Audio Frequency Atmospherics *

By E. T. BURTON and E. M. BOARDMAN

Various types of musical and non-musical atmospherics occurring within the frequency range lying between 150 and 4000 c.p.s. have been studied. Particular attention is directed to two types of the former, one a short damped oscillation, apparently a multiple reflection phenomenon, and the other a varying tone of comparatively long duration, probably related to magnetic disturbances. Several quasimusical atmospherics which appear to be associated with the two more distinct types are described. Dependence of atmospheric variations on diurnal, seasonal and meteorological effects is discussed. Characteristics of audio frequency atmospherics are shown in oscillograms and graphs.

Introduction

IN connection with a study of communication problems, observations of submarine cable interference were made over periods totaling about 20 months during the years 1928 to 1931. These experiments were conducted at Trinity, Newfoundland; Hearts Content, Newfoundland; Key West, Florida; Havana, Cuba; and at Frenchport, near Erris Head, Irish Free State. A few supplemental measurements of audio frequency atmospherics received on large loop antennas were made in 1929, 1931 and 1932. These experiments were made at Conway, New Hampshire, at two locations in New Jersey and in Newfoundland. Work carried out at the Newfoundland and New Hampshire locations has been commented upon in previous reports.[1]

Since, for the most part, industrial and communication interferences were of small magnitude at all locations, it has been possible to select for presentation data confined to atmospherics. These data will be limited mainly to the frequencies between 150 and 4000 c.p.s., although measurements were made over the range from 40 to 30,000 c.p.s.

The principal apparatus used at each location consisted of an especially designed vacuum tube amplifier with which all other apparatus was associated. The overall gains of the amplifiers used at the various locations varied somewhat according to the conditions to be met, the frequency characteristics being adjusted approximately complementary to that of the pick-up conductors. The Ireland amplifier consisted of seven transformer coupled stages grouped to form three units. The impedance at the junction points of units was

* Presented at U. R. S. I. convention, Washington, D. C., April 27, 1933. *Proc. I. R. E.*, 21, p. 1476, October, 1933.

[1] E. T. Burton, "Submarine Cable Interference," *Nature*, 126, p. 55, July 12, 1930; and E. T. Burton and E. M. Boardman, "Effects of Solar Eclipse on Audio Frequency Atmospherics," *Nature*, *131*, p. 81, January 21, 1933.

600 ohms to facilitate insertion of attenuators and filters. The maximum gain for the three amplifier units was 200 db, attenuators and filters being used at all times to control the output intensity. The amplifier was designed to minimize noise, inherent in such apparatus, and to be highly stable throughout long periods of practically continuous operation.

In addition to several high-pass and low-pass filters, 17 narrow band filters designed to cover in small steps the range from 150 to 3800 c.p.s. were available. A filter switching panel was used to facilitate observations of various frequency ranges in rapid succession.

The output was arranged to supply various recording and indicating devices. R.m.s. measurements were made by means of a thermocouple with a long period direct reading and recording meter. A device employing three-element gas-filled tubes was used to measure peak voltages. A magnetic recorder was employed in securing a few sound records of atmospherics. Oscillograms which are shown in this article were subsequently prepared from these records. The Ireland amplifier with some of its associated apparatus is shown in Fig. 1.

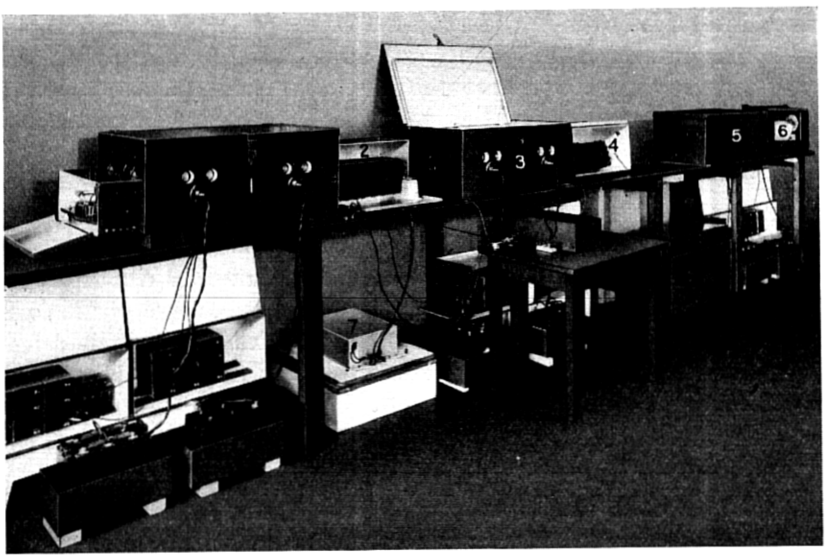

Fig. 1—Amplifier and associated apparatus used at Frenchport, Ireland.
(1) First amplifier unit
(2) 1st Attenuator
(3) 2nd Amplifier unit
(4) 2nd attenuator
(5) 3rd amplifier unit
(6) Recorder
(7) Band pass filter

The amplifier with each of the filters taken separately was calibrated with input supplied by the thermal agitation in standard resistances ranging from 50 to 250 ohms. The calibration temperature was approximately 23° C. Check calibrations were made weekly and at such times as changes were made in the apparatus. The stability of the entire system was such that over periods of months measurements were made with an accuracy closer than $\pm$ 1/2 decibel.

In interpreting data on atmospherics of low amplitude, such as received on submarine cables, it is necessary to take into account the random voltages generated in the amplifier circuits and the thermal agitation voltages of the conductor connected to the amplifier input. Both of these voltages appear in the output circuits mingled with the amplified atmospherics. The former originate principally in the first stage of the vacuum tube amplifier. Thermal agitation produces a random voltage, uniformly effective at all frequencies. The r.m.s. amplitude of this voltage is dependent upon the frequency range considered, the resistive component of the impedance of the conductor and the temperature of the conductor.[2] The conductor in this case is the cable or antenna circuit. The r.m.s. values of these voltages, when integrated over periods of time comparable to those occupied in taking data on atmospherics, are substantially steady; therefore, their separation from the atmospheric voltages is not difficult. Corrections for both amplifier and thermal noises have been made on the data presented.

Observations of audio frequency atmospherics received on long antennas and loop aerials have been reported by several observers.[3] Their accounts describe the general characteristics, although some confusion has occurred in identification of the musical atmospherics. In view of the fact that the apparatus used by us was particularly adapted to reception and analysis of frequencies in the audio range, it appears that our data may add considerably to the information previously disclosed.

Types of Atmospherics

Audio-frequency atmospherics observed on submarine cables are essentially the same as those received from a long antenna except for high attenuation and frequency discrimination attributable to the cable characteristics and to the shielding effect of sea water.[4] The low

[2] J. B. Johnson, "Thermal Agitation of Electricity in Conductors," *Phys. Rev.*, *32*, p. 97, July, 1928.

[3] H. Barkhausen, "Whistling Tones from the Earth," *Phys. Zeits.*, 20, p. 401, 1919. T. L. Eckersley, "Electrical Constitution of the Upper Atmosphere," *Nature*, *117*, p. 821, June 12, 1926.

[4] John R. Carson and J. J. Gilbert, "Transmission Characteristics of Submarine Cables," *Jour. Franklin Inst.*, *192*, p. 705, December, 1921.

frequencies, when observed on a submarine cable, are of comparatively high amplitude, appearing as a deep rumble intermittently broken by noises variously described as splashes and surges. The range from 500 to 1500 c.p.s. generally consists largely of clicks and crackling sounds which accompany the low-frequency surges. At times substantial amplitude increases occur accompanying quasi-musical sounds, which may dominate this frequency range. In the upper voice range intermittent hissing or frying sounds are observed, often accompanying surges in the low-frequency range. Above 1800 c.p.s. occur at least two ranges which at times possess slight tonal characters. In addition to the slightly musical sounds, two varieties of distinct musical atmospherics have been observed and given the onomatopœic names "swish" and "tweek." Particular interest attaches to these because of their extraordinary character.

Diurnal and Seasonal Characteristics

The daytime non-musical atmospherics consist ordinarily of intermittent low-amplitude impulses. As a general rule the night-time intensities are considerably higher; the impulses being more frequent and more prominent than during the daylight hours. The night intensity is further increased by the presence of the type of musical atmospheric known as tweek.

During a usual day, the intensity of audio-frequency atmospherics from sunrise until mid-afternoon is comparatively low. During the afternoon, a slow rise may or may not occur. Shortly following sunset, a gradual increase of intensity is usual. This rise continues for two hours or more after which a high level is maintained rather consistently until shortly before daybreak. A brief increase sometimes occurs at this time followed by a steady decrease, the daily minimum being reached usually shortly after sunrise.

Fig. 2 shows examples of summer and winter audio-frequency atmospheric intensities over 24-hour periods. While these curves show the usual characteristics, extraordinary conditions may result in wide variations. The occurrence of local electrical storms or intense disturbances of the earth's magnetic field usually contribute markedly to these anomalies.

The diurnal amplitude variations of certain types of atmospherics may be reasonably explained by assuming the continued presence of an audio-frequency reflecting layer in the upper atmosphere, and assuming a low lying ionized attenuating region [5] to be present during

[5] Such a region affecting radio frequencies is described by R. A. Heising, *Proc. I. R. E.*, 16, p. 75, January, 1928.

daytime only. During the sunlight hours, disturbances occurring in the vicinity of the observation point may be received by direct transmission without unusual attenuation. Atmospherics of distant or high origin should suffer considerable attenuation in passing through

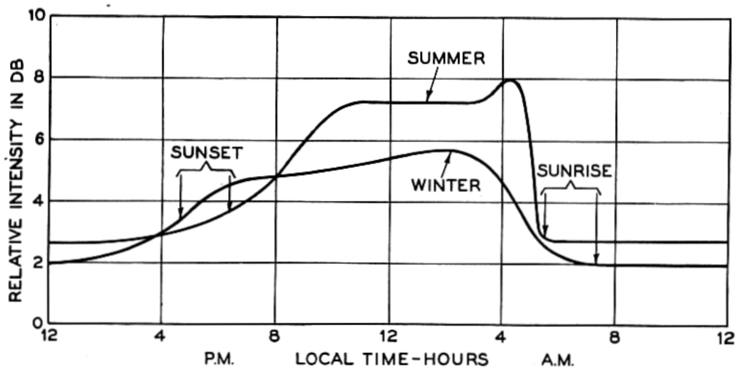

Fig. 2—Typical diurnal intensity curves, for frequency range from 150 to 3000 c.p.s.

the damping region. Following sunset, the damping ionization may be expected to gradually dissipate, resulting in a slow increase of the static intensity as transmission from the upper atmosphere and from horizontally distant regions is improved.

It is probable that in the morning the damping ionization appears at a given point almost immediately upon arrival of the first direct sunlight, and that the transition period corresponds to the time required for the earth to rotate through an angle corresponding to that section of the damping region which may appreciably affect the atmospherics reaching the observation point.

Our observations have shown that the general intensity of the regularly occurring types of atmospherics increases in the spring, the rise beginning about March. During a period from possibly May to September, the intensity is comparatively high. During September and October a reduction occurs, and from the latter part of October until March the intensity is low. The periods as given above are approximate, since they are based on fractional year observations in all except one case.

Comparison of Fig. 2 with diurnal variation curves of Potter [6] for 50 kilocycles and 2 megacycles, and with seasonal variations presented by Espenschied, Anderson and Bailey [7] for 50 kilocycles shows definite similarities.

[6] R. K. Potter, "Frequency Distribution of Atmospheric Noise," *Proc. I. R. E.*, *20*, p. 1512, September, 1932.
[7] Espenschied, Anderson and Bailey, "Transatlantic Radio Telephone Transmission," *Proc. I. R. E.*, *14*, p. 7, February, 1926.

TWEEKS

A tweek consists of a damped oscillation trailing a static impulse. Its audible duration appears to be less than 1/8 second and the initial peak amplitude may approximate that of the maximum audio frequency static impulses.

Oscillographic reproductions of sound records obtained in Ireland disclose that the tweeks practically always start above 2000 c.p.s. and reduce very rapidly toward a lower limiting frequency where a considerable portion of the time of existence is spent. In some cases the highest observed frequency at the beginning of a tweek was in the vicinity of 4000 c.p.s., which was the upper transmission limit of the apparatus. In Fig. 3 is shown an oscillogram of tweeks trailing

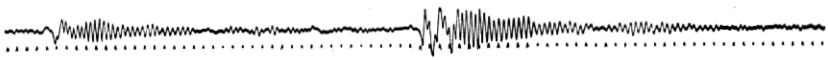

Fig. 3—Oscillogram of tweeks. Timing impulse frequency, 1000 c.p.s.

static surges. While in these tweeks, any initial high frequencies are obscured by the prominent static surge, some oscillograms have been made while using electrical filters to suppress the frequencies mainly responsible for the initial impulse. These oscillograms often showed

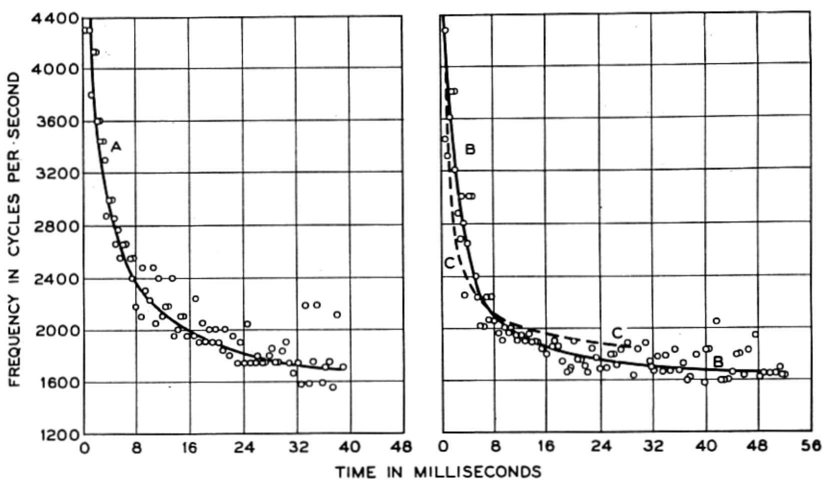

Fig. 4—A and B, tweek frequency variation curves. C, computed curve.

initial frequencies as high as 4000 c.p.s. Two tweek frequency determinations made from oscillograms are shown in Fig. 4. These illustrate the initial rapid frequency reduction and the subsequent gradual approach to a constant. While not an accurate definition, frequency, as determined from the oscillograms, is taken as the reciprocal of the time spacing of successive impulses. Due to the difficulty in accurately measuring these short time intervals, especially in the presence of other forms of atmospherics, there is a possibility of error which might account for the irregularities in the location of points. However, irregularities in effective height of the reflecting layer might be expected to produce a like result.

With one possible exception,[8] tweeks have never been observed by us during daytime except near sunrise and sunset. In the usual case, the intensity of static impulses increases during the early evening with no indication of tonal quality. At twilight certain of the impulses are observed to be accompanied by a slight indication of a highly damped frequency. Shortly thereafter the characteristic tweek tone appears, often trailing a good share of the static impulses. Both tweek rate and intensity ordinarily increase for some two hours. For the remaining hours of darkness the tweeks, usually of low damping, continue with many irregular variations in intensity. Just previous to the approach of daylight a brief increase in tweek rate often occurs followed by a rapid reduction in both intensity and rate of occurrence. The last highly damped tweek is usually observed several minutes before sunrise.

H. Barkhausen [9] in attempting to explain the type of atmospheric tone known as the "swish" or the "long whistler" considers the multiple reflection of an impulse. While our observations indicate this theory to fail in explanation of the swish, it appears to be applicable to tweeks. According to this theory a tweek may be produced by energy, from a source of momentary static disturbance, arriving at a receiving point as a series of impulses. The first impulse arrives by direct transmission. Shortly thereafter a second impulse arrives after having suffered one reflection at an ionized layer in the upper atmosphere. The third impulse arrives after two reflections from the ionized layer and one from the earth's surface. Other impulses follow in like manner. In case the origin of the disturbance is not near the observation point, the time spacing of the observed impulses results in a reducing frequency, initially varying rapidly and finally approaching an asymptotic value. The initial frequency is dependent upon the distance from source to observer and the reflecting layer height, while the lowest frequency depends upon the height alone. The failure of tweeks to appear in daytime may be attributed to damping by sunlight ionization at low altitudes. Occasional highly damped

[8] E. T. Burton and E. M. Boardman, "Effects of Solar Eclipse on Audio Frequency Atmospherics," *Nature, 131*, p. 81, January 21, 1933.

[9] H. Barkhausen, *Proc. I. R. E., 18*, p. 1155, July, 1930.

and weak tweeks observed before sunset or after sunrise probably originate at considerable distance respectively to the east or west within regions not exposed to sunlight.

The multiple reflection theory of tweeks, as explained above, concerns a single wave train originating in a disturbance located near one of the reflecting surfaces. It may be shown that an impulse originating anywhere in the intervening space might produce a similar effect, although the initial frequency would be altered by the location in altitude. Furthermore, were the point of origin well separated from both surfaces, two simultaneous wave trains differing somewhat in rate of frequency change would occur. Phasing effects, which might be attributed to this have been found in several oscillograms.

Based on the multiple reflection theory, the curve *C* in Fig. 4 was calculated assuming the point of origin to be located near the earth's surface. The altitude of the reflecting layer was taken as 83.5 km. (55 miles) and the distance between source and observer as 1770 km. (1100 miles). While this curve only roughly approximates the form of the tweek curves of Fig. 4, an explanation of the discrepancy may lie in a variation in effective layer height in accordance with the change in angle of incidence of the successive impulses. Such a relation in the case of radio frequencies has been described by Taylor and Hulburt.[10]

Comparison of the lower limiting frequencies of individual tweeks with an oscillator calibrated in small steps has shown at times an almost continual drift in frequency. This may be interpreted as a corresponding variation in the effective height of the reflecting layer. In one five-minute period during complete darkness, examination of 24 tweeks showed the lower limiting frequency to vary irregularly between 1690 and 1720 c.p.s. This indicates a variation in effective layer height between approximately 88.5 and 87 km. The variations of lower limiting tweek frequencies noted at our various observation points have indicated the reflecting layer to vary between 83.5 and 93.2 km. during the hours of complete darkness. No marked variations of mean tweek frequency, in respect to either season or latitude, have been observed.

During experiments carried out in New Jersey and New Hampshire,[8] a calibrated tone producing apparatus was available whereby frequencies of musical atmospherics, as observed by ear, could be closely followed. It was found that in addition to tones, which could be considered as individual tweeks, there appeared at times a slight, almost unbroken resonance quality in the static. This resonance was

[10] A. H. Taylor and E. C. Hulburt, "Propagation of Radio Waves," *Phys. Rev.*, *27*, p. 189, February, 1926.

always quite obscure, which may account for its escaping observation in previous work. It appeared to consist of a band of frequencies, the midpoint of which could usually be determined with an accuracy of approximately ± 50 c.p.s. The resonance was usually observed during the evening and morning twilight periods when the damping of tweeks was high, and appeared to be closely connected with the tweeks themselves, although ordinarily showing a somewhat higher frequency. During the hours of total darkness the resonance was either absent or obscured by tweeks. At evening, resonance sometimes appeared at sunset or a short time before. Usually the first highly damped tweeks were observed at about the same time. In the early morning the resonance was observed sometimes several minutes after the last tweek.

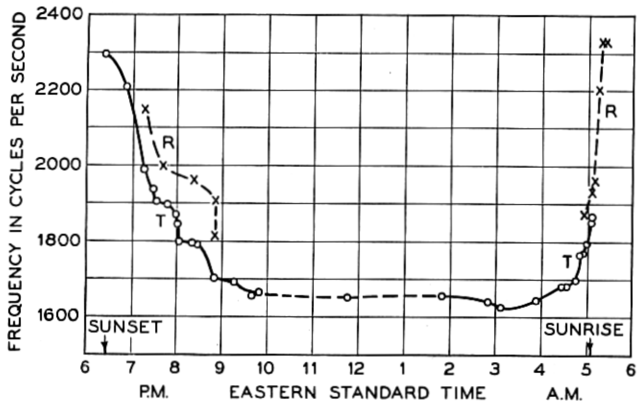

Fig. 5—T, T, lower limiting tweek frequencies.
R, R, evening and morning resonance frequencies.

Fig. 5 shows frequencies of the resonance tone and the lower limiting frequencies of individual tweeks as determined by aural observations made in the latter part of August, 1932. The tones began with frequencies well above 2000 c.p.s. and decreased to approximately 1650 c.p.s. in a period of $2\frac{1}{2}$ hours. The resonance disappeared as the tweeks approached the usual night intensity. Approximately 1/2 hour before sunrise the resonance reappeared and a rapid frequency increase began. The last definite tweek observed in the morning was still under 2000 c.p.s., although the resonance rose well above this frequency before disappearing. In approximate figures, the effective reflecting surface for audio frequencies is indicated by the data of Fig. 5 to be located at an altitude of 61 km. at sunset and to rise to 88.5 km. in a period of $2\frac{1}{2}$ hours. Half an hour before sunrise the indicated altitude is 87 km. and at 15 minutes after sunrise it has returned to 61 km.

It is possible that aural frequency observations result in erroneous determinations because of the rapid reduction in frequency which occurs during a tweek. If the damping is not excessive, the ear distinguishes the low frequencies of the tweek and thereon establishes the tonal characteristic. If the damping is great the lower frequencies may be reduced below audibility while the ear may distinguish the higher or intermediate frequencies as possessing tonal quality and thereon may base its estimation of frequency. Judging from the observations of resonance, where the sound may be almost continuous, it appears likely that these frequency determinations are of fair accuracy.

Observations have been made at various times to determine the time of appearance of the first and last tweeks of the night-time period. Fig. 6 shows the time of first tweek to be quite variable, extending from

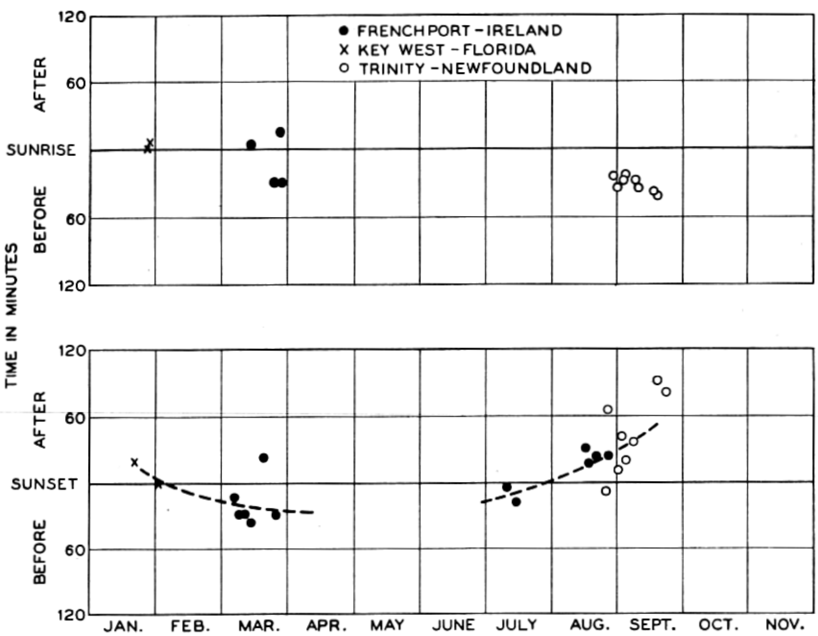

Fig. 6—Observations of first and last tweeks of night-time periods.

approximately 1/2 hour before sunset to $1\frac{1}{2}$ hours after. The time of the last tweek varies from 40 minutes before sunrise to a few minutes after sunrise. The points obtained in Florida differ somewhat from those obtained in Newfoundland and Ireland, possibly because of the difference of latitude. Since the Florida observation point lies approximately 24° south of the latter locations, it follows that here the interval between the time of incidence of the sun's rays at the position assumed for the damping region and actual sunrise is somewhat less than at the northern observation points. However, a seasonal effect may be responsible as is indicated by the dotted curve in Fig. 6.

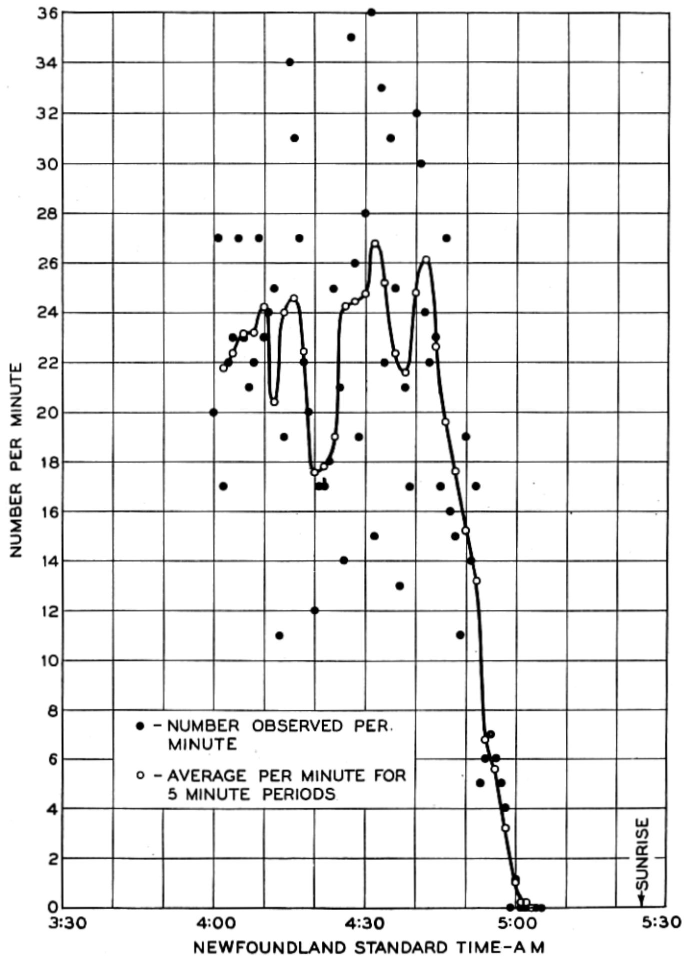

Fig. 7—Rate of occurrence of tweeks. Data taken during a period of high intensity.

There is a distinct seasonal variation in tweek numbers, the rate being consistently high during the summer and low during the winter and early spring—following approximately the variations in non-musical atmospherics. At times in the summer, tweeks have been observed to occur at rates exceeding 50 per minute while during the winter as few as one or two in five-minute periods is not unusual. A night completely free from tweeks has not been observed at any of our experimental locations. Fig. 7 shows results of a summer tweek count when the rate was high. This curve illustrates well the rapid variations which may occur during the morning twilight period.

Swish and Related Musical Atmospherics

Swishes observed in Newfoundland have been described as, "Musical sounds, such as made by thin whips when lashed through the air." [1] They are ordinarily distinctly musical in character, the frequency varying sometimes downward and at other times upward. At times upward and downward progressions are observed simultaneously. During the Newfoundland observations, the frequencies lay usually between 700 and 2000 c.p.s., but the individual tones in most cases did not exceed an octave in variation. The duration of these earlier observed swishes varied from approximately 1/4 second to more than a second. In Ireland swishes of the same nature were observed, but a more usual type was longer and much clearer in tone. These swishes were audible from 1/2 second to possibly 4 seconds and covered a frequency range from well below 800 to above 4000 c.p.s. To the ear the frequency appeared to progress steadily with perhaps a slight lingering near the termination of the descending variety.

While in the earlier Newfoundland observations the swish usually appeared to be accompanied by a rushing sound, later work disclosed many nearly clear whistling tones which may be identified as the "long whistlers" reported by other observers. These sometimes swept upward or downward through the entire voice range and at other times varied only through the range between approximately 3000 and 4000 c.p.s. On a few occasions the whistles have been observed to hesitate and warble slightly before disappearing. Series of swishes have been observed following each other with almost perfectly regular spacing of a few seconds, the train persisting on occasion for as long as a few minutes. Some of these trains have successively increased in intensity, terminating abruptly while other trains have reduced gradually until submerged in the usual static. In addition to the distinctly musical tones, swishes have been heard in which the rushing or hissing sound is prominent while the tone may be nearly or entirely absent. Our observations have shown these often to appear during periods when the whistling tones are frequent, to correspond approximately to the length of the whistles and at times to appear in regularly spaced trains.

Many observations have indicated a relation between swishes and the quasi-musical sound in the range between 500 and 1500 c.p.s., which in an earlier paper has been called "intermediate frequency noise." [1] Frequently this noise is first observed as a subdued jumble of hollow rustling or murmuring sounds. It often increases regularly in intensity for some time, after which faint swishes may begin to appear in the same frequency range. The swishes may increase in intensity and length, eventually submerging the murmuring sound. Occasionally the murmuring has continued for a short time after the swishes have reduced in amplitude or have disappeared. As a general rule the murmuring is not audibly prominent although it seems to be rather continuous in character. As a result it may considerably increase the atmospheric intensity in the intermediate voice range.

On a few occasions musical high frequencies similar in general character to the murmuring have been observed. This sound appears as a continual chirping or jingling in the vicinity of 3200 c.p.s. The amplitude is usually low and the duration short. Like the murmuring sound, it appears to accompany periods during which swishes are present, and probably is composed of large numbers of short, overlapping, high-frequency swishes.

These types of atmospherics appear to have no connection with the time of day, or with local weather conditions and there is no indication of any correlation with the time of year. During some periods they have been observed frequently during days and nights for possibly 48 hours or longer. They have been found at times to persist steadily through the early morning, bridging the transition period when the more common forms of atmospherics rapidly change character. At times several weeks of daily observation have passed with practically no appearance of swishes or related sounds.

During periods of prominent swishes the variation of intensity is usually gradual with maxima and minima spaced at irregular intervals of possibly a few minutes. At maxima, the swish may approximate the intensity of the usual audio night-time atmospherics. The intensity which swishes may attain is evidenced by their occasional observation without use of amplifying apparatus. A twelve-mile telegraph line free from power interference has been found a satisfactory antenna, and with a telephone receiver between the line and earth, swishes of remarkable clearness have been observed. Tweeks have been heard with the same equipment.

In the short time during which the sound recording apparatus was available in Ireland, swishes were very infrequent with the exception of one day when all swishes were of the descending frequency type.

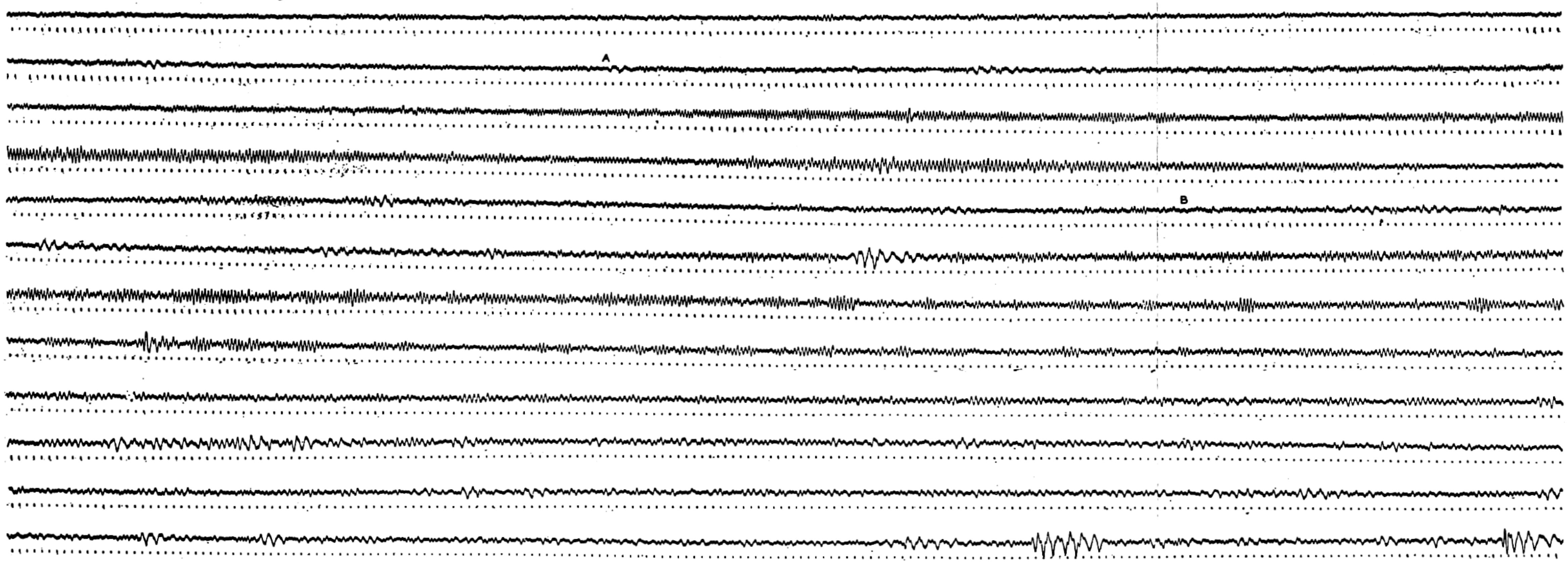

Fig. 8—Oscillogram of overlapping pair of swishes. A and B denote visible beginnings of the respective wave trains. Timing impulse frequency, 1000 c.p.s.

These swishes were unusual in that they appeared in overlapping pairs. Three minutes of record was obtained containing seven swish pairs. A representative oscillogram, shown in Fig. 8, is a record of 2.4 seconds,

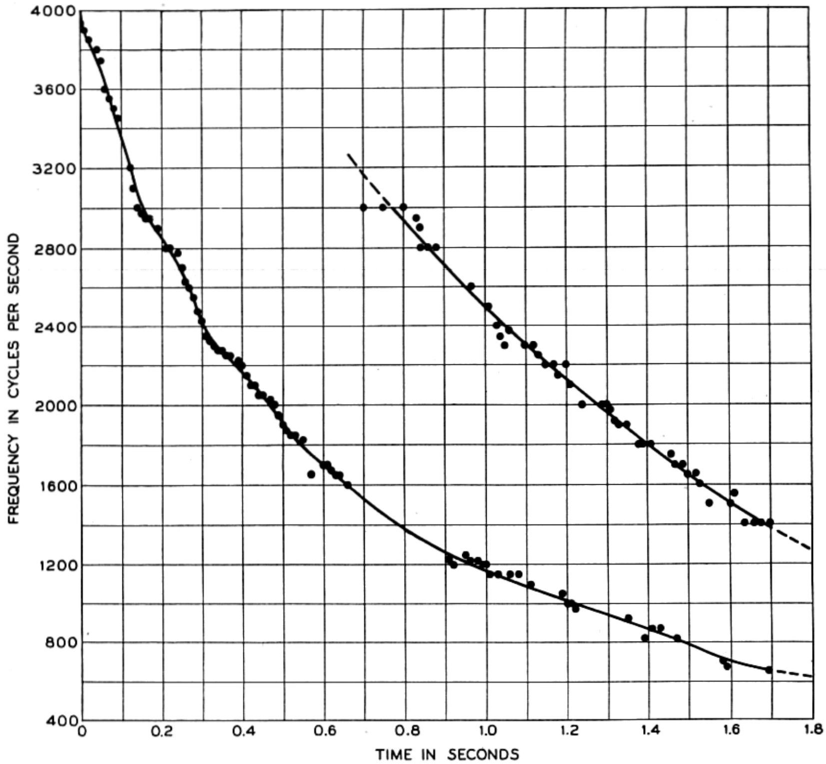

Fig. 9—Frequency curve of the swish pair shown in Fig. 8.

containing all that could be identified as a swish pair. The points "*A*" and "*B*" denote the visible starts of the first and second swishes respectively. Filters used during the recording of this oscillogram account for the absence of frequencies above 3000 c.p.s. and below 600 c.p.s. The frequency variation of this swish pair with time is shown in the curve of Fig. 9.

Eckersley [11] has reported observations of descending whistling tones following static crashes after a quiet period of a few seconds. During the New Hampshire observations this phenomenon was observed frequently. The swishes were observed to follow certain distinctive static crashes. This type of disturbance consisted of low and inter-

[11] T. L. Eckersley, "Radio Echoes and Magnetic Storms," *Nature, 122,* p. 768, November, 1928.

mediate impulses, persisting for a fraction of a second, accompanied by an unusually intense frying sound, indicating a predominance of high frequencies. At no time did this type of disturbance appear to possess marked tonal quality. Each impulse was followed by a quiet period after which a swish occurred. During several periods when the static was sufficiently intermittent, the interval between the beginning of the static impulse and the beginning of the swish was timed. Approximately 70 observations were made, the shortest period recorded being 1.2 seconds and the longest, accurately determined, 3.0 seconds. Many ranged between 2.5 and 2.8 seconds. No consistent progression of the length of this swish lag was observed although at certain times a predominance of either long or short periods existed. Later work indicated the long and short periods to be about equally divided between night and day.

During one night of the New Hampshire work an auroral arc appeared extending from northwest to northeast. Near the northwest end of the arc frequent flashes occurred, but these were too obscure for any details to be made out. A similar but much weaker flashing was observed to the southwest. At times the flashes appeared to extend along the horizon from northwest to southwest. By visual observation while listening to the atmospherics, it was found that nearly every flash coincided with a static crash possessing the prominent frying sound. These crashes were in most cases followed by swishes, usually of the descending variety, although occasionally a short ascending whistle occurred simultaneously with the start of the descending swish.

According to information supplied by the United States Weather Bureau, no lightning storms occurring during this period lay in the direction where flashes were observed to be concentrated and no storms were reported as near as 100 miles to our observation point. The Weather Bureau supplies the information that, under favorable reflecting conditions, lightning flashes might be seen 40 miles, but could not be seen 100 miles. It therefore appears reasonable to suppose that the flashes observed were of auroral origin. A report supplied by the United States Magnetic Observatory at Tucson, Arizona shows a magnetic storm beginning August 27. Through the following days the disturbance gradually reduced, reaching a low level on September 1. Our observations show the swish intensity to be high from the evening of August 30, when observations began, to September 1. Through September 1 and up to the termination of the test on the morning of September 2, the swish intensity appeared to be reducing although occasional high intensity periods occurred. These and earlier data of like nature obtained by us and others indicate a correlation between swish and magnetic disturbances. The accepted connection between auroral and magnetic field variations might justify a supposition that auroræ and whistling tones may be directly related as indicated by the New Hampshire observations. An assumption that the tones originate at the altitudes usually occupied by auroral displays might lead to an explanation of the apparent absence of marked diurnal variations in the swish tones. The observed correlation between certain atmospheric crashes and the subsequent swishes appears to indicate either dependence of the latter on the former or origin of the two from a common source of energy. The first assumption points to multiple reflection or dispersion phenomena which produce either ascending or descending tones. The time lag between the static impulse and the following swish would indicate either a low velocity or the traversing of a great distance. In either case, low attenuation is indicated by the long duration of some tones. It appears possible that the two radiations may result from sequential events occurring in the upper atmosphere by means of which non-musical as well as musical atmospherics are produced. Assuming an emission of energy which persists more or less steadily over a period comparable with the duration of a swish, it is possible to account for the approximately uniform amplitude of a swish without the necessity of assuming a very low damping.

It is suggested that swishes may be related to the occasionally observed phenomenon of swinging and flashing auroral beams. In this case it appears necessary to consider a cyclic process in the behavior of the aurora which would account for the time lag between the radiation of an initial static disturbance and the following varying tone. The varying tones might be produced by energy radiated from swinging beams resonating within the space separating beams or in the space between a beam and a stationary reflecting layer.

It might be possible for standing waves to occur within a beam, variations in the length or other constants of the path producing the varying tones.

A correlation between swish and auroral phenomena is indicated in statements by witnesses of auroral displays. Professor Chapman [12] reviews the testimony of many observers who have witnessed auroral displays at extremely low altitudes. Some attest to having stood within the glow and to having heard, directly from the atmosphere, disturbances accompanying the visible phenomena. Some of their sound descriptions follow:

[12] Prof. S. Chapman, "Audibility and Lowermost Altitude of Aurora," *Nature, 127*, p. 341, March 7, 1931.

"Quite audible swishing, crackling, rushing sounds"
"A crackling so fine it resembled a hiss"
"Similar to escaping steam, or air escaping from a tire"
"Much like the swinging of an air hose with escaping air"
"The noise of swishing similar to a lash of a whip being drawn through the air"
"Likened to a flock of birds flying close to one's head"

Some of these phrases coincide with those used by us in describing swishes. Certainly the correlation of sound descriptions is remarkable.

Dr. J. Leon Williams,[13] an observer of auroræ, comments on the sounds thus: ". . . On several occasions I have heard the swishing sound. The sound accompanies only a certain type of auroral display. I have never heard this sound except when those tall, waving columns, with tops reaching nearly to the zenith were moving across the sky. . . . When these tall sweeping columns die down the sound, according to my experience, disappears."

Consideration has been given to the likelihood of swishes or other appreciable audio frequency disturbances being produced by meteors. Lindemann and Dobson [14] estimate the energy liberation of an average meteor to exceed 3 kilowatts during the glowing period, and Skellet [15] states that a meteor may throw out an ionized trail extending laterally to a distance of a few kilometers. It has appeared advisable to search for magnetic disturbances which might show tonal qualities by resonance between the meteoric trail and some established reflecting surface. During two nights atmospherics were received with an audio-frequency amplifier and a loop antenna, located at a point in New Jersey. Observation of twenty-nine meteors, including six which could be classified as quite bright, disclosed no correlation with the sounds of audio-frequency atmospherics.

Some Theories of Musical Atmospherics

In a paper entitled "Whistling Tones from the Earth" Barkhausen [16] describes observations made during the World War on an atmospheric, which appears to have been the same as the descending swish heard by us.

He states, "During the war amplifiers were used extensively on both sides of the front in order to listen in on enemy communications. . . . At certain times a very remarkable whistling note is heard in

[13] "The Sound of the Aurora," *Literary Digest*, *112*, p. 28, February 20, 1932.
[14] Prof. F. A. Lindemann and G. M. B. Dobson, "Theory of Meteors," *Proc. Roy. Soc. Lond.*, *102*, p. 411, 1923.
[15] Skellet, "Effect of Meteors," *Phys. Rev.*, *37*, p. 1668, 1931.
[16] H. Barkhausen, loc. cit.

the telephone. So far as it can be expressed in letters the tone sounded about like *pēou*.[17] From the physical viewpoint, it was an oscillation of approximately constant amplitude, but of very rapidly changing frequency . . . beginning with the highest audible tones, passing through the entire scale and becoming inaudible with the lowest tones. . . . The entire process lasted almost a full second."

Barkhausen presents two possible explanations for these sounds. The first assumes the presence of a reflecting layer in the upper atmosphere. An electromagnetic impulse originating at the earth's surface arrives at a distant receiver first over the direct path and then from reflections in the order 1, 2, 3, to n. Such a series of reflections would result in a wave train of rapidly diminishing frequency becoming asymptotic to a value dependent upon the height of the reflector.

The second of Barkhausen's theories depends upon ionic refraction in the Heaviside layer, resulting in the breaking up of an impulse into its component frequencies and a delay in the transmission of the lower frequencies with respect to the higher. It gives a rate of frequency progression which varies with distance and with the refractive index of the medium.

Eckersley[18] in a paper on "Musical Atmospheric Disturbances" discusses apparently the same type of atmospherics. As an experimental background he notes frequent observations of audio-frequency disturbances received over large radio antennas. He states: "These (tones) have a very peculiar character: the pitch of the note invariably starts above audibility, often with a click, and then rapidly decreases, finally ending up with a low note of more or less constant frequency which may be of the order of 300 to 1000 a second.

"The duration . . . varies very considerably; at times it may be a very small fraction of a second, and at others it may be even 1/5 of a second." He observes that they are infrequent in morning, increasing throughout the day and reaching a maximum during the night. He develops a theory based on ionic refraction to account for these disturbances.

It appears that in these latter observations both swishes and tweeks were heard, but were not recognized as distinct phenomena. Such an error might be attributed to the irregularities of response which are common in the ordinary telephone receiver.

Barkhausen's first theory fails to explain swishes because of their upward as well as downward progression, long duration and frequency range. The theory, as previously pointed out, is adaptable to the

[17] *Pēou* slowly pronounced in a whisper excellently portrays a descending swish accompanied by the rushing sound.
[18] T. L. Eckersley, *Phil. Mag.*, *49*, p. 1250, 1925.

explanation of tweeks. It does not appear probable that either Barkhausen's or Eckersley's refraction theory properly explains the tweek because of its lower limiting frequency of approximately 1600 c.p.s. It seems more than mere coincidence that this frequency is in the range that the multiple reflection theory predicts. Any theory adequately explaining the swishes or long whistlers should account not only for long duration and apparently constant amplitude but for upward as well as downward progression and freedom from diurnal changes in tonal qualities.

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