(N_a + \Delta N)\nu}{\omega^2 + \nu^2}\right) - \frac{1}{\mu_a}\left(\frac{N_a \nu}{\omega^2 + \nu^2}\right)\right] \quad (1)$$

where

A' = added absorption in db per km

N_a = ambient electron density (elec/cm^3)

ν = collision frequency (coll/sec)

ω = angular operating frequency (rad/sec)

μ_a = real part of the ambient refractive index

μ_i = value of μ after the impulse

ΔN = X-ray deposited ionization

Figures 3 and 4 illustrate the absorption value A' as a function of height and time for a 1-kT, .5 kev X-ray impulse at 10^4 km for day and night respectively.

The one-way absorption, A, of galactic noise is then given simply by

$$A = \int_{30\text{ km}}^{140\text{ km}} A'\, dh \quad (2)$$

Values of A as a function of time, A(t), were calculated for a 1-kT X-ray impulse occurring at altitudes of 10^3, 3×10^3, 10^4, 3×10^4, and 10^5 km. They were calculated for temperatures of .5, 1.0, and 2.0 kev for both day and night, making a total of 30 cases studied. The values of A were examined primarily for an operating frequency, f = 30

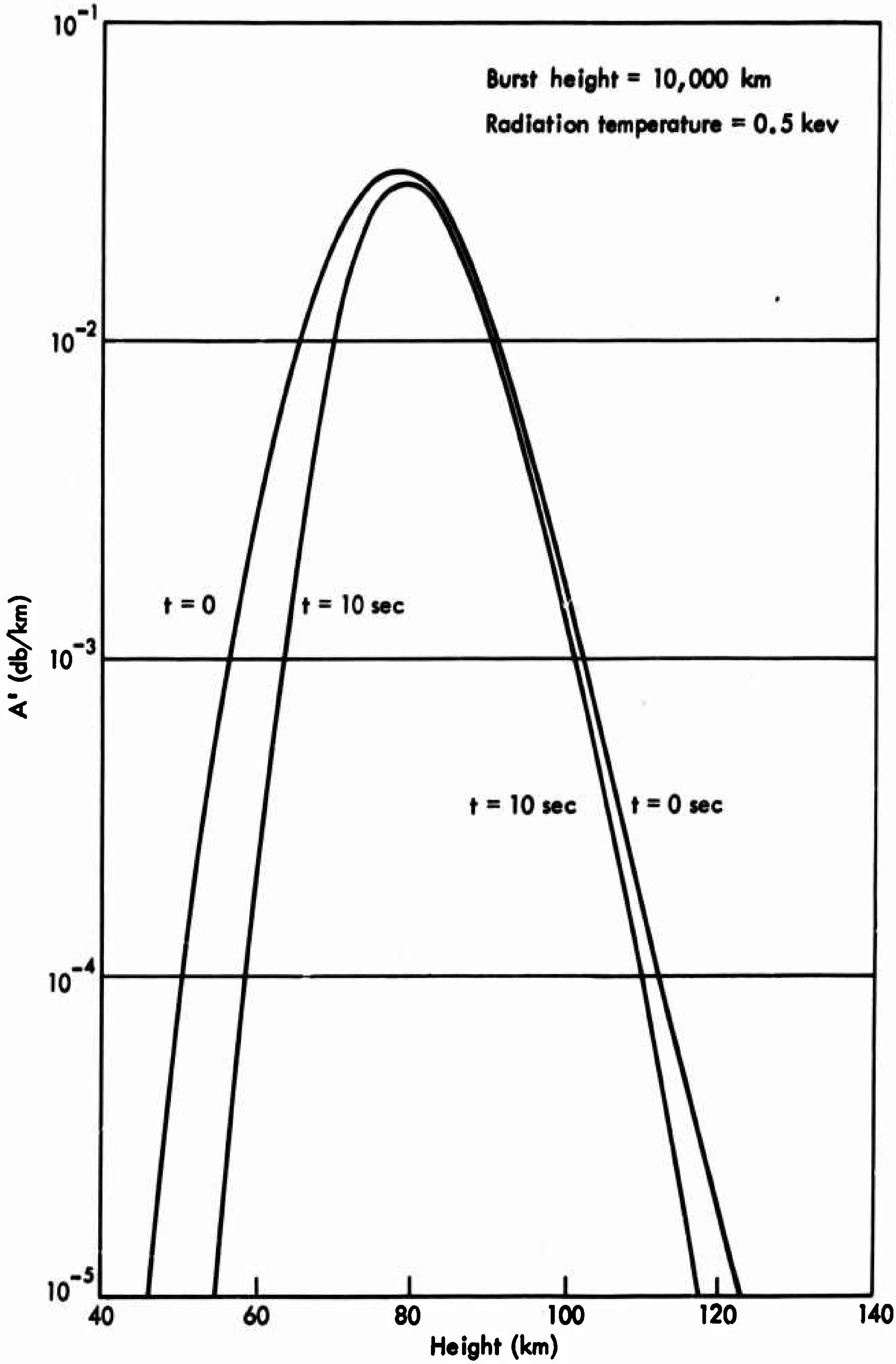

Fig. 3—Daytime absorption at 30 Mc versus height and time for a decaying ionization deposition

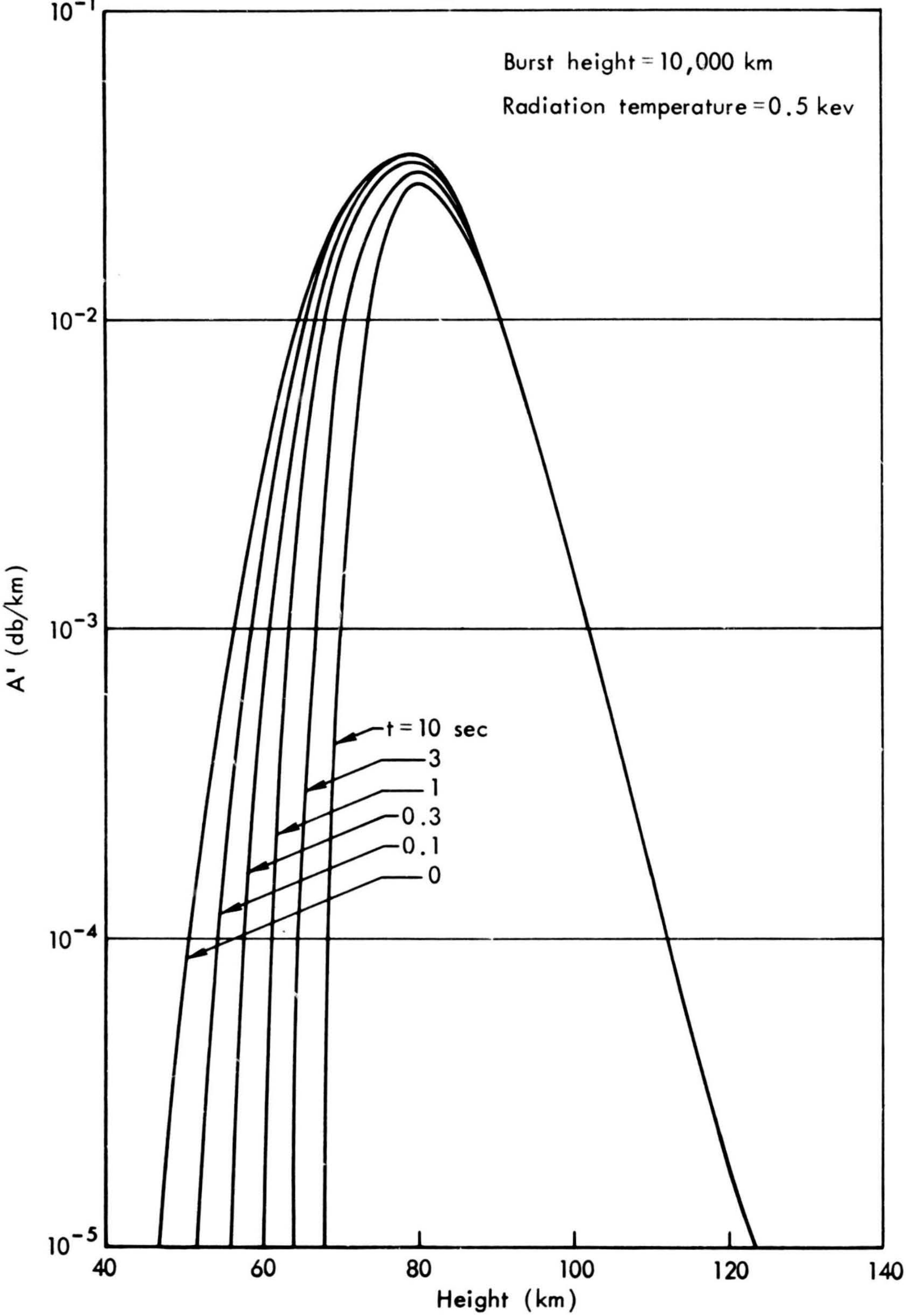

Fig. 4—Nighttime absorption at 30 Mc versus height and time for a decaying ionization deposition

Examples of the results obtained for A(t) are given in Fig. 5 for daytime conditions and in Fig. 6 for the nighttime. Figure 5 shows how the daytime one-way vertical absorption quickly decays to an almost constant value in the interval of interest due to the existence of photoattachment; while the nighttime decay, in the absence of photoattachment, has a more negative slope of dA/dt.

An interesting feature of Fig. 6 is that after approximately 2.2 sec, the value of A is higher for the 1.0 kev X-ray impulse temperature than for the 2.0 kev impulse. This is due to the fact that the higher temperature deposits more ionization at lower altitudes where the attachment rate is high. This does not occur during the day since the photodetachment causes slightly more presistance at the lower altitudes for times which are short compared to the recombination relaxation time.

The nonlinear recombination decay effect which occurs when initial depositions are quite intense has been demonstrated by Crain.[(4)] Figure 7 illustrates this effect. Note how the low-altitude impulse decays at a higher rate than the higher-altitude impulse due to the higher initial ionization, as shown in Table 1.

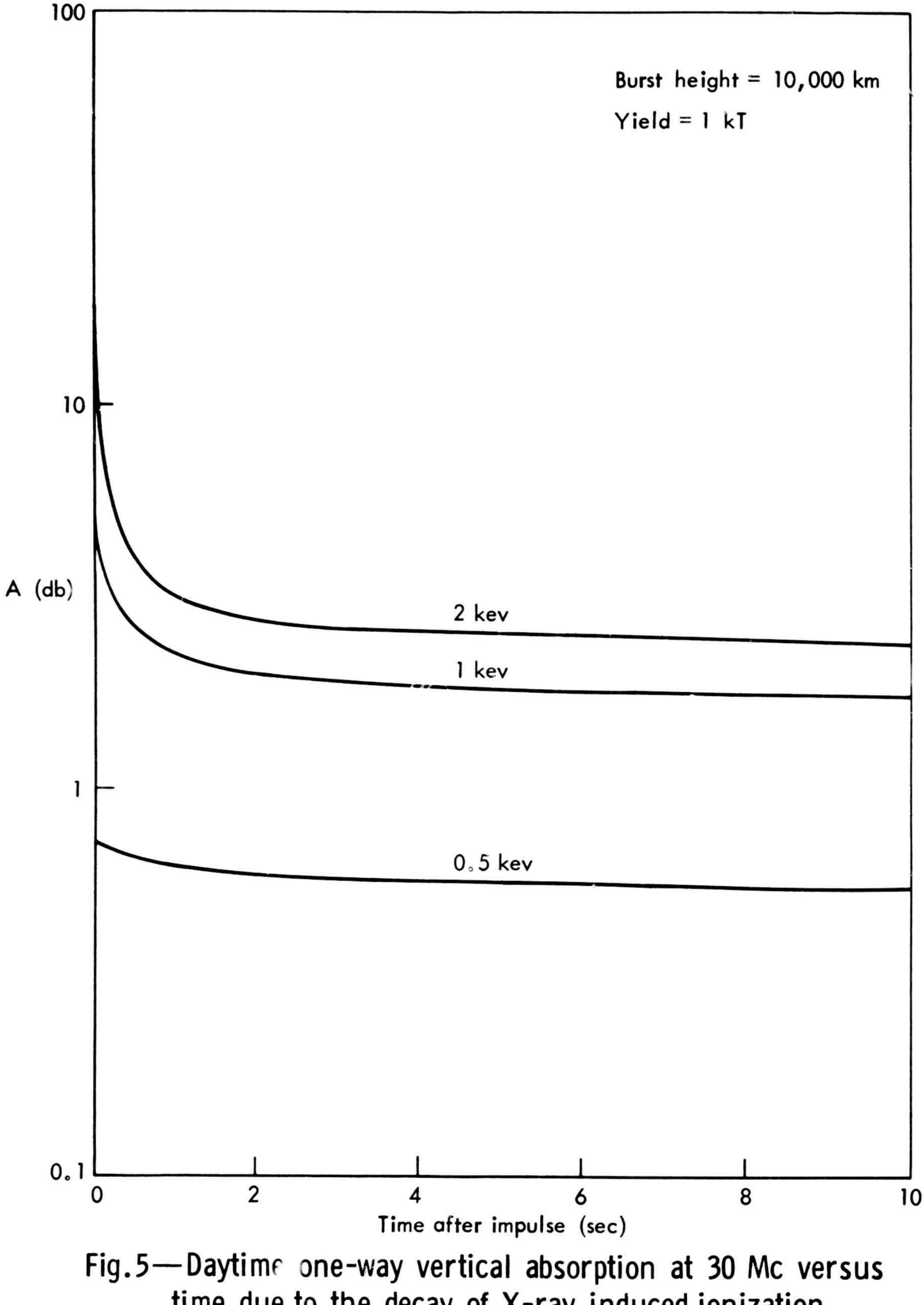

Fig. 5—Daytime one-way vertical absorption at 30 Mc versus time due to the decay of X-ray induced ionization

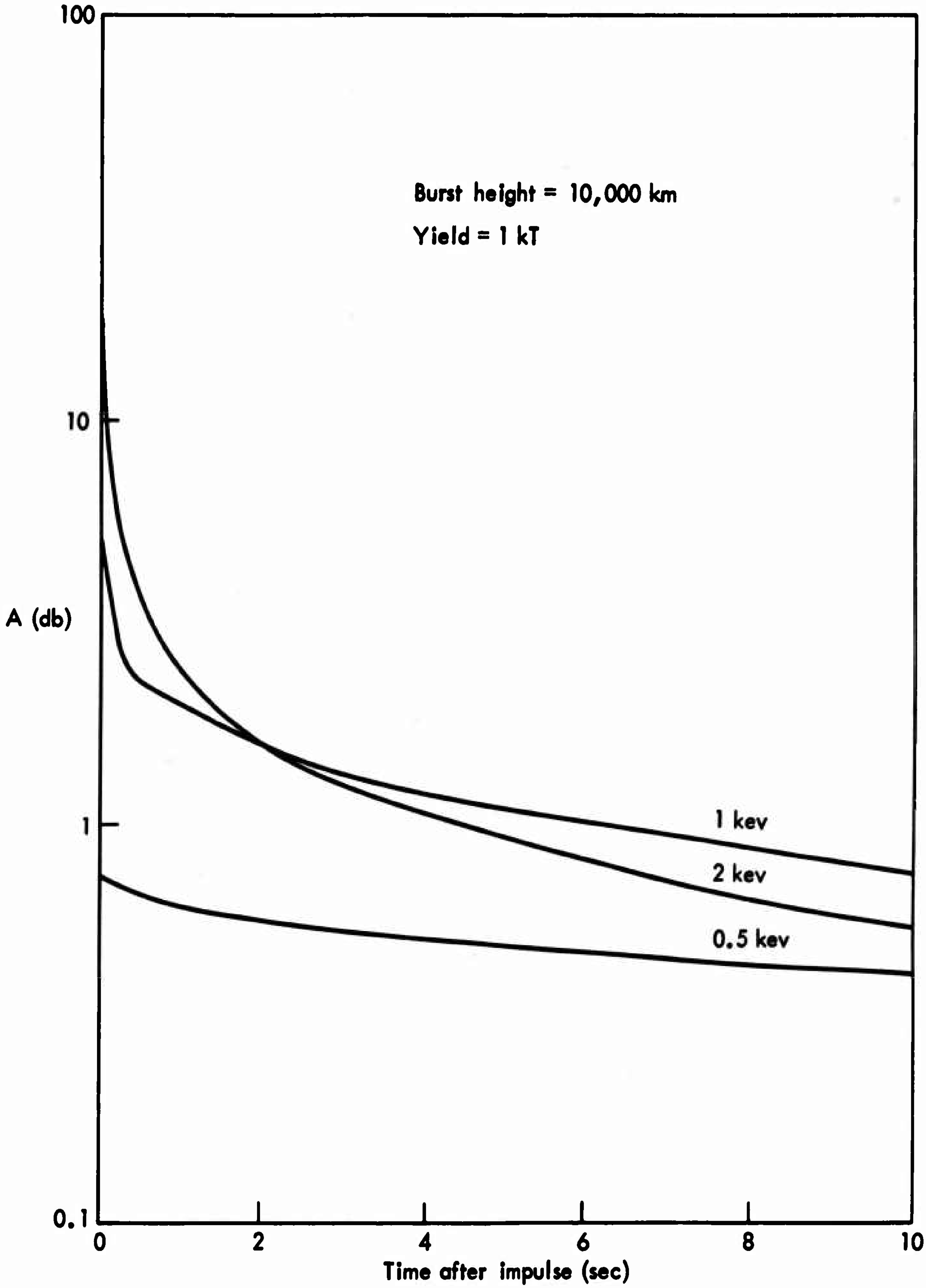

Fig.6—Nighttime one-way vertical absorption at 30 Mc versus time due to the decay of X-ray induced ionization

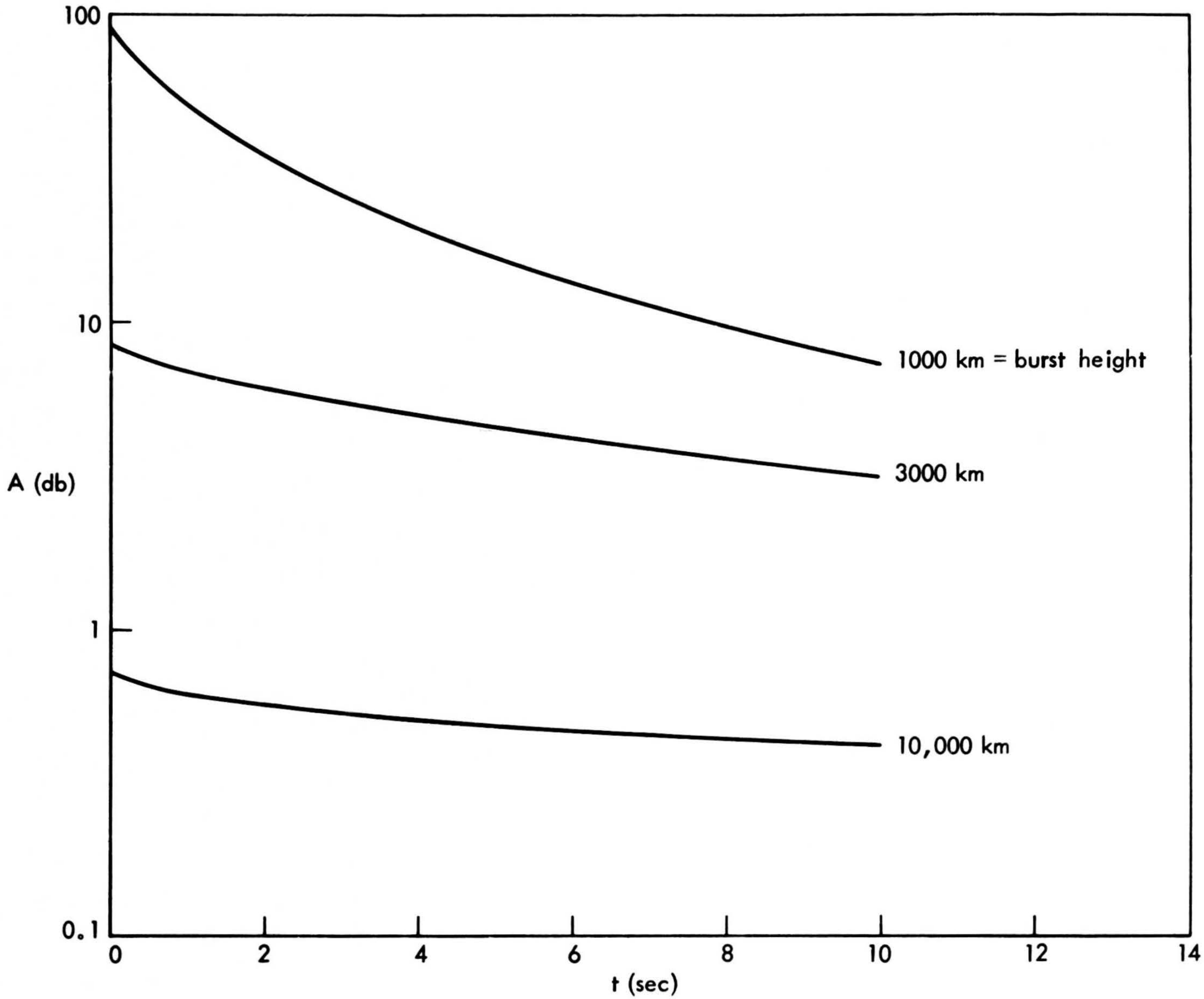

Fig. 7—One-way vertical absorption at 30 Mc versus time for a 1 kT, 0.5 kev nighttime X-ray impulse at several altitudes

V. RIOMETER RESPONSE TO ABSORPTION IMPULSES

A typical riometer operates by holding the equality[9]

$$T_A = T_R + 5800\ IR \tag{3}$$

where

T_A = riometer antenna temperature, ^oK

T_R = servo diode resistor temperature

I = servo diode current

R = value in ohms of the servo diode resistor

The value 5800 involves the electronic charge, e, and Boltzmann's constant, k.[10] Relative changes in antenna noise power, $\Delta P_A = k\ T_A B_W$ (where B_W is the bandwidth), cause proportional changes in the servo diode current so that

$$10 \log_{10} \left(\frac{\Delta P_A}{P_A}\right) \doteq 10 \log_{10} \left(\frac{\Delta I}{I}\right) \text{ ; steady state} \tag{4}$$

The above equality, however, does not hold instantanteously since riometers require integration over finite time in order to suppress the statistical fluctuations in P_A. The upper bound of the variance of the riometer response is[10]

$$\frac{\sigma_I}{\bar{I}} = \frac{1}{\sqrt{B_W T_c}} \tag{5}$$

where

σ_I = variance of the diode current

$\bar{I}$ = average diode current

B_W = predetection bandwidth

T_c = postdetection integration time constant

If a predetection bandwidth of 10,000 cycles per sec is used, it is found from the above relationship that the integration time constant must be 1 sec for the variance to remain at a 1 per cent level. This is why most integration time constants used in riometers range from .2 to 27 sec. The bandwidth cannot be greatly increased due to interference problems; therefore, the riometer must have integration time constants that are rather long compared to the time constants of the receiver AGC circuit.

The transfer function of a riometer must be of the nature

$$H(t) = \left(\frac{1}{T_c} e^{-t/T_c}\right) \tag{6}$$

where

$H(t)$ = transfer function

T_c = integration time constant (sec)

t = time (sec)

The response of the riometer is then

$$\Delta I(t) = K \frac{1}{T_c} \int_0^t \Delta P(\tau)\, e^{-(t - \tau)/T_c}\, d\tau \tag{7}$$

where

$\Delta I(t)$ = change in the servo diode current

K = a proportionality constant

$\Delta P(t)$ = change in noise power received

τ = a dummy variable in time

t = time measured from the instant the change in ΔP occurs

In the calculation of change in $\Delta I(t)$, the proportionality constant was unimportant since only relative changes of $\frac{\Delta I}{I}$ (in db) were of interest.

Figure 8 presents an example of the riometer response to X-ray impulse induced absorption phenomena for two different integration time constants. In Fig. 8, it is seen that the shorter the integration time constant, the higher the peak response of the riometer. However, as discussed previously, the time constant cannot be shortened without bound due to the statistical nature of the cosmic radio noise and the increased possibility of false alarms.

erest.

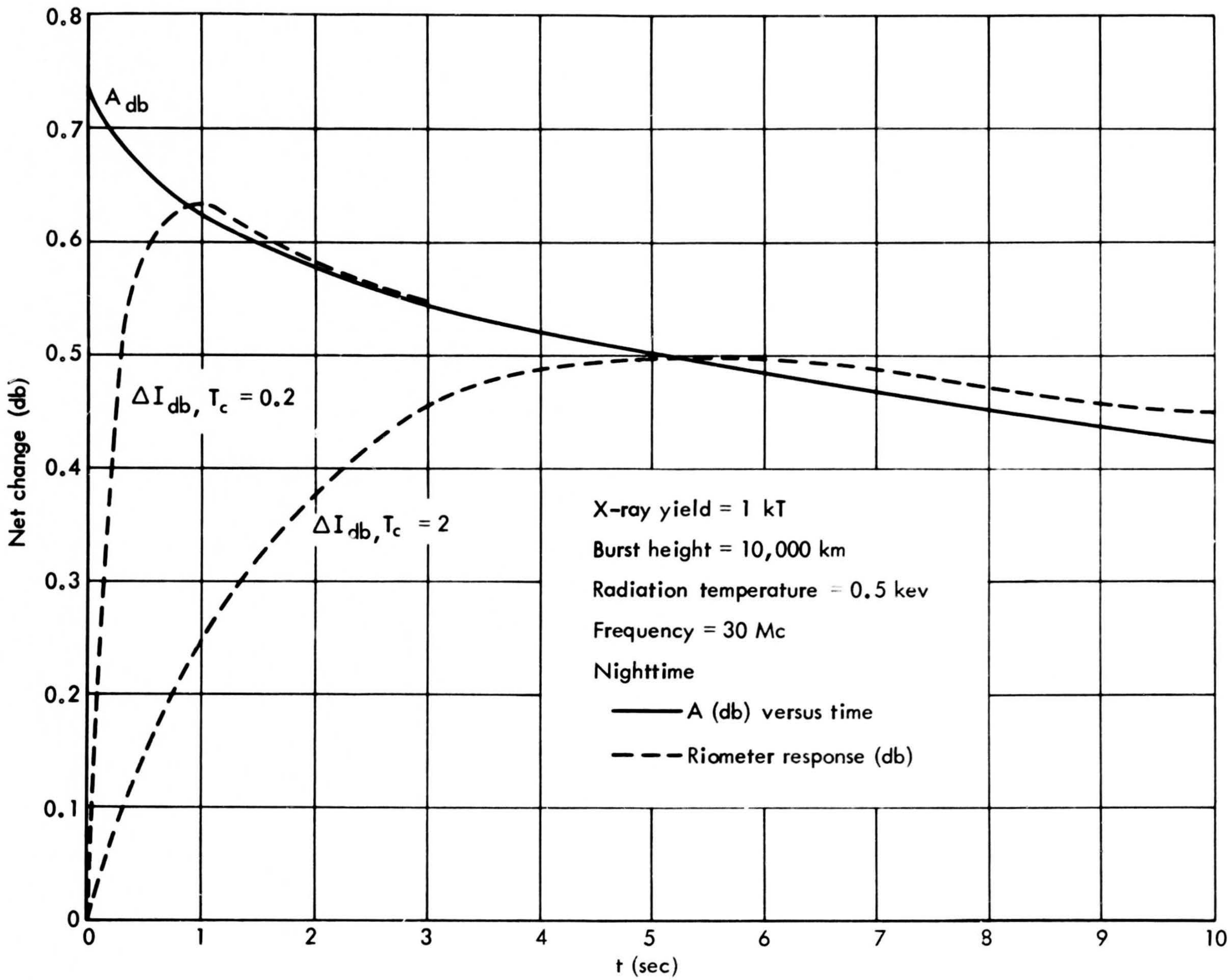

Fig. 8—Typical riometer response to an X-ray absorption event versus time for two integration time constants

VI. MAXIMUM DETECTION RANGE OF X-RAY IMPULSES

Latter and LeLevier[2] reported values of R (where R is the distance in km) at which a 1-kT yield of X-rays produces a one-way vertical absorption of 1 db at an operating frequency of 30 Mc. These values of R were reported for X-ray temperatures of 2, 1, .5, and .1 kev as well as for several angles of incidence of the X-ray energy to the vertical. These values of R were based strictly upon the initial or prompt absorption.

In utilizing riometers to measure the cosmic noise absorption, the initial absorption cannot be dealt with since the riometer will not respond instantaneously to the decreased power at its antenna terminals. Therefore, utilizing the previously discussed work of the absorption versus time and the convolved riometer response to this absorption, a new set of values for R is reported in Table 2 for vertical incidence only but as a function of several possible time constants. The results were obtained using peak value of plots similar to those shown in Fig. 8 for both daytime and nighttime conditions.

Table 2

VALUES OF R AT 30 Mc FOR WHICH A 1-kT YIELD
CAUSES A 1-db PEAK RIOMETER RESPONSE

	Nighttime				Daytime				Prompt	
(kev)	T_c=.2sec R(km)	T_c=.5sec R(km)	T_c=1sec R(km)	T_c=2sec R(km)	T_c=.2sec R(km)	T_c=.5sec R(km)	T_c=1sec R(km)	T_c=2sec R(km)	T_c=0 R(km)	T_c=0(a) R(km)
2.0	2.2×10^4	1.7×10^4	1.5×10^4	1.2×10^4	2.2×10^4	1.9×10^4	1.7×10^4	1.6×10^4	4.6×10^4	5.9×10^4
1.0	1.5×10^4	1.4×10^4	1.2×10^4	1.1×10^4	1.6×10^4	1.5×10^4	1.4×10^4	1.3×10^4	2.2×10^4	2.1×10^4
.5	8.0×10^3	7.5×10^3	7.3×10^3	6.4×10^3	8×10^3	7.8×10^3	7.6×10^3	7.5×10^3	8.6×10^3	7.3×10^3

(a) Values taken from Ref. 2.

It is seen from Table 2 that the maximum distance at which a 1-kT X-ray impulse can be detected in this temperature range using cosmic noise absorption is slightly over 3 earth radii. The daytime and nighttime detection ranges are comparable, although the range is always slightly less at night.

The small differences in Table 2 between the $T_c = 0$ values deduced in this paper and those given in Ref. 2 arise from the use of somewhat different collision frequency profiles and methods of integration.

VII. PRACTICAL CONSIDERATIONS IN THE UTILIZATION OF RIOMETERS

Many practical considerations exist in the utilization of riometers as part of a system for detecting nuclear explosions in addition to their limited detection capability. Some of these are: limited visibility, since most absorption occurs in the D region at 30 Mc; other sources of noise, such as man-made and lightning pulses; and natural absorption events due to solar flares which may cause false alarms. Extensive studies by Dyce *et al.*(11) have been carried out to examine these practical considerations.

Utilization of the proper antenna pattern with low side lobes is quite important in order to average over a large part of the sky and yet discriminate against man-made interference arriving at low elevation angles. The pattern of the antenna can actually change the values of R obtained in Fig. 8 since oblique angles are utilized in averaging over the antenna pattern. This nonlinear correction has been studied by Weir(12) and Bedrosian* and would increase R by a factor of the order of $\sqrt{1.5}$ for a $\cos^2 \theta$ (θ = aspect angle) antenna pattern.

*Private communication from E. Bedrosian, The RAND Corporation.

VIII. CONCLUDING REMARKS

The riometer is a relatively inexpensive device that can be distributed over the entire earth(13) for the measurement of natural ionospheric absorption. These instruments can then also be used to detect nuclear bursts in space as well as to provide one input to the picture of world-wide ionospheric conditions.

As a device for detecting deep space X-ray impulses, however, the riometer is rather insensitive when compared to other techniques such as phase-path sounders or HF-forward propagation, as illustrated by Crain and Booker.(3)

While only the detection of X-ray impulses in space is considered in this Memorandum, the riometer has further utility in detecting ionization from other sources associated with nuclear explosions, such as discussed by Latter and LeLevier.(2)

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10. ABSTRACT

A consideration of the detection of overhead nuclear explosions in space by riometer measurement of the effects of explosion-induced ionization on the absorption of high-frequency cosmic noise. The induced ionization is calculated as a function of height and time for a 1-kt X-ray impulse having temperatures of .5, 1.0, and 2.0 kev and having burst heights from 10^3 to 10^5 km. The absorption at each height due to the induced ionization is then calculated at a radio frequency of 30 Mc. In order to determine the change in the effective antenna temperature as a function of time at the riometer, the total absorption through the ionosphere is then determined. The response of a riometer with several time constants is found for this sharp change in received cosmic noise power. Detection ranges are calculated for each X-ray temperature and several possible riometer time constants, based on the criterion that the nuclear burst must produce a 1-db peak response in the diode current of the riometer. These detection ranges are tabulated and compared with those that were found neglecting riometer response time.

11. KEY WORDS

Riometers
Nuclear bursts
Detection
Ionosphere
X rays