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SPACE PHYSICS IN ANTARCTICA: AN ADVENTURE ON THE ICE

When I came to APL in 1981, I had no idea what I was getting myself into. Certainly I never suspected that six years later I would be standing on a 160-meter-thick floating shelf of ice and wearing sunglasses at midnight. Space physics in Antarctica? I will try to explain how it all came about and what the experience was like. A few of the results obtained from the Polar Anglo-American Conjugate Experiment will be described.

INTRODUCTION

When we think of space physics, we usually think about satellites (naturally enough), but a surprising amount of our knowledge about Earth's space environment actually has come from ground-based studies made with a variety of instruments such as magnetometers for measuring magnetic disturbances and electric currents, photometers and all-sky cameras for observing the auroras, and radars for observing the structure and motions in the ionosphere. The Earth's magnetic field focuses much of the activity in the magnetosphere (see the introduction by Mitchell in this issue for a discussion of the terminology of space physics) onto a relatively small region around the magnetic poles. Thus, it is not surprising that ground-based space physics is concentrated in the polar regions and that such studies are accompanied by their own unique problems and requirements.

The Goose Bay Radar

In 1983, three APL scientists and engineers (Principal Investigator Ray Greenwald, Roger Hutchins, and I) traveled to Goose Bay, Labrador, to install a high-frequency radar designed to look at density irregularities in the high-latitude ionosphere.[1] The radar, which operates at frequencies from 8 to 20 MHz, detects the coherent backscattered signal produced by ionospheric density irregularities that have a spatial periodicity equal to half the radar wavelength. By observing the motion of these ionospheric irregularities, it is possible to derive information about the electric field that drives the motion of plasma in the magnetosphere.[2] In addition to observing the bulk motion of the plasma, the radar can also determine the Doppler power spectrum. The width of the spectrum is related to the level of turbulence in the electric field.

Conjugacy

An interesting aspect of high-latitude studies is the phenomenon referred to as conjugacy. Charged particles and magnetohydrodynamic waves are channeled along the magnetic field lines within the Earth's magnetosphere. One would therefore expect similar physical processes to occur at the two ionospheric endpoints of a "closed" magnetic field line. On the other hand, magnetic field lines that originate in one hemisphere and connect to the solar wind (i.e., "open" field lines) would not be expected to show a conjugate relationship in the other hemisphere. These two situations are depicted in Figure 1. Studies of conjugacy could help trace magnetic field lines and determine the boundary between the open and closed regions and could also be used to examine

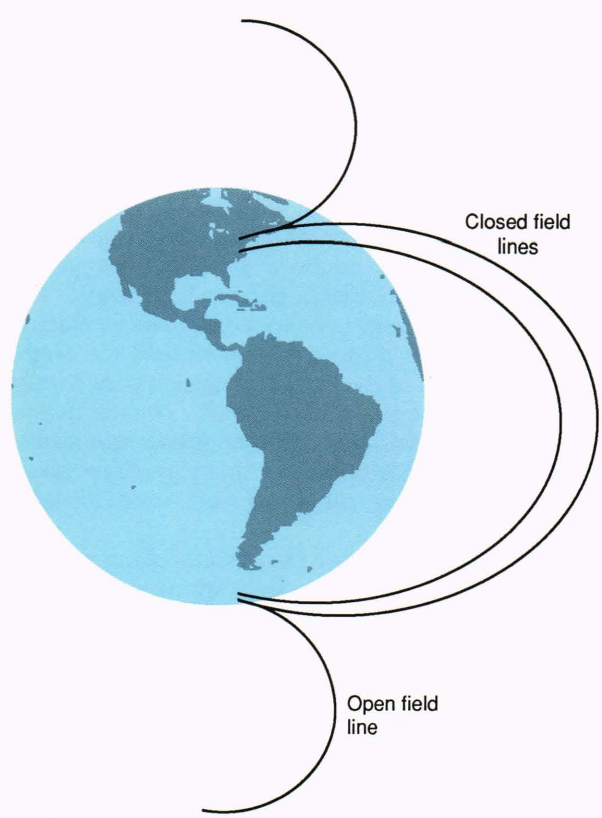

Figure 1. Points connected by a magnetic field line are referred to as conjugate points. Closed magnetic field lines channel energy and particles from one hemisphere to the other. Open magnetic field lines connect a point in the ionosphere to the solar wind.

the roles that solar illumination and ionospheric conductivities play in the formation of ionospheric irregularities and electric field turbulence.

When John R. Dudeney, the head of the Geospace Research Group at the British Antarctic Survey (BAS), heard about APL's plans for the Goose Bay radar, he realized that they could lead to the most ambitious conjugate experiment ever undertaken. The Goose Bay radar is located at a geographic latitude of 53°N but, because of the tilt of the Earth's magnetic axis, its magnetic latitude is 64°N and its conjugate point in the Southern Hemisphere is at a geographic latitude of 74°S, well within the Antarctic circle. Fortuitously, the Goose Bay conjugate point is located very close to Halley Station, an Antarctic research base operated by BAS on the Brunt Ice Shelf in the Weddell Sea. Figure 2 shows the field of view of a Halley radar and the projection of the Goose Bay radar field of view produced by tracing magnetic field lines from the Northern Hemisphere to the conjugate points in the south. The overlap of the two fields of view is very large, and a high-frequency radar at Halley Station would provide unprecedented opportunities for conjugate studies. Thus, almost from the inception of the Goose Bay radar, there were hopes that a similar radar could be installed at the magnetically conjugate location.

Because of BAS's interest in collaborating with APL in a joint project, a member of BAS, Mike Pinnock, joined us in building the Goose Bay radar. He wanted to familiarize himself with the construction in order to determine what could be accomplished at Halley and what potential problems might be encountered in building a similar system in Antarctica. At the time, we hoped to begin the construction of the Halley radar within two years, but budget problems caused a long delay, and it was not until 1987 that we were finally able to build the second radar.

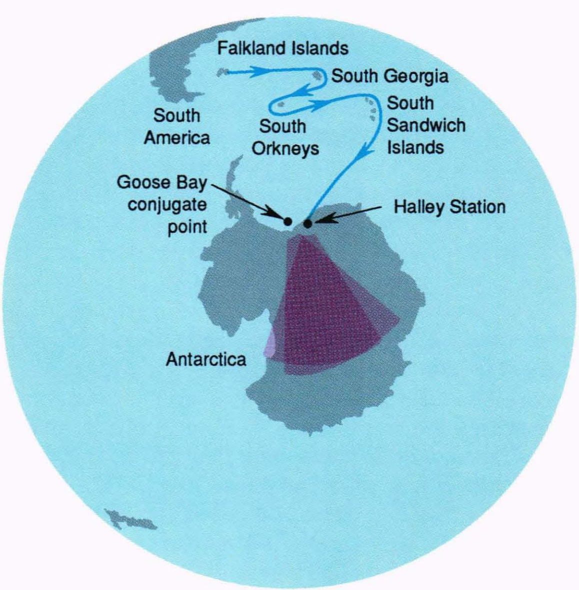

Figure 2. A map of Antarctica showing the field of view of the Halley high-frequency radar, the conjugate mapping of the Goose Bay high-frequency radar, and the path of the *Bransfield* (blue line) on the trip from the Falkland Islands to Halley.

THE POLAR ANGLO-AMERICAN CONJUGATE EXPERIMENT

Even when the funds to build a radar at Halley became available, they were limited, and a way of maximizing the scientific rewards while minimizing the cost had to be found. The solution was to make the project a joint effort between BAS and APL. A National Science Foundation grant enabled APL to purchase most of the necessary hardware, and BAS provided the remaining hardware and the manpower to build all the components of the radar, install the radar at Halley Station, and operate it. The joint project was called the Polar Anglo-American Conjugate Experiment (PACE) (see Fig. 3).

The Halley Radar

Although BAS was to bear the responsibility for the construction and operation of the radar, it was desirable that APL be involved with the installation. The one area where BAS had little expertise was the computer system to control the experiment. Since that area had been my responsibility at Goose Bay, I was the obvious APL person to join the BAS personnel at Halley.

The map of Antarctica (Fig. 2) shows the location of Halley Station. Because it is a long way from any airfield, and for various cost and safety reasons, BAS personnel generally do not fly into Halley, so that travel

Figure 3. The PACE logo.

to Halley is very different from what most Americans experience when they go to Antarctica. The American bases are usually reached by air on flights originating in New Zealand. The British reach their bases via one of two ships, the *John Biscoe*, which is primarily devoted to oceanographic research, or the *Bransfield*.

The *Bransfield* is an ice-strengthened cargo ship (Fig. 4) with a rounded, concrete-filled double hull that extends from the bow to nearly midships. This special hull allows the ship to ride up on top of ice rather than getting locked in. As it rides up on the ice, its weight causes the ice to break, and the ship can thus function as an icebreaker as well as a cargo ship. This does not always work, however, and travel through the ice can be a slow process of going back and forth trying to find a reasonable path. One problem with the rounded hull is that (in the words of Mike Pinnock) "she rolls like a pig," and travel in the open ocean can often be quite uncomfortable. Luckily, once the ship actually gets into the ice, the solid surface prevents any significant amount of swell and the ship remains quite steady.

FID's

Before going further into how one gets to Halley, I should say a few words about the type of people who go there. The BAS bases are generally manned by young men who are looking for a bit of adventure before settling down to join the "real world." These young men are referred to as FID's, an acronym derived from the fact that originally the territory in and around Antarctica claimed by Britain was all part of the Falkland Island Dependency. Of course, if you ask the FID's what it stands for, you get something about ". . . idiots down south." If you are going to work for BAS, you must sign on for a two-year tour of duty, and that really means more than two years. A FID going to Halley leaves England in October aboard the *Bransfield* and eventually arrives at Halley sometime in December or January. The ship usually makes the trip only once a year, so when it leaves (usually in late January or February), the base is isolated until the ship returns a year later. Once a FID has reached Halley, he will remain there for two years, departing on the ship at the end of his second year and returning home in March, two and a half years after he left.

Figure 4. The *Bransfield* docked at Stromness, an abandoned whaling station on South Georgia Island.

Although Halley Station is isolated physically for most of the year, it can still communicate with the external world. Telephone, facsimile, and digital communications are provided via the INMARSAT communications satellite. The satellite service is quite expensive, however, so communication traffic must be limited. During his two years of living at Halley, a FID is allowed to send a one-page fax message once a month and to receive one a month free of charge. All other communication is at his own expense, which effectively discourages excessive use of the communications systems. Although this policy may seem severe, it is actually very sensible; most FID's find that trying to maintain more constant contact with family and friends is something of an irritation, and one fax a month is quite enough.

The *Bransfield* left England in late October 1987 with a hold full of equipment for the PACE radars. Also on board was the FID who had been designated the PACE engineer, Mark Leonard. The rest of the PACE crew were all senior members of the BAS, and as such were not required to be on the ship for the entire journey south.

I flew to England to join the rest of the PACE crew in November, and on Thanksgiving day we were all flying south to join the *Bransfield* at Port Stanley in the Falkland Islands. The people involved with the installation of PACE included Mike Pinnock, who was in charge of the installation, John Dudeney, the head of the Geospace Research Group at BAS and the principal investigator for the British side of PACE, and myself.

In addition to the PACE people, a number of other members of BAS were to join the ship at Port Stanley, including the newly installed director of BAS, David Drewry, who was making a grand tour of all the BAS bases. Accompanying him was the deputy director, Nigel Bonner, who was making his last trip before retirement.

The British have always had a tendency toward formality and hierarchy; that tradition was maintained on the ship. At the top were the ship's officers and the "mega-FID's" such as Drewry, Bonner, and Dudeney. One level down were the "super FID's," permanent staff members of BAS and visiting scientists like myself. The next group comprised the regular FID's who were on their way to take up their two-year appointments, and finally came the ship's crew. Each group had its own mess. The crew and FID's served themselves and dining was quite informal, while the super-FID's and the officers were served by stewards and dining required jackets and ties. It was not an entirely bad thing to be at the low end of the hierarchy. The crew got their food first and had the best choice and the hottest food. The FID's came next, followed by the super-FID's, and finally the wardroom, where the officers and mega-FID's dined on rapidly cooling dishes.

South Georgia and Signy

Because the *Bransfield* is BAS's primary cargo carrier, it has to stop at all of their bases. We therefore did not head directly to Halley but steamed first to South Georgia Island. South Georgia was at one time a major whaling base, and five abandoned whaling stations are on the island. Until the time of the Falkland Island war with Argentina, BAS operated a permanently manned base on South Georgia at the former admistrative center, Grytviken. During the war, the Argentinian forces invaded the island and took a number of BAS personnel prisoner. Afterward, the base at Grytviken was taken over by the British military, and the BAS operations on South Georgia were greatly reduced. On this trip, a summer experiment investigating the sonar cross section of krill was to be placed in operation at the little harbor of Stromness, and that was to be our first port of call.

The first thing those of us who were new to the area noticed on our arrival at Stromness was the large number of elephant seals lolling about on the beach (Fig. 5). The second thing we noticed was the penguins. All the animals were remarkably unconcerned about the presence of humans, and it was quite possible to walk right up and touch an elephant seal. Such attentions obviously did not please the seals, who would rear up and attempt to look fierce, but their protests just were not very convincing. They are great, slow-moving beasts with a basically gentle nature (as long as you are not encroaching on a bull's harem). The penguins were also relatively unafraid of people. I sat down quietly near a small group of gentoo penguins, and within a few minutes a couple had waddled over to satisfy their curiosity about me. The harbor at Stromness was also home to a small colony of king penguins, one of the large varieties and equally unafraid of people.

In contrast to these friendly creatures, we also came across a number of fur seals, who showed a much more aggressive nature. Fur seals look very much like the sea lions we see in circus acts, the most obvious difference being the heavy coat of oil-rich fur that protects the fur seal from the cold Antarctic temperatures. Such beautiful coats were naturally in high demand on world markets, and the fur seals at one time were hunted almost to extinction. Luckily, they have since become an internationally protected species, and they have made such a remarkable comeback that some areas have become overpopulated.

In addition to the penguins and seals, South Georgia is also the home of a wide variety of birds and, surprisingly, two herds of reindeer, the free-roaming survivors of animals originally imported as a food source during the whaling years.

Although everyone wanted to enjoy the wildlife of Stromness, our first duty was to unload the cargo. In the Antarctic, one does not leave such tasks to the longshoremen's union. Everyone works during the cargo operations, from the director to the youngest FID—visiting American scientists included. The Antarctic summer is far too short to allow time to be wasted. We had one great advantage at Stromness: the harbor is very deep, and the ship was able to pull right up to what remained of the dock, where the cargo could be unloaded. We also discovered the remnants of a narrow-gauge rail system, along with a few flatbed cars. After a little work excavating the rails and fixing the cars, we were able to unload the cargo directly onto these small cars and push them right into one of the abandoned warehouses. With these advantages, the unloading was completed in a day, and while the biologists set up and tested their equipment, the rest of us had a couple of days free for "jollies" (see the boxed insert) before the ship left for Grytviken, where a freshwater supply was available.

From Grytviken, our journey took us away from Halley. The next stop was to be a small base on the island of Signy in the South Orkney Islands. The operations at Signy are primarily devoted to biological studies; the island is home to several penguin rookeries as well as nesting areas for a large variety of other birds. It was on this island that we saw the greatest concentration of penguins—gentoo, chin-strap, Adélie, and macaroni penguins. It is quite an experience both to the eye and the nose to be standing in the middle of a major rookery and be surrounded by penguins as far as you can see.

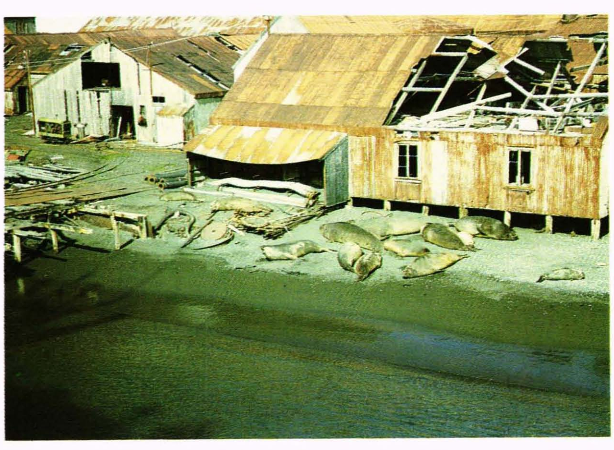

Figure 5. Elephant seals on the beach at Stromness, South Georgia Island.

THE BAS VOCABULARY

The members of BAS have their own vocabulary with some rather unusual terms for perfectly normal things. Thus a "thrutch" describes the heavy toil required to get the parts into the garage during a storm. After doing that, it was time for "smoko," otherwise known as a coffee break. When the weather finally turned sunny, calm, and nice, we had a "dingle day." When you have a "dingle day," it is pleasant (if you can spare the time) to get out for a "jolly," a hike or trip for pleasure. Of course, you want to take your camera with you to get some good "grips." You do not generally refer to going out on the ice, but rather being on the "bondu." Anything that is waste or trash is referred to as "gash," with the exception of the wood slats and boards used in packing the cargo holds of the ship, which are called "dunnage" (actually a standard nautical term).

Through the Ice to Halley

Our stay at Signy was short. Once the limited cargo operations had been completed there, it was time to head to Halley. The flow patterns of the ice in the Weddell sea make it difficult (if not impossible) to approach Halley directly from the west, so the route took us first north and then east through open water, until the ship was almost due north of Halley, before we finally turned toward our destination.

Travel through the ice is slow and often involves extensive backtracking while looking for the best passage. The ship's crew must be constantly alert, but for the rest of us there was little to do, and after a few days we became a bit bored. Those of us who were scientists used this opportunity to give mini-classes to the FID's about the science they were soon to become involved with, but even that did not occupy much time. So it was that, one evening, a few of the FID's organized a trivia contest. The entry fee was a six-pack of beer, which was to go to the winning team. Five four-man teams competed, including the four of us who made up the PACE crew. Team uniforms were required, and we were attired in blue coveralls and hardhats adorned with little PACE antennas made from pipe cleaners (Fig. 6). Although I am good at Trivial Pursuit at home, I discovered that English trivia was an entirely different matter. I am afraid I did not contribute much to our team's score, but I was the only person who knew how many men were on an American football team (that is, how many were on the field at one time) and also the only one who knew that Michael Jackson was making a Pepsi-Cola commercial when his hair caught on fire. My contribution, although minor, did help, and in the end we came in first and were pelted with empty beer cans for our trouble.

Figure 6. The PACE team preparing for the *Bransfield* trivia contest. The hardhats are decorated with miniature PACE antennas made from pipe cleaners. From left to right, John Dudeney (the BAS Principal Investigator for PACE), Kile Baker (APL), Mark Leonard (the PACE engineer), and Mike Pinnock (who was in charge of the PACE construction).

Figure 7. Cargo operations at Mobster Creek, showing the sledges being loaded with cargo from the ship.

Arrival at Halley

We finally arrived at Halley on the morning of 21 December. The ice shelf towers about fifty feet above the surface of the ocean, and the ship cannot unload cargo directly onto the shelf. There are areas, however, where a split in the ice shelf has formed and a ramp of ice can be found that leads from the shelf down to the sea ice on the surface. It was at one of these "creeks" (Mobster Creek, named after a long-gone dog team) where our Halley operations began. As before, everyone was put to work, this time supervised not by elephant seals, but by a group of emperor penguins, the largest and stateliest of all penguins.

The sea ice is only about ten feet thick, and cargo operations can be dangerous. Sledges are pulled up alongside the ship, and the cargo is lowered over the side and piled onto the sledges (Fig. 7). A Snowcat then is driven down the ramp; it hooks up a pair of sledges and pulls them back up the ramp. Because the ice can be unstable and break up, the Snowcats never stay any length of time on the sea ice. During cargo operations, it is quite common for a large chunk of the sea ice to break off and start floating away. At such times, everyone jumps back aboard the ship (if possible), and the ship has to move away from the ice until everything stabilizes again and operations can be restarted. During one of these breakups, a group of people was stranded on an ice slab that was floating away, and it was necessary for the ship to follow and lower a cargo net over the side so that they could be lifted back aboard the ship.

The more time the cargo operation requires, the more ice breaks away, and the more difficult the operation becomes. Therefore, once the cargo operation starts, it continues for twenty-four hours a day until it is completed. Everyone works twelve-hour shifts, moving the cargo from the ship's hold to the sea ice, from the sea ice to the ice shelf, and from there to the base itself, about 12 km from Mobster Creek.

Halley Station

By Christmas Eve, most of the cargo operations had been completed, and I finally left the ship to take up residence at Halley Station.

The Brunt ice shelf accumulates about four to five feet of snow every year, primarily from snow blown into the area from other parts of the ice, and that snow never melts. In addition, blowing snow tends to form drifts wherever there is an obstruction to the wind. It is therefore difficult to maintain a base on the ice surface, and so Halley Station was designed to bury itself in the snow. With each passing year, it lay another five feet deeper, and by 1987 it was about thirty feet below the snow surface. (A new base perched on stilts and designed to be jacked up every year is about to be completed, but in 1987 the new base was still in the design stage.)

Although the base had been designed to bury itself, a flaw in the design resulted in the walls being unable to withstand the mounting pressure of the accumulating snow and ice, and the outer walls of the base were being slowly crushed. Inside walls canted at odd angles, doors refused to close, and heat from the inside melted the ice that was building up around the inner walls, resulting in numerous leaks. There were two major tasks to be performed at Halley during this summer relief period: one was to set up PACE and the other was to clear enough ice out of the voids between the inner and outer walls so that the base could continue to be used until the new one was built.

The base was designed to house twenty men, but during this brief summer period it became home to about fifty. This high-density living required adjustments to the normal routine. Sleeping quarters were wherever there was room to put a sleeping bag. I shared the one-room library with two others. Some people ended up living in tents out on the ice and apparently did not find that to be too harsh.

Meals had to be taken in shifts, and because the water supply was limited, we were allowed only one shower a week. Since we were all working very hard, this meant that the base had a fairly ripe smell all the time. The water limitation is not based on the availability of water (after all, the ice shelf is pure, clean water) but on the limited capacity of the storage tank and on the time and effort required to dig up blocks of ice to put into the melter.

Construction of the Radar

A constant worry during any Antarctic operation is that the weather will turn bad and make it impossible to work for an extended period. Since the total time available for the summer relief is very limited, a few days' delay at a critical time could result in a full year's delay in a project. So if the weather allows work to continue, it continues. Christmas and New Year's Day were not holidays for the people at Halley Station. There is no such thing as a weekend. We maintained twelve-hour shifts from the time of our arrival at Halley until New Year's Day, when the shifts were moderated to nine hours. Even then, we had no days off until ten days later.

The radar has an array of sixteen log-periodic antennas whose largest elements measure nearly fifty feet from tip to tip. Each antenna is mounted on a very sturdy twenty-foot tower made of galvanized steel. The first job was to build the towers in the underground garage, and four of us (myself, John Dudeney, and two FID's) were building as quickly as we could. As soon as a tower was completed, another team moved it out of the garage and up to the surface. While all this was taking place, Mike Pinnock and Mark Leonard were preparing the antenna site and the "caboose" where the electronics was being installed.

On 26 December, the big storm we had feared hit us. The wind rose to around fifty knots, and it snowed heavily. Visibility was reduced to only a few feet, and work outside became impossible. Although we were able to continue building the towers in the garage, we could not move them out to the surface, and they had to be piled up on the ramp that led up from the garage to the surface. The parts for building the towers had been dumped outside, and we had to make several trips out into the blizzard to bring in the needed pieces. Staggering about in soft snow with your goggles iced over so that you have essentially no vision, holding a hand line with one hand and a bunch of heavy metal struts in the other while the wind howls about your head, is something not be be missed if you really want to experience adventure in the Antarctic. It was, as John Dudeney put it, "an awful thrutch" (see the boxed insert).

Luckily, the blow only lasted a day, and full-scale work was able to recommence the next day. By 28 December all the towers had been finished and moved out to the site where they were to be erected. Then, while a group of FID's under the direction of Mike Pinnock busied themselves putting up the towers, our inside crew started building the antenna booms. It was at this point that we encountered the only serious problem in the construction of the radar. The antenna booms were made of aluminum pieces fastened together with stainless steel bolts and Nyloc nuts. Some flaw either in the bolts or the nuts (I am still not sure which) resulted in a significant proportion of the nuts locking up before they were tight. Any attempt to either further tighten the nut or remove it resulted in the bolt suddenly shearing off. We all ended up with badly bruised and scratched knuckles, and in the end we did not have enough nuts and bolts to finish the job. Halley is well prepared for such problems, however, and a supply of metric-sized bolts and lock nuts was raided to allow us to finish the booms. This job was followed, several days later, by the task of connecting all the radiating elements to the antenna booms, making the electrical connections, and doing a final checkout on each antenna.

An unusual aspect of the antenna system is the way the towers are mounted. Normally at Halley a large antenna tower would be mounted by digging a pit and placing the lower portion of the tower in the pit and then filling the whole thing with snow. This solidly packed arrangement holds the antenna very firmly; however, because of the yearly snow accumulation, it is necessary to extend the tower every few years. The PACE array required sixteen antennas, and the work involved in extending sixteen towers every few years would overburden the Halley personnel. The PACE towers were therefore mounted on sled-like metal bases. The tower and its base are held in place by guy wires attached to "deadmen'' buried in the snow. The towers can then be dug out every few years and repositioned on their bases. Thus, no tower extensions are necessary, and the antenna configuration can even be changed, if desired.

The erection of the antennas was completed on 7 January (Fig. 8), and the next few days were spent completing the wiring. At this point, we also had to set up the data analysis software on the base's newly installed MicroVAX 2000 (Digital Equipment Corp.) and prepare some display software for use with an IBM personal computer. The outside work proceeded rapidly, helped in large part by the fact that we were enjoying remarkably beautiful weather. For several days there was no wind and bright sunshine all day. Since the Sun does not set at Halley at this time of year, this meant twenty-four hours of warmth, and the temperatures rose to slightly above freezing. In the calm air, it was quite possible to become overheated, and several of the FID's worked stripped to the waist.

Figure 8. The completed antenna array at Halley Station. The bright sunlight casts dark shadows on the snow, making it appear that each antenna is doubled. The red caboose houses the PACE computer and data acquisition system. (Photo courtesy of Mike Pinnock.)

First Results

On Sunday, 10 January 1988, all the preliminary work had been completed. Mike Pinnock's careful planning for the operation had been tremendously successful, and the construction of the PACE radar had taken a mere seventeen days. It was time to turn it on and see if it worked. At 2100 UT, everything had been checked out, and the radar was turned on for the first time. My diary contains the following note: "***IT WORKS***."

The data tape was taken from the radar computer and mounted on the VAX, where we ran it through our standard processing program. The results were then transferred to the IBM personal computer, and a color display program was used to show the results. The radar was detecting ionospheric density irregularities that were convecting in a westward direction with a velocity of about 600 m/s. John Dudeney immediately sent the following telex to Ray Greenwald at APL to announce our success:

> Be advised that PACE radar made first test sounding 2100Z 10 January. Received excellent data for approx one hour showing strong L-shell aligned region with Dopplers consistent with L aligned plasma flow westward at approx 650 m/s at about 600 to 800 km. Data have been analysed on Halley VAX and displayed on PC using the APL colour graphics software. Best wishes, John et al.

The next day we held the official opening of the PACE experiment, and that was followed by a party. Everyone on base joined us, gathering around the antennas to toast the radar with champagne and enjoying another "dingle day" (Fig. 9).

Figure 9. The PACE team celebrating completion of the radar. Clockwise from lower left, John Dudeney, Mark Leonard, Mike Pinnock, and Kile Baker. The two flags symbolize the joint nature of the PACE project, and the (artificial) Christmas tree at the top is for good luck.

The rest of our time at Halley was spent fine-tuning the transmitters, cleaning up the electrical cables, making minor repairs on the computer software, and looking at data. On 20 January, a special campaign was arranged between the Goose Bay and Halley radars. On the basis of observations made at Halley, a prediction was made as to where the Goose Bay radar should see backscatter from ionospheric irregularities. Shortly afterward we received a telex from J. Michael Ruohoniemi at APL:

> Kile/Mike, Our joint observations have been a success. I found a region of westward drift where you had predicted it. Observed: 2220–2300 UT.

Departure

On Friday afternoon, 22 January, I left Halley Station to return to the *Bransfield*. A party was held on the ship, and everyone from the base and the ship (except for a couple of people who had to stay at the base) had a great time. The next morning the ship pulled away from Mobster Creek, leaving 18 FID's (including Mark Leonard, the PACE engineer) behind to man the station for another year.

Our return through the ice was again slow, and stops were made for a second time at Signy and then South Georgia. Our last stop before returning to civilization was in little Rosita Bay. Having unloaded all the cargo on board, we were left with a lot of dunnage (see the boxed insert), but it was put to good use to make a grand bonfire on the beach. We grilled steaks and bangers (sausages—this is a common British word and not a BAS special) while fur seals milled all about us. One pup even crawled over a FID who was apparently in its way (Fig. 10).

We left South Georgia on 6 February and headed for Montevideo, Uruguay. We arrived there on 11 February, and I spent a few days enjoying the Southern Hemisphere summer before returning to cold temperatures, this time in Maryland.

The installation of the Halley radar had gone very well, and the PACE was under way. The radars run twenty-four hours a day, and in the first year of operation we accumulated over 20 GB of data. The data are stored on magnetic tape and shipped back to England each year when the *Bransfield* returns from its trip to Halley. If special campaigns require the information immediately, the compressed data are sent from the Halley MicroVAX to another VAX at BAS headquarters via the INMARSAT link. In addition, a daily short summary file is produced at Halley and is sent regularly by satellite to BAS headquarters.

RESULTS

Dayside Convection Studies

One of the primary areas that can be studied using these radars is ionospheric convection. The plasma in the ionosphere moves in response to the electric field that is generated by the Earth's interaction with the solar wind. Previously, ionospheric convection patterns had been investigated by measuring the electric field with a polar-orbiting satellite or by trying to infer the pattern from the magnetic perturbations set up on the ground by ionospheric currents. While these studies were very fruitful, several problems were encountered. The satellite studies involve measuring the electric field at the satellite as it crosses over the auroral zone and polar cap; thus, the electric field (or, equivalently, the plasma drift velocity) is determined along a line. But two-dimensional patterns must be built up statistically from many satellite passes. The ground-based magnetometer studies, on the other hand, can provide a two-dimensional view of the magnetic perturbations, but to derive the convection pattern, questionable assumptions have to be made about the source of the magnetic perturbations and the ionospheric conductivity. In addition, the magnetometer studies have limited spatial resolution.

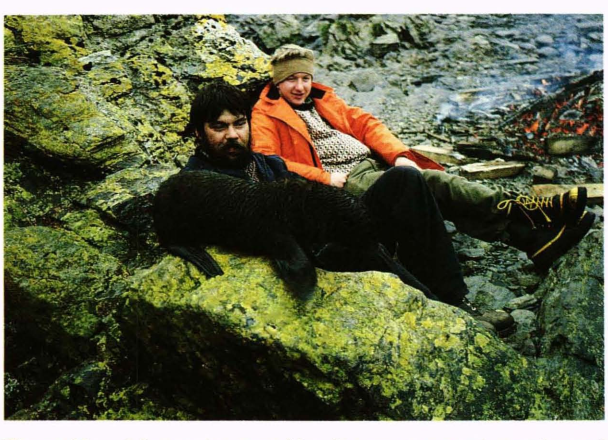

Figure 10. A fur seal pup making its way across the rocks and across FID's at Rosita Bay on South Georgia Island.

The PACE radars cover a very large area (on the order of 3×10^6 km^2) and have a range resolution of 30 to 45 km. Electronic phasing of the antenna array allows them to execute a very rapid scan of the field of view (a scan typically takes 96 s). Thus, they are ideally suited to studying the two-dimensional convection pattern over large areas with high temporal resolution.

Satellite studies (e.g., the study by Heppner and Maynard[3] based on data from the Dynamics Explorer 1 satellite) have demonstrated that the ionospheric convection pattern on the dayside is controlled by the magnetic field carried by the solar wind (the interplanetary magnetic field, IMF). Heppner and Maynard derived patterns based on the sign of the dawn–dusk component of the IMF B_y, but no direct evidence was available to show that these synthesized patterns were valid on an instantaneous basis. The two most important patterns are shown in Figure 11. It is important to note that the opposite hemispheres show opposite patterns. Thus, if B_y is negative, the Northern Hemisphere pattern should be like Figure 11A, while the Southern Hemisphere should be like Figure 11B. A study by Baker et al.[4] used the PACE radars to demonstrate that when the IMF was steady, the Heppner and Maynard convection patterns were a very good representation of the dayside ionospheric convection.

One question that Heppner and Maynard could not address, because of the statistical nature of their satellite studies, is how the convection pattern behaves when the IMF is changing. This question had been looked at by several groups, using the incoherent scatter radar at Sondre Stromfjord in Greenland[5] and the European Incoherent Scatter Radar (EISCAT) in Scandinavia,[6] but these large incoherent scatter radars cannot scan rapidly, and the studies were therefore limited essentially to producing flow vectors along a single direction and to examining the temporal response along that direction as the IMF varied.

Because of the rapid scanning ability of the PACE radars (and the fact that their fields of view are larger than the incoherent scatter radars can provide), these are the first experiments that can truly study the dynamics of ionospheric convection. Recently, PACE data have been used to demonstrate that the ionospheric response to

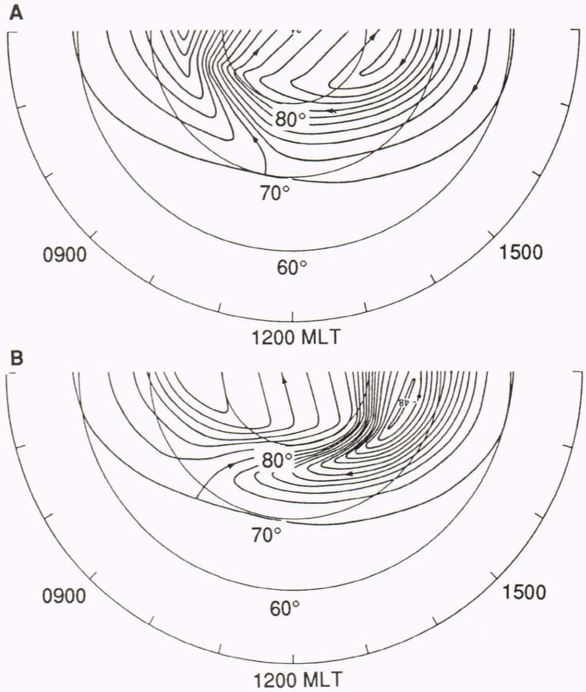

Figure 11. The ionospheric convection patterns derived from multiple satellite passes. **A.** The dayside pattern for $B_y > 0$ in the Southern Hemisphere or $B_y < 0$ in the Northern Hemisphere. **B.** The dayside pattern for $B_y < 0$ in the Southern Hemisphere or $B_y > 0$ in the Northern Hemisphere.

changes in the IMF is very rapid.[7] The response is initiated about two minutes after the change in the IMF encounters the Earth's magnetopause. This is the time it takes for the information about the changed IMF to propagate from the magnetopause to the ionosphere via an Alfvén wave (e.g., a magnetohydrodynamic wave). The change is initiated in a narrow latitudinal band that probably marks the footpoint of the line on the magnetopause where the IMF and the Earth's magnetic field merge. The change then propagates away from this narrow band, and within about six minutes the pattern within the radar's field of view changes from the pattern characteristic of one sign of B_y to the other. An example of an IMF sign change is shown in Figure 12.

Another aspect of the dynamics of the interaction of the solar wind and the magnetosphere involves the nature of the merging of the IMF magnetic field with the Earth's field. Transient phenomena clearly occur at the magnetopause, and these phenomena may be related to the merging process. It is of great interest to look for the ionospheric signature in the plasma convection that would result from these transient events, and a study has used the data set described previously for this purpose.[8] The results of the study indicate that the signature of enhanced magnetic field merging is consistent with many of the predictions of theoretical models that require the formation of vortices[9] and rapid poleward motion in a limited (≈ 200 km^2) area,[10] but the observed flows indicate that the ionospheric vortices do not form immediately (as predicted) but rather several minutes after the initial burst of rapid poleward flow.

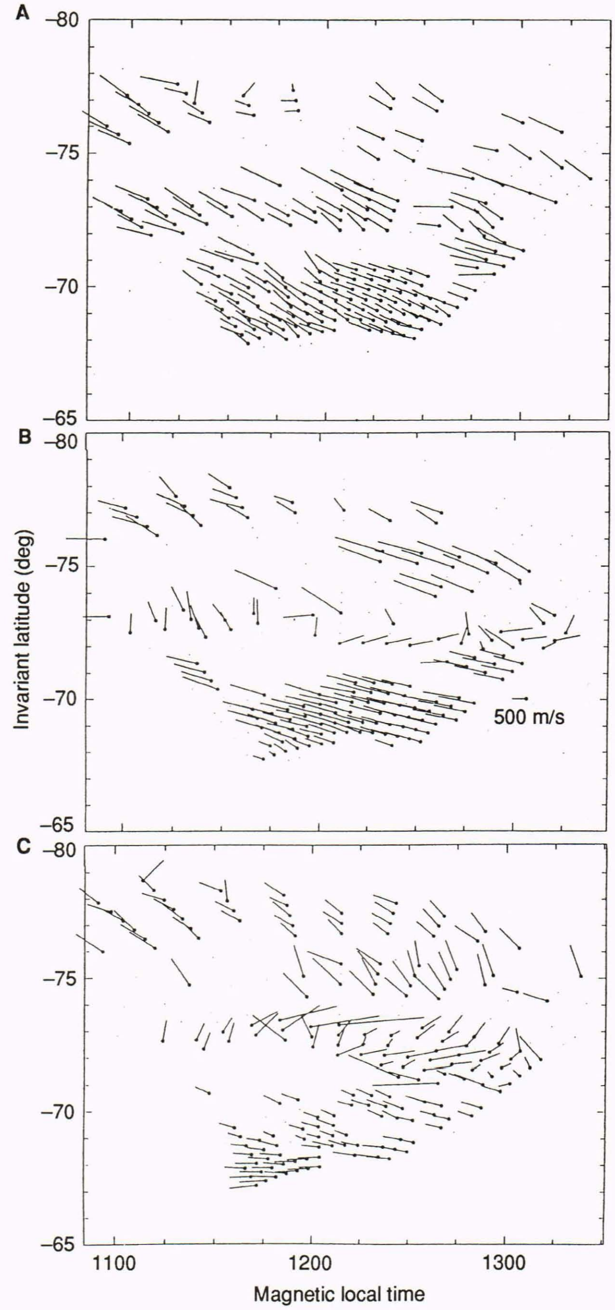

Figure 12. The change in the convection pattern due to a change in the IMF observed with the Halley radar. **A.** Pattern for $B_y < 0$. **B.** The flow direction changed in a narrow latitudinal strip around -73° (magnetic). **C.** Pattern for $B_y > 0$.

Nightside Convection

At least on the dayside, convection patterns such as the Heppner and Maynard patterns are available and give a fairly representative picture of the situation during periods of steady IMF. In contrast, the convection patterns on the nightside are very poorly understood and appear to be even more dynamic than the dayside ones. Satellite studies of the nightside convection have been of only limited use in understanding the plasma flows in that region. The PACE radars are therefore particularly valuable for studying the nightside. One of these studies[11] found that the nightside convection was not in good agreement with the synthesized patterns of Heppner and Maynard but were in reasonable agreement with magnetohydrodynamic simulations,[12] which invoked reconnection regions in the Earth's magnetotail that depend on the IMF B_y. The PACE radar studies are thus providing the first large-scale comparisons of experimental data with numerical simulations of this highly dynamic region.

At this point, the global ionospheric convection patterns are qualitative rather than quantitative, but further studies of convection using the PACE radars should enable us to provide more detailed and quantitative models for periods of steady IMF and should enable us to gain much greater insight into the dynamics of the coupling of the solar wind, the magnetosphere, and the ionosphere, both on the dayside and the nightside.

Geospace Environment Modeling

In recent years, emphasis has been progressively greater on global studies of the Earth's magnetosphere and its interaction with the solar wind and with the ionosphere. One such study by the National Science Foundation is the Geospace Environment Modeling project. At a recent workshop held at the University of Maryland at College Park, our current understanding of the ionospheric signatures of different magnetospheric regions and the boundaries between them was evaluated. The participants agreed that the best available low-altitude technique for categorizing these regions was through observations of charged particles made by polar-orbiting satellites. They also agreed that the cost-effective way to do global studies was through the large-scale, continuous monitoring of the ionosphere with ground-based instruments, including coherent and incoherent scatter radars, magnetometers, all-sky cameras and photometers, and riometers. Thus, it was important to relate the observations from satellites to the ground-based observations, to intercalibrate the different techniques.

A very recent study[13] has used data from the Defense Meteorological Satellite Program (DMSP) F9 satellite as it passed over the field of view of the Halley radar. The study was directed toward examining the ionospheric image of the magnetospheric cusp, and it showed that there was a clear correlation between the features seen by the satellite and those observed by the radar. The cusp was found to be a region where ionospheric irregularities on a scale of 10 m were generated, and the irregularities moved under the influence of a highly turbulent electric field. The convection pattern observed by the radar showed a flow reversal typical of the pattern expected in the Southern Hemisphere for an IMF B_y-positive condition. That flow reversal, embedded within the cusp (Fig. 13), was consistent with a change in sign of the horizontal plasma drift observed by the satellite. Studies with DMSP and the radar are now under way to examine the correlations under different IMF conditions.

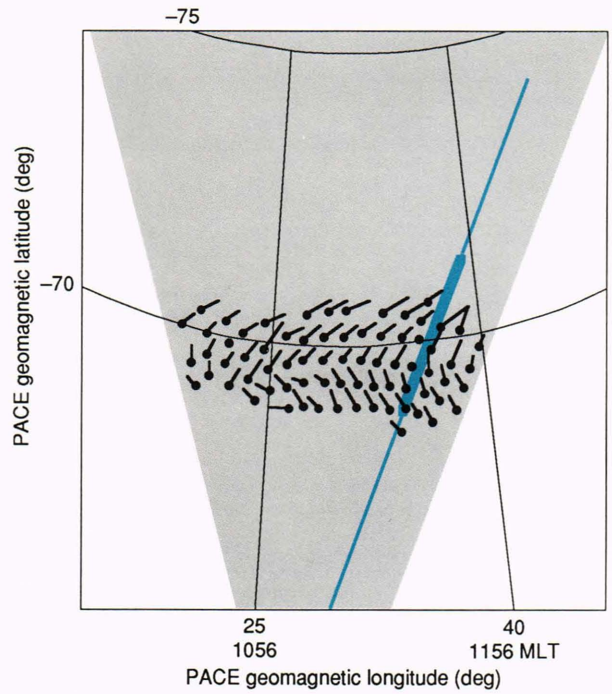

Figure 13. The ionospheric convection pattern observed by the Halley radar at the latitude of the cusp. The track of the DMSP F9 satellite is shown in blue, and the region where the satellite observed the particle precipitation characteristic of the cusp, along with large fluctuations in the electric field, is indicated by the thickened portion of the track.

SUMMARY

I have only been able to give the briefest introduction to the scientific results that have been and are being obtained from the PACE radars. They have clearly demonstrated their capabilities, and we expect them to continue in operation for many years. They are used for a variety of collaborative studies, including the Coupling, Energetics, and Dynamics of Atmospheric Regions initiative, the Sundial project, the Geospace Environment Modeling project, and pulsation studies in conjunction with instruments located at the South Pole. PACE will also play an important role in the ground-based portion of the International Solar Terrestrial Physics/Global Geophysical Survey project, which will begin collecting data in 1992.

Getting the PACE radars running was a big job and my Antarctic adventure lasted three months, a long time to be away from home and family. It was hard work, but it was also one of the most interesting experiences of my life. The places I saw and the animal life I encountered were fascinating, and the people I worked with must surely be some of the most dedicated, competent, and interesting people anyone could meet. We have plans for additional radars in Antarctica as well as in northern regions such as Iceland and Resolute Bay, Canada. Would I be willing to go on another such outlandish trip? Well . . . .

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