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# URSI National Committee Report, XIV General Assembly, Tokyo, September 1963:

# Commission 3. Ionospheric Radio

Edited by C. G. Little

## Introduction

The last triennium has seen a continued expansion of activities pertinent to Commission 3 (Ionospheric Radio Propagation) within the United States. The principal trend has been the continued rapid expansion of interest in the physics of the ionosphere at all heights, with particular reference to ionospheric constituents and electron density profiles. For this work, ground rocket and satellite platforms have been used. The more classical studies of ionospheric radio propagation have also continued, though there has been reduced effort on meteor and auroral radar studies.

This report is divided into seven principal sections. The first six of these cover the principal topics to be discussed at the Commission 3 meetings of XIVth General Assembly of URSI in Tokyo. These sections, and their authors are:

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|---|---|
| 1. Ionizing radiation and constitution of the ionosphere | T. E. VanZandt |
| 2. Geomagnetism and the ionosphere | S. A. Bowhill |
| 3. Ionospheric storms | S. Matsushita |
| 4. Radio, the ionosphere, and IQSY | R. W. Knecht |
| 5. The guided propagation of ELF and VLF radio waves between the earth and the ionosphere | D. D. Crombie and A. G. Jean |
| 6. Electron distribution in the ionosphere | J. W. Wright |

The final section summarizes some of the other aspects of the work of Commission 3.

# 1. Ionizing Radiation and Constitution of the Atmosphere

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## 1. Introduction

Progress during the triennium 1960–1962 in our knowledge of the structure of the neutral atmosphere in the ionospheric region, the flux density versus wavelength and time of the solar ionizing radiations, the rate coefficients of the ionic reactions which ionization in the ionosphere may undergo, and the construction of theoretical models of the ionospheric layers are reported in this section.

## 2. The Neutral Atmosphere

### 2.1. Density and Temperature

In the previous triennium [1957 through 1959] our knowledge of the density and temperature of the neutral atmosphere in the ionospheric regions was greatly advanced by observations made from rockets and especially by observations of satellite drag. Jacchia [1960] has described the diurnal variation of atmospheric density and scale height above 200 km. Jacchia [1961] has shown that the minimum nighttime temperature $T_0$ is related to the 10.7 cm solar flux $S$ by the relation $T_0=550°+3°S$, that the maximum daytime temperature is about $1.35T_0$, and that the temperature is augmented by geomagnetic activity by 1.5° per unit of $A_p$, Harris and Priester [1962a, 1962b] have fitted these observations with a theory of the processes of heat input and loss in the upper atmosphere. They find that the observed density variations cannot be explained by photoionization heating alone, but that an additional heat source, about equal to the photoionization flux and with a peak at about 09 hr must be hypothesized. They suggest that this source is the dissipation of hydromagnetic waves in the ionosphere.

### 2.2. Composition

The composition of the neutral atmosphere above 100 km has been extremely uncertain. For example, different model atmospheres have ranged from having the partial pressures of atomic oxygen and molecular nitrogen (the main constituents) approximately equal in the *F* region to having atomic oxygen much greater than molecular nitrogen. Hinteregger [1962] has shown from observations of the flux versus height in solar lines in the extreme ultraviolet that the atmosphere is mostly atomic oxygen above about 150 km and that it is almost all atomic oxygen throughout the *F* region. Model atmospheres consistent with Hinteregger's observations have been constructed by Hanson (in press) and Norton, VanZandt, and Denison (in press).

## 3. Solar Ionizing Radiation

The solar Lyman $\alpha$ line at 1216 Å and all emissions between 1027 and 1 Å can be important in creating the ionosphere by ionizing the atoms and molecules of the atmosphere. For convenience, the range from 1216 to 100 Å is called the extreme ultraviolet (*EUV*) region, and the range from 100 to 1 Å, the x-ray region.

From the point of view of ionospheric physics it is the photon flux density versus wavelength which is of interest. High resolution and line identification are of only secondary interest. Observations of the photon flux density versus wavelength in the *EUV* have been reported by Hinteregger et al. [1960], Detwiler et al. [1961], Hinteregger [1961], and Hinteregger and Watanabe [1962].

The flux density in Lyman $\alpha$ was already well-known before 1960. In any case, the theory of the formation of the *D* region, which is the only region in which Lyman $\alpha$ plays a role, contains so many adjustable parameters that more precise knowledge of the flux density of Lyman $\alpha$ would not yet be of much help. On the other hand, the flux density versus wavelength between 1027 and 100 Å, which is responsible for almost all of the ionization in the *F* region and part of that in the *E* region, was known only qualitatively before 1960. The aforementioned observations are, therefore, invaluable in theoretical studies of the *E* and *F* regions.

Observations of solar x rays, which are responsible for part of the ionization in the *D* and *E* regions, have been reviewed by Kreplin [1961].

The variations in time of the flux density of the *EUV* lines and x rays have been observed from the NRL Satellite Solar Radiation [Chubb et al., 1961] and the Orbiting Solar Observatory [Neupert and Behring, 1962; Behring et al., 1962]. During solar flares, the coronal lines in the *EUV* and the x rays are greatly enhanced, while chromospheric lines (including Lyman $\alpha$) are only slightly enhanced. This demonstrates that the enhancement of ionization and absorption in the *D* region during a solar flare is due to x rays, not Lyman $\alpha$. This conclusion was adumbrated by rocket observations [Chubb et al., 1960]. The enhancement of the x rays also accounts for the observed *E*-layer flare effects, and the enhancement of the coronal lines in the *EUV* accounts for the observed *F*2-layer flare effects [Knecht and Davies, 1961a, 1961b; Knecht and McDuffie, 1962]. Behring et al. [1962] also observed the variation of the intensity of Lyman $\alpha$ as a function of sunspot number.

## 4. Theories of the Formation of the Ionospheric Layers

### 4.1. The *D*-Region

Moler [1960], Nicolet and Aikin [1960], Crain [1961], Swift [1961], Poppoff and Whitten [1962], Webber [1962], and Aikin [1962] have developed theoretical models of the formation of the *D* region. Moler [1960] and Nicolet and Aikin [1960] consider the quiet *D* region. Nicolet and Aikin [1960], Swift [1961], and Poppoff and Whitten [1962] discuss the effect of solar flares (SID's). Crain [1961] concerns himself primarily with the rates of loss of ionization, Webber [1962] with the rates of ionization by cosmic rays, and Aikin [1962] with the sunrise effect in the normal *D* region. All of these theories are, however, in general accord. For the sun overhead and quiet, the ionization between 85 and 70 km is created by Lyman $\alpha$ ionizing NO, which is a trace constituent in the *D* region. The ionization below 70 km is created by cosmic rays, and the ionization above 85 km may properly be considered to be the tail of the *E* region. During solar flares the enhancement of absorption (SID) is due to ionization by x rays above 70 km, and during polar cap absorption events the enhancement of absorption is due to ionization by solar protons below 70 km.

### 4.2. The *E*-Region

Watanabe and Hinteregger [1962] have used the observed solar flux densities together with a model atmosphere and absorption and ionization cross sections to compute the rates of photoionization of the atmospheric constituents above 90 km. Similar inferences have been made by Hinteregger and Watanabe [1962] directly from observations of solar photon flux versus height. They find a peak rate of photoionization in the *E* region of the order of 3000 ion pairs/cm$^3$ sec at 105 km. This rate is about a factor of 10 larger than that inferred from ionospheric observations. They infer that the *E* layer is formed mainly by ionization of $O_2$ by solar emission in the wavelength range from 1027 to 911 Å.

Bowhill [1961a] has shown that the effective recombination coefficient of an ionosphere containing a mixture of ions may be quite different from that obtained from observations by the usual methods.

### 4.3. The *F*-Region

Watanabe and Hinteregger [1962] and Hinteregger and Watanabe [1962] have shown that the *F* region is formed almost entirely by the solar emission in the wavelength range from 170 to 911 Å. Hinteregger and Watanabe [1962] and Hinteregger [1962] showed that above 200 km the photoionization is almost entirely of atomic oxygen. They found a peak rate of photoionization in the $F1$ region at about 150 km of the order of 3000 ion pairs/cm$^3$ sec, which is about 10 times larger than that inferred from ionospheric observations. The rates in the $F2$ region are also correspondingly larger than most ionospherically inferred rates.

VanZandt et al. [1960a, 1960b] inferred rates consistent with those of Watanabe and Hinteregger and Hinteregger and Watanabe from ionospheric observations made during the eclipse of 12 October 1958.

By comparing rocket observations of the $F2$ layer with theory, Bowhill [1961b] inferred that the temperature was about 1100 °K by night and 1500 °K by day (at sunspot maximum), and that the linear loss coefficient at 300 km was about $5\times10^{-4}$. Bowhill [1962] found solutions of the steady-state continuity equation in terms of Lommel function and series, and he showed that the daytime $F2$ layer can be considered to be a region with diffusion and photoionization with all of the recombination much below the peak.

Schmerling [1960] and Goldberg and Schmerling [1962] have shown that the minimum of electron density at the magnetic equator can be explained qualitatively in terms of photoionization, recombination and diffusion along the magnetic field lines.

Chandra et al. [1960] and Garriott and Thomas [1962] have deduced the vertical drift velocity of charge from the continuity equation with hypothesized rate coefficients.

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# 2. Geomagnetism and the Ionosphere

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## 1. Field-Alined Ionization Irregularities in *E*-Region

Considerable progress has been made in the understanding of types of field-alined irregularities that can scatter VHF radio waves. On the geomagnetic equator, Bowles et al. [1960] found one type of irregularity scattering only in the E–W plane, which they deduced was in the form of a family of plane irregularities drifting from east to west, their planes containing the magnetic field direction. Egan [1960] described oblique incidence equatorial scatter which he attributed to linear irregularities. Cohen et al. [1962] and Bowles and Cohen [1962] gave detailed descriptions of the interpretation of equatorial sporadic $E$ echoes.

In the auroral zone, Leadabrand [1961] noted a type of field-alined echo, not associated with visible aurora, but frequently present during the day. Two types of auroral sporadic $E$ were attributed by Bates [1961] to least-time and aspect focusing by the same set of irregularities, in a similar way to the equatorial scatter. Leonard [1962] discussed the geographic distribution of radar auroras; Hook and Owren [1962] gave measurements of heights of $E$-region irregularities causing satellite scintillation in the auroral zone.

Heritage et al. [1962] gave further observations of medium latitude field-alined ionization, and suggested they originated by anisotropic diffusion of ionization from meteor trails.

## 2. Spread-*F* and Its Interpretation

A classification of spread-$F$ ionograms was suggested by Penndorf [1962a]; in a further series of papers [1962b, c, d] he described the morphology of spread-$F$ in the arctic regions.

Theories of spread-$F$ were presented by Renau [1960], Bugnolo [1960], Cohen and Bowles [1961], and Calvert and Cohen [1961]. The latter two papers suggested that many of the features of equatorial spread-$F$ could be explained by sheetlike irregularities, alined with the magnetic field, some situated below the $F$ layer, others embedded in it. In further papers, Pitteway and Cohen [1961] and Pitteway [1962] developed the theory that the spread-$F$ of temperate type appearing on equatorial ionograms could be explained by backscatter in the north-south plane (as opposed to the east-west propagation involved in the type previously described), the waves propagating along field-alined irregularities. Confirmatory evidence was produced by Knecht and Russell [1962] in the appearance of ducted echoes on topside sounder records obtained with a rocket-borne ionosonde.

## 3. Geomagnetic Control of the *F*2 Layer

The diffusion of ionization along the geomagnetic field lines, and its effect on the electron distribution near and above the $F2$ peak, have been the subject of considerable investigation. Wright [1960] proposed a Chapman-like model for the upper side of the $F2$ layer. Johnson [1960] suggested that the upper part of the layer was in equilibrium between oxygen ions and protons, through charge-exchange; this idea was elaborated by Hanson and Ortenburger [1961]. The possibility of explaining the anomalous behavior of the $F2$ layer near the dip equator on the basis of diffusion was investigated by Schmerling [1960] and by Goldberg and Schmerling [1962]. The effect of diffusion along the field lines on the formation of the $F2$ peak was discussed by Bowhill [1961 and 1962].

The time variations of the $F2$ layer and their relation to the geomagnetic field have been discussed by Chandra et al. [1960]. They deduced an apparent downward drift of the layer at night, upward in the day, its phase and magnitude agreeing with that predicted by dynamo theory. The anomalous time behavior of the polar $F2$ layer was treated by Hill [1960], who suggested wind shears in the atmosphere as a cause, and by Duncan [1962], who suggested negative ions might be important. Rastogi [1961] considered the lunar semi-diurnal variation in $foF2$ and showed it had the same dependence on magnetic dip as the $foF2$ itself, though changing in phase with latitude. Blumle [1962] showed that the equivalent thickness of the equatorial $F2$ layer had a large increase from night to day.

## 4. Dynamo Theory and the Sq Current System

Based on rocket-borne magnetometer results, Zmuda [1960a,b] calculated the surface and volume charges associated with the electrojet. White [1960] discussed the atmospheric motions producing the dynamo effect. Matsushita [1960] investigated criteria for locating the center of the Sq system. Spreiter and Briggs [1961a, b] suggested that the coupling between the $E$ and $F$ layers for dynamo currents would be much more pronounced at the medium latitudes than at the magnetic equator.

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# 3. Ionospheric Storms

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## 1. Introduction

During the past 3 years, many new techniques of observing various phenomena relating to ionospheric storms have been developed. For example, there are new radio methods, such as riometer, Doppler shift, and incoherent scatter techniques, and balloon and satellite observations. In order to cover the information resulting from the use of these methods, the present report includes not only ionospheric variations during geomagnetic disturbances (sec. 2), but also ionospheric variations caused by solar flares (sec. 3).

Since hydromagnetic waves and ionospheric currents have important relations with ionospheric storms, these are included in sec. 2. Also, polar cap absorption and bremsstrahlung x-ray observations are included in sec. 3. However, duplication of other articles, such as "geomagnetism and the magnetosphere" and "high-energy particle phenomena in the magnetosphere," is avoided by limiting the present report to the ionosphere and lower altitudes.

## 2. Ionospheric Variations During Geomagnetic Disturbances

### 2.1. Electron Density and Height Variations of the Ionosphere During Geomagnetic Storms

Statistical studies of *foF*2 and *h′F*2 values during geomagnetic storms are a common method of the study on ionospheric storms. Rastogi [1962] applied this method to the data obtained in central Africa and concluded that at low and middle latitudes ionospheric storm behavior is determined by the magnetic latitude of the station.

Somayajulu [1960] studied true-height variations of the *F*-region at Washington, D.C., for three severe magnetic storms. About 100 km decrease around noon was shown comparing variations on quiet days. Using all available parameters of electron density profile data obtained at eight stations along roughly 75° WMT, Matsushita [1963 a, b, and c] studied "storm-time" and "disturbance daily" variations of the maximum electron density, total electron content, and true height of the maximum electron density for 42 storms. He showed a remarkable dependence of these variations on season and latitude, and found relations among the maximum density, total content, and true height.

Vestine [1960] discussed the integral invariant of auroral particle motion and suggested its application to ionospheric disturbances at high latitudes. Matsushita [1962b] showed ionospheric height and density variations at the time of geomagnetic sudden commencements and sudden impulses.

In addition, artificial ionospheric disturbances are reported by a few workers. Samson [1960] and Steiger and Matsushita [1960] reported on "Teak" and "Orange" nuclear explosions, and Jackson, Whale, and Bauer [1962] showed local ionospheric disturbance created by a burning rocket.

### 2.2. Irregularities, Spread *F*, Slant *Es*, Traveling Disturbances, and Ionospheric Motions, During Geomagnetic Disturbances

In order to observe irregularities in the ionosphere, Little and Lawrence [1960] suggested the use of polarization fading of satellite signals. Also, Little, Reid, Stiltner, and Merritt [1962] observed the amplitude and angular scintillations of the Cygnus and Cassiopeia sources at College, Alaska, and discussed ionospheric irregularities during disturbances. Basler and DeWitt [1962] concluded that the heights of ionospheric irregularities in the auroral zone occurred mostly below 650 km, based on their observations of the 20 Mc/s signal strength of the satellite 1958 $\delta_2$ using a spaced-receiver technique.

Less occurrence of spread *F* during geomagnetic disturbances was reported for the Arctic by Penndorf [1962] and for the equatorial region by Cohen and Bowles [1961]. Bates [1961] confirmed that the high-latitude slant *Es* echo is associated with magnetic disturbances and concluded that it is the result of energy that is scattered by randomly distributed, field-alined irregularities.

Watts and Davies [1960] observed the frequency variation of HF propagation (WWV 20 Mc/s) and VHF (49.8 Mc/s) forward-scatter signals and obtained remarkable frequency variations during magnetic disturbances. Fenwick and Villard [1960] also obtained similar results for their observations of the WWV–20 signal. Davies, Watts, and Zacharisen [1962], Davies [1962 a and b] (see sec. 3.1) found frequency variations associated with solar flares and geomagnetic sudden commencements in the observation of WWV–10, WWV–15, WWV–20, and WWVH–10. By means of a similar technique, Chan and Villard [1962] observed large-scale traveling ionospheric disturbances. Tveten [1961] observed ionospheric motions with a high-frequency (13.7 Mc/s) backscatter technique and showed results similar to those obtained by other workers.

### 2.3. Increase of Radio Absorption During Geomagnetic Disturbances

Brown, Hartz, Landmark, Leinbach, and Ortner [1961] observed a burst of x rays at balloon altitude over Alaska, simultaneous with increase of cosmic-noise absorption by riometers in Alaska, Sweden, and Norway, at the onset of a sudden commencement. Another similar event was reported by Brown [1961a]. Matsushita [1961 and 1962b] suggested that the preceding reverse type of sudden commencement and impulse often accompany this increase of cosmic-noise, hence ionospheric, absorption. This was confirmed by Ortner, Hultqvist, Brown, Hartz, Halt, Landmark, Hook, and Leinbach [1962].

Anderson [1960], Anderson and Enemark [1960a and b], Bhavsar [1961], and Brown [1961a, b, and 1962] observed bremsstrahlung x rays during storms and bay disturbances with balloons. Anderson, Anger, Brown, and Evans [1962] reported simultaneous electron precipitation at balloon altitude in the northern and southern auroral zones (College, Alaska, and Macquarie Island, Australia). Basler [1961] studied aurorally associated ionospheric absorption of cosmic radio noise.

Campbell [1960 and 1961], Campbell and Leinbach [1961], and Campbell and Rees [1961] studied correlations among magnetic micropulsations, pulsating aurora, and ionospheric absorption. Campbell and Matsushita [1962] and Brown and Campbell [1962] reported correlations among micropulsations, bremsstrahlung x rays, ionospheric absorption by riometer, and ionospheric currents, during bay disturbances. Tepley and Wentworth [1962] also discussed micropulsations, x-ray bursts, and electron bunches.

Penndorf and Hill [1961] studied an absorption effect in the Arctic during a severe ionospheric storm using *f*min, *foE*s, and *foF*2 values. Gartlein and Sprague [1962] also studied auroral absorption using radio propagation quality figures.

The precipitation of energetic electrons during storms was extensively discussed by Winckler [1960] and by Winckler, Bhavsar, and Anderson [1962] based on their balloon observations.

### 2.4. Hydromagnetic Waves and Electric Currents in the Ionosphere During Geomagnetic Disturbances

In conjunction with ionospheric storms caused by electromagnetic drift effects, the ionospheric currents responsible for geomagnetic disturbance daily variations at high latitudes, which are called auroral jet currents, are studied by Akasofu [1960b], Kern [1961a and b], Sobouti [1961], and Barcus and Brown [1962]. Ionospheric currents accompanying geomagnetic micropulsations during bay disturbances are studied by Campbell and Matsushita [1962] and by Brown and Campbell [1962]. Currents associated with sudden commencements and their relation to ionospheric disturbances are discussed by Akasofu and Chapman [1960] and Matsushita [1960]. In a study of the association of plane-wave electron-density irregularities with the equatorial electrojet observed by means of radar echo at 49.96 Mc/s, Cohen and Bowles [1963] investigated disturbed ionospheric current effects of equatorial-type *Es*. Matsushita [1962a] discussed relations between *Es* in high latitudes and disturbed ionospheric currents in his study of interrelations of different types of *Es* and various ionospheric currents.

Ionospheric heating by hydromagnetic waves was discussed by Akasofu [1960a] and Francis and Karplus [1960], and hydromagnetic wave propagation in the ionosphere was discussed by Kahalas [1960]. Hydromagnetic waves certainly play an important role in some types of ionospheric disturbances, such as those associated with sudden commencements, impulses, rapid fluctuations, solar flares, and nuclear explosions. However, the heating effect should be studied further. Also, there still remains a basic question of electron density increase during storms in low latitudes.

## 3. Ionospheric Variations Caused by Solar Flares

### 3.1. Ionospheric Variations Immediately Following Solar Flares

Two interesting solar flare effects in the *F*-region of the ionosphere were found by Knecht and Davies [1961] and Knecht and McDuffie [1962]. One effect is an increase of *F*2 maximum electron density during solar flares that are associated with sea-level increases in cosmic ray intensity. They suggested that the height of the *F*-layer at the time of the solar event may play a role in determining whether the effect is seen at any given location. Another effect is ionospheric variations which can be observed as a sudden frequency shift with the Doppler shift technique [Davies 1962 a and b]. By means of a similar radio technique, Kanellakos and Villard [1962] discussed ionospheric disturbances associated with the solar flare of September 28, 1961, and Kanellakos, Chan, and Villard [1962] estimated the altitude at which some solar-flare-induced ionization is released by soft x rays; it is initially somewhere just above the *E*-region, very probably in the height region 120 to 200 km.

Barry and Widess [1962] studied solar flare effects on the frequency of 25 Mc/s ground backscatter, and Edwards and Thome [1962] also did a similar study of sudden frequency shift at 12, 22, and 25 Mc/s backscattered and forward-propagated signals. Herman [1961] studied flare effects on 2.5 and 5.0 Mc/s atmospheric radio noise.

Westfall [1961] observed VLF phase perturbations caused by solar flares, which show apparent decreases in ionospheric reflecting height. Pierce [1961] obtained the attenuation coefficient for propagation of VLF during a sudden ionospheric disturbance.

Hill [1960] studied *f*min variations following a solar flare in the northern hemisphere. Acton

[1961] examined relationships among short-wave fadeouts, magnetic crochets, and solar flares, and DeMastus and Wood [1960] showed short-wave fadeouts without reported flares.

Winckler, May, and Masley [1961] made a balloon observation of the solar bremsstrahlung burst associated with a class $2_+$ flare. Based on the observation of temporal and spatial variation of the energy spectrum of the solar protons of energies $0.5<E<60$ Mev by the particle detectors in the satellite Injun 1 during the disturbances in July 1961, Maehlum and O'Brien [1962] reached an interesting conclusion that the variations in the electron density in the lower ionosphere to be expected from the observed proton flux are in agreement with the observed variations in the ionosphere at high latitudes during the same period.

A model of solar-flare-induced ionization in the *D*-region was studied by Whitten and Poppoff [1961], and the production of free electrons in the *D*-region by solar and galactic cosmic rays of energy greater than a few Mev and the resultant absorption of radio waves were extensively discussed by Webber [1962].

### 3.2. Polar Cap Absorption

Morphology and interpretation of polar cap absorption events observed by riometers were shown by Leinbach [1960] and Reid and Leinbach [1961]. Other morphological work based on *f*min was carried out by Rourke [1961] and Hill [1961]. Using both riometer observations and *f*min values obtained at nearly geomagnetically conjugate stations in the auroral zone, Farewell and Campbell Island, Hook [1962] found that during polar cap absorption events the boundary of the absorption regions appears to occur at the same effective magnetic latitude in both hemispheres.

Bates [1962] studied VLF effects from a polar cap absorption event, and Herman [1962] investigated absorption effects on 2.5 and 5.0 Mc/s atmospheric noise. In polar cap absorption events, polar-glow aurora was reported by Sandford [1962], and geomagnetic storm effects were discussed by Ortner, Leinbach, and Sugiura [1961].

A relation between solar radio emission and polar cap absorption of cosmic noise was obtained by Kundu and Haddock [1960] and also by Hughes [1961]. An extensive study of solar activity associated with polar cap absorption was done by Warwick and Haurwitz [1962].

Balloon observations of low-energy solar cosmic rays during polar cap absorption were reported by Winckler and Bhavsar [1960], and the satellite Injun 1 observations of solar protons during polar cap absorption events were reported by Pieper, Zmuda, Bostrom, and O'Brien [1962] and by Maehlum and O'Brien [1962].

#### Additional Remark

Various papers published in the Proceedings of the International Conference on Cosmic Rays and the Earth Storm, Kyoto, 1961: Journal of the Physical Society of Japan, Volume 17, Supplement A, 1962, are excluded in the present report except one paper [Knecht and McDuffie, 1962] for the session of ionospheric disturbances.

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# 4. Radio, the Ionosphere, and IQSY*

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The purpose of this section is to review the plans of the United States as they now exist for studies of the ionosphere, using radio techniques, during the IQSY. Although this report emphasizes ground based studies, ionospheric experiments involving space vehicles (rockets) which employ radio waves as the principal exploring technique are also discussed.

This report is given in three parts: 1, Objectives of the U.S. IQSY Program; 2, Description of Synoptic Programs; and 3, Description of Special Experiments.

## 1. Objectives of the U.S. IQSY Program

The IQSY is intended to be the solar minimum counterpart of the IGY. The IGY studies took place during the peak of the most active solar cycle yet observed. It is important, therefore, to extend many of the synoptic observing programs through the period of solar minimum to place the IGY results in proper perspective with respect to the effects of changing solar activity. In addition, many new and powerful tools have become available since the IGY to monitor the ionosphere on a systematic basis. The exploitation of these techniques, such as scatter radar and topside sounding, will be another objective of the IQSY program.

During the IQSY, solar disturbance will be at a minimum, permitting detailed studies to be made of the undisturbed ionosphere and its latitudinal, diurnal, and seasonal changes. Special emphasis will be placed on studies of the lower regions of the ionosphere, the *D* and *E* regions, which are difficult to study in detail during times of high solar activity, and which also show marked solar cycle changes. Using the newer techniques mentioned above, observations well above the *F*-region peak will be possible on a regular basis over certain regions of the world.

IQSY will also see a continuation and intensification of the trend toward interdisciplinary studies, started during the IGY. The conjugate point program described below is a good example of such a study. Radio techniques (riometery, vertical soundings) are to be joined with observations of geomagnetic variations, micropulsations, all-sky camera photography, and auroral photometry at several magnetically conjugate pairs of stations.

In summary, the objectives of the U.S. IQSY program are threefold:

(1) to continue through the solar minimum period those IGY synoptic studies that are specifically related to solar activity,

(2) to bring to bear on important unsolved ionospheric problems the several new and very powerful techniques developed since the IGY, and

(3) to conduct special experiments that are particularly well suited to the solar minimum period.

## 2. Synoptic Programs

Several of the radio techniques that have been developed for ionospheric study lend themselves to synoptic use. Synoptic programs at networks of stations were an important part of the IGY program. Such programs provide a generalized description of the ionosphere and its regular variations in both space and time. In addition, network programs provide valuable data on a global basis for studies of the evolution and temporal behavior of geophysical disturbances of many kinds.

Because the ionosphere is so intimately controlled by solar radiation, both on a short and long term basis, it is imperative that synoptic programs include both the maximum and minimum phases of the solar activity cycle. The maximum phase of solar activity was relatively well covered during the IGY. The IQSY offers an opportunity to extend many of the IGY synoptic programs into the solar minimum period.

Listed below, along with a brief description, are the IQSY synoptic programs presently planned by the United States.

*This article was prepared in the spring of 1963 as a part of the U.S. report to the XIVth General Assembly of URSI.

## 2.1. Vertical Incidence Ground-Based Soundings Network

The Central Radio Propagation Laboratory of the National Bureau of Standards, in cooperation with the U.S. Signal Corps, has operated a network of vertical incidence ionosondes for a number of years. Data resulting from this synoptic program are used both in basic ionospheric research and in prediction of communications parameters. The ionosonde network, which includes a number of foreign stations operated in cooperation with CRPL, was increased in size during the IGY by the addition of new stations in South America and Antarctica and at several other locations. Many of these stations have continued to operate through the post-IGY/IGC period, though in some cases at a reduced level.

The majority of the stations operated during the IGY will be continued through IQSY. Efforts will be made to improve the reliability and accuracy of the synoptic data by making certain improvements to the ionosondes. In addition, the frequency coverage at the low end of the sweep will be lowered from 1.0 Mc/s to 0.25 Mc/s at selected locations in an effort to better observe the smaller electron densities present in the ionosphere at solar minimum.

Stations planned to be in operation during the IQSY are: Adak, Anchorage, Barrow, and College, Alaska; Thule, Greenland; Ft. Belvoir, Va.; Wallops Island, Va.; Boulder, Colo.; Ft. Monmouth, N.J.; White Sands, N. Mex.; Grand Bahama Island; Maui, Hawaii; Okinawa; Amundsen-Scott (South Pole), Byrd and Eights stations, Antarctica. Stations operated by other countries in cooperation with CRPL are: Godhaven and Narssarssuaq, Greenland; Rejkvik, Iceland; Kingston, Jamaica; Talara and Huancayo, Peru; Bogota, Colombia; La Paz, Bolivia; Concepcion, Chile; Natal, Brazil; Manila, Philippines; Hallett, Wilkes and Belgrano, Antarctica.

## 2.2. Topside Soundings

A valuable new technique has recently become available for synoptic study of the ionosphere above the *F*-layer maximum—satellite topside soundings. The first topside sounder, Alouette, was placed into a near-polar orbit (80° inclination) on September 29, 1962. This experiment, a cooperative venture of Canada and the United States, has opened up an entire new field of ionosphere research pertaining to the detailed exploration and monitoring of the high ionosphere (see, for example, Warren [1962] or Knecht and VanZandt [1963]). Plans call for a second topside sounding satellite, operating on six fixed frequencies, to be orbited later this year. It is likely that the useful lifetime of this satellite, designed particularly to study the nature of irregularities in the high ionosphere, will extend into the IQSY period. Also, consideration is being given to a follow-on program involving several topside sounder-type satellites in orbits that may extend to altitudes of 2500 km or more to be launched in the 1965–1968 period.

## 2.3. Scatter Radar Soundings

The development of the incoherent backscatter technique for studying the ionosphere and magnetosphere has been perhaps the most important innovation in ionospheric research during the last decade [Bowles, 1961]. Employing frequencies of 50 Mc/s or greater, free electrons scatter essentially as independent particles. Using a sufficiently sensitive system, the intensity of the backscattered energy as a function of height can be used to determine the electron density profile. Because of the thermal motion of the electrons and ions, the scattered energy is Doppler broadened. Not only are observations of the density of free electrons possible to very great altitudes (>5000 km), but electron temperature, the ratio of electron temperature to ion temperature, and information on ionic mass can also be obtained. Four groups in the United States will be using the scatter radar technique for systematic exploration during the IQSY. The CRPL group at Jicamarca, Peru, is already obtaining electron density profiles to 7000 km altitude using a transmitter operating near 50 Mc/s delivering a peak pulse power of about 5 Mw into a very large dipole array. They plan to undertake a program involving systematic observations of the electron density and electron/ion temperature profiles for about 10 days out of each 2 months. The Stanford group hopes to have in operation by 1964 a half-megawatt (average power) transmitter operating at 400 Mc/s for use in conjunction with a 45-m-diam steerable paraboloid antenna. In addition to observations of electron density and temperature profiles, the steerable antenna will be used to study ion gyromodulation effects occurring in the incoherent scatter spectrum when the beam is transverse to the magnetic field. Emphasis will be on obtaining observations during Regular World Days and World Geophysical Intervals. At Arecibo, Puerto Rico, Cornell University, in conjunction with the U.S. Air Force and the University of Puerto Rico, is constructing a large antenna some 300 m in diameter in a declivity in the ground. Transmitters producing 2.5 Mw of peak pulse power are being built to operate at 430 Mc/s and 40 Mc/s. Profiles of electron density and temperature, density fluctuations and motions of the medium will be studied from the lowest ionospheric heights to several thousand kilometers.

## 2.4. Fixed-Frequency Backscatter

During the IGY it was shown that fixed-frequency backscatter observations can provide useful information on ionospheric irregularities and auroral disturbances. During the IQSY, the Stanford station will be reactivated and data will be reduced from stations at Fort Monmouth, Thule, and Adak, which have been continued in operation since the IGY by the United States Army Radio Propagation Agency.

## 2.5. Radio Noise

During the IGY, CRPL set up and operated a network of radio noise recording stations. This network has been kept in systematic operation since and will continue through the IQSY, thus providing a continuous study of the temporal and geographical variations in radio noise from solar maximum to minimum. Properties of the noise at eight frequencies between 15 kc/s and 20 Mc/s are recorded at each of the stations in the network. United States stations are located at Balboa, Canal Zone; Bill, Wyo.; Boulder, Colo.; Byrd, Antarctica; Front Royal, Va.; Kekaha, Hawaii; Thule, Greenland; Warrensburg, Mo.; and aboard the Antarctic Research Ship *USNS Eltanin*. Stations operated cooperatively with the CRPL are located at Cook, Australia; Enköping, Sweden; Ibadan, Nigeria; New Delhi, India; Ohira, Japan; University of South Africa, Pretoria; Rabat, Morocco; San Jose dos Compos, Brazil; and Singapore.

## 2.6. Riometry

The riometer is a device for studying ionospheric variations, particularly in the *D* region, by observing the relative opacity of the ionosphere to galactic (cosmic) radio noise [Little and Leinbach, 1959]. Riometers were first used for synoptic observations during the IGY when several networks were organized to study the temporal and latitudinal distribution of auroral absorption across the auroral zone. It was soon realized that the riometer was also a very valuable technique for studying the newly discovered polar cap absorption events (PCA) and other phenomena associated with corpuscular bombardment of the ionosphere. The IQSY riometer program will allow a comparison of the behavior of ionospheric absorption during times of high and low solar activity and, in addition, will provide a synoptic network for monitoring PCA events and will provide information on the flux and energy of the particles causing ionospheric absorption.

Most riometers installed for the IGY program have continued in operation and many new stations have been added. The growth of the riometer network has been due both to their usefulness in many types of ionospheric research and to the fact that lightweight transistorized units have recently become available. The development of multifrequency riometery for the study of the *D* region and beam-switching techniques for localized studies has also taken place within the last year or two.

The U.S. riometer network planned for the IQSY is as follows:

CRPL: Amundsen-Scott, Byrd, Eights, and McMurdo, Antarctica; operated in cooperation with Canada at the conjugate points, Laurentides Park in eastern Quebec (conjugate to Eights), Great Whale River (conjugate to Byrd), and Shepard Bay (conjugate to McMurdo) and it is hoped) at Frobisher Bay, (conjugate to Amundsen-Scott).

*Air Force Cambridge Research Laboratory:* Hamilton, Mass.; Sacramento Peak, New Mexico; Maui, Hawaii; Thule, Greenland; and in cooperation with foreign colleagues at: Huancayo, Peru; Natal, Brazil; Accra, Ghana; Addis Abada, Ethiopia; Quilon, India; Garchy, France; Trinidad; Hallet, Antarctica; Cebu, Phillippines; Athens, Greece; Haifa, Israel; Delhi, India; Copenhagen, Denmark; Rome, Italy; Madrid, Spain; Hermanus, Republic of South Africa; and Kerguelen Island (France).

## 2.7. Whistlers and VLF Emissions (Ionospherics)

Several types of natural radio emissions occur in the VLF region of the spectrum. One family of phenomena, whistlers, is associated with the propagation, along the lines of the earth's magnetic field, of electromagnetic energy from lightning strokes. Another class of phenomena, termed "ionospherics," is thought to be generated in the magnetosphere by incoming streams of charged particles. In both cases, important information on the high ionosphere and magnetosphere can be obtained by ground-based and space vehicle study of the emissions. For example, ground observations of nose whistlers has permitted estimates of electron densities out to distances of 4 or more earth radii above the earth's surface. Emphasis during IQSY will be on obtaining observations at a number of magnetically conjugate locations on the surface of the earth as well as in and above the magnetosphere using receivers on board satellites.

Stanford University and Dartmouth College operated the two principal U.S. networks during the IGY. For the most part these networks have continued to function and, with some additions and changes, will be extended through the IQSY.

The Stanford network is planned to be as follows: Amundsen-Scott and Byrd Station, Antarctica Greenbank, W. Va.; Logan, Utah; Seattle, Wash.; Stanford, Calif.; *USNS Eltanin*, and probably at Barrow and Unalaska, Alaska. To be operated cooperatively are the stations at Lauder, New Zealand; Santiago, Chile; Ushuaia, Argentina; Wellington, New Zealand; and probably at Medicine Hat, Laurentides Park, and Great Whale River, Canada.

The Dartmouth stations will be located at Norwich, Vt., and Adak, Alaska, with cooperative programs at Halley Bay and Argentine Island, Antarctica; Ushuaia, Argentina; Bermuda; Knob Lake, Frobisher Bay, and Moisie, Canada.

## 2.8. Ionospheric Drifts

A synoptic drift program using the spaced-receiver technique is being planned by the Air Force Cambridge Research Laboratory. Lowell Technological Institute, with support from AFCRL, is installing a drifts station in Billerica, Mass., for operation during IQSY. A second station is being proposed for operation in Northern Michigan by the Michigan College of Mining and Technology. The instrumentation to be used at these stations has been completely modernized. Some of the features incorporated are a single receiver with antenna switching; recording on magnetic tape for automatic data reduction; recording of phase fluctuations additional to the amplitude fluctuations. For the data reduction, five different computer programs are available, ranging from a simple program equivalent to the manual similar fade analysis through a more or less complicated correlation analysis, to the most sophisticated analysis which permits determination of quantities like the average departure speed as a function of azimuth.

### 2.9. Optical and Radio Patrol Observations of the Sun

Continuous patrol-type observations of the sun are important even during the solar minimum period. Although relatively few solar disturbances are expected during the IQSY, it will be important to observe those that do occur as thoroughly as possible. The IQSY observations are likely to be of unique interest because the solar-terrestrial events are likely to be isolated and not confused by the interplanetary and atmospheric disorder from preceding events or from precursors of succeeding events as is the usual case during periods of high solar activity.

Optical flare patrols will be in operation during the IQSY at about six U.S. observatories with solar exposures taken as frequently as 6 per minute at certain locations. Radio patrols will also be maintained at a number of locations. CRPL will play an active role in the coordination of these activities to assure that adequate patrols, both optical and radio, are achieved, especially in the western hemisphere.

It is also likely that one or more satellites capable of observing solar radiation (optical, radio, or corpuscular) will be launched during the IQSY period and will provide important data on solar emissions on a quasi-synoptic basis. Additional information on the relevant satellite plans is given in sec. 3.8.

### 2.10. Geomagnetism

Continuous recording of variations in the earth's magnetic field makes possible the derivation of global indices of geomagnetic activity and provides information on sudden commencements, magnetic storms, and smaller disturbances. Such data are useful in attempting to deduce the nature of the interaction of solar particle streams with the earth's magnetosphere, the generation of hydromagnetic effects, and the development of ring current systems. Standard observatories will continue to be operated by the U.S. Coast and Geodetic Survey at eight locations in the continental United States, Alaska, and the Pacific area. Magnetic observations will also be made at several locations in Antarctica. It is also expected that a geomagnetic micropulsations program, now being undertaken by CRPL, will be continued through IQSY.

## 3. Special Experiments

A number of experiments are planned during the IQSY that cannot be classed as truly synoptic in nature, usually because the work is to be carried on only at one or two locations or on a nonsystematic basis. To the extent known at this time, a brief description of these special experiments is given below.

### 3.1. Conjugate Point Observations

Conjugate point experiments were not an important part of the IGY program, due probably to the fact that the earth's magnetic field at altitudes well above the surface was not sufficiently well known at that time. Recently, however, sufficient additional theoretical and observational material has become available to allow magnetically conjugate locations to be determined with acceptable accuracy. This made possible a number of conjugate point experiments during 1961 and 1962. The interesting and, at times, unexpected results of these experiments has led to an expanded program of conjugate point studies for the IQSY. Conjugate studies are planned for various pairs of stations in Alaska and New Zealand, Campbell Island and Macquarie Island, at $L$ values roughly in the range 2 to 7. Other studies are planned between Eights, Antarctica and Quebec, Canada ($L=4$); Byrd, Antarctica, and Great Whale River, Canada ($L\sim7$); McMurdo, Antarctica, and Shepard Bay, Canada ($L\sim25$) and Amundsen-Scott, Antarctica, and Frobisher Bay, Canada ($L=16$). Observations at several of these stations will include absorption studies (using riometers), geomagnetic variations and micropulsations, VLF, all-sky camera observations and auroral photometry, and probably vertical incidence soundings.

### 3.2. *D*-Region Studies

Several groups are planning *D*-region profile observations (electron density, collision frequency, etc.) using either the cross-modulation wave-interaction technique or the partial reflections (Gardner-Pawsey) experiment. These include Pennsylvania State University (cross-modulation), Naval Ordinance Laboratory, Corona (backscatter), and CRPL (partial reflections). The CRPL program also includes the simultaneous measurements of steep incidence reflection coefficients at 20 and 60 kc/s.

### 3.3. Study of Ionization Released by Low Energy Solar Flare Radiation

Recently a "Doppler technique" for the measurement of phase path changes produced by a changing ionosphere has been developed [Watts and Davies 1960]. Slight shifts in the received frequency of a stabilized transmitter can be directly related to changes in phase path due to the lowering of the height of reflection or the addition of ionization below the reflection height or both. It has been found that solar flares as well as certain magnetic disturbances produce effects that are easily observed. Both CRPL and Stanford University have employed this technique to good advantage over the last 2 years.

CRPL and Stanford have recently proposed to jointly undertake a program that will involve observations at Boulder, Colo.; Stanford, Calif.; and in Hawaii. A cooperative observational program with colleagues in Africa, South America, and the Indies is also under consideration.

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### 3.4. Satellite Beacon Observations

The total electron content of the ionosphere between the satellite and the receiver as well as information on ionospheric irregularities can be obtained from experiments involving the ground reception of satellite radio transmissions.

Beginning with the first Russian sputniks, Faraday rotation studies of satellite signals have provided important data on the structure of the $F$ region of the ionosphere. A U.S. satellite, designated S–66, specially designed as a radio beacon and transmitting on about 20, 40, 41, and 360 Mc/s, is due to be launched early in 1964 and will continue to operate into IQSY. Multifrequency radio beacons are also to be placed on later U.S. satellites of the EGO-type. Satellite radio reception programs are in progress at a number of U.S. institutions including Stanford University, University of Alaska, University of Illinois, Pennsylvania State University, CRPL, Air Force Cambridge Research Laboratory, Boston College, Dartmouth College, and Thule, Greenland. In addition, it is expected that observing groups in about 14 foreign countries will also be participating in the satellite beacon program.

### 3.5. Moon Radar Studies

Studies of the total electron content of the ionosphere and its fluctuations using Faraday rotation effects of radar echoes from the moon will continue through the IQSY. Scientists at the U.S. Army Electronics Research and Development Laboratory at Fort Monmouth, N.J., in conjunction with the University of Illinois are involved in this program.

### 3.6. Cosmic Radio Noise Spectrum Studies

The multifrequency, dual-polarization riometer observations to be undertaken at College, Alaska, jointly by CRPL and the University of Alaska will take advantage of the increased transparency of the ionosphere during sunspot minimum to obtain information on the low-frequency portion of the cosmic radio noise spectrum. The experiment is designed to (1) determine accurately the variation of the cosmic radio noise with frequency, (2) to give information from which the nature of the generating mechanism may be inferred and (3) study the interstellar and terrestrial media through which the signals have propagated.

### 3.7. Rocket Measurements in the Ionosphere

Several radio techniques can be used in conjunction with sounding rockets to provide measurements of various ionospheric parameters. The so-called CW propagation technique developed by Jackson and Seddon [1958] has been used in a number of rocket experiments to obtain the height profile of electron density. An experiment is being developed by Pennsylvania State University in which observations of radio transmissions between a rocket payload and an ejected subpayload will be used to make accurate *in situ* measurements of electron density. Also, CRPL is developing a swept frequency pulsed ionosphere probe rocket experiment in which resonances at the plasma frequency will be used to determine local electron density in the $E$–$F$ region valley and in the ionization structures responsible for sporadic $E$. It is likely that sounding rocket experiments involving all of these techniques will take place during the IQSY.

NASA's Goddard Space Flight Center is planning to undertake several types of sounding rocket experiments during the IQSY. One experiment will be designed especially for $D$-region studies and will involve Faraday rotation and differential absorption observations at several frequencies between 1 and 5 Mc/s as well as a conductivity probe for positive ion parameters and Lyman $\alpha$ and x-ray detectors. A second type of experiment will emphasize $E$-region studies and will include the conventional Jackson and Seddon dispersive Doppler technique and solar ultraviolet observations in the 100 to 1000 Å range. A third series of rocket experiments involving electron density, magnetic field, and collision frequency measurements in the equatorial electrojet is also being considered.

Air Force Cambridge Research Laboratory is also planning several different types of rocket experiments during the IQSY period. Firstly, a series of experiments involving studies of the auroral zone $D$ and $E$ region is to be conducted at Churchill, Canada. Instrumentation will include a conductivity probe, impedance probe, plasma frequency probe, retarding potential probe, absorption and pulse propagation experiments, Langmuir-type probe, and electrostatic analyzers. A second set of sounding rocket experiments, proposed by AFCRL for IQSY, involves the comprehensive measurement by rockets of a group of interrelated chemical and physical properties of the midlatitude $D$ and $E$ region together with simultaneous ground-based ionosonde measurements. This AFCRL program would involve a series of 25 firings from Eglin Air Force Base, Fla., at various times of day and during different seasons. The measurement techniques proposed include (1) chemiluminescent trails, (2) acoustic-detection of grenades, (3) falling sphere drag experiment, (4) bipolar spherical Langmuir probe, (5) 10 to 1000 Å photometer, and (6) ground-based ionosonde. Properties of the $D$ and $E$ region to be studied include winds and wind shears; turbulence; diffusion constants; temperature, pressure, and density of neutral species; temperature, energy distribution; and density of positive and negative ions; oxygen atom concentration; and solar flux.

AFCRL will also continue, through IQSY, a rocket program involving investigation of the extreme ultraviolet and soft x-ray portions of the solar spectrum (1 to 1300 Å). Approximately six firings per year during 1964–65 are planned.

### 3.8. Related Satellite Experiments

It is likely that several different types of NASA satellites will be in orbit during the IQSY period, providing information on solar emission (optical, radio, and corpuscular), the properties of the interplanetary medium, the nature of the earth's magnetosphere, and many properties of the upper atmosphere and ionosphere.

*OSO* (*Orbiting Solar Observatory*)—A second orbiting solar observatory (OSO–B) is scheduled for launch in 1963. Plans also call for launching two OSO's per year during 1964 and 1965. Emphasis in the OSO program is on measurements of solar wave radiation over a wide range of wavelengths. Details of the individual OSO experiments can be found in the National Academy of Sciences, *IG Bulletin*, 67, January 1963.

*IMP* (*Interplanetary Monitoring Probe*)—IMP will be spinstabilized satellite, similar to Explorer XII, and will be launched into an inclined, highly eccentric orbit (perigee of 180 km and apogee of 320,000 km). Launches are planned for 1963 and 1964. Experiments include a rubidium-vapor magnetometer, plasma probes and particle detectors of various sorts.

*Pioneer*—A series of solar probes, designated Pioneers, are to be launched by NASA beginning in late 1964 as a part of the U.S. IQSY effort. Though details are not yet available, it is believed that this series of experiments will be designed especially to study the nature of the interplanetary medium between the sun and the earth during the solar minimum period. In order to accomplish this objective, satellites would be placed in an elliptical orbit around the sun.

### 3.9. Related Radio Propagation Experiments

A number of oblique incidence radio propagation studies will be underway during the IQSY as a part of a continuing U.S. program in this field. AFCRL, for example, plans to operate an HF path between Thule and Boston to study effects of spread *F* on propagation quality, and to take HF–VHF step-frequency soundings over paths between Norway and Washington State, Norway and Boston, Palo Alto and Boston, and Puerto Rico and Uruguay.

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# 5. The Guided Propagation of ELF and VLF Radio Waves Between the Earth and the Ionosphere

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## 1. Introduction

The increased interest in the propagation of ELF and VLF electromagnetic waves noted in the last U.S. National Report [Wait, 1960a] has continued both theoretically and experimentally. Much impetus has been given at VLF by the stabilization of the radiated frequency of most of the U.S. VLF transmitters, and at ELF, by the investigation of earth-ionosphere cavity resonances.

It is the purpose of this report to summarize research work in VLF and ELF propagation carried out in the United States since January 1960. Attention is confined to published papers relating to propagation of waves guided between the earth and the ionosphere; thus, groundwave propagation, whistler mode phenomena, satellite observations, and ELF, VLF emissions in the upper atmosphere are not considered.

## 2. Theoretical Studies

The object of theoretical studies of ELF and VLF propagation may be briefly stated as the determination of the phase and amplitude of the field of a signal source as a function of distance, frequency, and the many other parameters of the path between source and point of observation. The signal may be considered as arriving at the point of observation either by multiple reflections between the ground and the ionosphere, or in the form of waveguide modes. At sufficiently great distances at VLF, and at almost all distances at ELF, it proves most convenient however to consider the waveguide mode form. This is because losses introduced by the earth and ionosphere make only a few of the lower order modes significant, the others being highly attenuated. Thus, the field at the point of observation can be obtained by summing the fields of each of these few modes.

The field due to one mode is proportional to the amplitude of the source, the amplitude with which the mode is excited (excitation factor), the variation of the mode amplitude with height (height gain factor), and the propagation constant (attenuation factor and phase velocity) of the earth-ionosphere waveguide for the particular mode being considered.

The propagation constant of a mode is strongly dependent on the reflection characteristics of the earth and the ionosphere. In the case of the earth the reflection coefficient is not difficult to obtain, although the curvature causes considerable complication at grazing incidence. For the ionosphere the situation is much more complicated because the reflection properties are determined in part by (a) the presence of the earth's magnetic field and (b) the presence of horizontal stratifications. The effects of the earth's magnetic field have been considered in some detail by Crombie [1961], Johler [1961], Johler and Walters [1960], Field et al. [1960 and 1962], Wait [1960b], and by Dobrott et al. [1961]. It seems that, for highly oblique incidence, the complication of including the effect of the earth's field by means of the quasi-longitudinal approximation is hardly worthwhile. This is because it is not yet possible at one frequency to distinguish experimentally between changes in the refractive index of the ionosphere due to including the magnetic field by means of the $QL$ approximation and those resulting from changes in the electron density or collision frequency when the magnetic field is ignored. However, the $QL$ approximation does account for the polarization of the reflected wave.

On the other hand, at VLF it is found that the transverse component of the magnetic field introduces nonreciprocity. At oblique incidence, the reflection coefficient is greater for signals incident from the west than it is for signals incident from the east. The effect of horizontal stratification in the ionosphere has been investigated by several authors [Johler and Harper, 1962; Wait and Walters, 1963]. It is found that variations in the gradient of conductivity have a marked effect on the reflection characteristics of the ionosphere.

A further important property of the ionosphere is its roughness. Because the ionosphere is not smooth and its detailed shape appears to vary with time and position, the reflection coefficient also varies with time and position. Some of the properties of a rough ionosphere have been investigated by Bowhill [1961]. Once expressions for the reflection coefficient of the ionosphere can be stated the properties of the modes can be determined [Wait, 1960b, 1961a]. A considerable amount of work has been done in extending the earlier plane earth, sharply bounded ionosphere, mode theory to cover the effects of a curved earth and ionosphere, stratified ionosphere, and the effects of the earth's magnetic field [Wait, 1960b, 1961a, 1962d, 1963a, 1963b; Spies and Wait, 1961; Johler, 1961a; and Swift, 1962]. It is found in particular that the curvature of the earth and the ionosphere tend to increase the attenuation and reduce the phase velocity of the lowest order modes, relative to the plane earth case. As a consequence, the phase velocity when referred to the earth's surface may be less than the velocity of light in free space.

At the shorter distances, less than a few thousand kilometers, several modes make significant contributions to the total field. Thus, the field as a function of distance, shows interference effects. A method of finding how the "average" field varies with distance has been discussed [Wait, 1962a]. In some instances, it would be desirable to reject, at the receiver, all but one of the modes. It has been found, however, [Wait, 1961b] that this is impracticable. Work has also been done on the effect of a localized change in ionospheric height [Wait, 1961c and 1962b] and on the effect of a smooth transition such as from daytime to nighttime heights [Wait, 1962c].

In the ELF region of the spectrum, further theoretical investigations have been made. Some of this was reported at an ELF propagation conference held in Boulder during January 1960 [Wait, 1960c and 1960d]. Calculations of the attenuation rate [Wait and Carter, 1960] and of the radial wave impedance [Wait, 1960e] have been made. The latter work indicates that only at very short distances (less than about 30 km) is it possible to ignore the presence of the ionosphere in ELF field strength calculations. The effect of an ionosphere varying exponentially with height has also been considered [Wait, 1960e, 1961e, and 1962d; Galejs, 1961b, 1962; and Harris et al., 1962]. It is found that this gives better agreement with experimental observations than the sharply bounded model. Poeverlein [1961] has pointed out that vertical resonances (as opposed to Schumann resonances) between the earth and ionosphere may produce increases in the intensity of the natural noise spectrum at frequencies of a few hundreds of cycles per second and at a few kilocycles per second. The dispersion of ELF pulses is described by Wait [1962e].

As an alternative to the description of the field as the sum of modes, Johler and Berry [1962] have returned to the classical representation in terms of zonal harmonies. Because of the poor convergence a large computer is necessary to evaluate the expansions. However, the method used by them to account for the earth's magnetic field appears to conflict with other work [Wait, 1963a, 1963b].

Some work on the calculation of excitation and height-gain factors has been done [Wait, 1962f; Wait and Spies, 1963]. At the higher frequencies in the VLF band and/or under nighttime conditions, it is found that the least attenuated mode is concentrated near the ionosphere. Galejs [1961a] has considered the excitation of ELF and VLF signals by means of a horizontal magnetic dipole.

Much of the above work has been collected and summarized by Wait [1962g and 1962i].

## 3. Experimental Studies

Experimental studies of VLF propagation may be divided into two classes: (a) those using continuous wave manmade signals from a source whose position is accurately known and (b) those using natural signals (atmospherics) occupying a wide bandwidth and whose precise location is not usually known. At ELF, the signals are usually in the latter category.

The advantage of manmade CW signals is that they are present most of the time and thus studies can be made of the diurnal and seasonal variation of phase delay and attenuation, as functions of distance, path orientation, etc. Some such studies have been reported by Chilton et al. [1962] and further work is being done in many places. It is found that the phase velocity decreases at night as the height of reflection increases, in a manner which is to be expected from theory [Spies and Wait, 1961]. Westfall [1961] has attempted to determine the mean height of reflection of VLF signals extending an earlier theory of Wait, but Wait [1962h] has pointed out that Westfall's method is not valid. A rather striking observation by Lewis et al. [1962] shows that the day to night change in reflection height occurs very rapidly for signals at very oblique incidence. Wait [1963c] has shown that the change in the magnitude of the diurnal phase variation with distance can be explained by assuming that more than one mode is present.

Although it is easy using phase-stabilized VLF signals to determine the diurnal *change* in phase velocity for a given path, it is a matter of great difficulty to determine the *actual* phase velocity. Using unpublished data from experimental studies of a VLF navigational aid communicated by M. L. Tibbals and colleagues, Wait [1961d] has been able to show that the actual phase velocity is in agreement with theory.

The use of atmospherics enables observations to be made instantaneously over a wide range of frequencies. It is desirable however to make the observations at two or more points along a line from the source and this is often difficult to do. Taylor [1960a and 1960b] has used this technique to determine attenuation rates both as functions of frequency and of direction. The latter observations show a surprisingly large nonreciprocity. The variation of relative phase velocity with frequency has also been investigated with this technique [Jean et al., 1960].

At ELF, atmospherics offer almost the only source of signals. The attenuation rates of such signals have been investigated by Jean et al. [1961], Raemer [1961a], and E. T. Pierce [1960]. In the latter paper, it is found that nighttime observations can be explained if it is assumed that the effective height of the ionosphere increases as the signal frequency decreases.

It is perhaps worth pointing out that nuclear explosions produce extremely large brief electromagnetic pulses [Latter et al., 1961]. In principle, the times and locations of such events could be known and observations of the signals using the atmospherics techniques could be obtained. Such observations would in many ways combine the advantages of CW and atmospheric observations.

A new field of investigation has arisen since the previous report. This is the ELF earth-ionosphere cavity (or Schumann) resonance which occurs at frequencies of a few cycles per second. Work in this field has been reported by Balser et al. [1960 and 1962]; Raemer [1961b] and by Polk et al. [1962].

The phase velocity of VLF signals propagating over long distances is dependent on the effective height of the ionosphere. Thus, during sudden ionospheric disturbances such as occur during solar flares, the effective height of the ionosphere is reduced causing an increase in phase velocity and a sudden phase anomaly [Jean and Crary, 1962]. Chilton has found a simple relationship between the change in height deduced from the phase anomaly and the zenith angle of the sun [Chilton et al. 1962]. The variation in attenuation of VLF signals during such events has been investigated by E. T. Pierce [1961].

During polar cap events, extra ionization is produced below the normal *D*-region, again producing phase anomalies [Bates, 1962].

Possible associations between magnetic activity and the phase velocity of VLF signals have been reported by Chilton et al. [1962], Sechrist et al. [1961] and Sechrist [1962].

Chilton [1961] has produced evidence that during meteor showers the phase velocity of VLF radio waves may be altered. The mechanism responsible for this effect is not certain and further work on this whole topic is justified.

The whole subject of the source of *D*-region ionization and variations in electron density with height, latitude, and time is not at present very well understood. It is one of the aims of VLF propagation research to throw light on this subject. Some theoretical studies have been made, particularly of the possible role of cosmic ray produced ionization [Nicolet et al., 1960; Moler, 1960; Aiken, 1961; and Crain, 1961].

## 4. Applications

The high phase stability and relatively low attenuation of VLF signals make their use attractive for the dissemination of standard frequencies and time signals and for use as navigational aids. Stone et al. [1960] have discussed the synchronization and stabilization of the U.S. Navy VLF transmitters and quoted operating experience with the system. Watt et al. [1961] have investigated the phase stabilities which might be obtained at long distances and have pointed out that the stability of group velocity may be worse than the phase stability by an order of magnitude or more, depending on the width of the signal spectrum. J. A. Pierce et al. [1960] have discussed the limiting stability of transatlantic 16 kc/s signals.

Two types of VLF direction finding techniques operating on transient atmospherics have been described [Lewis et al., 1960 and Hefley et al., 1961] and used for the location of thunderstorms.

Some attention has been devoted to the possibility of detecting distant nuclear explosions in and above the atmosphere [Zmuda et al., 1963, and Jean et al., 1963] by means of the increased *D*-region ionization which may be produced by them [Crain et al., 1961, and Glasstone, 1962]. This extra ionization produces sudden phase anomalies similar in some respects to those produced by solar flares. In order to assess the sensitivity of this method of detecting nuclear explosions, it is important that the natural phase fluctuations which occur during the ionospheric propagation of VLF signals be known. This problem is very similar to the problem of determining the precision with which standards of frequency can be compared using VLF transmissions. A further important question is that of determining the effects of small changes in the shape of the electron density profile of the *D*-region on the propagation constants of earth-ionosphere waveguide. The work mentioned earlier which takes account of horizontal stratification in the ionosphere is of importance in this respect [Wait and Walters, 1963].

## 5. Conclusions

The main advances which have been made in the 3 years covered by this report may be summarized as follows. On the theoretical side, the importance of excitation and height gain factors when the earth and ionosphere are curved has been recognized and intensive effort has been put into calculating the propagation constants of the earth-ionosphere waveguide, taking into account the presence of the earth's magnetic field and the horizontal stratification of the ionosphere in the case of a curved earth and ionosphere.

Experimentally, the frequency stabilization of several VLF transmitters has led to observation of the phase variations of VLF signals on a much larger scale than had been previously possible. This is leading to increased knowledge of the behavior of the lower ionosphere.

On the other hand, there remain some gaps in our knowledge of the propagation of ELF and VLF signals. Perhaps the most noteworthy deficiency is in the propagation of signals at the higher end of the VLF range and the lower end of the LF range, say between 25 and 50 kc/s. No doubt this is due to the absence of many CW sources in this region of the spectrum, but studies of atmospherics should yield the required information. It is perhaps in this region that studies of the electromagnetic signals radiated by nuclear weapons might be of most use. A region in which theoretical work seems to have outpaced experimental work is in the effect of the earth's magnetic field on VLF propagation. In particular, there is a need for further work on nonreciprocity both of attenuation and phase velocity.

Perhaps in the next 3 years progress will be made in these areas.

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# 6. Electron Distribution in the Ionosphere

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## 1. Introduction

Determination of the electron distribution in the upper atmosphere has been the central objective of the observational programs in ionospheric research for over 35 years, but awareness that these measurements contain important direct evidence concerning the state of the *neutral* atmosphere is much more recent, having occurred during the triennium 1960–1963.

The significance of such measurements is emphasized by the development of important new techniques which supplement the more conventional radio sounding and rocket-probe measurements and which have been, in turn, stimulated by rapid developments in space research [Johnson, 1961]. The information resulting from the use of all of these methods in U.S. programs over the past 3 years forms the subject of this report.

## 2. *D*-Region

A theoretical basis for the formation of the *D*-region was provided by Moler [1960] and by Nicolet and Aikin [1960]; two "layers" are predicted, with peaks (or dN/dh minima) at roughly 70 and 80 km. The lower layer is produced by cosmic rays and has a large diurnal variation in the height of its lower edge, thereby accounting for many aspects of VLF propagation. Rumi [1961, 1962] has employed the Luxenbourg effect to verify that weak ionization is detectable down to 30 km, which he attributes to galactic cosmic radiation. A theoretical basis for this view is provided by Webber [1962]. Rumi [1960, 1961] has also shown that the two-layer structure of the *D*-region is consistent with radio absorption observations. The higher layer is produced by photoionization of NO by Lyman-$\alpha$ [Nicolet and Aikin, 1960] or of $O_2$ by x rays [Inn, 1961]; probably both sources contribute [Poppoff and Whitten, 1962]. The various rate coefficients controlling the *D*-region profiles by day and by night have been discussed by Crain [1961], who gave quasi-equilibrium solutions for electron and ion densities for heights up to 90 km. Additional observational evidence has been obtained by VLF soundings [Paulson, Gossard, and Moler, 1963], and by rocket measurements [Smith, 1961; Kane, 1961; Bowhill, 1962]. The important enhancements of *D*-region ionization during solar flares and cosmic ray events have been studied by Maehlum and O'Brien [1962], Kanellakes, Chan, and Villard [1962], and Swift [1961]. The sudden enhancement *D*-region ionization produced at locations remote from high-altitude nuclear bursts has been discussed by Crain and Tamarkin [1961], and is attributed to the bombardment of the *D*-region by energetic electrons resulting from the radio active decay of neutrons which have traversed the geomagnetic field freely. Vertical incidence observations of a scattering layer in the auroral zone at heights between 80 and 95 km have been reported [Olesen and Wright, 1961], which appear to refer to the same region as that responsible for VHF *D*-scatter propagation.

## 3. *E*-Region

The main features of the daytime *E*-region electron distribution have long been known, but considerable uncertainty still exists regarding the source and distribution of nighttime *E*-region ionization and the presence and structure of a "valley minimum" above the *E*-peak. By a ray-tracing technique, applied to midlatitude ionograms, Davies and Saha [1962] have shown the existence in selected cases of an *E*-pause ranging from 30 to 70 km in width and of the order 0.6 to 0.8 of $N_{max}E$. A similar valley depth, indicated by magneto-ionic coupling phenomena at Thule, Greenland, was demonstrated by Wright [1960]. Rocket-borne probes have obtained greatly detailed profiles of the *E*-region. In a summary and review by Kane [1962], several *E*-profiles are shown in which the presence and structure of sporadic *E* may be clearly seen. Again, in a review by Bordeau [1962], two nighttime profiles and one from the daytime *E*-region are shown from the work of L. G. Smith (unpublished). A night *E* "bulge" is shown between 90 and 115 km (of density $4\times10^3/cm^3$) above which is found a broad deep minimum (density $3\times10^2/cm^3$).

The nocturnal *E*-layer has been studied using low-frequency pulse soundings by Hough [1961]. After the rapid decrease in *E*-ionization following sunset, *foE* decreases very slowly to a predawn minimum. No seasonal variation was evident, values of 0.5 Mc/s and 0.75 Mc/s being appropriate for average nighttime *foE* at sunspot minimum and maximum. The sunspot-maximum value of nighttime *foE* was confirmed by Wright [1962d] using extraordinary-ray observations near the electron gyrofrequency.

## 4. *F*-Region

Very great emphasis has been placed, over the past 3 years, on the measurement and understanding of the *F*-region, both above and below its peak. While the subpeak portion has long been easily observable by ground-based soundings, the true shape and location of this region have been little

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better known than those features of the "topside" *F*-region. In U.S. programs during the triennium 1960–1963, significant new techniques of observation and improvements of existing methods, together with much pertinent theoretical work, have been brought to bear on these problems. Although this report is organized in correspondence with the various altitude regions of the ionosphere, it is useful here to itemize the measurement methods employed, as several of these are useful in several regions, while others make no definite distinction among regions:

| | |
|---|---|
| Bottomside sweep-frequency soundings | (up to *F*-peak) |
| Topside sweep soundings from satellites | (down to *F*-peak) |
| Incoherent scatter soundings | (200 km to 7000 km) |
| Rocket probes | (to various altitudes to 7000 km) |
| Moon echoes; Faraday rotation | (total electron content) |
| Satellite signals, Faraday or Doppler measurements | (sub-satellite electron content) |

### 4.1. The Subpeak *F*-Region

Below the *F*2 peak, a large quantity of data is available through the calculation of electron density distributions from vertical soundings. The structure and variations of the mean quiet ionosphere between latitudes of 15° N and 50° N along the 75° W meridian have been described in some detail by Wright et al. [1961–1963], and summarized by Wright [1962a]. It is shown that the winter subpeak electron content varies in a consistent way at all latitudes, and that the summer should be considered the anomalous season for its low electron densities. Alternate views are proposed by Thomas [1963], who identifies a "spur" of increased density at 70° N in the wintertime; he suggests this may occur through leakage of ionization from the Van Allen radiation belts, or via transport along geomagnetic field lines. The thickness of the *F*2 peak has been interpreted as an indication of temperature by Wright [1962c, 1963], in which the solar-cycle, seasonal, diurnal, and latitudinal variations of this quantity are shown.

Large variations in electron distribution occur across the geomagnetic equator, as illustrated by Wright [1962b]. The predominant mechanism appears to involve diffusion of electrons along the geomagnetic field [Goldberg and Schmerling, 1962]. In the polar regions, by contrast, the main anomalies are the very presence of ionization during the winter midnight over the south pole and the universal time control exhibited by the *F*-region. Duncan [1962] observes the peaks in antarctic and arctic electron densities at 07 and 19 UT, in all seasons except arctic summer. Hill [1960] attributes the diurnal variation in antarctic *F*-region densities to the effects of a vertical wind shear.

The frequent occurrence of irregularities giving rise to the ionogram phenomenon of "spread *F*" has received both statistical and theoretical attention. The irregularities causing spread *F* at the geomagnetic equator are shown by Cohen and Bowles [1961] to be elongated (by a factor of 100:1) along the horizontal magnetic field lines, and this has provided a model for theoretical treatments of certain radio propagation properties of spread *F* [Calvert and Cohen, 1961; Pitteway and Cohen, 1961]. Pendorf [1962a, b, c, d] has examined the diurnal, seasonal, and geographic variations of spread *F* in the arctic, finding that a zone of maximum occurrence coincides with the auroral belt.

### 4.2. The Suprapeak *F*-Region

Rapid development of the incoherent scatter technique, frequent rocket experiments, the use of special earth satellites, and pertinent theory have all combined to make the topside *F*-region one of the better understood portions of the ionosphere, during the years 1960–1963. At the beginning of this period, much uncertainty remained concerning the temperature (and, therefore, the density) of the neutral atmosphere at levels much above 200 km [Hines, 1960]. Theory indicated clearly that the ion distribution at great heights should be governed almost exclusively by diffusion, and that the electron-ion gas should be distributed exponentially with a scale height just twice that of the neutral particules, provided all species were in thermal equilibrium [Johnson 1960a, b]. Near the *F*2 peak, the electron loss process becomes more important, the balance between the two processes of diffusion and loss resulting in an electron distribution of the classical "Chapman" form. Wright [1960], in calling attention to this, demonstrated that the shape and electron content of the topside *F*-region were that of a "Chapman" region with a neutral-particle scale height of 100 km, appropriate to sunspot maximum conditions, and showed how an extrapolation of ionosonde results could give some indication of the structure of the topside *F*-region. Such methods of extrapolation have been discussed in more detail by Seddon [1961]. At the *F*2 peak, the most abundant ion is of atomic oxygen, but at much greater heights the lighter ions of $He^+$ and eventually $H^+$ will predominate. Arguments were presented by Hanson and Ortenberger [1961] to show how a protonosphere might "float" on the underlying *F*-region, with only negligible coupling between the two regions. More recent experimental evidence [Bordeau et al., 1962] from the Explorer VIII satellite supports Nicolet's [1961] observation that a transition region exists (roughly between 1000 and 2000 km) where helium is the predominant ion, and above which hydrogen predominates. A NASA high-altitude rocket flight published by Bauer and Jackson [1962] shows the transition from the oxygen ionosphere to the helium ionosphere, at 1000 km, in some detail. Both the oxygen-hydrogen transition and the ternary case including helium ions have been discussed by Bauer [1962a, b], who shows how the observed electron distribution may be used to infer the relative concentration of the ions. The mechanisms of charge exchange among these ions have been treated by

Hanson [1962]. In the following sections of this report, the results of various measurement methods are presented, mainly pertinent to the regions within a few hundred km of the $F2$ peak.

### 4.2.1. Total Electron Content of the Ionosphere

The direct relationship between the electron content above the $F2$ peak and the temperature of the neutral atmosphere at these levels has stimulated study, first by lunar radio echoes and then by satellite techniques. Radar echoes from the moon have been used to derive the ratio of electron content above to that below the $F$ peak. Hill and Dyce [1960] and Dyce [1960] found values between 1.5 to 2.5. Millman, Sanders, and Mather [1960] reported larger values at a lower latitude, viz, 3 to 8. Radio transmissions from satellites, also subject to Faraday rotation and differential Doppler effects of the ionosphere and geomagnetic field, have been used to obtain the total electron content between the satellite height and ground. Garriott [1960a, b] has presented methods of analysis of total Faraday rotation and of rotation rate, from which the topside/bottomside content ratio, the total electron content, and an estimate of the topside electron distribution can be obtained. In an accompanying paper, Garriott [1960a] presents an analysis of eight months of data, finding values of 2 to 4 for the content ratio; he also presents a normalized topside distribution. The total content during magnetic storms was found to remain roughly constant, implying a large deviation from the quiet-day profile. This is in contrast to the results of Hame and Stuart [1960], who found the electron content reduced during storms, as did Yeh and Swenson [1961]. Faraday rotation observations were used in a different way by Little and Lawrence [1960], through comparison with calculations from model ionospheres. Irregularities of about 1 percent in electron content and with a scale size of a few hundred km were detected in this way. Near the geomagnetic equator, the Faraday technique has been used by Blumle and Ross [1962], and Blumle [1962], who reported electron contents exceeding by factors of 3 or 4, those found with similar methods at higher latitudes. A diurnal variation exceeding 10:1 was also found, together with evidence of a high electron temperature near sunrise. A technique for using satellite Doppler measurements for these purposes was given by Ross [1960], and in an accompanying paper the same author describes seasonal variations from over one year's data. Seasonal effects similar to those known in $foF2$ are found. Ross and Anderson [1962] further analyzed 2 years' data (1958–1960) from two satellites, finding a decrease in effective "slab" thickness with the declining solar cycle. Further evidence on ionospheric storm behavior has been obtained by de Mendonça [1960] using the satellite Doppler technique, who shows an increase in the north/south gradient of electron content during storms. Garriott and de Mendonça [1962] have generalized the Faraday and Doppler theory, and show how the two may be used jointly to get electron content from a single station, without uncertainties due to horizontal ionospheric gradients.

### 4.2.2. Electron Density Profiles by Rockets

The objectives of most rocket experiments in the ionosphere may be classified into two broad categories: that in which the electron concentration, particularly above $h_{max}F2$, is the primary objective, and that in which the concentrations of other ionic species are to be measured. The latter are of great importance to aeronomy, even if conducted at heights well below the $F2$ maximum. Frequently, a single rocket carries several experiments devoted to each of these objectives. The techniques of such measurements have been described by Jackson and Kane [1960]; Bordeau, Jackson, Kane, and Serbu [1960]; Pfister, Ulwick, and Vancour [1961]; Sagalyn, Smiddy, and Wisnia [1963]. Thorough reviews of U.S. ionospheric rocket results to date are given by Garriott [1962] and Bordeau [1963]. A totally different technique is described by Knecht, VanZandt, and Russell [1961] and by Knecht, VanZandt, and Watts [1962], in which the rocket carries a pulsed sounder functioning on the same principle as an ionosonde. Additional observations of this kind have been reported by Knecht and Russell [1962]. Another unusual technique results from the inclusion of an antenna impedance probe in Discoverer Satellite No. 34 [Ulwick and Pfister, 1962]. These measurements, continuous over long distances and times, have provided detailed information on horizontal gradients. The 250-km perigee of this satellite frequently placed it below the $F2$ peak, where electron density measurements agreed well with ground-based ionosonde values.

Berning [1960] obtained an electron distribution to 1500 km, showing evidence for a scale height gradient of 0.45 in morning conditions. Utilizing radio signals from missile tests in the course of their passage through the $F$-region, Nisbet [1960] has shown seven profiles to various altitudes; each are in substantial agreement with a "Chapman" distribution about the $F2$ peak. Nisbet and Bowhill [1960] have discussed the same data in more detail, presenting their method of analysis. Bowhill [1961, 1962] has shown how a theory of the $F$-region, including diffusion, permits estimation of the $F$-region temperature from the width of the $F2$ peak; he deduces values of 1140° K (nighttime) and 1490° K in the daytime. Jackson and Bauer [1961] reported an $N$(h) profile between 225 and 620 km, using the Seddon technique; this midafternoon profile exhibited a practically constant logarithmic slope corresponding to a diffusive equilibrium distribution in an isothermal atmosphere, and implied a neutral particle scale height of 100 km or a temperature of 1640° K. An evening electron density profile between 240 and 700 km was reported by Hanson and McKibbin [1961], again indicating a diffusive equilibrium distribution above the $F2$ peak, with a neutral scale height of 76 km (T=1240°K).

The growing sophistication of rocket measurements is exemplified by those experiments designed to measure electron temperature and positive ion density, usually in addition to the electron concentration. Spencer, Brace, and Carigan [1962] describe the flights of two rockets at Ft. Churchill, and two at Wallops Island, in which the electron temperature and positive ion density are measured. Large gradients of electron temperature are found between 150 and 250 km, becoming isothermal at greater heights. Significantly larger electron temperatures are recorded during disturbed conditions, and more variability is noted during "spread *F*" conditions. Most significantly, these results suggests a daytime electron temperature roughly twice those generally accepted for the neutral gas temperatures. Elsewhere, Brace [1962] describes additional data, using the same techniques which indicate thermal equilibrium at night. Ulwick, Pfister, Vancour, Bettinger, Haycock, and Baker [1962] have described perhaps the most elaborately instrumented ionospheric rocket to date. Eight distinct techniques, measuring electron density, electron energy, positive ion density, photoelectrons, and radiation were flown together to 240 km. A positive ion measurement between 150 and 520 km is described and analysed by Sagalyn, Smiddy, and Wisnia [1963]. Excellent agreement between two probes aboard the same rocket on ascent and descent, and (up to the $F2$ peak) with the electron profile from an ionosonde, is obtained. The ion temperature and (neutral) scale height implied by this measurement are 1300° and 80 km, respectively. A photochemical theory (i.e., neglecting diffusion) for the equilibrium density under these conditions is presented, and is shown to agree well in shape and height, although the magnitudes differ by a factor of two.

### 4.2.3. Electron Distributions by the Incoherent Scatter Technique

At radio wave frequencies well above the maximum ionospheric plasma frequency, the free electrons exhibit a weak incoherent scattering of incident radio energy which, with sufficient power, permits observation of the electron profile out to distances of many thousands of kilometers above the earth [Bowles, 1961]. Ionospheric measurements based upon this mechanism have developed rapidly during the years 1960–1963, and some of the most elaborate radio instrumentation ever conceived for ionospheric studies is now being completed for this purpose [Bowles, 1963b]. Much theoretical work on the scatter mechanism (which is not reviewed here) has shown the potentiality of the technique for measurement of ion temperature (and its ratio to the electron temperature), electron distribution, and (in directions perpendicular to the geomagnetic field) the identity of the various ionic species. Millman, Moceyunas, Sanders, and Wynick [1961] have shown how the dependence on an ionosonde for calibration of the electron density at $N_{max}\ F2$ might be avoided by observing the Faraday rotation of the scattered energy, thus making the incoherent scatter technique completely self-contained.

One of the most immediate applications of the method was discussed by VanZandt and Bowles [1960], who estimated a value for the ionospheric temperature of 1050 °K from the shape of the topside profile. Similar early measurements were reported by Pineo, Kraft, and Briscoe [1960]; Pineo, Kraft, Briscoe, and Hynek [1962] up to heights of about 700 km. These results indicated a scale height of about 100 km near the $F2$ peak, and a transition at about 500 km to a region of increasing scale height. Pineo and Hynek [1962] reviewed observations obtained over a 24-hour period at the Millstone Hill radar site. An approximately consistent agreement is shown over this period between the power scattered from the $F2$ peak, and $N_{max}F2$ judged from an ionosonde. The average day and night (ion) temperatures were 1200 °K and 650 °K, respectively, and the electron temperature was larger by a factor of 2 from dawn to midafternoon, independent of height. Essentially similar conclusions are reached by Evans [1962b]. A review of all 55 profiles made at the Millstone Hill facility in the period 1960–1961 is given by Evans [1962a]. Typical values of neutral scale height are 50 km (winter daytime); 65 km and 70 km, summer morning and daytime, respectively. In each case, the scale height appears to increase linearly with height, with an implied gradient ranging between 0.26 and 0.57.

Bowles [1963a] has published a selection of profiles recently obtained at the Jicamarca Radar Observatory at Lima, Peru. The high power (up to $4.6\times 10^6$ w) and large antenna cross section ($8.4\times10^4$ m$^2$) have permitted measurement of electron density distributions out to 7000 km above the geomagnetic equator. Typically, these profiles display a quasi-logarithmic decrement on the topside of the *F*-region, with an abrupt increase in slope at 1000 to 1200 km.

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# 7. Some Miscellaneous Topics

In addition to the above topics discussed at the XIVth General Assembly, many other U.S. studies of interest to Commission 3 were published during the triennium 1960–62. In order to present a slightly more complete picture of U.S. activities in the field of Commission 3, brief reference is now made to three of these areas.

## 7.1. HF Doppler Studies

The ionospherically-induced frequency variations of ionospherically-propagated HF signals have been studied by several authors [Watts and Davies, 1960; Fenwick and Villard, 1960; Davies, 1962; Davies, Watts, and Zacharisen, 1962]. The method typically involves recording the frequency difference existing between a very stable local oscillator and the ionospherically-propagated signal from a very stable transmitter (for example, WWV). These studies have shown that it is possible to identify regularly occurring frequency changes (upward in the sunrise hours, downward in the sunset hours) associated with the growth and decay of the ionospheric electron density. In addition, pronounced frequency changes have been found associated with solar flares, magnetic sudden commencements and magnetic storms, and ionospheric "ripples." By using simultaneous observations on several different frequencies, it has been possible to make deductions concerning the height of the changes in ionization responsible for the fluctuations in frequency. At times it is possible to identify different ionospheric propagation modes for a single transmission (such as the high and low rays) by the difference in observed frequencies.

## 7.2. High Latitude Studies

High latitude studies of ionospheric radio propagation and the ionosphere have been numerous during the triennium. A Conference on Arctic Propagation was summarized by Kirby and Little [1960]; this reference includes abstracts of 22 papers presented at the conference. Synoptic studies of anomalous $foF2$ variations in the Antarctic were made by Hill [1960] and of spread $F$ by Penndorf

[1962 a,b,c,d]. The fading characteristic of high-frequency auroral zone propagation paths have been discussed by Yeh and Villard [1960] and by Koch and Petrie [1962]. Auroral radar studies have been reported by Bates [1961] and by Leonard [1962 a,b].

Studies of high latitude absorption include experimental investigations of 2 Mc/s pulse echo amplitudes [Davies, 1960]; of 2.5 and 5 Mc/s radio noise intensities [Herman, 1962]; of ionosonde $f_{min}$ values [Rumi, 1960]; and the theoretical study of Webber [1962] on the production of an absorbing $D$ region by solar and galactic cosmic rays. Polar cap absorption events were also discussed by Reid [1961] and by Reid and Leinbach [1962]. Riometer studies by Brown et al. [1961] and by Ortner et al. [1962] have shown that absorption events frequently occur simultaneously over a wide range of longitude at the auroral zone, in synchronism with the onset of a sudden commencement storm. Also associated with riometer studies is the report of auroral radio noise at HF by Egan and Peterson [1960]. Thisnoise was detected at subauroral latitudes during disturbed periods, and is attributed to synchrotron emission.

The absorption of radio waves occurring simultaneously in magnetically conjugate regions was studied by Hook [1962], who used IGY riometer data obtained in Alaska and compared it with $f_{min}$ values obtained on an ionosonde at Campbell Island in the South Pacific. Good correlation was found in the times of occurrence of a number of events, but the difference in observing methods in the two hemispheres prevented detailed quantitative comparisons.

Penndorf and Hill [1961] conducted a detailed study of the morphology of high latitude absorption in the Arctic during the severe ionospheric storm of September 1957. A somewhat similar study of the worldwide patterns of occurrence of ionospheric blackout during five major absorption periods was conducted by Agy and Davies [1961], and resulted in an animated film.

Hunsucker and Owren [1962] investigated the relationships between sporadic $E$, all-sky camera observations and the local magnetic $K$ index at College, Alaska. In particular, $fEs$ was found to increase with auroral activity and to reach a maximum of 5 to 10 Mc/s when the aurora was overhead. Studies of 2.89 Mc/s equivalent antenna temperatures at College, Alaska, by Little, Lerfald, and Parthasarathy [1962] showed that the electrons in the lowest part of the absorbing region remain in thermal equilibrium with the ambient gas during aurorae.

## 7.3. High Altitude Explosions in the Ionosphere

Some of the effects of the July 9, 1962, high altitude explosion over Johnston Island are discussed in a series of collected papers in the February 1, 1963, issue of the Journal of Geophysical Research. Of particular concern to Commission 3 are papers by Basler, Dyce, and Leinbach [1963] and by Zmuda, Shaw, and Haave [1963]. The first paper briefly discusses observations of cosmic noise absorption observed at four locations in Alaska. Absorption commenced within 2 sec of the detonation, reached a first peak within the first minute and showed one or more subsidiary peaks some tens of minutes later, depending upon the location. Ionization was detected up to $L$ values of at least 6. The second paper is again concerned with $D$ region effects, but in this case the phase perturbations experienced on VLF paths in the United States were investigated. The time variations of the observed phase are presented for several paths, and are attributed to the neutron-decay model proposed by Crain and Tamarkin [1961], and to the longitudinal drift motion of the fission electrons released by the bomb.

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