PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Early History of Ionospheric Investigations in the United States

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Phil. Trans. R. Soc. Lond. A 1975 **280**, 11-25
doi: 10.1098/rsta.1975.0089

Phil. Trans. R. Soc. Lond. A. 280, 11–25 (1975) [11]
Printed in Great Britain

The early history of ionospheric investigations in the United States

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The early history of ionospheric investigations in the United States, from the first suggestion of its existence by Kennelly to the initial data procured with rockets, is outlined. A tabulation of the earlier groups and organizations in this field is followed by brief historical outlines of the work in certain technological and scientific areas. The report is concluded with an enumeration of several of the ionospherically related U.S. activities following the early 1950s.

Introduction

It is probably inherent in a subject involving World-wide phenomenon and technological communications interests that the studies of the ionosphere have nearly always transcended national boundaries. The writer well remembers munching sandwiches along a roadside with Mr Ratcliffe on the way to London from Cambridge in the late 1930s and asking him what had excited his interest in the ionosphere? His reply was 'because this subject deals with almost every type of physical phenomena', and this truism further contributes to difficulties in the delineation of the early developments in the field on the basis of national boundaries. As an example, the first words of Kennelly's note suggesting that an electrical conducting strata existed at a height of about 100 km are 'According to the measurements of Professor J. J. Thomson'.

These ideas were much better expressed by Lloyd Berkner in a talk he presented at a Conference on Ionospheric Physics in the U.S. in 1950 – approximately at the end of the interval of time which will be dealt with in this paper – and the liberty of extensively quoting from this is being taken. Speaking of ionospheric research he stated:

'I would like to visualize our special science as a geographic area with unknown boundaries bordering on and forming a part of the main body of science. Into this area we have driven new roads from the periphery of science to explore it. These main arteries delineate its main features. We have run laterals to join the main roads together to extend our knowledge of the area. And then we have cross-connected these roads with secondaries, that we might have detailed access to the whole area, to explore the hills and valleys that have been by-passed in driving ahead along the main lines of endeavour. Occasionally, a road encounters a real scientific barrier, but after some brief surveys we get around that barrier in one way or another that progress in the unknown may continue.

'The first main road was started by Gauss about a century ago with his separation of the Earth's geomagnetic field into internal and external components. This road was followed and extended by Stewart and by Schuster who conceived and defined broadly the characteristics of an electrified outer atmosphere in a form that could describe certain geomagnetic phenomena arising in the atmosphere.

'A second main artery was driven by Maxwell, Hertz, and Marconi in the discovery of properties of electromagnetic radiation that have become known as radio. Kennelly and Heaviside constructed a lateral to join, almost accidentally, the road being constructed by Stewart and Schuster, when it was realized that the electrified atmosphere affecting radio waves would also affect the geomagnetic field. The main road was driven on by Chapman and his colleagues who showed how sunlight would produce the necessary ionization. This wonderfully prolific work constructed a multitude of laterals that explored the physics of layer formation in considerable detail, and joined back to the main artery of exploration and also to the main area of expanding science at frequent intervals.

'At the end of the first quarter century the main road had reached some mountainous country. Direct access to the outer atmosphere was needed, and some powerful tools were necessary to obtain this access. These tools were promptly provided by the techniques of Appleton and Barnett, and by Breit and Tuve, who drove the main road across the barrier, and into the lucrative valley of direct ionospheric observation.

'Exploitation of this valley has gone on at a great rate with roads criss-crossing in all directions. The development of the multifrequency technique and of the magnetoionic theory are but two of the important tools devised for this exploration. From this work has developed, since 1930, a worldwide picture of ionization in the outer atmosphere with its D, E, F_1 and F_2 layers fluctuating sometimes smoothly and sometimes madly in the environment of the universe.'

Berkner then went on to discuss his prognosis of the future of the field which was, as one would expect, remarkably prescient.

This review of the early history of ionospheric investigations in the United States will attempt to cover the science and, to a more limited extent, the technology involving the propagation of radio waves via this medium. This will deal with the time period to about 1950 when the first rocket procured data were being obtained. A tabulation of the U.S. organizations most active in ionospheric research is followed by summaries of the work in several major areas of study. These are presented and referenced separately in order to provide continuity. The material is concluded with a listing of some major U.S. programmes related to ionosphere studies from about the 1950s to the present time.

U.S. organizations and groups

The following tabulation of groups and organizations active in the early days in ionospheric research is believed to be fairly complete and, in the main part, applicable even today. The listing of major subject matter of interest to a group is frequently far too restrictive. The names listed after an organization are limited to those who were active in or guiding programmes pertaining to studies in this field and are, particularly for the larger organizations, quite incomplete.

name of organization	major subject	some individuals
Department of Terrestrial Magnetism, Carnegie Institution of Washington	ionosphere characteristics	Fleming–Tuve Berkner–Wells
National Bureau of Standards	ionospheric radio wave propagation	Dellinger N. Smith Little
Naval Research Laboratory	physics of the ionosphere	Hulburt Friedman

name of organization	major subject	some individuals
Ballistics Research Laboratory	upper atmosphere studies	Berning Kaufman
Air Force Cambridge Research Laboratory	upper atmosphere studies	Pfister Chamberlain Penndorf
Applied Physics Laboratory	navigational satellites	Gibson
Bell Telephone Laboratory	communications	Jansky Southworth Bullington
R.C.A. Communications	communications	Beveridge Goldman
University of Alaska (Geophysical Institute)	high latitude studies	Elvey Mather
Dartmouth College	wave propagation and of whistlers	Morgan
Cornell University	ionosphere scatter	Burrows Booker Gordon
Harvard University	ionosphere studies	Mimno Pierce
Iowa State University	rocket studies	Van Allen
Massachusetts Institute of Technology		
Radio Research Laboratory	propagation	Terman–Loomis
Lincoln Laboratory	propagation	Evans
University of Michigan	rocket studies	Dow Jones Nagy
New York University (Courant Institute)	mathematical studies	Kline
Penn. State University	ionosphere characteristics	Gibbons Nisbet Waynick
Stanford University	propagation and whistlers	Villard Manning Helliwell

General major areas of study

This review of early ionospheric investigations in the U.S. is arbitrarily restricted in subject matter and in scope. In this way it is hoped that several of the more important areas in which U.S. contributions were made can be adequately covered. In one area (early physical studies) this is primarily a review of some of the work of one man, Dr E. O. Hulburt, and his collaborators and colleagues. Each area is dealt with, and referenced, separately.

The ionospheric medium

Kennelly's (1902) note suggested the existence of an 'electrically conducting strata' at a height of about 80 km to explain the propagation of radio waves over long distances by reflexion between it and the conducting ground. He furthermore published a paper 'The daylight effect on radio telegraphy' in 1913 in which it is assumed that the ionization forming the strata is produced by solar radiation. Other U.S. work in this area in these times was primarily concerned with empirical measurements of practical importance, leading to results such as the Austin–Cohen propagation relation in 1914.

As a result of several theoretical papers and radio observations, such as bearing errors in radio direction finding at night, a considerable interest arose in seeking to verify the existence of such a medium. Eccles (1912) had developed the theory of the bending of radio waves in passing through a medium of heavy ions. This was elegantly extended to consider electrons by Larmor (1924). At about this time A. H. Taylor (1925) in the U.S. summarized a great range of observations by radio amateurs and the U.S. Navy on the transmission of radio waves covering frequencies from 100 kHz to 20 MHz and distances of 0–16000 km. His 'range charts' illustrate the difference in behaviour of radio transmissions at wavelengths below and above about 200 m, skip distance phenomena at the higher frequencies and temporal effects and seasonal effects on propagation. Taylor and Larmor's work led to the classical theoretical paper of Taylor & Hulburt (1926). It is shown from Snells law and a real refractive index less than unity how the skip distance phenomenon is explainable, even for specular reflexion, as the result of total internal reflexion of a sky-wave. The authors take the Lorentz equations, with no restoring force or absorption (f and $g = 0$), considering electrons, following Larmor, but also considering the Earth's field. Longitudinal and transverse propagation are dealt with and the two modes for each case are considered. For an Earth's field of 0.5×10^{-4} T it is noted that the absorption of a wave is small except at a wavelength, λ_0, of about 214 m (agreeing with Nichols & Schelleng (1925)) and for longer waves. Four electron density against height models are assumed and the four modes of propagation dealt with in deducing skip distances when refractive effects are considered. It should be noted that this work was done before most of the model parameters involved had been determined experimentally.

In 1926, Breit & Tuve conducted experiments which showed that 'echoes from the upper regions' could be obtained with 70 m pulsed waves vertically incident. Layer heights of between 80 and 210 km and with multiple reflexions were noted. The heights were found to vary seasonally and diurnally and to be some function of wavelength and range between transmitter and receiver. The heights were deduced from the elapsed time between ground pulse and echo. A qualitative check on vertical directions of arrival was obtained by noting a maximum intensity of the echo for horizontal receiving antenna heights corresponding to $\frac{1}{4}\lambda$ above ground. Consideration of the relations between group and phase velocity in a dispersive medium were applied to the models of Taylor & Hulburt (1926), and the fact that the group delay would be greater than the 'true height' delay was noted. Also, pulse envelope distortion was considered and the Breit & Tuve theorem was deduced.

These workers improved upon their experimental techniques, Breit, Tuve & Dahl (1929), and reported on 4 MHz heights and relative amplitudes from two different height ranges during winter days. Thus, first and second hops were observed from apparent heights of about 225 and 500 km, respectively, with amplitude ratios of about 10/1 and similarly, from about 110 and 220 km with a ratio of unity. Heights in the ratio 1–2–4 were occasionally noted, apparently 2 hop E and 1 hop F simultaneously although the authors did not postulate this.

Changes in phase height were considered theoretically by G. Breit (1929) and observed experimentally by Hafsted & Tuve (1929*a*). The latter authors (1929*b*) reported on simultaneous two frequency observations, 4 and 8 MHz, where diurnal height variations are reported, spreading of the higher level reflexions noted (spread F?) and occasional intense lower level reflexions (E_s?).

Several groups at the Bell Telephone Laboratories reported on work on short wave communication circuits which were now of commercial interest since the amateur radio fraternity had shown their great range and value. Bown, Martin & Potter (1926) showed that distortion in the broadcast band was caused by variations in the received carrier. Heising, Schelleng & Southworth (1926) presented extensive transmission data on field strength, fading and intelligibility over the frequency range 2.7–18 MHz and distance up to 1600 km under most conditions. From transmission with horizontal and vertical transmitting antennas they showed that signals might arrive from different paths.

The above led to the work of Heising, reported in 1928, directed toward the utilization of short waves in communications networks. He first, in 1925, utilized signals in the frequency range 3–5 MHz which were switched on and off with the frequency sweeping at a uniform rate over a few kHz during the on period (chirp radar). Following Breit & Tuve, the pulse technique was employed in later experiments. Heising observed multiple F-region echoes and carried out oblique experiments to ranges up to several thousand miles. He pointed out that absorption was an important factor in the weaker daytime signals and stated the absorbing region was below the reflecting level through which the waves must pass at least twice. In daytime, he pointed out the need to go to higher frequencies for lesser absorption but restricted by the need for the waves to be refracted. He postulated that solar u.v. was the source of both the refracting and absorbing region and α particles the source for the generation of aurora.

It is believed that the above summarizes the contributions in the U.S. to the proof of the existence of the ionosphere and the initial studies on the determination of its characteristics.

Radio wave propagation in the ionosphere

This subject has two fundamental aspects. The first of these is in terms of the development of the magnetoionic theory. The second pertains to the application of medium characteristics in the determination of the propagation of waves through the ionosphere.

Magnetoionic theory

Confining attention mostly to U.S. contributions the first work on magnetoionic theory, including collisions and a generalized direction relative to the Earth's magnetic field, was apparently that of Nichols & Schelleng (1925). Their results were expressed in the form of a dielectric tensor. Aspects of this problem were also considered by Breit (1927) with applications suggested in a series of papers in following years.

The most useful presentation of the theory, however, was that of Appleton (1932) and involved an extension of the Lorentz theory (1952). This included the Lorentz polarization term, taking account of the corpuscular distribution of matter which had been found to apply to real dielectric materials. It further assumed an electron energy loss factor $g = 2m\nu$ where the electron-neutral collision frequency was assumed independent of the electron velocity.

The next U.S. input to this problem were suggestions of Tonks (1933) and of Norton (1933) that the Lorentz term should not be included for a medium with a random distribution of charges such as the ionosphere. This was shown mathematically to be the case by Darwin (1934) and verified experimentally in following years with oblique incidence experiments. The basic reference for dealing with the Appleton–Hartree magnetoionic theory is that of Ratcliffe (1959) covering all aspects of this complicated matter.

Following U.S. contributions were, however, made in these later years. Phelps & Pack (1959) obtained laboratory experimental verification that the electron collision frequency in nitrogen, at pressures applicable to the ionosphere, was directly proportional to the electron energy; i.e. the square of the electron velocity. They were able to deduce the energy loss factor for air and apply their results to *in situ* absorption measurements made with rockets. Finally, Sen & Wyler (1960) derived the magnetoionic equations from first principles based on Boltzman's equation and showed that the Appleton–Hartree equations were generally valid except for regions where high collision frequencies are encountered such as for long-wave and D-region studies. The exact applications of these concepts appear in Budden (1961).

Wave propagation

A World-wide surge of interest in the ionosphere and its role in the transmission of radio waves followed the experiments, proving its existence, of Appleton & Barnett (1925) and of Breit & Tuve (1926). This included initial work on the determination of region characteristics, for example, layer heights, etc.; the establishment of observatory type operations to measure these throughout the World and the application of such data to the determination of, and ultimately forecasting, optimum frequencies, etc., for given communication paths. Finally, the effects of solar and related geophysical phenomenon affecting radio propagation via the ionosphere were also included.

Only a minute portion of the extensive literature of this time can be considered. The review article of Kenrick & Pickard (1930) covers the transition period between the time when ionosphere region characteristics could and could not be considered in propagation studies. Work at the Carnegie Institution of Washington (C.I.W.) on initial studies of region parameters continued and the beginning of a World-wide, ionosphere observatory programme was started. In the early 1930s this resulted in the establishment of such observatories by this organization in Washington, D.C., Huancayo, Peru (on the magnetic equator), Watheroo, Australia, and College, Alaska – see, for example, Wells & Berkner (1947). This involved the development of automatic group height against frequency recorders (ionosondes) and the publication of the resulting data in observatory format.

Other early work concerned with radio wave propagation in the ionosphere was undertaken by the Bell Telephone Laboratory (see, for example, Schafer & Goodall 1931), but by far the major effort in this field in the U.S. was that of the National Bureau of Standards (N.B.S.). A review of the work of this time was published by Dellinger (1939) pointing out the extensive efforts of the, in particular, C.I.W. and N.B.S. groups which were closely correlated. The major emphasis of the N.B.S. group was the application of vertical incidence ionosonde data to oblique incidence propagation. Smith (1939) derived techniques wherein overlays of 'transmission curves' of frequency and given distances based on Martyn's theorem, permitted practical determination of the transmission mode, maximum usable frequency, etc., for given communications paths. These techniques were extensively used during World War II when an Interservice Radio Propagation Laboratory (I.R.P.L.) was established (Dellinger & Smith 1948). This was then reorganized into the Central Radio Propagation Laboratory (C.R.P.L.) of the N.B.S. with a 'weather bureau' type of mission for radio propagation. This involved the procurement of World-wide ionospheric data, the determination of methods of forecasting ionospheric conditions World-wide weeks and months in advance and the issuance of these in a format where a communicator could select in advance the best operating frequency for a given path and time.

An interesting experiment wherein oblique incidence equivalent path versus frequency measurements were directly recorded for comparison with simultaneous vertical h'–f data at the end and mid-points of a 1150 km path in the U.S. was carried out to check the above techniques (Sulzer & Ferguson 1952). Later developments, particularly during the I.G.Y., included true height determinations of electron density profiles and the application of ray tracing techniques.

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Early physical studies

The initial physical studies of the ionospheric medium by Taylor & Hulburt (1926), largely based on the summary of experimental radio observations by Taylor (1925), was apparently the first U.S. work on the physics of the ionosphere and referenced the then recent results of Breit & Tuve (1926). Dr Hulburt had just joined the Naval Research Laboratory as Superintendent of the Physical Optics Division and his influence and own contributions to this field in the U.S. were so outstanding, much of the original work was carried out by Hulburt and his colleagues and collaborators, that a review is essentially a summary of his contributions, as in the following. It will be noted that his continual emphasis was placed on the exploitation of radio data to deduce ionosphere and relevant upper atmosphere physical characteristics.

The Taylor & Hulburt (1926) paper dealt with obtaining estimates of likely N–h models which would explain the skip-distance observations and the ionosphere layer heights which had just been roughly determined. This involved extension and assumptions on the Lorentz theory and considered the effects of the Earth's magnetic field. Here the refractive indices for the four modes in transverse and longitudinal propagation were considered. An extension of this (Hulburt 1927), dealt with the imaginary part of the complex refractive index for these four waves by obtaining suitable approximations for 3 of them; an exact solution for the E-wave component perpendicular to H was obtained. The total absorptions, $\int k\,ds$, for the various electron density models were determined and compared with the oblique incidence intensity observations of Heising, Schelleng & Southworth (1926) at 44 and 66 m. This based on dealing with a refraction region above an absorbing region through which the sky-wave passed on both the upgoing and downgoing portions of the wave path. Here collisions between electrons and neutrals were assumed to be involved.

The first of a series of classic papers by Hulburt (1928) was titled 'Ionization in the upper atmosphere of the Earth.' The radio observations on skip distance, diurnal and seasonal variations for wavelengths less than $\simeq$ 40 m; limiting λ (m.u.f.) and h' of (E and F) are used as the experimental data. Model estimates for the pressure and density of total air and of O_2 are taken from Maris (1928) and the terms in the continuity equation for charge particle production by solar u.v. radiation deduced. Based on neutrality; diffusion, with and without the Earth's field; recombination, including radiative, and attachment processes are broadly considered. The ion pair production is determined on the assumption that all the absorbed energy produces ionization and where it is expressly noted that applicable atomic and molecular rate coefficients are not known; even if only O_2 and N_2 are considered. This leads to winter and summer, night and day models which compare, in some ways, with portions of the radio data. The really important matter here, however, is that this paper brings together first estimates of all factors involved in the production and loss processes in ionosphere layer formation. It concludes with a table giving estimates of the energy of the Sun's u.v. in various portions of the spectrum and descriptions of the possible effects produced by its dissipation, at various height regions in the Earth's atmosphere.

Maris (1928) and Maris & Hulburt (1929) deduced that noon-day temperatures above 100 km were about 500 K. With these, at that time, rather phenomenal values Hulburt (1929) continued his 1928 work but with emphasis on terrestrial magnetism as the experimental parameter. Current sheets at various height levels for several latitudes are deduced based on the ionization production concepts previously considered and with charge motions subject to gravitational, magnetic and, at certain levels, electric fields. The critical level, above and below which, respectively, the mean free path must, or is not, considered is taken at 150 km at the equator. The theory is shown to agree with the solar diurnal variation of the Earth's magnetism as well as the radio data.

In what is, essentially, the third paper in this series, Hulburt (1930) extends the previous studies in the consideration of longitude. The diurnal plots of the maximum electron density for various longitudes are of particular interest. Finally, Hulburt (1932) published his 'Tables of ionization in the upper atmosphere' which are based on a summarization of the previous papers of the series and '...as far as possible on the entire meteorology of the upper atmosphere...'. It is shown how certain radio and terrestrial magnetism observations can be accounted for from the tables. It is interesting to note that Chapman's (1931) first paper on simple layer formation was published at about this time.

While numerous valuable papers on many points of interest concerning the physics of the ionosphere were published by Hulburt, and many others, during succeeding years it remained for the procurement of *in situ* data for the next major advances in the physics of the ionosphere and upper atmosphere to be made. Some of Hulbert's contributions during this time were Hulburt (1935, 1937, 1939, 1947, 1950) whose titles are included in the reference material. While somewhat outside the time scale of this material, Hulburt and his colleagues, Havens, Friedman & Hulburt (1955), reported at the Cambridge Conference on Ionospheric Physics on extensive rocket data out to 219 km. This included neutral particle densities and temperature; the first mass spectrometer observations; electron densities determined by *in situ* radio techniques and solar radiation intensities in X-ray regions and for coronal lines. Finally, a survey of the advances in the physics of many fields of upper atmosphere research during the interval 1950–5 was published by Hulburt (1955). This had a major impact on the U.S. component of the following I.G.Y. programme.

Sudden ionospheric disturbances

One of the first observed phenomena directly linking solar observations with the ionosphere during disturbed conditions was reported upon in detail by Dellinger (1935). At one time this was called the Dellinger–Mögel effect but later the term sudden ionospheric disturbance (s.i.d.) became the accepted nomenclature. Close coincidence in time and in intensity were found to exist between the occurrence of bright chromospheric eruptions on the Sun and the strength of radio waves transmitted over the sunlit hemisphere of the Earth; and *not* the dark half. It was determined that pulses on the H and D traces of magnetograms and pulses in the Earth's currents were also observed. The radio fadeouts were shown to be due to an increase in the absorption of the waves below E-layer and were very abrupt in origin, lasting minutes to hours and with a slow decay; i.e. gradual increase in signal strength while returning to normal conditions. They were also associated with sudden enhancements of atmospherics observed by Bureau (1937).

McNish (1937) reported upon an augmentation of the diurnal variations in terrestrial magnetism which arises in the same regions of the upper atmosphere as the radio fadeout effects. These magnetic disturbances were unlike more usual magnetic storms; both in duration and in latitude. The latter were the opposite to those associated with the more common magnetic storms.

Relations based on h'–t and h'–f observations, the former in Watheroo, Australia, and Huancayo, Peru, as well as in Washington D.C. were reported upon by Berkner & Wells (1937*a*, *b*).

Verification of fadeouts occurring only in the sunlit hemisphere was obtained with the region about 30° from the sub-solar point being most affected. The abrupt time of starting of the fadeouts throughout the sunlit hemisphere on the start of a bright chromospheric eruption was noted at all high radio frequencies. No changes were observed in the F_2 and F_1-layer critical frequencies and heights though it was believed that small changes might have occurred in the E-layer. A summary of these observations was published by Berkner in 1939.

Budden & Ratcliffe (1937) noted early in an extended series of observations of the phase, related to height of reflexion, amplitude and polarization characteristics of long, 16 kHz, radio waves that short-lived disturbances in the smooth diurnal variation of phase occurred simultaneously with short wave fadeouts and enhancements of atmospherics. Here, however, a major lowering of the height of reflexion, and a probable small increase in signal strength, were noted with the magnitude of the height change approaching that obtained during an entire day for major enhancements. These were subsequently called s.p.a. (sudden phase anomalies).

Wulf & Deming (1938) discussed the theory of production of ionization to produce the above effects. They conclude that the ionization probably cannot be due to solar ultraviolet because of the low altitude it must reach to account for the long wave effects and intensity. They thus rejected the suggestion of Martyn, Munro, Higgs & Williams (1937) that the effective mechanism was L_α ionizing atomic oxygen; primarily on the basis of the probable height distribution of the latter. They state 'such ionization seems to require the presence of a new constituent, not present at greater heights, which possesses broad absorption in the near ultraviolet'. O_3 with $\lambda < 200$ nm was suggested.

Three matters remain in this evolving story. Nicolet (1945) showed that the ionization of nitric oxide by L_α was the most likely candidate for the production of the normal D region. In an extensive study of the long wave data, Bracewell & Straker (1949) emphasized the quantitative relation between H_α line width and long wave phase anomalies during s.p.a. The advantages of long wave techniques for quantitative measures was well illustrated.

Finally, and outside of the time scale of this report, Friedman & Chubb (1954) reported on rocket measures of L_α which conformed in intensity and height distribution with the postulates of Nicolet; though the constituent involved was not determined. Evidence that very hard X-rays, less than about 2 nm, intensity is strongly dependent on coronal activity was presented based on a number of rocket flights. Further, that increased D-layer ionization production to heights as low as 60 km or so could most efficiently be produced by these wavelengths. Finally, that rocket flights during a solar flare and fadeout, during which L_α and < 1 nm X-rays were measured *in situ*, would be the best way to determine which mechanism was effective. (Several years later this experiment was carried out by the Friedman group in the South Pacific with little change in L_α but great changes in hard X-ray production noted during a flare.)

Radio meteors

An extensive review of the use of optical meteor trails in the study of densities and temperatures in the upper atmosphere over the height range of about 50–110 km, was published by Whipple (1943). Simultaneous photographic measures with rotating shutters at two spaced locales against a stellar background are used to determine meteor trail heights and directions, velocities and decelerations as well as luminosity. These data permit the determination of atmospheric densities during deceleration; at maximum luminosity; near the initial and at the end point of a trail. From ρ determinations, and assuming constant mean molecular mass, the

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temperature height variations verifies a rise of temperature to a maximum of about 270 K near 60 km, falling to a minimum of 160 K near 82 km and a continual increase above that.

Immediately following World War II a great World-wide interest arose in the study of the ionized trails produced by meteors; due in part to the availability of radar and radio techniques useful for such studies. In the U.S., Manning (1948) developed the theory of radio detection of meteors based on the suggestions and studies of Skellet (1931, 1935) and of Pierce (1938). The physics and geometry for meteor trail detection and characteristic determination are deduced from up and down doppler signals associated with the head and tail of a trail. The condition for noting a burst of more intense signal from the formed column of the trail is likewise determined. It is shown that the trail trajectory and meteor velocities can be measured with three separate receiving stations and with c.w. plus pulse ranging.

A survey of the field by Millman (1950) including optical and radio studies was published by the Canadian Dominion Observatory. He refers to the very extensive meteor observational data of Olivier (1942, 1947) and, in particular, his studies of long enduring meteor trails, which can last several minutes although the usual length of trail life is in seconds. The physical processes occurring are outlined in detail with observational data such as mean height ranges of 105–80 km, electron densities per centimetre of path of 10^{10}–10^{14} electrons, optical luminosity and ionization of the trail being a function of meteor mass loss and not primarily decelleration, etc.

The most active group in the U.S. in the radio meteor field was probably that at Stanford University. Results from developments of Manning's work included the study of meteoric heights and velocities by radio doppler techniques (Manning, Villard & Peterson 1949), which checked with optical observations, and neutral winds from the observation of ionized trail displacements by the same authors (1950). Values of wind magnitude and direction at heights of 90–100 km could be obtained in 2 or 3 h of observations, with values of around 125 km/h. Somewhat later this group reported on extended range, 1000 km, oblique transmissions from meteor trails for use in communications (1953). The use of longer enduring meteor trails for 'burst' communications was the subject of many studies on the North American continent.

D and lower E-region studies using pulse transmissions

As stated earlier, the original pulse observations of the ionosphere were made in the U.S. in 1925. What became a rather standard instrument for such work, an electronically controlled ionosonde which covered the frequency range of about 1–25 MHz, was developed by Sulzer in 1946, following the earlier development of mechanically tuned systems at the C.I.W. Consequently, it was rather appropriate that work extending this technique to the lower frequencies should also take place in this country, but in about 1950.

A great deal of valuable information on the lower ionosphere had been obtained by radio techniques in other countries and, in particular, by the Ratcliffe group at Cambridge. However, the complexity of some of these data indicated a need for the separation of echo components in certain studies. From the applications viewpoint there was also need for more information about the lower ionosphere for certain navigational aids, such as Loran C, etc.

Helliwell (1949) published a description of a spark excited, 100 kHz horizontal loaded radiator to obtain about 150 μs pulses at this frequency. Night time virtual heights of 84–106 km are reported with echo splitting, usually into two components, and multiple hop signals usually having different envelopes. The average polarization was E–W. This was followed (Helliwell, Malinckrodt & Kruse (1951) by a paper on fine structure in the lower ionosphere at night based on shorter pulses and two frequencies of observation, – 100 and 325 kHz, and with some idea of the received echo polarization obtained by switching from N–S to E–W receiving antennas. Split echoes were observed on both frequencies with the virtual height being about 3 km higher on the higher frequency. The polarization characteristics of the two components were different and the authors conclude that their data might be associated with magnetoionic theory but they could not determine this from ray theory. They favour multiple layers or strata as being the cause for multiple echoes. Nertney (1951) indicated how these data could be explained by wave theory from a model for the lower ionosphere which was based on other 150 kHz data.

The first electron density model of the lower ionosphere based on long radio wave, vertical incidence pulse observations was presented by Kelso, Nearhoof, Nertney & Waynick (1951). The model resulted from an extensive series of 150 kHz group height, polarization, absorption and change in phase height observations, in which two echoes with distinctly different characteristics were observed. It is shown that wave theory is required to explain the data on the basis of magnetoionic theory involving the coupling phenomena between modes when the N_c and ν_c levels approach one another. The model covers both diurnal and seasonal variations and is not based on the continuity equation. A finalization of the model was published by Nertney (1953) which references much of the work upon which it is based. The model is applied to the date of the English and other workers with, in general, satisfactory agreement. Long wave winds, s.i.d. and oblique data are also accounted for by the model as regards height and other parameters.

A third group at the C.R.P.L. of the U.S. National Bureau of Standards initiated long wave pulse work in 1950 (Brown & Watts) with virtual height observations at 50 kHz. These were later extended to cover 37–200 kHz and a series of papers on their work culminated in the construction and operation of an ionosonde, of the Sulzer type, covering the frequency range from 50 to 1100 kHz which simultaneously recorded both group heights and polarization. Their records (Watts & Brown 1954), are shown to be extremely complex but tie in, of course, quite well with normal ionosonde data at the higher frequencies. Splitting and polarization characteristics are noted at the lower frequencies and diurnal and seasonal data are presented.

However, none of these data were applied to communications circuits and major advances in the study of the physics and chemistry of the D-region awaited the procurement of *in situ* rocket data to supplement the radio observations.

Scattering

Taylor & Young (1928) observed 'short-range' echoes from nearby high-power, short wave transmitters of 10–50 ms delays when studying round the world transmissions. They ascribed these to scattering from polar regions and echoes from roughness of the Earth's surface. This was followed by the studies of Edwards & Jansky (1941) with high-power beam transmissions where vertical and horizontal direction of arrival measurements permitted classification of the scattering process from multi-hop ground reflexions to randomly directed scatter signals associated with ionospheric irregularities. Following a suggestion of Newbern Smith, Benner (1949) utilized ground backscatter of F-region reflected pulse signal time delays to deduce maximum usable frequency for a given path via the secant law between an oblique incidence transmission frequency to an equivalent vertical incidence frequency. This work was continued by Peterson of the Stanford University Meteor Ionization Group and, ultimately, became a major component of the U.S. programme for the I.G.Y.

Very important work on ionospheric forward scatter by Booker, work by Booker & Gordon on the basis for what is now called incoherent scatter and studies by numerous workers on winds and drifts based on the original concepts of Ratcliffe (1948) are not considered here in view of their time scale and, in the first matter, classification, at that time, by the U.S. defence establishment.

Early studies with rockets

On 16 April 1946 the first of a series of V-2 rockets was fired by the U.S. Army Ordnance Command which carried instrumentation for the determination of upper atmosphere neutral characteristics. Attempts to determine charged particle densities by radio methods were successfully carried out in 1947. One of the first general reviews on upper atmosphere studies, including rocket results, was that of Sheppard (1949). This compared the results obtained by indirect methods, including ground based radio wave propagation studies, and direct methods; such as with rockets. Major emphasis was placed on neutral upper atmosphere characteristics, including P, T, ρ and composition at height ranges out to 100 km or so, and a comparison of data obtained by various techniques.

Newell (1950) reviewed the results of the first two years of U.S. rocket work with some emphasis on the results of the Naval Research Laboratory with which he was associated. Following a general description of the use of rockets for upper atmosphere studies he outlines the methods of measuring various types of parameters and the results obtained. These included ambient pressure to 130 km with various types of gauges over a range of about 6 orders of magnitude. The first determinations of solar spectra down to about 50 nm as a function of altitude with various types of spectrographs and resolution to about 0.1 nm are outlined. Data obtained on cosmic rays, magnetic field, sound velocity from grenade explosions and electron densities are mentioned.

The first of an extensive series of electron density against height rocket measurements utilizing radio wave propagation techniques was reported upon by Seddon (1953); including the 1947 data. A somewhat earlier publication by Berning (1951) appeared but these data were obtained from the development of a tracking system, *Dovap*, which did not provide optimum results for Ne profile determinations. The Seddon technique, modifications of which were extensively used by following workers, utilized two harmonically related radio transmission frequencies, one of which would be greatly affected by the ionosphere whereas the other was high enough not to be appreciably affected by the medium. By measuring the two magneto-ionic component amplitudes and doppler shifts of the lower frequency relative to the higher at the ground the following parameters were calculated for known height and radial velocities of the rocket. Daytime Ne against h from 80 to 150 km; verification that the Lorentz polarization term should not be utilized in the magnetoionic theory for the ionosphere; a measurement of the Earth's field at a known height and the determination of electron collision frequency and ion densities from the Goubau theory (1935) under certain assumptions. This work, with Jackson, was continued for many years including measures through F-region.

Finally, in the time scale of this paper, a summarization of the U.S. upper atmosphere rocket results pertaining to neutral atmosphere pressures, densities and temperatures was published by the Rocket Panel (1952). This was a group of representatives from four universities, two industrial firms and four D.O.D. laboratories who were engaged in upper atmosphere rocket studies under the chairmanship of J. A. Van Allen. The data quoted are a compilation from 68 V-2, 63 Aerobee and 7 Viking rocket firings over the interval April 1946–52. In spite of a disclaimer

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to the contrary, the results led essentially to the first standard atmosphere to a height of about 220 km. The temperatures obtained by several groups and by independent experiments are determined on the basis of a constant mean molecular mass. The pressures were obtained by numerical integration of $d \ln P/dh = -1/H$, with $H = RT/\mu g$ and ρ from P and T via Boyle's law. These data are compared with the meteor data of Whipple (1952) and the acoustical propagation studies of Crary (1950).

Conclusion

Rocket, and later satellite, based studies of the upper and outer atmosphere tended to change the emphasis of ionospheric investigations in many ways. The role of radio waves as the primary exploring tool changed greatly as *in situ* measurements by other techniques became possible. The emphasis on geophysical studies, solar-terrestrial relations and solar and planetary astronomy resulted in an influx of workers from other fields as well as the spawning off of subject matter which had been initiated by ionosphere workers; such as radio astronomy.

However, major developments also resulted in the field in following years and a listing of some of these in the U.S. follows. The list is by no means complete and for one or two of the items may only have a secondary role as an ionosphere related activity. A topic heading is followed by an explanatory note and the names of individuals, locations or organizations most closely associated with a programme.

Some major U.S. ionosphere related studies after about 1950

1. whistlers	topside and higher	Helliwell–Morgan
2. topside sounding	above F_2 maximum	N.B.S.–N.A.S.A.
3. incoherent scatter sounding	Jicamarca	Bowles
	Aerecibo	Booker
		Gordon
4. rocket programs	aeronomy	N.A.S.A.–Aikin
	negative and hydrated ions	A.F.C.R.L.–Narcissi
	solar X-rays	N.R.L.–Friedman
5. satellite programs	beacon-B	N.A.S.A.–Clark
	solar u.v.	A.R.C.R.L.–Hinteregger
	solrad	N.R.L.–Kreplin
6. sky laboratories		Garriot
7. space laboratories		N.A.S.A.
8. non-linear studies	Boulder	Utlaut
	Aerecibo	Gordon
9. extremely long wave communications		Project Sanguine
10. long distance radar		O.H.D.

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