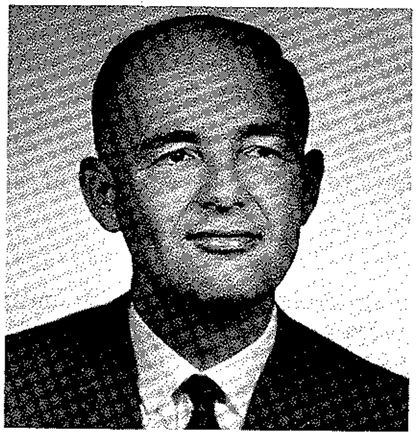
ROBERT A. HELLIWELL



"The antarctic is unparalleled as a scientific laboratory for the study of the upper atmosphere. Its geographic location, its freedom from many of the limitations of civilization and the spirit of international cooperation fostered by the Antarctic Treaty combine to make this forbidding continent unique in the history of science." Robert A. Helliwell, one of pioneer investigators of upper atmosphere phenomena in the antarctic program, is professor of electrical engineering at the Stanford Electronics Laboratories. He has served as a consultant to the National Bureau of Standards and the National Aeronautics & Space Administration.

The Upper Atmosphere as Seen from Antarctica

Study of the earth's atmosphere has long been motivated not only by the desire for more knowledge but also by practical applications, such as long distance radio communication via the ionosphere. In recent years additional practical problems such as air pollution and space radiation have been added to the list of those problems requiring more fundamental knowledge of atmospheric processes. For example, we are uneasy about the effect of pollution-stimulated changes in the composition of the lower atmosphere on the amount of ozone in the upper atmosphere. It is this ozone that absorbs deadly ultraviolet light before it can damage living organisms on the earth.

Led by the International Geophysical Year and the space program, the last decade has seen a remarkable expansion of our knowledge of the upper atmosphere and solar-terrestrial relations. We now have a much clearer picture of the ways in which the sun deposits energy in the atmosphere and the resulting response of the atmosphere to this input. With clarification of this picture has come a better appreciation of its extreme complexity and of the many questions that remain to be answered.

In all of this research, the importance and relationship of contributions from both the arctic and antarctic have come to be recognized. It is now clear that both polar regions will play an essential role in future research on the upper atmosphere.

One of the important energy inputs to the upper atmosphere is sunlight, which breaks down and ionizes the neutral particles of the air. As time passes the sunlit regions of the upper atmosphere eventually move into the shadow of the earth; there the ions tend to recombine to form neutral particles again. At middle and low latitude this sequence of events sets up a strong, 24-hour variation in the density of electrons in the ionosphere (60 to 1,000 km altitude). However, as we approach the poles an important change occurs. Because of the tilt of the earth's axis with respect to the plane of the earth's orbit about the sun, the seasonal effects, which are relatively small at low latitudes, begin to dominate the picture. At the poles there is one "day" and one "night," each six months long. Above 66.5° latitude and at the June and December solstices one end of the earth is entirely in darkness while the other is entirely in sunlight. Hence, as we would expect, there are marked changes in the temporal variations of the upper atmosphere with latitude. However, the observed changes often are as hard to explain as they are easy to detect. For example, the ionization at the south geographic pole not only does not disappear during the polar night, but shows a diurnal variation. Explaining this apparent anomaly will be one of the tasks of future research.

Superimposed on the effects of direct solar radiation (solar ultraviolet and x-rays) are other quite different effects that are connected with the earth's magnetic field. Like the ends of a giant bar magnet the polar regions of the earth draw in the lines of force of this field. Charged particles injected into this field from outside tend to be funneled into the polar regions. These particles, consisting mainly of electrons and protons covering a wide range of energies, may originate in the sun (the solar wind), the galaxy or the atmosphere of the earth. The fact that they have an electric charge causes them to travel in curved orbits, often tightly wrapped around a field line in the form of a spiral. Some of these particles are caught between "magnetic mirror" points in the earth's field, forming the Van Allen radiation belts of the magnetosphere. Others simply plow into the relatively dense lower regions of the ionosphere where they give up their energy in the form of ionization, heat and light (the aurorae).

These magnetically guided particles can produce important effects, such as ionization and radiation, in the polar regions. In fact, they are the dominant energy input to the auroral zone at night. Only recently (since the IGY), and with the aid of satellites, has the full range of fascinating phenomena connected with energetic particles in the polar regions been accessible to direct observation. Results of these new observations show the importance of coordinated ground and space vehicle measurements in the polar regions; they suggest that with improved understanding we can design ground-based experiments to do at least some of the work now done by satellites. They also show ways in which the polar magnetosphere can be used as a vast natural plasma physics laboratory in which experiments not possible on the ground can be performed.

ANTARCTIC vs. ARCTIC

It might be concluded that the upper atmospheres over the arctic and antarctic are alike except for the alternation of the seasons. It might then be further concluded that measurements made only in one hemisphere would suffice to study and monitor all high-latitude upper atmospheric phenomena. How convenient this would be. Many scientifically interesting locations in the arctic are accessible on a year-round basis and at far less cost than in the antarctic. Data show that there is indeed a close correspondence between the two polar regions for corresponding seasons. However, there are many surprising differences that must be explained if we are to reach a proper understanding of sun-earth interactions. For this reason alone it is necessary that research on the upper atmosphere be conducted in both the arctic and the antarctic. As we shall see, there are other factors that also attract us to Antarctica for upper atmosphere research.

The differences between the two polar regions with respect to upper atmosphere research can be classified as phenomenological, environmental or logistical. Phenomenological differences include (1) local effects that ought to be the same in the two polar regions and are not, and (2) the so-called conjugate-point phenomena. An example of the latter is the simultaneous observation of auroras at opposite ends of a field line. Sometimes conjugate auroras are the same and sometimes not, but the connections are not yet understood. It is therefore necessary to make observations at both ends of the path.

WHISTLERS

Environmental differences include both natural and man-made factors. In the study of whistlers and very-low-frequency (VLF) emissions, for example, the local atmospheric radio noise level in Antarctica is unusually low, thus enhancing the detectability of these phenomena. (A whistler is a VLF radio wave (1 to 30 kilohertz) excited by the electromagnetic impulse from a lightning stroke — often in the opposite hemisphere.) Furthermore, the lightning sources of whistlers observed in the Eights and Palmer Peninsula areas are unusually plentiful, because the conjugate area (in the northern hemisphere) is a region of high thunderstorm activity. Controlled experiments involving VLF whistler-mode transmissions are facilitated by the thick ice-cap of Antarctica which serves as a low-loss support for a long horizontal transmitting antenna. Furthermore, many scientifically desirable locations in Antarctica have readily accessible conjugate points in North America. This fact also serves to make existing VLF communication stations in North America useful in studies of artificially-stimulated VLF emissions.

Other environmental differences are associated with geographical features. The antarctic continent not only includes the south geographic pole, but it also includes a wide range of geomagnetic latitudes from the geomagnetic pole northward to 50° invariant latitude. Thus, it is possible in Antarctica to cover the south polar cap, the southern auroral and the subauroral zones. The location of the antarctic continent with respect to the earth's magnetic field fortuitously provides almost the maximum possible difference (~ 12°) between geographic and geomagnetic latitudes over a wide range of latitudes. Thus, the effects of high geographic latitude (long nights or days) can be blended with magnetic field effects of lower geomagnetic latitude. For example, at Eights Station during certain parts of the year one can observe mid-latitude geomagnetically-controlled phenomena while the station is dark or sunlit 24 hours a day.

Logistically, many locations in the arctic are not suitable for year-round occupancy because of the uncertain availability of a permanent solid surface for a station. Thus, the north pole is not suitable for continuous observations whereas the south pole is. Maintenance of a fixed network of stations for synoptic studies is often more practical in the antarctic than in the arctic. There are, admittedly, certain disadvantages of manned stations in the antarctic, such as isolation, low temperatures, support cost and delay in receiving recorded data. These problems may be reduced in the future by the introduction of unmanned automatic observatories capable of transmitting data back to home base via communication satellite.

GROUND vs. SATELLITE

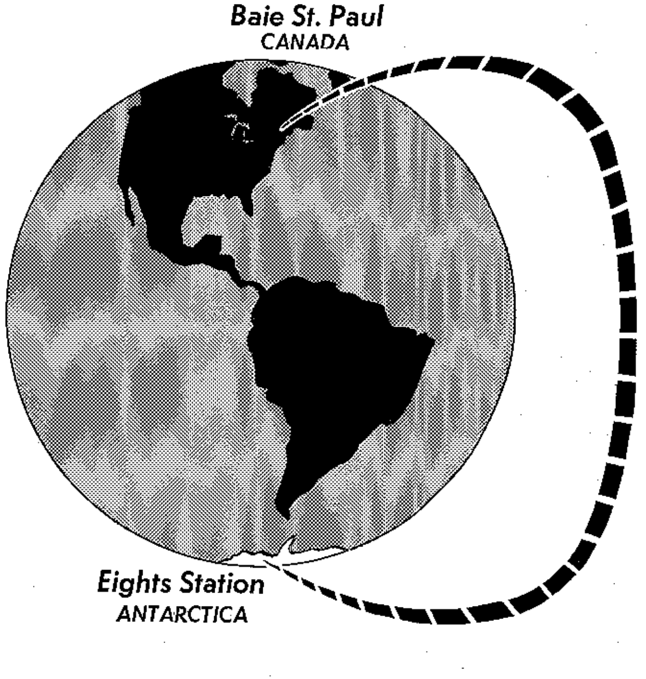
Because of their ability to scan large geographical areas, satellites might appear capable of replacing networks of ground observatories. This is not the case because of an essential difference between the two. Satellites (with the exception of a synchronous satellite at a geocentric distance of 6.6 earth radii) move rapidly (7 kilometers per second for low altitude circular orbits) in an earth-based coordinate system, providing detailed data on spatial variations. It is true that to duplicate this feat from the ground would in many cases be impossible because of the localized nature of the satellite measurements. On the other hand, since the satellite cannot be made to stand still, there is often an ambiguity in the data resulting from the mixture of temporal and spatial variations. Sometimes this ambiguity can be resolved using the satellite data alone, by comparing results from different spacecraft or from successive orbits of the same spacecraft (90 minutes or more between data samples). More often the time changes are too fast or complex to be followed in this way. Then a continuous observation from the ground is essential to establish the time dependence.

In the short time since the IGY, Antarctica has already made many contributions to studies of the ionosphere, magnetosphere, geomagnetism and solar cosmic rays.

The ionosphere is the region between altitudes of 40 and 1,000 km, in which most of the upper atmosphere chemistry and ionization phenomena are centered. It interacts both with the lower atmosphere (e.g., gravity waves) and with the magnetosphere through electric and magnetic fields and particle fluxes. The ionosphere is usually divided into three regions: the D-region, 40 to 90 km; the E-region, 90 to 130 km; and the F-region, 130 to 1,000 km. In general, as height increases, the ionization density increases (up to about 300 km) and the collision frequency decreases. These quantities are important in the refraction and attenuation of radio waves. It is the ionosphere that gave birth, over half a century ago, to long distance radio communication. Even now, after the introduction of world-wide satellite communication circuits, the ionosphere continues to play a vital role in radio communication and navigation systems. Furthermore, it is a vital link in the complex and as yet incompletely understood relationship between the sun and the earth's atmosphere.

The D-region is ionized by energetic particle bombardment as well as by direct solar radiation. Particles may arrive in dense streams of relatively low energy particles which are associated with geomagnetic and auroral activity. They are found in and outside the auroral zone. Another type of corpuscular bombardment is a flux of high energy particles — solar protons, 30 to 1,000 million electron volts (mev) — which causes polar-cap absorption (PCA) at relatively low altitudes. Particle events can be detected by a riometer, an instrument for measuring the relative absorption of high-frequency galactic radiation. Another method for detecting the low-altitude ionization caused by particle bombardment is forward-scatter propagation, in which high-frequency waves scattered from below the E-region are attenuated by absorption at lower altitudes.

In riometer data from the south pole there is a diurnal variation of absorption activity with two peaks, one occurring just before magnetic midnight and the other just before magnetic noon. No seasonal variation of the diurnal variation is found. Energetic particle activity controlled by the earth's magnetic field is thought to be involved. Data from conjugate stations (e.g., south pole and Frobisher Bay) show differences in absorption that undergo seasonal and diurnal changes. Differences of a few minutes in the times of appearance of events at conjugate stations suggest that auroral absorption may be connected with a hydromagnetic wave. Another important result is that the absorption tends to be greater in winter, when the station is nearer the tail of the magnetosphere. Movement of the conjugate points and hemispheric asymmetries related to the source of the absorption



Conjugate points in the northern and southern hemisphere are joined by magnetic lines of force.

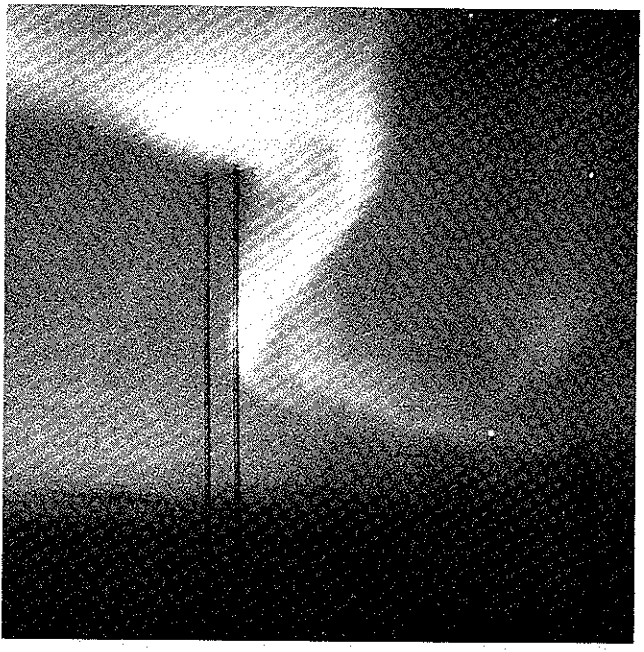


Fig. 1. An aurora photographed at Byrd Station with forward-scatter antenna towers silhouetted in foreground. (Courtesy W. Burtis.)

are thought to be connected with the differences in absorption observed between conjugate points.

Comparison of polar-cap absorption as measured from the ground with the solar-proton flux as measured by a satellite suggests that spatial variations can account for the enhancements observed both on the ground and by the satellite. These variations could be produced by the earth rotating under a pattern of precipitation or by the motion of the polar-cap field lines. There is some evidence to support the idea that field lines in the polar-cap regions may connect directly with the interplanetary field, causing asymmetry in the flux of protons reaching the two polar caps.

Like the D-region, the E-region is subject to both solar radiation and energetic particle bombardment. In addition to the normal solar-controlled E-layer, there is an enhancement of electron density at night which is caused by corpuscular radiation. By far the most dramatic aspect of the polar E-region is the colorful, dynamic aurora (Fig. 1). Auroras can be found all the way from 90 to 1,000 km, but appear most commonly between 90 and 120 km. Most of the light comes from the excitation of oxygen and nitrogen by electrons of around 10 kilo electron volt energy. Auroras at conjugate points often appear similar, but detailed studies indicate that significant differences can exist, probably reflecting the influence of local factors. The two auroral zones have different shapes and sizes, indicating important asymmetries in the earth's magnetic field. Recent studies have shown that auroral phenomena actually occur in an oval-shaped region which is eccentric with respect to the dipole poles. The auroral zone is simply the region of the oval where active auroras are most common.

For the F2-region, data from the south pole show that there is a 24-hour variation in electron density. Furthermore, F2-region ionization is somehow maintained through the antarctic winter. In fact, F2-ionization inside the auroral zone is mainly under Universal Time (UT) control, reaching a maximum at 0600 to 0700 UT. This leads to obvious anomalies. At Byrd Station, for example, the critical frequency in winter is a minimum near local noon and a maximum near midnight. These results show that in winter there is a major ionization input to the polar-cap region near 0600 UT. This source competes with photoionization in summer.

The source of the winter ionization is not yet known. It may involve horizontal transport of F2-ionization from middle latitudes driven by electric fields in the E-region. Diffusion of ionization along magnetospheric lines of force from the opposite hemisphere may also play an important role.

Another remarkable feature of the antarctic F2-region is that when the summer and winter diurnal variations of peak electron density are very different, the transition between them occurs suddenly (over the space of a few days) and at different dates at different stations. There is some evidence that this sudden change, involving an abrupt decrease in electron density, is associated with the onset of a polar stratospheric warming event. As yet there is no accepted explanation of this association. It has been suggested that the warming event causes an increase in molecular concentration at F2-heights which, in turn, increases the recombination coefficient, thus causing a lowering of the electron density. Clearly the behavior of the F2-region is complex and the influence of both the magnetosphere and the lower atmosphere must be considered in its further study.

BETWEEN THE HEMISPHERES

We now turn to the magnetosphere (Fig. 2), which extends from an altitude of 1,000 km out to the magnetopause (about 10 earth radii in the solar direction). Here the constituents are mainly protons and electrons that are bound to the magnetic lines of force. Below the auroral zones these lines tend to be "closed," providing effective conducting tubes in which charged particles and certain kinds of waves can flow between the hemispheres. Above the auroral zones the lines are usually "open" extending into the tail of the magnetosphere or connecting with the interplanetary field. It is the magnetosphere and its interaction with the solar wind that accounts for much of the interesting and complex phenomena in the polar-cap region. Because of the primary role played by the magnetic field it is convenient to use the "L" coordinate instead of height when describing position in the magnetosphere. Roughly speaking, the L value describes a particular magnetic shell on which an energetic particle remains trapped. In the dipole approximation, it is the geocentric distance to the top of the field line in earth radii.

The corresponding latitude is called the "invariant latitude."

Thermal particles in the magnetosphere arise mainly through diffusion upward from the F2-region. Energetic particles are mostly fed in from the outside, either from the tail region of the magnetosphere or directly from the solar wind. Substantial acceleration of certain particles occurs within the magnetosphere by processes as yet unknown.

One of the unique contributions of the antarctic program to the study of the magnetosphere is the discovery of the plasmapause and its movements by means of whistlers. At Eights Station, because of the low local noise level and the high lightning activity in the conjugate region, it was possible to observe many well-defined whistlers. They are easily heard by connecting a high-gain audio amplifier to a loop or long-wire antenna in a quiet location. Some of this energy enters the ionosphere where it may be trapped in a field-aligned enhancement of ionization, called a whistler duct. It propagates to the conjugate point where it emerges as a whistling tone as a result of dispersion along the path. From the observed curve of frequency versus time the latitude of the path and the average electron density near the top of the path is obtained (Fig. 3). Many such paths are often excited by a single flash, providing data from which a map of electron density in the equatorial plane can be derived. Whistler data obtained at Eights and Byrd Stations revealed for the first time a surprising and totally unexpected sharp boundary (the plasmapause) in the equatorial ionization profile at about L = 4 (60° invariant latitude). Within this boundary the ionization is essentially in thermal equilibrium with the ionosphere, and the equatorial densities at L = 4 are around several hundred electrons per cubic centimeter. Outside the plasmapause the density typically drops to one electron per cc, more or less, and then may recover somewhat as the outer boundary of the magnetosphere is approached. The plasmapause moves to lower L-values with increasing magnetic disturbance, apparently as the result of erosion of the external plasma. During quiet times it may extend out to L = 6.

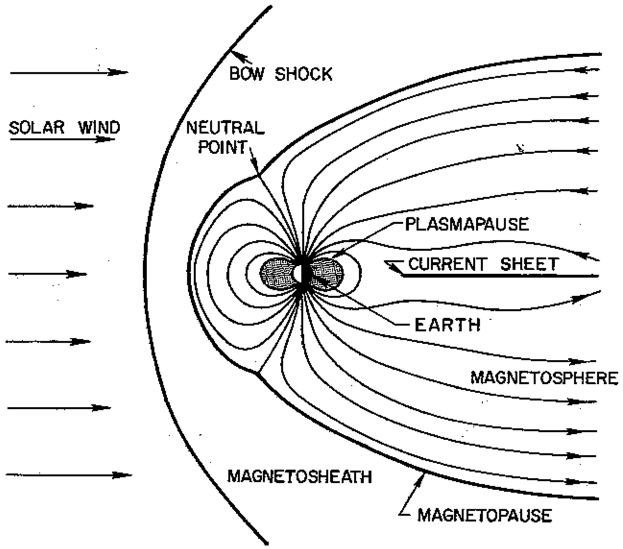


Fig. 2. Sketch of a model of principal regions of magnetosphere in noon to midnight meridional plane. From stations in the antarctic information can be obtained on most of the magnetosphere down to locations well inside the plasmapause.

By observing the change in latitude of individual whistler ducts with time, the north-south drift of the plasma can be measured. Inward drifts during a polar substorm imply east-west electric fields of about 0.3 millivolt per meter at 4 earth radii. These results provide a new technique for measuring electric fields deep in the magnetosphere on a more or less continuous basis. They also provide a unique tool for monitoring the convection patterns of the magnetospheric plasma, so essential to achieving a full understanding of magnetospheric dynamics.

The favorable location of certain antarctic stations (such as the new Siple Station) with respect to VLF transmitters on the east coast of the United States has led to another unique experiment. Along with VLF whistlers, an observer at middle and high latitudes can hear a variety of natural radio emissions, called chorus or hiss. Their sources are believed to be energetic electrons trapped in the earth's field, although the mechanisms of radiation are not yet fully understood. Certain discrete forms of chorus emission can be triggered reliably by signals from VLF transmitters. Morse code dashes (150 milliseconds) are most effective, while the dots (50 ms) seldom cause triggering. From data obtained in the antarctic and from satellites, the region of triggering has been placed near the equatorial plane. This is one of the first controlled experiments in the magnetosphere to be performed from the ground.

In the area of geomagnetism, the antarctic has made important contributions, both in supporting other types of measurements and in advancing our understanding of the external components of the earth's field. Generally speaking, geomagnetic variations are similar in the two polar regions. By comparing antarctic data with those from a low latitude station, it has been found that the first impulse of a sudden commencement occurs a few seconds earlier at the high latitudes. Comparison at conjugate points of the polarizations of the magnetic impulses of sudden commencements show that most are elliptical and of opposite sense. In general, the current systems deduced from magnetic measurements are mirror images of one another with respect to the geomagnetic equatorial plane.

In studies of micropulsations (period less than 10 seconds) of the geomagnetic field between Eights Station and its conjugate point (Baie St. Paul) in Canada, use was made of the tilt of the earth's dipole axis with respect to the geographic axis. Because Eights Station is near the meridian which passes through both geomagnetic poles and is above the Antarctic Circle, it is in darkness 24 hours a day at the June solstice, while the conjugate point cycles normally between day and night. Echoing micro-pulsations were observed under these conditions in the 0.5 to 1.0 hertz range, and their intensity was found to be reduced under the daytime ionosphere. The observed reduction was consistent with the assumption of propagation attenuation through the ionosphere.

In general, conjugacy has been established for micropulsations, but many exceptions are found. Movement of the conjugate points resulting from field-line distortion and the "opening" of field lines may both be involved in departures from conjugacy.

Geomagnetic variations are related to many other phenomena, such as auroras, particle precipitation and VLF emissions. It was found in conjugate studies between Byrd and Great Whale Stations, for example, that quasi-periodic variations in VLF emission (~ 1 kilohertz) intensity were often associated with geomagnetic pulsations in the period range 10 seconds to 2 minutes. One interesting suggestion advanced to explain this association is that the geomagnetic pulsations modulate a critical parameter in the VLF emission generation process, causing the VLF output to vary.

Another program of importance in the antarctic is the study of cosmic rays, principally those originating in the sun. Solar cosmic rays are nuclei generated in solar flares and have energies in the range 0.1 to 10^5 mev. Because of the shielding effect of the earth's magnetic field, it is only in the polar regions that the lower energy particles can reach the earth. Their directions of arrival and momentum spectra provide information on the magnetosphere and the interplanetary magnetic field. Comparison of balloon data from Mirny (antarctic) and Murmansk (arctic) has shown large north-south anisotropies. The same effect has been found in ground-based measurements with neutron monitors. It is thus clear that both polar regions must be involved in the continuing study of cosmic rays.

The brief period since the IGY might be called the exploratory or fact-finding phase of antarctic upper atmosphere research. From the wealth of data now in hand, many hypotheses have been generated and specific experiments are being devised, leading to what we might call the experimental phase of antarctic research. This does not mean that the exploratory phase has ended.

In designing upper atmosphere experiments we must resist the temptation to let a computer select our data for us. It is often better to record the raw data completely and, then, use the computer to select and process the data according to various strategies. Of course, some preprocessing of data in the field may be needed to speed up the analysis and, hence, useful changes in the experiment may be more obvious.

In planning future observational programs in the antarctic we can expect that many of the previous programs will continue but with different emphases. Perhaps the biggest change will be an increased emphasis on multi-discipline experiments in which recording methods, locations and scheduling of observing times are coordinated for maximum value in correlative studies. An example might be the simultaneous recording at the same location of (1) strength of the earth's field, (2) micropulsations, (3) VLF emissions, (4) auroral light, (5) absorption (by riometer) and (6) x-ray events (observed in a balloon). In view of the increased interest in comparative data from different locations, it is more important than ever before that instruments and measurement methods be standardized. Certainly standard chart speeds should be used whenever possible together with accurate clocks.

An exciting future prospect for antarctic research is the development of controlled experiments. In

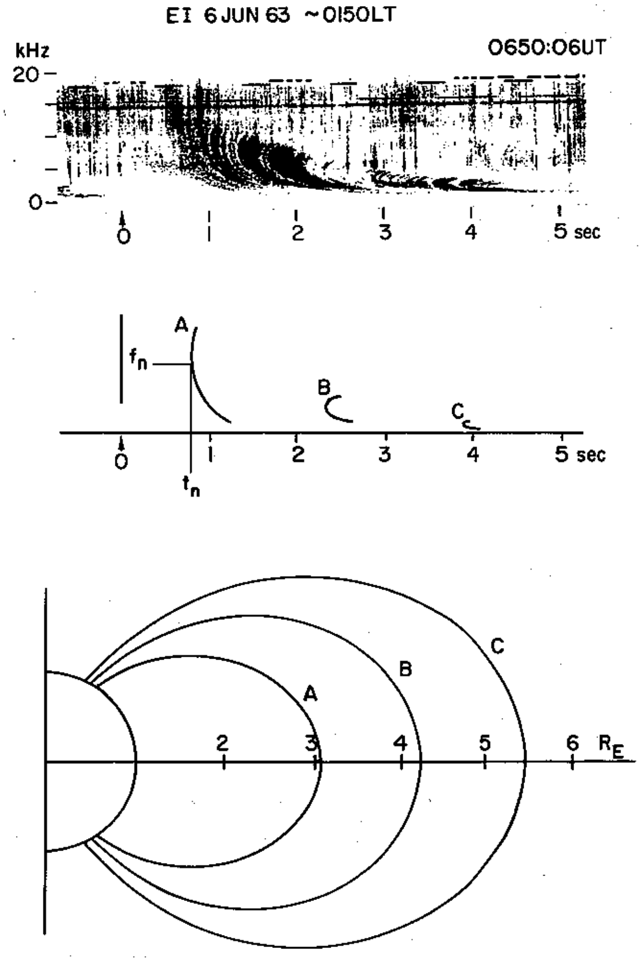


Fig. 3. Whistler spectra from Eights Station showing many separate components (upper panel). Three selected components (labeled A, B, and C) are traced in middle panel for greater clarity and corresponding magnetospheric paths are shown in lower panel. Path latitude is measured by the nose frequency f_n; electron content by nose delay t_n.

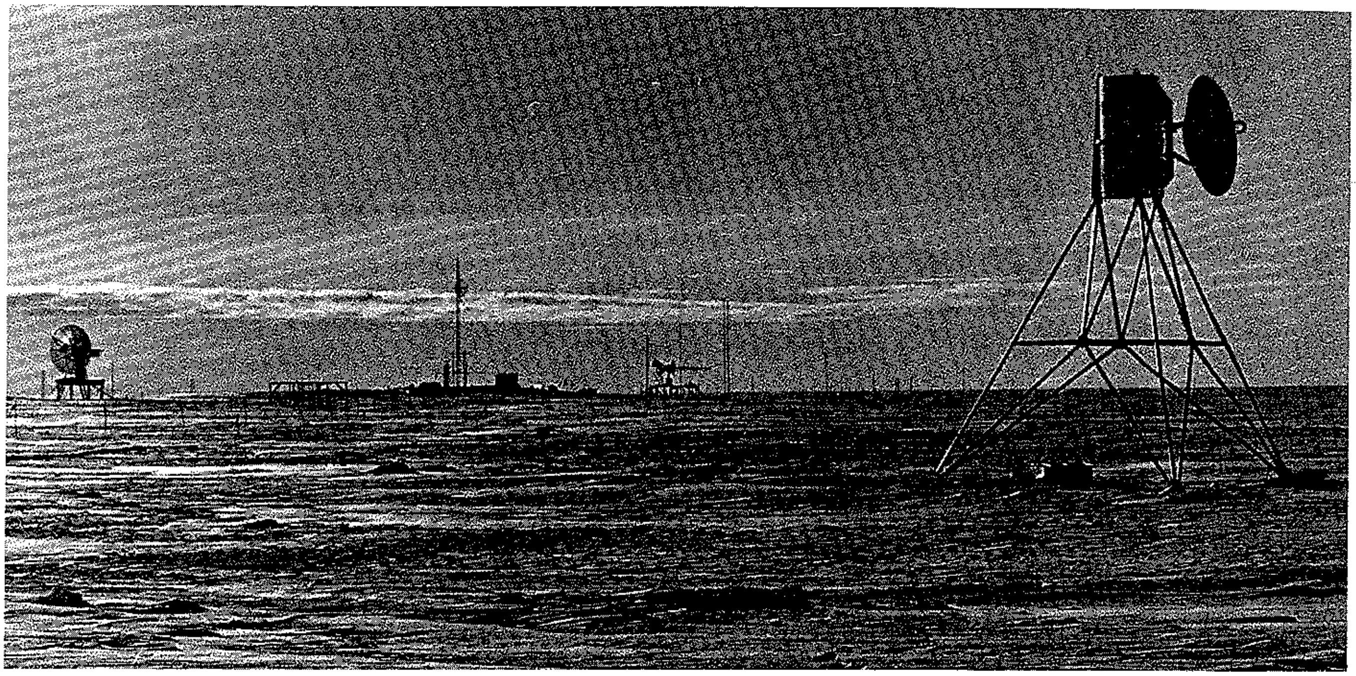


Fig. 4. Prototype of the capsule (shown in right foreground) for an unmanned geophysical observatory located at Byrd Station for purpose of conducting environmental tests on the structure. A satellite telemetry dish appears in left background.

the past we have depended mainly on our ability to isolate the effect of a given factor through statistical analysis of natural phenomena. Exceptions from the past are the Argus experiments of August-September 1958 in the Atlantic Ocean and the Johnston Island tests in the Pacific Ocean in which nuclear bombs were exploded in the upper atmosphere. These introduced known perturbations into the atmosphere, including both waves and particles, from which new knowledge was obtained. More recently, barium clouds released in the E-region and at high altitude in the magnetosphere have provided visible tracers by which drift effects can be studied.

An exciting new development is the successful creation of an artificial aurora by means of energetic electrons fired into the E-region from a rocket. Another type of controlled experiment is the injection of VLF wave packets to stimulate VLF emissions and modify the precipitation of energetic particles. (Preparations for a new controlled VLF experiment are now under way at Siple Station.) Repeatable controlled experiments should not only accelerate the solution of many problems but, more importantly, will elucidate effects that are either never produced naturally or are forever covered up by other effects.

As we look to the future we must recognize the role of new technology. Using space age circuitry and systems it now appears feasible to build an automatic multidiscipline station having remote programming control (Fig. 4). Such an observatory would be somewhat like an Orbiting Geophysical Observatory (OGO) satellite except that it would be geostationary at one earth radius. In the handling of data it appears that a big improvement is possible through the use of communication satellites. These would collect data from antarctic bases (including an automatic station) and transmit them to home laboratories in real time, thereby avoiding the costly and often frustrating delays (up to 18 months) presently encountered. In the area of sensors, new technology will also play a role. For example, the recent introduction of a TV camera for auroral studies has brought greatly increased sensitivity and time resolution to this field of study. This technique, combined with measurements of related phenomena, should aid in reaching a final understanding of the still enigmatic auroras. Another advance of considerable interest is the development at Byrd Station of a technique for vertical-incidence sounding of the D-region using a VLF sweep-frequency sounder.

Future upper atmosphere research in Antarctica should be extended upward to include more phenomena of the magnetosphere. This will require coordination between space measurements and ground measurements in the two polar regions. Thus measurements by a geostationary satellite should be coordinated with ground measurements made on the same line of force (e.g., Byrd and Great Whale).

More work is needed at the lower levels also, particularly in the D-region, where some of the most complex chemistry of the upper atmosphere takes place. A continuing challenge is to find and understand the connections between the lower levels of the atmosphere and the ionosphere as suggested by some of the antarctic data. Here the close cooperation of meteorologists and upper atmosphere physicists is required.

C. C. LANGWAY, JR.

and B. LYLE HANSEN

One of the major questions of polar research has been whether climatic changes in the northern and southern hemispheres have occurred at the same time. It bears on theories of ice ages which range from local to solar-cosmic processes. One approach to the answer is the analysis of ice in deep cores taken out of the ice caps of Greenland and Antarctica by drilling rigs capable of perforating the great sheets. Stored within the ice is a record of climate, extending back into time for thousands of years. The record is now beginning to show that climate changes in the northern and southern hemispheres are contemporaneous. B. Lyle Hansen, a veteran antarctic driller, is chief, Technical Service Division, and Chester C. Langway, Jr., is chief, Snow and Ice Branch, of the U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

DRILLING THROUGH THE ICE CAP: Probing Climate for a Thousand Centuries

Within the last few million years, up to one-third of the earth's land surface was periodically inundated by ice sheets, like those existing today in Greenland and Antarctica. These remnants of a past ice age play a very influential role in atmospheric circulation and contribute greatly to the meteorological and climatological conditions of the world, as did their former and more expansive counterparts.

Present-day glaciers permanently blanket about 12 per cent, or some six million square miles, of the earth's land surface and are found on all continents with the exception of Australia. Nearly 96 per cent of this total ice mantle is located in the polar regions of Antarctica (85 per cent) and Greenland (11 per cent), which contain 78 per cent of the earth's fresh water.

Although polar glaciers have been observed and investigated since historical times and have been the subject of numerous exploratory and scientific expeditions, surprisingly enough, up until a few years ago almost nothing was known of their internal nature and composition. The inner structure of a polar glacier has always been of fundamental interest to glaciologists; the problem was to obtain suitable samples for study.

Attempts to bore mechanically into glaciers for thickness measurements are reported to have begun in Switzerland as early as 1842, but it was not until 1950 that even limited success was achieved. At this time three major core-drilling projects were conducted by groups from France, the Scandinavian countries and the United States, almost simultaneously, on polar and temperate glaciers of the world. In all cases core diameter was small (5 to 8 centimeters), depth of penetration was shallow (100 to 150 meters) and core recovery was discontinuous and mainly of poor quality.

B. Lyle Hansen (left) and C.C. Langway, Jr., observing two pieces of the Greenland core.

The desire to develop a satisfactory method of continuous deep-core drilling in polar ice received considerable stimulus and support in the United States during the planning stages of the recent International Geophysical Year (IGY) and, in fact, was one of the principal study programs recommended by the National Academy of Sciences' Panel of Glaciology. Our laboratory, then called the Snow Ice and Permafrost Research Establishment, under the scientific leadership of H. Bader, accepted responsibility for implementing the entire program: designing and modifying drilling equipment, establishing techniques of ice core analysis and developing bore-hole instrumentation methods.

The deep-core drilling in ice program was initi-