Report of U.S. Commission 4, URSI

RADIO NOISE OF TERRESTRIAL ORIGIN

Edited by William Q. Crichlow*

The scope of Commission IV has expanded extensively since the XIIth General Assembly in 1957. This has largely resulted from the increased interest in the portion of the spectrum below 30 kc/s and the fact that the electromagnetic energy released by lightning discharges provides a very useful tool for investigating various modes of radio propagation.

The purpose of this report is to summarize significant research in this field that has been carried out in the United States during the past three years. Bibliographies have also been included. The topics covered are as follows:

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*U.S. Chairman, Commission 4, URSI.

1. Radiofrequency Radiation From Lightning Discharges

A. Glenn Jean*

A number of complex discharge processes which take place in lightning strokes are responsible for the emission of radiofrequency energy. The amplitude spectrum of such emissions extends from a few cycles per second to hundreds of megacycles per second, usually attaining a peak within the VLF region. The energy radiated from a cloud-to-ground stroke is of the order of 250,000 joules and can cause serious interference to radio communications systems. These emissions have been widely used as a source of signals in radio propagation research, in locating active thunderstorms, in identifying and tracking storms, and in basic investigations of the discharge mechanisms themselves. The radio engineer, the meteorologist and the physicist are concerned with the discharge processes and the nature of the resulting electromagnetic radiation.

It is the main purpose of this note to summarize recent research pertaining to the radiofrequency radiation from lightning discharges.

The most common type of lightning discharge occurs within the cloud between the two principle areas of opposite charge [Pierce, 1957]. The breakdown process involves the advance of a pilot leader through air that has not been ionized; and there is evidence that there is no return stroke as encountered in cloud-to-ground discharges. The pilot leader may advance in steps [Schonland, 1953], as in the case of the discharge to earth, and it is likely that the steps are mainly responsible for any induction and radiation fields produced. Radiation from the rapid field changes, such as the step referred to, has been observed at very high radiofrequencies. Atlas [1958], using a 2800 Mc/s radar, reported receiving atmospherics, having durations less than 1 msec and amplitudes of about 30 μv/m (in a 600 kc/s bandpass) from discharges which occurred within the upper regions of a thundercloud. It was postulated that these atmospherics resulted from stepped-leader type discharges in the ice crystal region of the cloud. Following the reception of these atmospherics, radar echoes lasting from 0.1 to 0.5 sec were obtained from ionized regions up to 27,000 ft tall with horizontal base diameters of 30,000 ft. It is thought that the radar signals were reflected from the ionization created by the discharges rather than from dielectric discontinuities associated with heated columns of air. There is evidence that the ionization is propagated up toward the cloud top after the discharge. Atlas [1958] estimated that partial or "soft" reflections were obtained from regions having electron densities between 10^6 and 10^9 electrons/cm^3. (A density of 10^{11} electrons/cm^3 is required for a unity reflection coefficient from a sharp boundary at 2800 Mc/s.) There is also evidence resulting from 3-cm radar observations that many of the discharges might have extended through the ice crystal anvil into clear air as reported on occasions by others [Ward, 1951; Bays, 1926]. The simultaneous observations of atmospherics and radar reflections from ionization created by the discharge constitute a powerful technique in exploring the mechanism of cloud discharges.

Cloud discharges which occurred in tornadoes were described by Jones [1958]. On three occasions, rapidly recurring light patches were observed which appeared to come from discharges within the cloud. Simultaneous observations of atmospherics indicated a noticeable absence of return-stroke discharges from cloud-to-earth and an unusually high rate of occurrence of atmospheric components at 150 kc/s. The 150 kc/s observations were made using crossed-loop direction-finding equipment. The direction-finder responses were observed to be straight lines rather than ellipses, from which it was inferred that the cloud discharges were vertical. Jones [1958] reported receiving approximately 45 atmospheric components per second at 150 kc/s from a severe storm at a 25-mile range in 1957. During this interval, 10 kc/s components were not observed. These atmospherics are reported to be related to "flare type" discharges which were visually sighted as streamers which projected over the leading edge of the anvil top of the cloud.

It would be of interest to compare observations of 150 kc/s atmospheric components observed by Jones [1958] during tornadoes with emissions at similar frequencies which might result from severe Pacific storms [Kimpara, 1958].

Most of the radiofrequency energy emitted in the VLF region from lightning discharges occurs from the return stroke. Since multiple return strokes play an important part in establishing the ambient noise level at VLF, it is of value to determine the radiation properties of individual strokes and the statistics regarding the occurrence of successive discharges.

Tepley [1959] observed two classes of ELF waveforms in Hawaii. The first class consisted of a single large half-cycle sometimes followed by a second half-cycle of substantially lower amplitude and of longer duration. This type of waveform may be obtained theoretically from a Dirac current source. The other class of waveform consists of two half-cycles of comparable amplitude, the second of which is longer than the first. A possible third half-cycle is sometimes observed. The first two half-cycles are explicable in terms of a unidirectional source current of longer duration than the current responsible for the first type of waveform. Pierce [1955] found that over 90 percent of all ground-return strokes are of positive polarity, corresponding to the lowering of a negative charge-to-ground. Brook [1957] reported one ground-return stroke in 700 produced a negative field change. Hence, it

*National Bureau of Standards, Boulder, Colo.

appears that the positive-to-negative polarity ratio of the ground-return stroke should be much greater than unity. On the contrary, Tepley [1959] found that slow-tails are negative by a ratio of more than 3:1. The possibility that most of the negative slow-tails do not originate in ground-return strokes is considered. Pierce found that the ratio of slow-negative to slow-positive field changes is about 2:1 for heat storms and about 7:1 for frontal storms. Tepley's observations are in reasonable agreement with these ratios.

Wait [1960a] pointed out that lightning discharges from cloud-to-ground and cloud-to-cloud are seldom vertical or horizontal. The modification of the pulse shape of the ELF waveform, as a result of the inclination of the current channel, would appear to be an important factor in interpreting observed data. In particular, pulses with both positive and negative polarities of the first half-cycles strongly suggest (as mentioned by Tepley) that the horizontal component of the source current is important. An observed pulse having a second half-cycle can only be reconciled with an inclined source. For certain small values of horizontal source component a third half-cycle of relatively small amplitude is also produced. In view of the small dimensions of the discharge paths in terms of a wavelength, Wait replaced the source channel by superimposed vertical and horizontal electric dipoles and calculated the resultant responses of the radiation field by superposition. Various ELF waveforms were given corresponding to different horizontal and vertical electric field components at the source. These waveforms agree remarkably well with observed waveforms.

A great number of experimental and theoretical investigations have been carried out to determine the nature of the atmospheric waveform near the source. Wait [1956b] presented calculations showing the nature of the transient response of an idealized lightning discharge at short ranges where the ionospherically reflected wave can be neglected or separately accounted for. An expression was derived for the instantaneous product of the dipole current and vertical height applicable to the return-stroke discharge. Solutions were given for moments having a buildup time of about 10 μsec and a pulse width of about 50 μsec which is representative of observed return-stroke discharges. Solutions are given in graphical form for the field response with time, parametric in distance, for a perfectly conducting earth. The effect of the earth conductivity upon the pulse shape at 100 km was demonstrated and the effect of the earth curvature considered. Additional terms can be used in the expansion of the dipole moment to include a sustained return current.

Wait [1958d] calculated the response of the waveguide to an impulsive current source for different ranges. The pulses have the appearance of damped sinusoids as the result of the modal characteristics of the propagation medium. The length of the first half-cycle becomes progressively shortened with increasing range while the oscillatory nature of the pulse is becoming enhanced. It is also shown that different exponential source functions produce waveforms having different quasi half-periods at a fixed distance. Thus, the quasi half-cycle of atmospherics is determined by the source pulse as well as by the propagation medium. The results of these calculations compare favorably with quasi half-periods of atmospherics observed by Hepburn [1957].

Watt [1957a] calculated a representative radiation spectrum of return-stroke discharges using waveforms recorded at short ranges. He then synthesized a radiation spectrum combining the radiation from the return-stroke discharge with radiation from stepped-leader discharges as observed by Norinder [1954]. The resultant spectrum was subsequently used in estimating ambient noise levels at distances between 1,000 and 4,000 km from thunderstorms. The predicted levels of noise, which extended over a frequency range from 1 to 100 kc/s, compared favorably with observed noise levels.

Hill [1957] formulated a theory for the generation of low-frequency radiation in the return stroke of the cloud-to-ground lightning flash. The radiated pulse is a single cycle with a field variation which varies linearly with time. The spectrum of the radiated energy is centered at 11 kc/s and the energy radiated is about 220,000 j.

Hefley et al. [1960] reported the development of equipment capable of automatically recording the directions of arrival and spectral components of atmospherics. Results of observations made at 10.5, 40, and 100 kc/s in the Northwestern part of the United States reveal the directions of arrival and the rates of reception of atmospheric components exceeding fixed amplitude levels.

Recently, observations of the radiation spectra of return-stroke lightning discharges were reported by Taylor and Jean [1959]. In this work, atmospheric waveforms were recorded at distances ranging from about 150 to 600 km. The locations of the individual lightning flashes were determined using a direction-finding network. At these ranges, it was possible to separately identify the ground and sky-wave components. The precautions taken in selecting atmospherics radiated from return-stroke discharges and in utilizing the ground-wave pulse are described. The atmospherics resulted from discharges over high terrain at altitudes of 5,000 ft or more in the Rocky Mountain area. Values of total energy were reported to be about 30,000 j compared with approximately 300,000 j reported by Lady et al. [1940] and as derived in other experiments from discharges which occurred over land of lower elevations. These results indicate the desirability to perform similar atmospheric observations at lower land elevations and over sea water.

2. Properties of Atmospheric Noise at Various Receiving Locations

William Q. Crichlow*

The properties of sferics from individual lightning flashes are dealt with in other sections of this report. On the other hand, the composite effects at the receiver resulting from simultaneous thunderstorm activity throughout the world are discussed in this section. Although extensive investigations of these phenomena have been made in the past by several agencies and predictions of worldwide atmospheric noise levels have been published [RPU Tech. Rpt .5, 1949; NBS Circ. 462, 1948; Crichlow et al., 1955; C.C.I.R. Rpt. 65, 1957], most of the recent studies in this country of worldwide noise levels and characteristics have been made by the Central Radio Propagation Laboratory of the National Bureau of Standards.

During the International Geophysical Year, a worldwide network of 16 radio noise recording stations was established by CRPL [Crichlow, 1957] at the following locations:

Station	Latitude	Longitude
Balboa, Canal Zone	9. 0N	79. 5W
Bill, Wyo	43. 2N	105. 2W
Boulder, Colo	40. 1N	105. 1W
Byrd, Antarctica	80. 0S	122. 0W
Cook, Australia	30. 6S	130. 4E
New Delhi, India	28. 8N	77. 3E
Enkoping, Sweden	59. 5N	17. 3E
Front Royal, Va	38. 8N	78. 2W
Ibadan, Nigeria	7. 4N	3. 9E
Kekaha, Kauai, Hawaii	22. 0N	159. 7W
Ohira, Japan	35. 6N	140. 5E
Pretoria, Union of South Africa	25. 8S	28. 3E
Rabat, Morocco	33. 9N	6. 8W
São José dos Campos, Brazil	23. 3S	45. 8W
Singapore, Malaya	1. 3N	103. 8E
Thule, Greenland	76. 6N	68. 7W

Five of these stations are operated by CRPL, two by the Signal Corps Radio Propagation Agency, and the remaining nine by foreign governments.

Standardized recording equipment, which was designed and furnished by CRPL, provides measurements on eight frequencies from 13 kc/s to 20 Mc/s. The mean received power in a 200 c/s bandwidth, averaged over a period of several minutes, is the basic parameter recorded. It is expressed as an effective antenna noise figure, which is defined as the noise power available from an equivalent lossless antenna in decibels above ktb, where k=Boltzman's constant (1.38×10^{-23}j/°), t=absolute room temperature (taken as 288 ° K), and b=bandwidth in cycles per second.

In order to obtain additional information on the character of the noise, two other statistical moments, the average envelope voltage and the average logarithm of the envelope voltage are recorded at 10 of the stations. All data from the network are processed at the NBS, Boulder Laboratories and are published quarterly [Crichlow, 1959a; Crichlow, 1959b].

The amplitude-probability distribution (APD) of the instantaneous IF envelope voltage provides a useful means of expressing the detailed characteristics of atmospheric noise. The first measurements of the APD by U.S. experimenters were made at the University of Florida [Hoff, 1952; Sullivan et al., 1955; Sullivan, no date; George, 1957] and subsequently in Colorado, Alaska, and Panama by NBS personnel. From the NBS [Watt et al., 1957b] measurements, it was found that the noise envelope at the low-amplitude levels is Rayleigh distributed, while that at the higher levels approaches a distribution having a much greater change in level for a given change in probability. The dynamic range between the value exceeded 0.0001 percent of the time and the value exceeded 90 percent of the time varied from 59 to 102 db at 22 kc/s in a bandwidth of 1 kc/s. As the bandwidth is reduced, the dynamic range approaches 21.18 db, the value expected for the Rayleigh distributed envelope of thermal noise. This occurs at a bandwidth of approximately 0.2 c/s for atmospherics at 22 kc/s. This study of the characteristics of atmospheric noise was extended to cover the frequency range from 1 to 100 kc/s [Watt et al., 1957]. The variation of level and dynamic range with frequency was examined both theoretically and experimentally.

The value of the APD in determining the performance of radio systems in the presence of atmospheric noise has been demonstrated by additional studies at NBS [Watt et al., 1958]. The expected error rates, both with manual telegraphy and FSK systems, have been calculated from the noise APD and confirmed experimentally.

*National Bureau of Standards, Boulder, Colo.

Direct measurements of the APD at a large number of locations and over a wide frequency range are prohibitive, both in equipment and personnel requirements. Since data on the statistical moments measured by the NBS noise recorder are available from the worldwide network over a wide frequency range, an investigation was made of methods for deriving the complete distribution from these moments [Crichlow et al., 1960a]. It was found that the distribution, when plotted on Rayleigh graph paper, had a characteristic shape that could be described graphically by three independent parameters. This characteristic shape was confirmed by measurements in Colorado [Watt et al., 1957b; Crichlow et al., 1960a], Alaska [Watt et al., 1957b], Panama [Watt et al., 1957b], Florida [Sullivan et al., 1955; Sullivan, no date; George, 1957], England [Horner, 1956], and Japan [Yuhara, 1956]. Using numerical integration methods on typical distributions, a relationship was found between the three moments measured by the NBS noise recorder and the three graphical parameters, thus providing the complete distribution from the three measured moments. Families of distribution curves in terms of the moments will be published in an NBS Monograph [Crichlow et al., 1960b] for ease in evaluation.

The effects of bandwidth on the APD have been published [Fulton, 1957] and further studies are in progress at NBS to determine the effect of bandwidth on the statistical moments.

3. Summary of Research on Whistlers and Related Phenomena

3.1. Stanford University

R. A. Helliwell*

The following is a synopsis of research on whistlers and related phenomena carried out at Stanford University since the XIIth General Assembly of URSI. Many results are presented here for the first time, and will be elaborated in reports and papers in preparation. Support for this work was obtained from several agencies including the National Science Foundation, the Air Force Office of Scientific Research, the Office of Naval Research, and the National Aeronautics and Space Administration.

a. Methods of Whistler Analysis

Techniques for spectrographic analysis of whistlers have been developed [Carpenter, 1960]. Included are methods for identifying the causative sferic associated with whistlers. In many cases, three sonagrams from a single two-minute run will provide unambiguous identification of the sources of both long and short whistlers. Simultaneous data from other stations are often needed to resolve ambiguities. Methods for quantitative description of whistlers are described.

b. IGY–IGC Synoptic Whistler Results

Some tentative results from the 10-station whistler-west program are summarized in the following paragraphs. The cooperation of the several persons and groups associated with the whistlers-west program is gratefully acknowledged. Results of pre-IGY experiments and details of the synoptic program have been published elsewhere [Helliwell and Morgan, 1959; Smith et al., 1958; Helliwell, 1958c]. At the time of writing this report, about 10,000 sonagrams of whistlers and VLF emissions had been produced. Some 1,500 whistlers had been analyzed, and the causative atmospherics for roughly 1,000 of these had been identified.

The statistical results obtained from the aural data are subject to some uncertainty because of differences in the training and ability of the listeners. For this reason, many of the indicated trends of the data can not be accepted without reservation. For example, VLF hiss is sometimes mistaken for background noise. However, the following results appear to be demonstrated by the data which have been examined.

More whistlers are heard at night than during the day, probably because *D*-region absorption increases the daytime attenuation from source to the input end of the whistler path and from the output end to the receiver.

Seasonal variations of whistler activity are complicated. Stations at geomagnetic latitudes lower than roughly 52° and greater than 62° show a wintertime maximum in occurrence, whereas stations between 52° and 62° geomagnetic latitude show a summertime maximum. This curious effect may possibly be related to differences in the behavior of long and short whistlers. Theoretically, wintertime should be more favorable for the observation of whistlers, since the local noise level is low and the sources of short whistlers are relatively numerous. However, at locations where long whistlers are known to occur frequently (principally middle latitudes), strong summer thunderstorm activity could easily produce a whistler rate exceeding that in winter. At high and low latitudes long whistlers are seldom heard, and so the wintertime peak above 62° and below 52° can be understood. The over-all whistler rate reaches a maximum at approximately 50° geomagnetic latitude.

Comparison of daily whistler rate with daily average magnetic index shows little correlation. However, any effect may be masked by the large day-to-day variation in whistler rate, which is probably correlated with variations in thunderstorm occurrence.

Comparison of daily whistler rates between stations indicates that for station spacings of 1,000 km or more, the occurrence rates tend to be independent. This conclusion includes stations of similar latitude. It is interpreted to mean that either the paths of propagation are highly localized in both latitude and longitude, or that the number of whistlers is highly sensitive to thunderstorm activity in the immediate vicinity of the ends of the path of propagation.

Chorus and hiss show a peak in occurrence at about 56° to 58° geomagnetic latitude, the distribution being skewed toward the high-latitude side. It was discovered that the latitude distribution of chorus is sensitive to magnetic index. For days of average $K_p \leq 1.5$, chorus peaks at 64°, while for days of average $K_p \geq 4$, the chorus peaks at 58°. Thus, it appears that location of chorus generation, like the aurorae, moves toward the equator during the disturbed periods.

Chorus and hiss occur more frequently on days of low-background noise than on days of high noise. The effect is apparently not due to increased detectability on days of low noise, since whistler rates do not show the correlation. This conclusion is based on one year of data from six stations. On the average, there was twice as much chorus and hiss on days of low noise as on days of high noise. The reduction in background noise is believed to have been caused mainly by increased absorption of

*Stanford University, Stanford, Calif.

atmospherics of relatively distant origin. This interesting and apparently significant result is interpreted to mean that the VLF absorption is correlated with the occurrence of chorus and hiss.

The effective area of discrete VLF emissions is found to be comparable with that for whistlers (i.e., about 1,000 km across), suggesting that the paths of propagation for emissions and whistlers may be the same. No cases of the same VLF emission forms occurring at conjugate stations have been found, indicating that the generation mechanism is highly asymmetrical with respect to the geomagnetic equator.

Whistler dispersion data show an interesting and unexpected annual variation for several stations. The dispersion was determined from time delay measurements at 5 kc/s [Carpenter, 1960]. Dispersion is minimum at the June solstice and maximum at the December solstice, and shows the same variation in both hemispheres. The explanation of this remarkable circumstance is not clear, but may be related to the eccentricity of the earth's orbit about the sun or to the seasonal asymmetry in the relation between the sun-earth line and the geomagnetic equator.

A comprehensive study of nose whistler dispersions using data from both hemispheres support the annual variation of dispersion found for ordinary whistlers. Furthermore, it is deduced that the annual variation in dispersion indicated by the nose whistlers must be caused mainly by actual electron density changes in the outer ionosphere rather than path changes.

c. Whistler Sources

The spectra and locations of whistler sources are being studied. Although final results of this work are not yet available, some tentative conclusions were reached in cooperation with the Boulder Laboratories of the National Bureau of Standards [Helliwell et al., 1958b]. It was found that often the spectrum of the source peaks at roughly 5 kc/s, whereas most lightning discharges peak at higher frequencies, near 10 kc/s. A tendency was found for whistler-producing discharges to occur more often over sea than over land. It was further shown in this investigation that the predicted time of origin using the Eckersley law of dispersion was often in error by as much as 0.4 sec. This discrepancy is readily explained in terms of the theory of noise whistlers.

d. Association Between Auroras and VLF Hiss Observed at Byrd Station, Antarctica [Martin et al., 1960]

At Byrd Station, Antarctica (70.5° S Geomagnetic) detailed and remarkably interesting records of hiss, chorus and whistlers have been obtained. Various bands of hiss have been identified ranging from the lower frequency limit of the recorder (150 c/s) to the upper frequency limit (16,000 c/s). The hiss above about 4 kc/s shows a close association with visual aurora observed at the same station. The center frequency of this hiss is about 8 kc/s and shows variations which may be related to the particular type of aurora; in particular, a center frequency of 9.6 kc/s appears to be associated with "red" aurora. The average intensity of the auroral hiss ranges from 1 to 3 mv/m.

e. Duct Theory

Multiple path whistlers are explained in terms of discrete paths of propagation in the outer ionosphere. It is postulated that such paths are created by columns of enhanced ionization alined with the earth's magnetic field. These "ducts" of ionization act much like ordinary wave guides. Experimental evidence supporting this hypothesis has been obtained from "hybrid" whistlers. A hybrid whistler consists of both long and short components excited by the same source. The delay of the short component is exactly one-half the delay of the long component. It is concluded, therefore, that the dispersion of a whistler is independent of the location of its source and depends only on the properties of the ionosphere. Further evidence in support of the duct theory is found in whistler echo trains, in which the echo delays are always multiples of some particular component in the initial whistler. Other evidence is found in the integral relation between the delays of simultaneous long and short whistlers excited by different sources in opposite hemispheres.

f. Ray-Path Calculations

The guiding of whistlers was treated using ray path consepts [Smith, 1960b]. The maximum allowable half-angle of the ray path cone was found to decrease from 19°29′ at zero frequency (deduced first by Storey) to 11° at $f=0.19f_H$, then increase to 90° at $f=f_H$.

Calculations based on the ray-path equation derived by Hazelgrove were made for various frequencies, geomagnetic latitudes, initial wave normal directions, and models of the ionosphere [Yabroff, 1959]. Generally speaking, the ray paths do not follow the earth's magnetic field when a smooth distribution is assumed. The final latitude may be either greater or less than the initial latitude depending on conditions. Under some conditions, there is spatial focusing of the energy for certain initial latitudes. There can also be time delay focusing in which wave packets entering the ionosphere over a range of latitudes arrives in the opposite hemisphere with the same total delay.

Ray theory concepts were applied to the problem of whistler propagation in ducts [Smith et al., 1960a]. It was found that total trapping of the whistler energy will occur whenever the electron density at the center of the column exceeds the background level by a certain amount. Under certain conditions the energy can be trapped in a minimum of ionization. For middle latitudes, enhancements of the order of only 10 percent are required to completely trap the whistler. The theory explains the marked decrease in whistler occurrence with decreasing latitude.

g. Electron Density of the Outer Ionosphere

Nose whistlers from stations in both hemispheres have shown a consistent relationship between nose frequency and nose time delay. Nose frequencies vary from 3.0 to 32 kc/s. Theoretical analysis of the dispersion of nose whistlers has led to a new method for calculating the electron density of the outer ionosphere. It is found that the shape of the nose whistler trace is insensitive to the shape of allowable electron density models. Application of this theory to the data gives a model of the outer ionosphere out to five earth radii. The average distribution of electron plasma frequency in cps can be given approximately by

$$f_o = 1{,}200\, f_H^{\frac{1}{2}}$$

where f_H is the electron gyrofrequency in cycles per second.

h. Theory of VLF Emissions

A theory of the origin of the VLF emissions was developed jointly by Gallet and Helliwell [1959a]. It accounts, in a general way, for VLF emissions and very long trains of whistler echoes.

The required magnitude of traveling wave gain was assumed in developing the theory. Further theoretical work has led to a quantitative solution for the gain along a low density stream flowing through a plasma [Bell and Helliwell, 1959]. For a particular simplified case thought to be typical of the conditions related to VLF emissions, a gain of approximately 2 db per wavelength in the medium was obtained.

i. Controlled Whistler-Mode Experiments

Observations at Cape Horn, South America, of pulses from Station NSS on 15.5 kcs, Annapolis, Md. demonstrated that the whistler-mode is open a large fraction of the time at night, but that the paths of propagation vary widely from night to night [Helliwell et al., 1958a]. Time delays from the man-made signals were in close agreement with those obtained from whistlers. Simultaneous recordings at Byrd Station (70.5° Geomagnetic) and Greenbank, W. Va. (50° Geomagnetic) showed that the Northern Hemisphere echo delays are not twice those from the Southern Hemisphere. Quantitative comparison of these results with Cape Horn NSS data and whistler data support the interpretation that the measured echo delay depends on the strongest component which in turn depends on the location of transmitter and receiver.

j. Satellite Measurements

Signal strength measurements of Station NSS and background noise were made at 15.5 kc/s in Explorer VI. Data are currently being analyzed. Clear signals from NSS were picked up by the satellite receiver from the launching point up to the D-region. Above 70 km NSS disappeared into the background noise, presumably because of D-region absorption. No unusual sources of natural noise were discovered within the ionosphere. However, the sensitivity of the receiver was limited by interference thought to have been generated by power converters within the satellite. It appears that for frequencies below the gyrofrequency the outer ionosphere is relatively quiet, being shielded from both extra-terrestrial noise and terrestrial atmospherics.

k. Geocyclotron

A new mechanism for accelerating charged particles in the outer ionosphere is proposed [Helliwell et al., 1960]. It is based on the properties of whistler-mode propagation, and the device for performing experiments is called the "geocyclotron". A circularly polarized swept-frequency VLF transmitter located on the ground or in a satellite accelerates relativistic electrons trapped by the earth's magnetic field. Energy from a ground-based transmitter reaches the interaction region by propagating in the whistler mode. The frequency of the radiation is adjusted so as to equal the gyrofrequency of relativistic electrons circling the lines of force of the earth's field in the plane of the geomagnetic equator. The frequency is decreased with time in such a way as to impart energy to the relativistic electrons. The mechanism is roughly analagous to that which takes place in a syncrocyclotron. The presence of the artificially accelerated particles, which should form a shell about the earth, could be detected with radiation counters carried in a satellite or probe.

The geocyclotron could be used in various ways to study dynamic processes in the outer ionosphere as well as whistler-mode propagation.

3.2. Dartmouth College

M. G. Morgan*

a. Whistlers-East

A meridional chain of observing stations, nominally along W75° was set up to make synoptic observations during the IGY from Thule to Florida, at Huancayo, and from Cape Horn to Antarctica. Fifteen stations were involved, each a story unto itself. Cooperating, in order of latitude, were Danes, Canadians, Americans, Bermudians, Peruvians, Argentines, and Britons. Some results have been published by independent cooperating workers as for example the Godhavn, Greenland, results by Ungstrup [1959], and the Washington results

*Dartmouth College, Hanover, N.H.

by Dinger [1960]. Geographically comprehensive studies have been made at Dartmouth and will soon be presented for publication. The following conclusions are based on the subjective reduction of the magnetic tapes and subsequent statistical analysis. (Latitudes given are geomagnetic.)

(1) *Whistlers.* In the Northern Hemisphere, in the longitude under study, very nearly all whistlers observed are found to be "long", and in the Southern Hemisphere, very nearly all to be "short". There is a pronounced seasonal variation in activity with a large maximum in July and August and a smaller maximum in January and February. These maxima are found in the data from both hemispheres. In the northern winter months, the northern stations report more activity in long whistlers than do the the southern stations in short whistlers.

The northern stations, Knob Lake (66°), Mont Joli (60°), and Dartmouth (55°), exhibit similar and consistent patterns of whistler activity, whereas, for reasons unknown, Washington (50°) and Bermuda (44°) are notably different. (A point to consider is that these two stations used long-wire antennas, whereas all others used loops.)

In the Northern Hemisphere, whistler activity reaches a peak at about 55° and falls off rapidly above and below that latitude. In the Southern Hemisphere, it can be said that activity at Port Lockroy (53.0°) is significantly greater than at Ellsworth (67°) or at Ushuaia (43.3°).

Generally speaking, there is a broad diurnal maximum of activity at each station during the nighttime hours, and a distinct minimum just before local noon. The ratio of maximum activity to minimum varies widely from station to station and seasonally.

At Battle Creek, 13° west of Dartmouth and 2° south, the pattern of behavior has been found to be similar to that at Dartmouth but at a much lower level.

At Huancayo on the geomagnetic equator, no whistlers were reported, though the station was well run throughout 1958 and all of the tapes carefully monitored. Taking a time of very high whistler activity at Dartmouth and listening to the corresponding recordings from Huancayo, it appears that very, very faint whistlers can occasionally be heard. They would never be detected without concentrating attention on a particular moment as directed by observations from higher latitudes. The noise level at Huancayo is, of course, uniformly high.

At Knob Lake (66°) only weak, long whistlers have been heard. At Frobisher Bay (75°), they are also heard but less often and even more weakly. They have not been heard at Godhavn (80°). Short whistlerlike signals having $D=40$ to 60 and a high minimum frequency have been heard at Frobisher Bay and Godhavn, but it is an unanswered question whether these are ordinary whistlers or some other form of emission.

A study has been made of meteorological conditions at 06 h Z for 1957 October, November, and December in an effort to discern a geographical pattern of storms associated with long whistlers observed at Dartmouth. Of the 92 days involved, whistlers were observed at Dartmouth on 66 and none on 26. Storms with electrical discharges reported were located in the general area of eastern United States and the North Atlantic on 89 days. It is interesting to note that on the three days when no storms were reported, long whistlers were observed.

The incidence of whistler echoes has been studied. Although it shows a large and smooth diurnal variation, very closely repeated from 1 yr to the next, ranging from 5 periods/month at 01 h Z to 0.3/month at 14 h Z (respectively, 20 h and 09 h W 75° time); the diurnal variation of the probability that echoes will occur when whistlers are present, is only about 2:1. The maximum and minimum of the probability curve occur at approximately the same time as those of the echo curves themselves.

(2) *Ionospherics.* During the IGY, naturally occurring VLF phenomena other than whistlers, were grouped into three ill-defined categories: "chorus", "hiss", and "other". Together these were called "VLF emissions". We have now adopted the term "ionospherics" for these, as contrasted with "tropospherics" (lightning). As defined for the IGY, "hiss" was taken to mean a broad band of noise of no special bandwidth or ferquency; phenomena which occurred as isolated events or "unusual" sounds were called "other"; and most everything else, "chorus." On the basis of these definitions, the following facts have been determined concerning chorus.

In the Northern Hemisphere, stations at 55° to 60° show the most activity. The activity has a sharp maximum in April and May and a minimum in November and December.

In the Southern Hemisphere, Ellsworth (67°) shows consistently greater activity than Port Lockroy (53.4°), and, remarkably, both show a pattern largely independent of the time of year. Chorus is rarely heard at Ushuaia (43.3°). At Ellsworth it is present about 40 percent of the time.

The diurnal variation of chorus activity is sharply defined at 11 h Z (6 h W 75° time), at Mont Joli (N 60°), and at Dartmouth (N 55°), whereas at Washington (N 50°) and Bermuda (N 44°), there is a maximum near 08 h Z (03 h W 75° time). Ellsworth (S 67°) and Mont Joli (N 60°) show almost identical activity but Port Lockroy (S 53.4°) shows hardly any notable diurnal variation.

The diurnal variation seems to differ but slightly with the season. At Dartmouth, the station for which most data are available, activity for May—July and for August—October have about the same diurnal variation with a peak at 10 h Z. The diurnal variations of the activity in the periods February—April and November—June are similar to each other but have a broad maximum at 09 to 12 h Z. The level of activity for the spring months is about twice that for the winter months.

As with whistlers, the pattern of chorus activity at Battle Creek has been found to be very similar to that at Dartmouth, but the level much lower.

No ionospherics were reported from Huancayo, but chorus is heard up to the very highest latitudes, including Thule (N 88°).

Very little analysis of "hiss" and "other" has been carried out so far. It can be said that more hiss has been observed at Dartmouth than at any other station.

b. E 4° (Geomagnetic) Stations: Successor to Whistlers-East

Recognizing that the three southern hemisphere points, Ushuaia, Port Lockroy, and Ellsworth are about the best that can be had for the foreseeable future, and that the northern conjugate positions of these stations line up along W 65° (E 4° geomagnetic), attention has been concentrated along that line in the Northern Hemisphere. Frobisher Bay (75°) and Knob Lake (66°) lie close to that line. Mont Joli (60°) is being moved 150 miles northeastward to Moisie (61.7°) 15 miles east of Sept Isles on the north shore of the St. Lawrence Gulf, and a station is being established in southernmost Nova Scotia. The Bermuda station has been moved to a vastly improved location. Washington and Gainesville, Fla., have been discontinued, and Huancayo has been discontinued.

c. Post-IGY Results

Commencing with all data taken after 1959 July 1, the classification of ionospherics has been greatly refined and this is producing interesting new results. For example, the chorus data from Mont Joli (60°) and Dartmouth (55°), when restricted to rising tones only, recurring faster than 2/sec, and going above 2 kc/s, have a maximum occurrence at the same local time rather than 1.5 to 3 hr later at the higher latitude when all forms of chorus are lumped together.

d. E 94° (Geomagnetic) Stations

At the instigation of Dartmouth workers, stations have been set up on Saltholmen Island in the strait between Denmark and Sweden at Copenhagen, and at Marion Island 1,400 miles southeast of Cape Town. Although in geomagnetic latitudes N 55° and S 49°, respectively, these stations are very close to conjugate positions. A station has also been set up at Naples which is close to the northern conjugate of Durban, South Africa. These stations are in geomagnetic latitudes N 42° and S 32°, respectively. The two pairs of stations lie close to the E 94° geomagnetic meridian and are, therefore, exactly 90° east of the E 4° stations. In addition to whistler observations, the 16 kc/s whistler-mode signals from GBR in Rugby will be observed at Marion Island, which is less than 400 miles from Rugby's conjugate position.

The cooperating institutions are the Royal Technical University of Denmark, the University of Naples, the University of Natal, and Dartmouth College. A graduate student from the University of Natal is spending a year at Marion Island.

e. Angle of Arrival Measurements

An experiment to measure the angle of arrival of whistlers and ionospherics by comparing the time of arrival at three stations mutually 100 km apart is in progress and results will be available for reporting to the XIIIth Assembly.

f. Acknowledgment

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4. A Summary of VLF and ELF Propagation Research

James R. Wait*

4.1. Introduction

The renewed interest in the VLF and ELF portions of the radio spectrum has been very evident in the 3 yr since the previous General Assembly of URSI. Applications of VLF and ELF to long-distance communication, worldwide frequency standards, navigational aids, and detection of storms, are providing continuous motivation for further research in this field.**

It is the purpose of this report to summarize research activity in VLF and ELF propagation carried out in the USA since January 1, 1957. Attention is confined to published papers relating to terrestrial propagation, and thus reference to solar and exospheric phenomena is excluded. Closely related work carried out in other countries is also briefly mentioned.

4.2. Theoretical Studies

For certain applications at VLF, particularly at short ranges, it is permissible to neglect the presence of the ionosphere. In fact, at frequencies of the order of 100 kc/s the groundwave may dominate the skywave for ranges as great as 500 km. Furthermore, with the use of pulse-type transmissions, such as used in the Cytac or Loran C navigation systems, the groundwave may be distinguished from the skywave for distances as great as 2,000 km [Frantz, 1957; Dean, 1957; Frank, 1957]. With this motivation, a number of theoretical papers on groundwave propagation have appeared in the literature dealing specifically with: (a) Amplitude and phase versus distance curves [Johler et al., 1956; Wait et al., 1956a; Johler et al., 1959a]; (b) land-sea boundary effects [Wait, 1958b; Wait et al., 1957c]; and (c) propagation of electromagnetic pulses over the surface of homogeneous and inhomogeneous ground [Wait, 1956c; Johler, 1957; Wait, 1957h; Wait, 1957a; Levy et al., 1958; Johler, 1958; Johler et al., 1959b; Wait et al., 1959b; Wait, 1957d]. The penetration of groundwave fields into the earth or sea has also been considered in some detail [Wait, 1959c; Wait, 1959d; Kraichman, 1960; Keilson, 1959] and the influence of earth stratification on the attenuation rate of the groundwave has been given further attention [Stanley, 1960; Wait, 1958e].

Unfortunately, in cw systems and at distances as small as 100 km from the source, the sky wave may often interfere with the groundwave. Thus, the total field may be considered as the resultant of a groundwave and a number of ionospherically reflected waves in the VLF band at moderate ranges (i.e., less than 1,000 km or so)[Wait et al., 1957b; Wait et al., 1957f; Johler et al., 1960; Pfister, 1953; Poeverlein, 1958a; Poeverlein, 1958b]. However, it appears to be more convenient to represent the total field as a sum of waveguide type modes for VLF at great distances and, for ELF, at nearly all distances. In fact, for many applications only one or two modes need be retained, since the higher modes are either "cutoff" or have severe attenuation. A number of papers on mode theory were presented at the VLF Symposium held in Boulder, Colo. January 1957 [Liebermann, 1956b; Budden, 1957; Wait, 1957g; Wait, 1957e]. In these, the ionosphere was represented by a sharply bounded and homogeneous ionized medium, and the influence of the earth's magnetic field was neglected. Also, since the frequency could be assumed to be much less than the effective collision frequency, the ionosphere was equivalent to an isotropic conductor. More recent investigations of mode theory have removed some of the earlier restrictions. For example, the influence of stratification in the D and E regions was accounted for by using layered and exponential models [Shmoys, 1956; Wait, 1958a; Wait, 1960b; Bremmer, 1959].

It is interesting to observe that Al'pert in the USSR has also pursued the mode theory of VLF propagation [Al'pert, 1956]. In his work he also neglects the earth's magnetic field and, in his initial formulation, the ionosphere is sharply bounded. He treats the effect of ionospheric stratification by using an Epstein model which is strictly valid only for horizontal polarization. In much of the work on this topic, the effect of earth curvature is neglected for purposes of computing the attenuation of the modes. Some time earlier, Budden [1952] had obtained a first-order correction for earth curvature by using an earth-flattening type of approximation, and more recently Wait [1958f] had used a similar modification in some published curves of VLF transmission loss. From this work, it appears that earth curvature has a negligible effect on the modes for frequencies less than about 15 kc/s.

Actually, for frequencies at the upper end of the VLF band (i.e., 15 to 30 kc/s), it is necessary to abandon first-order curvature corrections and to introduce higher-order approximations for the spherical-wave functions which occur in the rigorous formulation. This aspect of the problem is discussed at length by Wait in a recent paper which includes an extensive discussion of related theoretical work [Wait, 1960c].

The influence of the earth's magnetic field on the attenuation and phase of the modes is a difficult subject. However, if expressions for the plane-wave reflection coefficients for an anisotropic ionosphere can be derived, it is not too difficult to extend these to the computation of the modes [Budden, 1952; Wait, 1960c]. Thus, the results of Bremmer [1949],

*National Bureau of Standards, Boulder, Colo.
**The VLF band is here defined as the decade 3 to 30 kc/s and the ELF band covers the range 1.0 c/s to 3 kc/s.

Yabroff, [1957], and others [Wait et al., 1957b; Wait et al., 1957f; Johler et al., 1960] may be adapted for mode propagation between the curved earth and a doubly refracting ionosphere [Wait, 1960c]. Using such an approach, Crombie [1960] has adapted the plane-wave reflection coefficients for a *transverse* magnetic field to the case of mode propagation around the magnetic equator. The latter example clearly demonstrates nonreciprocity in VLF propagation.

While the mode theory would seem to be particularly appropriate at ELF, certain assumptions which are usually made become questionable. These longer wavelengths penetrate further into the ionosphere so that the sharply bounded model must be modified [Bremmer, 1959]. Another approach is to postulate an effective increase in the ionospheric height as the frequency decreases [Pierce, in press]. Even more important at ELF is the fact that distance from source to observer is usually comparable with the wavelength. Thus, the numerical treatment of the mode series has been considered by Wait [1960a] for unrestricted distances.

Again using the concept of modes, the propagation of both VLF and ELF pulses has also received considerable attention [Liebermann, 1956b; Wait, 1960a; Wait, 1958c]. Of some importance is the manner in which the quasi-half periods of the oscillatory waveform of the pulse vary with range and time [Wait, 1958c].

4.3. Experimental Studies

Since the observed characteristics of VLF and ELF propagation depend on so many factors, one should be careful in placing undue emphasis on any single experiment. In particular, the validity of a particular theoretical model cannot be established on a basis of experimental data obtained in a single geographical area and for restricted intervals of time. Nevertheless, certain experiments are crucial in the sense that they confirm the concept of the model. For example, if the measured dependence of VLF field strengths on distance and frequency are in general accord with theoretical predictions, one can say that, at least for those ionospheric conditions, the model is perhaps adequate in a phenomenological sense.

A crucial test of the waveguide mode concept of VLF propagation was provided by Heritage, Weisbrod, and Bickel [1957] in a series of airborne measurements of field strengths in the Pacific Ocean. They utilized transmissions in the frequency range of 16 to 20 kc/s from the United States, Hawaii, and Japan. The daytime experimental data were in good agreement with the mode theory as indicated by Wait [1957g]; however, the nighttime data were highly variable and certain nonreciprocal effects were in evidence.

The U.S. Navy is also conducting a long-range study of VLF propagation characteristics by means of measurements made over several paths selected to show the effects of various geophysical conditions encountered (private communications from H. E. Dinger, Naval Research Laboratory).

Phase variations of the 16 kc/s carrier signal of station GBR in England have been measured by Pierce (J. A.) [1955; 1957] in Cambridge, Massachusetts. The diurnal variation of the change of the phase has been interpreted by Wait [1959a] in terms of mode theory in a satisfactory manner.

4.4. Recent Applications of VLF Propagation

Research in VLF propagation has been prompted by many important applications. In particular, the low attenuation and high-phase stability of VLF signals make it feasible to set up a worldwide frequency standard employing only one transmitter. A careful study of this problem by Watt and colleagues [Watt et al., 1959] indicates that a minimum radiated power of 10 to 100 kw for frequencies of 20 kc/s would be required. Minimum observation times of 15 to 30 min would be needed to obtain a precision of frequency of 1 part in 10^9. Another application is to long-range navigational systems such as the Radux-Omega in which the phase difference between two widely separated transmitting stations is measured. Frequencies used in this system are in the range 10 to 18 kc/s with typical phase stabilities on a path of 8,000 km of 4μ secs in day and 5μ secs at night [Casselman et al., 1959].

By application of highly precise quartz oscillators coupled with the use of atomic frequency standards, it has become possible for the U.S. Navy to stabilize its existing VLF transmitters so as to provide extremely accurate frequency and time information to naval units on a worldwide basis. The Naval Radio Station (NBA) at Balboa in the Canal Zone, Panama, has been equipped by the Naval Research Laboratory for this service and is now transmitting precise time and constant frequency. The Pearl Harbor, San Francisco, Culter, and Annapolis stations will be controlled by constant frequency as soon as equipment becomes available. Thus, no additional VLF spectrum will be required to provide the entire Navy with complete synchronization of time and frequency. These transmissions should also provide an excellent tool for propagation studies at VLF (private communication from H. F. Hastings, Naval Research Laboratory).

Many studies of VLF propagation have been made using lightning strokes as a source of energy. For example, Watt and Maxwell [1957a] showed that the propagation modified the spectral content of atmospheric radio noise in a manner which again was quite compatible with mode theory. In particular, the predicted absorption band [Wait, 1957e] at frequencies around 3 kc/s was confirmed. Attenuation rates at VLF have been deduced from the spectral analyses of atmospheric waveforms observed simultaneously at widely separated stations [Taylor et al., 1959a; Taylor, 1960]. A similar technique has been developed for deducing phase characteristics of VLF propagation in a frequency range from 1 to 30 kc/s [Jean et al., 1960].

Experimental studies at ELF have been primarily devoted to the recording of the ELF or "slow tail" portion of the atmospheric waveforms [Liebermann, 1956a; Holzer et al., 1957; Tepleu, 1959]. In many cases, it appears that this ELF part of the waveform is a highly damped pulse with seldom more than two half-cycles with periods of the order of several milliseconds. The relation of ELF wave shapes to the orientation of the lightning stroke has been recently analyzed [Wait, 1960a].

In presenting propagation data at VLF and ELF care should be used in properly separating the losses due to propagation and those due to the antenna systems. It is important that the change of impedance of the antennas due to the ground plane be accounted for. To retain the basic idea of power transfer introduced by Norton [1953], yet separate out the influence of the antenna environment, the concept of "propagation loss" was proposed [Wait, 1959e]. It forms one component of the system loss [Norton, 1959] which is the decibel ratio of the power into the terminals of the transmitting antenna to the power available at the terminals of the receiving antenna.

5. Hydromagnetic Waves and ELF Oscillations in the Ionosphere

James M. Watts*

The hypothesis that hydromagnetic waves [Alfvén, 1942; Lundquist, 1949] occur in the ionosphere has been pursued theoretically, observationally and experimentally in the United States.

The theoretical investigations have usually taken the form of arguments for the existence of these waves, since the conditions for their propagation exist in the region [Dessler, 1958]. The theories of the consequences of the waves have then been extended to explain certain geophysical phenomena, such as the sudden commencements of magnetic storms [Francis et al., 1959; Dessler et al., 1959a] and auroras [*Warwick*, 1959], ionospheric heating [Dessler, 1959b], ionospheric tides [White, 1960a; 1960b], and the motion of ionized gas near the earth [Gold, 1959].

A review of the observations of geomagnetic oscillations suggests that they may be explained by waves of the Alfvén type [Maple, 1959] excited by solar disturbances since 27-day solar dependence and correlations with magnetic and ionospheric F-layer disturbances were evident [Campbell, 1959; Berthold et al., 1960; Campbell, 1960].

However, hydromagnetic oscillations do not seem to explain other classes of electromagnetic disturbances [Watts, 1957; Gallet, 1959b] whose frequencies are principally well above those characteristics of geomagnetic micropulsations. Therefore, emphasis has been placed on the the theory of traveling wave amplification to explain those phenomena [Gallet et al., 1959a; Bell et al., 1959].

During the triennium 1957 to 1960 controlled experiments have become feasible, using rockets, artificial earth satellites, and nuclear explosives. It has been possible to create hydromagnetic waves in the ionosphere by explosions and observe them by rockets and satellites [Nat. Acad. Sci., 1959; Kellogg et al., 1959]. That the magnitude of these effects is comparable with the magnitudes of natural occurrences is evidenced by the records of conventional magnetometers and by the sighting of auroras [Matsushita, 1959; Steiger et al., 1960].

A rocket alone has shown evidence of instability in the distant geomagnetic field. Measurement of the magnetic field intensity vector at large distances from the earth indicated a complex behavior, including nearly periodic oscillations which may have been due to hydromagnetic waves [Sonett et al., 1959].

*National Bureau of Standards, Boulder, Colo.

6. The Exosphere

James M. Watts*

6.1. Introduction

The lower boundary of the exosphere may be above defined variously as the ionospheric level just about the entire *F* region, as the critical level above which particles encounter no collisions and are, therefore, in free flight, or as the level above which hydrogen is the predominant constituent. If the outer boundary is taken to be 6 to 8 earth radii, including most of the gas within the region of influence by the earth's magnetic and gravitational fields, the exosphere includes the entire region in which whistlers are greatly dispersed, in which VLF emissions may originate, in which geomagnetic micropulsations are supposed to originate, and in which the earth's trapped radiation lingers.

Therefore, significant understanding of the exosphere has been achieved by observing those phenomena. The reader is referred to the USA report on whistlers for the extensive observations of whistlers and VLF emissions during the IGY, and to the report on hydromagnetic waves and ELF oscillations for references giving the USA work in that region.

6.2. Theories of the Exosphere

a. Magnetic Storm Effects

During 1956, the hypothesis was developed that solar corpuscular radiation can be injected into the earth's magnetic field and trapped there [Singer, 1956]. The particles were considered to create an electric current which was held responsible for the main phase of magnetic storms [Singer, 1957]. Later, a mechanism based on Fermi accelerations for increasing the energy of some of the particles sufficiently to produce some of the auroral effects was proposed [Singer, 1958a; 1958b]. It seemed very possible that the electrons thus accelerated can be identified with the outer radiation belt while the protons injected directly from the sun are removed after a very short time by charge exchange with neutral hydrogen in the earth's exosphere, thus bringing the magnetic storm to a decline after 1 or 2 days [Singer et al., 1960].

b. Radiation Belt Theory

Some work on properties of geomagnetically trapped particles was done prior to their discovery, for example: their penetration into the auroral ionosphere [Rhodes, 1959], the behavior of trapped cosmic ray albedo [Griem et al., 1955], and an experiment for their detection was discussed [Singer, 1958d].

Following the discovery of trapped radiation in Explorer I in May 1958, the neutron albedo theory was developed as a means of explaining the presence of hard radiation and calculated its approximate altitude distribution, noting the probable existence of a maximum close to the earth [Singer, 1958e; 1958f]. Following this, the existence of two belts was predicted explicitly, one an inner belt close to the earth's equator produced by cosmic ray neutron albedo, and another an outer belt of solar origin and connected with the aurora [Singer, 1958a]. These features were roughly verified by the Pioneer and Lunik probes.

In detail, calculations were made of the lifetime of trapped particles both for protons and for electrons [Wentworth et al., 1959]. The distribution in energy and in space of trapped protons was investigated [Singer, 1959c].

c. Composition of the Exosphere

The distribution of neutral particles in an exosphere, taking into account ballistic and escape orbits, was calculated [Opik, et al., 1959].

Some theoretical work based on knowledge of general features of the ionosphere have led to extrapolation of these features into the exosphere, in order to predict the composition [Singer, 1959*b*] and densities [Johnson, 1960; Wright, 1960] above the *F*-layer maximum. From the latter work it appears that the region of the exosphere nearest the *F*-layer is expected to have a profile resembling a Chapman layer with a scale height of 100 km.

6.3. Experiments in the Exosphere

Experimentally, the region has been explored in several different ways. Rockets for the first time penetrated the region [Van Allen, 1957; Harris et al., 1959] and were the forerunners of the well-known artificial satellite experiments which have delineated the high-intensity radiation belts in the exosphere [Van Allen, 1959b; Van Allen et al., 1959a; Van Allen et al., 1958a and 1958b; Stuart, 1959]. High-altitude explosion of nuclear devices has shown that the radiation belts can be modified artificially and the resulting decay studied to verify that the theory of radiation trapping provides the correct way of interpreting the natural radiation [Singer, 1959a; Nat. Acad. Sci., 1959b].

Experiments not involving satellites and rockets, however, are relatively inexpensive and are well adapted to measuring the electronic content of the exosphere.

The moon radar measurements of Faraday rotation [Bauer et al., 1958] have given an excellent picture of the total electron content of the ionosphere plus exosphere and its variation with time.

* National Bureau of Standards, Boulder, Colo.

An entirely new technique for vertical incidence sounding of the ionosphere [Bowles, 1958] has the advantage that blanketing reflections do not obscure details above the maxima of layers, since all reflections are partial for the frequencies used. This use of extra high power and sensitivity in a sounder enables true heights and electron densities to be measured directly and should be a powerful means of studying the nearer regions of the exosphere.

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