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Jungle Acoustics[1]

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The study of jungle acoustics was carried out during the wet season in Panama. Measurements permit the following conclusions to be drawn: Within a jungle the temperature and wind velocity gradients are so small that the sound refraction they produce may be neglected for all practical purposes. Humidity increases the transmission loss at high frequencies and field measurements of the loss agree with laboratory values reported by others. Terrain loss, measured in db, between any two specified distances from the sound source is defined as the transmission loss between these points less that caused by the geometrical divergence of the sound beam. Terrain loss in the jungle was found to increase linearly with distance. The terrain loss coefficients, measured in db per foot, were measured for various types of jungle and were found to be a function of frequency and of the density of the terrain, the density of terrain being measured by the difficulty of penetration and the distance a foreign object may be seen. The level of the ambient noise in the wet season jungle is very low especially for the quiet periods between animal calls. At night the low frequencies decrease as the light breezes cease and the high frequencies increase as the insects begin their nocturnal chorus. A jungle is a difficult place in which to judge the direction of a sound—a probable error of 20° is to be expected. The error is found to be smallest when the sound comes from a direction near the axis passing through the two ears, and in the range studied the error decreases as the sound source moves farther away. Reverberation and scattering are the cause of part of the error of judgment, but an improved technique of listening suggested may increase the observer's accuracy.

INTRODUCTION

The Problem

WITHIN a jungle, even more than in open terrain, information gained through hearing may be more important than that gained through sight. A sound will be heard if it is loud enough at the source so that after it has traveled over the terrain in question it still has strength enough successfully to compete with the other sounds surrounding the listener. Obviously this is an oversimplified statement of the situation; but, if the listener is to obtain a good estimate of the location of the sound source, he will have need of knowing:

1. The sound spectogram of the sound source;
2. The sound transmission loss through the jungle of the audible frequencies;

[1] This paper is the report of part of the work undertaken by the College of Engineering, Rutgers University, under Contract OEMsr-1335 with the office of Scientific Research and Development. The field work was conducted in the Canal Zone as Project SC-105 under the general supervision of the Signal Officer, Panama Canal Department, and was known by the name, Jungle Acoustics. The complete report of the project has been published as OSRD Report No. 4699, February 15, 1945, and OSRD Report No. 4704, February 17, 1945.

[2] On the Staff of Rutgers University, and on leave from Brigham Young University, during the period of the project.

3. The sound spectrogram of characteristic ambient jungle noise;

4. The error involved in judging sound direction in a jungle.

An investigation of the last three problems was undertaken and it is the purpose of this paper to report the results obtained.

Area of Operation

All measurements were made within fifty miles of headquarters, Fort Clayton, Canal Zone, and in terrain northward of Summit and, therefore, on the Atlantic slope. Two $1\frac{1}{2}$ ton trucks and a command car, furnished with drivers by the 10th Signal Company, served to transport equipment and personnel.

The Jungle

Roughly, Panama may be divided into two distinct zones, the Atlantic and the Pacific slopes, the latter being much more arid. All jungle areas investigated for sound transmission were in the Atlantic zone where "the high percipitation produces a luxuriance of vegetation never equalled on the Pacific slope." For over 400 years Panama has been dominated by Europeans, and comparatively little virgin vegetation remains, this being true especially of the areas accessible by roads. Yet in spite of these facts certain areas, such as those chosen for study, have had time to take on an approximate virgin forest aspect and are as typical of such a forest as the terrain on Barro Colorado Island, the "Canal Zone Biological Area."

Standley[3] writes: "The trees of these wet Panama forests are so tall that it is difficult to determine their identity, except in the case of a few with distinctive foliage. . . . In the wet forest there are distinct tiers of vegetation. Beneath the tallest trees lower ones of other kinds find space for expansion . . . (such as) the palms, most of which find in the deep shade their favorite habitat. A few of the palms thrust their crowns above the forest roof, but most of them are of humbler stature. . . . The diversity and relative abundance of palms and tree ferns is an excellent criterion for estimating the true nature of the forest whether it has ever been cut or not."

[3] Paul C. Standley, Smithsonian Institution, U. S. National Museum; Contribution from the U. S. National Herbarium Vol. 27, 1928.

FIG. 1. A jungle trail.

The herbaceous vegetation of the forest is relatively unimportant, but coarse woody naked vines often impede the explorer—vines which climb to the tops of trees where they "expand their foilage and inflorescences." Most large trees are heavily burdened by such vines and epiphytic plants. In some localities one may traverse the jungle at will; but in other locations near-by "it is necessary to cut a trail with a machete almost every foot of the way." Traveling along a highway, one might rate a forest as an impenetrable mass, but on closer study it is found that only in the margin next to the roadway, where sunlight can get through, is the undergrowth thick and the forest a veritable jungle. (Fig. 1.)

TRANSMISSION LOSS MEASUREMENTS

Introduction

Method

Sounds of octave band width, essentially "filtered noise" resulting from passing through a filter set the amplified output of a bank of direct-current-carrying carbon resistors, were produced by loudspeakers placed at convenient positions in a more or less flat terrain. Microphones—no fewer than two, often as many as four—were accurately located usually one hundred feet or more apart, on a straight line, the axis of the speakers. By the use of an electric circuit terminating in a power level recorder, the intensity levels of the sound at each microphone were recorded in turn. A comparison of these levels gave the drop in sound intensity level between microphone stations.

Definitions

In this report the following definitions apply:

Transmission Loss (L). Transmission loss, measured in db, means the drop in sound intensity level, for whatever cause, as sound travels from one designated location to another, the nearer distance from the sound source being X_1, the farther, X_2. The transmission loss is composed of that caused by (a) geometrical divergence of the sound beam; (b) refraction caused by temperature and wind velocity gradients; (c) air absorption, especially important for the higher frequencies; (d) the absorption of the surface and body of the terrain—the surface if the sound passes over, the body if the sound passes through the absorbing material; and (e) any other loss not here specified.

Terrain Loss (A). Terrain loss, measured in db, between any two specified distances from the sound source is the transmission loss between these points less that caused by the geometrical divergence of the sound beam. It is, therefore, a quantity which, when measured over unit distances, can be attached to a given terrain; that is, a quantity which is determined by the nature of the ground covering, including the conditions of the ambient atmosphere.

Terrain Loss Coefficient (α). The terrain loss coefficient, measured in db per foot, is defined by the relation

$$\alpha = \Delta A/\Delta X, \tag{1}$$

where ΔA is the terrain loss through a very short distance ΔX. Thus α is surely a function of the terrain (including kind of covering and condition of atmosphere) and it could also be a function of the distance, X, from the sound source. In the frequency range, 75 to 10,000 c.p.s., the terrain loss was usually found to increase linearly with the distance from the sound source. The nonlinearity, when present, seemed to be fortuitous in character and to suggest a non-uniformity of the terrain, rather than a real departure from the linear increase usually found. Accordingly it has been assumed that A increases linearly with distance between X_1 and X_2 and that

$$\alpha = A/X_2 - X_1; \tag{2}$$

and that the transmission loss between X_1 and X_2 may be written as,

$$L = 20 \log \frac{X_2}{X_1} + \alpha(X_2 - X_1). \tag{3}$$

Humidity Loss Coefficient (β). The terrain loss coefficient itself is a composite of losses. Knudsen has isolated one of these, air absorption. He defined the air absorption coefficient m such that

$$I_2 = I_1 \exp\left[-m(X_2 - X_1)\right], \tag{4}$$

where I_1 and I_2 are the sound intensities at the distance X_1 and X_2. In this report the humidity loss coefficient β (db/ft) is defined such that

$$I_2 = I_1\, 10^{-\beta(X_2 - X_1)/10} \tag{5}$$

At once it follows that $\beta = 4.34m$.

Knudsen[4] has measured values of m through the relative humidity range, and for various temperatures and frequencies. His results restated in terms of β and for temperatures of 75 and 80°F are shown in Fig. 2. Under constant frequency, relative humidity, and temperature, β is constant; therefore the humidity loss (B) between two points X_1 and X_2 is

$$B = \beta(X_2 - X_1). \tag{6}$$

Apparatus

Sound Generating System

Two loudspeakers were used (Fig. 3). One, the high frequency unit, was a Western Electric 594-A Loud Speaking Telephone connected to a multicellular high frequency horn. This unit, always used for frequencies above 300 c.p.s. (usually above 600 c.p.s.), has a nearly flat response from 300 to 5000 c.p.s., and is down

[4] Vern O. Knudsen, J. Acous. Soc. Am., April, 1935 and October 1933.

no more than 15 db at 10,000 c.p.s. The other unit, an *A* 15-PM Jensen Speaker, Spec. C-4351 with a special cone treated to withstand fungus growth and a high relative humidity of 95 percent, was mounted on a specially built plywood exponential horn with a taper cut-off of 80 c.p.s., a mouth dimension of 38 inches, and a square throat of area about $\frac{3}{5}$ that of the cone itself. This unit was used for frequencies below 600 c.p.s.

The sound emitted by the loudspeakers was essentially "filtered noise." The noise source consisted of two parallel banks of carbon resistors connected in series and energized by a 12-V battery. The minute random fluctuations in potential appearing across the resistors were delivered to the preamplifier through capacitive-transformer coupling. The output of the preamplifier was found to contain frequency components distributed throughout the audio-frequency range. The preamplifier output was transformer coupled to a special 500-ohm Western Electric RA-363 filter set, and after amplification by a power amplifier was fed into the loudspeakers. Thus, filtered noise in octave bands could be used as a sound source. The bands actually used were 75 to 150 c.p.s.; 150 to 300 c.p.s.; 300 to 600 c.p.s.; 600 to 1200 c.p.s.; 1200 to 2400 c.p.s.; 2400 to 4800 c.p.s.; 7000 c.p.s. and 10,000 c.p.s. The highest test frequencies were not "filtered noise," but were produced through the use of an audio oscillator.

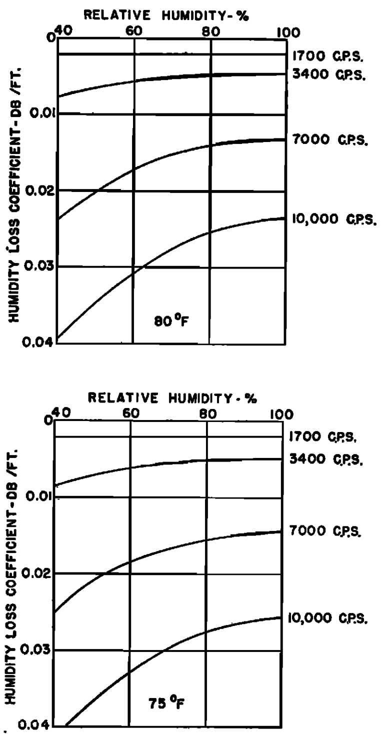

FIG. 2. Humidity loss curves (adapted from Knudsen's data).

For all experiments, the "Source Truck" was parked behind the speakers, usually 150 to 200 feet behind, to guard against feedback. A Homelite 650-w, 110-v, 60S a.c. gasoline motor driven generator, used to supply power to the power amplifier, was set an additional 150 feet behind the truck, and its noise, always much below the sound from the speakers in level, never interfered with acoustical measurements.

Sound Level Measuring System

The system, in its most elaborate form, consisted of four microphones with cables of suitable length arranged with a switch for connecting any particular microphone to the preamplifier input transformer. The preamplifier output was passed through an attenuator and matching transformer, for proper coupling to a 30-ohm, W.E. RA-363 filter set. By use of a second transformer, the output of the filter set was matched to the input impedance of a Sound Apparatus Company Model PL automatic, high speed, power level recorder (10,000 ohms). An auxiliary parallel resonant filter, used in conjunction with the 4800–∞ c.p.s. pass band of the filter set, was provided for the reception of the 7000 and 10,000 c.p.s. tones. A 120-v storage battery and rotary converter generated the 110-volt, 60-cycle, a.c. power required for the operation of the level recorder.

The four microphones, three W.E. 630-A and one W.E. 633-A, were all compared in the field at the various frequency bands so that corrections to render them equal in response could be made. The double filtering, first in the generating system and then in the sound level measuring system, permitted low level measurements. By proper switching, the intensity levels of the sound at each microphone were registered in turn on the automatic level recorder (Fig. 4). The drop in levels between the stations could be read directly from the records, there being no need

FIG. 3. Loudspeakers in place.

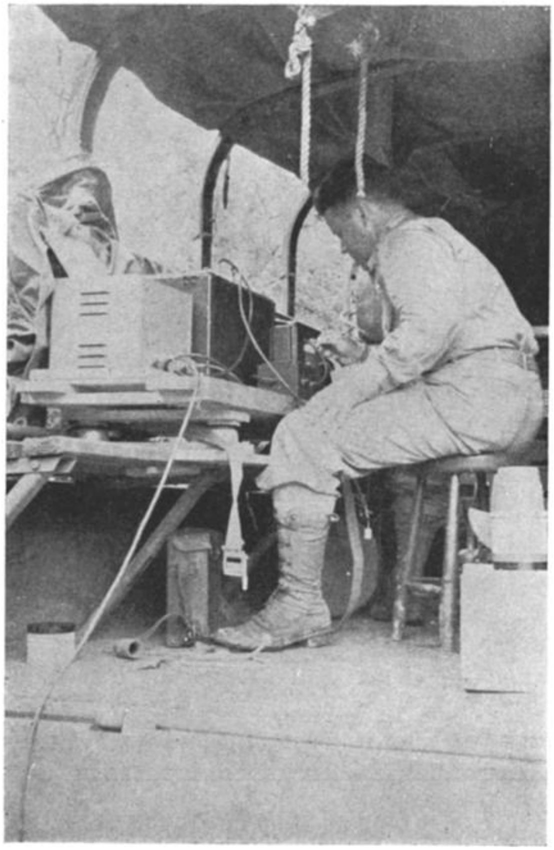

FIG. 4. Sound intensity levels being recorded on automatic level recorder.

to attempt to measure absolute levels. At once the transmission loss, the terrain loss, and the terrain loss coefficient could be calculated.

Meteorological Equipment

Outdoor acoustics must always include the meteorology of the terrain. Continuous records, one of temperature on one instrument and another of wind velocity on a second instrument, were obtained by placing thermistors in one arm of properly designed and calibrated bridges and recording on Esterline-Angus meters the unbalance introduced when the thermistors change in resistance owing, in one case, to an atmospheric temperature shift when operated cold (thermometer) and, in the other case, to a wind velocity fluctuation when operated hot (anemometer). Relative humidity was measured by the use of a recording hair hygrometer which was always checked against a sling psychrometer.

The thermistors responded so quickly to temperature changes and wind velocity fluctuations that it was easy to determine temperature and wind velocity gradients by placing the thermistor housing near the ground and then elevating it by some means to the desired height. In the jungle this elevation was achieved by attaching a pulley to the limb of a tall tree.

Care of Apparatus in Tropics

Because of moisture and fungi, it is difficult to keep electrical equipment in good working condition in the tropics. Fully sensing this fact, great care was taken to store all the smaller pieces of equipment in drying cabinets, and to keep an electric light burning within the larger equipment, when not in use. Not a single failure came because of the action of fungi; and moisture, the result of rain and dew, played only a delaying action.

Measurements

Air Absorption

The terrain loss coefficient, defined above, is a composite of losses, of which air absorption is one. It seemed reasonable to expect that a terrain loss coefficient, determined over a hard bare surface should represent, at least for the most part, the loss resulting from air absorption. Accordingly, measurements were made over the black, oiled runway of Madden Field.

Under the heating of the tropical sun a steep negative temperature gradient appeared in the atmosphere over the bare runway. Toward evening this negative gradient tended to decrease, and by early evening to disappear altogether. Preliminary tests and subsequent measurements and calculations revealed an upward refraction of sound under the negative temperature gradient of midday, but no such refraction in early evening. At midday the shadow zone caused by refraction, depicted in Fig. 5 and calculated[5] on the assumption of no diffraction and scattering, was actually discovered for frequencies above 2000 c.p.s. For lower frequencies, and especially for those below 500 c.p.s., the shadow zone was definitely "blurred." It was found possible to elevate the microphone till it moved through the shadow and into the beam above (dotted line of October 30). With the effect of the upward refraction thus substantially reduced, the terrain loss might be expected to represent simply the loss caused by the moisture in an atmosphere with a relative humidity of 55 percent and a temperature of 80°F. At the higher frequencies, the terrain loss coefficients agree remarkably well with Knudsen's values[4] which he obtained indoors. (See Table I.)

With no temperature and wind gradients, refraction would disappear, the shadow zone would be eliminated, and the microphones would not need to be elevated as before. Under this ideal condition (see Fig. 6), no terrain loss was clearly shown for frequencies below 500 c.p.s.; however, the 7000 and 10,000 c.p.s. did show a set of experimental values which indicate a linear relationship between terrain loss and range and, therefore, a *constant* terrain loss coefficient, presumably a loss caused by moisture in an atmosphere with a relative humidity of 95 percent and a temperature of 76°F. As before, a comparison is made with Knudsen's values. (Table II.)

Thus we may conclude that terrain loss is dependent on relative humidity at high frequencies and that field measurements of the loss agree with the laboratory measurements reported by Knudsen.

Open Tropical Terrain

At the lower frequencies, where air absorption is found to be very small, the terrain loss, as measured near a bare flat surface, is almost entirely dependent upon the refraction caused by temperature and wind gradients. It is not possible, therefore, to assign a terrain loss coefficient to open terrain unless at the same time the meteorological conditions are specified (see Table III).

In general, grass lands show a small terrain loss, even under conditions of no refraction caused by temperature and wind gradients. Five situations were studied: (*A*) over terrain thinly covered with short (6–12 in.) grass; (*B*) over terrain thickly covered with short (18 in.) grass; (*C*) through a thick stand of short grass; (*D*) through shrubbery and over thick short grass; (*E*) through thick tall (6 ft.) grass. The measured terrain loss coefficients are depicted in Fig. 7 and are free, as nearly as practicable, from the effects of refraction, the measurements having been made under very small temperature and velocity gradients.

A study of the curves of Fig. 7 (labeled to agree with the situations just described) reveals (1) that a rapid rise takes place in the terrain

TABLE I.

Frequency, c.p.s.	75 150	150 300	300 600	600 1200	1200 2400	2400 4800	7000	10,000
α db/ft. (our value)	0	0	0.01	0	0.015	0.011	0.020	0.045
β db/ft. (Knudsen's)	0	0	0	0.001	0.002	0.006	0.019	0.033

[5] A. B. Wood, *Sound* (The Macmillan Company, New York, 1930), p. 292.

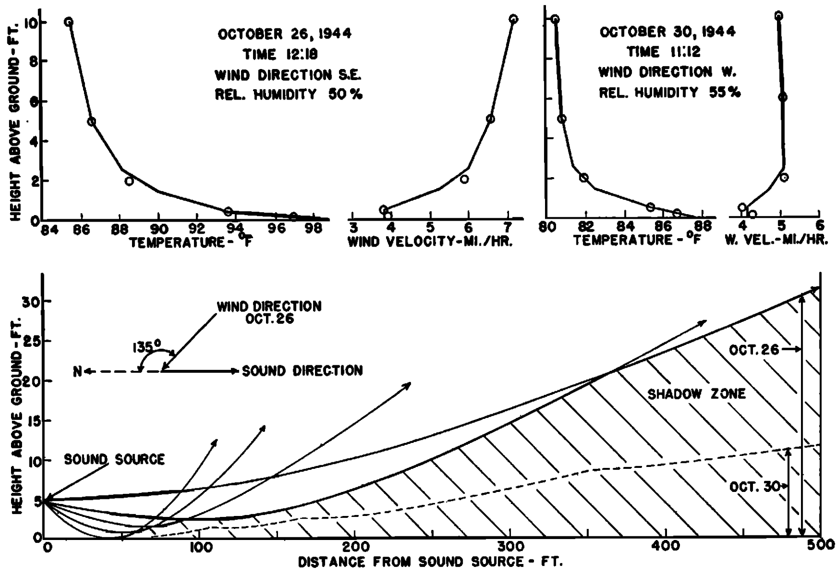

FIG. 5. Shadow zone over heated bare surface.

loss coefficient beginning first at about 300 c.p.s., and then again at about 4000 c.p.s.; (2) that between about 600 c.p.s. and 3000 c.p.s., the coefficient for a given terrain remains substantially constant; (3) that for frequencies up to 400 c.p.s., the coefficients for tall and for short grass and for shrubbery covered short grass are approximately of the same magnitude; (4) that for frequencies above 500 c.p.s. the coefficient is very sensitive to the type of terrain; for frequencies below 300 c.p.s., very insensitive. Large wind and temperature gradients would greatly upset the terrain loss coefficients shown in Fig. 7.

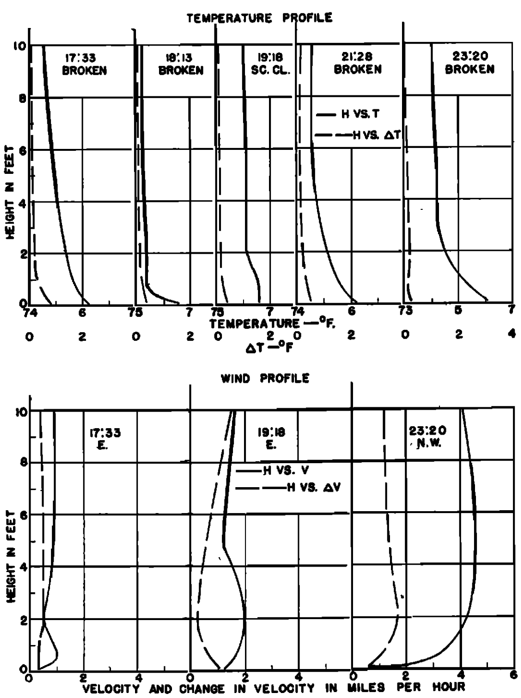

FIG. 6. Temperature and wind velocity profiles, Madden Field Runway, night-time November 13, 1944. Temperature variability, ΔT, is defined as half the difference between the maximum and minimum temperatures within a thirty-second interval. Wind velocity variability, ΔV, is defined as half the difference between the maximum and minimum velocities recorded within a thirty-second interval.

The Tropical Forest

In Panama it was difficult to find large flat areas near roads. Yet, in spite of this difficulty, the five distinct areas selected and studied are thought to be representative of the terrain which one would encounter in a tropical forest. The five areas may be briefly described as follows:

The Madden Field Jungle is not a virgin forest, but one which through the years has made considerable growth since being partially cut over. Many large trees are standing and smaller ones have grown up to completely fill the terrain. One can recognize with difficulty a moving white object a distance of approximately one hundred feet.

Las Cruces Jungle No. 1 is located in a forest preserve just south of Las Cruces Trail and just west of the Panama-Colon Highway. The area is very dense with leafy material. One has diffi-

TABLE II.

Frequency, c.p.s.	7000	10,000
α db/ft. (our value)	0.015	0.027
β db/ft. (Knudsen's)	0.0145	0.0265

culty seeing a moving white object for distances greater than fifty feet.

Las Cruces Jungle No. 2 lies just north of Las Cruces trail and west of the Panama-Colon Highway. In composition this jungle is similar to the Madden Field Jungle.

The Pina Jungle lies between the highway which runs from the Chagres River to Pina village and the Caribbean Sea. It is rated as being more like a South Pacific jungle than any other area on the Isthmus. Made up of heliconia, palms, and other densely growing undergrowth, this jungle, although not as high as others, presents a very distinct jungle aspect. One enters certain areas in this jungle only by cutting.

The Fort Sherman Forest is probably a virgin growth of cativo (*prioria copaifera*) and fig trees with many manicaria palms growing beneath. The buttressed trunks and surface-running roots of the fig trees give the landscape a weird appearance. The brackets forming the buttresses serve as sound reflectors. Little light filters through the canopy; but, except for the palms, leafy material near the ground is definitely absent. One walks over the flat muddy ground and among the trees with comparative ease, but the path is a crooked one, and buttressed tree trunks seem always to loom ahead.

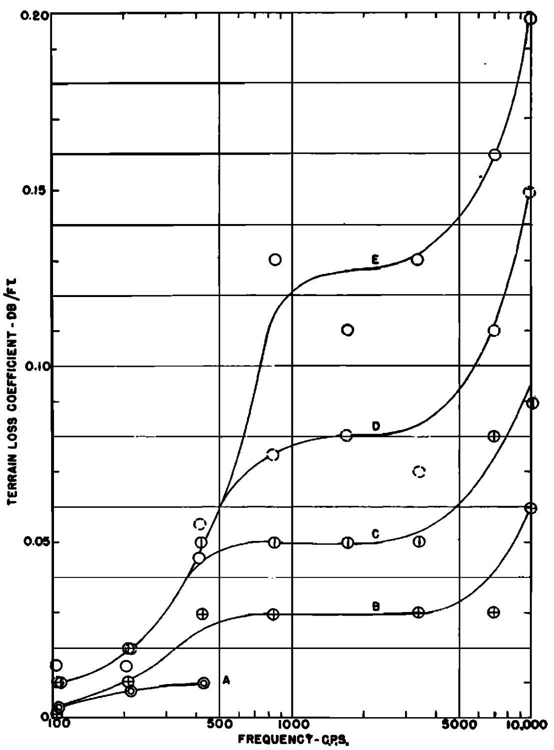

FIG. 7. Terrain loss coefficients for grass areas. (*A*) over terrain thinly covered with short (6–12 in.) grass; (*B*) over terrain thickly covered with short (18 in.) grass; (*C*) through a thick stand of short grass; (*D*) through shrubbery and over thick short grass; (*E*) through thick tall (6 ft.) grass.

In all of these jungle areas the atmosphere under the canopy is found to be very quiet, and the temperature inversion during the day and the lapse rates during the night are very small (Fig. 8). Therefore it is safe to assume that *refraction plays a very minor role in a tropical jungle.*

The measured terrain loss coefficients for the five jungle areas are depicted in Fig. 9. A study of these coefficients in relation to the physical aspects of five jungles leads to a technique of describing jungle types in terms of penetrability and visibility. Five types are described below, and five zones representing the terrain loss coefficients for these types are shown in Fig. 10.

Jungle types may be described as follows: (1) very leafy, one sees a distance of approximately 20 ft., penetration by cutting; (2) very leafy, one sees approximately 50 ft., penetrated with difficulty but without cutting; (3) leafy, one sees a distance of approximately 100 ft., free walking if care is taken; (4) leafy, one sees a distance of approximately 200 ft., penetration is rather easy; (5) little leafy undergrowth, large bracketed trunks, one sees a distance of approximately 300 ft., penetration is easy.

In the dry season certain trees drop their leaves and, therefore, a given jungle may not maintain its type in all seasons. This means that a jungle should be typed every time it is involved in a sound transmission problem. The terrain loss coefficients, especially for the low frequencies where humidity loss is negligible, are essentially independent of daily weather changes.

Summary of Data

As a summary it seems wise to put down in tabular form the terrain loss coefficients which

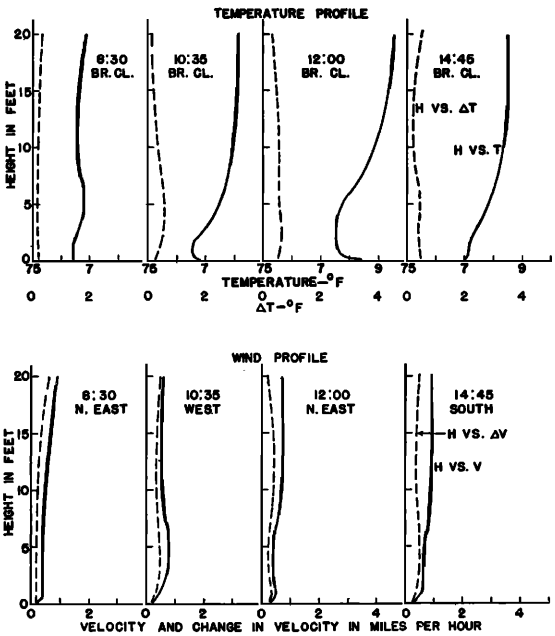

FIG. 8. Temperature and wind velocity profiles, Madden Jungle, November 2, 1944.

seem to be appropriate to use for several kinds of terrain under various weather conditions. In the use of these data it is assumed that the listener is in the tropics, that the sound source and ear are 5 feet above the ground, and that the optimum frequency at which sounds are heard

TABLE III. Estimated terrain loss coefficients open terrain —200 c.p.s.

Weather	(db/ft) Bare or thin grass	Thick grass
Midday, sky clear		
Wind under 6 mi/hr. or cross wind	0.005–0.01	0.008–0.01
Head wind 6–12 mi/hr.	0.008–0.012	0.008–0.012
Tail wind 6–12 mi/hr.	0.005	0.005
Midday, overcast, or early morning or evening, clear		
Wind under 6 mi/hr. or cross wind	0.003	0.006
Head wind 6–12 mi/hr.	0.006	0.010
Tail wind 6–12 mi/hr.	0.002	0.005
Night, sky overcast		
Wind under 6 mi/hr. or cross wind	0.002	0.005
Head wind 6–12 mi/hr.	0.005	0.009
Tail wind 6–12 mi/hr.	0.001	0.004
Night, sky clear		
Wind under 6 mi/hr. or cross wind	0.001	0.004
Head wind 6–12 mi/hr.	0.005	0.008
Tail wind 6–12 mi/hr.	0.000	0.003

TABLE IV. Terrain loss coefficients for jungles—200 c.p.s.

Type of Jungle (see text for description of type)	(db/ft.)
1.	0.04
2.	0.03
3.	0.02
4.	0.015

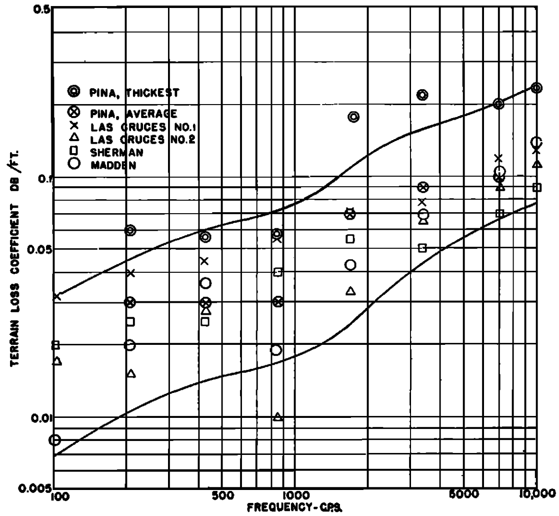

FIG. 9. Terrain loss coefficients for tropical forest areas.

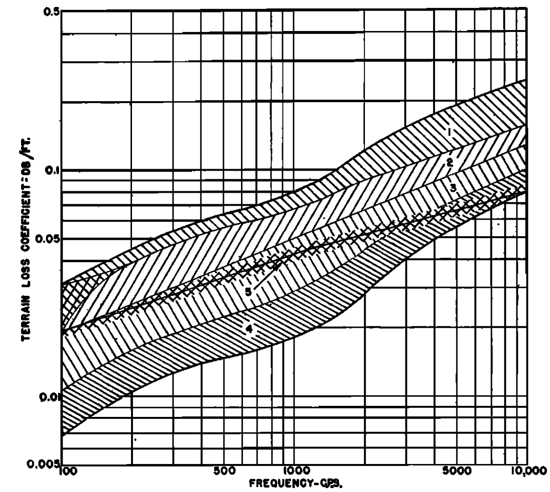

FIG. 10. A chart from which to estimate terrain loss coefficients for tropical jungles. Zone 1, very leafy, one sees a distance of approximately 20 ft., penetration by cutting; zone 2, very leafy, one sees approximately 50 ft., penetrated with difficulty but without cutting; zone 3, leafy, one sees a distance of approximately 100 ft., free walking if care is taken; zone 4, leafy, one sees a distance of approximately 200 ft., penetration is rather easy; zone 5, little leafy undergrowth, large bracketed trunks, one sees a distance of approximately 300 ft., penetration is easy.

is 200 c.p.s. For open terrain these coefficients are so dependent on weather that the values listed in Table III must be thought of as *estimates*; yet, the values do have a foundation in field measurements. Since in a jungle the terrain loss coefficients at 200 c.p.s. are essentially independent of daily weather changes, the values listed in Table IV are certainly not estimates;

they are scientific data. The vegetation of a jungle changes with the season; therefore, if the coefficients of Table IV are to be used with confidence, a jungle must be typed by observation every time it is involved in a sound transmission problem.

AMBIENT SOUND OF THE JUNGLE

Jungle Sounds

A jungle far removed from human activities at times may be deathly silent. At other times it is filled with animal sounds: humming, buzzing, chirping, noisy and musical "mate" calls; with the rustle of palms under wind action; with the sound of dropping and rushing water, the result of heavy dew and rain; and even with the sound of thunder. Seldom, if ever, do all possible jungle sounds join in a grand finale. When rain and wind are at their height, animal life is usually quiet; when the weather is fine, birds sing at daybreak; but insects, which have maintained a chorus all night, slowly bring their night calling to a close.

"The songs of birds and the calls of insects and amphibia are primarily indications of the breeding season and, since this period is of comparatively short duration and for each individual occurs only once a year, the major sounds produced by them are distinctly cyclical. In the tropics, however, there is not the concentration of breeding seasons of many species into a few months that one finds in Northern latitudes. While the peak of the breeding season for birds, for example, probably occurs in April, there are some birds nesting every month of the year and the main period extends from February to July. In the case of amphibia, the breeding seasons and resulting calls seem even less regular than with birds and more dependent on water conditions. Even in one spot like Barro Colorado Island all individuals of one species do not seem to come into breeding activity at the same time, as they do in Northern latitudes, with the result that there will be feverish activity and much singing for a few days followed by a lapse of a week or more with no activity. This all helps to make the general picture of animate sound in the jungle rather complicated."[6]

Ambient Sound Levels

During early December two twenty-four hour records of ambient sound levels were obtained; the first, during fair weather; the second, during stormy weather. The microphone was placed well within the jungle and approximately 300 feet from the measuring equipment. Readings of levels were made every 30 minutes for over-all and for seven frequency bands of octave band width. The equipment was standardized against a calibrated condenser microphone (W.E. 640-AA, No. 428), and the field microphone was furnished with a heating coil to keep it free from heavy dew during the night.

The intensity levels, measured every 30 minutes during the 24-hour runs, were averaged for two-hour periods. The data, originally intensity levels for octave bands, were first changed to levels for single frequency bands and then to levels for critical bands[7] and thus to a set of so-called masking level curves. (See Figs. 11–14.) Such curves are used in listening problems because they show directly the masking effect of the ambient jungle noise.

A daytime average masking level curve for a wet day in a typical jungle is plotted as "Jungle Ambient Noise" in Fig. 15. In this figure, the threshold of hearing for a typical American group is represented by the dashed line. The solid line represents the threshold of hearing for those with most acute hearing. A study of these curves reveals the fact that below 1000 c.p.s. the ambient noise masking level curve either is below or just touches the threshold hearing curve of the average listener. This means that for frequencies below 1000 c.p.s. the average person is not deafened by the noisy background found in a wet season jungle. This statement applies only to the quiet periods between animal calls, because the peaks were not included in the noise measurements; only the general more or less steady background out of which the occasional calls appear was measured. The listener will usually select these quiet periods; therefore, the ambient noise masking level curve depicted is the one to use in practical problems.

It is important to observe that between 1000

[6] "Recordings of jungle sound," OSRD No. 4704, February 17, 1945, pp. 6–14.

[7] H. Fletcher, "Auditory patterns," Rev. Mod. Phys. **12**, 47–65 (1940).

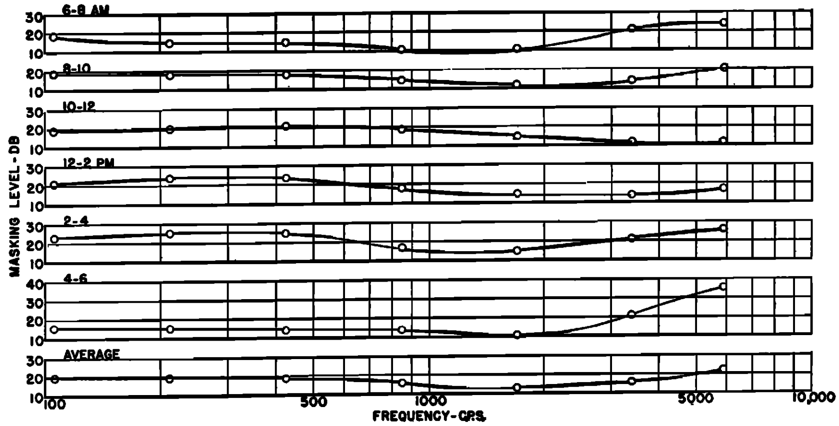

FIG. 11. Masking level curves, daytime, Madden Jungle.

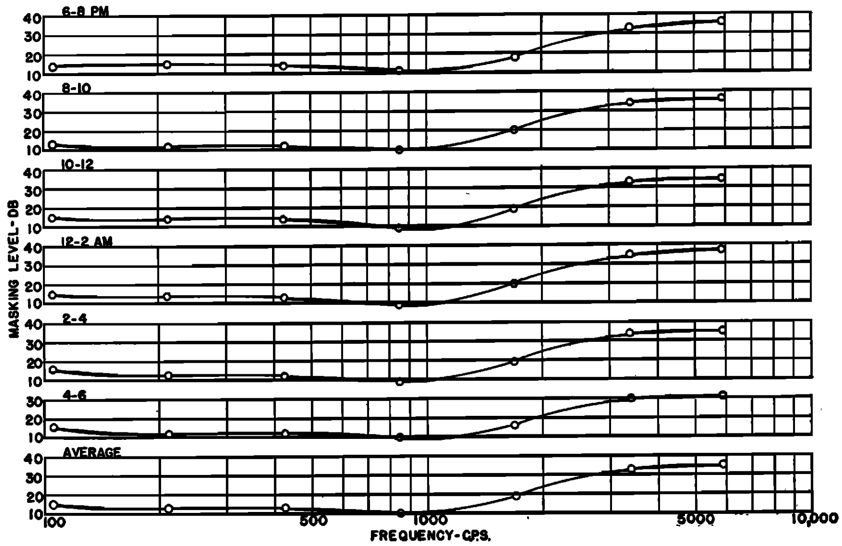

FIG. 12. Masking level curves, night-time, Madden Jungle.

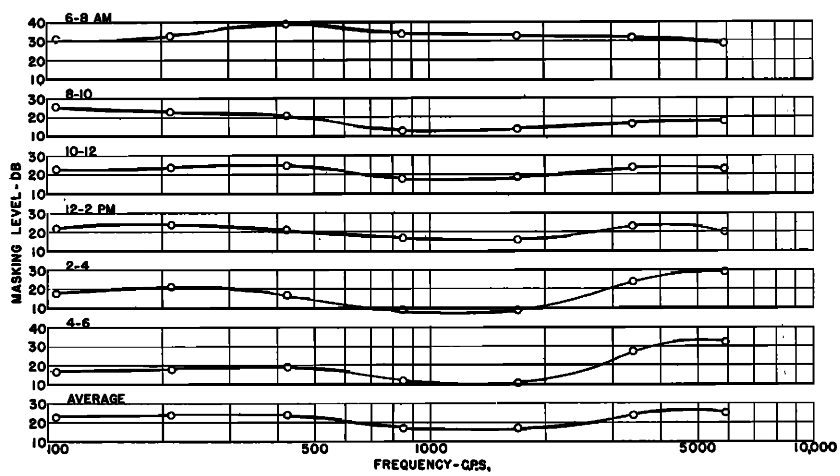

FIG. 13. Masking level curves, daytime, Las Cruces Jungle.

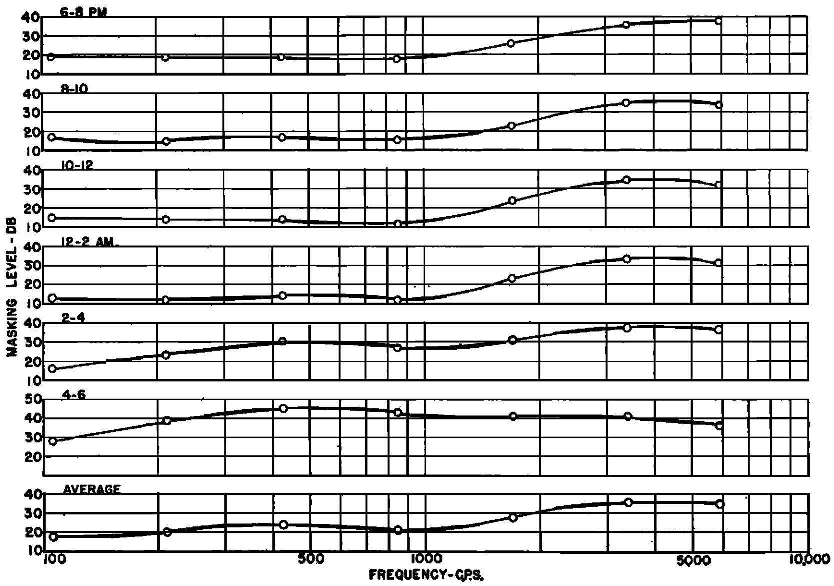

FIG. 14. Masking level curves, night-time, Las Cruces Jungle.

c.p.s. and 400 c.p.s. the average listener will hear as well as the one with very acute hearing, because the latter will be deafened by the ambient noise just enough to render him average also. But below 400 c.p.s. the listener with acute hearing will have a definite advantage. In general, then, an average listener located in a tropical jungle is limited by his threshold of hearing up to 1000 c.p.s. and by the masking of the jungle noise for frequencies above that.

Sound from a $2\frac{1}{2}$-ton army truck,[8] as measured 100 feet away in open terrain, has a masking curve as illustrated in Fig. 15. As the sound from the truck passes through the jungle, it suffers transmission loss and therefore the masking level curve representing the decreasing truck noise will move steadily down in level. But, since the terrain loss coefficient goes up with increasing frequency, the curves will also get steeper and steeper as it moves downward in level. Because of this rotation, the 200-c.p.s. sound will be heard last and 200 c.p.s. becomes the so-called optimum frequency when listening for a truck in a jungle. At 200 c.p.s. the difference in level between the masking curve of the truck (100 feet away in open terrain) and that of the ambient jungle noise is 32 db. In a typical jungle, with a terrain loss coefficient at 200 c.p.s. of 0.02 db/ft., the masking curve of the truck, as measured *100 feet away in the jungle*, would be approximately 2 db lower in level than that depicted in Fig. 15. Hence, the 32 db should be lowered to 30 db, and if the transmission loss which takes place in the jungle between a point 100 feet from the truck and the listener is just 30 db, then the truck will just be heard. Making use of Eq. (3), a calculation shows that the distance of the listener from the sound source (truck) is 750 feet.

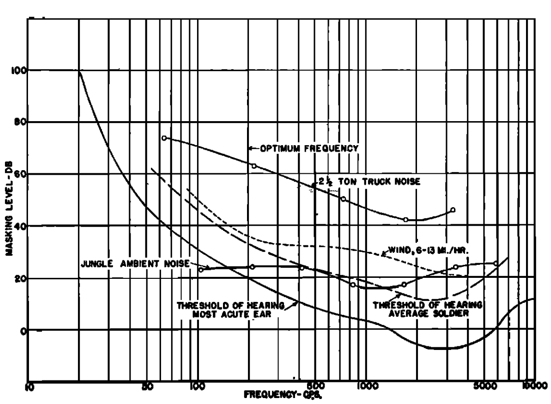

FIG. 15. Showing masking levels of certain noises.

In order to test the method just described, a sound level meter was set up 100 feet from the center of the Panama-Colon Highway, and the over-all maximum sound level was read for each

[8] OSRD No. 4254, August 21, 1944.

vehicle that passed. The time of passing was noted very carefully. A distance of 1000 feet from the highway was measured into the jungle on a line normal to the highway, and a listening post was set up. The observer listened very carefully for vehicle sounds and wrote down the time when the sound was heard. This process was continued for exactly two hours. A careful comparison of data revealed that no car with a level below 68 db at a distance of 100 feet was heard at a distance of 1000 feet; no car with a level above 75 db at a distance of 100 feet failed to be heard at 1000 feet. The "just heard" level can be placed at approximately 73 db. The over-all sound level 100 feet from a $2\frac{1}{2}$-ton truck is about 75 db. Therefore, the vehicles which were just being heard at 1000 feet were $2\frac{1}{2}$-ton trucks or their equivalent, a somewhat better range than predicted. But the audiogram of the listener shows him about 5 db better than average in the range below 500 c.p.s., and he listened for "peak" sounds. Thus, it appears that the experiment and the calculations are in good agreement.

JUDGING SOUND DIRECTION IN A JUNGLE

Method

The method consisted of three steps: the random firing of guns at selected locations in the jungle but unknown to the listeners, the judging of the sound direction for each shot, and the recording of each judgment on a specially prepared chart. The area of operation is known as the Pacora Maneuver Jungle.

The listening area, located in the midst of the jungle, was a small square, oriented to the cardinal points of the compass, with sides, designated as positions I, II, III, IV, set off by ropes. Twenty men, in groups of five, were located within the square. A group was assigned to each of the four positions and each man stood against a rope and faced outward. Thus, the twenty men all faced outward, but five faced north, five east, five south, and five west.

A single trial consisted of judging the direction of six shots, fired at random and in slow succession, time being given between shots for a judgment to be recorded. The order and speed of firing was controlled by telephone communication from a central point. A person was given four of these trials of six shots while facing in a given direction. After a cycle of four trials, each group moved to the position at its left, from I to II, II to III, III to IV, IV to I, thus changing the direction of facing by 90°. The experiment was finished when each group had stood in each of the four positions. When finished a total of 1920 direction judgments had been made.

The men were asked to pay no attention to compass directions, but to judge every sound direction in "terms of the clock," the 12 o'clock being *straight ahead no matter on which side of the square the listener stood.* The personnel had had experience in thus judging direction and readily adjusted to the method.

By changing the orientation of the listeners, as just explained, it was not thought necessary to relocate the firing positions. In general the last judgments were no better than the first judgments, and this is evidence that the pattern of the firing positions was not memorized and that the procedure was justified.

Summary of Results

In judging the direction of a shot in a jungle, the following conclusions seem to be supported by field measurements:

1. The probable error of judgment is large, of the order of 16.5°.

2. The error is greatest if the sound source is either directly in front or in back—the error may even show marked confusion in these directions.

3. The error is least if the sound source is near the axis passing through the ears.

4. Within the range studied—300 to 600 feet—the error decreases with the distance from the source.

5. Hearing two shots fired in succession in the same general direction does not help in determining the direction of the second shot. (This might not apply if by the time the second shot is fired the head has been turned to a more effective angle—see 9 below. Such a technique was not permitted in the experiment.)

6. There is a tendency to fail to remember the exact orientation of the head at the time a sound is heard and this may lead to recorded judgments with persistent errors in one direction—to the right, for example.

7. There is a minor tendency to bring the observed direction into line with the axis passing between the two ears.

8. Some observers are better than others—abilities seem to follow a normal distribution.

9. Although the response of a jungle to the sound produced in it will continue to be a hindrance, there is reason to believe that sound direction judgments may be improved by following two simple rules based on facts brought out in this investigation: (a) keep the orientation of the head at the time when the sound was heard clearly in mind; (b) remember that smaller errors are made when the sound source is near the axis passing between the ears.

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