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Contents

JANUARY 1970

NATIONAL SPELEOLOGICAL SOCIETY

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The Society serves as a central agency for the collection, preservation, and dissemination of information relating to speleology. It also seeks the preservation of the unique faunas, geological and mineralogical features, and natural beauty of caverns through an active conservation program.

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Measuring Cave Air Movements with Condensation Nuclei

By F. W. Went *

ABSTRACT

Using condensation nuclei (*cn*), conveniently measured with a *cn* counter, outside air penetration and internal air movements in Lehman Cave were monitored. Whenever outside air temperatures are well below the cave temperature, outside air enters cave openings, but in summer, the *cn* concentration inside the cave drops to nearly zero, unless matches or flames are lighted. The *cn* produced by a single match could be detected for as long as 12 hours in the cave, and at times without outside air penetration, a slow air circulation of about 40 m/hr occurred from the highest part of the cave to the lower regions.

Introduction

Recently, staff members of the Desert Research Institute of the University of Nevada System have made a study of Lehman Cave. This cave is 50 miles east of Ely in eastern Nevada, in the Wheeler Peak area, and it has been made accessible to the public through the National Park Service as Lehman Caves National Monument.

The cave is a typical limestone cave with stalactites, stalagmites, and many other cave structures. Figure 1 shows a plot of the cave, which has an approximate total volume of 40,000 m^3, making it one of the smaller cave systems in the U. S. It is at a high altitude (2,200 m) in a desert area; therefore the stream erosion producing the cave must have occurred long ago.

Under a special contract with the National Park Service, a study was made of the air movements in Lehman Caves. The following is a partial report of this study; special thanks are due to Park Superintendent Lee Robinson and Chief Ranger Naturalist Roy Graybill for the invitation and permission to work in Lehman Caves. Other studies have been reported earlier (Stark, 1969; Went, 1969); there are no other studies published on Lehman Caves.

The many studies of air movements in caves already made have been summarized by Cullingford (1962). A detailed study on air circulation in a specific cave has been presented by Little (1952). To the author's knowledge, condensation nuclei have never been used before in the analysis of air movement in caves.

Methods

In addition to the standard methods of wind measurement, air movements can be followed by labeling air. The latter method has the advantage that air masses can be followed and detected long after local movements have subsided and rates of movement of 1 m/min or less can be measured.

Many materials have been used for labeling air: dyes, odors, pollen, radioactive material, smoke, etc. For cave studies, particle size of the tracers is of importance, because larger particles are not kept buoyant except by major air turbulence while molecularly

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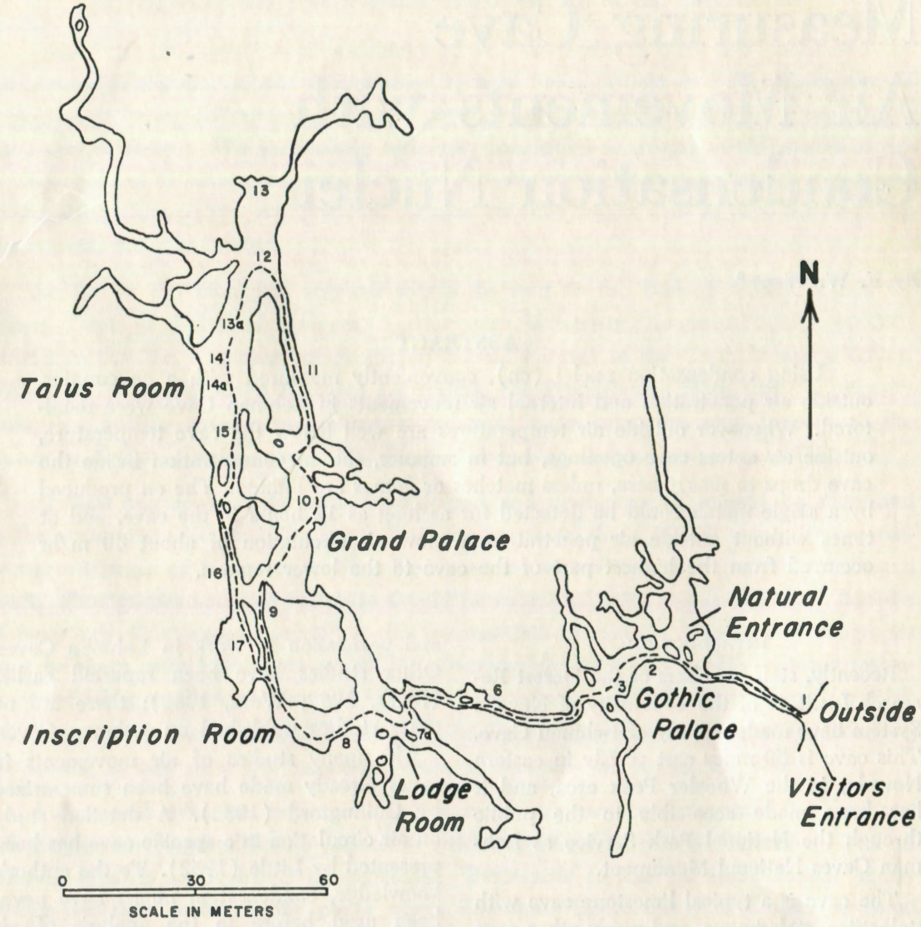

Figure 1. Map of Lehman Cave, showing numbered measurement stations.

dispersed material does not disappear in stagnant air in darkness.

Aitken condensation nuclei (*cn*), measured with condensation nucleus counters, have turned out to be ideally suited to study air movements in and air penetration into caves. These *cn* are particles of submicron size which occur normally in all air and on which water droplets can condense from air supersaturated with water vapor. Their concentration normally fluctuates from 10^2 to 10^6 *cn*/cc of air. They have been used by meteorologists to study air movements and air provenance (Went, 1966). The Gardner Associates CN Counter (Fig. 2) was used to measure *cn*. It gives reliable measurements, each determination takes about one minute, and a set of 3 successive determinations gives highly reproducible values for the *cn* content of more or less stagnant air masses. A difference of more than 10% in successive measurements indicates that an air mass with less or more *cn* is moving in.

The major sources of *cn* are: (1) combustion processes, such as flames, smoke, fires, or internal combustion engines; (2) photochemical decomposition of organic

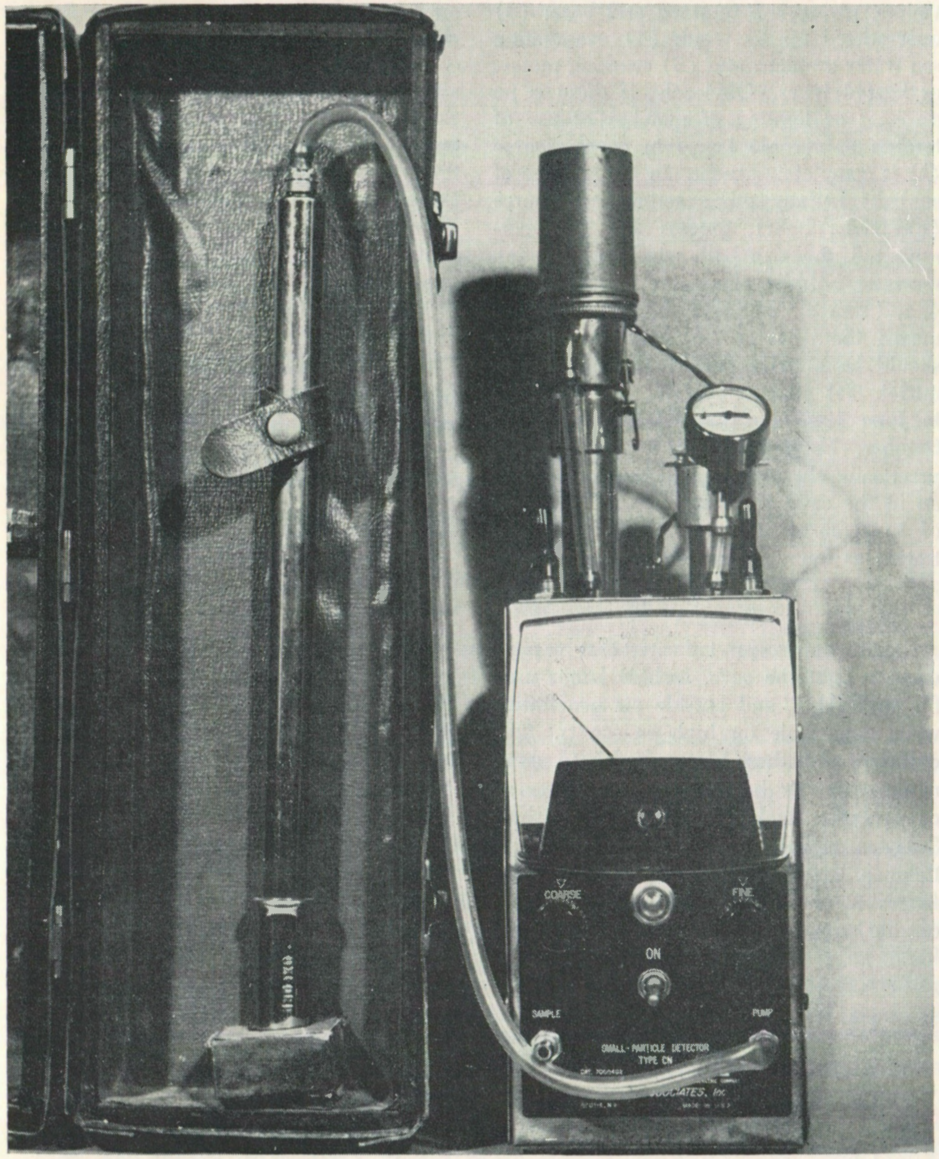

Figure 2. Condensation nucleus meter used in *cn* studies. At left, carrying case with bicycle pump for sucking air into sample tube of counter (left side of instrument). Vacuum produced in right-hand tube (shown with pressure gauge) produces adiabatic cooling of humidified air in sample tube, causing water droplet condensation on *cn*. This is measured by reduction in light transmission through sample tube. Instrument available from Gardner Associates, Scotia, N. Y.

vapors, giving rise to smog and haze; (3) dust stirred up by wind; (4) evaporating sea water droplets; and (5) sparking motors or heated wires. Obviously, if there is no smoking or lighting of matches or use of torches or carbide lamps in caves, source #1 is completely absent. In the absence of sunlight or any other actinic ray source (ultraviolet light), process #2 is inoperative too. Lack of both wind and bursting seawater bubbles eliminates sources 3 and 4, and source 5 can easily be excluded. This means that, having no sources, cave air should be entirely devoid of condensation nuclei. Yet measurements in Lehman Cave in June 1967 and June, July, September, October, November, and December 1968 practically always indicated the presence of *cn* in the cave air, sometimes of the order of 1,000 *cn*/cc or more, the same concentration as found in outside air.

RESULTS

Measurements soon indicated that matches used to light the cave, carbide lamps used for spelunking, and outside air penetration were responsible for high *cn* counts. Several days after these sources had been eliminated, cave air became essentially free of condensation nuclei. Figures 3 and 4 show 3-day sequences of *cn* measurements in Lehman Cave when no matches or other flames were being lighted and when high outside temperatures had prevented outside air penetration into the cave. These figures show the *cn* concentration in a cross-section of Lehman Cave. The numbers on the abscissa refer to the individual stations in the cave, as in Fig. 1. Station 1 is just outside the entrance, stations 2-7 are from the visitors entrance through the Gothic Palace and the Queens Room to the Lodge Room, and stations 8-17 are from the Inscription Room to the Talus Room and back again along the loop trail, station 12 being furthest north in a high part of the Talus Room.

Figure 3 shows that, on the afternoon of July 1, 1968, the *cn* concentration outside the caves was high (2,100 *cn*/cc), but it decreased to 200 to 400 *cn*/cc inside, except for the south part of the Talus Room (station 15), where matches had been lit during the day. Next morning, the *cn* concentration had dropped everywhere, and on the following day (curves 3 and 4) concentrations had dropped to near zero. Similarly, on September 24 (Fig. 4), the *cn* concentration inside the cave varied between 300 and 600 *cn*/cc in the morning, decreasing to about 200 *cn*/cc toward evening. The next day, concentrations decreased further—to well below 100 in the evening, and to below 50 *cn*/cc the following day. On Sept. 27, in the morning, no measurable numbers of *cn* were left at most locations in the cave.

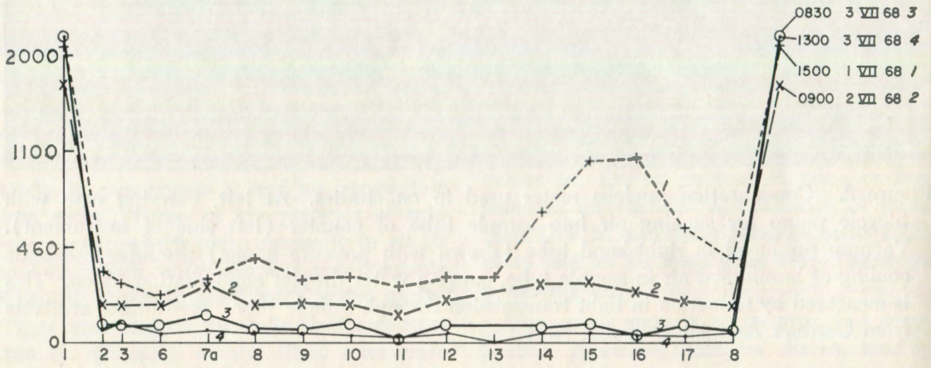

Figure 3. Number of *cn*/cc at the different cave stations, on July 1, 2, and 3, 1968.

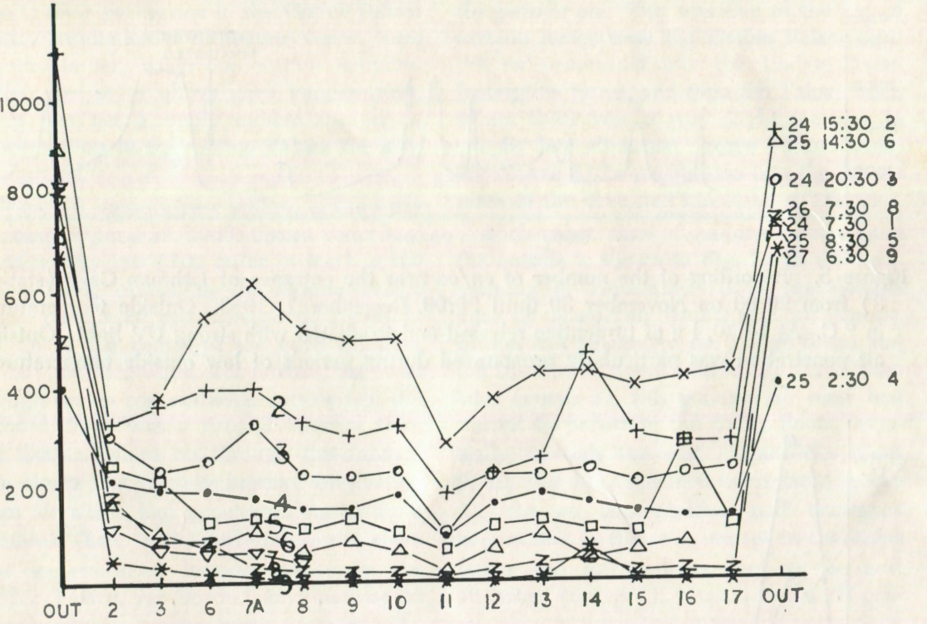

Figure 4. Number of *cn*/cc at the different cave stations, from September 24 through September 27, 1968.

In these cases the outside temperatures were higher than temperatures in the cave, and no outside air with high concentrations of *cn* penetrated. The natural rate of disappearance of these condensation nuclei can be calculated. This turns out to be a 4 to 5% decrease every hour or a three-fold decrease per day. It is about the same in the Talus Room (stations 12, 13, 14, and 15) as in the corridors. This may be due to a slow rate of mixing of the cave air.

In certain parts of the cave, there were higher concentrations of *cn* than in other parts. In Fig. 3, for instance, the south end of the Talus Room (stations 14 and 15) and adjoining corridor (stations 16 and 17) had twice as many *cn* on July 1 than any other part of the cave. This was due to four matches which had been lighted between stations 14 and 15 during the day. The occasional rises in *cn* (*e. g.* at stations 7a, 14, and 16 in Fig. 4) are tentatively attributed to local penetration of outside air.

These data have established that cave air is free of Aitken condensation nuclei, and without pollution from flames or outside air, the *cn* count in the cave is reduced to zero. This also means that the occasionally heard statements that reduction of the number of *cn* in air may lead to sudden bursts of *cn* or that after *cn* have been filtered out of air, new ones can be formed by a dark process (Bricard *et al.*, 1968), have to be explained in a different way. Only high energy processes—such as bursting bubbles, high temperatures, high winds, or high light intensities—can lead to *cn* production. The work of Bricard *et al.* has to be interpreted by assuming that when all measurable *cn* have been filtered out of day-air, a big population of sub-measurable nuclei are left which then grow to measurable size during the subsequent quarter hour.

Whenever there is an increase in the number of *cn* inside the cave, either nuclei are released inside or outside air is penetrating. The latter case is clearly exemplified by Figure 5, which represents a continuous record of *cn* present in the Gothic Palace at station 3. This record was taken

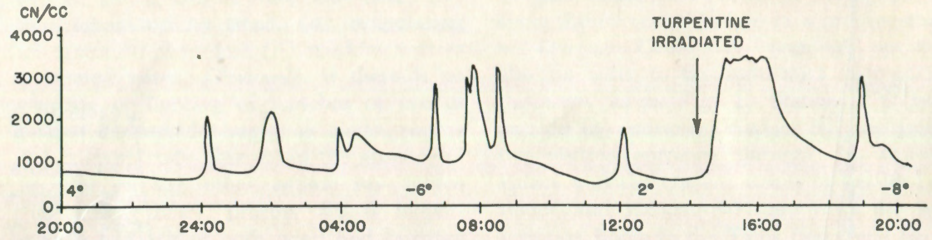

Figure 5. Recording of the number of *cn*/cc near the entrance of Lehman Cave (station 3) from 20:00 on November 30 until 20:00 December 1, 1968. Outside temperatures in ° C. At 14:10, 1 g of turpentine released and irradiated with strong UV light. Outside air penetration was particularly pronounced during periods of low outside temperatures.

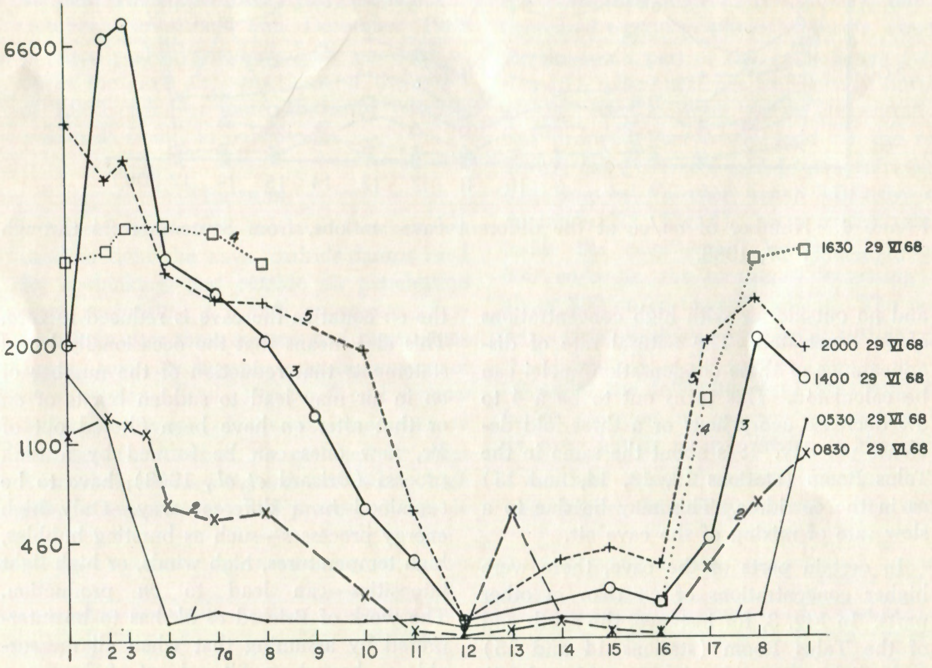

Figure 6. Number of *cn*/cc at the different cave stations, on June 29, 1968, from 05:30 till 20:00.

in late autumn, with outside temperatures mostly below freezing. Whereas the number of *cn* in the outside air was usually low (under 1,000 *cn*/cc in the morning), occasional high values were encountered, generally in the absence of wind, probably due to contamination from car exhaust near the cave entrance and from the oil furnaces of the administration building. These periods of high *cn* in the outside air are reflected in sudden rises in *cn* in the Gothic Palace. Most of the penetration of nuclei-rich air occurred while the outside temperatures were lowest, whereas a general decrease in *cn* occurs during the warmer periods. At 14:00 on December 1, the rise of *cn* was due to their generation in the Gothic Palace by UV irradiation of turpentine vapor. Two months earlier, when the outside temperatures were at or above cave temperatures, there was not a single sudden rise in *cn* concentration in the Gothic Palace for a 3-day period.

Figure 6 shows a case where, in the early morning of June 29, 1968, the *cn* count had become very low (100 *cn*/cc or less) in the whole cave, except in the Gothic Palace where outside air had penetrated. By 08:30 the *cn* in the center of the cave (stations 11-16) had decreased still further, but even though the *cn* concentration outside had decreased, there was a general increase from the Gothic Palace on through the Inscription Room and slightly beyond, originating from air which had penetrated earlier from outside. Then, in the early afternoon, there was an enormous increase in *cn* in the Gothic Palace, far beyond any increase in the outside air. This was due to the use of carbide lamps near the Gothic Palace, and the *cn* penetrated into the Lodge Room, Inscription Room, and even the Talus Room, where there was a very slight increase in *cn*. By late afternoon (curve 4) and evening (curve 5)the penetration into the deeper parts of the cave had increased still further.

A clear-cut case of *cn* penetration from the outside is shown in Fig. 7. In the early morning of November 28, a considerable mass of outside air with a high *cn* concentration had penetrated the Lodge Room and the Inscription Room (curve 1). Eight hours later (curve 2), this polluted air mass had started to penetrate the Talus Room, especially through the east entrance (stations 9, 10, and 11). Again 6 hours later (curve 3), the *cn* concentration had decreased everywhere in the cave, except in the Talus Room and surroundings, and in the next 10 hours (curve 4), the maximum *cn* con-

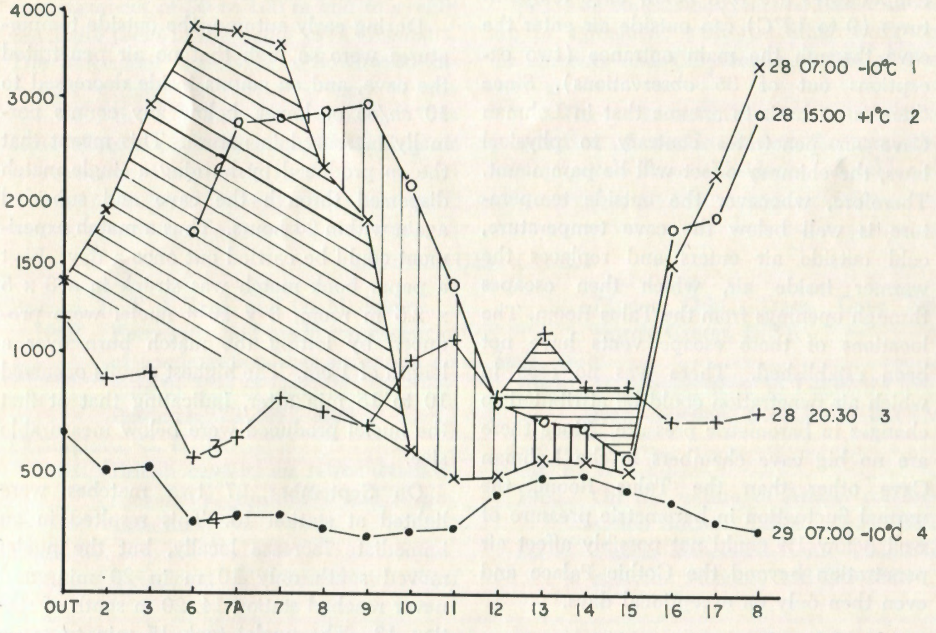

Figure 7. Effect of outside air penetration on *cn*/cc in Lehman Cave. Sloped hatching: airmass penetrated before 07:00 on November 28 from the visitors entrance and Lodge Room; vertical hatching: further penetration of this airmass toward Talus Room by 15:00; horizontal hatching: final penetration into Talus Room by 20:30.

centration had moved further south into the Talus Room. The hatching in Fig. 7 shows how an air mass, containing easily measured *cn*, moved gradually from south to north in the cave.

When all data on outside air penetration into the cave is pooled, the following picture emerges. When maximum temperatures exceeded 5°C (41°F), in only 1 out of 11 days was air penetration observed between noon and evening. On all 4 days with maximum temperatures below 5°C, outside air entered the cave all day and night.

On many days during the observation period, the early morning temperatures were below freezing, and thus on 7 of 8 days outside air entered the cave. On the 2 days that minimum temperatures were between 0 and 5°C, a small amount of air penetrated; whereas during the 7 days that minimum temperatures ranged above 5°C, only once did outside air enter the cave. The picture is therefore very clear. Only when outside temperatures are well below cave temperatures (9 to 12°C) can outside air enter the cave through the main entrance (two exceptions out of 35 observations). Since there is no basis to assume that in Lehman Cave air penetrates contrary to physical laws, the chimney effect will be paramount. Therefore, whenever the outside temperature is well below the cave temperature, cold outside air enters and replaces the warmer inside air, which then escapes through openings from the Talus Room. The locations of these escape vents have not been established. There was no case in which air penetration could be attributed to changes in barometric pressure. Since there are no big cave chambers in the Lehman Cave other than the Talus Room, the normal fluctuation in barometric pressure of well below 1% could not possibly affect air penetration beyond the Gothic Palace and even then only on exceptional days.

Artificial Production of *cn*

Air movements within the cave were measured by artificial production of condensation nuclei. One such case has already been discussed in connection with *cn* produced by carbide lamps.

Several methods were used to produce condensation nuclei in Lehman Cave. First, a high pressure mercury arc lamp was lighted in the Gothic Palace on November 30. Apparently there was not enough organic matter in the air to produce *cn* with the ultraviolet light of the mercury arc, since there was no measurable increase in *cn*. One day later the mercury arc again was lighted (at 14:20), but this time 1 gram of turpentine was volatilized in the Gothic Palace (from 14:10-14:30), which resulted in a six-fold increase in *cn* (Fig. 5). These nuclei penetrated further into the cave and 100 min later could be found in the Inscription Room and slightly beyond (stations 9 and 17). Six hours later the *cn* count in the Talus Room had increased 50% (except at stations 13 and 14, the highest locations), whereas the natural decay of *cn* should have resulted in a 40% decrease.

During early autumn, the outside temperatures were so high that no air penetrated the cave, and *cn* counts inside decreased to 10 *cn*/cc or lower, below any counts normally measured in nature. This meant that the *cn* produced by burning a single match dispersed through the cave and subsided again within 24 hours. Thus a match experiment could be carried out once a day. First a paper book match was struck in a 3 x 5 x 2.5 m room; 3 x 10^{12} nuclei were produced by letting the match burn over a length of 1 cm. The highest counts occurred 10 to 15 min after, indicating that at first the nuclei produced were below measurable size.

On September 27 two matches were lighted at station 13. This resulted in an immediate increase locally, but the nuclei moved south only 10 m in 20 min, and never reached station 14, 20 m south of station 13. The nuclei took 15 min to move 10 m northward and reached station 12 (30 m north of station 13) in the center of the Talus Room 41 min after the match was struck. Within 1 hour they had spread all through the end of the Talus Room and 2 to 3 hours later could be measured at station 11; after another 3 hours, the *cn* were found in very low concentrations at stations 9 and 10 as well. Twelve hours after lighting the match, *cn* could not be detected anywhere in the cave. Interestingly, these two matches produced slightly more nuclei in the whole cave (3.1 x 10^{12} *cn*) than the single match in a small room (3.0 x 10^{12} *cn*).

On September 26 a match was lighted at station 16. The nuclei never reached station 15, which is 30 m north at a higher elevation, but they moved readily to station 17, 15 m south of 16 and were found at still lower elevations at stations 8, 9, and 10 three hours after lighting the match. In July a match was lighted at station 17, with similar results. Therefore, during periods when there is no outside air penetrating into the cave, there is a sufficiently effective air circulation within the cave to transport *cn* over distances of 50 to 100 m and to evenly distribute them in the major cave chambers. The movement is only in a downward direction within the corridors, and in the chambers there is an even spreading. This latter effect is probably caused by rising air currents near the electric lights.

Summary

(1) Under natural conditions no condensation nuclei are formed in the cave.

(2) Outside air, with concentrations ranging from 200 to 5,000 *cn*/cc, penetrates into the cave whenever the outside temperature is 5°C or lower.

(3) Use of carbide lanterns, cigarettes, and matches cause a significant increase in *cn*, which can be used to label air and follow its movement through the cave.

(4) Outside air can penetrate all the way into the center of the cave (the Talus Room), indicating that there are air exits from the center of the cave.

(5) During periods without mass air penetration into the cave, there is a slow mass air circulation inside the cave, at the rate of 40 m/hr. This mass air flow is downward from the highest area in the cave (station 15).

(6) Within each chamber there is a thorough mixing of the air, probably due to thermal currents set up by the electric lights.

(7) The conclusions reached based on *cn* are in agreement with the other work on air currents and CO_2 concentration of the cave air.

(8) Except in summer, there is an active penetration of outside air into the cave, resulting purely from subsidence of cold air.

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Optimum Frequencies For Underground Radio Communication

By Nevin W. Davis *

ABSTRACT

The radiating properties of loop and wire antennas through conducting rock are analyzed. Along with measured curves of atmospheric noise vs. frequency, this enables calculation of the signal-to-noise ratio (a measurement of received signal quality) for frequencies between 1 kHz and 10 MHz. For induction surveying equipment, the optimum frequency is about 3.5 kHz. This gives an 8-db improvement in the received signal-to-noise ratio and about a 30% increase in range over the much-used 2 kHz.

For voice communication, the optimum frequencies lie near the 160-meter amateur band. The signal path attenuation is demonstrated to be not as severe as some people surmised. At a distance of 500 m from a buried 1-watt, 1-MHz transmitter (buried 100 m), using a 25-m wire for an antenna, the calculated signal-to-noise ratio at the receiver would be 70:1 during the day.

Introduction

In the past few years interest has been shown in small portable communications and surveying equipment for caving use. The devices which have been built to date use magnetic induction at 2,000 Hz. In general, the papers by Charlton (1966), Mixon and Blenz (1964), Plummer (1964a), and Roeschlein (1960) cover the subject in detail as far as the range of the actual units and use of the units for surveying are concerned. Some work has been done by Plummer (1964b) on making the antenna more portable by using an iron core solenoid. Other work has involved simplifying the electronic circuitry by using more available components. However, nothing has been published about optimizing the transmitted frequency to improve the received signal-to-noise ratio or analyzing the effects of using higher frequency electromagnetic radiation in cave-to-surface or cave-to-cave communication.

Published work on underground electromagnetic propagation deals mainly with low frequency, very long range communication. Recent work has been spurred by the need for development of "hardened" underground communication sites. The problem in caves is not long range communication (1,000 miles or more) but communication over ranges of feet or thousands of feet; however, the analysis of some of the problems in long range communication is applicable to this situation. In any investigation of this problem, the requirement that the equipment must be portable in a cave environment should be kept in mind. The equipment should fit in a small box with the antenna being either small or collapsible.

Noise

Noise is of primary importance in any communications system. The amplitude of

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the received signal must be greater than or nearly equal to the received noise. Of importance is the ratio: $\frac{H_s}{H_n}$ or $\frac{E_s}{E_n}$ where E_S = electric field intensity at the receiver due to the signal, E_n = the electric field intensity at the receiver due to the noise, and H_S and H_n are the same for magnetic field intensities. Above 30 MHz, antenna and receiver front end noise are usually greater than atmospheric noise; however, below 30 MHz, the region of interest, atmospheric noise greatly exceeds receiver noise. In this region, the receiving antenna makes very little difference as long as sufficient atmospheric noise is received to overcome the receiver input noise. For instance, a portable broadcast band receiver (500 kHz to 1600 kHz) needs only a small ferrite loop stick antenna for good reception. (In this case the efficiency of a loop stick antenna is so poor that the received noise is very nearly equal to the receiver noise.) Thus, either the E or H field ratios can be used at the receiving site as indicators of the quality of the transmitting system.

Atmospheric noise is primarily due to electromagnetic radiation from lightning discharges. The majority of noise originates from several large storm centers located over land masses near the equator. Noise intensity varies with time of day, distance from the equator, and with the seasons as the storm centers shift. Most atmospheric noise tends to be impulsive in character and, as a result, is quite different from thermal or Gaussian noise. The impulses are sharp, and being such, a c.w. signal can be detected by selective listening by the ear below the peak noise level, *i.e.*, $\frac{S}{N} < 1$, while a voice-modulated signal cannot be understood unless $\frac{S}{N} > 1$ or the noise pulse rate is very low. N = peak noise value (μv/m) and S = signal level (μv/m).

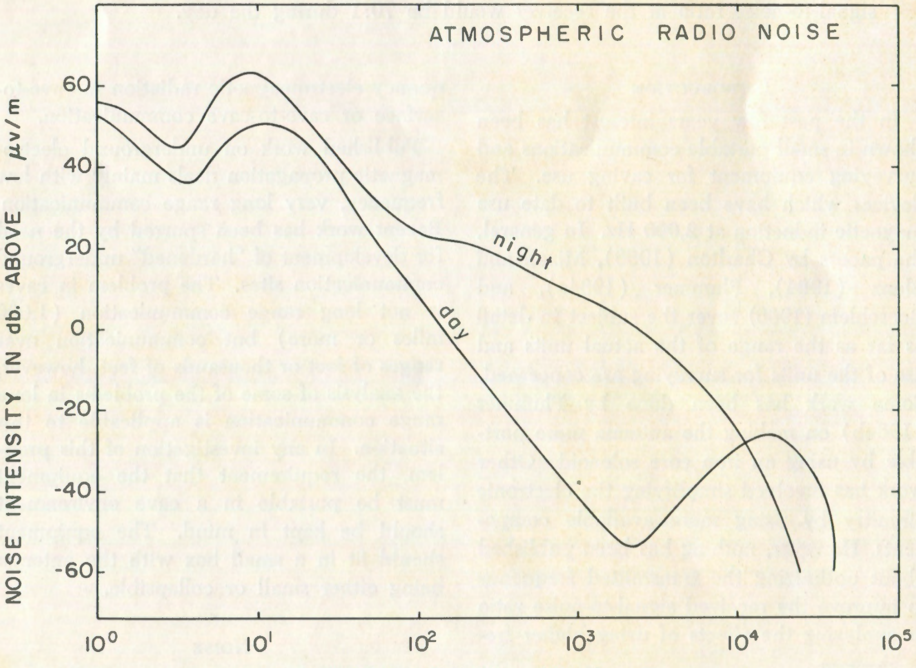

Figure 1

The distribution of the noise is of primary importance in selecting an operating frequency. Figure 1 is a plot of atmospheric noise (electric field intensity) for a 100 Hz bandwidth versus frequency, adapted from Watt and Maxwell (1957) and "Reference Data for Radio Engineers" (1956). The values shown are 0.1% values, *i.e.*, the values shown are exceeded by noise pulses only 0.1% of the time. Notice the nulls at 3.5 to 4 kHz and 2 MHz (daytime). These are due to selective attenuation or poor propagation by the ionosphere. The effects of these null frequencies on short distance communication will be investigated.

Plummer (1964a) indicates problems with a different kind of noise with inductive "cave radios". This is the familiar 60-Hz A.C. line hum, which is usually of no consequence if the loop atenna is shielded and the amplifier following the antenna is sufficiently selective to reject 60 Hz.

BASIC ELECTROMAGNETIC CONSIDERATIONS

Before considering factors such as antennas, the variation of field strength with distance, and the subsequent variation of signal-to-noise ratio (S/N) with distance, depth, and frequency, the conditions of the propagating medium should be discussed. The earth will be treated as a poor conductor rather than a lossy dielectric. For a poor conductor the conductivity (σ) is much greater than the product of radian frequency (ω) and ground permittivity ($\epsilon_o \epsilon_r$):

$$\sigma \gg \omega \, \epsilon_o \epsilon_r$$

$\omega = 2\pi f$.
f = frequency, Hz.
σ = conductivity, mho/m.
ϵ_r = relative dielectric constant (10 for limestone).
ϵ_o = permittivity, 8.85×10^{-12} farads/m.

This inequality expresses the fact that the conduction current is much greater than the displacement current. Both conductivity and permittivity are functions of frequency (Keller and Licastro, 1959); however, for this investigation they will be set constant within the limits of the above inequality.

For a poor conductor there are several special considerations which arise. First, the velocity of propagation (phase velocity) is a function of frequency:

$$v = \sqrt{\frac{2\omega}{\mu\sigma}}$$

$\mu = 4\pi \times 10^{-7}$ (permeability)

Second, waves through ground are attenuated by a factor:

$$e^{-a/\delta} = e^{-1.987 \times 10^{-3} a \sqrt{f\sigma}}$$

where:

$$\delta = \text{skin depth} = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

a = distance from source

For higher frequencies or lower conductivities where $\sigma \ll \omega\epsilon$, the above generalizations are not true. The velocity approaches a value:

$$v = \frac{1}{\sqrt{\mu \epsilon_o \epsilon_r}} = \frac{c}{\sqrt{\epsilon_r}}$$

c = velocity of light in a vacuum

and the attentuation approaches a constant with respect to frequency equal to:

$$e^{-\frac{\sigma}{2}\sqrt{\frac{\mu}{\epsilon_o \epsilon_r}}}$$

Only the region $\sigma \gg \omega\epsilon$ will be considered, keeping in mind that at higher frequencies and lower conductivities (beyond the ends of the graphs on Figs. 6 to 14), the attenuation becomes independent of frequency.

THE NEAR FIELD OF A SMALL LOOP ANTENNA

The popularity of the loop antenna for cave radios is understandable. The antenna can be electrically and physically small; it can be easily carried into remote areas of caves. Electrically small means the loop radius (r) is less than one-sixth of a wavelength (λ). Indeed, antennas described for most "cave radios" have r < 1 m and λ about 150 km at their operating frequency.

The magnetic field intensity for the induction field (H_I) on the axis of a loop in air is given by:

$$H_I = \frac{NIA}{2\pi \, (r^2 + a^2)^{3/2}}$$

where: I = loop current, amps
N = number of turns
r = coil radius, m
a = distance from plane of loop on the axis, m
A = area of the coil, m^2

For this case, $a \gg r$, and the equation can be written:

$$H_I = \frac{NIA}{2\pi a^3}$$

When this loop is buried in the ground, there is an attenuation of the field due mainly to ground conduction in the form of eddy currents. This loss in the induction field should be proportional to frequency, but the literature contains very little information on the treatment of eddy currents in bulk conducting media. Hansen states that for the near field, using the "Lien approximation," the field is reduced by an inverse cubic distance relationship with an attenuation factor of approximately $e^{-a/\delta}$. This is the same factor discussed under "General Electromagnetic Considerations" and is the attenuation factor which will be used here. The induction (near) field for a buried loop is now:

$$H_I = \frac{NIA}{2\pi a^3} e^{-a/\delta} \qquad (1)$$

at the surface on the axis of the antenna (Fig. 2).

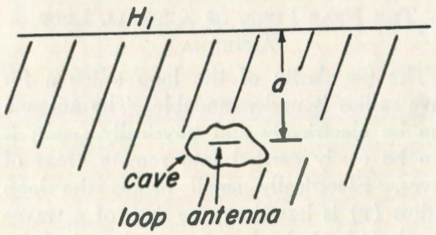

Figure 2

The Far Field of a Small Loop

For the same loop in air, considered as an electromagnetic radiator,

$$H_r = \frac{\pi NIA}{a\lambda^2} \sin\theta \qquad (2)$$

where: H_r = radiated magnetic field intensity
θ = angle measured from the axis of the loop to the direction in which H_r is desired.

Notice that H_r is zero where H_I is maximum, and H_r is maximum at $\theta = 90°$ (in the plane of the loop). The maximum value of H_r will be used for this investigation.

For the loop buried in ground, the wavelength (λ) is a function of conductivity.

$$\lambda = 2\sqrt{\frac{\pi}{f\mu\sigma}} \qquad \sigma \gg \omega\epsilon_0\epsilon_r$$

Also, the field is attenuated by $e^{-a/\delta}$. Then

$$H_r\,(\text{max.}) = NIA \left[\frac{f\mu\sigma}{4a} e^{-a/\delta}\right] \qquad (3)$$

at the surface directly above the antenna (Fig. 3).

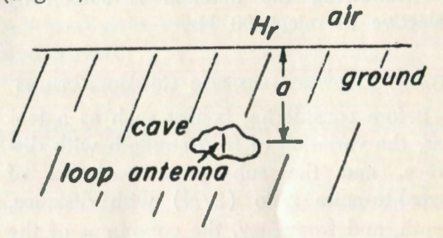

Figure 3

Once on the surface the electromagnetic waves will propagate along the surface with very little attenuation. The attenuation will be due mainly to spreading and will be inversely proportional to distance.

Consider the case where H_I (max.) = H_r (max.). Setting (1) equal to (3) gives

$$f = \frac{2}{\pi a^2 \mu\sigma} \quad \text{or} \quad a = \frac{\lambda}{4.4}$$

As a consequence, if

$$f > \frac{2}{\pi a^2 \mu\sigma} \equiv a > \frac{\lambda}{4.4},$$

the radiation equation should be used to describe the maximum field, and if

$$f < \frac{2}{\pi a^2 \mu\sigma} \equiv a < \frac{\lambda}{4.4},$$

the magnetic induction equation should be used.

The Buried Radiating Wire

Ghose (1961a, b) treats the case of a buried radiating wire where the field intensity is desired at a distance greater than the depth of burial. He explains that the primary waves, those generated by the antenna and propagated through the ground, will be of no consequence at the receiver. However, the set of secondary waves generated at the earth's surface by the transmitted field will propagate to the receiver and can be received underground by the refraction of the secondary wave at the surface. The electric field at the receiver is given by:

$$|E_h| \cong \frac{P}{2\pi\sigma\rho^3} e^{-(d_t + d_r)/\delta} \times$$

$$|1 + i B_2\rho - B_2^2\rho^2| \cos\phi \quad \text{volt/meter}$$

for a short underground antenna (Fig. 4)

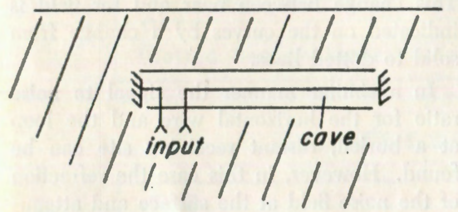

Figure 4

where: P = dipole moment of the antenna, amp-meters
σ = average earth conductivity at the transmitter and receiver, mho/m (geometric mean)
d_t, d_r = depths of transmitter and receiver, m
$B_2 = 2\pi/\lambda_0$, propagation constant in air
λ_0 = free space wavelength, m
ϕ = azimuthal angle of the receiver measured from the transmitter antenna axis
ρ = distance between transmitter and receiver, m
E_h = radial, horizontal component of the electrical field underground

Notice that the field strength is zero opposite the antenna and is a maximum at the ends. This is a distinct change from the field of an above ground dipole which is maximum opposite the antenna and zero at the ends. This equation is valid as long as $|B_2/B_1|^2 \ll 1$ where B_1 is the propagation constant in the earth. The above requirement reduces to $\sigma \gg 2\omega\epsilon_0$. In this discussion only cases where $\sigma \gg \omega\epsilon_0\epsilon_r$ and $\epsilon_r \approx 10$ are considered; so the equation is valid.

For $a \ll \rho \gg \lambda_0/4$ and setting $\phi = 0$, the equation for E_h reduces to a simpler form:

$$|E_h\,(\text{max.})| = \frac{2\pi P}{\sigma\rho\lambda_0^2} e^{-(d_t + d_r)/\delta}$$

which can be used for the signal-to-noise ratio calculations.

Notice the mention of refraction of the waves in the above discussion. When an electromagnetic wave is interrupted by the interface of air and earth, whether it is propagated from the earth or into it, there is a refraction of the wave from a predominately horizontal polarization below the surface to a predominately vertical polarization above. The ratio of the electric field intensities is given by the ratio of their characteristic impedances below and above the ground. The ratio

$$\frac{E_v\,(\text{above})}{E_h\,(\text{below})} = \sqrt{\frac{\sigma}{\omega\epsilon_0}} = 4240\sqrt{\sigma/f}$$

where: $\epsilon_0 = 8.85 \times 10^{-12}$, farad/m
f = frequency, kHz

gives their relative field strengths. Note also that the atmospheric noise near the surface is predominately vertically polarized and upon entering the ground becomes horizontally polarized.

The Small Loop at a Distance

The propagation equation for a buried loop antenna with its axis horizontal and pointed toward the receiver can be derived from the equations for a loop above ground and the equations for a short wire above and below ground as:

$$|E_h\,(\text{loop})| = \frac{4\pi^2}{\sigma}\,\frac{A}{\rho\lambda_0^3} NI e^{-(d_t + d_r)/\delta} \cos\phi$$

where: ϕ = the angle measured from the axis of the loop to the receiver.

THE SIGNAL-TO-NOISE RATIO

Four equations now describe the signal field of a buried loop and a buried horizontal wire, with the conditions under which each is valid. These equations can be rearranged as shown below:

Buried Inductive Loop:

$$H_I = NIA \left[\frac{1}{2\pi a^3} e^{-a/\delta} \right] \quad a < \lambda/4.4$$

Buried Radiating Loop:

$$H_r = NIA \left[\frac{f\mu\sigma}{4a} e^{-a/\delta} \right] \quad a > \lambda/4.4$$

Buried Loop at a Distance:

$$|E_L\ (\text{max.})| = \frac{NIA}{\rho} \times$$

$$\left[\frac{4\pi^2 f^3}{c^3\sigma} e^{-(d_t + d_r)/\delta} \right] \quad a \ll \rho \gg \lambda/4$$

Buried Wire at a Distance:

$$|E_h\ (\text{max.})| = \frac{P}{\rho} \times$$

$$\left[\frac{2\pi f^2}{c^2\sigma} e^{-(d_t + d_r)/\delta} \right] \quad a \ll \rho \gg \lambda/4$$

where the term outside the brackets denotes mainly transmitter antenna properties and the term in brackets is the propagation term.

These equations and the graph in Fig. 1 can now be used to find the signal-to-noise ratio at the receiver. Using the relationship for plane waves in air, $H = E/120\pi$, gives noise magnetic field intensity at the surface using the electric field intensities from the graph. The ratios directly above the loop antenna at the surface are now available:

$$\frac{S}{N} \equiv \frac{H_I}{H\ (\text{noise})} =$$

$$\frac{10\ NIA}{\sqrt{BW}} \left[\frac{60}{a^3 E\ (\text{graph})} e^{-a\sqrt{\pi f \mu \sigma}} \right] =$$

$$\frac{10\ NIA}{\sqrt{BW}} [G(f,\sigma,a)]$$

$$\frac{S}{N} \equiv \frac{H_r}{H\ (\text{noise})} =$$

$$\frac{10\ NIA}{\sqrt{BW}} \left[\frac{30\pi f\mu\sigma}{aE\ (\text{graph})} e^{-a\sqrt{\pi f \mu \sigma}} \right] =$$

$$\frac{10\ NIA}{\sqrt{BW}} [H(f,\sigma,a)]$$

The functions $G(f,\sigma,a)$ and $H(f,\sigma,a)$ are plotted in Figs. 5 and 6. Figure 5 is for daytime noise and Fig. 6 for nighttime. The actual signal-to-noise ratio for given conditions of f,σ,a, and time of day can be found by adding the value from the appropriate curve to $20\log_{10} \left[{}^{NIA}/_{\sqrt{BW/10}} \right]$ where "BW" is the receiver 3 db bandwidth in Hz and the other symbols for the transmitter antenna are as described before.

The curves of the function $G(f,\sigma,a)$ are plotted until $H_I = H_r$; then the antenna is considered rotated 90° and $H(f,\sigma,a)$ is plotted. This change between near and far field is indicated on the curves by a change from solid to dotted lines.

In a similar manner the signal to noise ratio for the horizontal wire and the loop at a buried, distant receiving site can be found. However, in this case the refraction of the noise field at the surface and attenuation of this field in the earth must be known. After evaluating constants:

$$E_h\ (\text{earth}) = 7.46 \times 10^{-6}\ E\ (\text{graph}) \times \left[\sqrt{f/\sigma}\ e^{-d_r/\delta} \right]$$

and for the horizontal wire,

$$\frac{S}{N} \equiv \frac{E_h}{E_h\ (\text{noise})} = \frac{P}{\rho\sqrt{BW/10}} \times$$

$$\left[\frac{\frac{2\pi f^2}{c^2\sigma} e^{-(d_t + d_r)\sqrt{\pi f\mu\sigma}}}{7.46 \times 10^{-6}\ E\ (\text{graph})\ \sqrt{f/\sigma}\ e^{-d_r\sqrt{\pi f\mu\sigma}}} \right]$$

Notice that d_r, the depth of receiver burial, cancels from the expression, so that

$$\frac{S}{N} = \frac{P}{\rho\sqrt{BW/10}} [I(f,\sigma,d_t)]$$ is not a function of the receiver depth. Again this is true as long as sufficient noise voltage is delivered to the antenna terminals to overcome the receiver noise. The function $20\log_{10} [I(f,\sigma,d_t)]$ is plotted in figures 7, 8, 9, and 10. As

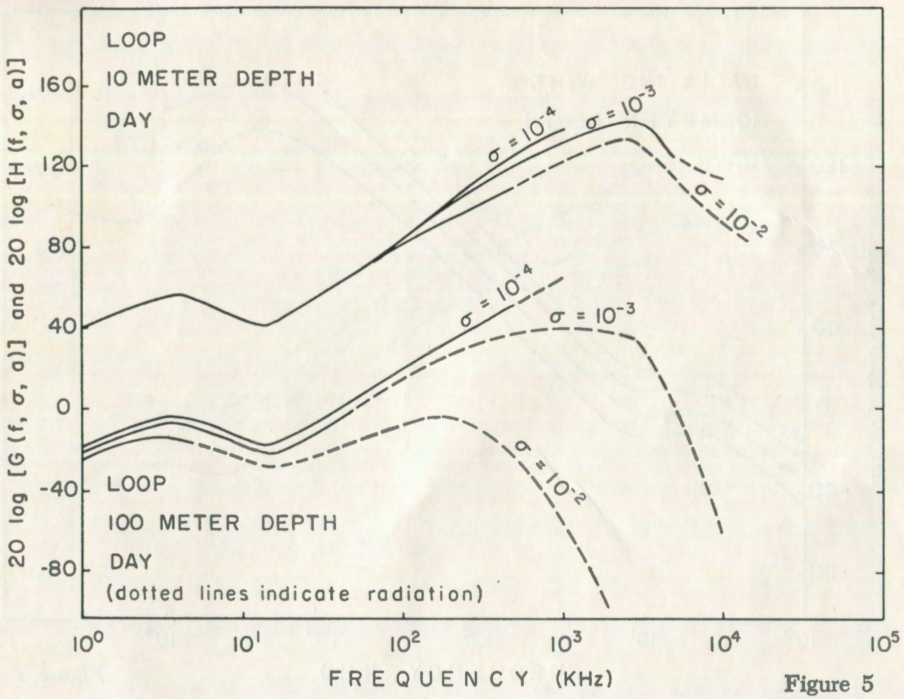

Figure 5

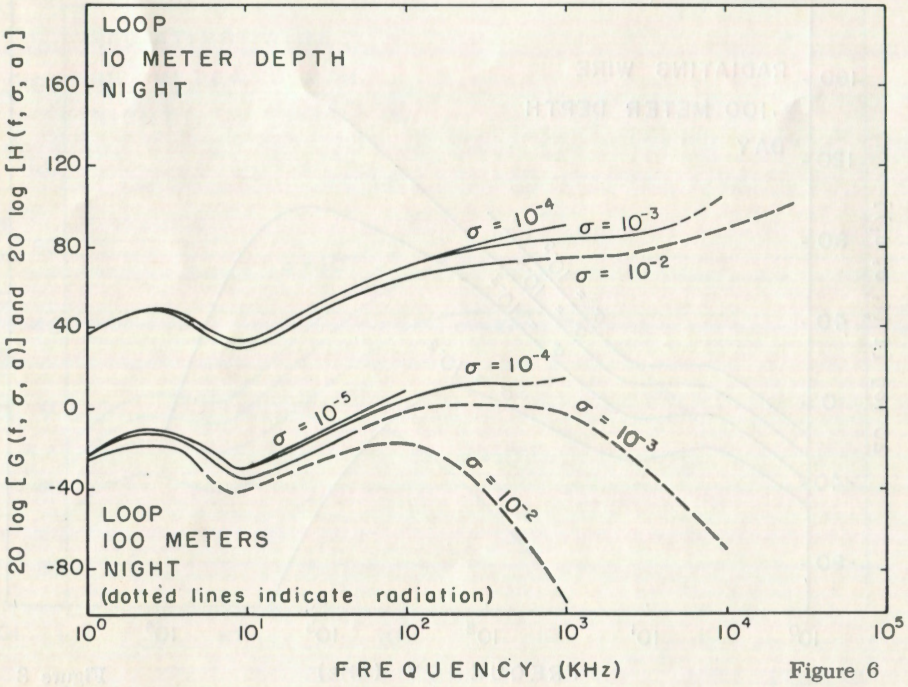

Figure 6

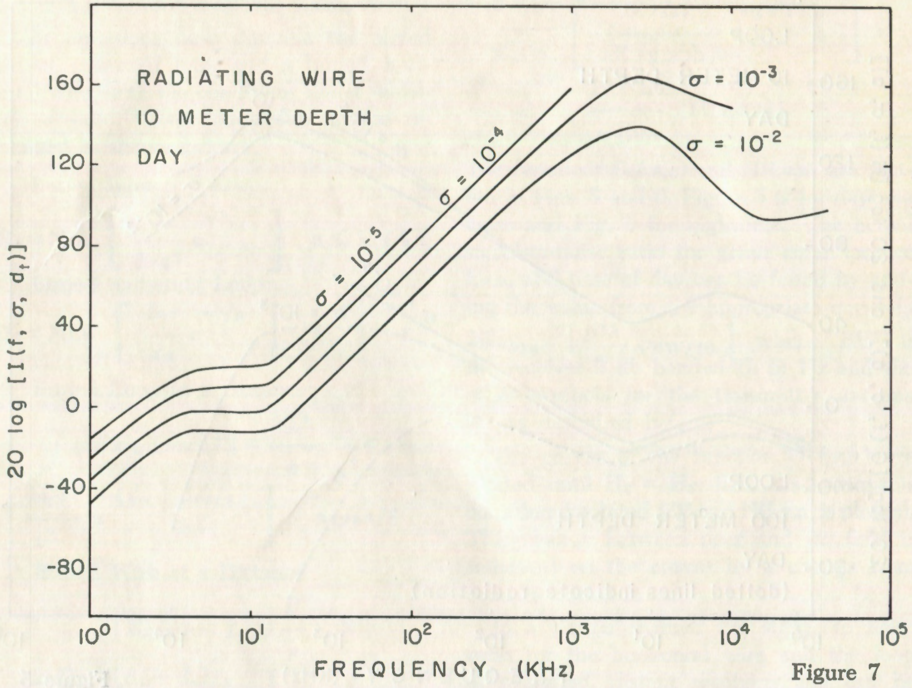

Figure 7

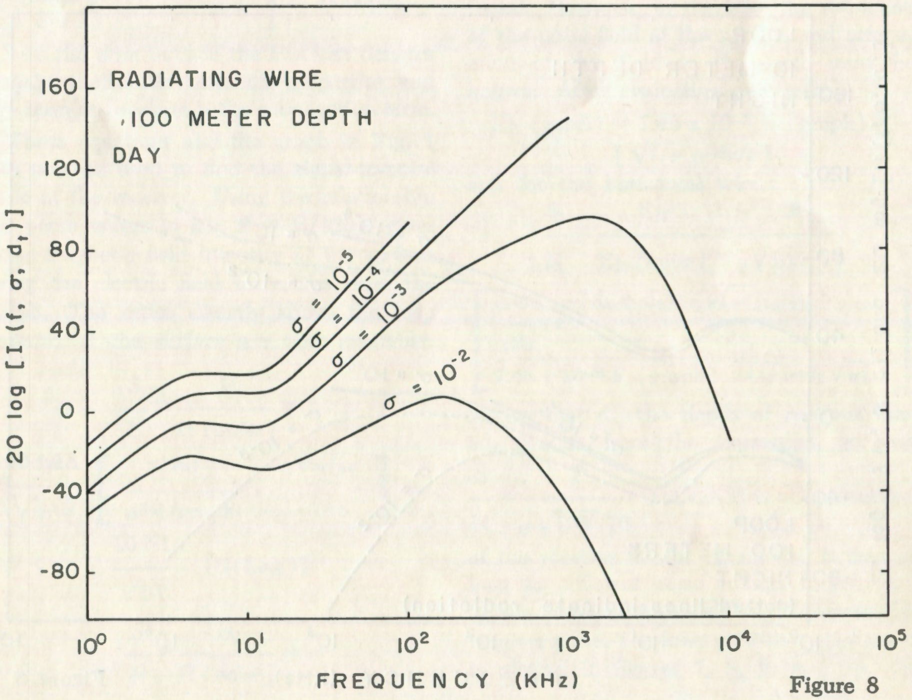

Figure 8

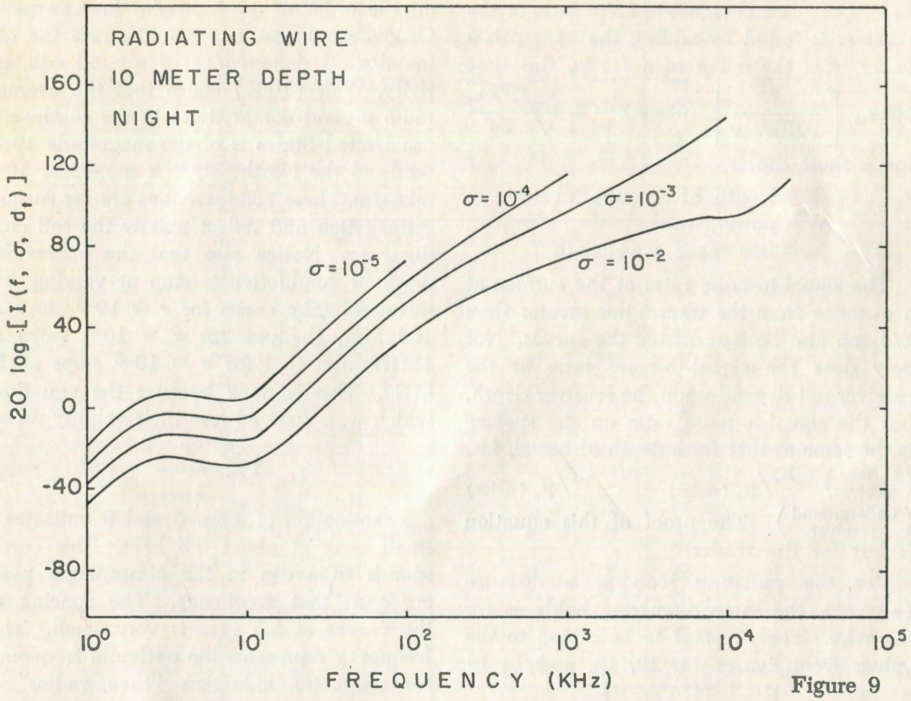

Figure 9

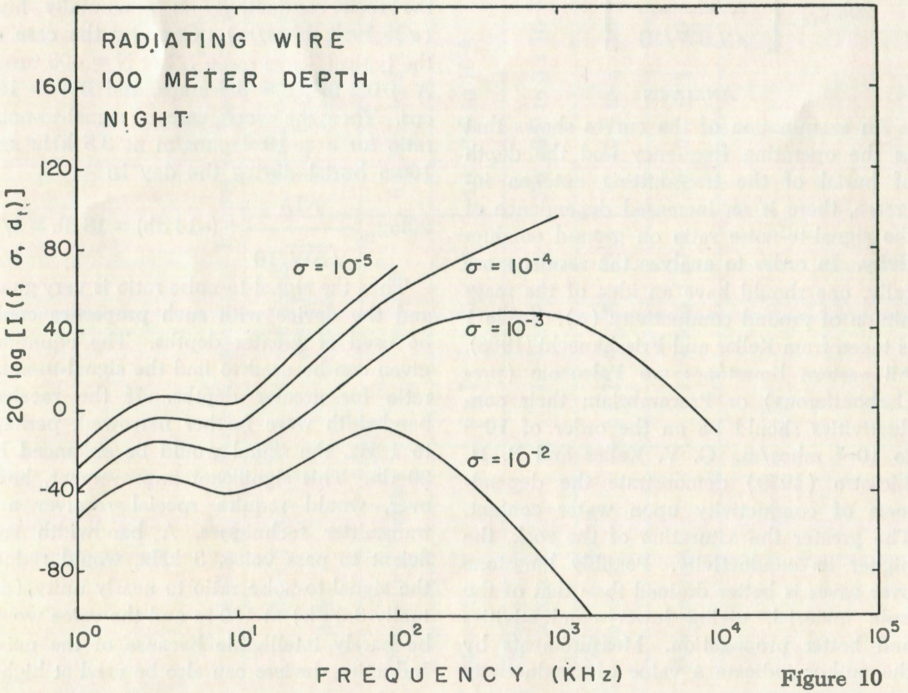

Figure 10

before, the actual signal-to-noise ratio at the receiver is found by adding the appropriate value from the curve to a factor, this time

$$20\log_{10}\left[\frac{P}{\rho\sqrt{BW/10}}\right] \quad \text{where } P \approx IL \approx \sqrt{\frac{WL\lambda_o}{30}}$$

for a short dipole.

L = length of antenna, m
W = power, watts
λ_o = free space wavelength

The signal-to-noise ratio at the *surface* at a distance from the transmitter greater than $\lambda/4$ can also be found from the curves. Not only does the signal-to-noise ratio at the receiver not depend upon the receiver depth, but the signal-to-noise ratio on the surface is the same as that for a depth of burial, *i.e.*,

$$\left(\begin{smallmatrix}\text{surface}\\ \text{receiver}\end{smallmatrix}\right) \; {}^{E_v}/_{E_v\,(\text{noise})} = {}^{E_h}/_{E_h\,(\text{noise})} \left(\begin{smallmatrix}\text{underground}\\ \text{receiver}\end{smallmatrix}\right).$$

The proof of this equation is left for the reader.

For the radiating loop at a distance ($\rho > \lambda/4$), the same discussion holds as for the wire. The constant to be added to the values from figures 11, 12, 13, and 14 is:

$$20\log_{10}\left[\frac{NIA}{\rho\sqrt{BW/10}}\right]$$

Analysis

An examination of the curves shows that as the operating frequency and the depth of burial of the transmitting antenna increase, there is an increased dependence of the signal-to-noise ratio on ground conductivity. In order to analyze the results more fully, one should have an idea of the magnitude of ground conductivity (σ). Table 1 is taken from Keller and Frischknecht (1966). All eastern limestones are Paleozoic (pre-Carboniferous) or Precambrian; their conductivities should be on the order of 10^{-4} to 10^{-5} mhos/m. G. V. Keller and P. H. Licastro (1959) demonstrate the dependence of conductivity upon water content. The greater the saturation of the rock, the higher its conductivity. Possibly limestone over caves is better drained than that of the bulk material, giving lower conductivities and better propagation. Measurements by the author indicate a value of conductivity on the order of 10^{-4}mhos/m for cavernous Ordovician limestone. To illustrate the climatological dependence of ground conductivity, Wait (1966) states that the average radio ground conductivity in the southwestern United States is of the magnitude 10^{-2}, while in the Northeast, it is more like 10^{-3} mhos/m. These conductivities are for surface propagation and reflect mainly the soil conductivity. Notice also that the curves for different conductivities stop at varying frequencies. The curve for $\sigma = 10^{-5}$ stops at 100 kHz, the one for $\sigma = 10^{-4}$ stops at 1MHz, and that for $\sigma = 10^{-3}$ stops at 10 MHz. This is done because the equations which were derived lose their validity unless

$$f < \frac{\sigma}{2\pi\epsilon_o\epsilon_r}$$

Examination of Figs. 5 and 6 indicates a small peak at about 3.5 kHz. This corresponds to a dip in the atmospheric noise curve at that frequency. The spacing of the curves at 3.5 kHz is very small. This frequency represents the optimum frequency for magnetic induction "cave radios" if the rock conductivity is abnormally high ($\sigma > 10^{-2}$ mhos/m). Consider the case of the typical "cave radio". Let N = 400 turns, A = 0.2 m^2, I = 0.5 amps, and BW = 100 cps. Then the worst case of signal-to-noise ratio for $\sigma = 10^{-2}$ mhos/m at 3.5 kHz and 100m burial during the day is:

$$20\log_{10}\frac{NIA}{\sqrt{BW/10}} + (-14\text{ db}) = 18\text{ db} = S/N$$

Thus the signal-to-noise ratio is very good, and the device with such properties could be used at greater depths. The equations given can be used to find the signal-to-noise ratio for greater depths. If the receiver bandwidth were further narrowed, perhaps to 1 Hz, the signal would be enhanced by 20 db. This significant improvement, however, would require special receiver and transmitter techniques. A bandwidth sufficient to pass voice, 3 kHz, would reduce the signal-to-noise ratio to nearly unity (actually 3.2 db) at 100 m and the voice would be barely intelligible because of the noise. Induction devices can also be used at higher

TABLE 1. Probable Conductivity Ranges of Rocks as a Function of Lithology and Age (After Keller and Frischknecht)

Rock Type Age	Marine Sand and Shale, Growacke	Terrestrial Sands and Claystones, Arkose	Extrusive, Volcanic Basalt, Ryolites, Tuffs, etc.	Intrusive Igneous Rocks, Granite, Gabbro	Chemical Precipitates, Limestone, Dolomite, Anhydrite, Salt
Quaternary, Tertiary	1 to 10^{-1}	6 x 10^{-2} to 2 x 10^{-2}	10^{-1} to 5 x 10^{-3}	2 x 10^{-3} to 5 x 10^{-4}	2 x 10^{-2} to 2 x 10^{-4}
Mesozoic	2 x 10^{-1} to 5 x 10^{-2}	4 x 10^{-2} to 10^{-2}	5 x 10^{-2} to 2 x 10^{-3}	2 x 10^{-3} to 5 x 10^{-4}	10^{-2} to 10^{-4}
Carboniferous Paleozoic	10^{-1} to 2 x 10^{-2}	2 x 10^{-2} to 3 x 10^{-3}	5 x 10^{-2} to 10^{-3}	10^{-3} to 2 x 10^{-4}	5 x 10^{-2} to 10^{-5}
Precarboniferous Paleozoic	2 x 10^{-2} to 5 x 10^{-3}	10^{-2} to 2 x 10^{-3}	10^{-2} to 5 x 10^{-4}	10^{-3} to 2 x 10^{-4}	10^{-4} to 10^{-5}
Precambrian	10^{-2} to 5 x 10^{-4}	3 x 10^{-3} to 2 x 10^{-4}	5 x 10^{-3} to 2 x 10^{-4}	2 x 10^{-4} to 5 x 10^{-5}	10^{-4} to 10^{-5}

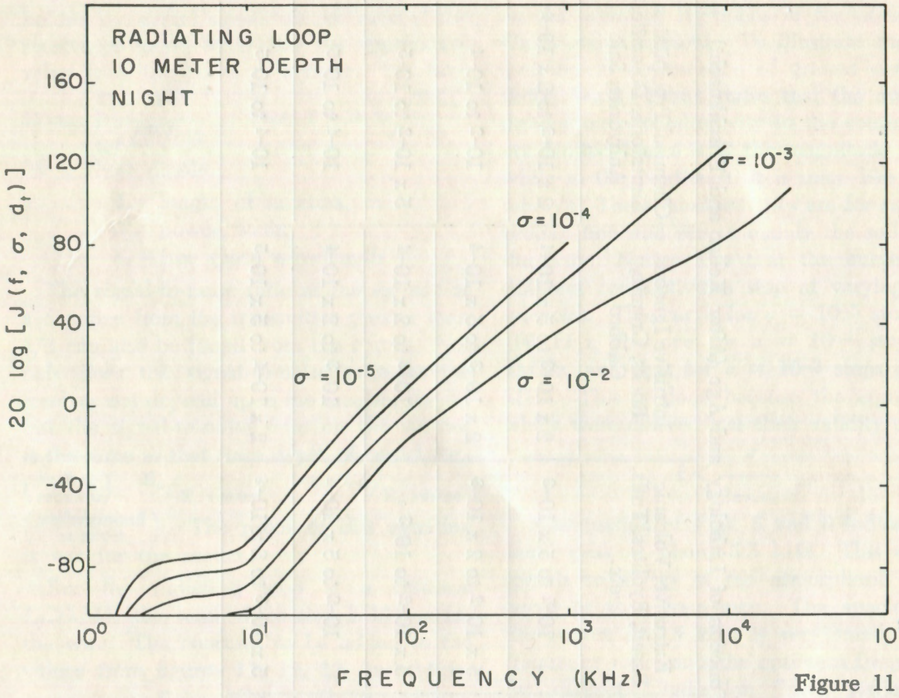

Figure 11

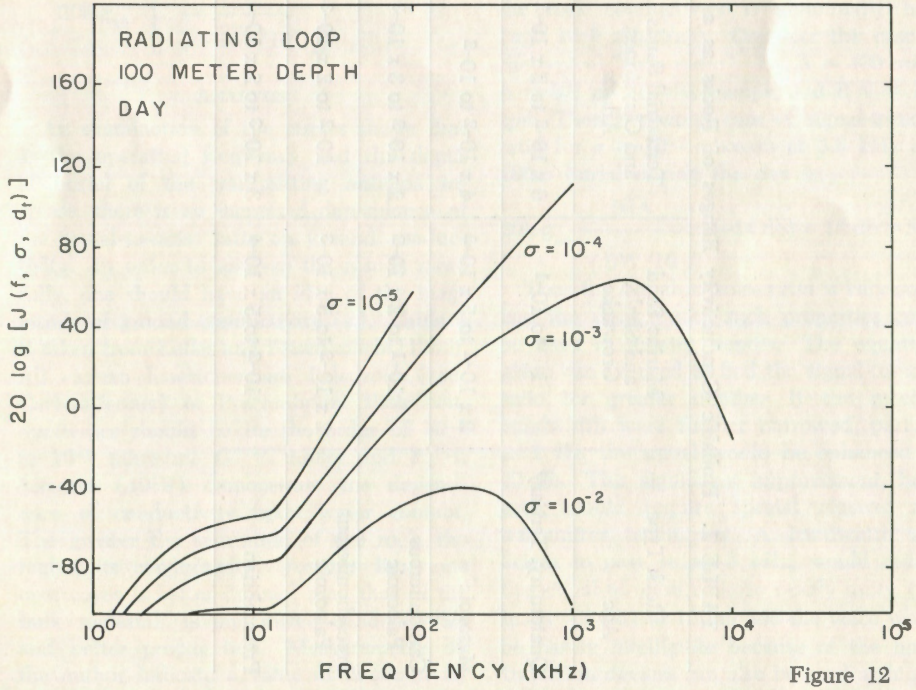

Figure 12

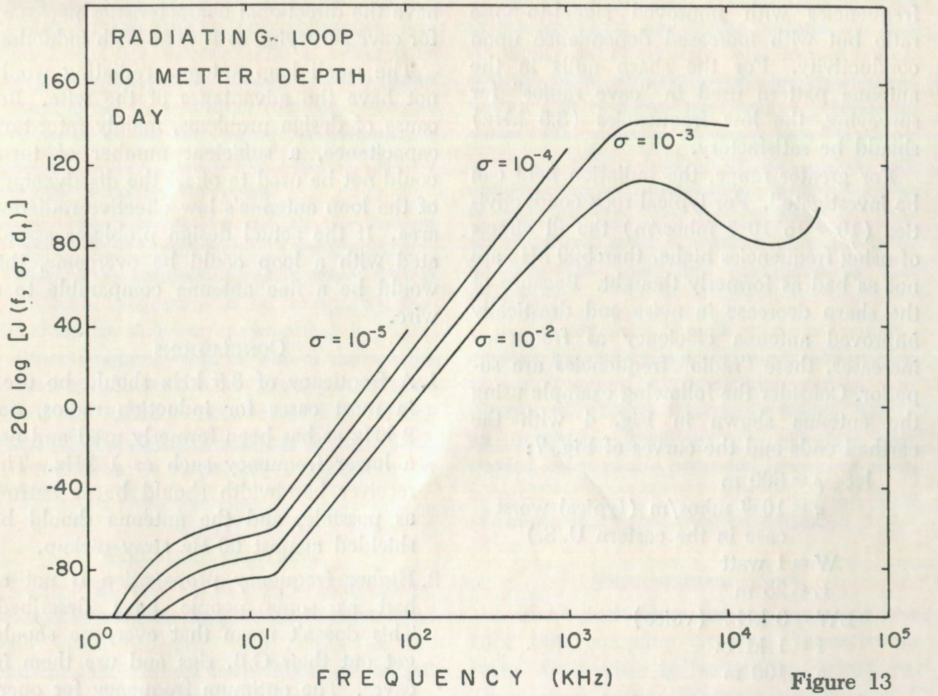

Figure 13

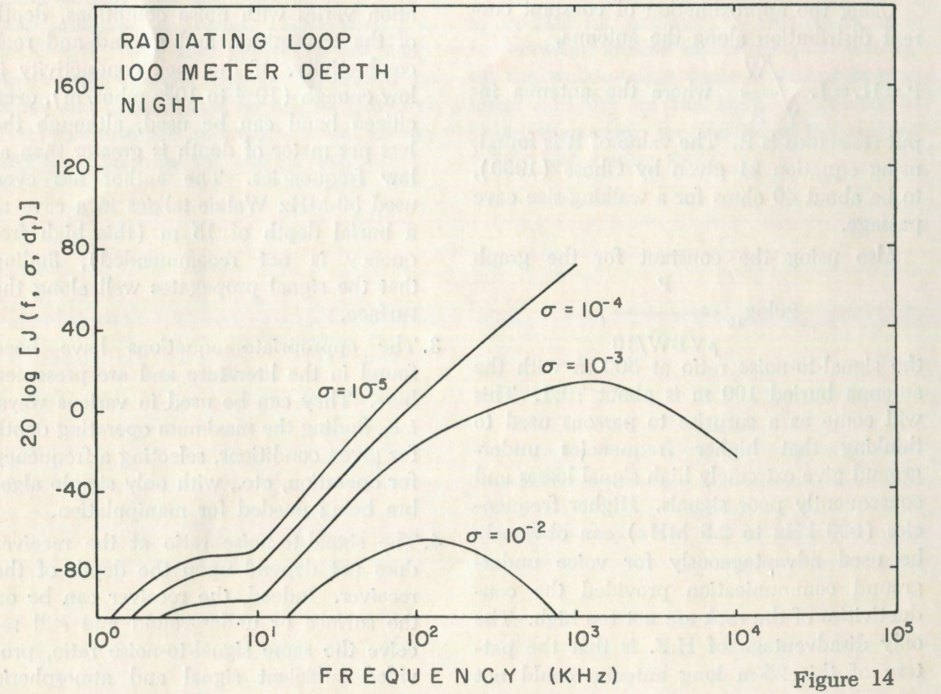

Figure 14

frequencies with improved signal-to-noise ratio but with increased dependence upon conductivity. For the sharp nulls in the antenna pattern used in "cave radios" for surveying, the low frequencies (3.5 kHz) should be satisfactory.

For greater range, the radiation field can be investigated. For typical rock conductivities (10^{-3} to 10^{-5} mhos/m) the ill effects of using frequencies higher than 500 kHz are not as bad as formerly thought. Because of the sharp decrease in noise and drastically improved antenna efficiency as frequency increases, these "radio" frequencies are superior. Consider the following example using the antenna shown in Fig. 4 with the earthed ends and the curves of Fig. 7:

let $\rho = 500$ m
$\sigma = 10^{-3}$ mhos/m (typical worst case in the eastern U. S.)
W = 1 watt
L = 25 m
BW = 3 kHz (voice)
f = 1 MHz
a = 100 m

Using the approximation of constant current distribution along the antenna,

$$P = IL = L\sqrt{\frac{W}{R}}$$

where the antenna input resistance is R. The value of R is found, using equation 21 given by Ghose (1960), to be about 40 ohms for a walking-size cave passage.

Also using the constant for the graph

$$20\log_{10}\frac{P}{\rho\sqrt{BW}/10},$$

the signal-to-noise ratio at 500 m with the antenna buried 100 m is about 70:1. This will come as a surprise to persons used to thinking that higher frequencies underground give extremely high signal losses and consequently poor signals. Higher frequencies (500 kHz to 2.5 MHz) can obviously be used advantageously for voice underground communication provided the conductivities of the rock are not too high. The only disadvantage of H.F. is that the pattern of this 25-m long antenna could not have the directional characteristics necessary for cave surveying as is done with induction.

The small loop antenna radiating would not have the advantages of the wire. Because of design problems, mainly inter-turn capacitance, a sufficient number of turns could not be used to offset the disadvantage of the loop antenna's low effective radiation area. If the actual design problems associated with a loop could be overcome, this would be a fine antenna comparable to a wire.

CONCLUSIONS

1. A frequency of 3.5 kHz should be used in most cases for induction radios, not 2 kHz as has been formerly used and not a lower frequency such as 1 kHz. The receiver bandwidth should be as narrow as possible, and the antenna should be shielded against 60-Hz stray pickup.
2. Higher frequency propagation is not as bad as some people have described. This doesn't mean that everyone should get out their C.B. rigs and use them in caves. The optimum frequency for operation varies with noise conditions, depth of the transmitter, and ground and rock conductivity. If the rock conductivity is low enough (10^{-4} to 10^{5-} mhos/m), even citizen band can be used, although the loss per meter of depth is greater than at low frequencies. The author has even used 50-MHz Walkie-talkies in a cave at a burial depth of 15 m (this high frequency is not recommended), finding that the signal propagates well along the surface.
3. The appropriate equations have been found in the literature and are presented here. They can be used in various ways, *i. e.*, finding the maximum operating depth for given conditions, selecting a frequency for operation, etc., with only simple algebra being needed for manipulation.
4. The signal-to-noise ratio at the receiver does not depend upon the depth of the receiver. Indeed, the receiver can be on the surface or underground and still receive the same signal-to-noise ratio, provided sufficient signal and atmospheric noise are received to overcome the receiver's noise figure. This stipulation implies that an antenna with a sufficiently large effective area must be used. Some small loops do not meet this requirement. In most cases, for higher frequencies, a wire antenna (electric dipole) works much better for receiving.
5. The discussion at the end of the section "Basic Electromagnetic Considerations" provides an interesting observation. If the optimum frequency or an acceptable frequency for a given environment is at the upper frequency end of one of the graphs (the graphs end at σ slightly less than $\omega\epsilon$), the signal-to-noise ratio will be improved if a higher frequency is used. This observation is especially applicable at shallow burial depths.

FIELD OBSERVATIONS

Using BC-611 military walkie-talkies, qualitative measurements in the 160-m band were made to verify the results of the mathematics. These units have an output power of only 125 mw coupled to a 3-foot whip antenna. A buried 120-ft wire (¼-wavelength) was used instead of the whip. The buried antenna was not grounded on its far end as indicated by Ghose (1960 or 1961) because the antenna was not electrically short such as the one he used.

The first tests used a horizontal antenna in the cave and one on the surface. In this situation, communication was lost at about 300 ft from directly over the transmitter buried 120 ft below the surface. However, when the surface antenna was elevated vertically with a balloon or kite, a two way conversation was maintained to about 2,000 ft from directly over the transmitter. This improvement with a vertical antenna is to be expected from the mathematical discussions.

In the course of the above measurements, another important factor in a cave-to-surface or cave-to-cave communication system was discovered. This is manmade noise. Before an operating frequency is selected, one should listen to the proposed frequency with a sensitive receiver to determine what type of interfering signal may be present.

ACKNOWLEDGEMENTS

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