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The Upper Atmosphere Observatory

American and Canadian scientists plan to build a major research center.

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Despite the enormous growth in our knowledge and understanding of the earth's atmosphere at heights above 50 kilometers from satellite and rocket measurements, ground-based research continues to play an important and vital role. Now plans are well advanced for the construction of a major new observatory for the study of the upper atmosphere (*1*). This new facility will be built around an extremely powerful radar system employed for incoherent-scatter sounding of the ionosphere (80 to 1000 kilometers).

For a quarter of a century prior to 1950 the study of the earth's upper atmosphere and ionosphere were inseparable, since the principal observing techniques available were radio reflection experiments and the detection of optical emissions, both of which require an ionized atmosphere. It is frequently stated that the idea of an electrically conducting region in the upper atmosphere was first introduced by Stewart (*2*) in 1878 when he was attempting to explain the existence of rapid variations in the earth's magnetic field, but suggestions of this type were made by Thomson, later Lord Kelvin (*3*), in 1860 and Gauss (*4*) in 1838. Lord Kelvin was surprisingly accurate in surmising that this region was located at a height of 100 miles (160 kilometers); in contrast, Stewart had estimated that the region occurred at the upper cloud level, that is, 5 to 10 miles.

Heaviside (*5*) and Kennelly (*6*) revived this idea in 1902 in order to explain Marconi's observation, made the previous year, that radio signals could be received across the Atlantic Ocean at distances too great to be explained by refraction along the curved surface of the earth. It was not until 1926 that the existence of this "Kennelly-Heaviside layer" was established beyond all doubt through radio reflection experiments conducted by Appleton and Barnett in England (*7*) and Breit and Tuve in the United States (*8*).

Breit and Tuve employed an experimental technique consisting of the transmission of short radio pulses and the observation of the delayed reflected pulse, using a cathode-ray tube display (oscilloscope). This technique was a forerunner of the early British coastal radar system developed by Watson-Watt, who coined the term "ionosphere" (*9*).

A vertically propagating radio wave is reflected at the altitude where its frequency f is equal to the plasma frequency f_N ($= 9 \times 10^{-6} N_e^{1/2}$, where N_e is the electron density per cubic meter and f_N is measured in megahertz). By increasing the frequency of the exploring signal, it is possible to examine the distribution of electron density versus altitude up to the height of maximum density near 300 kilometers. It was found that the electron density does not increase monotonically from the lowest reflecting point (near 100 kilometers) to the highest; instead, well-defined stratifications in the distribution of the electrons appear to exist that became known as the D, E, and F layers (*10*). Instruments were built to sound the ionosphere automatically over a range of frequencies and record the results on film. These "ionosondes" dominated the experimental investigation of the upper atmosphere until 1950.

The advent of rocket and satellite-probing techniques opened up whole new avenues for research and permitted for the first time direct observation and measurement of the spectrum of solar extreme ultraviolet and x-ray emissions responsible for ionizing the upper atmosphere. Rockets and satellites have been employed to carry a variety of pressure gauges, ion traps, ion mass spectrometers, and Langmuir and other electron probes that have been used to measure the density, temperature, and chemical composition of both the neutral and charged constituents. Surprisingly, most of the information on the density and temperature variations in the neutral atmosphere has come from observations of the orbital decay of the satellites rather than from measurements made with the instruments they carry. The use of space vehicles also led to the discovery of belts of energetic particles trapped in the earth's magnetic field and the knowledge that the outermost parts of this field are confined to a comet-like tail by the pressure of ionized particles streaming from the sun at great speeds (250 to 800 kilometers per second). As a result of these in situ studies, enormous advances have been made that are truly staggering when compared with the progress made in earlier years. As is often the case, the new wealth of knowledge has made possible the solution of a few of the old problems but created an even larger number of new ones. As a result, experimental study of the upper atmosphere and ionosphere by means of ground-based measurements remains an active field. Among the various techniques, radio methods

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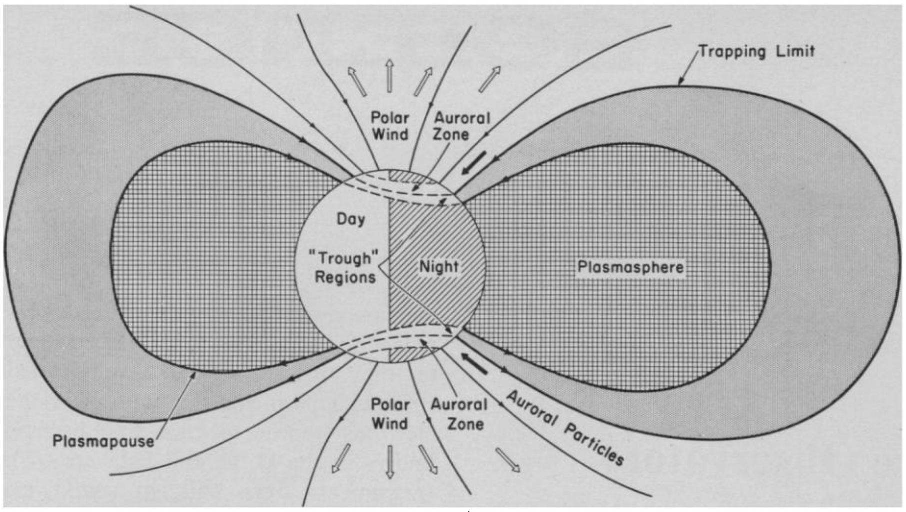

Fig. 1. Sketch showing the relationship of the plasmapause, the trough regions, and the auroral zones.

continue to be important, in large measure because of the development of additional methods of study that depend upon radio waves.

Lightweight ionosondes have been placed in satellites, and these sound from the height of the satellite (usually $\geqq$ 1000 kilometers) *down* to the peak of the F layer. The global coverage that they afford has provided a great deal of information on the behavior of the ionosphere in the polar regions and revealed the existence of hitherto unsuspected features. One of these is a trough of low electron density that forms on the night side of the earth near 60° magnetic latitude (*11*). This trough is thought to mark the boundary between two regions of the ionosphere. At mid-latitudes the ionosphere is under solar control and tightly coupled to the earth by its magnetic field. At latitudes higher than that of the trough the ionosphere is less tightly coupled and is ionized by the precipitation of energetic particles (Fig. 1).

One of the new radio methods is the study of whistling atmospherics (*12*). These are audio-frequency electromagnetic waves that appear as tones gliding from high to low frequency. They can be received on very long wire antennas and were first heard on telephone circuits. After World War II, Storey (*13*) demonstrated that these "whistlers" were produced by lightning strokes, which emit a wide spectrum of electromagnetic radiation. The low-frequency radiation in the stroke can escape through the earth's ionosphere and propagate along the earth's magnetic lines of force to the conjugate hemisphere. The propagation time varies rapidly with frequency, thus giving rise to the dispersed falling tone. Studies of whistlers have permitted the electron density to be determined out to distances of 6 radii from the earth's center (*14*), and have identified a transition from high to low density at about 4 earth radii, called the plasmapause (*15*) (Fig. 1).

The plasmapause appears to mark the boundary between magnetic field tubes that are permanently closed and filled with ionospheric plasma and field tubes that are broken or opened at intervals permitting the escape of the ionospheric plasma and the entry of plasma from interplanetary space. The plasmapause and the high-latitude ionospheric trough, discovered in the records obtained by the orbiting ionosonde, appear to be linked by the earth's magnetic field lines (*16*), (Fig. 1), and the study of this transition is one of the principal objectives of the proposed new observatory.

Incoherent Scatter

The most powerful of the new radio methods is known as incoherent scatter or Thomson scatter, and it differs from the reflection technique in that it provides information about the regions both above and below the height of peak electron density. The method was first proposed by Gordon (*17*) and demonstrated experimentally by Bowles (*18*) in 1958.

The reflection of a radio wave in the ionospheric plasma (at $f = f_N$) is a resonance phenomenon and has a first-order effect on the exploring wave. Ra-

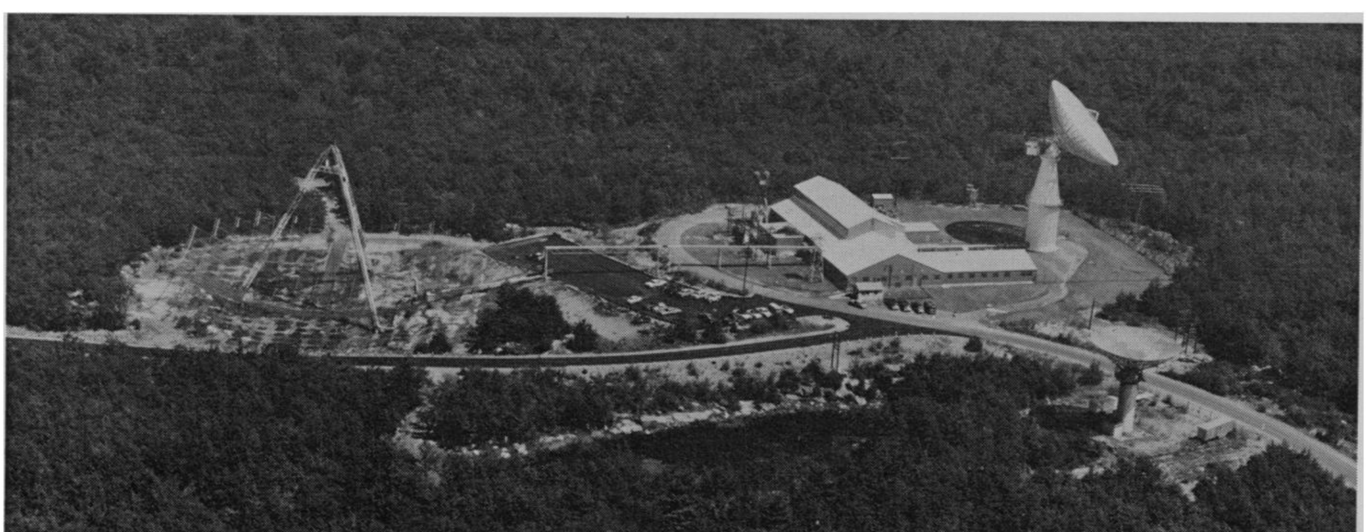
Fig. 2. Two radar systems that can be employed for incoherent-scatter studies of the ionosphere located at Millstone Hill, Westford, Massachusetts. On the left is a fixed vertically pointing antenna (68 meters in diameter) that works in conjunction with a radar (wavelength, 68 centimeters) located in the building. The larger of the two antennas at the right is a fully steerable radar (25 meters in diameter) operating at a wavelength of 23 centimeters.

Table 1. The location of existing incoherent-scatter facilities.

Facility	Location	Affiliation	Geographic		Dip latitude*	L† (200 km)
			Latitude	Longitude		
Jicamarca Radio Observatory	Peru	Geophysical Institute of Peru	11.9°S	76.0°W	1°N	1.1
Arecibo Observatory	Puerto Rico	Cornell University	18.3°N	66.75°W	30°N	1.4
St. Santin	France	Centre National d'Etudes des Telecommunications				
		Transmitter	44.65°N	2.2°E	47°N	1.9
		Receiver	47.4°N	2.1°E		
Malvern	England	Royal Radar Establishment	52.1°N	2.3°W	50°N	2.6
Randle Cliff	Maryland	Naval Research Laboratory	38.7°N	76.5°W	54°N	2.7
Millstone Hill	Massachusetts	Lincoln Laboratory, M.I.T.	42.6°N	71.5°W	57°N	3.2
College	Alaska	Stanford Research Institute and University of Alaska	64.9°N	147.7°W	65°N	5.8

* Magnetic or dip latitude is defined as arc tan (½ tan I), where I is the inclination of the earth's magnetic field or "dip angle." † The value of L is approximately given by the average geocentric distance of the magnetic shell passing through the station measured in the equatorial plane in units of earth radii.

dio waves at a frequency substantially above the critical frequency f_N can completely traverse the ionosphere. Some of the power in the wave will be scattered out if at any height there are appreciable density irregularities with a spatial scale equal to half the radio wavelength. A number of plasma instabilities appear to exist that are capable of exciting such irregularities in directions orthogonal to the earth's magnetic field. The phenomena of "spread F" and auroral echoes are thought to be two examples (*19*).

Scattering from irregularities caused by plasma instabilities is a second-order effect that disappears at frequencies of the order of several hundred megahertz and for ray directions that make an appreciable angle with the magnetic field. Under these circumstances the intensity of the density fluctuations of the correct spatial scale is set simply by the random thermal motion of the electrons and ions, and the scattering is then extremely weak. This third-order effect has been shown (*20*) to give rise to reflected signals whose intensity P_s is proportional to $N_e\sigma$, where σ is the scattering cross section of an electron for electromagnetic waves computed by Thomson (*21*), hence the name "Thomson scatter." Because the electrons are in random thermal motion, the phases of their reflected waves bear no relation to one another; that is, there is no coherence between the signals reflected by individual electrons. This circumstance has given rise to the more widely used name "incoherent scatter."

Owing to the weakness of incoherent scatter, an extremely powerful radar system is required in order to exploit the phenomenon for ionospheric studies, and such radar systems have been built in a limited number of locations listed in Table 1. The magnetic latitude of each radar is given, as well as the value of the L parameter that defines the magnetic shell on which it is located. The most powerful of these radar systems is the one at Arecibo, Puerto Rico (*22*), where the antenna is a spherical reflector [1000 feet (300 meters) in diameter] constructed in a limestone sinkhole. Somewhat similar to the radar at Arecibo, except for the antenna, is the vertically directed radar system at Millstone Hill, Massachusetts (Fig. 2). The only other radar system in North America regularly being used in incoherent-scatter studies is a smaller, fully steerable system similar to that shown in Fig. 2 that is located in Alaska.

In most of the radar systems listed in Table 1 short pulses are used to define the volume under study. The exception is the French system which employs the intersection of the transmitting and receiving beams (Table 2). This approach affords superior height resolution at low altitudes but has the drawback that only a single volume can be examined at a time. The differences in wavelength, transmitter power, antenna size, and other parameters cause the radar systems to have different sensitivities. In Table 2 an attempt is made to indicate the sensitivity of the systems relative to the first one listed (*1*).

The great strength of the incoherent-scatter technique lies in the fact that it affords one the ability to determine several properties of the ionospheric plasma simultaneously over a wide range of altitudes. This ability stems from the characteristic Doppler-broadening imparted to the signals by the particles at each altitude, which may yield information about the electron temperature T_e and ion temperature T_i, the ionic composition, the rate of collisions between ions and neutral particles, the mean drift velocity of the ions, and the existence of fast photoelectrons (*23*).

Over the altitude range of approximately 200 to 800 kilometers, collisions between ions and neutral particles are unimportant and a single ion predominates, namely, O^+. In this region the measurements yield the altitude variation of N_e, T_e, and T_i, as shown in Fig. 3. During the daytime the absorption of solar ultraviolet radiation maintains $T_e > T_i$, but at night the temperature difference usually falls to a small value. Since the measurements can be repeated at will, it is possible to construct diagrams such as those in Fig. 4 showing the altitude and time variation of these parameters.

The discovery that T_e and T_i differ in the F region stimulated a great deal of interest in the thermal structure of the ionosphere (*24*), and this in turn led to the realization that these measurements of N_e, T_e, and T_i can be used to infer the "exospheric" temperature T_∞ of the neutral particles. This is the uniform temperature attained by the neutral particles at altitudes above about 250 kilometers, and it is an important parameter in describing the state of the upper atmosphere.

Above about 800 kilometers, depending upon the latitude, the time of day, and the point in the sunspot cycle, there is a transition from O^+ ions to lighter H^+ and He^+ ions. The relative abundances of these three species can be determined from incoherent-scatter soundings at these altitudes, provided that the behavior of T_i and T_e can be inferred by extrapolating measurements made lower down. From these measurements of relative ion abundance the concentration of neutral hydrogen atoms can be determined as well as the ex-

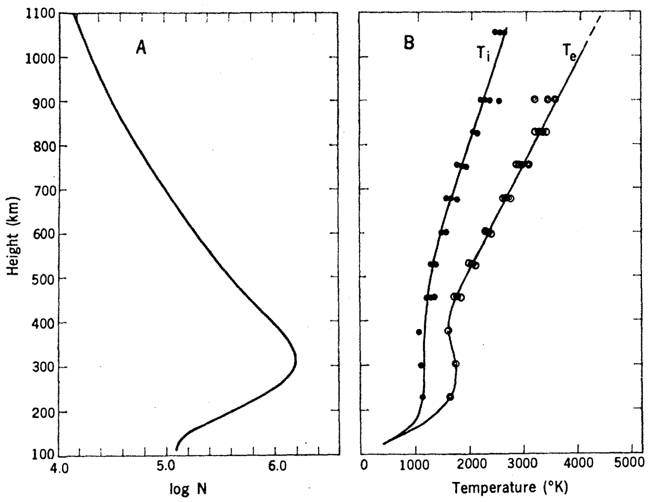

Fig. 3. Vertical profiles of (A) the electron density ($\log_{10} N$) and (B) the electron temperature T_e and ion temperature T_i in the F region obtained with the incoherent-scatter radar (wavelength, 68 centimeters) shown in Fig. 2; 24 March 1970, 1417 to 1435 E.S.T.

istence of vertical fluxes that transfer ions between the ionosphere and the region above 1000 kilometers known as the magnetosphere.

Below about 200 kilometers molecular ions such as NO^+ and O_2^+ become more abundant than O^+ ions, and measurements of the percentage of O^+ ions can yield information on seasonal variations in the relative abundance of O and N_2. At still lower altitudes (≤ 120 kilometers) collisions between ions and neutral particles become important and the character of the spectrum of the signals changes in a way that makes it possible to determine T_i (here believed to be the same as T_e and the temperature of the neutral particles) and the ion–neutral particle collision frequency ν_{in}. These parameters serve to define the temperature and density of the neutral atmosphere at these altitudes, and together with T_∞ effectively bound possible models for the upper atmosphere. Table 3 summarizes some of these capabilities of the technique (*1*).

Table 2. Parameters of existing incoherent-scatter radars.

Facility	Operating frequency (Mhz)	Type of radar	Antenna	Sensitivity relative to Jicamarca
Jicamarca	49.92	Vertical; pulsed	290-m by 290-m dipole array	1
Arecibo	430.0	Vertical; pulsed	300-m spherical reflector	8.0
St. Santin	935.0	Bistatic continuous wave; transmitter (vertical); receiver (oblique)	20-m by 100-m reflector	0.8
Malvern	400.5	Vertical; pulsed	42.5-m parabola	1.6
Randle Cliff	138.6	Oblique; pulsed	45-m parabola	0.1
Millstone I	440.0	Vertical; pulsed	68-m parabola	1.0
Millstone II	1295.0	Oblique; pulsed	25-m parabola	0.2
College	1300.0	Oblique; pulsed	25-m parabola	0.4

Table 3. Ionospheric parameters obtained from incoherent-scatter radar measurements. N_e, electron density; T_e, electron temperature; T_i, ion temperature; T_∞, exospheric temperature of the neutral particles; V_d, ion drift velocity with respect to the radar; $V_\parallel$ and $V_\perp$, drift components parallel and perpendicular to the magnetic field, respectively; E_{ph}, photoelectron energy; ν_{in}, ion–neutral species collision frequency; ν_e, the electron–neutral particle collision frequency; N(XY), number of diatomic molecules.

Altitude (km)	Directly measured	Derived quantities
< 100	N_e, ν_e (from heating experiments)	($T_i \nu_{in}$)
100–120	N_e, T_i, V_d, ν_{in}	N(XY)
120–220	N_e, T_e, T_i, V_d	$V_\parallel$ (neutral winds)
220–600	N_e, T_e, T_i, V_d	E_{ph}, T_∞, N(O), $V_\perp$ (electric fields)
< 600	N_e, T_e, T_i, V_d $O^+ \rightarrow H^+$ transition	E_{ph}, vertical fluxes of heat and ionization

Ionospheric Motions

As a result of the enormous amount of experimental and theoretical work carried out over the past decade, most of the important chemical processes involved in the workings of the upper atmosphere and ionosphere seem to have been identified. The action of solar ultraviolet radiation in the formation of the ionosphere and the removal of the ionization through charge-exchange and recombination processes seem well established (*25*). Nearly all of the major uncertainties that remain involve dynamical or transport processes, many of which are still poorly understood.

Solar ultraviolet radiation absorbed by a layer of ozone in the middle atmosphere (50 to 70 kilometers) is believed to cause tidal oscillations of the atmosphere at altitudes up to at least 200 kilometers (*26*). Several modes of oscillation seem possible, but the predominance of any single one remains to be established. The solar heating of the atmosphere above 120 kilometers is also believed to cause air motions. At F-region altitudes air is thought to move roughly along great circular paths from the most expanded and heated region on the dayside near 1400 local time to the coldest region of the atmosphere near 0400 local time. The wind speeds are of the order 100 to 200 meters per second (*27*). Other thermospheric wind systems appear to be established during magnetic storms when large amounts of energy are deposited in the auroral regions through the precipitation of energetic particles and the maintenance of large electric arcs at an altitude of about 110 kilometers. The amount of energy deposited in the auroral zones at these times is comparable with that available over the whole globe from solar ultraviolet radiation, and the manner in which it is redistributed is not understood. One mechanism for transporting the energy appears to be large surface or "gravity" waves propagating at altitudes of 100 to 200 kilometers (*28*).

The ions and electrons in the F region are thought to be driven across the magnetic lines of force by electrostatic fields. These fields are generated in the E region, where winds can force ions (but not electrons) across the magnetic field lines, or in the magnetosphere where large-scale convection of the magnetic field lines seems to occur as a result of the pressure on the magnetosphere of the solar wind particles and the solar magnetic field they carry with them. At mid-latitudes the electric field generated in the E region seems to dominate in the daytime, but in the polar regions the electric fields are believed to be of magnetospheric origin and to be capable of moving the ions horizontally with speeds comparable to the rotation of the earth.

At mid-latitudes the magnetic field tubes extending out into the magnetosphere are filled with plasma of ionospheric origin. There appears to be an upward flux of ions into the tube by day and a return flux at night. Field tubes beyond the plasmapause appear to be broken during magnetic storms, thus permitting the ionospheric plasma to escape; these field tubes then require many days to refill following their reconnection. Field lines close to the magnetic pole are thought to be permanently open and stretched into a tail on the nightside by the action of ionized particles streaming from the sun. Light ions such as H^+ and He^+ are thought to be capable of escaping from the earth along these open field tubes (*29*). This escaping stream has been termed the polar wind (Fig. 1).

The processes enumerated above are only some of the ones involved in the dynamics of the upper atmosphere where theory awaits the test of experimental investigation. Unfortunately, there are few measuring techniques for studying atmospheric motions that can yield information continuously. Herein lies the greatest potential of the incoherent-scatter method, since it can be used to determine the average drift velocity of the ions as a function of altitude and time at will.

At E-region altitudes we expect the ions to move with the same speed and direction as any neutral wind and to serve as a tracer that can be observed. Thus, the tidal oscillations of the atmosphere can be studied directly with a suitable radar. In the F region the neutral particles cannot drive ions across the field lines (except possibly at night). Instead, a neutral wind will tend to drive the ions in a direction along the field lines. Other forces acting on the ions include pressure gradients and gravity, and the diffusion velocity these should produce can be calculated given the altitude variation of N_e, T_e, and T_i. Thus, by measuring these quantities and the actual velocity $V_{\parallel}$ of the ions along the field lines, the speed of the neutral wind in the magnetic meridian plane can be determined. This measurement is best conducted for an altitude near

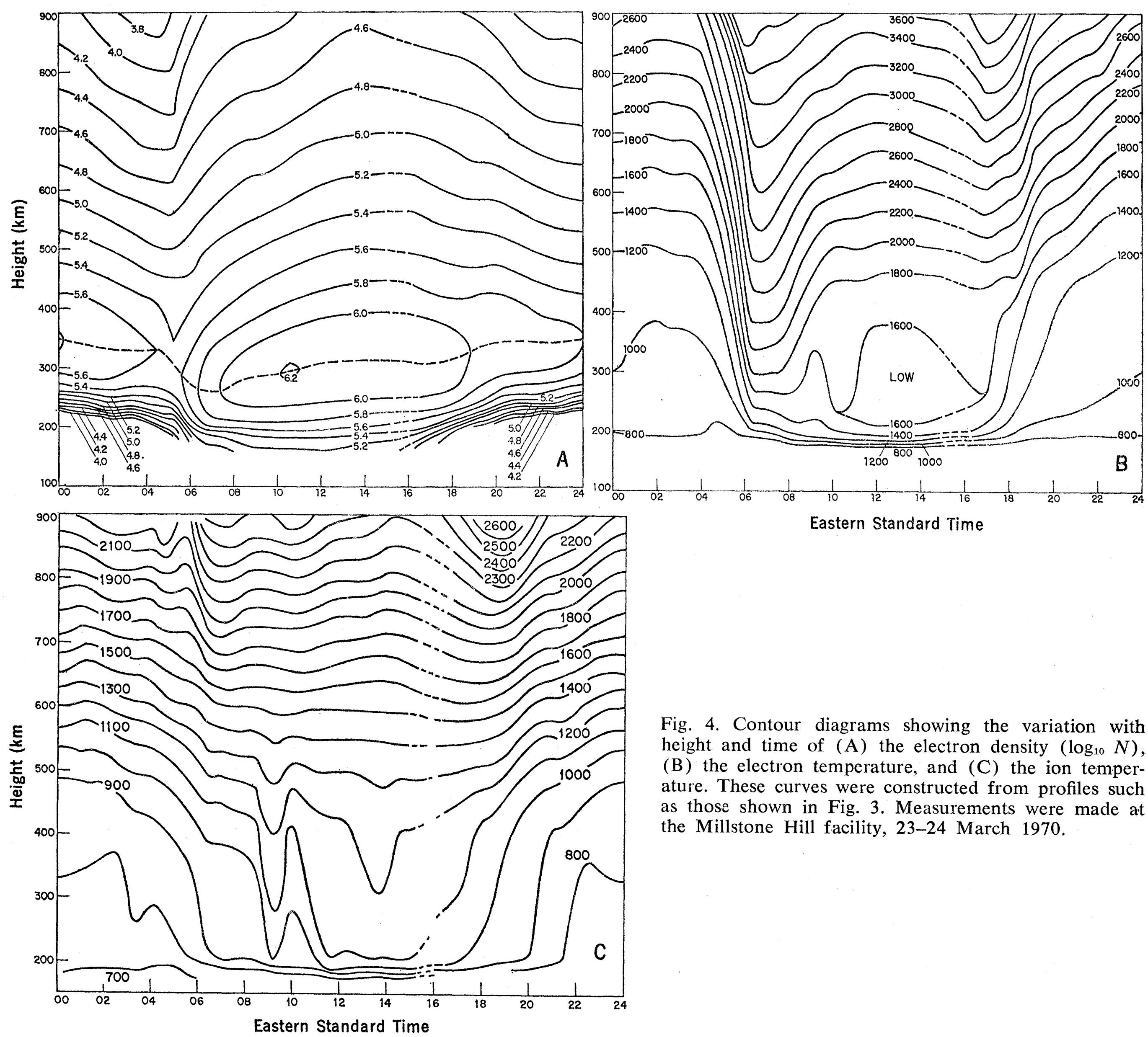

Fig. 4. Contour diagrams showing the variation with height and time of (A) the electron density ($\log_{10} N$), (B) the electron temperature, and (C) the ion temperature. These curves were constructed from profiles such as those shown in Fig. 3. Measurements were made at the Millstone Hill facility, 23–24 March 1970.

the peak of the F2 layer. By measuring the drift motion $V_\perp$ normal to the magnetic field in the F region, the magnitude of the impressed electrostatic field can be remotely monitored. This measurement is of special interest in the auroral region since it should yield information on convective processes taking place out in the magnetosphere that cannot readily be studied in any other way. These magnetospheric convective motions are thought to be responsible for energizing the particles that precipitate during auroral substorms, and other particles that are scattered into trapped orbits within the magnetic field to become the Van Allen radiation belts. The ionization fluxes into and out of the magnetosphere along magnetic field lines can also be determined by incoherent-scatter measurements of $V_{\parallel}$ at altitudes of ~ 1000 kilometers.

Evidently the incoherent-scatter technique offers great promise for tackling the outstanding problems of upper-atmosphere physics. Unfortunately, as we have seen, only a small number of incoherent-scatter radar systems exist and these have various drawbacks.

Limitations of Existing Incoherent-Scatter Radars

With the exception of the radar systems at Jicamarca and Arecibo (Table 1), all the existing systems were constructed of available transmitting, receiving, or antenna equipment. As such, their sensitivity is marginal for many of the measurements discussed above, and inadequate for the drift measurements which require a high signal-to-noise ratio. Of the radars listed, only the one at Arecibo is not seriously hampered by lack of sensitivity.

The second major limitation of the existing radar systems is that, with the exception of the radars at Randle Cliff, Millstone II, and College, they can only "view" the ionosphere overhead and hence give no information concerning latitudinal variations. In addition, they are nearly all constrained to "view" the ionosphere in a fixed direction and hence can measure only a single component of the drift velocity. At Arecibo, where the radar has both adequate sensitivity and limited capability of beam steering, it is still not possible to measure three independent components of the drift velocity simultaneously.

The last drawback of all the existing radar systems (except that at College) is that they are located at low geomagnetic latitudes. None is located near the boundary between the mid-latitude and polar ionospheres (Table 1). The radar at College should provide valuable information concerning the behavior of the ionosphere within the auroral zone, but, like most of the others, this radar is limited in sensitivity with the result that the measurements will largely be confined to the daytime.

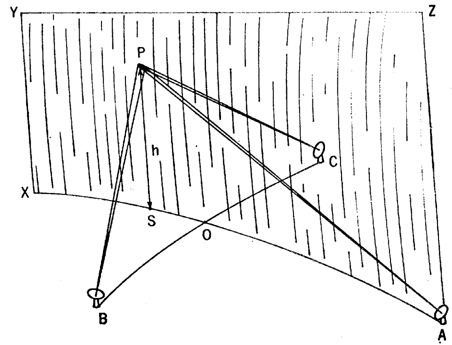

Fig. 5. Sketch showing the vertical plane $AXYZ$ in which the new radar system will be able to make measurements. The main transmitting station is located at A, and the auxiliary receiving stations are at B and C. The point S lies at a height h below the volume P under investigation; AX is directed approximately toward the magnetic north.

The idea of constructing a new incoherent-scatter radar system in North America was seriously advanced in 1966, but did not receive broad scientific support until 1969, when a panel, convened by the Geophysics Research Board of the National Research Council to consider the role of ground-based research in solar-terrestrial physics, strongly endorsed the concept (*1*). In considering the design of the new system, great importance was attached to locating the facility close to the transition between the mid-latitude and polar ionosphere so that regions on both sides of the transition could be studied (*1*). The behavior of the mid-latitude ionosphere, which has been more extensively studied than the polar ionosphere, should serve as a "control" for the measurements in the region on the polar side of the transition. Since the transition can reach as far north as $L = 7$ during particularly quiet magnetic conditions and as low as $L = 2.5$ during major magnetic storms, a compromise must be made in choosing a location for the facility. The most probable location for the plasmapause appears to be about $L \sim 3.7$, but there is a diurnal variation of as much as ± 0.5. By designing the radar so that it can explore the ionosphere in a north-south plane, some freedom to examine the region on either side of the transition would also be obtained. For example, a coverage of 1000 kilometers in the magnetic north-south direction corresponds roughly to a change in the L value of approximately ± 0.5, and hence the ability to explore regions on either side of the transition could be achieved for much of the time by a steerable radar placed near $L = 4$.

Design of the New Radar System

Supported by a National Science Foundation grant made to Professor S. A. Bowhill at the University of Illinois, a design team has now completed a preliminary engineering study (*30*) of the proposed new radar. In the remainder of this article I shall describe the design and possible location of the facility.

As discussed above, a major objective of the new incoherent-scatter radar system is the study of the dynamics of the upper atmosphere. For this purpose the new radar system will be employed to measure three orthogonal components of the ionospheric plasma motion simultaneously. This requires that the same volume of plasma be viewed in at

Table 4. Requirements for measurement of F-region drift velocity (see Table 3 for explanation of symbols).

Objective	Component observed	Expected value (msec^{-1})	Desired accuracy (msec^{-1})	Required height resolution (km)			
				V	N_e	T_e	T_i
Measure electric fields	$V_\perp$	20–200	< 10	≤ 100	≤ 100	≤ 100	≤ 100
Measure thermospheric winds	$V_{\parallel}$	0–50	< 5	≤ 50	≤ 10	≤ 50	≤ 50
Measure protonospheric fluxes	$V_{\parallel}$	0–10	< 2	~ 100	~ 100	~ 100	~ 100

least three directions, and consequently that there be three widely separated receiving stations. An additional requirement for the new facility is that it be capable of making measurements over a north-south plane with an extent of the order of 1000 kilometers. These two requirements make it necessary that the design differ considerably from that of all existing facilities.

At high latitudes, where the dip angle of the earth's magnetic field is large, the horizontal motion of F-region ionization is expected to result chiefly from the $E \times B$ drift produced by electric fields. Indeed, observations of horizontal drift will primarily be undertaken in order to measure these electric fields. Over the height range from approximately 200 to 1000 kilometers, the electrical conductivity along magnetic field lines is very high as compared with that transverse to magnetic field lines so that the impressed electric fields cannot change significantly with altitude. It follows that to determine the strength E of the impressed electric field it is only necessary to measure the drift velocity of the ions orthogonal to the magnetic field B at a single altitude. This, in turn, means that a high degree of height resolution is not required.

In the E region, electric fields can produce both transverse and Hall currents, and it is also possible for ions to be driven across the field lines by neutral winds. Owing to the rapid variation with height of the transverse and Hall conductivities, and wind speed and direction, the horizontal component of the ion drift is likely to vary rapidly with altitude. Thus, in the case of the E region, good height resolution is required, so that height intervals that are small relative to the scale height of the neutral atmosphere in this region ($\sim$ 10 to 20 kilometers) may be resolved.

The atmospheric gravity waves, which are thought to be a principal means of redistributing energy in the thermosphere, are believed to have horizontal wavelengths greater than 100 kilometers and to have phase fronts that are tilted with respect to the horizontal by no more than 5°. If the speed, wavelength, and phase-front tilt of these waves are all to be determined, then, ideally, one should observe the ion motion simultaneously at a large number of altitudes in three equidistant vertical columns separated by $\sim$ 100 kilometers.

In Table 4 the three different types of measurements expected of the F-region system are listed. The expected magnitude of the drifts are given together with the desired velocity accuracy and height resolution (*30*).

Table 5. Requirements for measurement of E-region drift velocity.

Objectives	Components observed*	Expected value (msec^{-1})	Desired accuracy (msec^{-1})	Required spatial resolution
Study gravity-wave, neutral wind, and electric field–induced plasma drifts	$V_{N\text{-}S}$	0–50	± 1	Examine $\leq$ ten heights simultaneously between 100 and 140 km
	$V_{E\text{-}W}$	0–50	± 1	$\Delta h \leq 1$ km near $h = 100$ km; $\Delta h \leq 2$ km near $h = 140$ km; examine alternately two regions separated horizontally by $\sim$ 100 km

* The observed components here are the horizontal drifts in the north-south and east-west directions.

Table 5 presents the corresponding requirements for measurements of the drift velocity in the E region (100 to 140 kilometers). It is clear from Tables 4 and 5 that the requirements for studying the E region are a good deal more complicated than those for the F region. Thus, at an early stage in the design studies, it became necessary to consider two separate measuring systems—one for the F-region and one for the E-region winds—embodying a number of common elements. The design of the F-region system was tackled first.

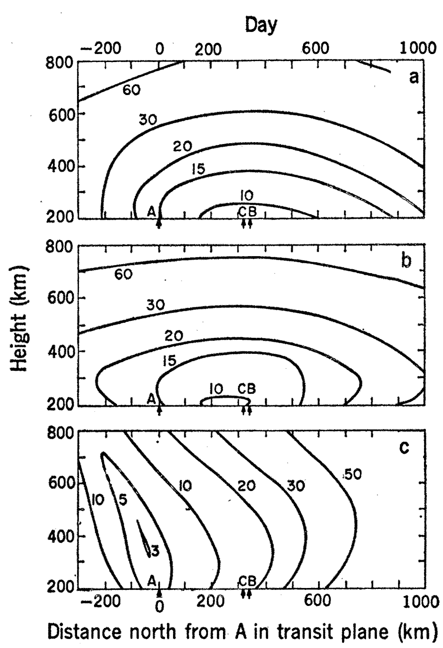

Fig. 6. Contours of constant velocity resolution versus altitude and distance in the plane *ASP* (Fig. 5) for the proposed separation between the stations when the radar parameters are as given in Table 5: (a) ΔV_x; (b) ΔV_y; (c) ΔV_z, where $V_{\parallel} = V_z$. These diagrams were computed for daytime conditions of the ionosphere near sunspot maximum, for a 10-minute observing period. The z direction is along the magnetic field; x and y are orthogonal in the south and east directions, respectively.

As illustrated in Fig. 5, the proposed F-region system consists of three stations arranged approximately at the corners of an isosceles triangle. Only one of these stations (the main station at A) is capable of transmitting and receiving. The auxiliary stations at B and C are receiving stations.

It is proposed that the main station employ an antenna with a circular pencil beam that can be tilted in the meridian plane over $\pm$ 85° from the zenith. In most cases, the signals will be transmitted with one sense of circular polarization. This antenna can be built, at least cost and with least technical risk, as a transit parabola. In order to secure adequate sensitivity to explore regions above 1000 kilometers where the O^+/H^+ transition should occur, and to make measurements substantially below 100 kilometers (that is, in the D region) where the electron density becomes low, a power-aperture product comparable to that of the existing Arecibo instrument is required. This requirement will be achieved by employing a reflector antenna with a diameter of 100 meters in conjunction with a transmitter of 5- or 10-megawatt peak power. The main station will be capable of operating independently and can, for example, study the F-region electron density and temperatures at an altitude of 300 kilometers over $\sim \pm$ 13° of latitude.

The two auxiliary receiving stations (at B and C) are needed so that three components of the ion drift velocity at a given point can be determined. It is proposed that a smaller, fully steerable antenna be placed at each of the two auxiliary stations; these would provide pencil beams that could be made to intersect the beam from the main station. Precise matching between the widths of the beams for the three antennas will be possible over only a limited portion of the sky and does not appear to be necessary from the sensitivity standpoint, provided that the auxiliary antennas have collecting areas of $\gtrsim 10^3$ square meters. It has been decided to use antennas with diameters of 46 meters, because designs are available for this size of instrument and the cost of larger ones does not seem wholly justified. Table 6 summarizes those design parameters that appear necessary in order to conduct F-region measurements.

For measurements of the vertical structure of the ionosphere (electron density, electron and ion temperature, ion composition, and vertical fluxes) one can collect the best data by means of monostatic radar measurements (that is, using the main station by itself) with the beam directed along the magnetic field lines. This suggests that the beam of the main station should be oriented to lie in the plane of the magnetic rather than the geographic meridian, although an angle between the magnetic meridian and the plane containing the radar beam of up to 10° could probably be tolerated.

By making observations over a number of fixed elevations (say, 20), the electron density and temperature behavior of the F-region forward of the radar over a region 1000 kilometers high and 1000 kilometers in north-south extent could be determined in the course of about 1 to 2 hours. By restricting the range of heights and latitudes, this time resolution could be improved.

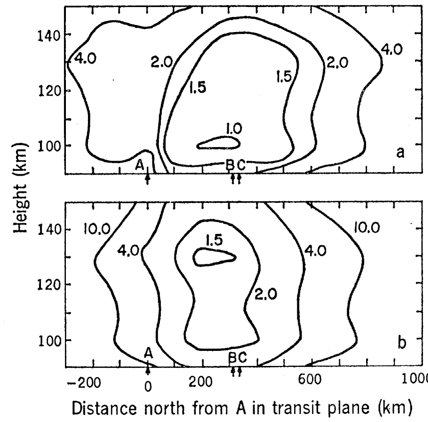

Fig. 7. (a) The north-south velocity resolution (ΔV_{N-S}) achieved with the proposed E-region winds system (Table 7) and (b) the east-west resolution (ΔV_{E-W}) when both auxiliary antennas are employed to view the same altitudes simultaneously. The calculations apply to midday ionosphere conditions near sunspot maximum with a 10-minute observing period.

In order to determine the electric fields as a function of latitude, it is necessary to obtain three independent components of the drift velocity in the F region at a single altitude. Accordingly, the best procedure will be to direct the beams of the auxiliary antennas to intersect the transmitting beam near the peak of the F layer—say, at an altitude of 300 kilometers. As the main beam is moved, the remote beams will be moved to follow.

It is evident that the radar system will be employed in a wide variety of different modes depending upon the objectives of the experiment. These require flexibility in the way in which the transmitter can be operated as well as in the data-handling equipment. In order to permit a rapid changeover between experiments as well as unlimited freedom to design new ones, it is highly desirable that all the equipment be controlled by the digital computer at the main site.

During the design studies considerable effort was devoted to finding the best spacing for the three stations. The sensitivity to horizontal drifts increases with greater spacing, but the echo intensity decreases. Not unsurprisingly, the best separation appears to be about equal to the height under study. The separation of the auxiliary stations *BC* was set at 400 to 500 kilometers and the distance *OA* (Fig. 5) was chosen as 300 to 350 kilometers.

On the basis of these separations and the equipment parameters that are listed in Table 6, the accuracy of determining the drift velocity along the magnetic field (z direction) and perpendicular in the south (x) and east (y) directions was calculated for a number of models for the ionospheric density and temperature. Figure 6 shows contours of the accuracy achieved in these three directions for daytime conditions near sunspot maximum during a 10-minute observing period. At night, when the electron density is lower, the accuracy is about half as good but still adequate for most purposes, and some improvement is possible if a number of measurements are averaged.

It is expected that the vertical motion of the ions in the E region will be small in comparison to the horizontal motion, and hence the E-region system need only be capable of measuring the horizontal component of the drift velocity as a function of height h (Table 5). In order to obtain the variation of velocity with altitude, it is necessary that simultaneous measurements of the horizontal drift be made at ten or more points spaced between 100 and 140 kilometers. The height resolution Δh required is about 1 kilometer at the lower end of this interval, but may be relaxed to 2 kilometers at the upper end. A velocity resolution of 1 meter per second after a 10-minute observing period is also desired. Since the main

Table 6. Elements of the system for measurements in the F region.

Element	Characteristics
Transmitter	Frequency, ~ 430 Mhz Peak power, 5 Mw (minimum) Average power, 300 kw (minimum) Pulse length, ~ 10 μsec to 2 msec (variable) Pulse repetition frequency, ≤ 1 khz (variable)
Main antenna	Transit parabolic reflector (± 85° zenith distance coverage) Diameter, 100 m Effective collecting area, ~ 4 × 10^3 m^2 Beamwidth, 0.5° (0.01 radian)
Auxiliary antennas (two)	Fully steerable parabolic reflector Diameter, 46 m Effective collecting area, ~ 850 m^2 Beamwidth, 1.0° (0.02 radian)
Receivers	Low-noise superheterodyne (system temperature ≤ 200°K)
Data processing	Digital preprocessors and general-purpose computer
Intersite coupling	Telephone lines

Table 7. Elements of the system for the measurement of the E-region winds system.

Element	Characteristics
Transmitter	As for the F-region system (Table 6)
Main antenna	As for the F-region system (Table 6)
Auxiliary antennas (two)	Forms ten pencil beams 1° wide over a 10° field; collecting area per beam, ~ 10^3 m^2; beams can be moved to view the main antenna beam at 20° or 30° elevation
Receivers	Low-noise superheterodyne (system temperature ≤ 200°K); one per beam
Data processing	Digital preprocessors (one per beam) and general-purpose computer
Intersite coupling	As for the F-region system (Table 6)

F-region transmitting station can illuminate points only in a north-south plane, it is clearly not possible to explore the gravity-wave structure in three directions. Thus, the measurements are to be made alternately at two points spaced about 100 kilometers apart (see Table 5).

After exploring a number of possible arrangements, it was concluded that the cheapest and best way of making the drift measurements in the E region (Table 5) was to employ the same three antennas that will be used for studying the F region, as described above. To examine two regions ~ 100 kilometers apart, the main antenna beam will be placed alternately at elevations of 30° to 20°. The auxiliary antennas will be modified to produce a fan of ten adjacent beams lying in a plane. The orientation of the plane will be adjustable so that all ten of the beams can be made to intersect the main beam at once. In this way, an adequate collecting area for the auxiliary antenna can be achieved over the desired height range.

In order to obtain adequate height resolution for the main station measurements, short pulses must be transmitted. To increase the energy in the pulses, use will be made of a coding scheme that permits a long pulse to be transmitted and then compressed on reception to yield the equivalent of a shorter, higher-power pulse. The drift velocity can then be determined by transmitting pairs of these pulses and determining the average phase difference between the two on reception. In order to remove the mutual interference between the echoes produced by these pulses, it is necessary to transmit them with opposite senses of circular polarization and to receive them separately. Table 7 summarizes the radar requirements necessary to achieve measurements of the drift velocity in the E region to the degree detailed in Table 5. Figure 7 shows the accuracy that the system can achieve during the day near sunspot maximum.

It would be out of place here to describe in detail the engineering design of the components of the radar system. An artist's sketch of the main station antenna is shown in Fig. 8. The capital cost of this instrument is estimated to be \$3 million, and that of the entire facility, \$13 to \$14 million. It is expected that the time required to complete the design of the facility, construct the radar, and bring it into operation is 4 years.

Location and Operation of the Facility

As we have seen, the power of the incoherent-scatter technique rests in its ability to measure many independent quantities of aeronomic interest simultaneously and, in particular, to provide information on the dynamics of the upper atmosphere and ionosphere. The newly proposed instrument has been designed to exploit this last capability to the fullest. The design also reflects the scientific importance attached to a location near the transition between the mid-latitude and polar regions of the ionosphere near $L = 4$.

Figure 9 shows contours of shells with constant L values for an altitude of 300 kilometers. It can be seen that $L = 4$ is inaccessible from land in the Southern Hemisphere. In the Northern Hemisphere $L = 4$ crosses Siberia and Scandinavia and reaches its lowest geographic latitude near the 80°W meridian where it lies close to the U.S.–Canadian border.

A final decision on the three sites needed for the observatory remains to be made. A preliminary site search has been conducted with the view to satisfying certain scientific, engineeering, and administrative criteria. The principal

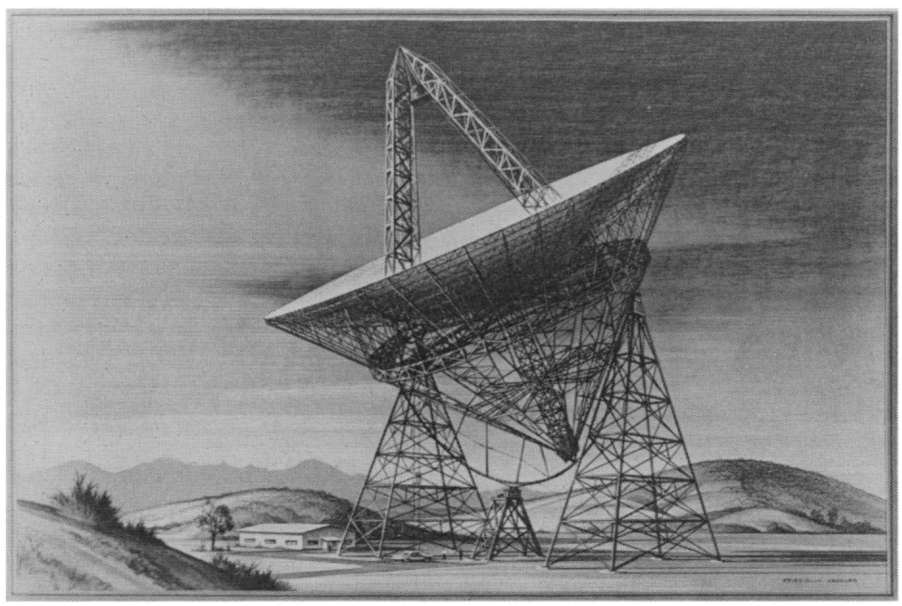

Fig. 8. An artist's drawing of the transit antenna (diameter, 100 meters) to be employed at the main transmitting station.

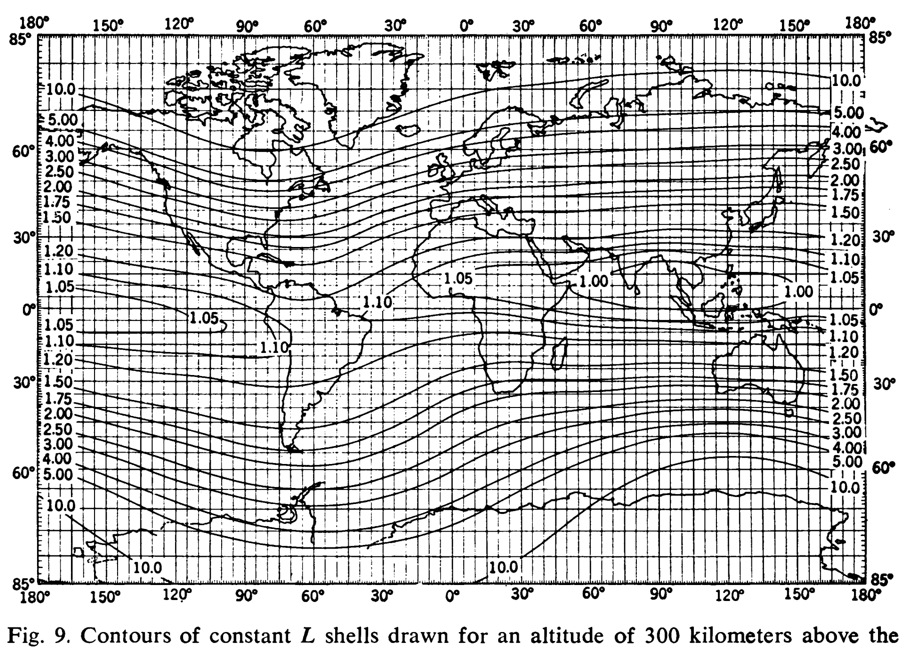

Fig. 9. Contours of constant L shells drawn for an altitude of 300 kilometers above the ground.

scientific criterion—that of the magnetic latitude—has been discussed above. This can be satisfied east of the Great Lakes by stations that straddle the U.S.–Canadian border, or possibly west of the Great Lakes by a group of stations wholly within northern Minnesota. The other scientific requirements are the need for good seeing conditions for optical (airglow and auroral) observations and the possibility of locating a rocket range close to the facility capable of launching small rockets to E-region altitudes (~ 120 kilometers).

Among the engineering criteria, the most important is freedom from radio interference. For the auxiliary antennas the most potent source of interference will be the main transmitter itself, and careful siting will be necessary to achieve adequate isolation between the two. It appears that this can best be accomplished if the main station is located in a valley where the local horizon screens from view more distant mountains that could act as diffracting edges and scatter signals to the auxiliary stations. This condition appears very difficult to meet in northern Minnesota, but can be readily satisfied in upper New York State.

The administrative criteria that have been considered include the need for good communications to a nearby large town that can serve as administrative center and provide attractive living conditions for the observatory staff and visitors. It is also regarded as desirable to locate the main station of the observatory near a large university. Of course, many of these administrative and other criteria tend to be contradictory, and some compromise must be made. One satisfactory arrangement for the sites that has been found is to place the main station in northern New York and the auxiliary stations in the provinces of Quebec and Ontario, Canada, but other arrangements may exist that are as good or better.

After the completion of the preliminary design and site survey described above (*30*) in June 1971, a consortium, called the Upper Atmosphere Research Corporation (UARC), was formed to perform the final design work and to construct and operate the observatory. Presently UARC consists of the following seven cooperating universities: Massachusetts Institute of Technology, Pennsylvania State University, Rice University, the University of California, the University of Illinois, the University of Pittsburgh, and the University of Western Ontario, Canada. Each cooperating university nominates two trustees, one of whom must be a senior administrator and the other a scientist actively working in the field. At their first meeting the trustees chose W. E. Gordon, dean of engineering and science at Rice University, as UARC chairman.

In considering how the observatory will be organized and operated, the most frequently cited model is the National Radio Astronomy Observatory (NRAO) at Greenbank, West Virginia. The new observatory, however, will be a binational one serving scientists in Canada and the United States. These two countries already have a long history of cooperation in ionosphere physics and studies of the upper atmosphere which has involved the joint use of the rocket range at Fort Churchill (on Hudson Bay in Manitoba, at about 57.5°N, 94°W), and the construction and launching of the extremely successful Alouette and ISIS satellites. To encourage wide participation in the use of the new facility when built, the UARC board of trustees has published a statement of policy (*31*) making the facilities available to all investigators regardless of institutional affiliation, subject only to the suitability of the instrumentation for the proposed research.

A number of administrative matters remain to be worked out. For example, it is intended that special links be established with the government agencies or departments working in this field. In Canada these are the National Research Council and the Communications Research Centre and in the United States the National Oceanic and Atmospheric Administration. Means must be found by which the Canadian and U.S. funds can be spent in a coordinated way in building and operating an observatory that straddles national borders. A mechanism for planning the observatory schedule to the satisfaction of the users must be developed. However, these problems appear small at present when compared to the major one now facing UARC, namely, that of obtaining a commitment from the two governments concerned to build the observatory.

Summary

A proposal has been developed to build a ground-based, upper-atmosphere observatory where, for the first time, measurements could be made of essentially all the parameters believed to be important in the upper atmosphere. Measurements would be made up to an altitude of 1000 kilometers and over a north-south extent of over 1000 kilometers. The Upper Atmosphere Observatory would be built and operated by U.S. and Canadian scientists who have a tradition of successful cooperation in this field. The planned location (near magnetic latitude 60°) close to the U.S.–Canadian border would afford the users the special opportunity of observing two distinct parts of the upper atmosphere and the transition between them, one part tightly coupled to the rotating earth by the magnetic field, and the second part loosely held and subject to particle bombardment from outside the earth. Practical applications of the observatory include long-distance radio communication, long-range weather prediction, and international cooperation in research and education. The new observatory will represent a significant major facility, but its cost (about $14 million) is a small fraction of most satellite programs or the Global Atmospheric Research Program, both of which the Upper Atmosphere Observatory will complement.

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32. The work of developing the proposal outlined in this article was performed by a series of ad hoc committees chaired by Prof. W. E. Gordon, Rice University. In the reports that constitute (*1*) and (*30*) are listed the names of all who contributed to the studies, which were supported by the National Academy of Sciences and by the National Science Foundation under grant GA-27447. I thank S. A. Bowhill and W. E. Gordon for critical comments on the manuscript.

Bioelectric Control of Ciliary Activity

Locomotion in the ciliated protozoa is regulated by membrane-limited calcium fluxes.

Roger Eckert

Recent findings offer compelling evidence that membrane-regulated changes in the concentration of intracellular calcium ions control ciliary activity and, thereby, the locomotion of ciliated protozoa such as *Paramecium*. The relations between membrane function and ciliary activity appear to be as follows: The intracellular concentration of free calcium ions (Ca^{2+}) is maintained far below the extracellular concentration. An increase in the intracellular Ca^{2+} concentration produces a shift in the direction of ciliary beating along with an increase in frequency. In the absence of stimulation the Ca^{2+} which slowly leaks into the cell is pumped out at a similar rate to maintain a steady state. Depolarization increases the Ca^{2+} conductance of the membrane, permitting a strong influx of extracellular Ca^{2+}. As a consequence, the Ca^{2+} in the cell cortex reaches a concentration sufficient to activate a shift in the direction of the effective stroke as well as an increase in the frequency of beating. This causes the ciliate to swim backward. Thus, the cell membrane in responding to environmental stimuli with altered conductances and potentials controls the ciliary apparatus by regulating the rate at which Ca^{2+} leaks into the cell.

The electrical properties of the ciliate membrane are of interest for several reasons. Besides providing a relatively complete mechanistic picture of integrated locomotor behavior, recent technical advances in this area have opened the way for some novel approaches to the investigation of membrane function. In one such approach, use is made of a mutant of *Paramecium* in which electric properties of the cell membrane have been genetically altered (*1*).

Membrane Potential and Ciliary Activity

A relationship between ciliary activity and electric current is evident in the galvanotaxis of *Paramecium* (*2*). When a current is passed through the medium in which a *Paramecium* is grown, the cilia on the side of the cell facing the anode increase their frequency of beating. The cilia on the cathodal side beat in reverse if the current is strong enough. The result of such differential ciliary activity is that the paramecium swings around so that the anterior end points toward the cathode, and then swims, with servo correction of its orientation, toward the cathode. At currents sufficiently strong to produce reversal over more than half the surface from the fore end back, migration is toward the anode. Jahn (*3*) has suggested that paramecia act as core conductors, since the cell membrane provides a large resistance compared to the cytoplasm and the surrounding volume conductor of pond water. Although Jahn chose to stress electrophoretic migration of Ca^{2+} in the applied field, it now appears to be the local potential difference across the cell membrane produced by the applied current which is the basis of the galvanotaxis. Thus, the membrane on the side facing the anode is somewhat hyperpolarized by inward electrotonic current while the membrane facing the cathode is somewhat depolarized by outward electrotonic current. As noted below, depolarization elicits ciliary reversal and hyperpolarization elicits an increased frequency of beating in the "normal" direction.

The importance of membrane potential in the control of ciliary activity has become evident from the work on *Paramecium* and *Opalina* at Tokyo University (*4, 5*), and more recently from our laboratory at the University of California, Los Angeles (*6–8*). It has been demonstrated by means of intracellular recording and stimulating techniques that depolarization and hyperpolarization are both accompanied by an increase in the frequency of ciliary beat-

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