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Measured Frequency Spectra of Very-Low-Frequency Atmospherics[1]

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New spectroscopes recording continuously the amplitude-frequency spectra of vlf atmospherics have been developed. Two receivers cover the frequency ranges 1 to 10 kc and 5 to 70 kc sweeping the respective bands repeatedly, and their outputs are displayed on intensity modulated cathode-ray tubes which are photographed on slowly moving film.

Observations have been carried out since June 1958, and it appears that the results provide an excellent experimental basis for comparisons with the mode theory of vlf ionospheric propagation. It is found that the frequency spectrum of distant atmospherics indicates a pronounced absorption near 3 to 5 kc, a broad intensity maximum around 10 to 20 kc, and a general decrease towards higher frequencies with undulating peaks. The selective absorption bands appearing in the spectrum are variable according to the time of day and seasons. These changes may be interpreted loosely as an ionospheric effect which is associated with the cutoff frequency of the waveguide bounded by the earth and the ionosphere. The solar flare effect on vlf atmospherics propagation is also revealed, which indicates a sudden shift of the spectrum to higher frequencies owing to the increase of ionization and the lowering of a reflecting height of the ionosphere.

1. Introduction

Considerable attention has been given recently to the very-long-distance propagation of radio waves in the very-low-frequency band (vlf). It is known that naturally-occurring atmospherics can provide excellent information about vlf propagation. Many investigators have found that vlf waves propagate to great distances with very small attenuation; however, they have also found evidence of a pronounced absorption band between 2 to 4 kc. Chapman and his colleague [1, 2],[3] for example, have made precise observations on waveform characteristics as well as the amplitude-frequency spectra of individual atmospherics. Their results showed that the spectrum of atmospherics varies with the distance of propagation, indicating the existence of an appropriate mode of propagation and of the strong selective attenuation due to ionospheric influences.

Meanwhile, a new theory of vlf ionospheric propagation, known as the mode theory, was suggested by Budden [3] in 1951. According to his theory, waves that have traveled considerable distances act as if they were propagated in the space between parallel reflecting surfaces representing the earth and the lower edge of the ionosphere, and the observed presence of an absorption band for frequencies of the order of 3 kc could be explained with this model when an appropriate value for the electron density of the reflecting layers is assumed. Further progress in theoretical studies have been made recently, particularly by Wait [4, 5], who has carried out elaborate computation of the modes of ionospheric propagation and showed that the characteristics predicted by the theory are in good accord with the experimental facts gathered from many sources.

In the present investigation, further experimental proof of the mode theory of vlf ionospheric propagation is presented. A new apparatus is described which records continuously the frequency spectrum of atmospherics. Two such radio spectroscopes covering the frequency ranges 1 to 10 kc and 5 to 70 kc are used. The basic action of the spectroscope is to scan the respective vlf bands continuously; the outputs are displayed on an intensity-modulated cathode-ray oscillograph and recorded photographically, instead of conventionally recording the amplitude of signals at several fixed frequencies. The pattern on the photographic film is, therefore, an intensity-modulated plot of frequency against time; and the variations of frequency spectrum such as the diurnal characteristics or ionospheric disturbances are clearly demonstrated.

It appears that the results provide excellent experimental proof for the mode theory of vlf ionospheric propagation. The results obtained so far are very encouraging. Some novel results are also found and their interpretations given in the present paper.

2. Measuring Equipment

The main purpose achieved with the present apparatus is the continuous observation and a direct display of the frequency spectra of atmospherics. Although there are several kinds of spectrum analyzers which could be applicable to the study of atmospherics, a scanning type of spectroscope is considered to be preferable because of the requirement of continuous observations.

The apparatus consists of two sets of radio spectroscopes covering the frequency ranges 1 to 10 kc and 5 to 70 kc. Each set has a conventional vlf atmospherics receiver, a frequency-scanning device, and a display unit including a photographic motion camera. A block diagram of the spectroscope is shown in figure 1. The antenna is a vertical whip with an effective height of 10 m. The receiver is a superheterodyne type consisting of hf and IF amplifiers,

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[1] A preliminary account of this work is given by T. Obayashi, S. Fujii, and T. Kidokoro, An experimental proof of the mode theory of vlf ionospheric propagation, J. Geomagnetism and Geoelectricity **10**, 47 (1958).

[2] Radio Research Laboratories, Kokubunji, Tokyo, Japan (invited paper).

[3] Figures in brackets indicate the literature references at the end of this paper.

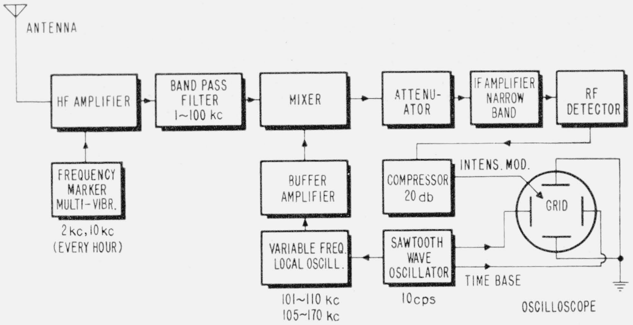

FIGURE 1. *A block diagram of vlf spectroscope.*

mixer, and detector. The local oscillator sweeps frequencies between 101 to 110 kc and between 105 to 170 kc by using a dust-core to alter its inductance. The sweep voltage is fed from a sawtooth generator. Simultaneously, a synchronized sweep is applied to the time-base of a cathode-ray oscilloscope so that a given horizontal position of the oscilloscope spot corresponds uniquely to a single frequency. By mixing this local oscillator with the external signal and applying a narrow-band IF transformer of 100 kc, the receiving frequency ranges are converted to 1 to 10 kc and 5 to 70 kc. The IF bandwidths are ±600 cps respectively, and the frequency scanning rate is about 10 cps. These are appropriate for the present purpose. Special attention has been paid to provide a flat frequency response of the receiver over the swept-frequency range and with strong attenuation for the rest of frequencies. The overall frequency response of each receiver is shown in figure 2. It is evident that the receiver has a flat characteristic over the respective sweep-frequency range and a large attenuation more than 30 db at the rest of frequencies.

Thus, as the receiver sweeps the frequencies, giving complete covering of vlf band, the output is displayed as an intensity-modulated line on a cathode-ray oscilloscope. This is photographed on a slowly moving (1.5 cm/hr) 35-mm film, producing a frequency-time record with intensity of atmospherics appearing as variations in photographic density. The combination of the film characteristic and the logarithmic compressor permits the recording of a wide range of signal intensities (more than 20 db) in considerable detail. The record is calibrated by the frequency markers of the 2 kc- and 10 kc-multivibrators every hour which is switched on automatically by a standard time clock.

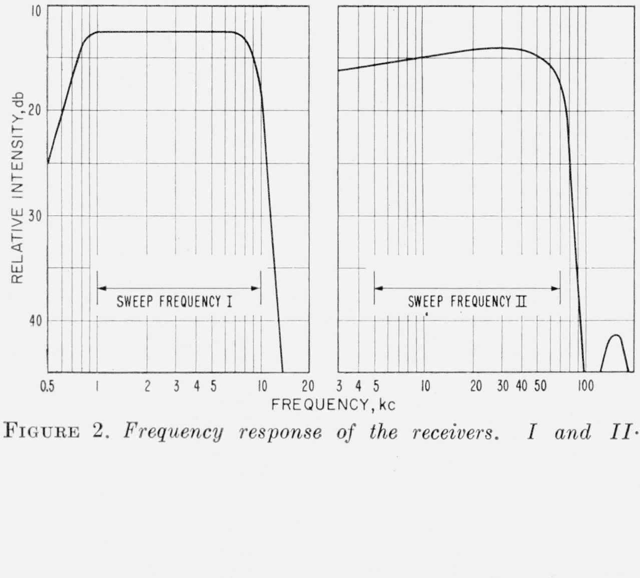

FIGURE 2. *Frequency response of the receivers. I and II·*

This type of vlf atmospherics spectroscope certainly has a major advantage over that of recording of atmospherics intensities at a number of single frequencies, and so far the results obtained have been very successful. Since the pattern on the film is an intensity-modulated plot, an auxiliary apparatus to reproduce an amplitude-frequency spectrum has also been designed. This is accomplished by successive scanning on the film using a photoelectric tube. An original amplitude of the signal is obtained in db scale with the aid of a suitable comparison technique.

3. Frequency Spectra of Atmospherics Propagated Through the Ionosphere

Observation of atmospherics using the present vlf spectroscopes has been carried out at the Hiraiso Radio Wave Observatory since June 1958. Simultaneously the continuous measurement of the intensity of atmospherics at 28 kc has also been made. Some of the records obtained are reproduced in figure 3, which are shown by the frequency-versus-local-time patterns, highlighted and dark portions indicating intense atmospherics and weak or no atmospherics, respectively. Signals from radio stations are also recorded, which appear at white straight lines indicated by cw. As can be seen clearly in these records, it is significant that there exists a strong absorption band for atmospherics propagation around 2 to 4 kc. The intensity of atmospherics is maximum at about 10 to 20 kc, and it decreases towards higher frequencies with remarkable undulating peaks. Considerable diurnal and seasonal variations are noticed.

In the discussion of these frequency spectra of atmospherics, however, the following point must be made in order to have an understanding of the frequency-versus-time characteristics of atmospherics displayed in the present records: since the duration of atmospherics is usually less than a few milliseconds, individual atmospherics photographed cover only a limited range of the frequency band, since the time-base of the oscilloscope is converted to the frequency sweep. In other words, the period of sweep frequency (order of 0.1 sec) is not short enough to cover the whole spectrum of individual atmospherics. However, if it is assumed that numerous atmospherics are occurring at random within a short duration, the film recorded with a sufficiently long time exposure should reveal the relative amplitude-frequency spectrum in a loose statistical sense.

Looking through the records, it has been found that the short-distance atmospherics (probably less than 100 km) do not show complicated spectral patterns, but they indicate rather a flat spectrum over wide frequency range (fig. 4). Therefore, the

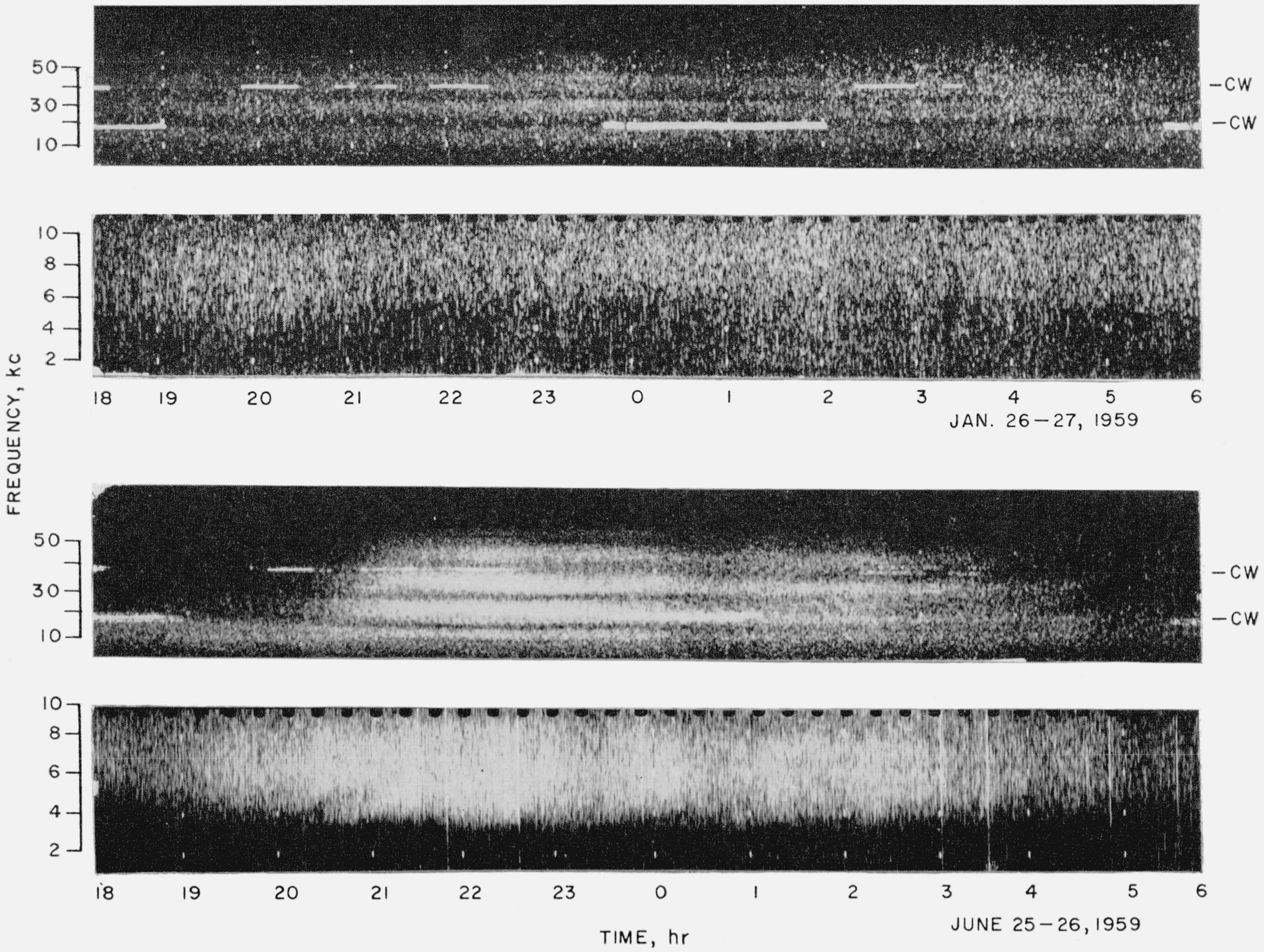

FIGURE 3. *Frequency spectra of vlf atmospherics of ionospheric propagation.*

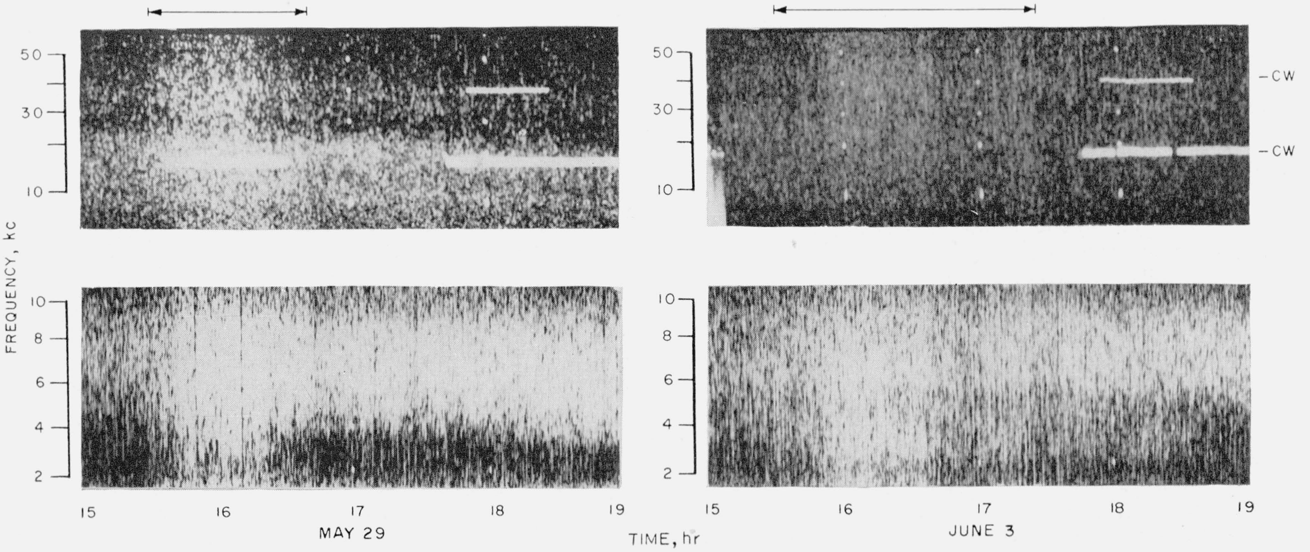

FIGURE 4. *Records of short-distance atmospheric, indicating a flat spectrum over a wide frequency range* (↔ *time during which local thunderstorms were active*).

outstanding features of strong selective absorption bands appearing in the records must be due to atmospherics propagated through considerable distances, which may be largely influenced by the ionospheric conditions.

In order to show more clearly the observed characteristics of vlf atmospherics, detailed analysis is made using those data of measured amplitude frequency spectra, which are obtained with the aid of the photoelectric scanner. In figure 5, average diurnal variations of amplitude-frequency spectrum of atmospherics for winter (January) and summer (June) seasons are shown, in which local short-distance thunderstorms are excluded. The characteristics of vlf radio-wave propagation are well represented, though the detailed structure of spectrum is rather smoothed out. For comparison, the average diurnal variations at the fixed frequency, 28 kc, are also reproduced in figure 6. Double maximums appear in the summer afternoon. The one around 16 hr is, however, more or less attributed to the thunderstorms in the vicinity of Japan, and hence the spectrum of atmospherics during this time of day shows a slightly different nature when compared with other seasons. From this analysis, it is confirmed that the nighttime spectrum shows strong absorption at about 2 to 3 kc and has a broad maximum at 5 to 50 kc with several undulating peaks. On the other hand, the daytime spectrum has smooth double maximums at 15 kc and 40 kc, its intensity being weaker than that of nighttime. Such general characteristics are well illustrated in figure 7, in which typical amplitude-frequency spectra at nighttime and daytime are shown.

One of the most interesting phenomena appearing in the records is the effect at the transition of spectrum between daytime and nighttime. Since two

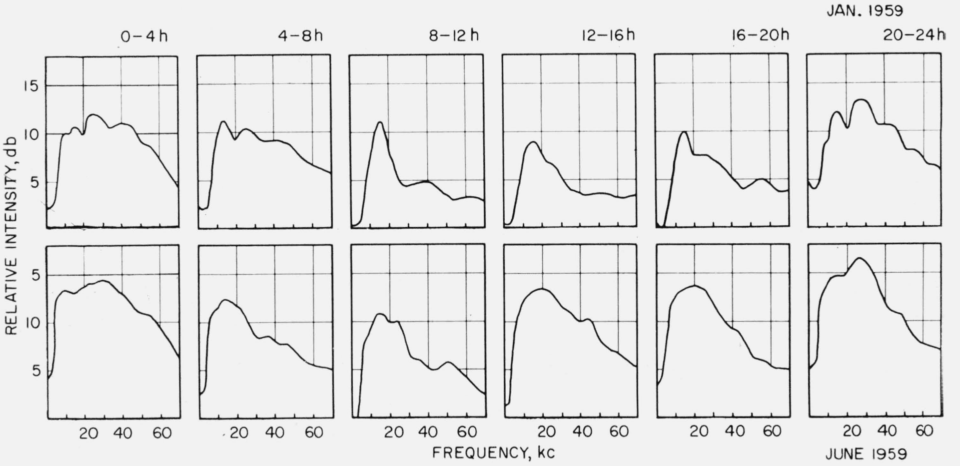

FIGURE 5. *Average diurnal variations of vlf amplitude-frequency spectrum at atmospherics in winter and summer seasons (shown in upper and lower sets, respectively).*

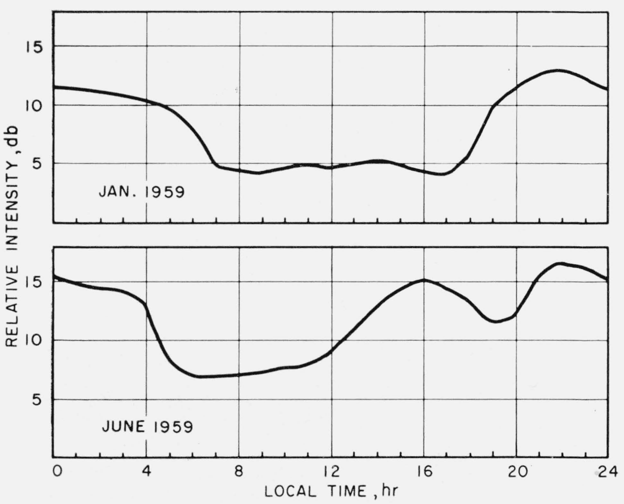

FIGURE 6. *Average diurnal variations of integrated field intensity of atmospherics (28 kc) observed at Hiraiso.*

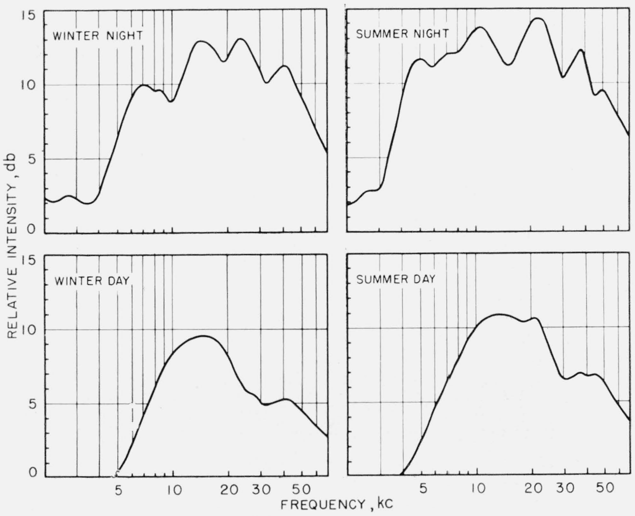

FIGURE 7. *Typical amplitude-frequency spectra of distant vlf atmospherics for nighttime and daytime.*

types of spectrum interchange rather distinctly at local sunset, the daytime maximum about 15 kc is shifted towards lower frequencies, while the effect at sunrise is reverse. Changes in cutoff frequency and the shift of spectral pattern at local sunset or sunrise are shown by several records in figure 8.

These characteristic features of the amplitude-frequency spectrum of vlf atmospherics cannot be explained by the simple Austin-Cohen law of vlf propagation, but more likely by the waveguide mode theory. The conception that vlf radio waves propagate to great distances via multiple reflections in the waveguide bounded by the earth and the ionosphere has been developed by Budden [3] and Wait [4] as the mode theory of vlf ionospheric propagation. An essential part of this theory is the existence of definite modes of propagation. In order to simplify the evaluation of these mode characteristics, let us consider the ground and the ionosphere as a waveguide of perfectly conducting plates. Then, the cutoff wavelengths would be given by $2h/n$, where n is the integer specifying the number of the mode and h is an effective reflecting height of the ionosphere. When the boundary of the waveguide is not perfectly conducting, as the case of the actual ionosphere, the cutoff wavelength is not sharply defined and, crudely speaking, the effective reflecting height of the ionosphere appears to be higher [4].

From the above consideration, it may be expected that the effect of the transition of spectrum from daytime to night conditions, which appeared as the shifting of the maximum intensity and also the cutoff frequencies towards lower frequencies, can be explained as the upward shift of the ionospheric height or else the decrease of the conductivity in the lower ionosphere. On the other hand, it is already well known from a number of experiments that the reflecting height of vlf radio waves in the ionosphere varies consistently from 70 km during the day to 90 km at night [6, 7]. Therefore, this is in accord with the present conclusion.

There is another interesting fact lending further support to the mode theory of vlf propagation. That is the effect of SID's, which are known as the sudden enhancement of atmospherics (SEA). Many SEA's accompanied by prominent solar flares were observed. Two such examples of changes of the spectrum of atmospherics are shown in figure 9 with the records of integrated level of atmospherics at 28 kc. A solar flare occurred at 16 hr 50 min (l.t.), March 29, 1959, which was associated with a very pronounced SEA. A sudden shift of the frequency spectrum at the beginning of the solar flare is evident. As shown in figure 10, the band of strong intensity of atmospherics was around 10 to 15 kc before the flare as in the case of usual daytime, and then at

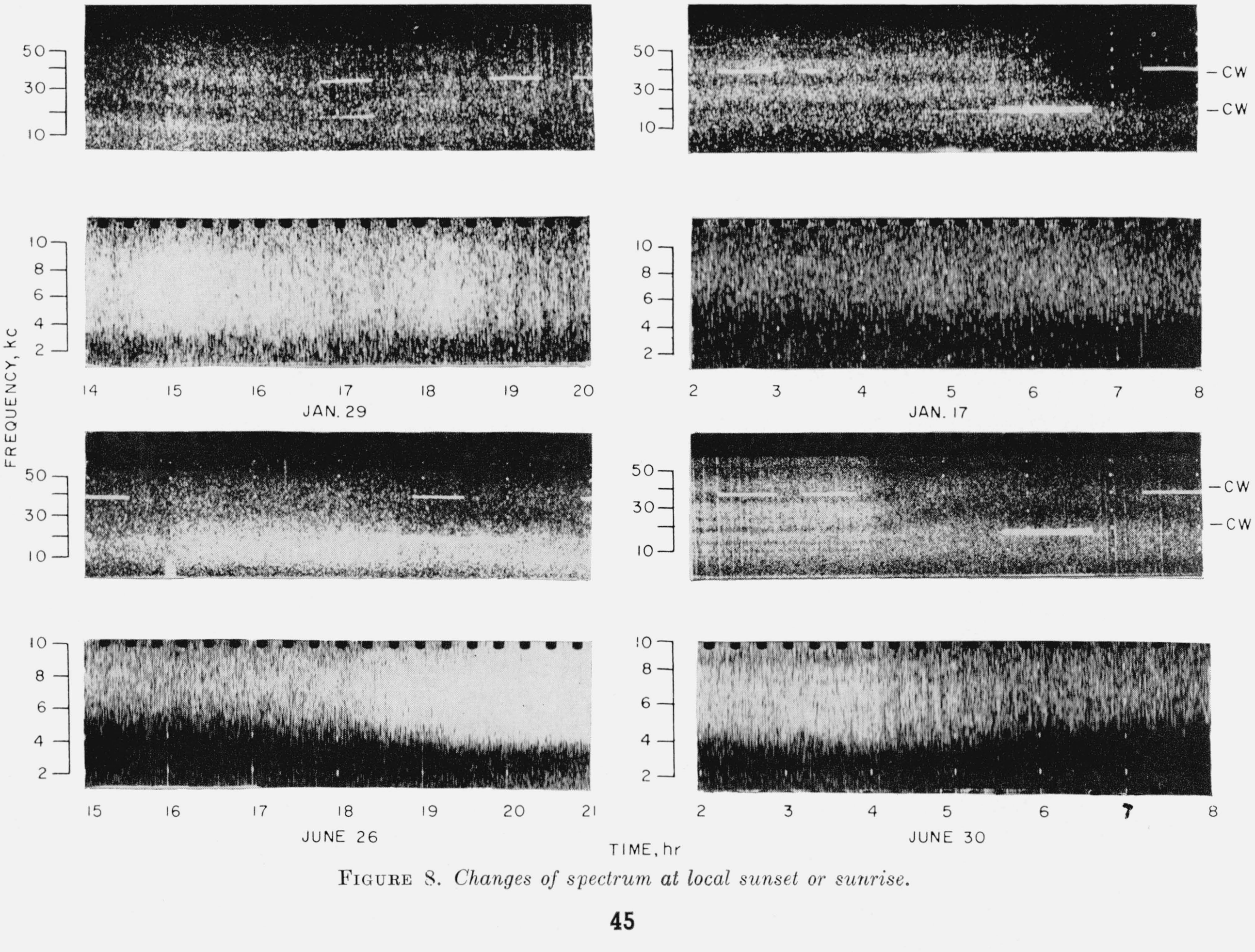

FIGURE 8. *Changes of spectrum at local sunset or sunrise.*

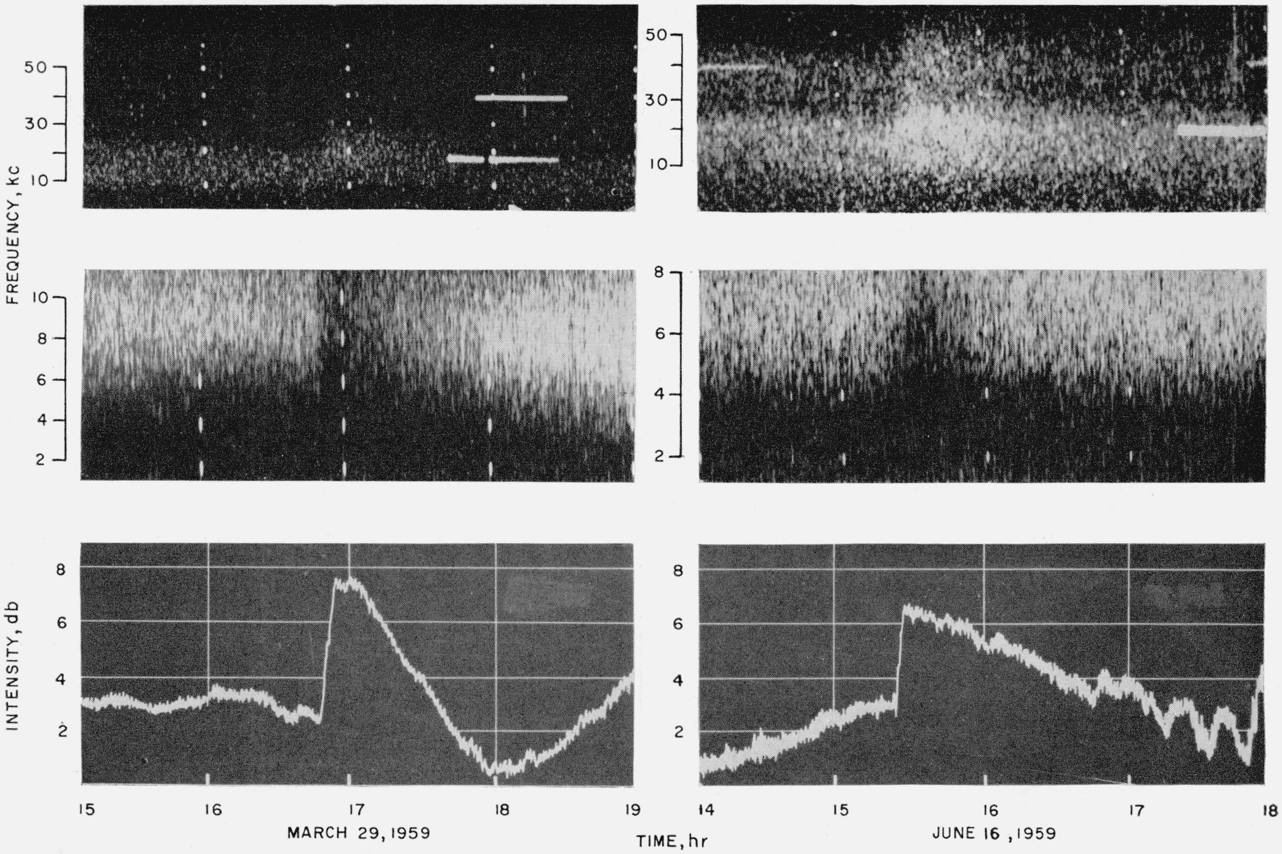

FIGURE 9. *Changes of spectrum during SEA's and records in the integrated intensity of atmospherics at 28 kc.*

16 hr 50 min the intensity was raised up, shifting the band of strong intensity towards the higher frequency band of vlf. The intensity of distant atmospherics is also enhanced, while at the frequency below 10 kc a sudden reduction in intensity occurs. Another record shows the effect of a solar flare at 15 hr 25 min (l.t.), June 16, 1959. This SEA occurred during rather greater thunder activity; however, the same effect mentioned above can be seen considerably well. It has been confirmed that all SEA's found in the records of 28 kc showed such a sudden shift of spectral pattern towards higher frequencies, though the amount of shift was variable for individual cases.

Since it is known that during SID's the electron density in the lower ionosphere is increased and its height is lowered considerably, these facts would eventually yield the explanation that the reduction of field intensity in the lower vlf band is caused by the shifting of the cutoff towards slightly higher frequencies, while in the frequency above the cutoff the intensity is enhanced owing to the good reflection condition in the lower edge of the ionosphere.

The observed stripe of absorption bands is still puzzling. However, it is expected that the actual observed intensity of distant atmospherics must be the sum of contributions from many waveguide modes [4], which are appreciably influenced by the distance from the source and the condition of the lower ionosphere. A detailed investigation of the theory of the waveguide modes would possibly give the appropriate solution.

4. Discussion of the Results

In the discussion of the frequency spectrum of atmospherics, the waveform characteristics must be mentioned, which have been studied extensively by many researchers in this field. Since the investigation of waveforms and of frequency spectrum are merely different approaches to a single phenomenon, their results must be mutually equivalent. Mathematically, the waveform $G(t)$, the amplitude-frequency spectrum $S(\omega)$ and the phase-frequency spectrum $\phi(\omega)$ have the following mutual relations:

$$G(t)=\frac{1}{\pi}\int_0^\infty S(\omega)\cos(\omega t+\phi(\omega))d\omega$$

$$S(\omega)=\sqrt{\left(\int_{-\infty}^{+\infty}G(t)\cos\omega t\,dt\right)^2+\left(\int_{-\infty}^{+\infty}G(t)\sin\omega t\,dt\right)^2}$$

and

$$\phi(\omega)=\tan^{-1}\left(-\int_{-\infty}^{+\infty}G(t)\sin\omega t\,dt\Big/\int_{-\infty}^{+\infty}G(t)\cos\omega t\,dt\right)$$

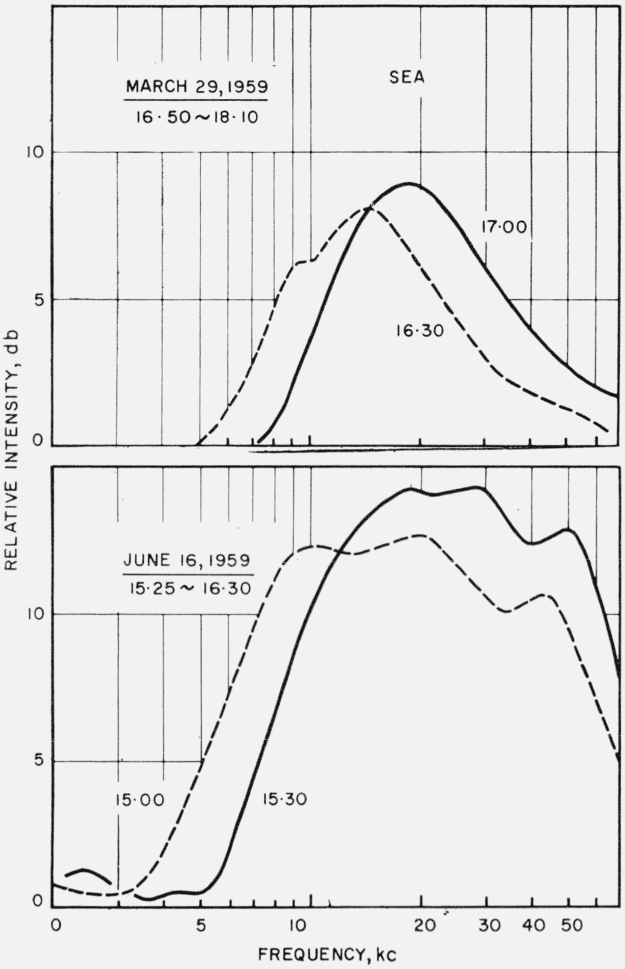

FIGURE 10. *Change of frequency spectrum at the SEA on March 29 and June 16, 1959 (---- presolar flare; —— during SEA.)*

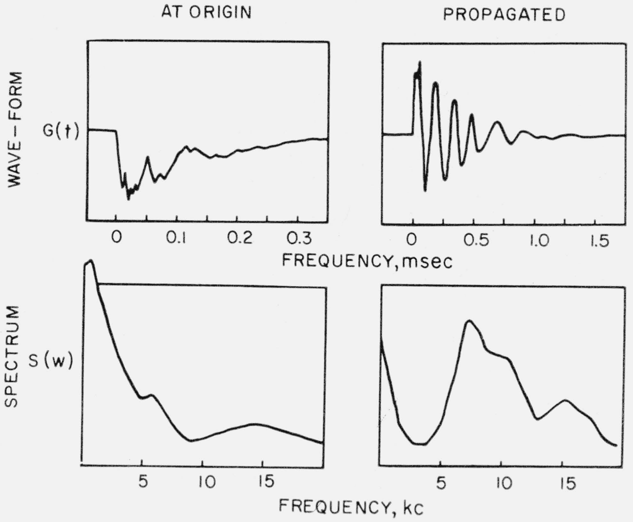

FIGURE 11. *Waveforms of atmospherics and their frequency spectra (after K. Sao [8]).*

Therefore, from the known waveform it is possible to compute its frequency spectrum. Using these Fourier transform expressions, Sao [8] has made the frequency analyses of a number of waveforms of atmospherics. Two types of frequency spectrum are characteristic; one is of the origin of an atmospheric and the other is of a distant atmospheric. Those waveforms and their spectra obtained by him are reproduced in figure 11. The frequency spectrum at the origin of a lightning stroke shows a gradual decrease of amplitude towards higher frequencies, having almost flat characteristics at about 10 to 30 kc. This result is in accord with the frequency spectrum of short-distance atmospherics shown in figure 4. Waveforms of distant atmospherics are more complicated and show the influences of the ionosphere. They often have the appearance of a damped sinusoid; the apparent frequency within the pulse is decreasing with time whereas the mean spectral maximum is increasing with range. Such a behavior has been predicted theoretically by Wait [5, 9]. The derived spectrum indicated heavy attenuation around 2 to 5 kc and small attenuation at around 10 kc, which is generally in good agreement with our observations.

Another investigation has been carried out by Chapman and Matthews [1] who used a spectroscope consisting of a number of narrow band-pass filters tuned to frequencies in the range of 40 cps to 16 kc, recording the amplitude-frequency spectra and corresponding waveforms for individual atmospherics. They also discussed the relation between the waveform characteristics and the significant changes in the spectrum as the distance of propagation increases. Summing up their results, Chapman and Macario [2] derived attenuation curves with respect to frequency for those of distant atmospherics. It is indicated that in the frequency range from 200 cps to 10 kc the greatest increase of attenuation occurs at about 2 kc, it being about 20 db per 1,000 km by day and 10 db by night.

Here, it might be worthwhile to link up this with our result. For this purpose, the frequency spectra shown in figure 7 can be used. Since their curves were given by attenuation in decibels per 1,000 km, our results must be converted to this scale. Although the distribution of the originating source of atmospherics cannot be identified in the present observation, according to Kimpara and Kimura [10] distant atmospherics received in Japan mainly come from regions in south and east China and the Philippines. Therefore, the average distance from the sources is of the order of 2,000 km. Assuming this, and also that the minimum attenuation around 10 kc is about 2 to 3 db per 1,000 km, the curve of the variation of attenuation with frequency in the range 1 to 100 kc is illustrated in figure 12. This curve, for the frequency range of 1 to 10 kc, can be compared with Chapman and Macario's. Also Taylor and Lange [11] reported nighttime attenuation values in good agreement with values presented here. These results

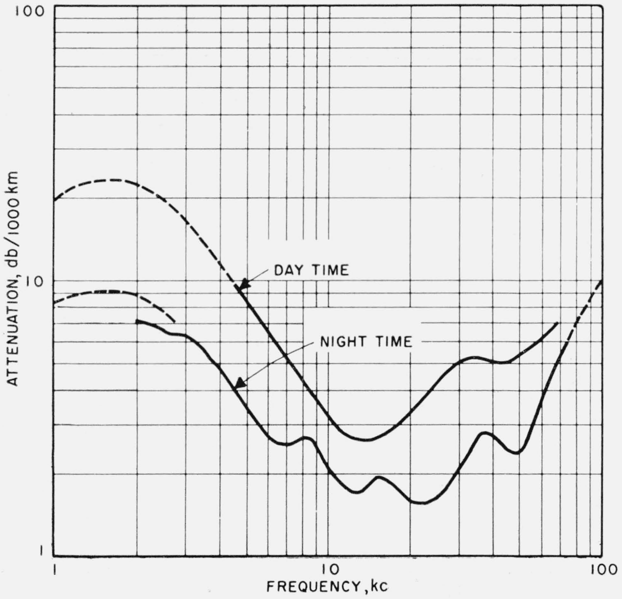

FIGURE 12. *The variation of attenuation with frequency.* The dotted curves for 1- to 10-kc range are taken from Chapman and Macario [12].

give a general idea of the way vlf waves are attenuated and can propagate to great distances.

In concluding, it is emphasized that the continuous observation of the frequency spectrum of atmospherics reveals important characteristics of vlf radio waves propagated through the ionosphere. The general agreement between the experimental and theoretical results substantiates the mode theory. The fact that certain bands of vlf radio waves propagate to great distances with small attenuation accounts for the success of long-range navigational systems, worldwide communications or standard radio-wave systems, and the tracking of atmospheric storms.

5. References

[1] F. W. Chapman and W. D. Matthews, Audio-frequency atmospherics, Nature **172,** 495 (1953).

[2] F. W. Chapman and R. C. V. Macario, Propagation of audio-frequency radio waves to great distances, Nature **177,** 930 (1956).

[3] K. G. Budden, The propagation of a radio atmospheric, Phil. Mag. **42,** 1 (1951); **43,** 1179 (1952).

[4] J. R. Wait, The mode theory of vlf ionospheric propagation for finite ground conductivity, Proc. I.R.E. **45,** 760 (1957).

[5] J. R. Wait, The attenuation vs. frequency characteristics of vlf radio waves, Proc. I.R.E. **45,** 768 (1957).

[6] A. H. Waynick, The present state of knowledge concerning the lower ionosphere, Proc. I.R.E. **45,** 741 (1957).

[7] J. R. Wait, Diurnal change of ionospheric heights deduced from phase velocity measurements at vlf, Proc. I.R.E. **47** (1959).

[8] K. Sao, Researches in the frequency analyses of waveforms of atmospherics, Proc. Research Inst. Atmospherics, Nagoya Univ. **5,** 12 (1958).

[9] J. R. Wait, Propagation of very-low-frequency pulses to great distances, J. Research NBS **61,** 187 (1958) RP 2898.

[10] A. Kimpara and Y. Kimura, On field intensity recording of atmospherics at 27 kc, Proc. Research Inst. Atmospherics, Nagoya Univ. **5,** 21 (1958).

[11] W. L. Taylor and L. J. Lange. Some characteristics of vlf propagation using atmospheric waveforms, Recent advances in atmospheric electricity (Pergamon Press, New York, N.Y., 1959).

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