Spacebound

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Spacebound

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Foreword

Spacecraft launchings, particularly by the United States and the Soviet Union, are now commonplace, and only the extraordinary ones catch our attention. In a very real sense, however, space is a new frontier and people everywhere thrill at each discovery or major accomplishment. Canada, the third nation to build a successful spacecraft, has been playing a significant role on this new frontier from the earliest days of the space era. Nine Canadian satellites have been placed in orbit about the earth and additional ones are currently being prepared for launch. Clearly, as a nation we have recognized the suitability of space techniques for solving our country's needs, and we have become a major user of space technology.

This book tells the story of how we embarked on this course. It describes five different ventures in space involving Canadian-built satellites, the first of which was launched 20 years ago. It documents briefly the research and development efforts that went into these, and describes their impressive accomplishments. It is being published now to record the scope and flavor of these initiatives and achievements while they are still vivid.

Phenomenal technological developments have taken place since the space age began, and space applications are now a routine part of our lives. Daily, we see satellite pictures of the weather, and millions watch television programs and news reports from various parts of the world, all delivered by satellite. The research and development that preceded such applications are frequently overlooked; however, new applications for space systems depend on our understanding of the nature of space and the technology of space systems. The early stages of the Canadian space program focused on exploration of a portion of space known as the earth's ionosphere. Later activities have had as a major element the development and application of new technology for communications satellites. These endeavors formed the basis of Canada's space program: they are described by two of the people who were intimately involved in the space activities at the Communications Research Centre of the Department of Communications.

Dr. Irvine Paghis directed the scientific program undertaken with the four exploratory satellites from 1962 until 1969, following which he was program manager for the Communications Technology Satellite developments. Dr. Theodore Hartz was a principal investigator for the Cosmic Noise Experiment on each of the four ionospheric satellites and, after 1973, was chairman of the ISIS Working Group. This book presents their perspective on these programs. The non-specialist should find here a useful description of what was done with the Canadian satellites, why these activities were undertaken and some highlights of their achievements.

These Canadian satellite programs involved the efforts of a large number of people in government, industry and universities and Canadians can justifiably be proud of their contributions. If one person deserves special mention here, it is John H. Chapman. Assistant Deputy Minister for Space in the Department of Communications at the time of his death in 1979, Dr. Chapman was the principal architect of Canada's space program and its driving force for more than 20 years.

The programs were made possible through partnership with the US National Aeronautics and Space Administration and co-operation with several European countries. They were given life through the contributions of experimenters in Canada and in a number of other countries around the world. Initially, the programs were the responsibility of the Department of National Defence. From the earliest phases, however, the civil applications of space technology loomed much larger than the military, particularly those related to communications. Accordingly it was logical to transfer those programs to this department when it was formed in 1969. On this foundation, Canada's space program has been built.

Francis Fox
Minister of
Communications

Ottawa, July 1982

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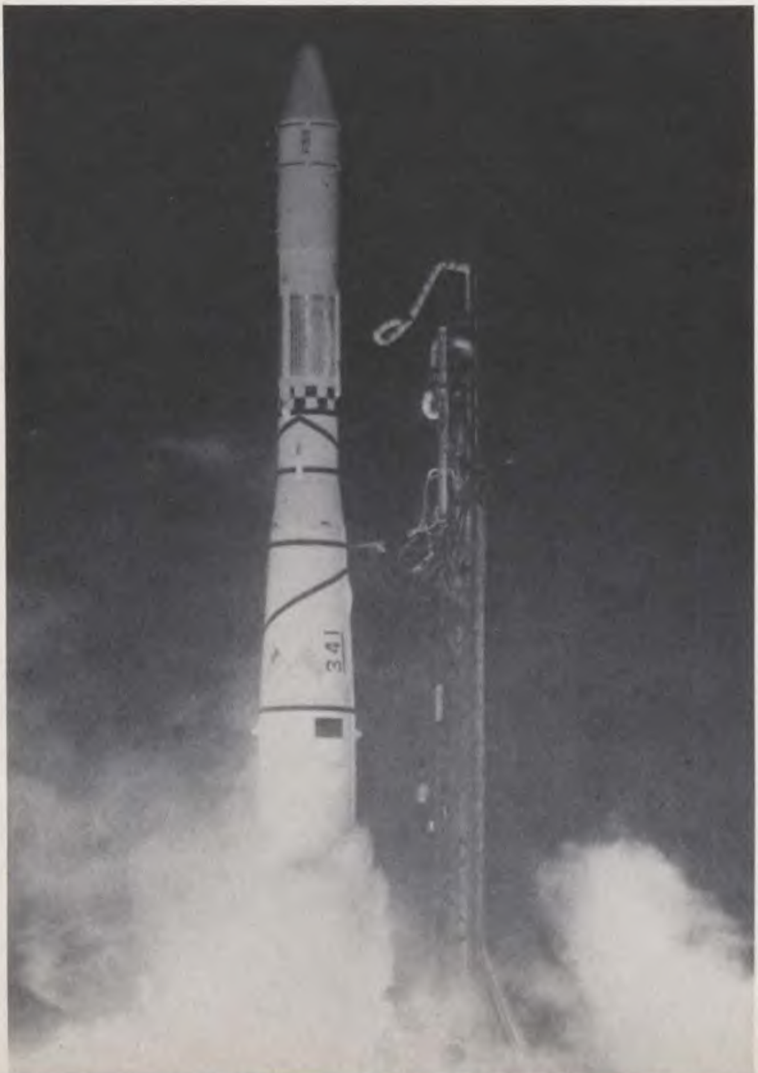
Space: A Canadian Overview

Introduction

Late on the evening of September 28, 1962, with a bone-chilling breeze blowing in from the Pacific, a US Thor-Agena rocket, belching brilliant orange and white flame, lifted off its launch pad in southern California, pushing Canada's first satellite into orbit about the earth and thereby propelling this country into the space age.

Figure 1
Launch of Alouette 1, September 29, 1962. It is customary to describe space activities in Universal Time; in local time, this event took place on the evening of September 28.

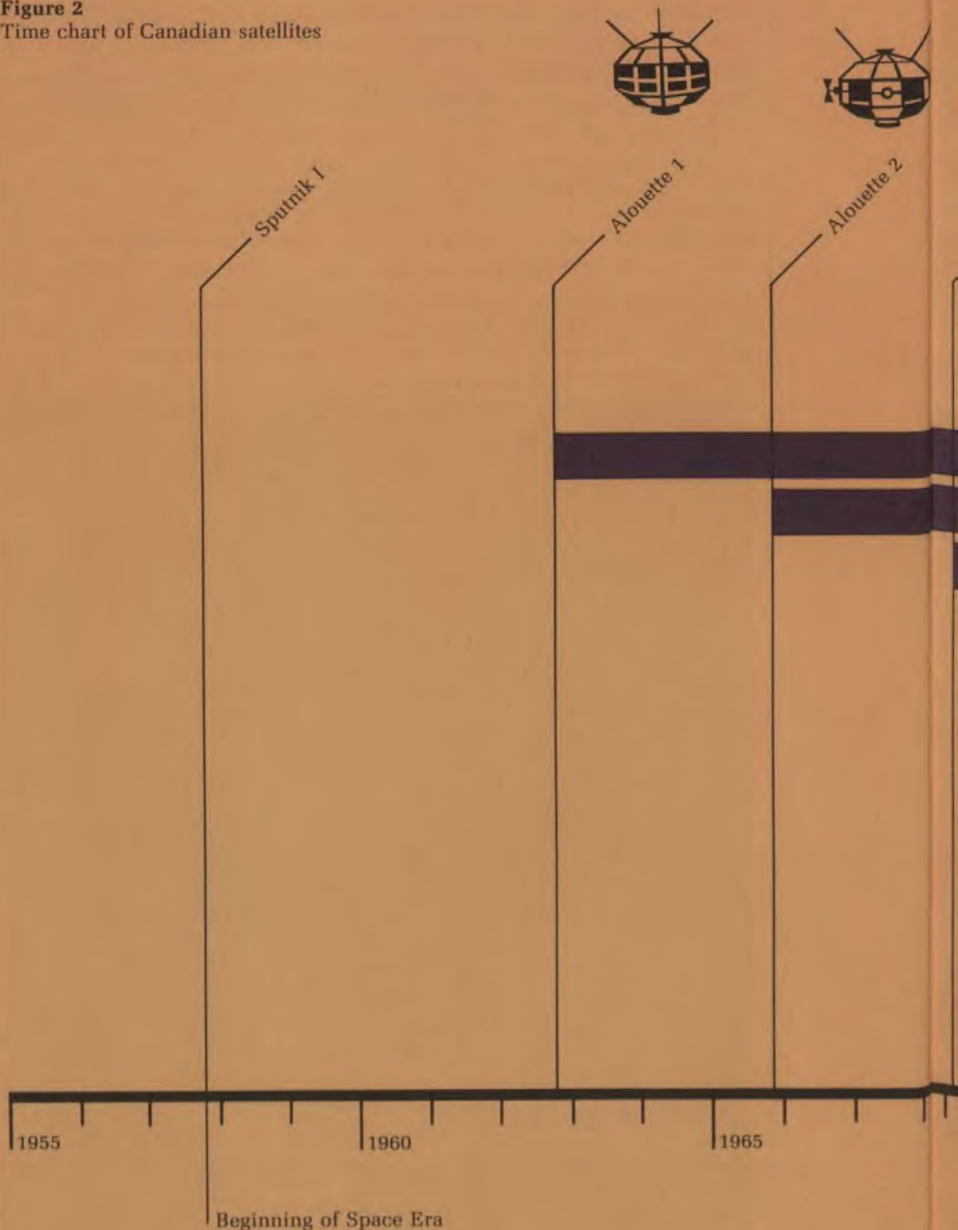


So many satellites have been launched since that notable evening including eight other Canadian ones, that many people have forgotten that Alouette was the first spacecraft entirely designed and built by a nation other than the United States or the Soviet Union.

Why was Canada so keen to compete then in that costly and hazardous activity? Was it likely that we could make a significant contribution with our limited research resources, and what return could we expect? Having been conditioned, as many Canadians now are, to the need to exploit technological and industrial development, we can easily point to favorable answers to these questions. The record will show that Canada's contribution has been significant and there have been substantial economic benefits as well. We have now had a number of outstanding satellite programs whose achievements have won national and international acclaim. One of these is the Alouette-ISIS program which included four Canadian satellites; another is the Hermes program. Both programs have been extraordinarily successful and fruitful; indeed, the position of prominence that this country enjoys in space science and technology is, in very large measure, a direct result.

The space age began a little more than two decades ago with the launch of the Sputnik and Explorer satellites by the Soviet Union and the United States in 1957 and 1958. Those events clearly identified space as a unique environment; they also opened the door to a whole new field of technology by demonstrating that satellites could be used for practical applications as well as for scientific exploration of the environment. Canada quickly decided to become familiar with and use this new technology and consequently undertook the development of the Alouette spacecraft for ionospheric research purposes. That venture's remarkable achievements in both science and technology led to a rapid expansion of Canada's activities in space. It also led to a decision by the government to involve industry in the space endeavors in order to increase our industrial capability and to encourage applications for the benefit of all Canadians. Alouette was followed by a series of experimental satellites identified as ISIS, for International Satellites for Ionospheric Studies. These, together with Alouette and two US satellites, constituted the principal components of the Alouette-ISIS program, which was undertaken jointly with the United States.

Figure 2
Time chart of Canadian satellites



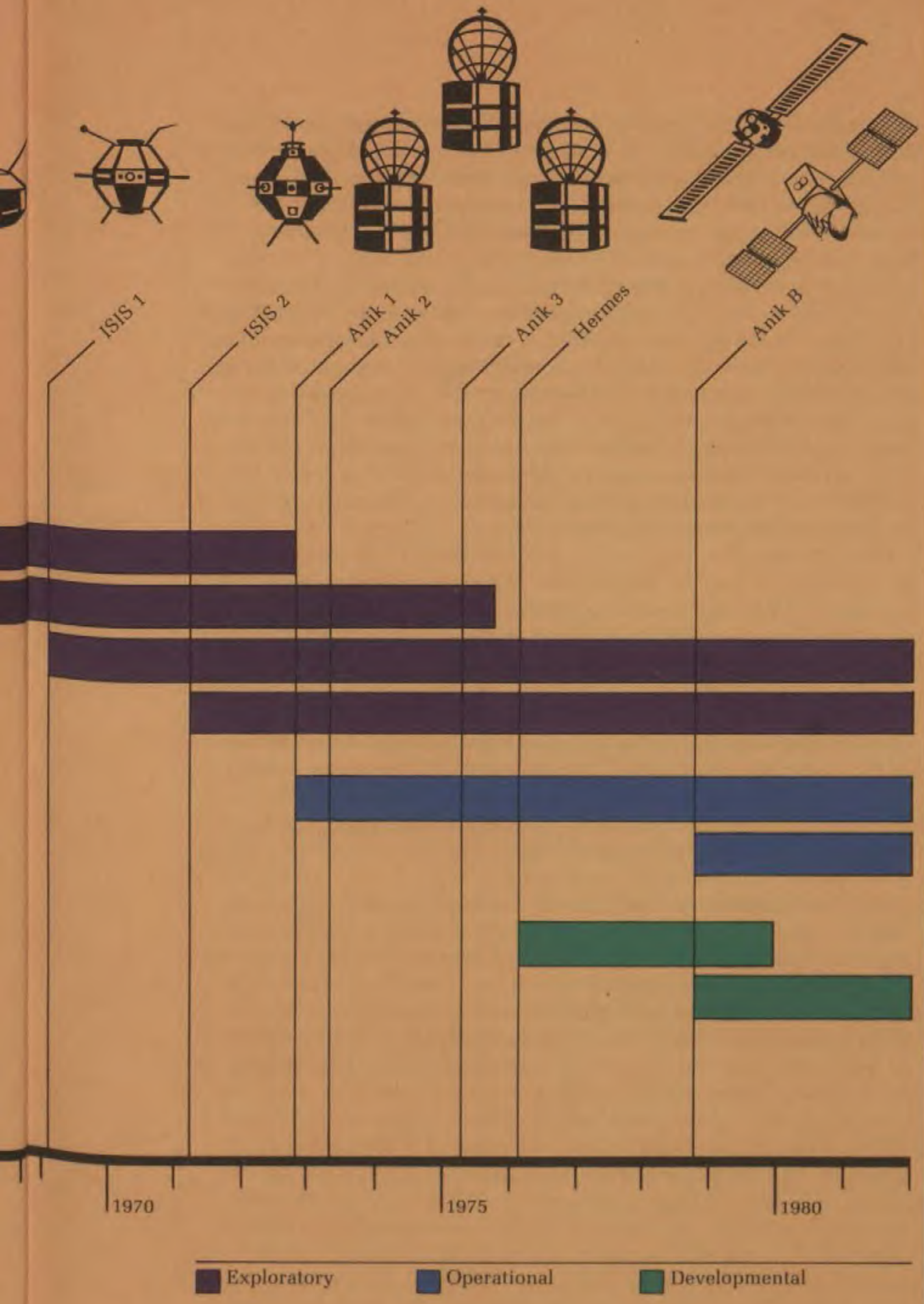
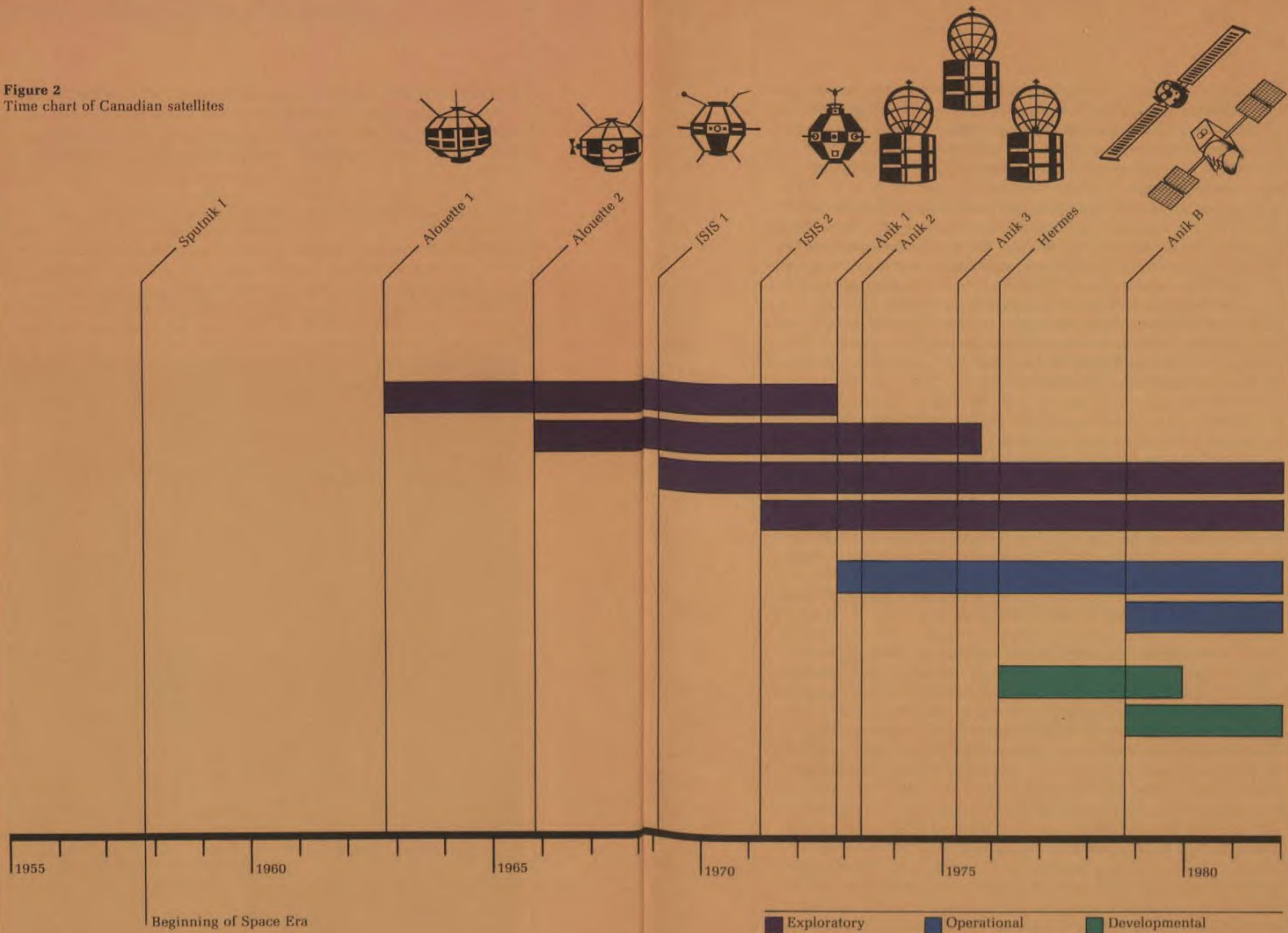

ISIS 1
ISIS 2
Anik 1
Anik 2
Anik 3
Hermes
Anik B
1970
1975
1980
Exploratory
Operational
Developmental

Figure 2
Time chart of Canadian satellites



Before that program came to full fruition, work began on another joint Canada-US experimental program that involved the Communications Technology Satellite, now better known as Hermes. In contrast to the more scientifically oriented objectives of the Alouette-ISIS program, the objectives of the Hermes program were to develop new spacecraft technology and apply it to communications satellite systems. Hermes was launched in January 1976, and was used in a series of communications and technology experiments until November 1979, to demonstrate the value of the newly developed technology for a wide range of communications services. These successful demonstrations led to an expanded experimental program using transponders on Telesat Canada's Anik B satellite, which was launched in December 1978. This latter spacecraft is a successor to the earlier Anik A series of satellites with which Telesat had inaugurated a domestic satellite communications service in January 1973.

At this stage, it may be worthwhile pointing out that satellites can be classified into three main categories, according to their primary purpose. These are: *exploratory*, to uncover basic information about some aspect of our space environment; *developmental*, to develop new technology and to prove or demonstrate feasibility of new techniques or operations; and *operational*, to serve as an essential part of some operation or service, such as communications or weather monitoring. The Alouette-ISIS satellites belong to the first category, Hermes to the second, and the Anik A satellites to the third. Anik B is a hybrid satellite, being partly developmental and partly operational.

As an industrialized nation, Canada has always been concerned with its competitive position. Accordingly, an important Canadian objective in both the Alouette-ISIS and Hermes satellite programs was to stimulate technological innovations and product development. Innovation is here taken to mean the introduction into everyday usage of some new product, method, device or service. In most instances, the innovation process can be said to include three distinct stages and is probably most efficient if all stages can be carried out in close juxtaposition. The *conceptual* stage is concerned with the discovery or establishment of a phenomenon or principle; this usually results from research of a fundamental nature. The second stage is concerned with how to use that information or principle, and how to apply it to a problem or social need; this is the *definition* stage and generally involves applied research or experimental development. The third stage is concerned with bringing a product or process into use; this implementation stage usually depends on the initiative of entrepreneurs, but it involves, as well, various aspects of development, production, marketing and sales. The government also may become involved in the development of new products and services that are not profitable in the short term, but which are justified for other reasons, such as their long-term social benefits. In such cases, the entrepreneurial aspects of the third stage may be delayed until the activity can become self-sustaining.

Most of the early research and development on the Alouette-ISIS and Hermes programs was undertaken in laboratories of the federal government. From the beginning, however, a sustained effort was made to bridge the technology gap from government to industry, not only in communications, but in space technology generally. This effort was designed to stimulate an industrial capability that would, in due course, develop profitable high-technology products and services. Various means were used, including the training of industrial staff in specialized government facilities, the integration of industrial and government engineers in project teams, and federal funding support for industrial research and development.

Such measures, plus the normal market incentives, have brought a number of changes to Canadian industry in the past two decades, and have led to innovations in areas pertaining to space technology. In addition to working on the nine Canadian satellites, industry has sought markets abroad for space components and subsystems produced in this country. Two examples of such developments are the STEM (Storable Tubular Extendible Member) devices developed by Spar Aerospace Limited and the microwave components developed by Com Dev Limited; such products have been important items in the space ventures of other countries. In essence, Canada's space activities have provided new opportunities for industry and have enabled it to build up a high level of competence in many aspects of space technology. The government's continuing involvement in space research and development, however, makes unlikely the rapid replacement of the existing team capability between government and industry by a completely industrial capability.

This book describes the early Canadian space activities. The introduction summarizes our space interests and endeavors, while the second chapter outlines some of the environmental factors and considerations that affect space exploration and applications. The third and fourth chapters describe the Alouette-ISIS and Hermes programs; both these chapters begin with a historical perspective and continue through the various stages of implementation, down to the more recent results. The fifth chapter summarizes some of the key accomplishments of the two programs. Of necessity, the text cannot be comprehensive; so much was undertaken and accomplished in the 23 years since the start of these space programs that only selected highlights can be presented here. Finally, a glossary of technical terms and abbreviations is appended to assist the reader, along with a chronology of significant dates and a bibliography for further reading.

The book presents a Canadian viewpoint. The Alouette-ISIS and Hermes programs were undertaken jointly with the US National Aeronautics and Space Administration (NASA). Moreover, significant additional international participation developed during

Figure 3
Presentation of crossed flags at launch of Alouette 1.

the lifetimes of both programs. For Alouette-ISIS, this included co-operation and collaboration with agencies in the United Kingdom, France, India, Japan, Australia, New Zealand, Norway and Finland. In the case of Hermes, the European Space Research Organisation (ESRO) became a participant about two years after the program began. Four of the six Alouette-ISIS spacecraft and the Hermes spacecraft were designed and built in Canada, and their operations were all controlled from Ottawa.

The Canadian responsibilities for both programs were undertaken by the federal government in its laboratory at Shirley Bay near Ottawa. Originally a part of the Defence Research Board (DRB) and known as the Defence Research Telecommunications Establishment (DRTE), in 1969, when the Department of Communications (DOC) was formed, this laboratory became a part of it and was renamed the Communications Research Centre (CRC). A number of other agencies and organizations were involved in different aspects of the development and the subsequent studies. A few of the principal participants are identified at appropriate points throughout this book but, unfortunately, space does not permit acknowledgement of all the efforts and contributions of the many others.

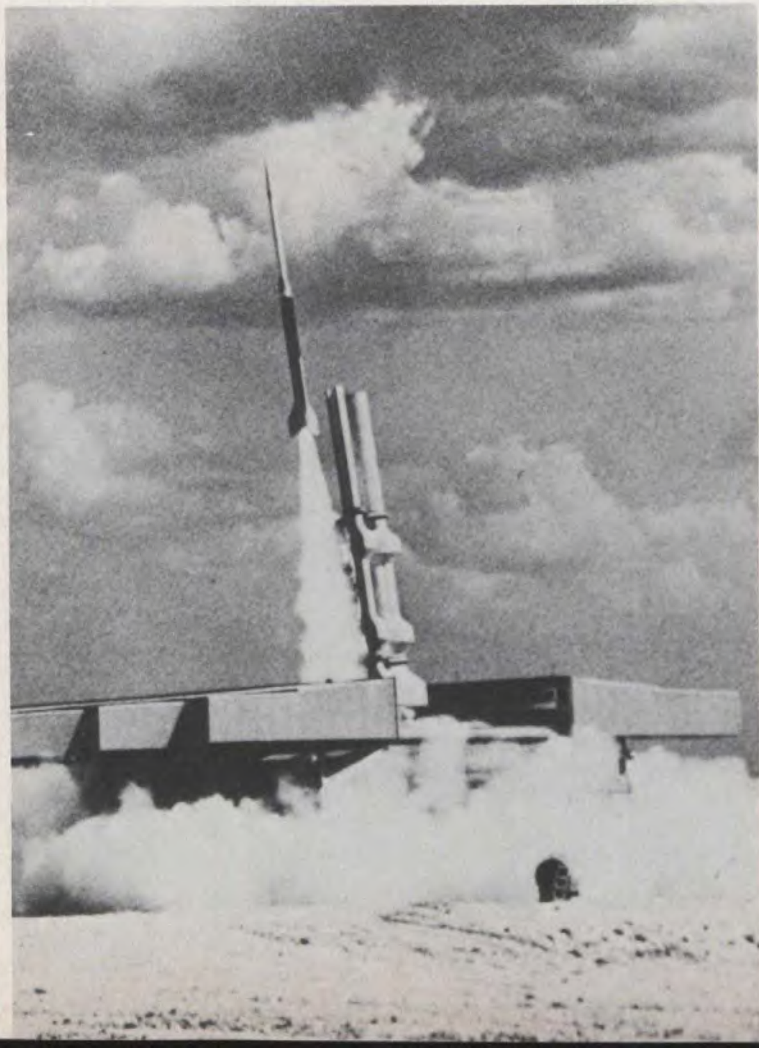
Summary of Canadian Space Activities

The use of satellites for communications has particular advantages for Canada because of its size and sparse population. Resource surveys, ice reconnaissance, weather monitoring and mapping also are much better carried out from space than by conventional methods; those have been so difficult and expensive that, for instance, until 1950 only about one quarter of the Canadian terrain had been mapped accurately. These considerations, and their implications for sovereignty over our vast land area and adjacent oceans, were already being discussed two decades ago as we became aware of some of the early accomplishments of the space programs of the United States and the Soviet Union.

With the successful launch of our own Alouette 1 satellite came the realization that the capability existed in Canada, as well, to build satellites for such applications. The government's decision, however, not to develop satellite launch facilities in Canada because of the large capital costs involved meant that space programs could be undertaken only through an international arrangement with an organization like NASA, as in the Alouette project. Joint arrangements were subsequently negotiated internationally, not only for spacecraft launches, but also for a number of other space activities.

Canadians were active on the fringes of the space game from the start, finding it a rather easy transition because of our earlier experience with high-altitude balloons and rockets. Scientists at DRTE monitored the Sputnik 1 transmissions and were among the first in the world to determine that satellite's orbit. Later, they and their colleagues at the National Research Council (NRC) recorded telemetry data from several US satellites. In due course, both groups became deeply involved in the Alouette 1 experiments. That satellite's successful development and operation

Figure 4
Rocket exploration of the upper atmosphere, Churchill, Manitoba.



demonstrated that there was already a Canadian competence for space activities in the government laboratories, and the federal government was anxious to see this directed to applications which would serve Canadian needs and interests. The 1963 decision to transfer technology to industry during the course of the ISIS program was the first major step in a policy of encouraging a Canadian industrial space capability.

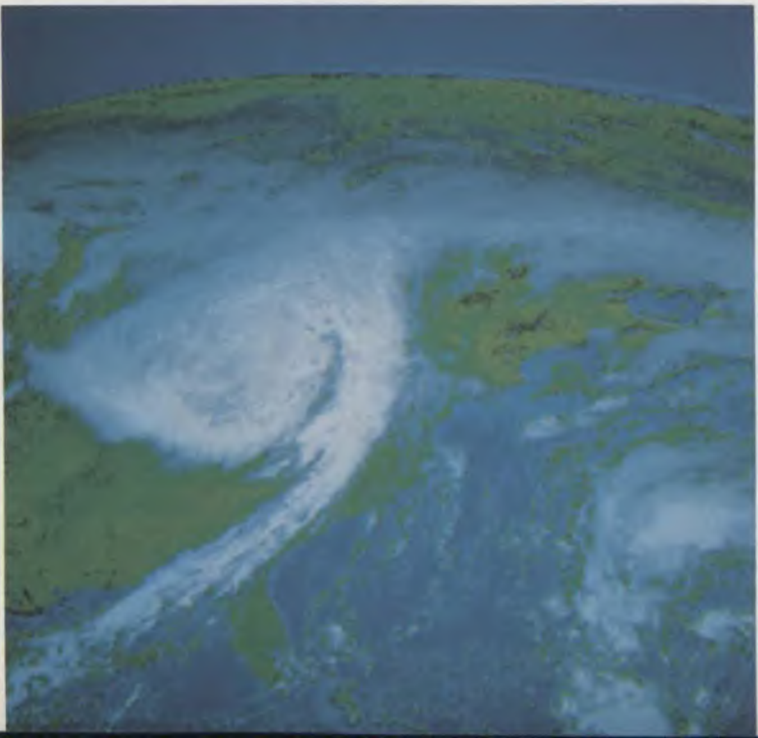
Within weeks of the Alouette 1 launch, negotiations began with NASA for a joint follow-on program that would allow an extensive and thorough exploration of the ionosphere through a variety of experimental techniques. Identified as the ISIS program, this would require a series of satellites that were to be designed and built by Canadian industry under the overall direction of DRTE. The RCA Victor company of Montreal was selected as the prime contractor for the first spacecraft in the series, with de Havilland Aircraft of Canada in Toronto as associate prime contractor. It was planned to use Alouette 2 as a training ground for industry, and industrial personnel commenced work at DRTE in September 1963. The work was deliberately organized in such a way as to transfer to industry, as soon as possible, the design and development knowledge that had been acquired by the DRTE scientists and engineers.

Significant progress in technology transfer was made during the successful rebuilding of the Alouette 1 back-up spacecraft into Alouette 2. This was followed by the ISIS 1 and ISIS 2 spacecraft, for which RCA of Montreal was again prime contractor, with responsibility for the management, design, manufacture and test, while Spar Aerospace Ltd. of Toronto was the associate contractor for certain mechanical aspects of the design. The DRTE involvement was gradually reduced with each successive spacecraft until, in the case of ISIS 2, industry accepted complete responsibility for meeting the performance specifications. As we shall see later in this book, all of the Alouette and ISIS satellites have had exceptionally long and productive lifetimes, thus amply demonstrating the competence of the industries involved.

While the ionospheric satellites were being built and operated, there was a rapidly growing Canadian interest in space applications, and a vying among other government departments for some involvement in space. The collection of meteorological information was an obvious early objective and the Meteorological Service joined with NRC in 1964 to develop ground equipment that could be used to collect data in Canada from the US automatic picture transmission satellites. Later, industry-built equipment was deployed at Toronto and Halifax, and since then, data from a series of US satellites have been used for research, weather forecasting and ice reconnaissance. Most Canadians have now come to expect, as a matter of course, that they will see on their television screens the daily weather pictures obtained from the US spacecraft.

Satellite communications, as already noted, roused an early interest and here again it was found more advantageous to join an ongoing activity than to pursue a separate national course. In August 1963, the Canadian Department of Transport entered into an agreement with NASA which provided for Canadian participation in the testing of experimental communications satellites and

Figure 5
A color rendition of a satellite image showing a weather system over the Atlantic Ocean as received in Toronto from the US Geostationary Operational Environmental Satellite (GOES).



included a commitment to build a ground station. The early US experiments with low-orbit satellites led to the placing of Syncom 3 in a geostationary orbit in August 1964. On the basis of the newly proven technology, an international consortium, Intelsat, was formed to promote and develop international communications via satellites. Teleglobe Canada (then the Canadian Overseas Telecommunications Corporation), a Crown corporation, became the Canadian signatory of the Intelsat interim operating agreement; it now operates 3 earth stations for trans-Atlantic and trans-Pacific communications using the Intelsat geostationary satellites.

Figure 6
Earth station at Mill Village, Nova Scotia.

By 1966, there was a fairly general awareness in Canada that we were involved in the space game, and that there was a growing number of potential space applications that we might address. In typical fashion, this situation prompted the government to create a study group to examine the upper atmosphere and space programs in Canada. Its February 1967 report recommended that the prime Canadian objective in space technology be its application to domestic telecommunications and to resource survey problems. This represented a redirection of the space activities from the scientific to the applied and was to be a significant factor in the Canadian government's decision to terminate the Alouette-ISIS program with ISIS 2, instead of continuing with an additional satellite. The translation of the study group report into positive action proceeded under the critical scrutiny of an eager industry and the unco-ordinated urging of various interest groups. In 1969, an industry-government corporation, Telesat Canada, was created by Parliament to operate a commercial system of satellite communications throughout the country. Key engineers from the Alouette-ISIS program joined this new corporation and helped to plan Telesat's initial system. With the launch of the first Anik in November 1972, Canada became the first country to operate a domestic communications system based on a geostationary satellite. That satellite was followed into orbit in April 1973 and May 1975 by two others in the Anik A series. Each has 12 commercial radio-frequency channels in the 4 and 6 gigahertz (GHz) portions of the radio spectrum. The system as a whole provides service to Canadian customers through more than 100 earth stations scattered over the length and breadth of the country.

The primary structure and the communications electronics payload of the Anik A spacecraft were manufactured in Canada by Spar Aerospace Ltd. and Northern Electric respectively, under contract to Hughes Aircraft, the prime contractor to Telesat. Raytheon Canada and RCA Ltd. supplied the initial earth stations.

Anik B, Telesat's most recent communications satellite, was launched in December 1978. This spacecraft has 12 commercial radio-frequency channels in the band between 4 and 6 GHz, plus four experimental channels in the 12-14 GHz band. These latter experimental channels are leased to the Department of Communications for field trials which are an extension of the successful series of communications experiments and demonstrations begun on the Hermes satellite and which are described elsewhere in this book.

Telesat has ordered two new series of satellites to replace the aging Anik A and Anik B satellites. The Anik C series will operate in the 12-14 GHz band, and the first of three 16-channel satellites is scheduled for launch in November 1982. The Anik D series will operate in the 4-6 GHz band, and the first of two 24-channel satellites is also scheduled for launch in 1982.

The establishment of the first Canadian satellite communications system by 1972 was a major undertaking, and many problems had to be identified and solved. To reduce the cost and have an operational system at an early date, the Anik A system was based on off-the-shelf technology that had been developed in the United States for the Intelsat IV satellites. Technological advances would obviously be needed for future high-powered communications satellites, and Canada wished to participate in the development of such technology and reap some of the industrial benefits. Thus, at the same time as Telesat embarked on the Anik program, the government authorized a new developmental spacecraft, the Communications Technology Satellite (CTS), later known as Hermes. This program was a bold new initiative to design, build and demonstrate advanced technology in the field of satellite communications. It was undertaken jointly with NASA and was aimed at developing high-power satellite transmission in the 12-14 GHz portion of the radio spectrum, which had previously not been used for this purpose.

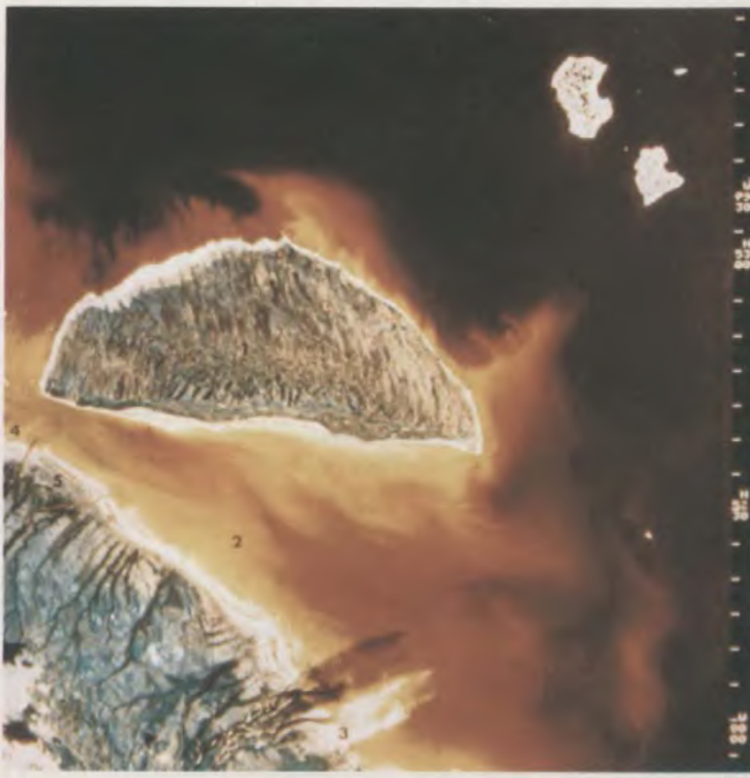
The program began in 1970 and involved a number of industries, including Spar Aerospace Ltd. and RCA Ltd. It also included a formal agreement between DOC and ESRO under which several subsystems and components were provided by ESRO with the help of European industry. On the completion of the spacecraft, some of its functional and environmental tests were carried out in the David Florida Laboratory at CRC. Named after the first program manager of the CTS program, this was a new facility, built to handle all of the Hermes subsystem test requirements. Because this facility was too small at that time to take the entire spacecraft, the qualification tests of the completed Hermes were carried out by CRC personnel at the larger NASA facilities. The David Florida Laboratory has since been expanded so that Canada now has the capability to do integration and check-out of complete communication satellites.

When Hermes was launched in 1976, it was the world's most powerful communications satellite, the first to operate in the 12-14 GHz band and the forerunner of a generation of direct-to-home broadcast satellites. For almost four years, it was used to conduct communications experiments aimed at identifying and satisfying communication needs for the 1980s in both Canada and the United States, as well as performing a number of other demonstrations and evaluations.

The Canadian interest in resource surveys from space had been underlined in the 1967 study group report. At that time, improvements were being made to the sensors on meteorological satellites, and they soon reached the point where they could be used to study the natural and economic features of the earth's surface for resource management purposes. In 1972, the United States launched an Earth Resources Technology Satellite, later named Landsat 1, into a highly inclined orbit from which the terrain of many countries, including Canada, could be surveyed. Canada responded to the opportunity to acquire remote sensing data over this country and, in 1971, set up the Canada Centre for Remote Sensing (CCRS) within the Department of Energy, Mines and Resources. With the assistance of CRC, the large radar station near Prince Albert, Saskatchewan, was converted to a data readout station for Landsat 1. A data handling centre was set up in Ottawa to produce imagery from that satellite and its successor, Landsat 2. Later, a new station was set up at Shoe Cove in Newfoundland to supplement the coverage of the Prince Albert station and to ensure that data could be obtained for the whole of the country. Canada was the first nation after the United States to build earth stations for the reception of Landsat data.

Canada also participated in the US Seasat program, in which satellite-borne microwave radar sensors were used on a trial basis to monitor the ocean surface and to provide updated reports on weather and sea conditions. Microwave imaging radar is capable of penetrating fog and cloud and can operate in darkness; it is of particular interest to this country because of our very long coastline, the ice conditions in the Arctic and on the eastern seaboard, and the long periods of Arctic darkness. The Seasat A satellite was launched in June 1978. During its four months of operation, it provided extremely useful data, proved the effectiveness of the sophisticated radar for monitoring ice and sea conditions, and demonstrated reasonable capability for monitoring shipping. Canada developed both digital and optical processing for the data transmitted by this satellite and produced digital images with the highest resolution of any of the participating countries. To this day, Canada is the prime world source for high quality imagery from this satellite. Recent announcements by the Canadian government of additional support for space technology include provision for further development of remote sensing for resource management and surveillance.

Figure 7
Imagery obtained from Landsat 1 satellite showing silt deposits around Akimiski Island, James Bay. False color is used for the data presentation.



In 1977, the feasibility of a satellite-aided search and rescue system for the location of downed aircraft was successfully demonstrated by Canada using the Amateur Radio Satellite, OSCAR. The work was carried out by CRC with Department of National Defence funding. Subsequently, Canada (led by DND), France and the United States agreed to a joint program, identified as SARSAT, to demonstrate the use of spaceborne technology to detect and locate downed aircraft or ships in distress by means of the transmissions from emergency radio-beacons. This will involve equipping three US Tiros weather satellites, with transponders being designed and provided by Spar Aerospace Ltd. under the Canadian portion of the joint program. Canadian Astronautics Limited of Ottawa is building one earth station for Canada, four for the United States and portions of one for France. A separate Memorandum of Understanding has been signed by the participants with the Soviet Union to provide for that nation's participation in the demonstration and evaluation. For this the USSR will orbit at least one satellite, called COSPAS, having characteristics that are technically compatible with the SARSAT system. The long-term goal is to involve more nations and to establish eventually a system that is accessible worldwide. The SARSAT group has recently entered into another agreement under which Norway will participate as an investigator and the United Kingdom and Japan have made formal applications for investigator status.

The invitation in 1969 for this country to participate in the US Space Shuttle development program led in due course to a joint agreement between NRC and NASA for a co-operative program on a Remote Manipulator System (RMS). The RMS is a remotely-controlled multi-degree-of-freedom arm for the shuttle and is to be used for various manipulations in space, including the deployment of satellites into separate orbit about the earth and their retrieval. NRC undertook to have the design, development, testing and evaluation of the RMS carried out in industry, with NASA being responsible for its integration with the shuttle. Spar Aerospace Ltd. is the prime contractor, supported by an industrial team that includes CAE Electronics, RCA Ltd. and Dilworth, Secord, Meagher and Associates. The development has been conducted by Canadian engineers and technologists and, as a result, a unique capability now exists in this country for remote manipulator systems. The first RMS flight unit, or the *Canadarm* as it is also known, was an outright Canadian contribution, and was successfully tested in late 1981 and early 1982 on the flights of the Space Shuttle, Columbia. Additional units are being purchased by NASA to meet its further requirements.

In concluding this summary, it is appropriate to look again at space science, which had provided much of the early impetus to our space activities. A new co-operative space science program has recently been negotiated with NASA, more than 10 years after the launch of ISIS 2, our last satellite with space research experiments. This new program will include three separate Canadian contributions to missions on the Space Shuttle; various ground-based observations in support of a major NASA study into the origin of plasma in the earth's environment and provision for Canadian participation in future program opportunities. These activities are expected to involve scientists from various agencies within both the universities and the government. Co-ordination and funding will be provided by the Canada Centre for Space Science at NRC.

Organizational Arrangements

Notwithstanding one of the main recommendations in the 1967 study group report on space programs in Canada, this country does not have a space agency and, up to the present, has had no central management for its space activities. Several departments of the federal government are responsible for significant space programs, which have been arrived at by identifying needs pertaining to space within the departmental objectives. Co-ordination is achieved through an Interdepartmental Committee on Space (ICS), which currently reports to the Minister of State for Science and Technology. This committee is supported by a permanent secretariat. Three ICS subcommittees are responsible for the international, scientific and industrial aspects of space policy.

Since most of Canada's space projects have involved co-operation with other nations, the international subcommittee has been very active. It has become involved in such issues as the peaceful uses of space and the remote sensing of one nation's territory by another. It has also been active because of Canadian participation in international organizations and programs, including the International Telecommunication Union (ITU), Intelsat, NASA, the Commonwealth Telecommunications Organization, the European Space Agency (ESA), and SARSAT, among others.

The ICS subcommittee for scientific aspects of space policy is also the Associate Committee on Space Research of NRC. Thus, it advises both the ICS and NRC on scientific aspects of space research, including the special requirements of Canadian scientists.

NRC has recently established the Canada Centre for Space Science (CCSS) to co-ordinate space research activities of the various groups of researchers in government departments and the universities.

The subcommittee on the industrial aspects of space policy is concerned with developing strategies for the maintenance and expansion of a viable space industry in Canada.

Space Communications

Communication via satellite is no longer a novelty. After two decades of space activities, we take for granted live television coverage of major or popular events anywhere in the world, from the maiden flight of the US Space Shuttle, Columbia, to a golf tournament in Japan.

The first satellite communications experiments used *passive* reflectors, to avoid temporarily the problems of developing electronic devices and power supplies that would work reliably in space. The US ECHO project of the late 1950s used large aluminized balloons in low-altitude orbits. Two earth stations could periodically communicate with each other for short intervals when an ECHO balloon was within line of sight of both stations. At about the same time, a somewhat similar approach had been taken in a Canadian experiment at DRTE in which the moon, a very high-altitude ready-made satellite, was used as the passive reflector. In that case, the two earth stations remained within line of sight of the moon and could communicate with each other for much longer periods.

By the early 1960s, space technology had developed sufficiently to permit the design of *active* satellites that could receive signals from earth stations, amplify them and then retransmit the information. The US Telstar I, for example, carried the first trans-Atlantic TV signals in 1962. Satellite altitudes were still relatively low (less than 5,000 km), and the satellite was simultaneously within the line of sight of earth stations in Europe and North America for only a few minutes during an orbit.

Continuous communications via satellite between two fixed earth stations can be obtained either by launching a sufficiently large number of spacecraft, so that at least one is always visible from both stations, or by placing a satellite in a *geostationary* orbit. Each of these approaches has been successfully developed and implemented — the multi-satellite system by the Soviet Union and the geostationary system by the United States. During the

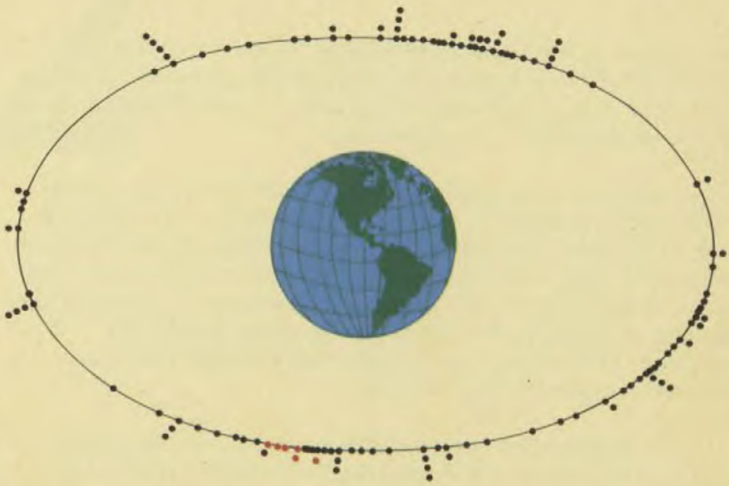


Figure 8
Current orbital locations of geostationary satellites.

past decade, it has become increasingly evident that the latter system has major economic and operational advantages over the former for communications; as a result, it is now being adopted almost exclusively by user countries.

Since modern communications involve interconnected systems (cable, radio, telephone, and so on), especially in a country as large as Canada, it is axiomatic that space systems must interface and coexist with other communications systems. The main tenet of our federal government policy for communications is that the systems and services in Canada be Canadian-owned and regulated. Within this broad policy, two specific space communications policies have evolved:

(a) The government encourages the development of an efficient satellite communications system that is integrated with existing systems.

(b) The government supports the development of a Canadian industrial capability that can provide in this country the communications satellites to meet our needs.

The institutional structures that provide Canadians with telecommunications services, and the associated regulatory agencies are complex, to say the least, but a simplified outline is sufficient for present purposes.

Telephone, television, radio, data and other communications services are provided by a mixture of private and publicly-owned common carriers, some of which are regulated provincially and others federally. Long-distance services are co-ordinated by an association of telephone companies, the Trans-Canada Telephone System (TCTS). Competition to TCTS, particularly in business services, is offered by the Canadian National/Canadian Pacific (CNCP) network. Canada has three east-coast to west-coast terrestrial microwave systems; two are operated by the TCTS members and the third by CNCP. Teleglobe Canada, a government Crown corporation, is responsible for international communications services of all types. Telesat Canada, a commercial corporation owned equally by the government and the carriers, and also a member of TCTS, is responsible for domestic satellite communications services.

2

The Space Environment

The environment into which satellites are launched and in which they must operate is one of the most complicated and challenging known to man. Contrary to popular belief, space is not empty. It is a region in which there is gaseous material but only in extremely small quantities. A number of physical processes that are not commonly observed on earth operate in that near-vacuum. Our understanding of this region has progressed tremendously since the first satellite went into orbit.

In this chapter, we will consider briefly some features of the space environment that shaped the development of early spacecraft. We will discuss, in turn, the environment of the earth, the general nature of satellite orbits, and the interaction of spacecraft with the environment. In these discussions we deal only with earth-orbiters, as opposed to space probes, such as those to Mars or Jupiter.

The Environment of the Earth

The earth has an extensive and very complex environment that includes a gravitational field, a magnetic field and a vast gaseous atmosphere. These three components are important in any understanding of physical phenomena near the earth, particularly in that portion of space known as the earth's ionosphere. The environment of the sun is also important in this regard, influencing the earth's environment and merging with it at the greater heights.

We can look at the earth's environment in several different ways. The earth-bound observer is aware that atmospheric density and pressure decrease systematically with increasing height because of the diminishing influence of gravity. Changes in composition of the atmosphere set in above a certain altitude where the molecules become dissociated into atoms by solar ultra-violet radiation. The atoms, and even some molecules, may be ionized by the ultra-violet radiation. In this process of ionization, an electron is liberated, leaving a positively charged ion in place of the neutral particle. The free electrons and the positive ions, always influenced by gravity, then become subject to the magnetic field as well, and their motions to a large extent are controlled by it.

Fundamentally, the earth's magnetic field is dipolar, much like that of a bar magnet. Conventionally, it is represented by lines of magnetic force in the form of large loops that link the two poles. In the upper atmosphere, the charged particles spiral around such lines of magnetic force. At heights where the atmosphere is sufficiently dense that particle collisions are frequent, the ions and electrons can be considered *en masse* and the trapping influence of the magnetic field on individual particles is not of primary concern. At greater heights, collisions are less likely and the field is a dominant factor in determining the distribution of the particles. At those heights, the geomagnetic field is like a container separating the ions and electrons associated with the earth from those that move freely in interplanetary space.

The height region in which there exist significant numbers of ions is known as the ionosphere. There are no definite boundaries or limits to the ionosphere; it is a dynamic region in which neutral particles are ionized, and ions combine into neutrals again. The degree of ionization changes with time and location and is influenced by such factors as the sun's radiation, atmospheric composition, pressure and temperature. In general, ionization exists to a greater or lesser degree throughout the height region from about 60 km to some 10 earth-radii. These limits depend on an arbitrary measure of significance: the lower limit occurs where the atmosphere is so dense that solar ultra-violet radiation cannot penetrate to produce measurable ionization, while the upper limit occurs where the atmosphere is so rare that there are relatively few particles to ionize. At some intermediate height, the concentration of ions (that is, the number of charged particles per unit volume) becomes a maximum; this is also known as the *electron number density* maximum and is generally found to be near a height of about 300 km.

Now if, the observer's vantage point were changed so that the earth's atmosphere could be viewed from some point in space, the influence of the sun could be more readily appreciated. There is a continuous outflow of charged particles from that body, which is called the solar wind. The earth, with its magnetic field, presents an obstacle to the solar wind. The streaming charged particles, often referred to collectively as a *plasma*, cannot readily penetrate the geomagnetic field, except in the vicinity of two rather localized areas near the poles. The solar wind, however, is capable of deforming the geomagnetic field in its outer regions, and has permanently changed its primordial dipolar shape by compressing it somewhat on the sunward side and stretching it substantially on the night side into a long trailing tail. The interaction between the solar wind and the earth's *magnetosphere*, as this elongated mantle is called, is complicated, and is made all the more so by the continual pressure fluctuations or gustiness of the solar wind. By processes that are not at all clear, some of the solar particles and various effects of these interactions are transmitted along the geomagnetic field lines and become manifest at the higher latitudes as changes in ionization in the lower ionosphere, as magnetic storms and as visible aurora.

In much the same way as the low-energy particles are trapped by the geomagnetic field, energetic charged particles also may become trapped by the field. Such particles have been known historically as *cosmic rays*, and the discovery of zones about the earth so populated led to their designation as radiation belts. Usually named Van Allen belts after their discoverer, they are essentially regions where energetic particles, originating in the magnetospheric tail, or on the sun, spiral about the magnetic field lines that link one hemisphere to the other. The angle of the spiral (the pitch angle) changes in regions of increasing magnetic field, in such a way that the spiral becomes a circle and then reverses its direction. Thus the particles bounce back and forth between hemispheres while all the time continuing to spiral about the field lines. As a consequence, they remain trapped until a particle collision occurs, then they lose energy and become part of the ion population.

Some of the most fascinating research problems in physics relate to the magnetosphere, how it interacts with the solar wind and the interplanetary magnetic field, what physical processes go on within it, and how it interacts with the underlying dense atmosphere. From this point of view, the ionosphere is at the transition between the neutral atmosphere and the magnetosphere. On the one hand, it is atmosphere-like in that the particle concentrations are high, whence particle collisions are sufficiently frequent that the transport of ionization is of only secondary importance to the processes of ionization and recombination. On the other hand, the ionization in the upper ionosphere, and particularly in the polar regions, can move rather freely along the geomagnetic field, and, in consequence, these regions have magnetosphere-like properties.

Figure 9
The aurora borealis over Churchill, Manitoba.

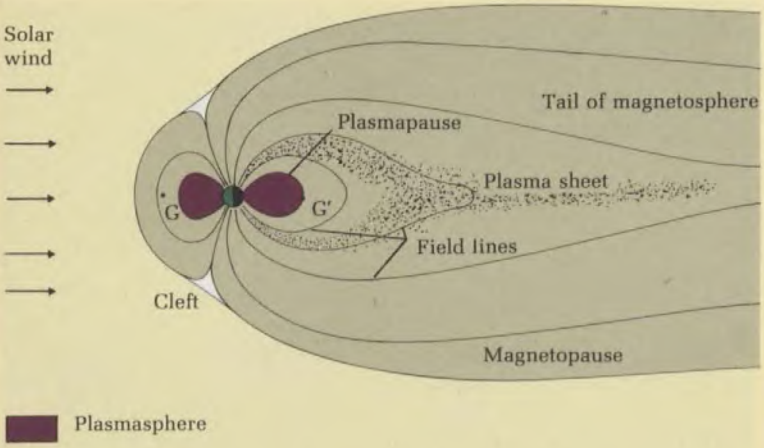


Figure 10
Diagrammatic cross-section of the magnetosphere. The points marked G and G′ at about 6 earth-radii show the approximate location of satellites in geostationary orbits.

A representation of the magnetosphere is shown in Figure 10. This depicts a planar section through the earth and through the near tail of the magnetosphere. The configuration is that of the geomagnetic field lines; within about one or two earth-radii of the surface, these have the characteristic shape of field lines for a dipole magnet. At the greater heights, the stretching into a long tail can be seen on the night side with some compression on the day side. Other characteristic features to note are the *cleft*, which marks the separation between field lines that close on the sunward side of the magnetosphere and those that stretch far into the tail; the *plasmasphere*, a denser plasma region with field lines that show little change with time of day; the *plasmapause*, the outer boundary of the plasmasphere; the *plasmasheet*, which is the inner portion of the tail just beyond the plasmapause; and the *magnetospheric* tail.

Since the configuration of the geomagnetic field has a controlling influence on most of the physical processes in the magnetosphere and the upper ionosphere, workers have found it convenient to use a co-ordinate system based on the magnetic field. *Geomagnetic latitude*, in particular, is widely used; in its simplest form, a dipolar field is assumed, the two poles are located on the earth's surface and latitude is measured uniformly relative to them. Where non-uniformities of the geomagnetic field are an important consideration, this simple geomagnetic latitude is often replaced by a so-called *invariant latitude* system that incorporates the non-uniformities. The distinction between these two systems, however, is usually not too great.

The altitude regions of primary interest in the Alouette-ISIS program extend from about 100 km to some 3,500 km. The bulk of the ionosphere is contained within these limits, while the magnetosphere generally is considered to be well beyond. The distinction, however, is not always very precise, particularly in the polar regions where the geomagnetic field is nearly vertical; there measurements made with satellite-borne instrumentation often lead to interpretations that apply much beyond the vicinity of the spacecraft. The Hermes satellite, on the other hand, was located at an altitude of some 36,000 km, which placed it well out in the plasmasphere and magnetosphere.

Satellite Orbits

Some people find it difficult to understand the concept of orbiting satellites and the apparent anomaly that they do not fall to the ground. In fact, satellites in orbit are continually falling in the earth's gravitational field. Just as a cannon ball fired from a hilltop in a horizontal direction will fall to the ground in a gently curved trajectory, so a spacecraft launched horizontally by a powerful rocket will describe a gently curved trajectory under the influence of gravity. If the rocket velocity is correctly chosen so that the curvature of that trajectory matches the earth's curvature, the spacecraft will orbit the earth. Of course, the rocket must first take the satellite above the dense atmosphere to where injection into the chosen orbit can occur. The velocity of injection is critical: where a certain velocity will result in a circular orbit, a somewhat lower one will mean that a stable orbit is not achieved and the satellite will return to earth. On the other hand, a somewhat higher velocity will result in an elliptical orbit, in which the satellite altitudes will range between some minimum and maximum values that are designated the perigee and apogee heights respectively.

Some of the most critical parameters in achieving a particular predetermined orbit for a satellite are the total weight of the spacecraft, the thrust capability of the rocket — which is related to its fuel load — and the direction in which the rocket is launched in relation to the direction of the earth's rotation. Almost invariably, a multi-stage rocket is used. The first stage provides the lift through the dense lower atmosphere, and the last stage imparts the final thrust at the right time and in the right direction to place the spacecraft in the desired orbit. In each case, the satellite mission determines the most appropriate orbit; thus, in the case of the Alouette 1 satellite, for which operations at high latitudes were required, the angle between the orbital plane and the earth's equator was chosen to be close to 80° (see Figure 11).

The Alouette 1 orbit was almost exactly circular at an altitude of about 1,000 km. Its 80° orbital inclination meant that it could explore all latitudes, except for a small circle around each of the earth's poles. The orbital period was about 105 minutes; this was the time it took Alouette 1 to make one complete circuit around the earth, during which the earth rotated some 26° in longitude. For a satellite in a circular orbit, the orbital period increases with increasing altitude. Thus, at about 36,000 km, the orbital period is 24 hours, and further increases in height lead to still longer orbital periods. The moon, for example, at an altitude of about 384,400 km, has an orbital period of approximately 29 days.

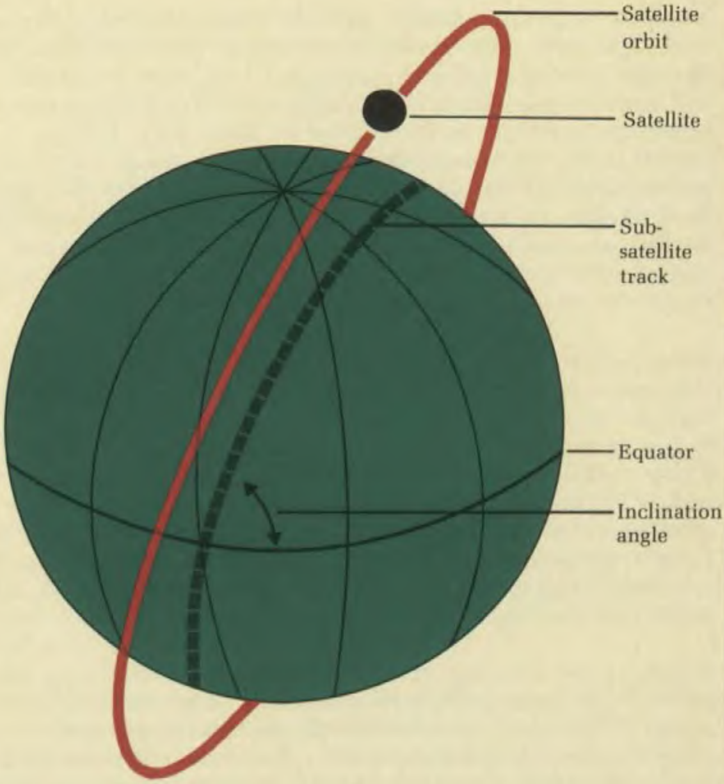


Figure 11

Diagrammatic representation of a satellite in an elliptical orbit about the earth

Because of its correspondence with the rotation period of the earth, a 24-hour orbit has some very useful properties. Thus, an eastward moving satellite in such an orbit with a 0° inclination will circle the earth directly above the equator and will appear to be stationary relative to an observer on the surface. Such a satellite is described as *geostationary*, and it is one of a class of *synchronous* satellites. In practice, minor perturbations may cause these satellites to drift slowly from a chosen position. This drift is usually corrected with small on-board jets. Such small jets can also be used to change a geostationary satellite's location over the equator to some different longitude.

If the inclination of a 24-hour orbit differs from 0°, the satellite will appear to move north and south of the equator at about a constant longitude between latitude limits corresponding to the degree of inclination. Another useful synchronous orbit is a 12-hour elliptic orbit, ranging in height between about 500 km and 39,000 km, and having a high inclination. For about seven or eight hours, while such a satellite is approaching and receding from its apogee and is therefore moving at its lowest velocity, it will remain high in the sky for a high-latitude observer and will move only very slowly across his field of view.

Clearly, there are many options in choosing a satellite orbit and, in each case, mission objectives determine which one will be selected. The major economic advantage of a geostationary satellite is that the associated earth stations can use simple fixed antennas, whereas expensive steerable antennas are required for most other satellites. Not all parts of the globe, however, can be viewed from a geostationary satellite; coverage cannot extend beyond a latitude of about 80°. For communications or earth-resource surveys beyond that limit, some other choice of satellite orbit must be made.

The orbits of the four Canadian satellites in the Alouette-ISIS program are summarized in Figure 12. Since their mission was to explore the ionosphere, these satellites operated over a range of heights and latitudes appropriate for that purpose. The Hermes spacecraft, on the other hand, was a communications satellite and was therefore placed in a geostationary orbit; it was initially positioned at a longitude of 116°W so that its antennas could provide coverage for locations in Canada and the United States. By contrast, it is interesting to note that the Soviet Union's Molniya communications satellites were placed in a 12-hour synchronous orbit.

Figure 12
List of Canadian satellites in the Alouette-ISIS program.

	Launch date	Termination of operations	Perigee & Apogee heights (km)	Inclination (°)
Alouette 1	Sept. 29, 1962	Sept. 30, 1972	996-1032	80.5
Alouette 2	Nov. 29, 1965	Aug. 1, 1975	502-2982	79.8
ISIS 1	Jan. 30, 1969	—	574-3522	88.4
ISIS 2	March 31, 1971	—	1355-1424	88.1

Environmental Factors for Satellites

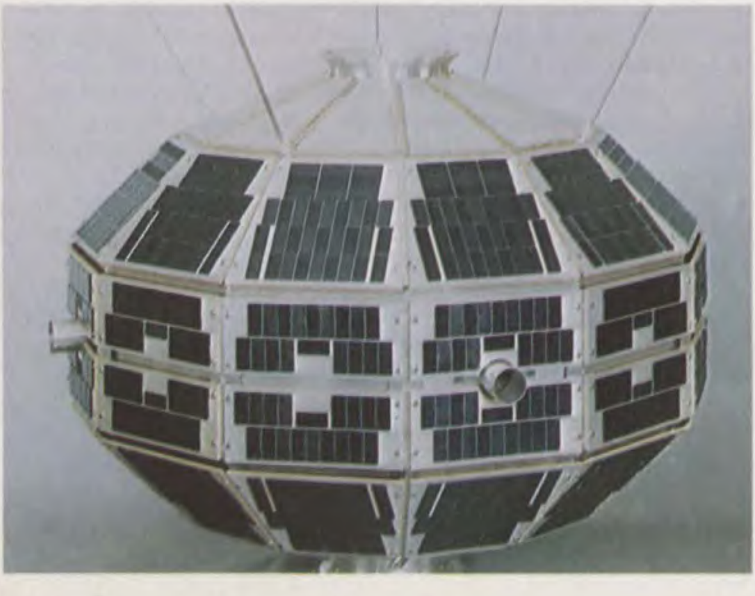
Spacecraft behavior is influenced by many environmental factors and over the years designers have learned how to accommodate for each. The more important environmental constraints that shaped the design and operation of the Alouette, ISIS and Hermes satellites are summarized below.

Measures must be taken to stabilize an orbiting spacecraft so that its orientation is optimum for the intended operation of the on-board equipment. Stabilization was provided for the four ionospheric satellites by spinning them at about two or three revolutions per minute. In the case of Alouette 1, the spin rate decayed in orbit much more rapidly than expected with the result that stability was lost prematurely. Fortunately, this did not seriously affect the operations, and the satellite continued to produce data of excellent quality. The unanticipated spin loss was apparently due to a combination of thermal distortion of the long dipole antennas, solar radiation pressure and atmospheric drag. Reflective plates were placed on the ends of the Alouette 2 antennas and these reduced the spin-decay effects on that satellite. For the ISIS satellites, special coils were installed around the spacecraft which, when electric current was caused to pass through them, could be used to increase the spin rate of the spacecraft. These coils were also used to change the orientation of the spin axis.

The Hermes satellite had an on-board three-axis stabilization system which maintained a fixed orientation for the spacecraft. This system included a momentum wheel and small jets of hydrazine gas; it operated to correct any pointing errors determined by orientation sensors directed at the earth and the sun.

The spacecraft were powered by batteries which received their charge from a large number of solar cells. For the Alouette and ISIS satellites, the solar cells were arranged in panels mounted on the outer surface of each spacecraft so that some number of them continued to function throughout each revolution. For Hermes, the solar cell panels were in the form of long wing-like structures on either side of the spacecraft. Because this spacecraft maintained a constant orientation relative to the ground, the panels were rotated throughout each 24-hour interval so as to always face the sun. For both types of orbit, there were intervals during which the sun was eclipsed by the earth and no charging current was produced by the solar cells. At such times, the spacecraft functions were completely dependent on the batteries.

Figure 13
Alouette 1 spacecraft showing solar cells on its surface. The long dipole antennas are not extended, and only the antennas for the telemetry and command functions are visible.



A spacecraft is designed to operate over a wide range of on-board temperatures. The overall temperature depends on the balance between heat generated internally and heat absorbed or radiated by the external surfaces. The medium surrounding a spacecraft is almost a complete vacuum, so that very little heat is conducted to or from the spacecraft; heat is transferred by radiation. The main source of radiation heating is the sun, with minor contributions from the earth; heat loss is primarily by radiation to the near-absolute-zero-temperature cosmos. There are major differences between the thermal design of a spin-stabilized spacecraft such as Alouette, whose surfaces are alternately heated by the sun and cooled by radiation to the cosmos, and a three-axis stabilized spacecraft, such as Hermes, one side of which is continuously exposed to the sun while the other side is freezing. Thermal design for spacecraft has become a highly specialized skill, the main objective of which is to ensure that all systems operate reliably. Accordingly, hot and cold temperature limits appropriate to selected internal locations are specified, and temperatures are maintained within these limits by a judicious choice of spacecraft configuration, surface reflectivity and emissivity, configuration of internal heat sources, internal heat conduction channels and insulation.

When a conductor moves in a magnetic field, a voltage is induced on it. This principle is applied extensively in the generation of electricity. It applies, as well, to metallic spacecraft orbiting in the earth's magnetic field, and the potential generated in such cases is proportional to the dimensions of the satellite. In the Alouette-ISIS program, the longest satellite antennas were 73 m from tip to tip, which meant that significant voltages were induced on the antenna elements. Special measures were taken with ISIS 1 and 2 to isolate their antennas from the spacecraft body so that the induced voltages would not affect the sensitive probes and detectors mounted on the satellites' surfaces. Since these satellites were always immersed in ionization, electric currents could flow to and from the ionosphere to prevent any significant accumulation of charge on the surface of the spacecraft.

The Hermes satellite, on the other hand, was located at a height where the ionization densities are extremely low. In that situation, electric currents to the surrounding medium are unlikely to be strong enough to remove all the charges that accumulate on the satellite's surface because of induced voltages or the direct ionization effects of sunlight. Because spacecraft surfaces have various irregularities and discontinuities, such charges are not uniformly distributed. This may lead to localized discharges or arcing on parts of the surface, which may produce harmful effects in the satellite's electronic systems. These include radio static which can interfere with the command receiver, surges on the power system which can harm the switches and relays, pulses on the logic system which can introduce false commands and cause improper functioning of on-board computers and electronic circuits, and physical damage to components due to voltage breakdown.

Spacecraft charging is now recognized as a serious space hazard. It is by no means well understood, but some preventive measures are already being introduced into satellite designs. In the past, mysterious gremlins have upset the operations of a number of satellites for short intervals and, in at least one case, a complete spacecraft failure was attributed to spacecraft charging. Though alerted to this phenomenon, the Hermes designers were able to incorporate only one or two preventive measures on that spacecraft, but no diagnostic equipment was included other than an impulse counter to monitor discharges. Because of this, there is no way of knowing for certain whether Hermes suffered in any way because of spacecraft charging, though at least one glitch — a sudden loss of about 15 per cent of the array power — is thought to have been caused by a static discharge.

Figure 14
Alouette 1 with ionosonde antennas fully extended.

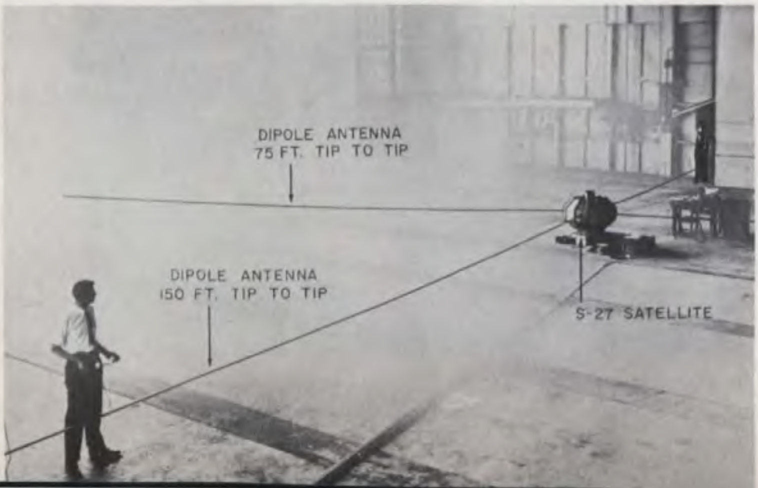


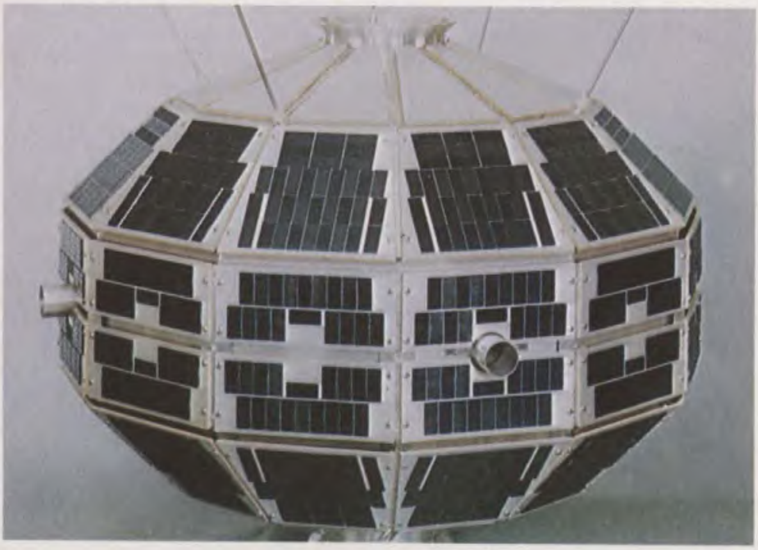
Figure 15
The Ottawa ground station.

In concluding this brief summary of environmental factors, it is worth emphasizing that each satellite is only one component of a system that includes one or more earth stations. Such stations may serve to control the satellite functions or merely to monitor satellite transmissions and relay transmissions to and from the satellite. In the former case, in addition to sending out the required commands, the station also monitors and maintains a record of the satellite's location, orientation and the status of onboard equipment and facilities. Low-altitude satellites, such as ISIS, that are within line of sight of a station for only 10 to 20 minutes at a time, may operate with many earth stations of both types located around the world. Spacecraft in a geostationary orbit, on the other hand, are within line of sight of some 40 per cent of the surface area of the earth, and may operate with any earth stations in that area, but will usually have only one control station.

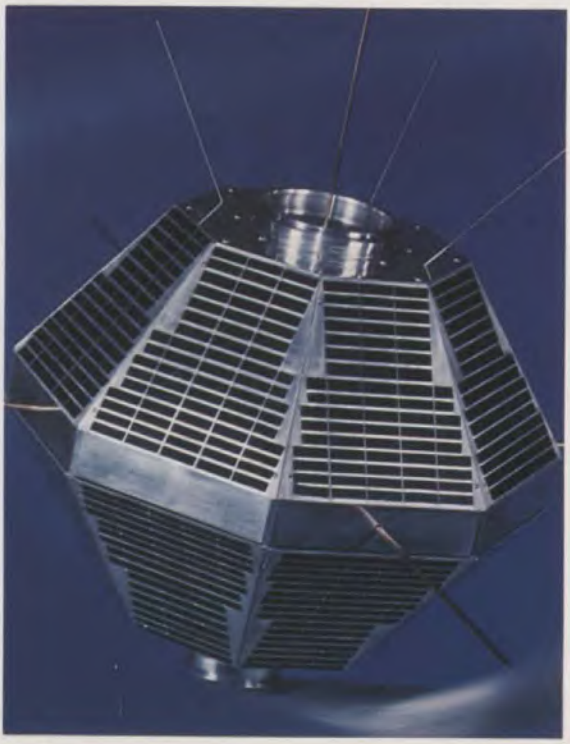
3

The Alouette-ISIS Program

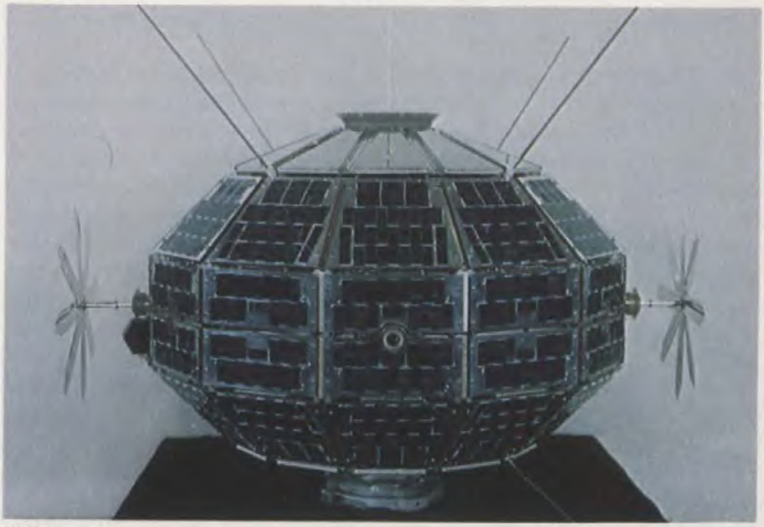
Figure 16
Alouette 1



ISIS 1



Alouette 2



ISIS 2

Introduction

Throughout countless ages, the inhabitants of this planet have gazed at the sky on cloudless nights and speculated about what might exist "out there". Even to this generation, many of our myths and beliefs stem from limited astronomical observations and a preoccupation with the heavenly unknown. The advent of the space age was an event of great significance in that it enabled man for the first time to engage in direct exploration of the regions remote from the surface of the earth. This he can now accomplish by sending instruments — or even observers — out into space for long periods of time, choosing where they go, controlling their operation and receiving back on the earth the acquired observations. After a quarter century of space activity, we are likely to take such endeavors for granted; however, they constitute a remarkable achievement in human progress. Now that modern technology has given us the means, we can explore the environment of the earth and some of the more distant regions of space, and can try to satisfy our curiosity about the universe and our place in it.

Canada was one of the first countries to embark on space exploration endeavors. A year after the first Sputnik launch, plans were already being prepared for our first space venture, and this was the third country, after the Soviet Union and the United States, to produce a satellite of the earth. The launch of Alouette 1 came barely five years after the space age began, and was so successful that an expanded Canadian space program was a logical consequence. There followed the series of ISIS satellites that have operated over almost two decades to produce an immense fund of knowledge about the earth's ionosphere and related aspects of the upper atmosphere. By almost any criteria, the Alouette-ISIS program must be considered one of the most successful space programs to date.

This chapter starts with a brief overview of earlier ionospheric research leading up to the satellite experiments. It goes on to describe the Alouette-ISIS program and summarizes some of its principal accomplishments. The description includes a brief summary of the roles played by the main participating organizations and agencies; although the Alouette and ISIS satellites were built in this country, and more than half of the principal investigators were Canadian, the program was a joint US-Canadian venture, with active participation by 10 other countries. This international aspect was deliberate; the ionosphere is global in extent and an understanding of its features and behavior can best be achieved through comprehensive studies that involve investigators from around the world.

Early Ionospheric Studies

One of the most significant events in the history of radio occurred on December 12, 1901, when Guglielmo Marconi received a Morse signal in Newfoundland from a transmitter 2,900 km away in England. Although the evidence could not be denied, no one could then understand how radio waves were able to travel so far beyond the horizon. An explanation came the following year when Arthur Kennelly and Oliver Heaviside suggested the existence of a conducting layer in the upper atmosphere capable of reflecting radio waves, thus enabling them to travel great distances beyond the line-of-sight horizon. Their ideas started a long series of studies to try to define the origin and nature of what for years was called the Kennelly-Heaviside layer, but which we now know as the ionosphere.

While those studies were being pursued, the simple fact that radio waves could travel great distances was a sufficient basis for the commercial exploitation of wireless for communications. Much empirical experience was accumulated from such practical use in a number of countries, but almost 25 years went by before there were any very systematic studies to determine the properties of the ionosphere. By then, it had become obvious to the communicators that they needed to know much more about what was happening to the radio waves. Wireless radio traffic was turning out to be haphazard and, at times, impossible because the effect of the ionosphere on the radio waves was difficult to understand and to predict. A better knowledge of the ionosphere was essential, and this was made possible with the introduction of a new tool, the pulse ionosonde, which resulted from the work of G. Breit and M.A. Tuve in the mid 1920s. That development was probably the most important single achievement in ionospheric research.

An ionosonde is essentially a radio transmitter-and-receiver combination, which functions on the established principle that a concentration of ionization is capable of reflecting radio waves. On illuminating the ionosphere with short pulses of radio waves of varying frequency and noting the time difference between the transmission of a pulse and the return of an echo, one can deduce the height of the reflecting level. The particular frequency reflected is determined by the degree of ionization at the reflecting level. Thus, by noting the frequency of the wave reflected along with the pulse delay, one may obtain the height level in the ionosphere of that particular electron number density.

The electron density increases with height in the lower ionosphere. If a particular frequency is reflected at one level, a slightly higher frequency will travel almost unaffected through that level, but will be reflected somewhat higher up. If the transmitted frequency is systematically increased, the resulting sequence of delay times will provide a profile of the ion distribution in the ionosphere beneath the level of maximum ionization. The profile obtained in this way is known as an ionogram; it customarily shows *apparent heights* that are deduced from the observed pulse delay times by assuming propagation at the speed of light. Modern computing techniques now make it feasible to determine the actual velocity of the radio waves along the entire propagation path and thus to compute the real height of the reflecting region or regions; when this is done, real-height ionograms are obtained. Figure 17 illustrates the situation described here and also shows a simple representation of an ionogram that includes two reflecting layers.

In practice, ionograms are more complicated than this example. Radio waves in the ionosphere propagate in two modes that have different polarizations and different velocities, each of which results in a separate trace on the ionogram. Other complicating features are introduced by multiple reflections, by scattering from small-scale structures and by the presence of ledges or of additional ionization maxima below the main peak.

Following the development of the ionosonde in the United States, scientists in many countries became active in ionospheric studies, largely because the developing field of electronics made such studies possible. Detailed measurements established that there were at least two ionospheric layers, identified as the E and F layers, capable of reflecting radio waves, with the former appearing as a ledge on the bottom of the other, more dominant layer. They also demonstrated that there were many occasions when reflections could not be observed and that the ionosphere was anything but dependable.

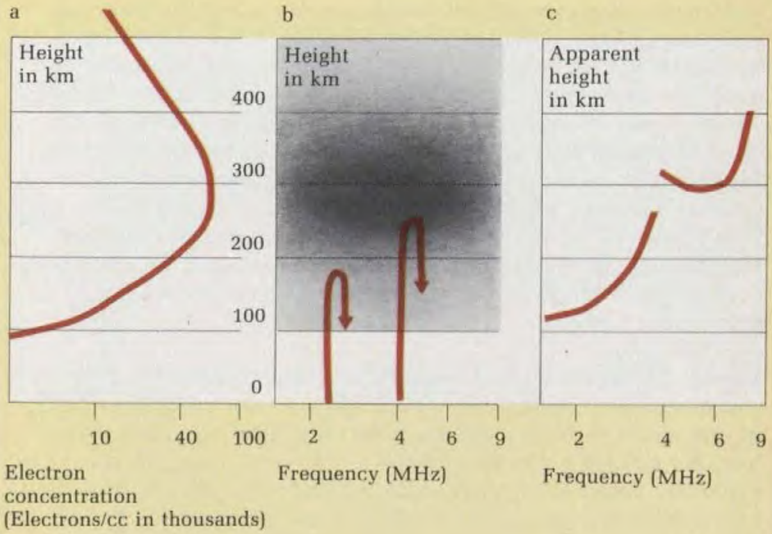


Figure 17
(a) A representative electron density vs. height profile.
(b) Diagrammatic representation of sweep-frequency sounding of ionosphere, showing the greater penetration as the frequency increases until no reflection occurs.
(c) The ionogram for a single propagation mode and for the electron distribution shown in (a).

In Canada, some ionospheric work was started at the National Research Council (NRC) in the early 1930s, but no systematic studies were undertaken until World War II when it became evident that improved communications were needed in the Atlantic. At the higher latitudes, serious communications disruptions and radio blackouts were common, and almost all were unpredictable. Accordingly, in 1941, NRC built and installed an ionosonde at Chelsea, Quebec, where it was used by a small group under F.T. Davies to predict optimum operating frequencies for communications. In the next few years, further stations were opened so that, by 1945, there was a network of seven ionosondes throughout Canada.

Similar developments had occurred in other countries to support communications needs, and a rudimentary international network of ionosonde stations existed at that time. This was used as the basis for making predictions of the ionospheric behavior, a service extremely valuable to communicators and one that has since been improved and expanded, and which is still being used for that purpose today: in spite of serious deficiencies at high latitudes, the predictions for low and middle latitudes have indeed been most useful.

With the removal of wartime restrictions in 1945 and the easing of operational demands, scientific studies commenced into some of the tantalizing research questions that had cropped up in the ionosonde data during the war years. The Canadian ionosonde studies became the responsibility of the newly formed Defence Research Board (DRB) and were pursued at the Defence Research Telecommunications Establishment (DRTE) under F.T. Davies and J.C.W. Scott. That establishment undertook an extensive research and development program into military communications requirements of which ionospheric communications, otherwise known as shortwave or high-frequency (HF) communications, were an important component. The ionosonde data provided information on the vertical distribution of ionization and how this changed with time and location. The DRTE studies showed that the ionosphere exhibited a wider range of conditions over Canada than over any other country. Under some of the extreme conditions, shortwave communications were impossible for days on end between, say, Montreal and northern communities such as Yellowknife or Inuvik. This behavior was shown to be associated with the *auroral zone* – a belt-like region at mid-Canadian latitudes in which the occurrence of aurora borealis is most frequent (see Figure 18). This phenomenon is a manifestation of the influx into the earth's upper atmosphere of energetic charged particles from the sun. By means that are not yet well understood, such particles can penetrate at the higher latitudes and can produce

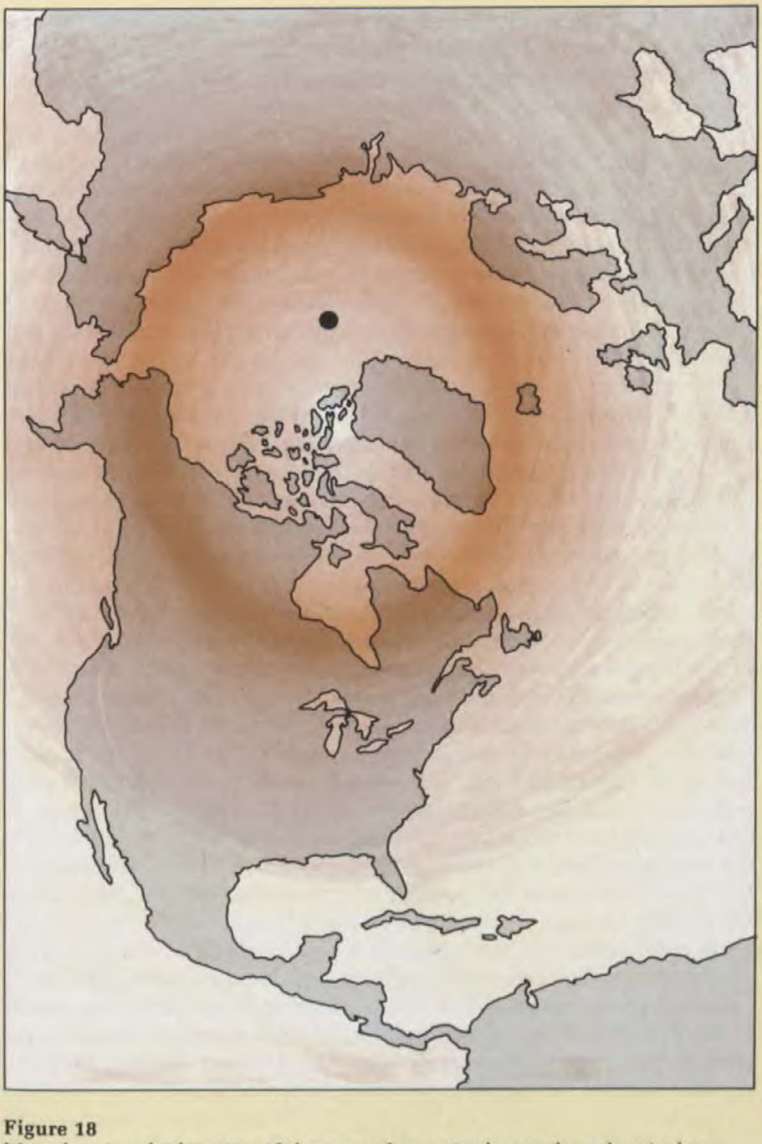


Figure 18
Map showing the location of the auroral zone in the northern hemisphere.

ionization abnormalities throughout the ionosphere. Since Canada has essentially the only accessible terrain for studying both the auroral zone and the polar cap, this was a most interesting and fruitful field of research endeavor.

In 1957, when the nations of the world joined together in a major study of this planet known as the International Geophysical Year (IGY), Canada expanded its ionospheric research efforts. New experiments were designed, additional stations were set up at the higher latitudes, and there were additional major ventures such as the opening of a joint US-Canada rocket-launching range at Churchill, Manitoba, for upper-atmosphere exploration from rockets.

The consequence of all this work, and of the parallel activities in other countries and at lower latitudes, was that a satisfactory picture of the underside of the ionosphere began to emerge. There were, however, many unanswered questions as to what happened at high latitudes and during disturbed intervals. More than a decade of intensive research by many workers around the world had made little progress toward improving the reliability of shortwave radio communications at the higher latitudes. During this time period, there were ever-growing demands for more and better long-distance communications to meet civil as well as military requirements. A new approach was needed. The opportunity for this came with the advent of the space age. The successful launchings of the first man-made satellites led to the resolve to pursue ionospheric research above the ionization maximum of the F layer. Optimistically, such a satellite research program would lead to a thorough understanding of the physics of the ionosphere on a global scale and provide a basis for substantial improvements in shortwave radio communications. From the DRB point of view, it would have the added benefit of providing other information on this unfamiliar environment that might be useful for defence against intercontinental missiles. Moreover, it was also recognized that the accompanying developments in space technology would most likely open the door to other advances in long-distance communications where there would be little or no dependence on the vagaries of ionospheric behavior.

These considerations were not unique to Canadian planners; however, because workers in this country were intimately aware of the communications problems associated with the high-latitude ionosphere, they were among the first to advocate applying the new technology to ionospheric research. They were fascinated by the then on-going series of rocket launchings at the newly established Churchill range, which had whetted their scientific and technological appetites. In spite of keen competition in that post-Sputnik era, their case was soundly reasoned, was strongly presented and, moreover, was persuasive.

The Alouette Project

In July 1958, the Space Science Board of the US National Academy of Sciences invited proposals for scientific experiments that might be included on satellites to be launched under that country's space development program. A number of ionospheric studies were suggested and discussed by research groups in the United States and Canada. These subsequently stimulated a proposal from DRTE for a satellite-borne ionosonde to explore the regions above the ionospheric maximum. This proposal was submitted late in 1958 to the newly formed National Aeronautics and Space Administration (NASA), which accepted it as a joint undertaking between Canada and the United States. The acceptance was due in no small measure to the reputations the Canadian scientists had built up in ionospheric research among their international colleagues.

The basic arrangement was that DRB would design, construct and pay for the satellite with NASA providing, at no cost to Canada, the launch vehicle and all support needed for environmental testing, qualification and launch of the spacecraft. It was also agreed that DRB would establish three telemetry-and-command earth stations in Canada and that NASA would make available its global network of earth stations so that ionospheric data could be obtained around the world. Canada and the United States were to share the data. A joint announcement of this agreement was made in April 1959, and the formal agreement between DRB and NASA was signed later that year.

Several of the DRB people most closely associated with the initiation and development of this pioneer space project deserve particular mention. J.H. Chapman and E.S. Warren were responsible for the original proposal and continued to be associated with the program through most of its life — the former as the Alouette program co-ordinator and the latter as principal investigator for the ionosonde experiment. F.T. Davies and J.C.W. Scott, who alternated in the position of chief superintendent of DRTE, had the difficult jobs of obtaining approvals for the program, defending it in the face of adverse criticism and getting the necessary resources to carry it out.

At the time, there were other agencies with definite interests in and competing proposals for top-side sounding. The Central Radio Propagation Laboratory in Boulder, Colorado, a main centre for ionospheric research and a keen competitor for the top-side experiment, was chosen by NASA to develop a fixed-frequency sounder as a first generation satellite experiment, to be followed by the more complex swept-frequency sounder that DRTE was to develop. The similarity of objectives led logically to the setting up of a joint working group early in 1960 to co-ordinate the overall activity.

The United Kingdom, which also had a long and illustrious history of ionospheric studies, expressed a strong interest in participating in the sounder program. In March 1961, the Radio Research Station at Slough, England, formally undertook to provide telemetry stations in the South Atlantic and at Singapore, in return for which it was to have early access to all the top-side sounder data. Thus, international participation and collaboration were features of the program from the beginning.

The objective of the joint undertaking with the United States was to study the top-side ionosphere. The Canadian objectives were shaped by the experimental capabilities of the Alouette satellite; they were mainly addressed to the high latitudes and depended on the swept-frequency nature of the ionosonde and on a constant height for the satellite in orbit. This experimental configuration was adopted so that top-side ionograms could be obtained which would be analogous to those obtained with ground-based equipment. Furthermore, the disturbed ionosphere in the auroral zone and polar regions was to receive particular consideration.

As the Alouette project progressed, it was recognized that three additional experiments could be included to advantage: these were to measure cosmic radio noise, very-low-frequency radio emissions and energetic charged particles. The last experiment was contributed by NRC; it was to determine the distribution of energetic particles and to investigate their relationship to the ionosphere. The other experiments, along with the ionosonde, were designed and built by DRTE in support of its role in long-distance radio communications.

Canada also had secondary objectives for the project, which included becoming knowledgeable in space technology and learning to design and build equipment that could operate reliably for long periods in the hostile space environment.

The Alouette satellite was designed and built at DRTE. Not unexpectedly, its development posed some exceptionally difficult problems for which novel engineering solutions had to be found. Satellite technology was still in its infancy when the design was initiated and the payload requirements presented the engineers with a number of major hurdles. One of the first was the development of suitable antennas for the sounder. For the frequency range under consideration (0.5-12 MHz), long antennas were required for reasonable efficiency, and the design indicated that two rigid dipole antennas, with tip-to-tip lengths of 23 and 45 m, would be necessary. There had been no previous satellites with antennas longer than about 6 m, so this presented a formidable research problem which was finally solved by adapting an antenna developed for use on an army tank. In this design, thin ribbons of pre-stressed steel, rolled up like a carpenter's rule, would be propelled out by an electric motor to form tubular semi-rigid antenna members after the satellite was in orbit (see Figure 20). Development work on this critical component was done by Canadian industry in co-operation with DRTE, and the antennas were successfully tested in space in a qualification experiment performed on a NASA Javelin rocket in June 1961.

Figure 19
Assembling the Alouette 1 spacecraft.

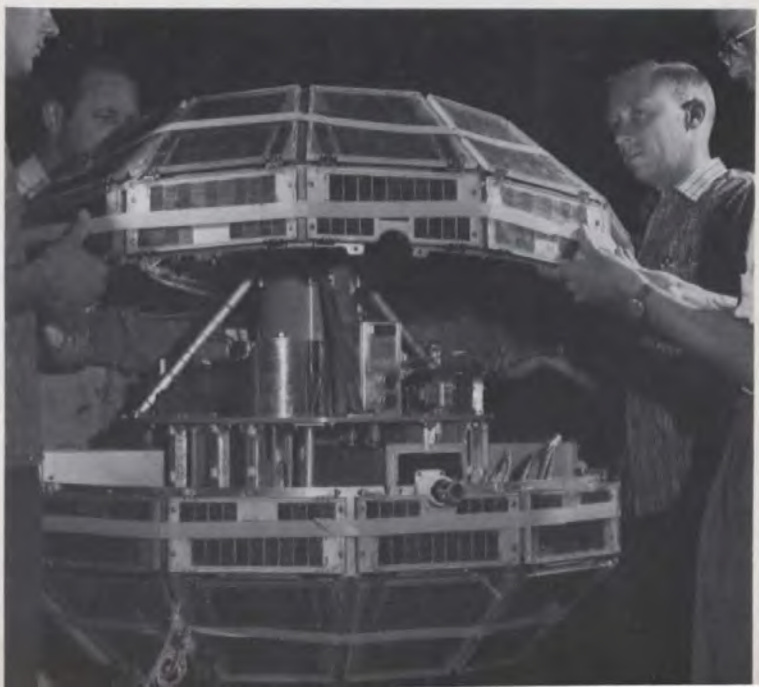


Figure 20
Storable Tubular Extendible Member (STEM) — developed from the antenna units used on Alouette 1.

Two other critical design problems involved the sounder transmitter and the spacecraft storage batteries. For the transmitter, solid-state circuitry was used throughout, but the first estimates of its required power level were much higher than appeared possible and practical at that time. The transmitter had to have sufficient power that an echo pulse from the ionosphere could be detected above the cosmic radio noise level. Accordingly, the transmitter design could not be decided until the cosmic noise level above the ionosphere had been measured. This was done using a special receiver flown on the US Transit 2A satellite in June 1960. In the case of the storage batteries, any defect or failure could bring an end to the mission. With the help of a group at DRB's Defence Chemical, Biological and Radiation Laboratories led by E.J. Casey, a major effort was made to increase the reliability of commercially available nickel-cadmium batteries by improving the electrolyte, plates and separator material.

Throughout, the engineers placed the greatest emphasis on reliability. At this early stage in space technology, satellite equipment and components were prone to failure, and most spacecraft had a lifetime of only a few months. Alouette was to be at least as complex as any spacecraft developed previously, with features that had never been used in space before. The designers therefore adopted the principle of identifying and eliminating generic design weaknesses, and then incorporating in the final payload only reliable units and components that had been satisfactorily tested in a simulated environment. To optimize the chance of success, undue complexity was avoided in the equipment design, and redundancy of the most vital components was stressed. Thus, onboard data storage, although desirable, was not provided; spare batteries were included; extremely large operating margins were emphasized in the design; and extensive testing and re-testing were done to discover unsuspected weaknesses. Above all, great care was exercised during assembly and inspection. The various measures taken to achieve reliability ultimately proved worthwhile, though at the time the uncertainties seemed mountainous.

After much hard work and extensive diversion of resources from other DRTE projects, the Alouette spacecraft was completed almost two years ahead of its US fixed-frequency counterpart. That spacecraft was delayed by contractor problems; it was finally launched as Explorer 20 on August 25, 1964.

The advocates of caution for pioneering spacecraft developments can find ample vindication in the Alouette experience. The conservative DRTE design approach proved its value during the environmental tests of the assembled spacecraft. At that late stage, it was learned that the vibration levels specified by NASA for the launch vehicle had been revised to much higher values. The prospect of damage to Alouette during the tests and the launch loomed very large and the consternation of the designers could not be eased by the senior NASA official who said confidently, "If we damage the spacecraft, I'll buy you another one." Alouette, however, passed all its tests with no problems, and was then ready for launch.

At Vandenberg Air Force Base in California, the launch had to be fitted in between the fruit trains of the Southern Pacific Railroad that passed within 75 m of the launch pad at unpredictable hours. Moreover, the entire population (43) of the little village of Surf had to be evacuated for the duration of the countdown and the several delays. When they were finally able to return to their homes and the satellite was in orbit, the uncertainties vanished and Alouette was recognized as a success within hours. John Chapman later said: "I had my fingers crossed, my legs crossed and everything else crossed. At that time, there was a 50 per cent

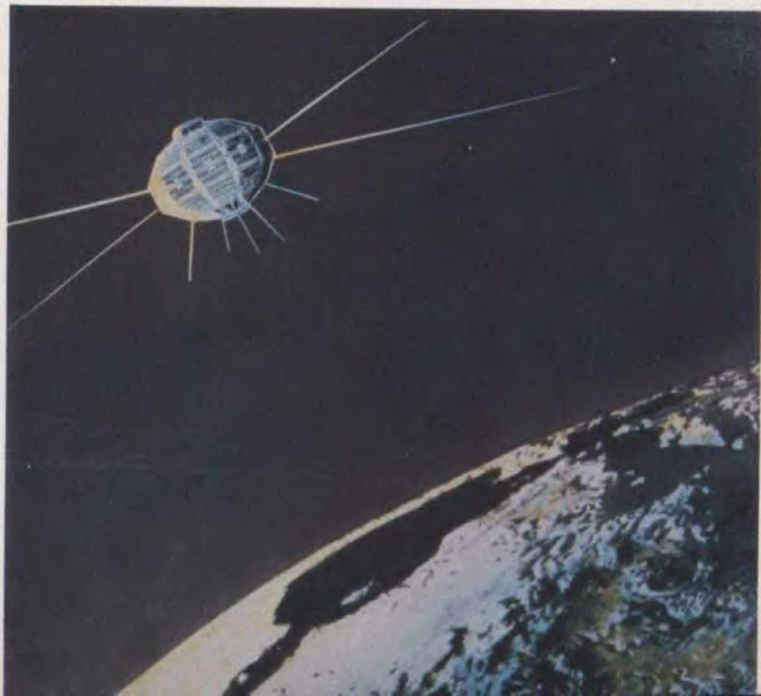
Figure 21
J.H. Chapman during the launch sequence for Alouette 1.

chance of failure in launchings." The orbit was one of the best that had been achieved in American space history, and the sounder and other on-board equipment performed essentially as their designers had hoped.

That launch must now seem very remote and rather ordinary. To the people involved at the time, the satellite constituted a miniature laboratory full of sophisticated instrumentation that had just been blasted into space and had somehow escaped being destroyed in the process. It was then expected to perform four different kinds of scientific measurements in an environment full of hazards.

Just before the launch, when the criteria were set that would be used in formally deciding the success or otherwise of the mission, the conservative approach was again evident. Though Alouette had been designed for a nominal lifetime of one year, a three-month period of operation was chosen as the criterion for a "complete success" since that would contribute enormously to the then very limited knowledge of the top-side ionosphere. As it turned out, the spacecraft operated for an unprecedented 10 years and set a record for the greatest number of scientific papers based on data produced from a single satellite.

Figure 22
Artist's conception of Alouette 1 in orbit.



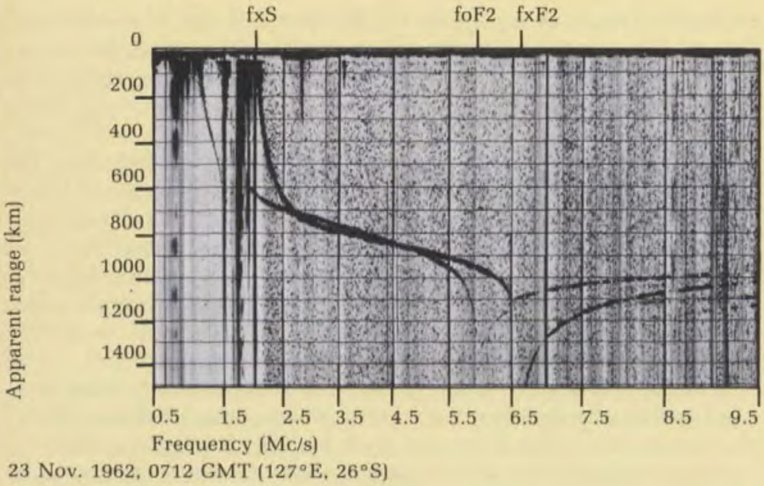


Figure 23
Sample top-side ionogram from Alouette 1. The two traces correspond to the two propogation modes in the ionosphere. The portion above 6.5 MHz is due to reflection from the ground and from the bottomside ionosphere.

Within weeks of its launch, it was clear that Alouette 1 would provide the comprehensive and detailed data on ionospheric structure that was its primary mission. Ionograms were being acquired at a steady rate at 13 ground stations around the world. When activated by a station in accordance with a pre-determined schedule, the satellite would operate and relay data to the ground for about 10 minutes, then automatically shut down. Those data were recorded on magnetic tape and subsequently processed into other forms. The sounder data were converted into ionograms, each representative of a vertical section directly beneath the satellite and separated from its adjacent neighbor by approximately 100 km. An example of a top-side ionogram is shown in Figure 23; as anticipated, such ionograms are closely analogous to bottom-side ionograms. The reflection traces (between about 2.0 and 6.5 MHz in this instance) represent the frequencies reflected by the top side of the ionosphere, at the indicated apparent ranges directly below the satellite. As in the case of bottom-side sounding, the apparent ranges can be converted to real heights so that the electron-density distribution with respect to height can be determined.

Figure 24
DRTE scientists examining some of the first ionograms from Alouette 1.

The other experiments on Alouette 1 also performed well, providing new and exciting data. Since no one could be sure that the satellite would continue to operate, as many data as possible were taken and processed in the first few months. That initial operation produced some of the most interesting and definitive data obtained during the entire 50-year history of ionospheric research, results that could not have been obtained in any other way.

As the weeks went by, it became more and more apparent that the satellite would continue to function well and would provide an extensive volume of data from which temporal, seasonal and latitudinal variations of the electron distribution could be studied. The detailed analyses of the data would challenge the Alouette investigators for many years. Those data would also create requirements for additional experiments involving other ionospheric parameters, which could only be satisfied by subsequent satellites.

The ISIS Program

Within weeks after the launch of Alouette 1, it was apparent that the satellite was a significant technological accomplishment. The designers' bold endeavor to adapt the swept-frequency ionosonde for use on a satellite had not only succeeded, it had surpassed their own expectations. The sounding technique was proving to be well suited to the exploration of the top-side ionosphere, and there appeared to be no reason why its frequency range could not be expanded to provide a more extensive exploration capability. Accordingly, in 1963, the United States and Canada undertook a new joint program to launch four more satellites, which would progressively move the region of exploration to greater altitudes and expand the ionospheric research horizons.

This program, which would constitute the ionospheric research satellite program of both countries, was to be known as ISIS (International Satellites for Ionospheric Studies). The satellites were to be designed and built in Canada and launched by NASA at intervals throughout the rising portion of the sunspot activity cycle between 1964 and 1970. One of the guidelines set by the Canadian government was that our industry should be brought into this program to the fullest extent possible. This was to entail a studied transfer of the DRTE skills and expertise acquired in the Alouette 1 program to a number of industries where they could be applied to the development of marketable space products and services.

The ISIS program was announced in January 1963. Its broad objective was to conduct comprehensive studies of the ionosphere, making ionosonde measurements over at least one sunspot cycle (11 years) and over a wide range of heights and latitudes, but aimed always at achieving understanding rather than merely acquiring data. The program was also to include mutually related measurements required for the prime objective and made by other experimental means, and the opportunity was provided for investigators from agencies other than NASA and DRTE to compete for these supporting experiments. The resulting scientific data were to be made available to the scientific community through the World Data Centers. Each country was to supply the necessary resources for its share and the responsibility for implementing the overall program was given to a joint DRB-NASA working group.

In its pursuit of the program objective, the working group developed an overall plan for the four projected satellites. High-inclination orbits were chosen and emphasis was given to the exploration of a greater range of heights. In addition, direct measurement experiments were to be added to sample the satellites' immediate environment and thus help to establish the constituents of the ionosphere and their properties. More extensive measurements were also required of the charged particle influx into the ionosphere, and of its relation to the auroral processes and to the production of ionization.

The first of the new series of satellites was to be known as Alouette 2; it was to be a modification of the back-up spacecraft for Alouette 1 which had been prepared as insurance in the event of a launch failure. That spare spacecraft was to be altered to include a probe experiment, and the frequency range of its sounder was to be increased to better suit the chosen elliptical orbit with its apogee height of 3,000 km.

In order to carry out some co-ordinated direct measurements, NASA was to launch a satellite of its Explorer series in conjunction with Alouette 2. This joint mission, consisting of Alouette 2 and Explorer 31, was identified as ISIS X. The Explorer satellite was to provide probe and mass-spectrometer measurements along the same orbit and within close range of Alouette 2 for comparison with the sounder and the other observations made on that

Experiments	A1-1(C)	Exp-20(US)	A1-2(C)	Exp 31(US)	ISIS-1(C)	ISIS-2(C)
Swept frequency sounder	● Canada		● Canada		● Canada	● Canada
Fixed frequency sounder		● United States			● Canada	● Canada
VLF receiver	● Canada		● Canada		● Canada	● Canada
VLF exciter					● Canada	● Canada
VLF antenna impedance						● Canada
Red line photometer						● Canada
Energetic particle detectors	● Canada		● Canada		● Canada	● Canada
Cylindrical electrostatic probe			● United States	● United States	● United States	● United States
Thermal ion probe				● United States		
Thermal electron probe				● United States		
Electron temperature probe				● United States		
Spherical ion mass spectrometer		● United Kingdom		● United States		
Energetic electron current monitor				● United States		
Ion mass spectrometer				● United States	● United States	● United States
Ion probe					● United States	● United States
Soft particle spectrometer					● United States	● United States
Radio beacon					● Canada	● Canada
Auroral scanning photometer						● Canada
Cosmic radio noise receiver	● Canada	● Canada	● Canada		● Canada	● Canada

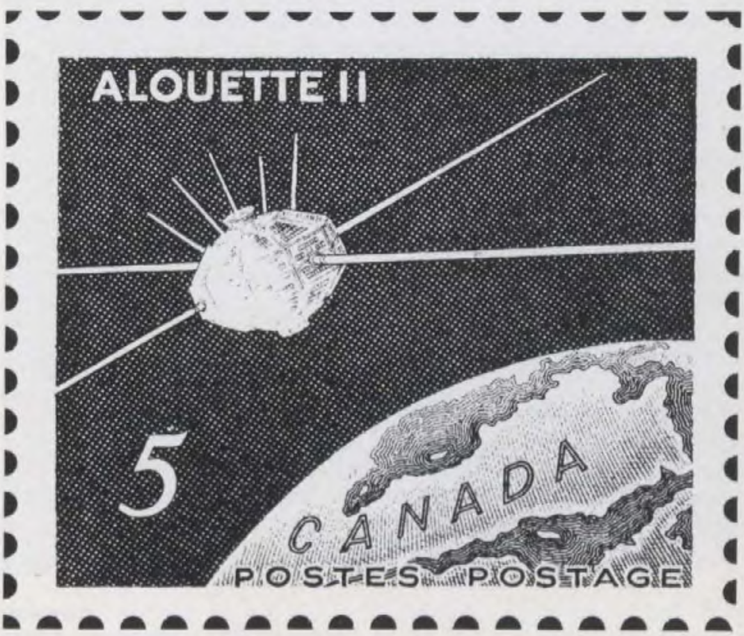
● Canada ● United States ● United Kingdom

Figure 25
List of experiments on the various satellites in the Alouette-ISIS program.

spacecraft. ISIS X was to provide an answer to the critical question of whether an electrostatic probe (planned for the later ISIS satellites) could be operated satisfactorily on a satellite fitted with the very long antennas that were required by the sounder. Identical probes were placed on Alouette 2 and Explorer 31, and simultaneous operations were planned so that variations in the data could be assessed in detail. It is noted in passing that the results of those tests were entirely satisfactory and the designers were able to proceed with a full complement of experiments for the subsequent ISIS satellites.

The remaining three satellites in the program were to have the name ISIS. An ionosonde, provided by Canada, was to be the principal experiment on at least the first two, and other supporting experiments, as deemed appropriate, were to be solicited in Canada and the United States (see Figure 25). The intention was to amass on each spacecraft as many different mutually-supporting experiments as possible and to operate them all

Figure 26
Postage stamp issued to commemorate the Alouette 2 mission.



simultaneously, thus obtaining data on the various ionospheric parameters that could be intercompared in a meaningful way. To help facilitate this, and also to collect data in remote regions of the world out of range of earth stations, a broadband tape recorder was to be incorporated on each of the ISIS satellites.

Work on Alouette 2 commenced at DRTE in March 1963, and that spacecraft was launched with Explorer 31 on November 29, 1965, from Vandenberg Air Force Base in California. Again, the desired orbit was achieved with remarkable accuracy (see Figure 12, page 39). Canadians viewed this second space endeavor with great interest and the event was marked by the issue of a special commemorative postage stamp that featured the satellite. Like its predecessor Alouette 2 was a complete success; it was operated for just four months short of 10 years and also had a high scientific productivity.

Work on ISIS 1 began in March 1964. DRTE retained responsibility for the spacecraft system design, and the Canadian prime contractor, RCA Limited of Montreal, took responsibility for the design of most other systems, along with the construction, integration and testing. The satellite was ready for launch in January 1969.

For that event, the fruit trains proved to be a minor hazard compared with the problems produced by the California weather. Those included a persistent dense fog which delayed the arrival of the launch crew and equipment, hail stones that damaged the gantry, and a series of storms that flooded the launch complex, submerged some of the ground support electronic equipment and left a thick layer of mud and slime in many of the buildings. A near-miraculous salvage operation was able to get the range functional again in three days, thanks to the dedicated labors of the scientists and technicians, as well as the wives and friends who were there to view the launch.

ISIS 1 was launched on January 30, 1969, into an elliptical orbit with apogee at 3,500 km. Operation of the spacecraft has continued from that day until the present. Not all of the on-board experiments are now operable but the sounder still is, and the solar cells, batteries and telemetry equipment are fully capable of supporting data collection. After more than 13 years in space, excellent ionograms are still being acquired with that satellite.

Figure 27
Artist's conception of ISIS 1 in orbit.

ISIS 2 was similar in design to ISIS 1, except that two optical experiments were added. Those were to permit the study of airglow emissions from the ionosphere, particularly the aurora borealis (otherwise known as the northern lights) and aurora australis (its southern hemisphere counterpart). ISIS 2 was launched on March 31, 1971, into a circular orbit at a height of 1,400 km. For this spacecraft, RCA Limited, Montreal, was responsible for all aspects of design, construction, integration and testing. ISIS 2 lived up to all expectations; it has recently passed its 12th anniversary in space and it, too, continues to operate and produce high-quality ionograms.

In the planning of the ISIS series, it had been intended that the final satellite, designated ISIS C, would be placed in a highly elliptical orbit which, at the extreme, would attain a height of some 10 earth-radii (see Figure 10, page 34). This was to permit studies of the linkage of magnetospheric processes to the ionosphere and would have provided opportunities for Canada to participate directly in some of the exciting magnetospheric exploration going on in other countries. In 1969, however, because of a government decision to redirect the Canadian space activities into the area of applications, planning was terminated on this satellite to the extreme regret of the scientists involved.

Thus, ISIS 2 was the final and, not surprisingly, the best satellite in the Alouette-ISIS program. From the early experience with Alouette 1, it was clear that a knowledge of electron distribution was insufficient for an understanding of the ionosphere, and that such additional information as ion mass, and electron and ion temperatures would be required to interpret the ionospheric behavior revealed by the sounder. The ISIS satellites, with their complements of carefully selected experiments, provided much of the necessary supporting data. Other valuable data were acquired for selected intervals from other satellites, from rockets and from ground-based equipment. Later in this chapter, we shall see how the Alouette and ISIS observations, bolstered where appropriate, were used in various studies of the ionosphere and magnetosphere.

The Working Group

A program of this magnitude and complexity, in which developmental work was being done in Canada and the United States, and for which data were being acquired at stations scattered round the world, required substantial co-ordination. This was recognized early in the program, and in January 1960, an international working group, named the Topside Sounder Working Group, was set up. Initially, its purpose was to guide and co-ordinate the Explorer 20 and Alouette 1 developments, but, with the inception of the ISIS program, it was renamed the *ISIS Working Group* and assumed responsibility for co-ordinating the overall Alouette-ISIS program. All of the participating agencies had membership in the working group. At its meetings, they discussed both the scientific goals of the program and the proposed solutions to the associated engineering and operational problems. A valuable consequence was that the scientific, engineering, operational and administrative personnel developed an understanding of all the important issues as the program evolved.

At first, the main concern was with planning and co-ordinating the satellites and the on-board experiments. The working group established the experimental complement for each of the satellites through a series of meetings that first decided what particular observations of the ionosphere were required from each spacecraft to meet the overall program objective. Subsequently after inviting submissions from various investigators, it chose the experiments to be included and the orbit for the satellite. Each of the experimenters provided his own experiment, and DRTE was responsible for its integration into the payload.

Later, as the program developed, the working group also co-ordinated the acquisition, processing, publication, storage and exchange of data. The members met regularly, which led to personal rapport, excellent communications and a genuine spirit of co-operation. Apart from the occasional broken leg on the ski slopes and an unintended swim in the Thames River, the informal portions of the meetings were also most valuable since they encouraged uninhibited discussions and helped everyone understand the various problems.

For more than 22 years, the working group has provided the framework for an extensive international collaboration that has been an important factor in the remarkable success and duration of the program. It has also been a shining example of scientific and technical synergism that has spawned activities and results greatly in excess of any prior expectation. The agencies and scientists in the various countries other than Canada and the United States who gathered data, analyzed them and published the results have expanded and extended the program immensely at only a relatively small incremental cost to the two original partners.

It had been realized very early in the program that the scientific resources available in Canada and the United States were nowhere near sufficient to exploit the scientific value of the sounder data. Moreover, as soon as ionospheric workers in other countries saw some of the Alouette ionograms and recognized their potential, they began to seek direct access to the sounder data pertinent to their geographic locations. Such outside participation was actively encouraged. Of those that indicated a definite interest, agencies in the United Kingdom, France, India, Japan, Australia, New Zealand and Norway set up command and telemetry stations to acquire data over their regions for their own use, as well as to share with the other participants. Agencies in Hong Kong, Brazil and Finland set up telemetry read-out stations and acquired data for their own use during scheduled intervals after the satellites had been turned on by some other command station. A number of other agencies in the Federal Republic of Germany, Sweden, the USSR, and other countries expressed interest in participating but eventually did not set up the required facilities; instead, they used Alouette and ISIS data obtained from the World Data Centers.

Two years after the launch of ISIS 2, the routine processing of the data from the program ceased and thereafter only selected data were processed. That meant that the scientific program converted, almost entirely, to specific multi-experiment studies of particular phenomena or ionospheric features. An experimenters' subcommittee of the working group acted to co-ordinate such special studies, and most of the activities of the working group have devolved to this committee in the last few years.

The first chairman of the working group was J.E. Jackson of NASA. He shaped and guided the program until 1974, when he was succeeded by T.R. Hartz of the Communications Research Centre (CRC). W.J. Heikkila, of the University of Texas in Dallas, was chairman of the experimenters' committee until 1976, and, since then, G.G. Shepherd of York University in Toronto has been chairman.

Throughout the course of the program, the experimenters continually upgraded their analysis techniques and expanded their studies so that the capabilities of the satellites for exploring the ionosphere and magnetosphere increased greatly. In addition to the extensive studies planned and carried out within the framework of the working group, many of the data have been made available through the World Data Centers and are being used by scientists around the world. The attractive features of the data are their high quality, the long duration of the observations and the variety of simultaneous interdependent observations that are available for comparison with other ground-based and satellite data.

Satellite Operations

Operation of the Alouette and ISIS satellites has been a Canadian responsibility, carried out by the satellite controller at DRTE (later CRC) in response to the experimental requirements established by the working group.

The launch of each satellite was followed by a series of maneuvers to inject it into the desired orbit, to give it the desired orientation and spin, and to extend the antennas and erect any other probes or structures. This was then followed by a series of tests to ensure that the spacecraft systems and on-board experiments were functional. When these tests were satisfactorily completed, the spacecraft was ready to begin its operational role, the end product of which was the provision of data to each experimenter. The operations included:

(a) The determination of the status of the spacecraft through the monitoring of such housekeeping parameters as temperature, battery voltages and charging current, spacecraft orientation and spin rate.

(b) Changing the orientation of the spin axis on the ISIS satellites so as to accommodate the experimenters; two preferred orientations were parallel to the orbital plane (orbit-aligned) and orthogonal to it (cartwheel).

(c) The accurate determination of the satellite position, and the prediction of such positions several weeks in advance for the benefit of the experimenters and the controller.

(d) The preparation of a weekly schedule of satellite operations, which also specified in which of the various possible experimental configurations or modes the satellite was to operate.

(e) The transmission to the various ground stations of the prepared schedules and details of operations for each station. The station would then send the necessary commands to the satellite, which would execute the particular functions or operations for an interval typically 20 minutes long, then revert to its dormant state. During the course of the Alouette-ISIS program, 47 stations at one time or other were involved in sending commands and receiving satellite data, of which some two dozen were operative at any one time. Only eight are now active; of these, two (Ottawa and Winkfield, England) have contributed continuously to the program since September 1962.

(f) The recording of the satellite data on magnetic tape at the ground stations. The tapes were subsequently sent to a data-processing centre. DRTE being the main processing centre for the Alouette data. For the ISIS satellites, the bulk of the ionogram processing in the last nine years has taken place at CRC, while data from most of the other experiments were processed mainly at NASA's Goddard Space Flight Center (GSFC) near Washington. In the case of the international participants, several undertook to process the ionograms that they acquired; they then provided copies for the working group and, as well, sent the primary tapes to GSFC or CRC for further processing. At the height of the program, a typical day's operation would produce a total of about 25 km of magnetic tape, so it is easy to see that the logistics associated with the data processing were not trivial.

(g) Provision to each experimenter of the data from his experiment, along with ancillary data as arranged. Each experimenter was responsible for calibrations and quality control of his data.

(h) The processing, on occasion, of "quick-look" data which was carried out at the Ottawa ground station to satisfy experimenter requirements, schedule and operational changes could then be implemented to advantage on a time scale much shorter than that associated with the normal data processing cycle.

The flexible and extensive satellite operations contributed enormously to the scientific success of the Alouette-ISIS program. J.D.R. Boulding, the satellite controller throughout most of the program, and his associates in the Ottawa ground station provided many voluntary services beyond the expectations of the experimenters.

Scientific Results

At the start of the program, almost nothing was known about the ionosphere above an altitude of about 300 km. Only a few measurements had been made with rockets and with very costly ground-based equipment at several isolated locations, and the resulting ideas about that height region were, at best, fragmentary. That situation is now completely changed, largely because of the extensive data accumulated by the Alouette and ISIS satellites. Alouette 1 alone produced more than 2 million ionograms during its 10-year lifespan, and the other on-board experiments were also very fruitful. The rest of the satellites in the program also had notable operational lives, and the two ISIS satellites are still active. Much of the enormous volume of data has been deposited in the World Data Centers where it is available to the scientific community for further studies and analyses. The portion that has already been analyzed has produced a wealth of information on the ionosphere, with more than 600 scientific publications, more than 280 of which were based on Alouette 1 data. Unquestionably, very substantial advances have been made toward the program objective of understanding the ionosphere.

In the following pages, some of the principal results of the program are summarized. Such a summary is indicative only and cannot do justice to the findings. The reader wishing more detail is referred to the more extensive descriptions published elsewhere (see bibliography).

The present summary is organized in four parts. The first describes results on the distribution of ionization, and on the related physical interpretations. The second part includes results from other radio measurements, and the third gives an indication of some of the findings from the probe and particle experiments. The final part outlines the measurements made by the optical experiments and indicates the relationship of those data to the other observations on the ionosphere.

Because the program is international, involving numerous cooperative studies, it is virtually impossible to draw national boundaries through the scientific findings. The data have been shared freely among the participants, while respecting the proprietary rights of each experimenter. No attempt has been made here to segregate the accomplishments by country of origin. It is however, interesting to note that of the 603 identified papers published prior to August 1979 in referred journals for the six satellites in the Alouette-ISIS program, 203 were by Canadian authors, 223 by authors in the US, 44 came from the UK, 37 from the USSR, 33 from Japan, 22 from France, and the remaining 41 were by authors in 10 other countries.

Electron Distributions

The main instrument for studying the distribution of ionization was the swept-frequency ionosonde, which produced data in the form of ionograms. From these, vertical profiles were derived of the electron number density between the ionization maximum (usually at about 300 km) and the satellite altitude. Statistical patterns of electron distribution in the top-side ionosphere were then compiled from the vertical profiles, as illustrated in this section.

Figure 28(a) shows an Alouette 1 ionogram, and the portion of Figure 28(c) above the ionization peak at 250 km shows the corresponding profile of electron number density computed for this ionogram. To complete the profile, results were obtained from ground-based equipment at about the same time and location; the bottom-side ionogram is shown in Figure 28(b), and the corresponding computed electron distribution is included in Figure 28(c) in the portion below 250 km. This profile shows a representative ionosphere between about 100 and 1,000 km, which includes the bulk of the ionization.

Generally, however, suitable bottom-side data were not available to complete the vertical profiles, and most of the studies have been limited to the top side. In these studies, ionization patterns have been compiled from a sequence of satellite soundings, such as the sequence portrayed in Figure 29 which shows the electron density as a function of height and latitude, obtained at a particular time of day and season of the year. Similar diagrams, obtained at other times, show the gross features of the ionosphere and how these changed under different conditions. During the past two decades, sample latitudinal and height distributions have been obtained at all times of day, all seasons of the year and all phases of the 11-year sunspot cycle, during a variety of disturbance conditions and at heights up to about 3,500 km.

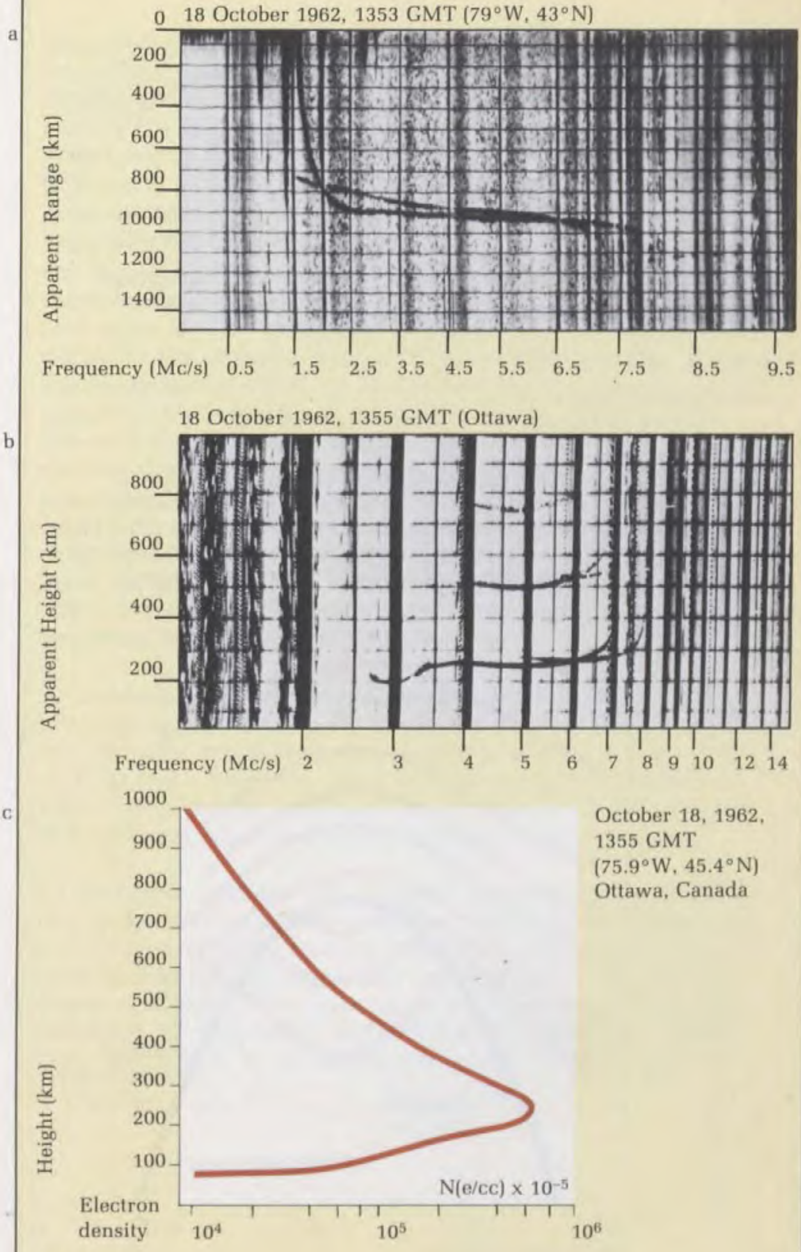


Figure 28
(a) Alouette 1 ionogram obtained over Ottawa.
(b) Ionogram obtained at about the same time with ground-based equipment at Ottawa.
(c) The deduced height profile for the ionization based on the two accompanying ionograms.

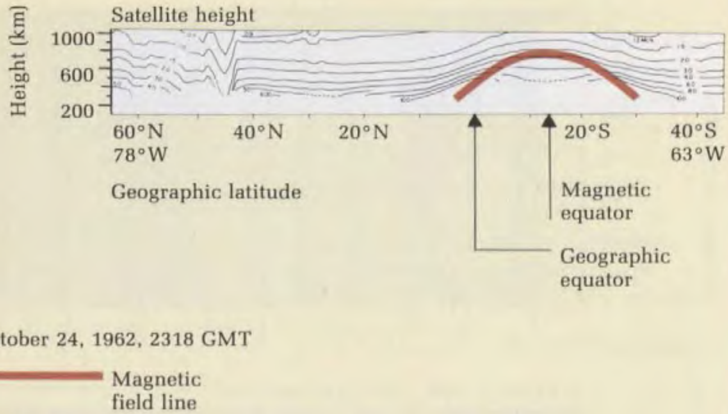


Figure 29
Contours of electron density (labelled with the corresponding plasma frequency in MHz) as a function of height and geographic latitude for an Alouette 1 pass close to 70°W longitude on October 24, 1962, at about 1800 hours local time. The location of the geomagnetic equator is indicated and one magnetic field line has been sketched in for reference purposes.

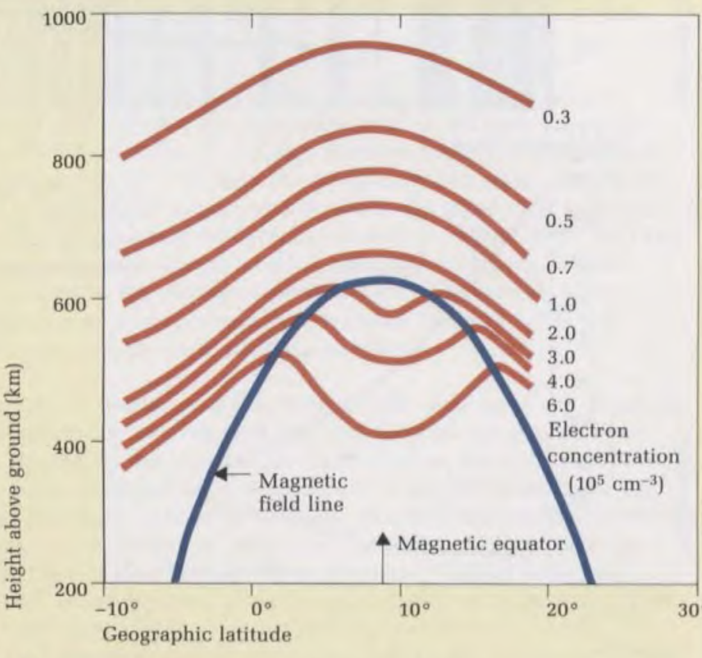


Figure 30
Contours of electron density as a function of height and geographic latitude for a north-south satellite pass over the equatorial region. The location of the magnetic equator is indicated and one magnetic field line has been sketched in.

Because the ionosphere is in a continual state of change, such a mass of data was necessary to establish the pattern of ionization distribution about this planet, from which it should be possible to identify the various physical processes that produced that pattern. Only some of the features of the top-side ionosphere had been anticipated in advance, and much systematic work was required to isolate and interpret the many others. Diagrams such as Figure 29 illustrate some of the principal features. The latitudinal variation can be related to the production of ionization by ultra-violet radiation from the sun with some redistribution that is temperature sensitive. The redistribution is controlled to a considerable degree by the magnetic field, and this is most noticeable in the equatorial region where the contours of electron density appear parallel to the field lines at the greater heights. This equatorial feature is shown in more detail in Figure 30. The single hump in electron density that is centred on the magnetic equator becomes less accentuated at lower heights, and is then replaced by two peaks, one on each side of the magnetic equator. This double peak is a day-time feature, forming soon after sunrise and decaying in the late afternoon; it is known as the *equatorial anomaly* and is a consequence of the strong control of the motion of ionization by the geomagnetic field.

At mid-latitudes, the day-time electron density contours are relatively smooth and slowly varying, indicating that the distribution probably results from simple solar ionization and recombination. At night, however, when the ionizing source is removed, there is considerable irregularity in the contours, which suggests that processes other than recombination are also operative.

At the higher latitudes, there is much temporal and spatial variation in the electron density contours, with many latitudinal peaks and troughs. Here the ionizing influence of incoming charged particles is an important factor, and one that is evident to some degree at all times. The resulting complex pattern of ionization formation, recombination and redistribution, especially during disturbed periods, is not understood in any detail.

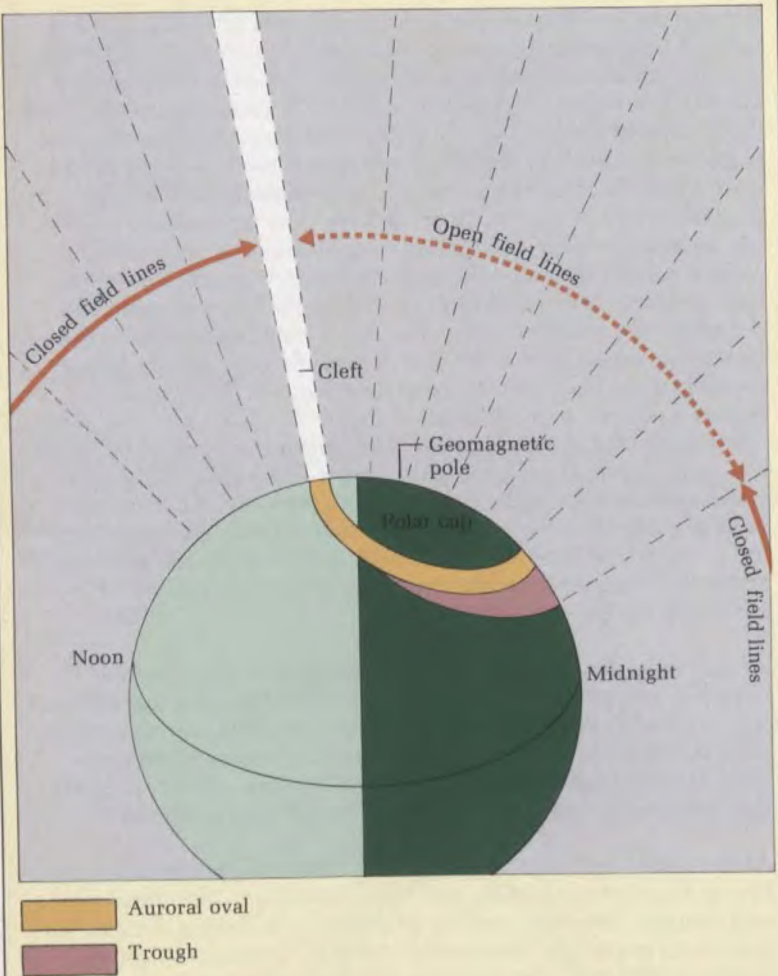


Figure 31a
Schematic drawing of the earth showing the locations of the auroral oval, the cleft and the mid-latitude trough in relation to the geomagnetic field lines, which are shown in the meridian plane only.

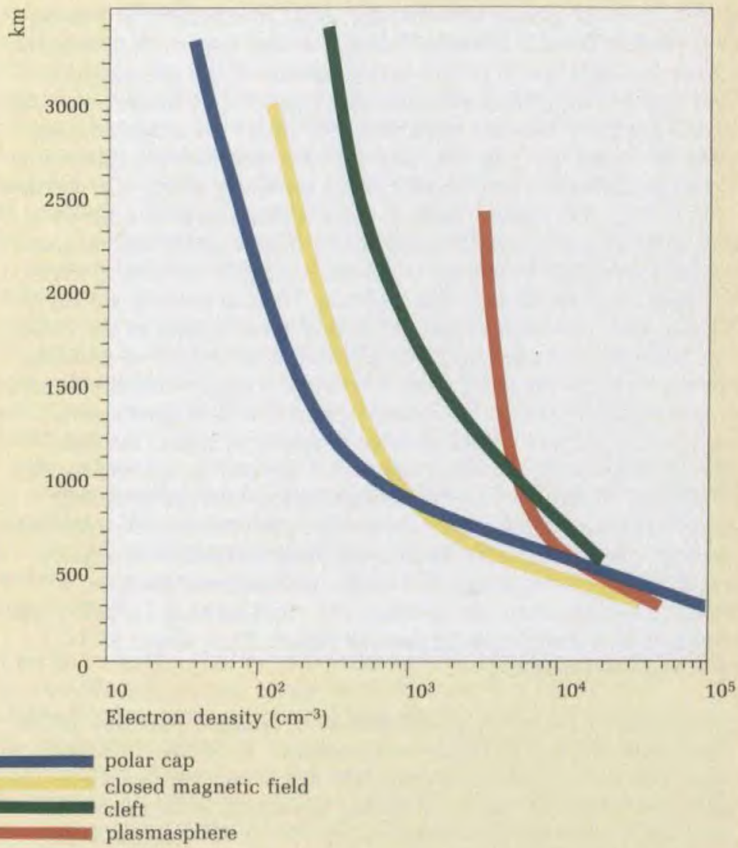


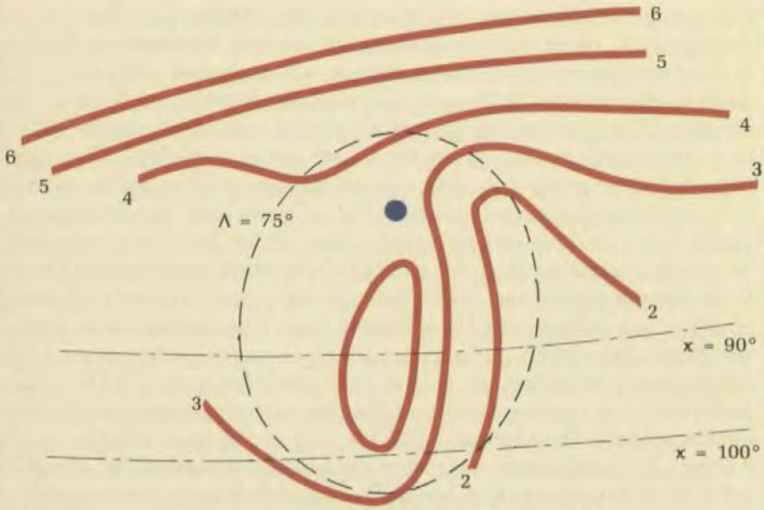
Figure 31b
Typical height profiles of electron density for four different regions of the ionosphere: the polar cap, the middle latitude region where the field lines are closed, the cleft and the low latitude region within the plasmasphere.

If one looks in greater detail at the data, particularly at the vertical profiles for the different latitude zones, one finds systematic differences that relate to the configuration of the geomagnetic field and its controlling influence (see Figure 31a). In the polar cap where the field lines are open into the tail of the magnetosphere (refer to Figure 10, page 34), the top-side densities are rather low since the ionization can migrate away relatively freely. On the day side, in the cleft region, there is extra ionization produced by incoming solar particles that can enter from outside the magnetosphere through this narrow channel. At middle latitudes, where the field lines are closed, the day-time vertical profiles are fairly regular and the densities are noticeably greater than in the polar cap because of the greater solar illumination and the restraining effects of the geomagnetic field. This trend is much more accentuated at low latitudes within the plasmasphere), where significantly higher densities are found at most heights. At night, the field lines in a relatively narrow region just beyond the plasmapause, which are closed by day, become extended and are probably open; because the ionization at that location can then migrate into the tail, one consistently finds much lower densities in a fairly restricted belt from about 60° to 65° geomagnetic latitude, a feature that has been identified as the "mid-latitude trough". (An example of a trough can be seen in Figure 29 at about 45°N geographical latitude.)

At the higher latitudes, where incoming charged particles are an important additional source of ionization, a number of ionospheric features associated with that influx can be identified. The most consistent are (a) the mid-day ionization enhancements associated with the cleft (from about 75° to 80° geomagnetic latitude), (b) night-time ionization increases at auroral latitudes (ranging from about 65° to 70° geomagnetic latitude) that result from the sporadic influx of low- and moderate-energy electrons associated with the auroral processes, and (c) the very frequent, almost persistent, occurrence of small-scale ionization structures or irregularities. The presence of such irregularities is indicated by an extension, or spread, of the echo traces that appear on the ionograms, which denotes multipath propagation and scattering of the ionosonde radio waves from numerous small-scale ionization structures.

One important objective of the ionospheric studies was the development of an improved model or models representing the typical variations of the ionosphere as a function of altitude, geographic location, time, geomagnetic conditions and solar activity. The term model does not refer to a physical model but to a comprehensive summary of a large amount of data. This was intended to provide the radio communicators with a better basis for predicting operating conditions at all times and for all of the globe. The previous ionosphere models, which had been compiled by organizations such as the Comité Consultatif International des Radiocommunications (CCIR) from ground-based ionosonde data, could now be improved considerably with the satellite data, from which in turn should come major improvements in shortwave radio communications. As one step toward this goal, DRTE undertook the routine scaling of the Alouette 1 ionograms to obtain electron densities at 1,000 km and at the peak of the F layer. These synoptic data were eventually compiled for about 1.5 million ionograms and formed a valuable base for the modelling efforts. Several models have now been produced in a form that can be readily accessed by a computer; these are used extensively by communicators, though refinements are still being incorporated.

In addition to the studies of the general distribution of ionization for modelling purposes, many interesting features and more localized ionospheric processes were also investigated. The top-side ionosphere typically shows much irregularity; most such structures are aligned with the geomagnetic field and may be observed at all latitudes. At low latitudes, they often extend from one hemisphere to the other. The irregularities are seen less frequently at middle latitudes, but are a constant feature of the high-latitude ionosphere. Under such conditions, the top-side ionograms depart substantially from the simple example depicted in Figure 23, page 62. The variations or anomalies have uncovered some unique phenomena and interesting ionospheric features, which have been given such descriptive names as ionization ledges, clouds, sheets and ducts. In this connection, it is worth reminding the reader that the ionosphere is a dynamic medium that is influenced by a great variety of factors in much the same way as the weather systems in the lower atmosphere. Much as in the meteorological studies, it has been possible to distinguish trends and patterns in the ionospheric behavior, some of which are quite subtle, because of the extensive and high-quality data that were available.



April 25, 1971, 0440 UT

● Geographic pole

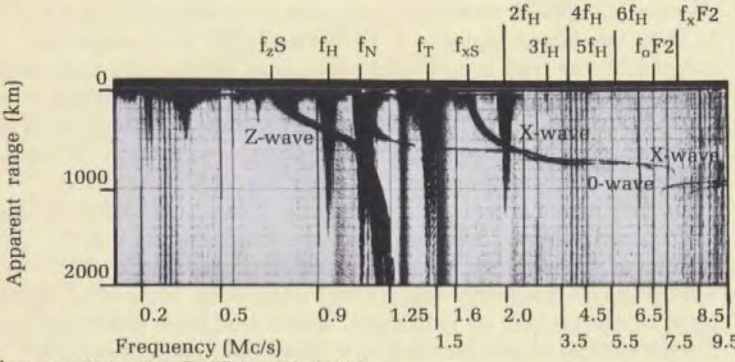
Figure 32
Contours of electron density (labelled with the corresponding plasma frequency in MHz) at the peak of the F layer over the north polar regions. The geographic north pole is indicated, as is the line of constant geomagnetic latitude of 75°. x is the angle between the zenith and the sun, and two contours of constant solar zenith angle — at x values of 90° and 100° — are included to show that solar radiation does not control the ionization contours except well in the sunlit ionosphere.

As one example, a series of ionograms were obtained from each of three satellites (Alouette 2, ISIS 1 and ISIS 2) in near-time coincidence as they criss-crossed the polar region. The data were then processed and combined to produce contour diagrams of electron densities at several fixed heights. An example of such an "instantaneous snapshot" of the horizontal distribution of ionization at the peak of the F layer in the polar cap is shown in Figure 32. In the sun-lit ionosphere, the contours lie close to lines of constant solar zenith angle, but over the pole there is an interesting tongue of ionization that stretches into the night ionosphere. This clearly represents a large-scale horizontal movement or convection of ionization, which had been predicted by theory for this region but had not previously been observed.

Other Results from the Radio Measurements

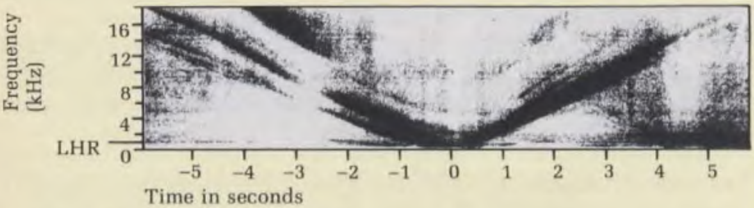
The early concentration of effort on the ionograms produced a great deal of statistical data on gross electron distributions. Eventually, this effort began to wane as other phenomena were identified and interest in other aspects of the program grew. Then the sounder data were scanned for abnormalities that might signify new phenomena. They were also used to support and supplement other observations since they could provide measurements at a distance from the satellite. The fixed-frequency sounders provided data on a much finer time and spatial scale than was possible with the swept-frequency sounder and, in some studies, this was very valuable.

Ionospheric resonances have been dramatic features of the ionograms, though initially they were quite unexpected. They appear as spikes, or long duration signals, at certain frequencies, and some examples can be seen in Figure 33 at 0.95, 1.10, 1.48 and 1.85 MHz. The resonances do not result from energy reflected at some distance from the satellite, as is the case for the normal ionogram traces. Rather, they represent energy from the sounder transmitter that is stored by the local ionization and released after some delay.



February 1966, 1702 GMT (66°W, 33°N)
Satellite height 900 km

Figure 33
A sample Alouette 2 ionogram showing a number of resonances. These are identified as f_N, the plasma frequency at the satellite; f_T, the upper-hybrid frequency at the satellite; f_H, the electrocyclotron frequency; and $2f_H$, $3f_H$, $4f_H$, etc., the harmonics of the electron cyclotron frequency.



ISIS 2 November 27, 1971 0418/32 UT
Satellite height 1428 km Λ = 69° LMT 0039

Figure 34
Sample recording from the VLF receiver on ISIS 2 showing characteristic traces, known as saucers, that result from one type of radio emission.

The resonances occur at certain characteristic frequencies of the ionospheric plasma. One such is called the plasma frequency; it is the frequency at which electrons, if displaced from their equilibrium position, will oscillate while establishing equilibrium. Another is identified as the transverse-plasma or upper-hybrid frequency, and it results from oscillation transverse to the magnetic field. Yet another is the electron cyclotron resonance, at the frequency of gyration of an electron in the magnetic field. Other resonances appear at combination frequencies and at multiples of the cyclotron frequency, while still others involve the cyclotron frequencies of some of the positive ions. There now exists a long list of ionospheric resonances that were first identified in the Alouette and ISIS satellite data.

The ionospheric sounders, as well as the very-low-frequency (VLF) receiver, have proved to be tools well suited for this type of plasma physics research. In laboratories at the earth's surface, it is very difficult to produce plasmas whose properties are not dominated by effects arising from the walls of the container. The ionosphere surrounding the satellite constitutes an essentially uniform plasma without walls, a situation that is unexcelled for certain studies.

The above-mentioned resonances are stimulated by the satellite transmitter at characteristic frequencies of the plasma. Natural processes in the ionosphere, such as the influx of energetic charged particles, may also stimulate resonant behavior in the plasma, with accompanying radio emissions, and such have been observed in the satellite data from the cosmic noise and the VLF receivers.

The VLF receiver data have provided examples of this in the observations of what have been designated lower-hybrid-resonance (LHR) emissions, which are radio noise emissions stimulated by particle precipitation at high latitudes. They have a sharp lower-frequency cut-off which can be used to determine the average mass of the positive ions. This was found to be a useful technique early in the program before data from the ion mass spectrometers were available. These LHR results could also be used with the measured electron density profiles to determine electron temperatures, which were not otherwise measured on Alouette 1.

Other VLF emissions of note are the *whistler* emissions and the so-called *saucers.* An example of the latter is shown in Figure 34; such phenomena are initiated by the influx of a beam of energetic electrons. The whistler emissions get their name from their decreasing frequency with time. They are initiated by terrestrial lightning strokes, which produce short-duration bursts of wide-band radio static that, after radiating up into the ionosphere, travel along ducts of enhanced ionization aligned parallel to the magnetic field. Their frequency components do not all travel with the same velocity, resulting in the observed characteristic sliding tone. Where the ionization ducts extend across the equator, the study of whistlers that bounce back and forth from one hemisphere to the other has led to important conclusions about the structure and content of the plasmasphere.

An observed additional feature of some whistlers was a distinctive rising tone that approached the proton cyclotron frequency. This was identified as a proton whistler in the early satellite data and its detailed analysis led to determinations of the proton concentrations in the plasma surrounding the satellite. Later the helium whistler was also identified, and studies of these ion whistlers led to results on the relative abundances of the three principal ions (hydrogen, helium and oxygen) over the height regions sampled by the satellites. Figure 35 shows examples of such ion whistlers.

Observations made with the cosmic noise receiver showed a number of bands of radio noise whose origin was linked to precipitating charged particles. Other studies involved radio noise emissions from the galactic background, often called cosmic noise, and several types of radio emissions from the sun. As in the case of many other observations in the Alouette-ISIS program, these were pioneering measurements; cosmic noise at the lower frequencies does not penetrate through the ionosphere, and no extensive measurements had been possible before in this frequency range. Likewise, solar noise emissions, of value in studies of particle ejection from the sun, had previously not been observed in this part of the spectrum. An example of some solar noise bursts is shown in Figure 36, in conjunction with ground-based observations made at the same time.

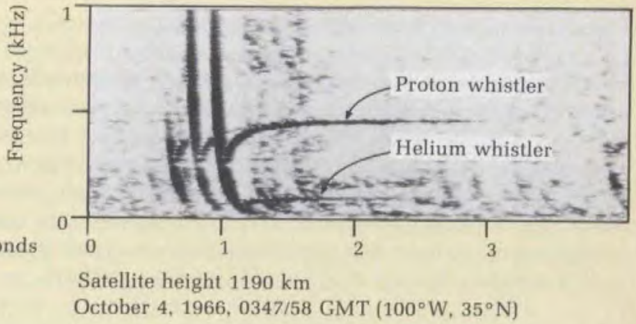


Figure 35
Examples of whistlers as found in the recordings from the Alouette 2 VLF receiver. Ordinary whistlers exhibit decreasing frequencies with time, while the proton and helium whistlers show rising frequencies at first which then become constant. The analysis of these traces has led to a determination of the relative abundance of the positive ions in the vicinity of the satellite of 75% hydrogen, 21% helium, and 7% oxygen.

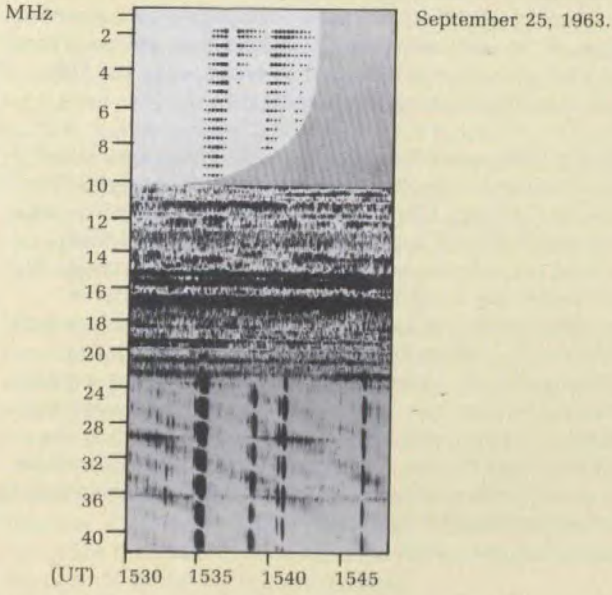


Figure 36
Examples of solar radio noise bursts seen in the frequency versus time recordings made with ground-based receivers (the frequency range above 10 MHz) and with the cosmic noise receiver on the Alouette 1 satellite (at frequencies below 10 MHz). The bands of radio interference obscure the solar bursts between about 10 and 20 MHz, but they can be clearly distinguished above and below that range becoming somewhat more spread in time and delayed at the lowest frequencies.

Results from the Probe and Particle Experiments

Observations with the electrostatic probes have produced many synoptic data on electron distribution and on electron temperatures on a global basis. The former show general agreement with the sounder data, save that the probes sample the ionosphere much more frequently and thus the data are much better suited for studies of irregularities. Also, of course, the data from the probes apply only to the spacecraft altitudes since those instruments sample only the near vicinity of the satellites.

The ion probes, and particularly the ion mass spectrometers, have provided definitive information on the ion species in the various height and latitude regions of the ionosphere. The statistical picture, together with observations in the polar regions of a vertical-directed flow of hydrogen ions, substantiates the polar-wind concept and helps clarify some theoretical aspects of the ionospheric models. Where the magnetic field lines are open into the magnetospheric tail, hydrogen ions (together with electrons) may migrate upward into the tail in the form of a general polar wind. By contrast, at low latitudes, the lighter ions are buoyed up on top of the heavier ions, but cannot escape into the tail because of the configuration of the magnetic field.

The energetic particle experiment on Alouette 1 was conceived just after the discovery of geomagnetically trapped energetic particles by some of the early US satellites. Canadian scientists, led by D.C. Rose and I.B. McDiarmid of NRC, recognized that Alouette 1 could provide them with an excellent opportunity to expand their cosmic ray studies into space. Their persuasive arguments resulted in the inclusion of an energetic particle experiment to study the Van Allen belts and their relationship to auroral activity and other ionospheric phenomena. That experiment was able to perform the unplanned function of measuring the decay of the energetic particles artificially injected into the trapped radiation belts by the 1962 Starfish high-altitude nuclear test, which, among other things, caused the Alouette solar cells to deteriorate at an accelerated rate.

The various electron and ion detectors included in this experiment on the four satellites were so located on the spacecraft that the pitch-angle distributions of the energetic particles could be determined from the known satellite spin data. Except for the particles in small range of pitch angles near zero degrees (the loss-cone population), such particles remain trapped by the geomagnetic field for a long time. With the satellite instrumentation, extensive observations were obtained on the particle distributions as functions of energy, magnetic co-ordinates, pitch angle and geomagnetic activity. From these, a number of interesting results have been obtained, of which the following are a few examples.

It was found that characteristic changes occurred in the energetic electron data when portrayed as a function of magnetic latitude. These could be used to distinguish geomagnetic field lines that are closed (that is, linked directly to the opposite hemisphere) from those that are open into the magnetospheric tail. This ability to use the pitch-angle distribution to distinguish stably trapped and precipitated particles has been of great value in studies of the ionospheric effects of the precipitation. Such particles are able to penetrate deep into the atmosphere, down into the lower E region, or even lower at times. There, they can produce extra ionization which is effective in absorbing radio waves. Thus, the particle influx is often associated with fades and blackouts on HF communication circuits that depend on reflection from the E or F layer of the ionosphere. Two main types of radio wave absorption are recognized; these are known as polar cap and auroral absorption. Satellite particle data have been studied in relation to each type.

Polar cap absorption occurs over the entire polar cap in each hemisphere. It is associated with an intense solar flare, which is a violent explosion on the surface of the sun. Energetic protons are ejected by such an event, and some are channelled by the geomagnetic field to the polar regions where they precipitate over the whole polar cap, as illustrated in Figure 37. This influx produces a blanketing type of radio-wave absorption that may endure for hours or even days. The Alouette and ISIS satellites, because of their high inclination, were able to make detailed assessments of the particle influx during such events.

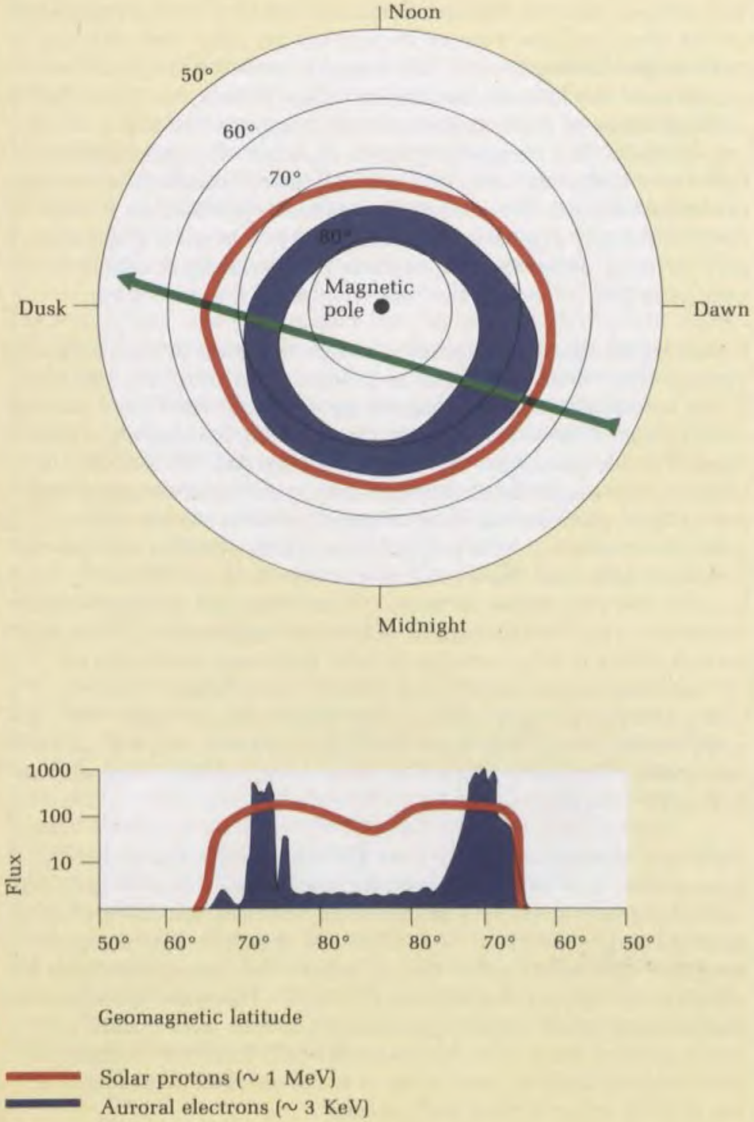


Figure 37
Particle fluxes observed on a transpolar passage of ISIS 2 from the dawn to the dusk side of the earth during the solar particle event of March 6-7, 1972. The location of the auroral oval is shown for reference along with the low-latitude limit of the proton flux. The flux of solar protons and of auroral electrons, is plotted as a function of geomagnetic latitude.

Auroral absorption occurs in association with electron precipitation that is related to the auroral phenomena (see Figure 37). This type of absorption is often quite variable, especially when it occurs near midnight. Satellite studies of such particle precipitation gradually became more generalized when the particle influx was recognized as a phase of a large-scale process in the magnetosphere known as a *sub-storm.* This phenomenon occurs on a time scale of several hours and produces characteristic effects of various kinds throughout the whole magnetosphere and ionosphere. Soon after the start of a sub-storm, the satellite data for night-time auroral latitudes show an erratic electron influx, with often intense bursts which appear to correlate well with discrete auroral events, and with the absorption of radio waves that propagate in the lower ionosphere. Such a burst apparently is the precipitated portion of a population of electrons energized in this phase of the sub-storm. The trapped electrons are also observed to increase sharply at this time, and this trapped population appears to drift slowly around the earth toward the morning sector, where the particles gradually precipitate out in the form of a quasi-uniform "drizzle". This morning influx penetrates into the lower ionosphere where it produces ionization enhancements that result in pronounced radio-wave absorption.

Early attempts to link particle precipitation data to the auroral phenomena were inconclusive due to observational limitations. The Alouette satellites had no means to observe the aurora and its occurrence could only be inferred from observations with a few ground-based cameras or with radio-wave absorption measurements. As well, those satellites provided no electron data in the lower-energy ranges that are appropriate for many studies of the aurora and of other ionospheric phenomena. The ISIS satellites, however, each carried a soft particle spectrometer to provide particle data throughout all of the required energy ranges. In addition, ISIS 2 included two optical experiments from which data on the aurora were obtained. Thus, these later satellites were able to provide a wealth of new information on the morphology of auroral particles, which, when combined with other observations and prior findings, led to many new insights and conclusions.

One of the most striking early results from the soft particle spectrometer experiment was the observation of an intense flux of electrons on the day side at about the cleft latitude. This is a consistent feature, seen on every pass almost without exception, as exemplified in the noon-to-midnight polar-transit shown in Figure 38. The flux has been identified as solar-wind plasma that has penetrated directly through the cleft, and consists of low-energy electrons that are usually accompanied by some low-energy protons. The particle influx typically extends several degrees in latitude, and several hours on each side of the noon meridian.

Figure 38 also shows data taken in the polar regions, where typically the electron fluxes are found to be rather soft and weak, though isolated bursts may be seen on occasion. In the auroral oval, the electron and proton fluxes are generally enhanced. The night-time precipitation is quite variable in its intensity and location, and the energies tend to be somewhat higher on average than on the day side. On the low-latitude side of the auroral oval, the flux is typically more energetic and represents electrons from closed field lines and in the form of a more steady drizzle.

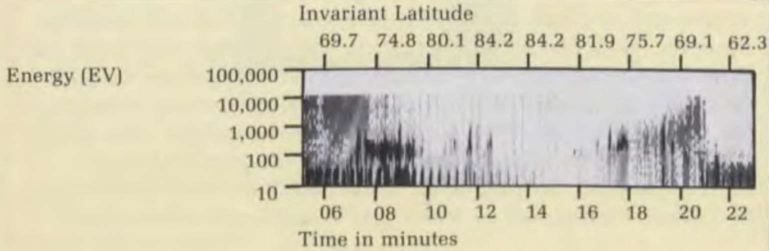


Figure 38
Electron data from the soft particle spectrometer on ISIS 1 obtained on February 4, 1969, between 0205 and 0223 Universal Time on a transpolar pass. The recording shows the electron flux, in terms of the density of the trace, as a function of energy and geomagnetic latitude. The cleft is indicated by the intense flux in the left-hand portion of the record at energies from about 100 to 300 electron volts (EV) and extends from about 73° to 78° geomagnetic latitude. The right-hand part of the recording was obtained when the satellite was passing through the auroral oval on the night side of the earth.

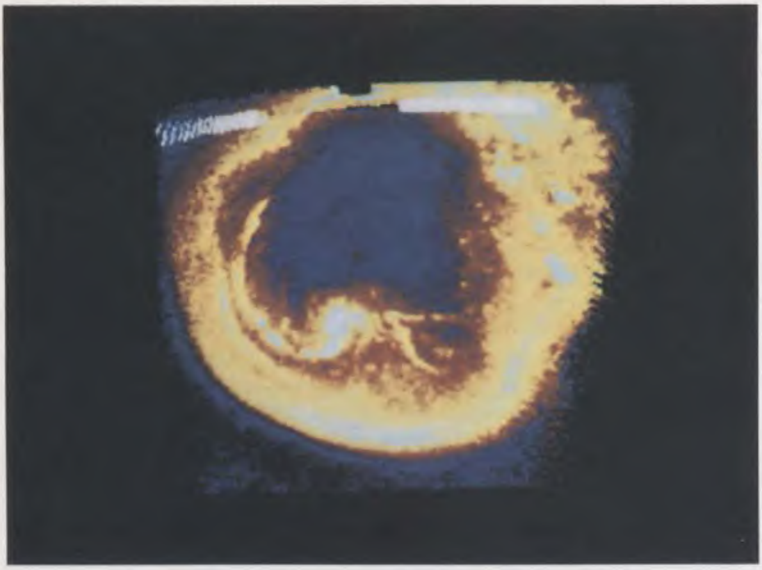
The soft particle spectrometer results have been of great value in the ionospheric studies since they have provided detailed information on one of the ionization sources. At high latitudes, incoming particles in the energy ranges sampled by this experiment are at least as important as solar ultra-violet radiation. During the long polar night, such particles are a major factor in ionization production and, at any time, they contribute to a number of ionospheric phenomena.

Optical Observations

It was apparent early in the Alouette-ISIS program that the deductions concerning the influx of auroral particles would be much more meaningful if those data were accompanied by auroral observations. Thus, it was only natural that the program should try to include optical experiments on at least one satellite. Two Canadian universities, Calgary and York, that had been active in ground-based auroral studies, proposed such experiments for ISIS 2, and both were accepted by the working group. The instruments consisted of photometers with narrow-band filters which could monitor three characteristic emissions from the aurora. The photometers were so disposed on the spinning satellite that their narrow fields of view could sweep across the ground on successive revolutions as the satellite progressed along its orbit. One experiment provided measurements in the red portion of the spectrum, the other in the blue and the yellow-green part of the spectrum. In each case, the auroral emissions originated below the satellite, typically at an altitude near 100 km, which meant that a complicated set of computations were required to produce plots of auroral intensity that could be compared to the particle measurements made at the spacecraft. Through such procedures, it has been possible to map the distribution of auroral and airglow emissions over the portion of the dark earth visible to the spacecraft.

These experiments have produced some of the most spectacular results of the whole program. Like the sounder, the optical experiments provide data obtained at a distance from the spacecraft; the sounder yields electron densities in a vertical plane extending downward from the satellite, while the optical data apply to a nearly horizontal plane that lies beneath the satellite at a height of 100 km. The optical scan data obtained during successive revolutions of the satellite are subsequently processed into a snapshot of the aurora; two such examples are shown in Figure 39. Each shows the entire polar cap with the auroral oval as a structured ring completely surrounding it.

a



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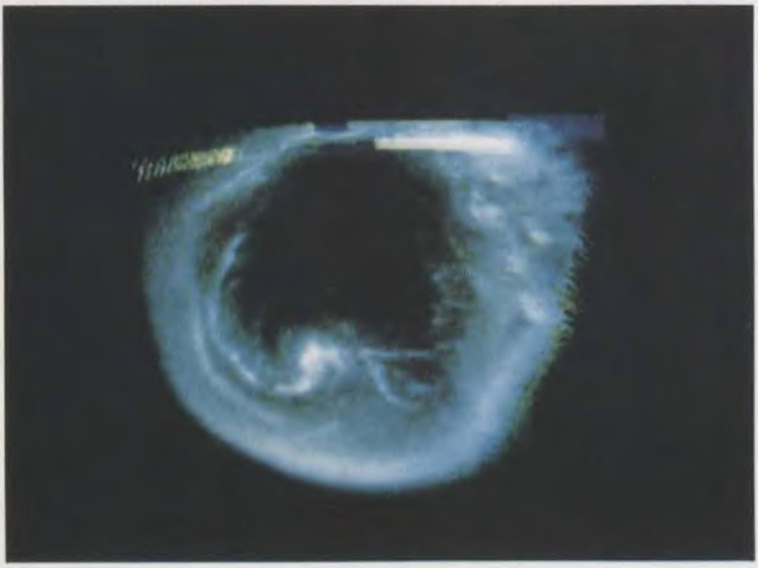
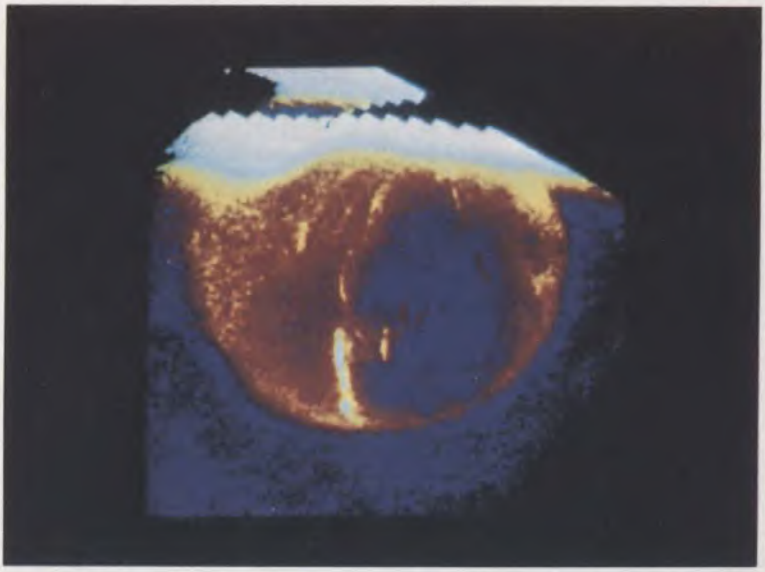


Figure 39
Two examples of data from the auroral scanning photometer on ISIS 2. In each case, two pictures of the aurora have been prepared: (a) is in false color, for which the auroral intensity is represented as red if weak, yellow if moderate and white if strong; (b) represents an intensity-weighted composite of the data obtained in the green and blue spectral lines and hence is a closer approximation to an actual color photograph. All of the presentations

a



b

show the whole of the auroral oval and the polar cap. The day side in each case shows contamination by sunlight. Note the poleward bulge near midnight in the one example and the sun-aligned arcs that traverse the polar cap in the other example. These color figures were prepared with the aid of the computer graphics facilities of the Kitt Peak National Observatory in Tucson, Arizona.

Such satellite pictures include a wealth of detail which has given new insights into the global morphology of the aurora. They have shown that activity is usually continuous around the oval, something that ground-based data had been unable to establish. They have revealed a number of auroral features that were largely unknown from ground-based observations. These include the diffuse aurora on the low-latitude side of the auroral oval, the polar sun-aligned arcs and also the diffuse polar aurora, as well as the predominantly red day-side aurora in the cleft region.

Some of the most significant insights have come from comparisons of auroral data with particle, ionosonde and other observations. For the first time, it was possible to study in detail the particle influx at all energies and relate this to the resulting auroral intensities and ionization densities. Correlation of the auroral data for various sectors of the oval with observations of the interplanetary magnetic field made from a distant satellite are helping to unravel some of the processes in the magnetospheric tail. The high quality of the data and the different mutually-supporting experiments have made this a very valuable program for studying all aspects of the ionosphere as well as many related auroral and magnetospheric processes.

The auroral data have also been studied in relation to satellite measurements of electric currents. For this, an ingenious analysis routine has provided data on aurora-associated electric currents flowing along the magnetic field lines between the magnetosphere and the ionosphere. This was an unplanned and unexpected bonus; it has involved detailed analysis of the data from the onboard magnetometer that had been included for orientation information only. The results from this non-experiment, however, have been most interesting and most welcome since they are leading to new conclusions about auroral excitation mechanisms.

As in any thriving research program, new problems kept arising with each advance. In such cases, the experimenters would define a new series of observations to be made, the satellite controller would be asked to schedule operations of the spacecraft at the desired locations and times, and a new special investigation would be started to provide data and a definitive answer to the question raised. Most such special studies involved the optical data since those provided a convenient two-dimensional reference frame in which the other observations could be better assessed. In this way, the ISIS satellites proved to be flexible and powerful tools for ionospheric and magnetospheric studies.

The ISIS program has clearly demonstrated the value of simultaneous observations of the ionosphere using a wide variety of instruments, of which the optical are particularly important since they provide a comprehensive reference frame. Accordingly, simultaneous data from ISIS 2 have been published for selected observational intervals in data booklets that are available for other workers (see bibliography). It is expected that these booklets, and also the voluminous data already deposited in the World Data Center, will continue to be used profitably long after the satellite operations cease.

Technological Accomplishments

The main technological accomplishments of the Alouette-ISIS program involved specific aspects of the design, construction and operation of the Canadian satellites. It was recognized at its inception that this would be a rather ambitious, pioneering venture, both scientifically and technically. The exploration of the top-side ionosphere required the adaptation of ground-based techniques to a spacecraft and involved severe constraints of size, weight and power consumption. The additional requirement of high reliability, along with the need to deploy a large rigid antenna from a small satellite, were demanding challenges. It is a credit to the designers that the technological objectives of the program were met or exceeded on the original Alouette and on all of the other missions.

Alouette 1 was at least as complex as any previously launched satellite. It was the first satellite to operate for as long as 10 years, and set an achievement standard for the other Alouette and ISIS spacecraft, each of which acquired ionograms on its 10th anniversary in orbit; one is now operating well into its 14th year. The extraordinarily long life of these satellites can be attributed to several factors, one of which was the special effort made to improve the reliability of commercially available nickel-cadmium storage batteries. As a consequence of that work, carried out mainly by the Defence Chemical, Biological and Radiation Laboratories, later renamed the Defence Research Establishment Ottawa, the batteries in these Canadian satellites were superior to those used in any other space program up to that time.

Another factor contributing to the longevity of the satellites, and probably the most important one, was the design approach for the critical on-board electronic circuits. So that they would never have to operate near their thermal limits, which would have shortened their life, they were all so designed as to operate satisfactorily over a range of temperatures substantially greater than they were expected to encounter in space.

An achievement of considerable importance was the successful design of the long rigid spacecraft antennas. These had lengths as great as 73 m tip-to-tip and had to be extended after the satellite was in orbit. The development work on this device was done by a division of de Havilland Aircraft of Canada Limited in Toronto, later to become Spar Aerospace Limited, which co-operated with DRTE in this application of an earlier NRC invention. Originally developed for Alouette 1, it was used on all missions in this program and in each case there was perfect deployment in space of the long antenna structures. Since then, the technology underlying this development has been successfully adapted to a growing number of aerospace applications where reliable deployment of very long structures is required. Such extendible units or appendages, now generally termed STEM devices (see Figure 20, page 58), have been used in space as instrumentation booms, to deploy solar panels and for astronaut attachment systems, as well as for antennas on rockets and satellites. Indeed, such applications have resulted in considerable export business for Spar; since 1960 more than 350 such devices have successfully been flown on Canadian, US and European space missions. STEM units have also been used for ground and seaborne masts and antennas.

Other technological accomplishments of the program include the first and highly successful use of sounder techniques on a satellite, the combination on the same spacecraft of probe and particle experiments with the sounder, the operation of sensitive photometers in space, and the progress made in the understanding of the dynamics of long spacecraft structures in the space environment. Above all, however, it is worth emphasizing that the swept-frequency ionosondes on the various spacecraft gave outstanding performance that has been unmatched anywhere, and that all the satellites performed essentially as planned, with more than 90 per cent of the experiments operating successfully for at least one year, and most for considerably longer.

Concluding Remarks

The Alouette-ISIS program started more than two decades ago and is still actively pursuing its primary objective of ionospheric exploration. From its modest beginnings as a joint one-satellite effort between Canada and the United States, the program experienced a bandwagon-like growth as other satellites were added and other investigators and other nations joined in. On the national scene, the heightened appreciation of the technological accomplishments of the Alouette project started a movement toward a much more ambitious Canadian space program. Though no government department at the time had (or has yet) a mandate for space, DND was convinced that the developed capability ought not to be allowed to dissipate. With not too much difficulty, it was able to get approval for a follow-on expanded program, not for defence requirements, but on the basis of national scientific and industrial arguments. A sense of confidence and optimism prevailed in many circles, which has carried through to influence and shape such subsequent space programs as Hermes, Anik and the Remote Manipulator System.

One of the many real and important achievements of the Alouette-ISIS program was that it set this country on the road to a space applications program that might not otherwise have happened, at least not in such a short time period.

Recognition of the Alouette-ISIS program accomplishments has come in many forms. In 1964, the Professional Institute of the Public Service of Canada awarded a gold medal to the DRB scientists responsible for the Alouette satellite project. In 1969, a special issue of the Proceedings of the Institute of Electrical and Electronic Engineers was published, which was devoted to topside sounding and the ionosphere. In 1972, NASA recognized the Alouette team with its Group Achievement Award. Numerous awards have also been made to individuals, prominent among whom was the Alouette program co-ordinator, J.H. Chapman, whose dedicated efforts in this and subsequent space activities were recognized in many ways, including the award of the 1966 Dellinger gold medal of the International Union of Radio Science.

The Alouette-ISIS program brought Canada into the space age, gave Canadians a measure of recognition and acclaim, and helped to involve Canadian industry in space endeavors. The subsequent governmental shift in emphasis from scientific space programs to space applications seriously curtailed this program, although it was not cancelled outright. The operation and data analysis have continued, albeit at a reduced level, to try to meet the continuing interest and requirements among ionospheric and magnetospheric workers that derive from the unique capabilities of the ISIS experiments.

4

The Hermes Program

Figure 40
Artist's impression of the Hermes spacecraft in orbit.

Introduction

The Communications Technology Satellite (CTS) was a geostationary satellite that was located in the western hemisphere at one position 35,800 km above the equator for most of its lifetime. From this vantage point, it overlooked about 40 per cent of the earth's surface.

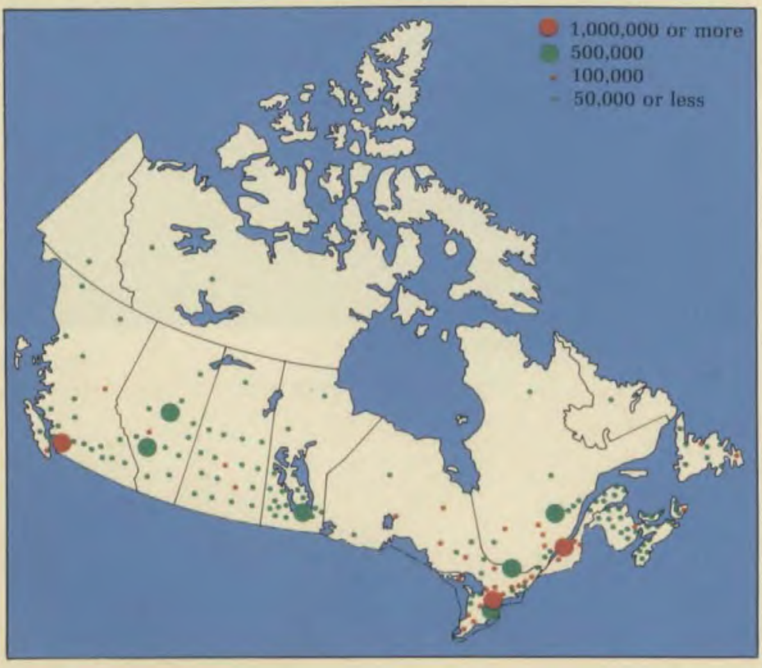
Like most experimental satellites, CTS began life with a functional name. Only after it began to operate in space was it named Hermes by the Honourable Jeanne Sauvé, then federal Minister of Communications, during in-orbit inauguration ceremonies on May 21, 1976.

This name was an excellent choice. Hermes, son of Zeus, was a god of versatile gifts and many attributes. Best known as the messenger of the Olympian gods, Hermes was also the god of science and invention, of eloquence and of dreams. In a sense, the very concept of CTS/Hermes was based on a dream - a dream that all Canadians, regardless of where they lived, should be able to share the benefits of the on-going revolution in communications and information processing.

The difficulties in realizing this dream are formidable. Canada is a vast country, and many of its regions have rugged terrain and inhospitable climates. About 80 per cent of the population lives in cities and towns in a narrow belt within 350 km of our southern border, but a significant minority - about five million people - lives in or near remote, sparsely-populated areas (see Figure 41). By 1970, the urban population was receiving excellent communications services from three terrestrial microwave systems and local broadcast stations. Moreover, these households, in ever-increasing numbers, were being connected to cable systems that carried additional television programs originating in Canada and the United States. The remaining five million Canadians were much less fortunate and had very little, if any, choice of television and radio programs.

Geostationary satellites offered the only practical hope of providing individuals in these remote communities with modern communications services in the following decade. The great advantage of the communications satellite is that it does not matter whether you are communicating with your next-door neighbor, or from the Atlantic to the Pacific coast, or from southern Ontario to Resolute Bay in the far North – the only distance that matters is the 35,800 km from the ground to the satellite.

Figure 41
Map showing distribution of Canadian population, 1976.



The first step in realizing the dream of communications services for all was the creation of Telesat Canada in September 1969 and the inauguration of domestic satellite communications services by that corporation in early 1973, making Canada the first country with such commercial services. The three Telesat Anik A spacecraft were based on well-established technology, developed in the United States. Their low-power spacecraft transponders operate in the 4 to 6 GHz portion of the radio frequency spectrum, in the so-called 6/4 GHz band.[1]

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[1]A commercial satellite communications system includes uplinks from ground stations to the satellite and downlinks in the reverse direction. These links usually operate within well-separated portions of the radio-frequency spectrum, called frequency bands. The Anik A satellites have uplinks at about 6 GHz and downlinks at about 4 GHz.

Figure 42
A Telesat major earth station at Lake Cowichan with antenna diameter of 30 m. This station became operational in 1973 and is approximately 39 km outside of Duncan B.C.

The next step was authorization of the joint Canada-US Communications Technology Satellite Program in 1971, to explore the higher-frequency 14/12 GHz band.

Even as long as a decade ago, it was apparent that the equatorial orbit positions available for 6/4 GHz geostationary communications satellites would soon be filled, and the demand for additional satellite communications services could only be met by opening up new frequency bands. Another problem was the use of the 6/4 GHz band by both space and terrestrial communications systems, which has a serious negative impact on operation of the space systems. To avoid interference with other uses, in particular with inter-city services provided by the telephone companies, the 4 GHz power radiated by the satellites must be strictly limited and, as a direct consequence, the satellite earth stations are relatively large and expensive. The uplink 6 GHz power radiated by these earth stations can also cause interference, and the stations therefore have to be carefully sited, usually at some distance from urban areas.

In contrast, the 14/12 GHz band has been allocated for the exclusive use of space communications services. In 1971, this frequency band was still virgin territory; at these frequencies the orbital positions were all vacant and there were no formal limitations on downlink radiated power. High-power transponders could thus be used in the satellite, permitting reception of their signals by small, inexpensive earth stations that could be sited anywhere, provided only that there was a clear line of sight from the ground antenna to the satellite.

In spite of these advantages, there was considerable opposition in Canada to the proposed CTS/Hermes program, both within and outside the government. The main criticism was that the cost of an operational 14/12 GHz space communications system would be very high. Since Hermes would be the first communications satellite to operate in this band, new space systems and components would have to be developed for these higher frequencies. At the same time, satellite power levels - and satellite weight - would have to be greatly increased to overcome the anticipated effects of increased attenuation in this band caused by rainfall. The critics predicted that the cost increases due to the extensive technological developments and the increased weight of the satellite would be excessive.

The technological problems involved in developing a 14/12 GHz space communications capability were indeed serious, but the government decided that these problems should and would be overcome because of the major advantages of opening up this higher-frequency band. The proposed Hermes communications experiments, it was believed, could demonstrate the feasibility of providing a wide variety of one-way and two-way communications services via satellite, using parabolic (or dish) antennas with diameters as small as 0.6 m.; in particular these services would include direct broadcast of television from satellite to individual homes (see Figure 43). It was apparent, however, that industry was not prepared to accept the high technical and financial risks of the proposed program, and that the government would have to take the lead. Fortunately, the Department of Communications, through its Communications Research Centre (CRC), was well-prepared to undertake this responsibility as a result of the experience gained on the Alouette-ISIS program.

Figure 43
A Hermes earth terminal with 0.6 m diameter antenna, developed by the CRC for reception of color television broadcasts directly from satellite to home.

Hermes Program Objectives

Hermes was a joint Canada-US program carried out from 1970 to 1980 by the Canadian Department of Communications (DOC) and the US National Aeronautics and Space Administration (NASA). Our common goals were to advance the state of the art by developing a satellite communications system to operate at higher powers and higher frequencies than existing systems, thus making possible direct communication with low-cost ground terminals in individual homes and communities, and to conduct communications and technological experiments using this system. The objective of these experiments was to evaluate the economic, social and political impact of the future introduction of new services such as two-way tele-education and telemedicine, direct broadcasting via satellite, and special community services. Canada designed, built and operated the spacecraft, while the US provided the high-power tube for the satellite transponder, test and launch services for the spacecraft, and the launch rocket. Use of the satellite was shared equally between the two countries.

The European Space Research Organisation (ESRO) also became a participant about two years after the start of the program. ESRO's main objective was to obtain a flight test of several payload components to be used in future European communications satellites. In return, ESRO agreed to supply these components and to develop solar-cell arrays without cost to Canada, to meet Hermes payload requirements.

The main additional Canadian objective was to improve our industrial capability to design and manufacture spacecraft and space subsystems for domestic use and for export.

Summary of CTS/Hermes History

During 1970, a team from DOC led by J.H. Chapman undertook conceptual studies on the development of advanced technology for satellite communications and initiated discussions with NASA on a joint program. The proposed program, in effect, would replace the final satellite in the Alouette/ISIS series, ISIS C. It took more than one year of lively debate within both Canada and the United States to shift from a space science to a space applications program, and to agree on objectives and implementation plans.

One major issue was that the projected weight of the desired rocket payload was significantly greater than what could be lifted into orbit by the rocket that had been assigned by the United States. The Canadian position was that a larger rocket should be provided; the American position (which prevailed) was that the extra cost of about $12 million for a larger rocket could not be justified, and that it would be more economical to develop lighter subsystems for the payload. Weight reduction, therefore, remained a constant pre-occupation throughout the development phase, and in the end added much more than $12 million to the cost of the joint program, and resulted in a launch delay of one year.

On April 20, 1971, NASA and DOC formally agreed on a CTS program. Canada undertook to design and build the spacecraft, and operate it in its planned geostationary orbit; the US agreed to provide a launch vehicle and specialized space facilities and to develop a high-power, high-efficiency transmitting tube for the satellite. Use of the satellite for technological and communications experiments would be shared equally by both parties. On May 18, 1972, ESRO and DOC signed a protocol of agreement on the CTS program. ESRO undertook to develop and supply specific components, including 20-watt transmitting tubes, a sensitive microwave amplifier and solar cells mounted on a light, flexible supporting material. These components were to be flight-tested on Hermes for the benefit of both parties.

In Canada, CRC was responsible for systems engineering and for management of the Hermes program from initial concept through design and manufacture of spacecraft to its use in communications and technology experiments. The first program manager was David Florida and the project manager was C.A. Franklin. Canadian industry undertook the design and manufacture of the spacecraft subsystems. Spar Aerospace Limited of Toronto supplied the spacecraft structure and mechanical subsystems. RCA Limited of Montreal (later to become a division of Spar) built the electrical and electronic systems, as well as the spacecraft's antennas and 18 small earth stations. SED Systems Limited of Saskatoon provided three larger earth stations capable of wideband transmission and reception, and also developed the computer software for a critical portion of the launch phase. Other participating Canadian companies included: Bristol Aerospace Limited, Winnipeg; Canadian Astronautics Limited, Ottawa; COM DEV Limited, Dorval; Digital Devices Limited, Montreal; Digital Methods Limited, Ottawa; Fleet Industries Limited, Fort Erie; HiTech Canada Limited, Ottawa; and Miller Communications Systems Limited, Kanata.

In July 1972, DOC invited all interested Canadian groups, associations, provincial governments and other organizations to participate in a planned two-year program of experiments using CTS. B.C. Blevis was put in charge of the experiments program.

On January 17, 1976, the spacecraft was launched from Cape Kennedy, Florida, by a Delta 2914 rocket, and subsequently was positioned in a geostationary orbit over the equator south of Calgary, at a longitude of 116°W. Two weeks later, the two long solar-cell panels were extended, and began to provide the power to operate the world's most powerful communications satellite. During the following weeks, the spacecraft was commissioned; this included a thorough check of subsystems to confirm that the measurable parameters were normal, and the testing of procedures for station-keeping, thermal control, battery charging, attitude control and antenna-beam pointing. On May 21, 1976, DOC and NASA joined in an inaugural ceremony that formally began the experimental operations, and at this ceremony the satellite was named Hermes. This inauguration included an hour-long two-way color television teleconference linking CRC, Ottawa, with NASA facilities in Cleveland, Ohio.

It is standard practice to establish "success/failure" criteria for experimental space programs before launch, and Hermes was no exception. On the evidence of the successful operation of all spacecraft systems, and the excellent progress of the communications experiments, Hermes had fully met these pre-launch criteria and was declared a mission success by Canada on October 21, 1976.

On January 17, 1978, on the second anniversary of the Hermes launch, Hermes had met its design-lifetime objective of two years and was still operating well. Accordingly, the government approved plans for a "bonus" third year of communications and technology experiments. A year later, Hermes was still operating satisfactorily, and a further extension of the experimental program until August 1979 was authorized.

The Hermes experiments stimulated interest in several countries that were considering the adoption of domestic satellite communications systems. In May 1978 a demonstration of direct broadcasting was arranged for an international meeting in Peru. A year later, the Australian government requested Canadian participation in a joint satellite-communications workshop to be held in Australia in late August and indicated that a demonstration of the Hermes system would be especially welcome. Canada agreed and Hermes was moved from 116°W longitude to a location over the Pacific at 142°W longitude, where it was visible both from the eastern part of Australia and from the Ground Control Centre in Ottawa. The extensive and successful Hermes demonstration in Australia stimulated a request from Papua New Guinea for a demonstration of direct-to-home television reception, which took place at Port Moresby on September 4 and 5, 1979.

In mid-September 1979, the Australians requested a further extension of the Hermes mission to measure attenuation of the satellite signals in areas of tropical rainfall in Queensland. Canada agreed but on November 24, 1979, before the measurements could be completed, all radio contact with Hermes was lost.

Figure 44
Direct-to-home reception of color television via Hermes at Port Moresby, Papua New Guinea.

Hermes Design, Construction and Launch

System Design

That Hermes was an experimental, not a commercial spacecraft, had a strong influence on the system design. Commercial communications satellites achieve a lifetime of six to 10 years by using conventional technology, conservative structural-safety factors and redundant electronic systems, and by including substantial reserves of battery power and of hydrazine to operate the stabilization jet thrusters. Each of these items adds significantly to the weight of the basic spacecraft. In the case of Hermes, however, the lift capability of the assigned launch vehicle was barely sufficient for the basic spacecraft, and only a small weight margin was available to provide redundancy in several critical electronic units. Nevertheless, the spacecraft had to operate reliably on command, and continue to operate without repair for a minimum of two years. This reliability requirement has been compared, with justice, to the design problem of making a color TV set that will work without repair for a thousand years.

Figure 45
Hydrazine was used to power the Hermes jet motors during launch and on-orbit operations. This compound is highly corrosive and toxic, and had to be stored in specially-designed gold-plated titanium spheres.

More specifically, the system design of Hermes was dominated by the need to operate the communications transponders at much higher power levels than ever before available (see Figure 46) to provide coverage over North America, and do this reliably in a new frequency band, within the severe weight limits imposed by the Delta launch vehicle. This meant that Hermes not only had to generate much more power, it also had to make more efficient use of that power.

These requirements were met by the development of three major advanced-technology subsystems: (1) an extendible array of solar cells, large enough to provide the required power and, at the same time be as light as possible; (2) a dynamic stabilization system to maximize power production and maintain accurate antenna pointing in spite of the long (13 m tip-to-tip) and flexible solar arrays; and (3) a high-power 14/12 GHz communications transponder subsystem to use the power efficiently. The high-power tubes were developed in the United States in parallel with the design of CTS in Canada, and their specifications were necessarily provisional. In 1974, it became clear that the heat generated by these tubes would be significantly greater than forecast and that (again because of payload weight limitations) the excessive heat could not be dissipated by conventional means, such as conduction by copper strips to the exterior of the spacecraft. Accordingly, a novel thermal subsystem using heat-pipes was designed by NASA, and CRC modified the CTS structural and payload design to include this subsystem.

In the early 1970s, geostationary communications satellites were powered by solar cells mounted on a spacecraft body whose orientation was stabilized by spinning it like a top around a central axis. This is not efficient for high-power satellites, since solar cells mounted on a spinning body like this absorb on average only one-third as much energy as the same number of solar cells maintained facing the sun. The most important design innovation in Hermes was elimination of the requirement for obtaining dynamic stability by rotation. Instead, the payload included an attitude-control subsystem that maintained the spacecraft in a fixed position and orientation with respect to the earth. Spacecraft power could then be provided by solar cells mounted on the large flexible sails that were unfolded from the sides of Hermes after it was stabilized in orbit, as in Figure 47. These sails were maintained at right angles to the sun, so that maximum energy was absorbed by the solar cells.

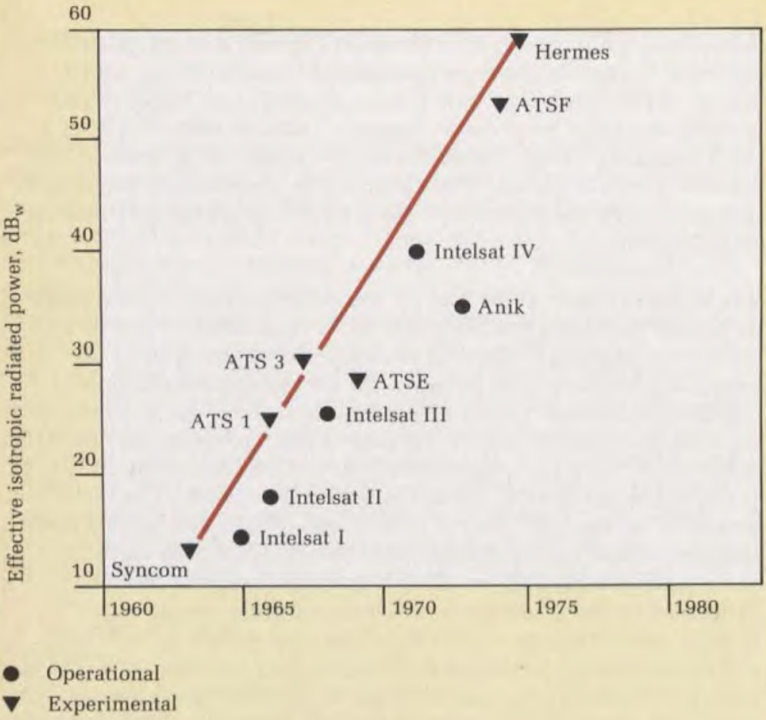


Figure 46
Growth in power radiated in each satellite radio-frequency channel.

The Hermes program provided the opportunity for the development of important new component technology in government laboratories which was subsequently transferred to and exploited by industry. In particular, it was found necessary to develop Field Effect Transistor (FET) amplifiers for the 14/12 GHz transponder in-house, because performance, cost and schedule could not be promised when this work was originally tendered to industry. A team of about 25 persons worked on this at the CRC over a two-year period between 1972 and 1974 providing a reliable design and fabrication of these amplifiers using new microwave integrated circuit techniques and experimental devices. These FET amplifiers were the first developed for space application, and their use is now commonplace in satellites at both 14/12 and 6/4 GHz, as well as in ground terminals.

Figure 47

The Hermes system design also tried to keep spacecraft weight to a minimum by improving the efficiency of power conversion, particularly in the high-power transponders. The power supply subsystem was a major portion of the total payload, and the weight of this subsystem was very dependent on the efficiency of power consumption. The transmitting tubes used in Anik A, for example, deliver 6 W in the 4 GHz band at 30 per cent efficiency; that is, each tube consumes about 20 W to produce 6 W. The Hermes 200 W tube had to operate in the 12 GHz band with about 45 per cent efficiency, to hold the power consumption of this tube down to 450 W. NASA's Lewis Research Center (LeRC) in Cleveland, undertook to develop a new tube and associated power supply to meet these stringent requirements, and this development proceeded in parallel with the design, engineering and test at CRC of the other Hermes subsystems.

Figure 48
Major specifications of the Hermes spacecraft.

Launch weight 676 kg
Launch vehicle Thor Delta 2914
In-orbit weight 346 kg

Size
Height: 1.8 m
Depth: 1.7 m
Length with solar arrays extended: 16.1 m

Position in synchronous orbit 116° W longitude

Planned operational life 2.0 years
(Actual operational life) 3.8 years

Communication subsystem
Receive: 14 to 14.3 GHz
Transmit: 11.8 to 12.1 GHz
(Each divided into two 85 MHz channels)
Maximum output power: 200 watts (antenna 1)
20 watts (antennas 1 and 2)
Antenna coverage: two antennas, beamwidth 2.5°
steerable within a 15° cone

Attitude control
0.1° accuracy in pitch and roll
1.1° accuracy in yaw

Attitude sensing elements
Earth sensors, sun sensors, rate gyro

Solar power system
Two solar sails, each 7 m by 1.3 m with initial power output of 1365 watts; spacecraft body-mounted solar cells, with initial power output of 100 watts

Batteries
Two nickel-cadmium batteries, each with 5 ampere-hours capacity

Major specifications of the Hermes spacecraft are listed in Figure 48. Hermes weighed 676 kg on the launch pad. Fuel consumption by the apogee motor and the small jet thrusters to place Hermes on orbit reduced the mass by about half.

In addition to the spacecraft, the main components of the Hermes communications satellite system were a Ground Control Station that received telemetry data from the satellite and controlled its operation, and numerous earth stations that transmitted signals to and/or received signals from the satellite.

The system design of the Hermes earth stations was dominated by economic considerations. Satellite communications services such as direct-to-home and direct-to-community television broadcasts become uneconomic if the cost of an earth station is excessive for the household or the community. Accordingly, small, lightweight, readily transportable and relatively low-cost earth stations were specially designed for the experimental program. Canadian industry developed and manufactured four prototype systems, ranging in size from a terminal that had complete transmit and receive capabilities with a 9 m diameter antenna to a telephony terminal with a 1 m diameter antenna. CRC concentrated on the development of a prototype television receive-only (TVRO) terminal, with optional antenna diameters of 0.6, 0.9 and 1.2 m that were used in a major direct-to-home broadcast experiment late in the program (see Figure 49).

The system design of the Ground Control Station, located at CRC, was generally straightforward and conventional. This station, however, had to deal with a unique requirement during the launch phase. During the early part of this phase, the spacecraft was spun up to provide dynamic stability. Later, the Ground Control Station transferred the satellite from this spin mode to the three-axis stabilized mode. There was little margin for error in accomplishing this complex and difficult maneuver. Before launch, the planned operational procedures were rehearsed and refined using a simulator at CRC. The simulation model was necessarily incomplete, and the accomplishment of this maneuver was therefore considered to be a significant mission hazard. The necessary technology and procedures were developed in Canada, and worked flawlessly during the launch.

Figure 49
(a) TV receiver terminal with 0.6 m and 1.2 m diameter antennas, operating on a rooftop at CRC Ottawa.

(b) Communications Control terminal at CRC with 9 m diameter antenna, and a 1 m telephony terminal at CRC Ottawa.

(c) TV interactive terminal (TV-receive, telephony-transmit) with 2 m diameter antenna.

(d) Telephony terminal with 1 m diameter antenna at Kashechewan, Ontario.

The Spacecraft and the Launch Sequence

The launch sequence consisted of three phases: a *transfer orbit* phase lasting three days, which culminated in the firing of an apogee motor that placed the satellite in its final orbit; a *drift* phase (nine days) to permit the satellite to drift in orbit until it reached the planned geographic location; and an *attitude acquisition* phase (two days) in which the satellite was despun and stabilized, and the solar sails were extended and oriented to face the sun.

The spacecraft had three primary sources of electric power. During the 14-day launch sequence, two storage batteries and solar cells mounted on panels on the body of the spacecraft were used to provide power until the main power supply, the solar sails, became operational.

The body-mounted cells produced 100 watts, reducing the drain on the storage batteries during the launch, and providing a small amount of insurance against excessive power drain in case of delay in executing the sequence of launch maneuvers. Two of these body-mounted solar-cell panels were jettisoned during the second day of attitude acquisition (see Figure 52), to make openings in the satellite surface through which the tightly folded solar arrays could be extended.

The Hermes spacecraft is shown in Figure 50 with solar arrays fully extended. About 27,000 individual solar cells were mounted on two very thin lightweight blankets, which converted solar energy to electricity to power the satellite. Control signals, derived from sun sensors mounted on each array, operated drive motors that kept the solar cells facing approximately perpendicular to the sun.

When the solar cells were shadowed by an eclipse, the storage batteries enabled essential units, such as telemetry and command, thermal-control heaters and the momentum wheel, to operate without interruption.

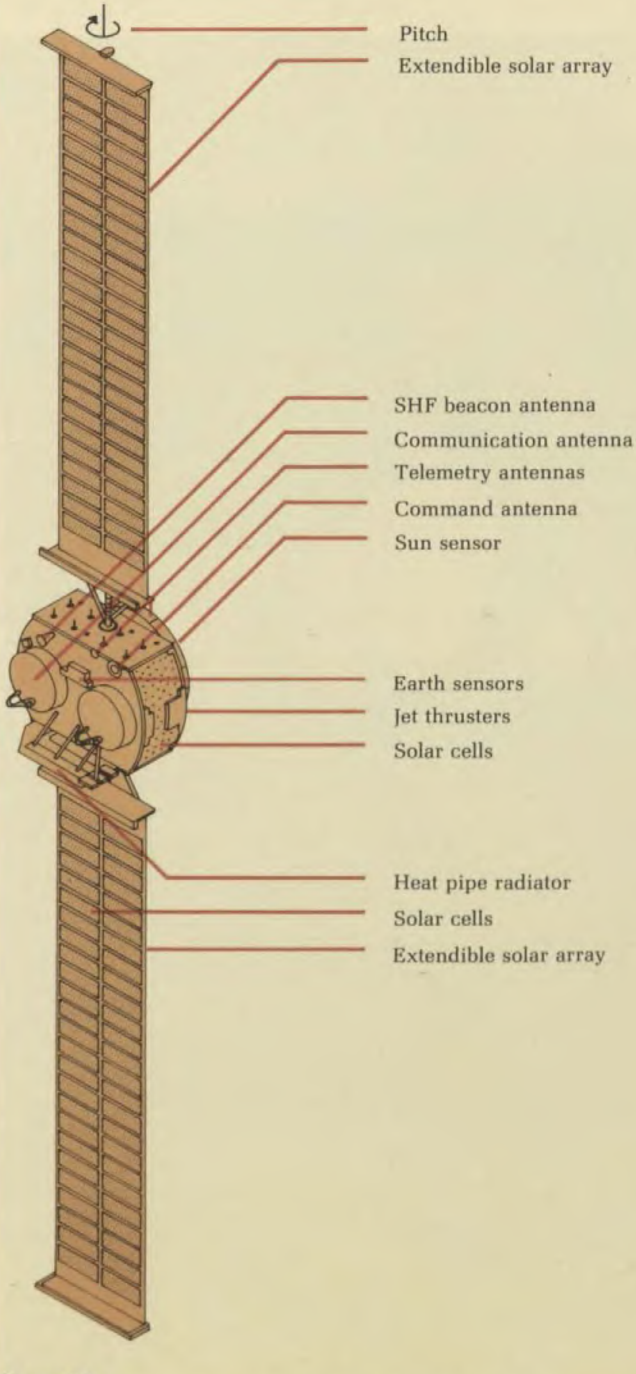
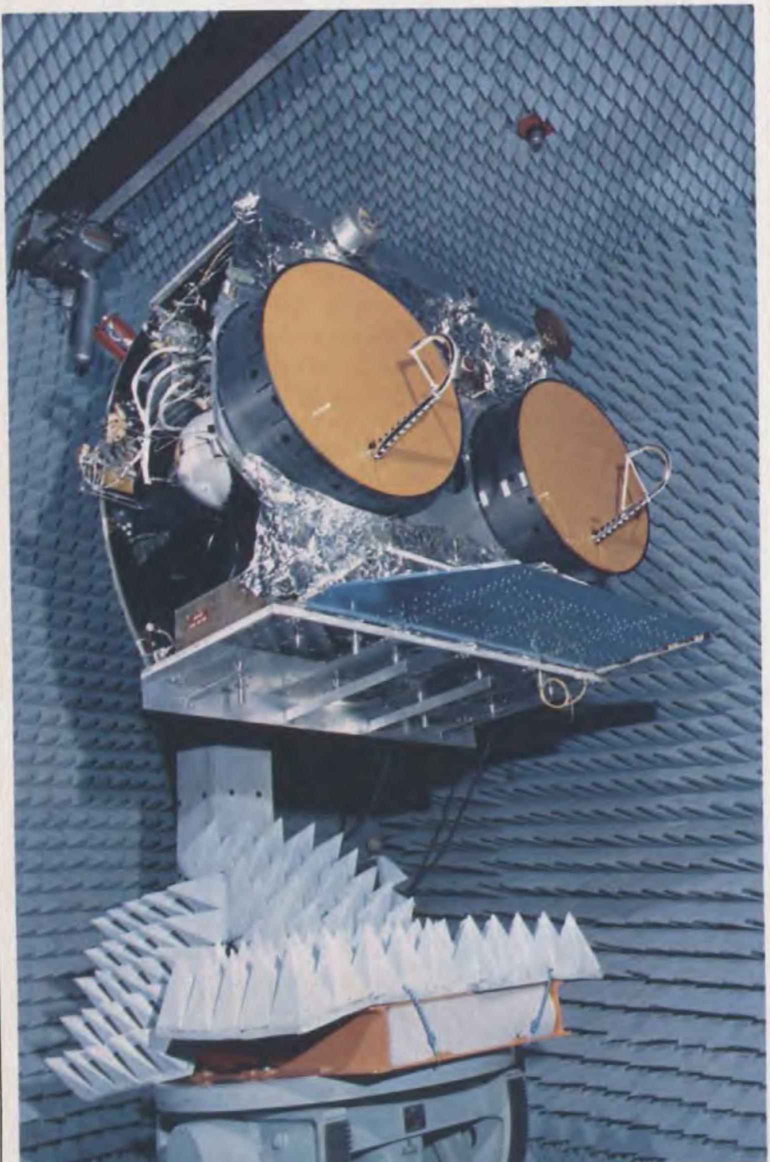


Figure 50
The Hermes spacecraft with solar sails extended, as in orbit.

Figure 51
The Hermes engineering model and flight spacecraft under test in the DOC's David Florida Laboratory at the CRC.



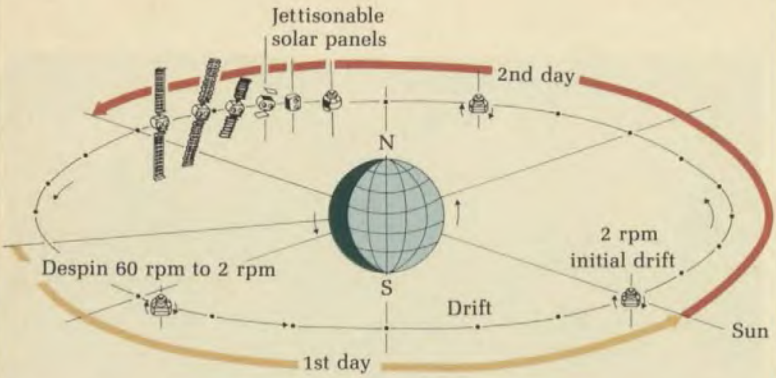


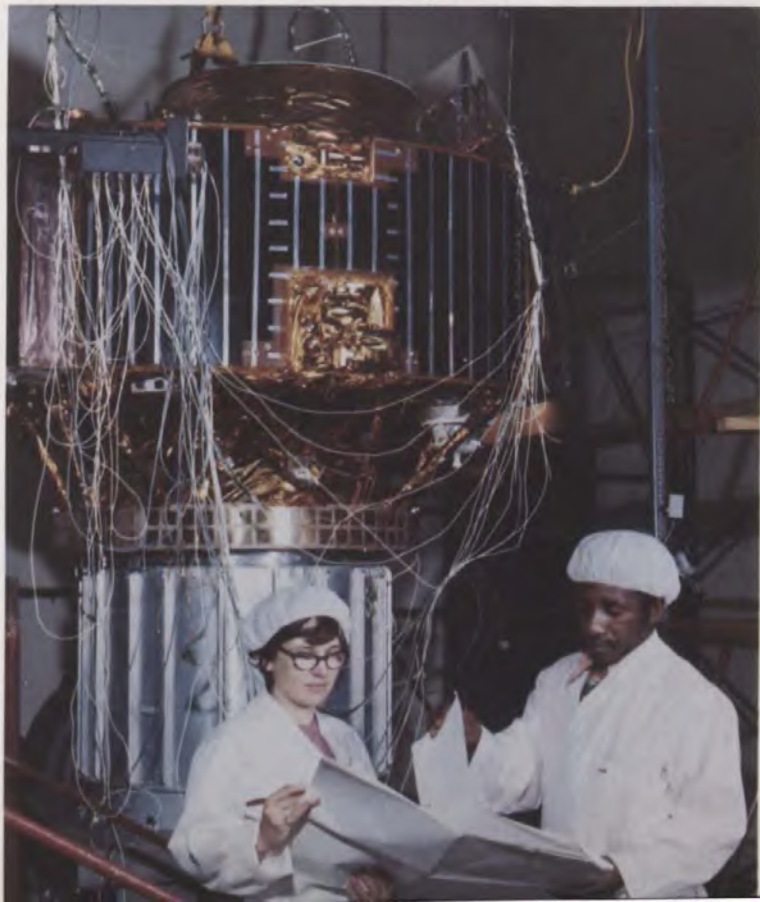
Figure 52
Main attitude acquisition events

The fixed position and orientation of the spacecraft increased the difficulty of keeping all parts of Hermes within specified temperature limits. The spin-stabilization of the Alouette/ISIS satellites tended to equalize temperatures, whereas one side of the three-axis stabilized Hermes continuously baked in the sun while the shaded opposite side froze in the near-absolute-zero temperatures of space. Moreover, the amount of heat generated internally or radiated externally varied enormously during the Hermes mission, primarily because of the wide range of operating conditions for the communications transponder.

A wide variety of active and passive devices spread through the spacecraft were required to maintain the internal temperature within specified limits. This was called the *thermal control subsystem*, in spite of the fact that it did not consist of a separable piece of hardware. This subsystem had to ensure that, regardless of operating conditions, all critical payload components would be maintained at temperatures that would permit satisfactory operation until the Hermes mission was completed. The thermal subsystem included heaters at critical locations, heat-pipes to lower the temperature of hot spots, thermal coatings, second-surface mirrors, jettisonable covers and superinsulation blankets.

Another important operational requirement was to maintain the Hermes satellite in a stable position, while its communications antennas were accurately pointed at specified earth targets and its solar sails were rotated to keep facing the sun. This was accomplished by an on-board three-axis stabilization system, whose main elements were a momentum wheel, position sensors and hydrazine jet thrusters. The momentum wheel was spun up to provide stability along one axis. The sun and earth sensors provided information on changes in the satellite's position or orientation; this information was used to operate the hydrazine jet thrusters to make the desired corrections.

Figure 53
Hermes flight spacecraft under test in the DOC's David Florida Laboratory at the CRC.



Hermes had two relatively large jets (thrust of 22.2 newtons) and 16 smaller jets (thrust of 0.67 newtons). The latter served not only for three-axis stabilization but also for north-south station-keeping maneuvers and for despin and momentum dumping. The larger jets were used primarily for transfer-orbit maneuvers and for controlling the satellite's drift to its location just before attitude acquisition. Much later, during July 1979, in response to the Australian request for a Hermes demonstration, the smaller jet thrusters were used to move the satellite from its station at 116°W to 142°W longitude.

The two communications antennas on the front face of Hermes (see Figure 50) each had a beamwidth of 2.5° and could be individually steered to cover any portion of the earth visible from the satellite. The capabilities of the communications subsystem are described in more detail later in this chapter.

Successful accomplishment of the Hermes mission required detailed knowledge of the spacecraft position and orientation, and the operational status of on-board units, as well as the ability to command changes in the operational configuration, charge the storage batteries, control temperatures at selected points and operate the jet thrusters. A surprisingly large number of independent narrow-band telemetry channels were needed between the Ground Control Centre and the satellite to meet the many monitor and control requirements. For example, the thermal system alone used 34 channels. The total requirement of 590 telemetry and 255 command channels was met by the *telemetry, tracking and command* (TT&C) subsystem, operating in the 2.0 to 2.3 GHz band. This Canadian-designed subsystem was fully compatible with the NASA global network of satellite ground-control stations.

The launch of Hermes was a critical event in the Canadian space program. Because Hermes was an experimental satellite that explored the frontiers of technology, it was necessarily a high-risk program. Because of the cost, there was no back-up spacecraft in case of a launch failure, or imperfect stabilization, or failure of any of the as-yet-unproven advanced-technology subsystems. Any of these failures would have been a serious blow to Canada's space program, not only because of the loss of an investment of about $60 million in Hermes, but also because of the loss of several years of precious time. During the preceding three years, Canadians across the country had expended a large amount of time and money to prepare plans and equipment for the planned Hermes two-year experimental program. The recognition of this risk was one reason why the Department of Communications arranged with Telesat Canada for the launch of a hybrid experimental-commercial satellite, Anik B, in late 1978. The 14/12 GHz portion of the Anik B communications system has essentially the same capability as the lower-power (20 W) part of the transponder system in Hermes. In the event of a Hermes failure, many of the Canadian experiments planned for Hermes could in theory have been transferred to Anik B, albeit with a delay of more than two years.

Fortunately, the Hermes launch was successful and the experimental program began on schedule. This does not mean that everything went smoothly; there were many problems, several of them serious, but the design flexibility of the Hermes system and the ingenuity of the Canadian and American participants overcame all difficulties. Further information on operational problems encountered by Hermes and their solution is available in the technical literature listed in the bibliography at the end of this book.

Hermes was launched by NASA from the Cape Kennedy range in Florida using a Delta 2914 three-stage rocket. Hermes had been spun up for stability at the conclusion of the second-stage Delta firing, and was spinning at about 60 rpm when placed on station over the equator at a height of 35,800 km at 116°W longitude. At this point, the end of the second launch phase, NASA handed over control of the satellite to DOC.

The final launch phase, attitude acquisition, consisted of a complex series of operations that had to be accomplished precisely and on schedule within a two-day period (see Figure 52). The Hermes batteries had only modest spare capacity and the solar arrays had to be deployed and oriented with minimum delay to provide power before the batteries became too depleted to accomplish this task. The main operations were to:

- despin Hermes from 60 to 2 rpm, thus maintaining just sufficient dynamic stability while preparing for the next series of maneuvers;
- despin to zero;
- re-orient so that the communications antennas would face the earth;
- jettison the two body-mounted solar-cell panels that covered the stowed solar arrays;
- extend the solar arrays and rotate them to face the sun;
- recheck the orientation, spin up the momentum wheel, turn on the on-board three-axis stabilization system and verify that stabilization had been achieved;
- begin checkout of spacecraft systems.

Communications Capability

Hermes was initially positioned to meet the earth-coverage requirements of the two-year planned program of US and Canadian experiments. This coverage extended from Alaska in the west to Newfoundland in the east, and included Hawaii to the south and a substantial part of the Arctic Islands to the north. The spacecraft remained in this position during the first two extensions of the experimental program. During July 1979, however, Hermes was moved over the Pacific to provide coverage for a special series of demonstrations in Australia and Papua New Guinea.

Each of the two independently-steerable communications antennas had a circular beam width of 2.5°, and each beam could be positioned to cover any point on the earth visible from the satellite. The 2.5° beam illuminated a circular area, or footprint, under the satellite and this footprint became increasingly elliptical as the angle of illumination became more oblique (see Figure 54). In most experiments, the Communications Control Centre in Ottawa was within one of the antenna beams. When the satellite is 5° or more above the horizon, as seen from the earth station, variations in signal strength caused by the earth's atmosphere become negligible. This 5° elevation-angle contour to the satellite is shown in this illustration to indicate the practical limits for location of an earth station that could provide high-quality service using this type of communications system.

Figure 54
True view of the earth from Hermes when stationed at 116°W longitude. The communication antennas could be pointed anywhere within the large circle. The two small circles show the location of the antenna beams for a specific Canadian experiment.

Figure 55
Earth coverage provided by the Hermes antenna beams for one specific experiment when the satellite was at 116° W longitude.

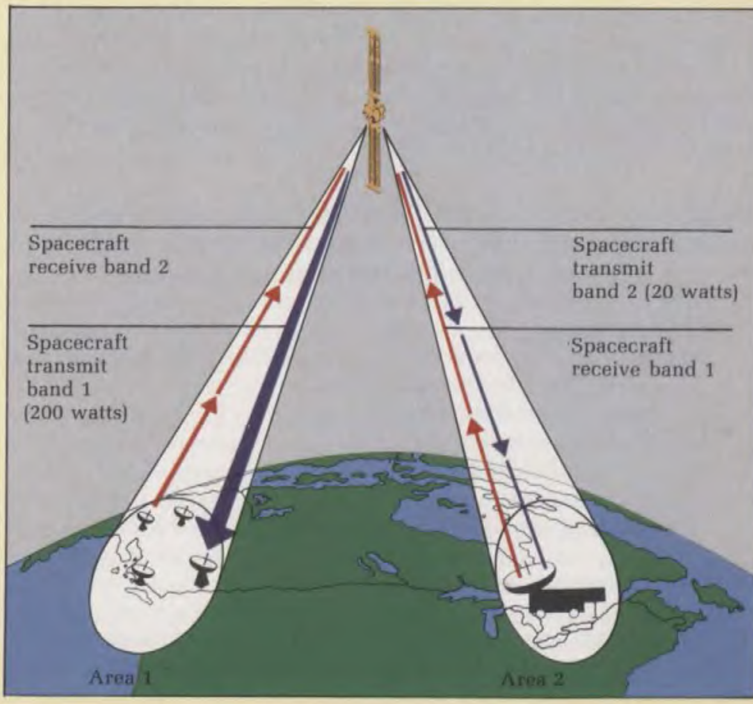


Figure 56
Typical communication system configuration. The CRC control station (on the right) normally used earth terminals with 3 m or 9 m diameter antennas. The experimenters' terminals (on the left) normally used antenna diameters within the range 0.6 to 2.0 m.

The Hermes system was versatile, permitting a wide range of experiments. As indicated in the specifications (Figure 48, page 118), each of the two antennas could receive and transmit, using different frequency bands for each function. Two transmitter power levels, 200 W and 20 W, were available. A typical experimental configuration is shown in Figure 56.

The Hermes channels were 85 MHz wide and could be used to transmit almost any form of information, for either one-way or two-way experiments. Examples included:

- TV broadcast;
- educational TV with a voice or data-return channel;
- TV originating from remote locations;
- two-way TV for teleconferencing;
- telephony (two-way voice);
- radio-program broadcasting;
- digital communications;
- experimental time-division multiple access (TDMA).

In-Orbit Operations

The four-month interval between the positioning of Hermes in orbit and the beginning of the first communications experiment was an exceptionally busy period. The spacecraft and associated ground facilities had to be checked out, and operational procedures had to be verified. At the same time, the staff and organization that had designed and launched Hermes had to be replaced by a new operational team. The Hermes project manager at CRC, J.N. Barry, retained responsibility for the satellite until all systems were checked out and Hermes was formally handed over to N.G. Davies, director of the Space Communications Program Office (SCOPO).

The transition did not take place overnight. It started several months before launch, when operations staff were recruited, the nucleus of SCOPO was formed and a training program began. The specialists who had designed Hermes and its operational control systems knew exactly how all the parts should function, and therefore played a major role in the first few months after launch when the early teething problems were resolved. They then gradually disappeared from the scene as SCOPO staff took over their operational responsibilities. Several specialists remained on-call throughout the mission, however, and their support was vital to the continuing health of Hermes.

A pioneering venture such as Hermes has always involved risks. Hermes had been tested extensively on the ground, in simulated space environment conditions. For technical and economic reasons, simulation of some of the conditions (such as zero gravity and solar-radiation effects) was crude and it was clear that a definitive test of the design could only be made in space.

After launch, the success or failure of the Hermes program was in the hands of the operations staff and the supporting specialists. A few troublesome surprises were almost inevitable. But the team demonstrated outstanding skill, resourcefulness and coolheadedness, and coped successfully with every problem until the end of the mission.

From January 17 to February 1, 1976, all NASA and CRC post-launch maneuvers were successfully accomplished. One major problem arose during the transfer-orbit phase when the spacecraft did not respond to repeated ground commands to open a hydrazine valve and permit operation of the jet thrusters. The valve had to be opened within the few minutes in each transfer orbit that the satellite was within range of the Mission Control Station. The satellite was held in transfer orbit for two days while this valve problem was investigated, but the cause of the command failure could not be established. There was no longer any time to investigate or to cautiously try half-measures. Accordingly, the duration of the command signal was increased from its specified value of 0.05 seconds to 3 seconds – and the hydrazine valve opened! (Within a few days, it was discovered that the event which caused this hydrazine valve problem had also damaged several of the telemetry channels that monitored spacecraft temperatures. Fortunately, it was possible to change the thermal control procedures and manage satisfactorily without these telemetry data.)

During the first two days of February, the spacecraft was stabilized on station over the equator at 116°W longitude, the solar-cell arrays were deployed, and satisfactory operation of all the principal subsystems was confirmed. The next three weeks were occupied with technical check-outs (including nine days of around-the-clock operation of the high-power transponder), and with rehearsal of operations for the approaching solar-eclipse season.

The Hermes solar arrays were shadowed by the earth for a short period ranging from a few minutes to as long as 72 minutes just after midnight every day for 48 days each spring and fall. The first eclipse occurred on February 28. Because of payload weight limitations, the satellite did not carry sufficient storage batteries to permit full operation during eclipse. Each day, during the few minutes of eclipse, communications and other subsystems had to be shut down and only essential services, such as attitude and thermal control, were maintained. The daily shut-down and turn-on procedures had been meticulously rehearsed and worked well until March 4, when a component failure damaged a unit of the electronic power supply. The cause of the failure was unknown. Ground Control, rather than replace the damaged unit with the one-and-only spare unit and risk a complete failure, placed Hermes on standby status. An immediate investigation by a team of CRC, NASA and industrial specialists determined the cause of the component failure. CRC then designed an automatic monitoring procedure that greatly reduced the risk of a similar failure for the spare unit. This procedure was adopted, the Hermes communications system was reactivated on April 20, and the three-and-a-half year program of communications and technological experiments began.

Other problems with spacecraft operation occurred later in the mission, especially in the telemetry and attitude-stabilization systems. Both systems gradually became less reliable as the spacecraft aged, but by this time the experienced staff were able to quickly identify anomalies and correct them. These operational problems did not affect the performance of the communications transponders, and they thus had no noticeable effect on the program of communications experiments. On November 24, 1979, however, with the satellite at almost twice its design lifetime, an anomaly occurred, resulting in the loss of attitude control. This anomaly could not be corrected sufficiently rapidly, and all radio contact with Hermes was lost. Contact was not regained in spite of several weeks of intensive endeavor.

Experimenters in the United States and Canada shared the use of Hermes, usually on alternate days. Obviously, the experimental plans and operational activities had to be thoroughly integrated. Figure 57 shows the main elements of the Canadian organization that provided the CRC Spacecraft Ground Control Centre with co-ordinated inputs on all experimenter requirements. The NASA Lewis Research Center, Cleveland, provided inputs to Canada through a US Hermes Experimenters Co-ordination Center.

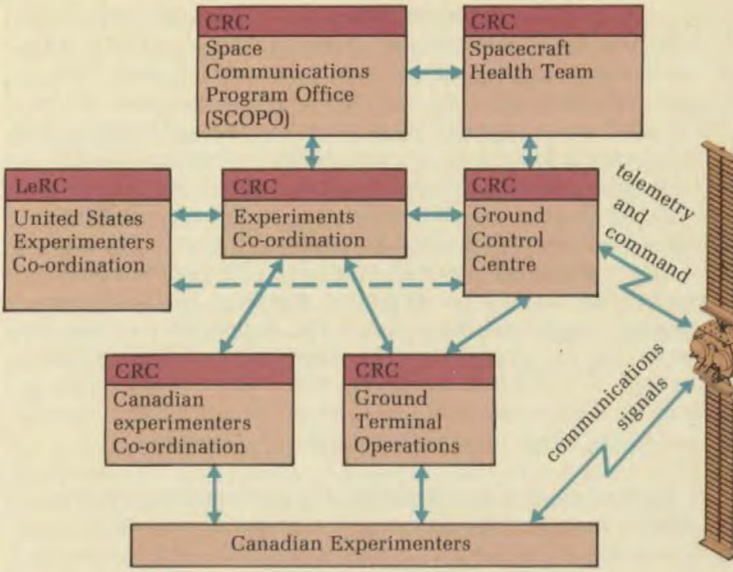


Figure 57
Organizational structure for the Canadian Hermes experiments.

SCOPO managed the Canadian experimental program, as well as scheduling the total joint program. Most of the Canadian experimenters had little or no practical experience with modern communications technology, and one of the critical functions of the SCOPO staff was to provide these experimenters with timely and effective support in spite of severely limited resources. SCOPO provided earth stations, transported and installed them at sites across the length and breadth of Canada (and at sites in Peru, Australia and Papua New Guinea), arranged for technical support to the experimenters as required, conducted US-Canadian experimenter planning and co-ordination meetings, evaluated the experimental results and did as much else as possible to make the program a success. In particular, to maintain the tight experimental schedule, SCOPO had to identify and overcome delays introduced by the bureaucratic processes in the government structure and in the larger agencies conducting the experiments.

Figure 58 shows major events during the experimental program. The satellite communications transponders performed well throughout the entire period, and all scheduled Canadian experiments were completed successfully.

The Canadian Experimental Program

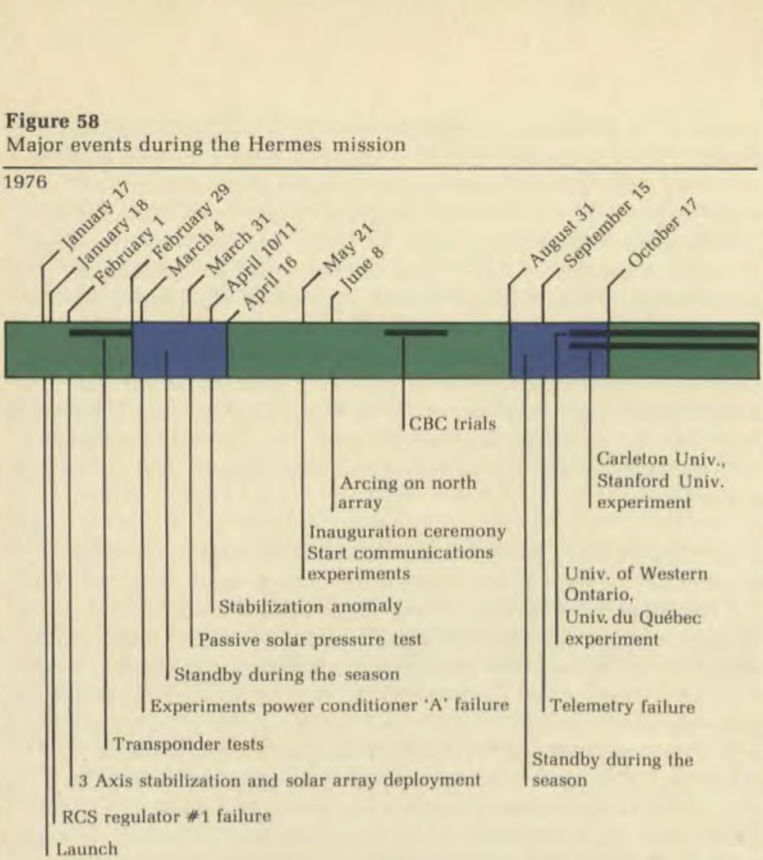
Background

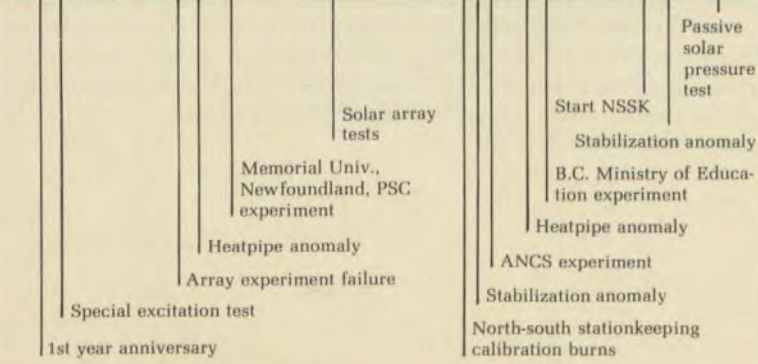
The original plan for Hermes envisaged a two-year program of experiments and demonstrations, with time shared equally between the United States and Canada. In fact, the Hermes program lasted almost four years. In both countries, the experimenters made full and profitable use of their allocated time on Hermes, and they have published extensive reports of their findings. One particularly useful source is the Proceedings of the Royal Society of Canada Symposium of 1977 (see bibliography). These proceedings include keynote presentations on the Hermes mission and on its medical and educational implications, as well as detailed papers on the major Canadian and US experiments. This book describes only the highlights of the Canadian experiments, selected to illustrate the main features of the overall program.

In late 1972, when serious planning of the Canadian experiments began, Hermes was admittedly a high-risk program, with many unsolved technical problems and no back-up spacecraft in the event of premature failure either during launch or in orbit. Potential Canadian experimenters were naturally reluctant to invest their time and resources on faith three or four years before launch. Nevertheless, DOC realized that the success of the program depended on user participation in the planning, organization, implementation and evaluation of the experiments. Each experimenter group would have to be primarily responsible for the planning and system design of its own experiment. DOC helped, however, by providing and installing the earth stations needed for each experiment and by providing technical support and advice as required.

Accordingly, DOC made a major effort to inform potential experimenters of the Hermes program and its ground rules and of the opportunity they had to help shape future satellite communications systems and services. It was emphasized that a major objective of Hermes was to address communication needs. An attractive feature of the Hermes system was its ability to provide two-way voice communications along with picture transmissions, and thus transform passive listeners into active participants. The small, portable earth stations were easy to install and operate, and added considerable versatility to the experimental possibilities. The experimental proposals could be flexible; details were to be gradually developed through discussions among experimenters and with DOC. By late 1972, a sufficiently positive initial response had been achieved, and a public invitation was issued to experimenter groups, associations, provincial governments and individuals to submit proposals for communications experiments using Hermes. An independent evaluation committee, nominated by the Royal Society of Canada, advised the Minister of Communications on the scientific merit and social relevance of these proposals, as well as their relevance to the development of future satellite communications services. When the Hermes program was extended beyond the initial two-year period, similar procedures were used to select new experiments and extend some of the existing ones. Figure 59 lists all of the Canadian communications experiments.

Figure 58
Major events during the Hermes mission





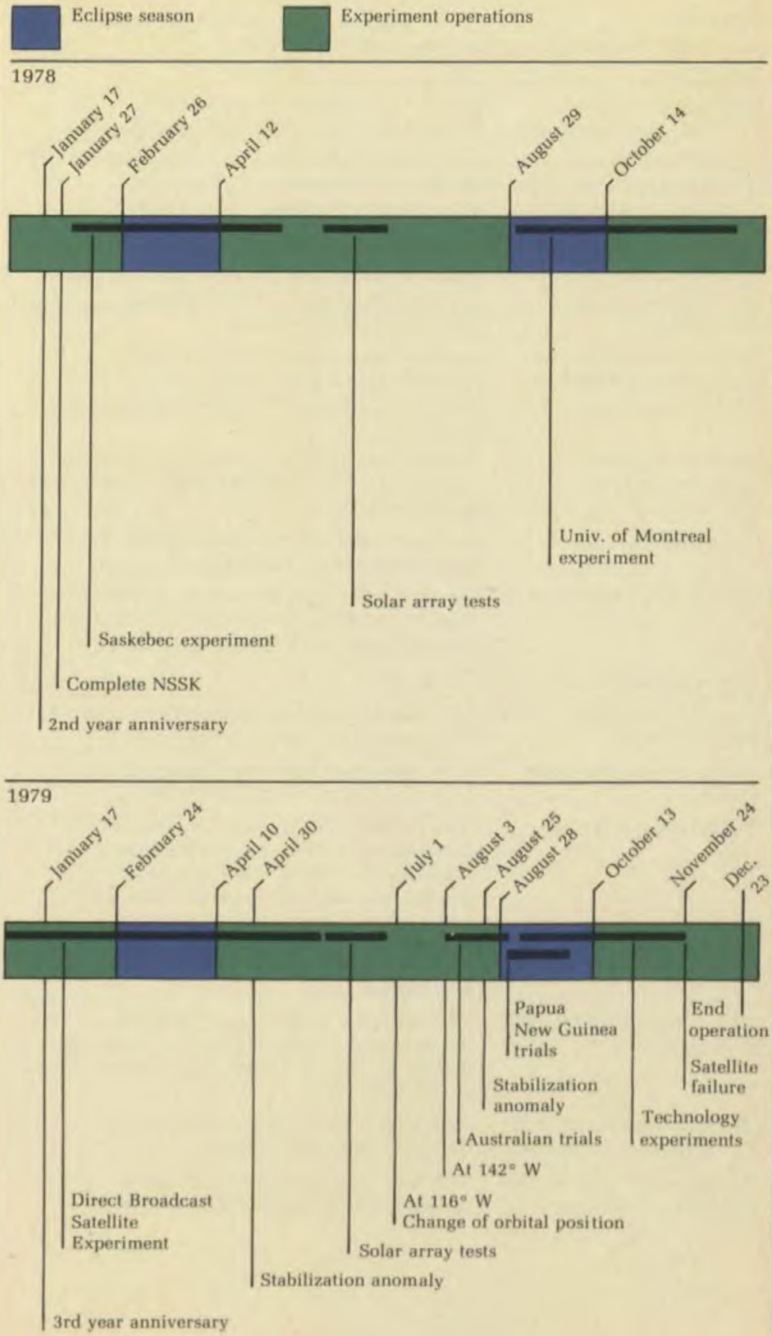

Eclipse season
Experiment operations
1978
January 17
January 27
February 26
April 12
August 29
October 14
Univ. of Montreal experiment
Solar array tests
Saskebec experiment
Complete NSSK
2nd year anniversary
1979
January 17
February 24
April 10
April 30
July 1
August 3
August 25
August 28
October 13
November 24
Dec. 23
Papua New Guinea trials
End operation
Satellite failure
Stabilization anomaly
Technology experiments
Australian trials
At 142° W
Direct Broadcast Satellite Experiment
At 116° W
Change of orbital position
Solar array tests
Stabilization anomaly
3rd year anniversary

Figure 59
Canadian communications experiments using Hermes.

Telehealth	
Memorial University, St. Johns, Newfoundland	video to hospitals at Stephenville, St. Anthony, Goose Bay and Labrador City.
University of Western Ontario, London, Ontario	video from the Moose Factory General Hospital and telephony to a nursing station at Kashechewan on James Bay.
Community interaction/community communications	
Alberta Native Communications Society, Edmonton	video programming to native communities at Wabasca-Desmarais, Fort Chipewyan, Assumption and Grouard.
Taqramiut Nipingat, an Inuit communications society in Quebec	radio between communities in Sugluk, Payne Bay, Wakeham and Koartuk, in Nouveau Québec on the shores of Hudson Strait.
Wa Wa Ta Native Communications Association, Ontario	radio between native communities in Sioux Lookout, Fort Hope, Trout Lake and Sandy Lake in northern Ontario.
Université du Québec	two-way video between Buckingham and Saint-Raymond-de-Portneuf.
University of Regina	two-way video between widely separated French speaking communities at Zenon Park, Saskatchewan, and Baie St-Paul, Québec.
Tele-education	
Carleton University, Ottawa, Ontario	with Stanford University near San Francisco, USA (exchange of courses).
Université de Montréal, Quebec	with stations at Rimouski, Hauterive and Sept Îles, Quebec (nursing education).
Université du Québec	with campuses at Quebec City, Montreal, Trois Rivieres, Hull, Rouyn, Rimouski, Chandler, and seven other centres in Quebec. (In addition to a wide variety of educational projects, this experiment included such items as cultural exchange, library access, document transmission, teleconferencing).
British Columbia Ministry of Education	with cable-TV systems in Chilliwack, Kelowna and Campbell River, a community college in Dawson Creek, and a lumber camp at Pitt Lake.
The Ontario Educational Communications Authority	with cable-TV systems in Fort Francis, Chapleau and Owen Sound.
The federal Public Service Commission, Ottawa	with four classrooms in St. Johns, Newfoundland (staff training courses).

Administrative and community services	
Government of Ontario	audio and video teleconferencing between Toronto and various locations in northwestern Ontario.
Canadian Broadcasting Corporation (CBC)	small roof-top terminals at urban sites in Montreal, Ottawa and Toronto. The CBC experiments included tests of urban reception of TV and radio broadcast, and direct-to-home TV broadcast, as well as special events such as TV broadcasts of the 1976 Olympics' equestrian events at Bromont, Quebec.
DOC/CBC/OECA	with terminals at remote communities in western Ontario and Labrador. (This was a six-month direct-to-home TV broadcast experiment using CBC and OECA programs).
Gouvernement du Québec	telephony with remote camp sites in the James Bay development area.
Technological and scientific	
Bell Canada and Telesat Canada	evaluation of Hermes terminals.
Communications Research Centre (CRC)	radiowave propagation, time-division multiple-access systems, high data-rate transmissions, evaluation of terminals.
CRC, COMSAT and NASA	digital television systems.
Hydro-Québec	clock synchronization for power lines.
Government of Manitoba	computer communications.
McMaster University	digital modems.
National Research Council	time transfer.
University of Toronto	radio interferometry.
University of Waterloo	data communications.

Figure 60
Location of Hermes earth terminals during the first two years of experiments.

In addition to the main experimental program, Hermes was used for a wide variety of short-term demonstrations. Two examples were a five-hour video teleconference in February 1978 between specialists in Ottawa and Washington on the Shuttle Space Transportation System, including the Canadian Remote Manipulator System (RMS) or Canadarm, as it is now called, and a demonstration of direct-to-home television broadcasting in May 1978, during an International Seminar on Satellite Communications in Lima, Peru. A highlight of this seminar was the use of a 0.6 m diameter terminal to obtain excellent reception of a National Hockey League game.

There were also several occasions when experimenter time was pre-empted to provide communications services during emergencies. In one instance, on July 25, 1977, heavy flooding disrupted all telephone communications with Johnstown, Pennsylvania, and a Hermes link helped co-ordinate rescue operations for nine hours until other communications systems became operative. In another case, a forest fire threatened an isolated survey camp at Fire Lake in the James Bay area in July 1976. A Hermes terminal at the camp was used to communicate with the survey headquarters (The James Bay Development Company) and plan for a possible emergency evacuation. Fortunately, the wind changed direction before the fire reached the camp and evacuation was unnecessary.

Communications Experiments

Hermes served in a large number of communications experiments and demonstrations. Allowing sufficient satellite time for each experiment was a serious problem, especially during the first year of operation. The only practical way to meet the ever-increasing experimental requirements was to schedule several experiments on each available day. Whenever one experiment was shut down and another turned on, a number of changes would have to be made in the spacecraft and in the earth stations. For example, the spacecraft antenna beams might have to be steered to new locations, the transponder power changed and a new set of earth stations activated. Accordingly, a half-hour gap in the schedule was left between experiments, to allow time for all the necessary changes.

Later in the program, it was possible to concentrate on one experiment, direct-to-home TV broadcasting, for six months from January 1 to June 30, 1979.

The communications experiments are arbitrarily categorized here as social, technological or scientific, according to their principal objectives. In general, the social experiments required extensive trials and demonstrations, and they therefore occupied nearly all of the available satellite time. The main areas investigated in the social experiments were telehealth (or telemedicine), community interaction, tele-education, and administrative and community services. Of course, there are important connections between these areas, for example in medical education.

Due to space limitations, only a few of the many Hermes experiments listed in the preceding tables have been selected for description. The selection process was difficult, and necessarily biased by the broad nature of this publication, the availability of data, and the backgrounds of the authors. Readers interested in more comprehensive information on the experiments are referred to the bibliography.

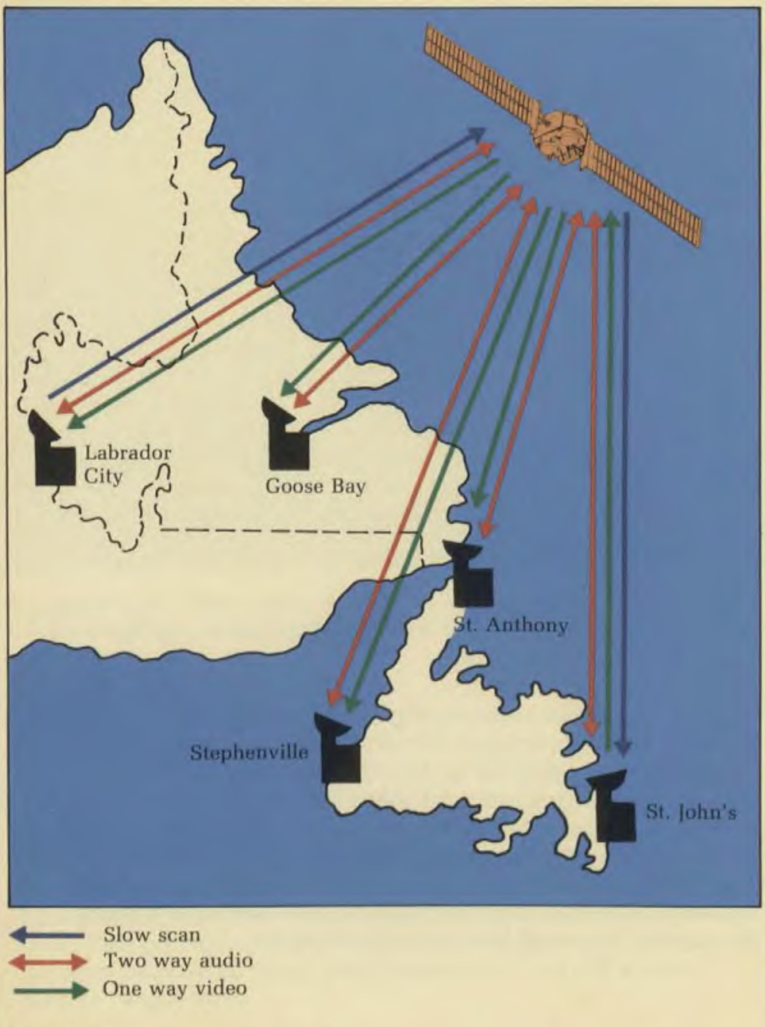


Figure 61
Broadcast configuration of the Hermes telemedicine experiment in Newfoundland.

Telehealth

There were two major Hermes telehealth experiments, one conducted by the Memorial University, St. John's, Newfoundland, and the other by the University of Western Ontario, London, Ontario.

Medical and health-care services in populated centres are vastly different from those in remote (especially northern) areas of Canada. Many Canadians who live in the North cannot call for help in an emergency because of unreliable or non-existent communications. Transportation to a reasonably well-equipped medical centre takes a long time, is costly and is sometimes downright dangerous. Medical diagnosis and treatment may be seriously delayed while the patient's condition deteriorates. Nurses and physicians in isolated regions are usually highly trained, dedicated individuals, whose efforts on behalf of their patients are often negated by the cumulative effects of poor communications and transportation.

The medical-care system in remote areas of Canada usually consists of three distinct levels: the local first-aid or nursing station; the regional hospital staffed by general practitioners, a surgeon, and perhaps an anesthetist; and a large, usually distant hospital with specialist facilities and staff. Communications between the three levels, while critical to the effectiveness of the overall system, have been woefully inadequate. The population density in the vast regions of northern Canada is too small to justify the cost of terrestrial microwave systems, northern shortwave radio is unreliable because of ionospheric disturbances and specialist visits to the remote communities are also severely limited by costs.

The telehealth experiments using Hermes attempted to show how the application of modern technology could improve this situation. It will undoubtedly always be necessary to concentrate expensive services in relatively few medical centres. For some services, such as major surgery, there is still no viable alternative; the surgeon must operate directly on the patient and the patient must go where the surgeon and his support facilities are located. The Hermes experiments, however, demonstrated that the delivery of a wide range of medical services to the patient could and should be supported by telecommunications links.

The Newfoundland project used Hermes to support an on-going medical-education program for doctors, teachers and school nurses. Programs were sent from a central point to four remote hospitals, and a one-way video, two-way voice telecommunications system was used to present material and to discuss patients and their case histories. Each remote hospital had a two-meter terminal mounted on its roof, to receive the St. John's audio-visual program and to transmit audio only in return. Figure 62 lists the co-ordinating agencies and their programs.

About 20 per cent of the Hermes time in this experiment was left open for patient presentations that could not be pre-programmed, and for last-minute insertion of consultations and other special requirements. This made it possible, for instance, to hold two major teleconferences, a joint Symposium of Physicians and Pharmacists, and the annual meeting of the Eastern Canadian Surgical Society.

Figure 62
Telemedicine Programs Planned for Broadcast via Hermes, March 28 – June 18, 1977.

Program Title	Co-ordinating Agency
Continuing Medical Education • Communication/Development Disorders in Children • Therapeutics • Anaesthesia • Medicine (e.g. Cardiology, Neurology, Gastroenterology, Paediatrics)	Faculty of Medicine
Continuing Nursing Education	School of Nursing Memorial University
Standards in Health Care	Newfoundland Hospital Association
Community Health Education • Nutrition for Pregnant Women and Diabetics • Child Abuse	Departments of Social Services & Health, Government of Newfoundland, Memorial Extension Service
Consultation Services and the Transmission of Medical Data: Slow Scan Transmission of X-rays from Labrador City to St. John's	Faculty of Medicine

The University of Western Ontario project, on the other hand, was primarily aimed at providing medical consultation services. Medical consultants at the University Hospital in London received video transmissions from the Moose Factory General Hospital on the shores of James Bay. London, Moose Factory and a remote nursing station at Kashechewan in the James Bay region were interconnected by audio links. Sixty-four specialist physicians in London made themselves available for consulting and teaching during this experiment.

In a typical scenario, a surgeon would be located with his patient in an operating room at the Moose Factory Hospital and a specialist surgeon plus anesthetist would provide consultation support from London. The specialists in London could remotely control the TV camera at Moose Factory and in this way zoom in to examine in detail any areas of particular concern. The nurse who had sent the patient to Moose Factory, and who would subsequently provide nursing care, would be at Kashechewan, and through an audio link with Moose Factory would obtain direct knowledge of the treatment given to her patients. This experiment included a wide variety of consultation; a normal morning's work might include hematology, dental surgery, general practice, orthopedics, obstetric ultra-sound, radiology and psychiatric consultation.

The value of better human communications in medical practice became evident time and again during these experiments, and is clearly revealed in Figure 63. Here, an Inuit woman in Moose Factory is seen talking over the Hermes link to her husband who was hospitalized in London. Both man and wife could speak only their native tongue. The hospital staff could not communicate with him; he was unfamiliar with and frightened by even the most ordinary hospital procedures, to the point where it was beginning to affect the medical prognosis. Through Hermes, he could see his wife, explain his difficulties and, even more important, obtain human support and reassurance.

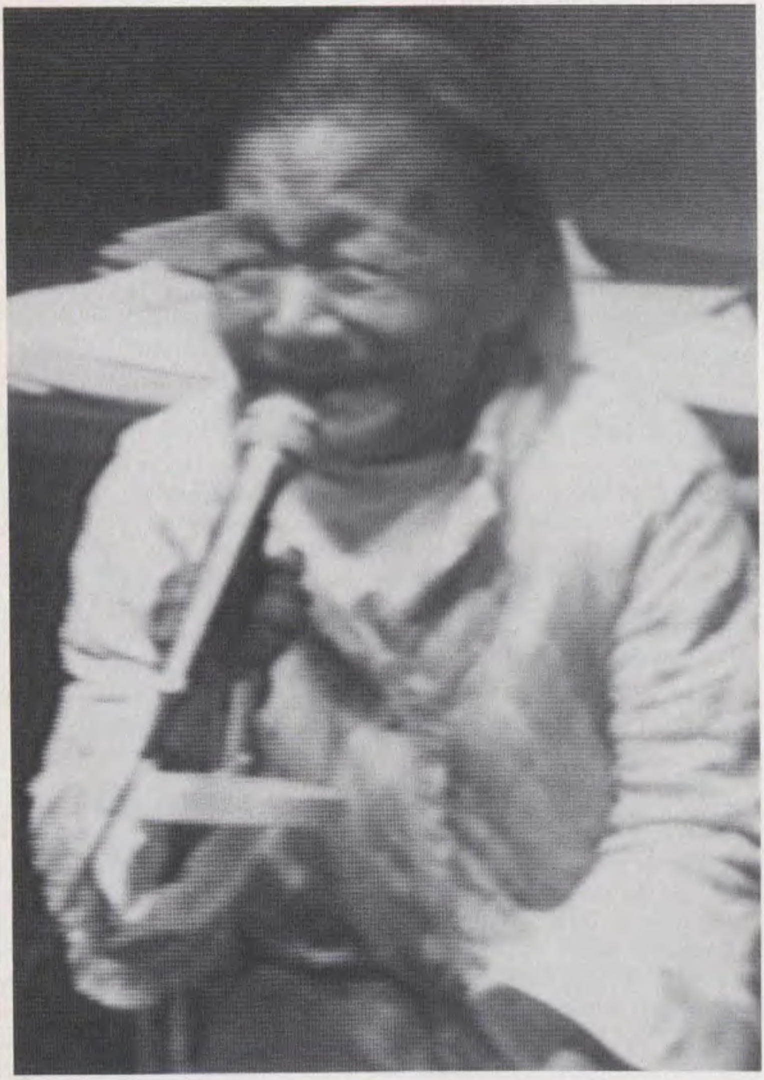


Figure 63
Inuit woman in Moose Factory providing love and reassurance to her husband in hospital in London, Ontario.

Two typical cases, reported in the Royal Society Proceedings, demonstrate the value of telehealth services.

Case 1. At the Nursing Station – The northern nurse at Kashechewan had been trying unsuccessfully all morning to contact Moose Factory by radio-telephone. She wanted an airplane to transport a sick child with chicken pox, pneumonia and high temperature to the hospital. Scheduled communications via Hermes was established late in the morning. The nurse was assured by the physician at Moose Factory that she was already doing everything possible for the child and that it might be unwise to expose the child to a cold plane ride. The nurse discussed the case with ease, often not possible on the radio-telephone due to the low quality of the transmissions. She was reassured and able to concentrate on other pressing duties at the Nursing Station.

Case 2. At the Base Hospital – A young woman on crutches was experiencing pain and weakness following placement of a Kuntscher rod in her thighbone five months previously. Consultation with London via Hermes revealed that the fracture had united, but that due to inadequate and improper exercise, her muscles were wasting away. A series of consultations with specialists in London followed, to regain the patient's confidence and establish an exercise program. The patient's progress and her gait patterns were monitored using the video link to London and the exercises were modified as needed. The patient gradually moved from two crutches to one, to walking with a cane, and then to walking without a cane indoors. Three months later, the patient was able to climb stairs, walked with only a slight limp and was working hard on exercises. She was discharged with confidence that the residual disability would soon clear. The evidence indicates that without the consistent specialist support from London provided through the Hermes experiment, this patient would have become permanently crippled.

Figure 64

Figure 65

Community Interaction

The five Hermes experiments in community interaction were naturally less dramatic than the telehealth projects. Their main objective was to demonstrate that satellite communications are effective in enabling individuals to express their opinions and to influence events beyond their immediate neighborhood. Three of these experiments were conducted by native associations: the Alberta Native Communications Society (ANCS); Taqramiut Nipingat Inc., an Inuit communications association in Quebec; and the Wa Wa Ta Native Communications Association of Northern Ontario. The remaining two were carried out by the University of Regina and the Ministry of Education of Quebec.

According to Larry Desmeules, the former executive director of ANCS, "The satellite has replaced the smoke signal as the native's best means of communication." The ANCS has a long and successful history of developing native Indian and Métis communications in Alberta and the Northwest Territories. Their staff members, almost all natives, produce radio and television programs in their own studios in several native languages and also in English, and publish Canada's first weekly native newspaper. They also produce training, educational and short feature films. The ANCS Hermes project, *Iron Star*, was the first native proposal to be carried out, and the problems encountered and results achieved have been well documented.

The Iron Star project had a difficult time getting started not only because of the usual bureaucratic delays, but also because its objectives were too extensive for the available resources. To begin with, the society's very wide interests include social development, education, training, health, medicine, law, culture and entertainment. The society proposed to link about 20 communities via Hermes in innovative experiments that would take full advantage of Hermes' interactive capabilities, and believed that the experiments should take new forms as experience and new insights were achieved.

Practical considerations, such as the short time available to prepare a detailed program, modest budgets and the difficulties of staff recruitment and training, all led to a drastic reduction of the original plan. In the end, a 3 m earth terminal was installed in Edmonton, and three 2 m terminals were located at native communities in northern Alberta. Adult education, community interest and school television programs were transmitted from Edmonton to the remote communities where native audiences were joined by staff from various provincial government departments. The audiences participated in the program by using a telephone return channel via Hermes. The community discussions were almost as wide-ranging as the ANCS interests listed above, and in at least two situations, the ANCS believes that Iron Star played a vital role in relieving native distress. To quote Desmeules again: "In Wabasca-Desmarais, where some natives were considered to be squatters on land they had inhabited for generations, we provided programming advising them how to secure land tenure. And in Assumption, natives' apprehensions over housing development delays due to flooding was eased through a regular flow of information."

Tele-education

Telecommunications have been used for many years to allow students to receive instruction via a convenient telephone, radio or television terminal. In recent years, cable-television return links have provided additional options. Satellite communications links add a new dimension to tele-education by increasing the flexibility of interconnection between the various ground terminals and facilitating interactions between the participants.

An interactive communications system provides a bond between widely dispersed students and their instructors. It also lets the students become active participants in the educational process, even though they are not physically present in the classroom. The value of such student-to-instructor and student-to-student interactions depends on both the type and the quality of communications system used, as well as on how the interactive process is conducted. This is still a fertile area for research and evaluation, and many options need to be explored.

It is, therefore, not surprising that there were seven different Hermes tele-education experiments and that several of the other experiments contained a significant educational element. Four experiments were conducted by universities – two by the University of Quebec and one each by Carleton University in Ottawa (with Stanford University in California) and the University of Montreal. The remaining three were conducted by government organizations – the Distance Education Planning Group of the British Columbia Ministry of Education, the Ontario Educational Communications Authority and the federal Public Service Commission.

The British Columbia Satellite Tele-Education Program (STEP) has many aspects of interest to other agencies conducting tele-education projects. B.C. has considerable mountainous terrain, which greatly increases the cost of providing education at a distance using terrestrial communications services, and provides a strong incentive for investigating the potential of satellite links. The main objective of the STEP experiment with Hermes was to explore the possibility of using existing educational institutions in B.C. as the prime delivery system for distance education. After successful completion of this phase, a follow-on project by the B.C. Ministry of Education was selected as one of the Anik B pilot projects. In this pilot project, the main objective is to design interactive educational programming for satellite delivery as part of a comprehensive distance-education system in B.C.

The STEP participants included all three provincial universities, the major provincial technical institute, community colleges, a remote logging camp, several public-health associations, a native Indian cultural centre, several library associations and the National Film Board of Canada. None of the participants had substantive hands-on experience with satellite-based tele-education technology, and some training was obviously desirable. Accordingly, the program goals were reviewed at a workshop attended by all participants, including community animators and cable television system operators. In addition, the two weeks immediately preceding the start of satellite-delivery programming were used for dry runs of the experimental set-up.

In general, audio-visual educational programs originated at and were controlled from a central point, and were distributed via the Hermes satellite and earth stations to terrestrial communications systems. The experiments were conducted during an eight-week period in 1977, and involved 64 hours of color-television programming at six sites. Interactive feedback from the audience was provided by audio links on Hermes or the telephone network, as appropriate to the particular experiment. In a few cases, the program was presented by an expert located at one of the remote sites. This person ran the audio-visual program via the audio link, and this configuration was surprisingly successful. Evidently, members of the audience at remote sites resent the dominance of central institutions located in the more populous areas. When the program was presented by a local expert, the quality of audience participation improved significantly. A wide variety of communications configurations were tested: community cable-TV systems were linked to college classrooms; computer terminals at several sites were linked with a central computer at the University of British Columbia (U.B.C.) – which in turn was linked with computer systems elsewhere in North America; and a remote logging camp (accessible only by airplane and water taxi) was linked into the tele-education network via radio-telephone.

Each participating group developed programming to meet its own requirements and the programming format was periodically reviewed and revised during the experiment in response to audience reactions. A major effort was made to encourage innovation while avoiding repetition of program ideas. For example, the Fraser Valley Community College proposed a series of programs centred on subjects such as pensions and health care, to deal with the well-known concerns of senior citizens in the Fraser Valley and in other communities. However, the college's senior citizen advisory committee decided that current issues would be of greater value and interest and selected programs dealing with topics such as women's rights and native land claims. The University of Victoria developed a series of programs for social service education, including soap opera presentations, workshops and off-air group discussions. The B.C. Institute of Technology produced eight vocational training programs on forestry, including a forest-fire simulation exercise. Local arthritis, heart and diabetes associations developed public forums on health care in conjunction with U.B.C.

The Hermes STEP program was an unqualified success. It was the first province-wide, large-scale demonstration of the viability of using a satellite-based system to deliver a wide variety of educational programming to a varied and geographically dispersed population. The technology worked reliably, and the quality of audio-visual transmission was excellent. In general, the planned experiments were completed satisfactorily, and problem areas were identified for future exploration. A detailed evaluation process for STEP was set up at the beginning, so that early results could be recycled into both the Hermes experiments and the Anik B follow-on activities. In addition, a workshop was held in early 1978 to review what had been learned and to discuss the evaluation, conclusions and recommendations. The following were among the initial conclusions.

(a) Satellite delivery of education at a distance should be selectively used as part of a multi-modal communications system. It should not replace programs that could be transmitted just as effectively by more economical modes, such as video cassette. The emphasis should be on interactive programs.

(b) Good audience interaction is vital to the success of a program, and an animator or tutor should be present at the receiving end to stimulate such interaction. In addition, the programming format should include a minimum of pre-taped material and be specifically designed to encourage animated interaction.

(c) A major unresolved issue is the optimum audience size for effective interaction, that is, the number of remote sites and the number of people at a given site.

The interested reader is referred to the bibliography for details of the formal evaluation. In a post-script to his final evaluation report, the principal evaluator, J.M. Richmond, clearly brings out the danger of making premature judgments in the field of human communications. A particular STEP session, an exchange between school drama classes at Campbell River and Dawson Creek (separated by about 700 km) was judged to be a "particularly awkward use of the system." Richmond later discovered that, in spite of the mechanical problems the students had encountered in establishing "natural" communications between the two sites, the experience had a catalytic effect. The students were eager to continue the exchange initiated via Hermes. A teacher from Dawson Creek visited Campbell River, an exchange of visits by the students was planned, and the Campbell River school planned to establish a program for gifted children modelled on one already established in Dawson Creek. This interactive process between the schools at Campbell River and Dawson Creek is expected to continue – all triggered by one brief STEP session.

Administrative and Community Services

The Province of Ontario carried out an experiment involving several government departments, with a view to the eventual application of satellite communications where present communications services are unsatisfactory or inadequate for provincial operations. The experiment consisted of demonstrations and tests of selected operational services, two-way video teleconferences and general administrative applications. More than 200 people from seven different ministries were involved in the experiment, under the overall management of the Telecommunication Services Branch of the Ministry of Government Services.

One of the objectives of the multi-ministry experiment was to evaluate the technical and operational performance of a DOC-designed Hermes earth station with a 1 m diameter antenna. During 1977, this earth station was installed, taken apart and reinstalled at 12 locations, and was transported more than 7,000 km by road and almost 2,000 km by air.

Four operational services were investigated:

- emergency communications for remote police patrols, fighting forest fires and other disaster situations;
- mobile communications for land-mobile operations of police and ambulance services;
- delivery of health-care service in remote areas;
- remote sensing of meteorological and other environmental data, for application in environmental and forest-fire control programs.

As an example, the telecommunications network used in the remote-sensing experiment is shown in Figure 66. The data were automatically collected and stored at a remote location, transmitted to Hermes using the 1 m earth station, and then passed to a data retrieval centre in Toronto via the CRC Hermes Ground Control Station.

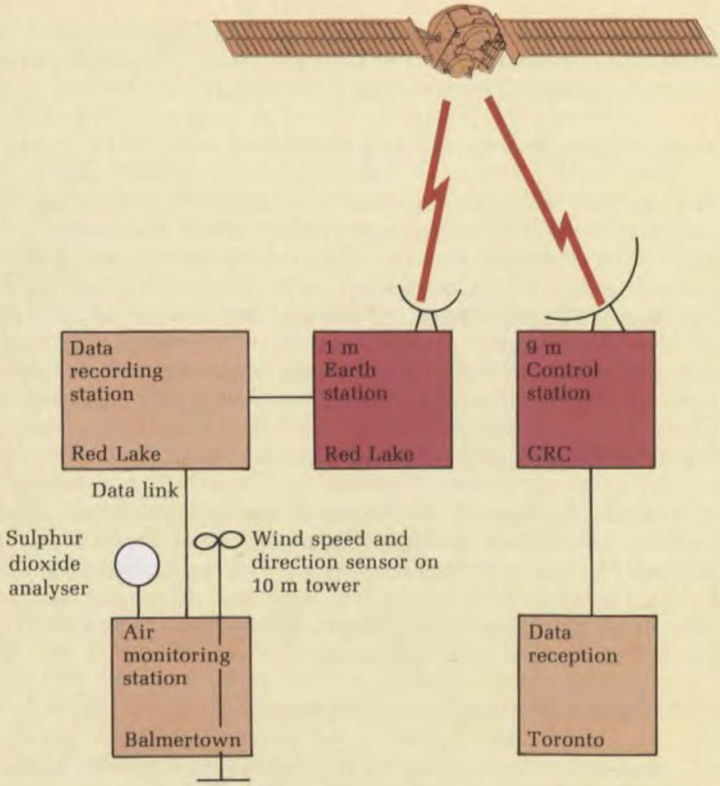


Figure 66
Experimental configuration of the Hermes remote-sensing experiment, Ontario.

A wide variety of general administrative applications was demonstrated, including information transfer between regional centres and remote locations, civil-service training, teleconferences and ad hoc management meetings that included remote locations.

The general conclusion of the experimenters was that the multiministry program had been a valuable and rewarding experience. The technical feasibility of providing improved telecommunications services had been clearly demonstrated. In addition, the participating ministries were now better able to identify specific administrative needs that could be met by particular teleconferencing networks. As a direct consequence, a full-scale pilot project in teleconferencing is now being implemented using Anik B.

In another series of experiments, the Canadian Broadcasting Corporation (CBC) and the Ontario Educational Communications Authority (OECA) used Hermes to provide a variety of services to communities and individuals.

The initial CBC experiment was designed to evaluate the quality of direct-to-home reception of television, using terminals located on rooftops in the downtown areas of large cities (Figure 67). Experiments were conducted at two sites in Montreal, two in Ottawa and one in Toronto. The high-power Hermes transponder was used with 10 different types of small earth terminals, two Canadian, five Japanese and three from the Netherlands. Antenna diameters ranged from 0.6 to 2.0 m, and the sensitivities of the microwave receivers varied considerably. The experiment was deliberately scheduled during a rainy season. A deterioration in the quality of the television pictures due to heavy rain was noticeable on the 0.6 m terminals, but had little effect on the (subjective) quality of reception on the 2.0 m terminals.

This experiment demonstrated that Hermes could reliably provide direct broadcasts of television pictures of very good quality for either community or individual home services. On the basis of these encouraging results, home reception with the antenna *inside* a building was demonstrated using a 0.6 m terminal on the 18th floor of a building in Ottawa. The window had a double pane of plate glass, and it caused only a slight decrease in the signal level.

Figure 67
A Hermes terminal with roof-top 1.2 m diameter antenna used for direct-to-home reception of television.

In another community-services experiment, OECA used Hermes to extend its network in Ontario to cable systems in three communities, Fort Francis, Chapleau and Owen Sound. Earth stations with 2 m antennas were used to feed the cable systems. The quality of reception was excellent during a three-month trial period.

From January 1 to June 30, 1979, the Canadian time on Hermes was dedicated to trials of direct broadcasting to communities using CBC and OECA programs. The objective of these experiments was to evaluate how acceptable viewers found the quality of television reception, as well as how reliably the small earth terminals performed when used by unskilled persons in a wide range of climatic conditions. Four television receive-only (TVRO) terminals with antenna sizes of either 1.2 or 1.6 m were located at the small communities of Summer Beaver (see Figure 68), Slate Falls, Mine Centre and South Bay Mine in northwestern Ontario (see Figure 69) to receive OECA educational programs during normal school hours. Three 1.6 m TVRO terminals were placed in community centres in Makkovik, Postville and Hopedale, Labrador (see Figure 70), to receive the CBC Northern Service during the evening hours. This six-month experiment demonstrated reliable operation of these TVRO terminals even during the worst Canadian winter conditions, when the outdoor equipment was exposed to rain, snow, ice storms and blizzards, with temperatures

Figure 68
Summer Beaver.

as low as -45°C. The non-technical people who operated the terminals quickly learned how to maintain good picture quality by removing a build-up of ice and snow in the antenna dish or by re-adjusting the antenna position. All the communities reported excellent reception of television throughout the experiment and expressed confidence that similar performance could be achieved in an operational situation.

Technological and Scientific Experiments

Hermes was used by several groups and individuals in a wide variety of communications technology experiments, ranging from radio wave propagation to synchronization of high-stability clocks to enable Hydro-Québec to locate the position of line faults more accurately. There was also one astronomy experiment with scientific objectives.

Figure 69
South Bay Mine.

The largest technological experiment was the investigation by CRC of a novel synchronization system for a Time Division Multiple Access (TDMA) system. In a TDMA system, several users can share a single satellite channel by transmitting signals in short bursts at very high data rates. The signal bursts emitted by the satellite must not overlap, and yet the time gap between bursts must be kept small or too much time is wasted. Optimum timing of these burst transmissions involves a precise determination of the travel time of the signals from each originating ground station to the satellite. This is a major technical challenge because of the small, but significant, motion of the satellite around its nominal fixed position. The Hermes experiment demonstrated a synchronization technique that enabled a user to join the TDMA network with an accuracy of a few billionths of a second. The feasibility of this technique, which is particularly applicable to satellite systems using narrow antenna beams, was established with Hermes.

Figure 70
Hopedale.

The University of Toronto used Hermes to link together the output of radio telescopes located at Lake Traverse, Ontario, and Green Bank, West Virginia. These telescopes constitute a Very Long Baseline Interferometer (VLBI), used to investigate the structure and variability of extra-galactic radio sources, at extremely high resolution. The Hermes satellite link replaced magnetic tape recordings at each site, thus permitting real-time correlation of the broadband data outputs which resulted in an improvement in the resolving power of the VLBI. During a two-day period, 150 radio sources were observed and several new individual sources were identified.

Space Technology Experiments

Several of the Hermes experiments were concerned with space technology (that is, with technology used in spacecraft design), rather than with communications technology as such. Because of its innovative design features, an assessment of Hermes' flight performance was essential to check the validity of ground tests and theoretical predictions. This activity included extensive pre-flight analysis and ground tests, evaluation of data obtained by special instrumentation of spacecraft subsystems, routine in-orbit observations and specially designed in-orbit experiments. The bibliography at the end of this book lists reports that provide more detail on the space technology experiments.

In general, the operational environment and flight performance were much as forecast before launch. The stabilization system maintained the spacecraft orientation and position within the limits required for efficient satellite communications, and the high-power transponder performed flawlessly throughout the mission.

Two of the in-orbit experiments, the Attitude Control System Experiment (ACSE) and the Solar Array Technology Experiment (SATE), helped advance our knowledge of the dynamic effects of long, flexible appendages on a rigid spacecraft body and laid the basis for improved design techniques for future satellites and large space platforms on which a number of payloads could be mounted.

The ACSE experiment was designed to determine the effect of solar pressure on the spacecraft. Most of the pressure is obviously on the large surface of the sails on which the solar cells are mounted. The experimental procedure was to turn off the hydrazine jets controlling the spacecraft's attitude and let the satellite drift in response to solar pressure for a five-day period. This was done during an eclipse season, when no communications experiments were scheduled. A momentum wheel inside the spacecraft provided adequate stabilization throughout this experiment. The error in the spacecraft's roll-yaw attitude gradually increased from less than 0.1° to about 1.0°, and thermal shock (thermally-induced structural deformation) during eclipse entry and exit caused minor but noticeable changes in attitude. This test demonstrated that even without attitude control by thrusters, the Hermes spacecraft maintained its stability in sunlight and eclipse for at least a week.

Figure 71
In September 1979, the Anik B satellite began transmitting TV programs directly to rural homes, community centres and cable TV systems. This DOC pilot project used 100 small, low-cost earth terminals procured from SED Systems, Saskatoon. The first home users were the King family in the village of MacDiarmid, Ontario.

The SATE experiment was designed to measure the natural vibration frequencies of the solar sail arrays and the damping of these vibrations in orbit, that is, under the exotic conditions of zero gravity. The basic procedure was to turn off the attitude-control and array sun-tracking systems and to conduct a vibration test in space. Three sets of thruster jet firings were used to set up the vibrations. The agreement between measurements and predicted values of natural vibration frequencies was reasonably good. However, the measured damping factors were substantially higher than expected from ground tests. This discrepancy is a definite area of concern that merits further investigation. Another interesting result was that there was a marked difference in the response of the two arrays. One array showed a persistent low-amplitude oscillation long after the other had subsided. The cause of this difference has not been fully explained, but it is probably due to a difference in structural damping between the two arrays.

Concluding Remarks

The Hermes program fully met its objectives of developing a high-power space communications system operating in the 14/12 GHz band and of conducting communications and technological experiments using this system. In spite of the high technological risks that had to be taken in this pioneering venture, the Hermes communications system performed magnificently and operated for almost twice its two-year design lifetime. The Canadian experiments using Hermes were all completed successfully and provided clear evidence that we now have the potential capability to effectively link individuals and organizations throughout Canada. The communications experiments demonstrated that this versatile space communications link could provide a wide range of desirable services to meet identified social and commercial needs and could thus improve the quality of life in Canada.

Hermes was the first communications satellite to operate in the 14/12 GHz band, and the power levels it transmitted per channel were up to 20 times those of conventional satellites then current.

One of the major concerns in selecting this frequency band had been the attenuation by rainfall, which would be greater than in the lower 6/4 GHz band. Earlier experiments at the CRC and elsewhere, however, had predicted that excessive attenuation would occur only during very heavy rainfall and then for only a few minutes at a time. The Hermes experiments confirmed these predictions, and the short communications outages caused by rain attenuation did not interfere with any of the scheduled Hermes operations. TV programs of excellent viewing quality, and many other commercial-type services, were received directly by portable earth terminals with antenna dishes as small as 0.6 m diameter. The most attractive feature of the Hermes system was its ability to provide two-way voice communications along with picture transmission, and thus transform passive listeners into active participants.

Figure 72
Anik B terminal (circled) on the Parliament Buildings, Ottawa.

The Hermes program clearly demonstrated the advantages of exploiting the 14/12 GHz band for commercial space communications. Since this band is reserved solely for space services, there are no limits on the power density of the satellite transmissions, and relatively small and inexpensive earth stations can be located almost anywhere, to suit the needs of the users. Because of these advantages, the Department of Communications negotiated an agreement with Telesat Canada to include a 14/12 GHz transponder system along with the standard commercial 6/4 GHz system in Anik B. Communications pilot projects using the 14/12 GHz system on this satellite began in 1979 and they are producing excellent results. As a consequence of the Hermes experience, both Telesat Canada and the Satellite Business Systems Corporation in the United States are now establishing commercial space communications services in the 14/12 GHz band.

What are the next steps? It will be recalled that a major reason for the Hermes initiatives was our desire that all Canadians, regardless of where they live, should have a fair opportunity to share in the benefits of the on-going revolution in communications and information processing. Converting this desire into reality will not be an easy matter. This is a large and highly controversial subject that will undoubtedly occupy Canadians for many years to come.

One major lesson re-learned by DOC, as the sponsor of Hermes, was that existing institutions and the individuals within them are very resistant to change. A high level of confidence must be established before any effective changes in communications technology can occur. This is particularly relevant to the development of new social communications services that involve many disciplines. Even after all the technological problems have been resolved, there are significant barriers - economic, organizational, institutional, cultural and professional - to the rapid implementation of new communications services by satellite. The completed Hermes program and the current pre-commercial applications experiments using Anik B have helped to identify these barriers and to lower them in some cases - but a great deal still remains to be done.

5

Summary and Epilogue

The Alouette-ISIS and Hermes programs have been described at some length in the preceding chapters. Those programs, however, should not be viewed as isolated segments of Canada's overall space activities. On the contrary, they were integral steps along the way to the ambitious space program we now have. Space ventures are very costly, and when Canada undertook its first satellite project there were doubts and misgivings in many quarters as to what we were about and where we were going. Nevertheless, we went ahead with Alouette 1 and that saw us embarked on a course for space which we have been pursuing ever since.

Our first venture into space was with a scientific satellite. At the time, this was a natural choice as Canada had a strong base in ionospheric studies in government and the universities and could see how to build toward a space program from that base. The necessary key people were at hand and they worked as a team. In addition, individual initiative did much to shape the program and to ensure its scientific and technological success. Indeed, throughout our space endeavors, individual audacity and perseverance have been significant and positive factors of comparable import to the team efforts. Those efforts have been recognized through the obviously-merited group awards made at various times. In addition to that, however, the name of one individual stands out prominently in this context. J.H. Chapman was the principal architect and driving force behind Canada's space program for more than 20 years. From the time of the original top-side sounder proposal that led to Alouette 1, he was deeply involved in the ISIS and Hermes programs, was largely responsible for the 1967 report, *Upper Atmosphere and Space Programs in Canada* (commonly referred to as the Chapman Report), that helped shape our early space policy and, until his untimely death in 1979, served as Assistant Deputy Minister for Space Programs in the Department of Communications. He was also chairman for seven years of the Interdepartmental Committee on Space, and played a key role in initiating or influencing virtually every space activity in Canada.

His determination, supported by the efforts of many others, has given Canada a prominent position in international space endeavors. The main steps through which we attained that position are readily identified. First, Canada's entry into the space club in 1962 with a successful scientific satellite gave us an excellent start on an overall space program. In due course, it, together with the following ISIS activities, served as stepping stones to other things. Scientific curiosity, so vital in the initial phases of most new activities, could not long compete with Canada's growing technological and applications requirements in space. The Alouette-ISIS program was an invaluable training ground in technology and systems management, first for those in the government laboratories, then, through the technology transfer process, for industrial personnel. The program had highly laudable technological accomplishments which, together with the remarkable scientific achievements, gave this country a credibility in space. This was a major factor in the government's decision to proceed with a domestic communications satellite system: Telesat Canada was established to implement and operate the system, and that activity was greatly facilitated by the availabilty of experienced personnel from the ISIS program.

The change in focus toward applications is recognized as the second major step toward a national space program. Here, satellite communication was a logical choice because of the country's strong base in all aspects of communications, and also because of a recognized national need. Telesat Canada was to address the immediate need, while the longer-term requirements prompted DOC to embark on a space technology program based on the Hermes satellite. The existing base in communications expertise was an important factor that shaped the program. From that came a build-up of Canadian competence in communications satellite technology, the establishment of various related facilities, as well as a number of noteworthy industrial spin-offs. Furthermore, it resulted in a substantial build-up of capable personnel in the space and communications fields and established additional links with the space community in other countries.

A third step was taken in 1976 with the decision to design and build the Remote Manipulator System for the US Space Shuttle (see Figure 73). This was undertaken by Canadian industry under contract to NRC, the industry having already reached the point where it could take such a major initiative. This led to a further build-up of our industrial technological capability.

The consequence of these initiatives was the building of a solid base in space science and technology, the development of a prime contractor capability in government and the emergence of a number of healthy new industries with capabilities for the design and development of space subsystems and components. These are all essential ingredients for a co-ordinated space program by a nation that is space bound and we can justifiably take pride in having come so far along the way. Recalling that, to date, Canada's application satellites have all been devoted to communications, and confidently expecting that new space ventures will follow in due course, we anticipate that the next major step will be the expansion of our space capability into such areas as remote sensing

Figure 73
The Remote Manipulator System (Canadarm) on the Columbia Space Shuttle in flight.

and resource management. This was already indicated in the December 1981 announcement by the government of increased space funding. In the next few years, the augmented program is to include the engineering and planning studies for MSAT (a proposed communications satellite for mobile radio users) and for the proposed Radar Satellite. If, later, the government decides to proceed with one or both of these programs, Canada would be well positioned in a market that could be worth several billion dollars by the end of the century.

If we are bound in that direction, we may yet have a significant new success story to add to the achievements Canada has had in space. Indeed, when we look back, Alouette 1 was a Horatio Alger type of success story. Designed and built in a government laboratory that had never before done space technology, it embodied a number of new concepts and components, and set an example of the kind of reliability that could be achieved in spacecraft equipment. It quickly built up a remarkable fund of information on the ionosphere and showed that there were many more aspects to investigate than could be accomplished by one satellite with its few experiments. The expansion into the ISIS program not only strengthened the scientific studies but also led to an increased emphasis on building up industry so that space applications could be undertaken.

The Alouette-ISIS program has produced a very detailed appreciation of the ionosphere on a global scale and of its behavior during all phases of the solar activity cycle. Moreover, it has contributed enormously to the understanding of the auroral processes, the interaction of magnetospheric phenomena with the ionosphere and the aurora, and the interaction of charged particles and radio waves. It has also produced results and uncovered phenomena that were entirely unplanned and unanticipated, something that should surprise no one considering that this was an exploratory-type program.

At the inception of the program, the ionosphere was considered the key factor in long-distance radio communications, and the primary objective was to understand its behavior. As the results accumulated, however, it became obvious that the ionosphere was intimately linked to the overlying magnetosphere, and responded to physical processes that occurred in the magnetotail.

Thus, a full understanding of the ionosphere will require a much better understanding of the more distant regions. Unfortunately, the impetus that might have produced such results was essentially lost with the decision to cancel ISIS C. Nevertheless, the ionospheric data are of inestimable value; not only have they given us information on the earth's environment, they have also been converted to statistical patterns and adapted for the benefit of the many HF communicators who continue to use the ionosphere in spite of the competition from satellite and other forms of communications.

The Hermes program represented a decided shift for DOC toward space communications. It was also a departure from the direction Telesat was taking with its more conventional communications service; it was aimed at developing new technology, opening up a new portion of the radio spectrum and demonstrating new communications services. Those objectives, and more, were achieved, and the Hermes program has been as remarkable as its predecessor. Given the opportunity, scientists and engineers of the Communications Research Centre and in industry again demonstrated that they could perform in an outstanding fashion in spite of severe constraints.

Conducting a development program that had inflexible schedules in a government laboratory posed formidable management problems. The need for timely project decisions followed immediately by actions did not fit readily into the rigid bureaucractic processes peculiar to the public service. Nevertheless, the numerous impediments were successfully overcome and the innovative features of the completed Hermes spacecraft were fully proven. It was capable of carrying payloads of various types and could have been used for a number of other missions. For the Hermes mission, the important subsystem was the communications transponder equipment in the 14/12 GHz band, which featured a medium-power and a high-power transmitter. For almost four years after launch, this transponder facility was used in an extensive and intensive series of communications experiments and demonstrations on both sides of the Canada-US border. Those experiments with Hermes, and their Canadian continuance with the leased channels on Anik B, have been and continue to be highly successful and the results are enthusiastically received by all involved. They are harbingers of communications services that may be available to all Canadians, regardless of geographic location, at some future time.

DOC, the prime contractor for the Hermes spacecraft, concentrated on the overall systems aspect and subcontracted almost all of the development to Canadian industries. This was in keeping with the government's desire to build up our industrial capability and, at an early date, to terminate the prime contractor capability as a government function. Accordingly, some of the important consequences of the program were that the industries involved acquired skills and knowledge in several pioneer areas that did not exist before. From these consequences have come new Canadian space-related products and new opportunities for worldwide sales. Com Dev Limited is one example: the founders of this company were trained on the Hermes program and took the opportunity to exploit and further develop that expertise on a commercial basis. They have created an international market in the design and manufacture of UHF and microwave components and subsystems for various space applications and for use in earth stations. For the past five years, Com Dev has grown at an annual rate greater than 40 per cent, during which time it has supplied microwave hardware to more than a dozen space programs. Moreover, virtually every earth station manufacturer outside of Japan and the communist bloc uses some Com Dev microwave products.

The Com Dev case, while impressive, is not unique. Canada's space activities have produced other industrial successes; for example, the development and export of earth terminals for remote sensing earth resources satellites, and of structural components for foreign spacecraft. All these represent tangible and valuable spin-offs from our space program. To date, they have been largely in the area of communications, a consequence no doubt of the strong influence exerted by DOC. In time, we can expect that other areas, too, will experience a similar stimulation.

As Canada's space program develops and matures, there will be a growing need for central planning of the space activities in the different disciplines. The government has already recognized this and has set up the ICS for this purpose. This is a co-ordinating body, however, and its functions do not extend far enough to eliminate all tendencies toward fragmented programs, divided responsibility and omissions in planning. At some future time, it may well be that a Canadian space agency will be set up to serve as a central focus for all of our space programs.

A mature space program should be based on a judicious balance between space science, technology and applications. It is a moot point whether Canada has already achieved a reasonable balance, or at what stage we are likely to do so. Considering the high cost of each space venture, it is not surprising that trade-offs have had to be made between these areas, and also between specific applications. Thus, for instance, in the decade between 1969 and 1979, while the Hermes program was underway, the percentage of Canada's space budget devoted to science dropped from 50 per cent to five per cent. Until Canada can take a longer term view of its space activities, we will continue to be faced with further detrimental trade-offs. One essential, and probably very difficult requirement will be to find within the country the necessary skilled manpower in all categories ranging from space scientists to industrial support.

There are already signs of a change toward a better balance between space science and space applications. The National Research Council has provided a focus for space scientists in the universities and government laboratories, initially in its Space Science Co-ordination Office and more recently in the Canada Centre for Space Science. Much as DOC has taken the lead in different aspects of space pertaining to communications, NRC is providing leadership and co-ordination for a number of space science projects, some of which it is hoped will be included on the US Space Shuttle in the not-too-distant future.

Looking back on the Alouette-ISIS and Hermes programs and their impressive achievements in science and technology, one cannot escape a feeling of regret that trade-offs had to be made and that some areas suffered in the process. The solid base in space science that Canada built during the 1960s was seriously eroded during the 1970s while the technology and application areas were being nurtured. Lack of continuity extended to those areas, as well, in that no technology development satellite has followed Hermes, although Anik B has provided follow-on for the communications experiments. Nevertheless, the expertise in space technology acquired during the past two decades has not been lost. Some of the CRC personnel who participated in the Alouette and Hermes developments are now involved in other space activities, while others have migrated to industry to augment the growing Canadian industrial capability that can now be identified for many space applications.

Looking ahead, one can see opportunities and potential applications in a number of areas. Work is already underway on several, including future Aniks, the RMS and SARSAT. The recent announcement of further government support for remote-sensing and communications satellites must be considered as only the initial steps in a continuing series of future Canadian space endeavors. Canada's initiatives here are prompted by the same considerations that took this nation into space a generation ago; the desire not to buy the technology in other countries, which would export jobs and dollars, but to build it ourselves and reap the benefits from domestic as well as international markets. The series will need careful planning and the whole space program will require the continued vision and dedication of the key people involved. For this country to get where it should be in space will require organizational changes so as to bring better co-ordination and focus to our diversified space activities. Given such an organization, together with a balanced space program and, hopefully, a well-stocked manpower pool, this country's space activities need only be limited by the amount of money and imagination that government and industry are prepared to invest. Canadians can then expect to realize an even greater return from all their space expenditures.

Canada has chosen a course for space and we are on target.

Glossary

Alouette	The name given to the first Canadian satellite. It is the French word for a high-flying bird, the lark. It is also the title of a well known, French-Canadian song.
ANCS	Alberta Native Communications Society.
Anik	The name given to the communication satellites of Telesat Canada. The word is taken from the Inuit language and means brother.
Auroral oval	The location, in latitude and time of day, of the aurora in each hemisphere.
Auroral zone	A ring or belt in each hemisphere marking the zone of most frequent occurrence of night-time auroras.
CBC	Canadian Broadcasting Corporation.
Cleft	A transition zone on the day side of the magnetosphere in each hemisphere between geomagnetic field lines that are closed and those that stretch far into the magnetotail.
CRC	Communications Research Centre.
CTS	Communications Technology Satellite, later renamed Hermes.
DND	Department of National Defence.
DOC	Department of Communications.
DRB	Defence Research Board.
DRTE	Defence Research Telecommunications Establishment.
Earth radius	A convenient unit of distance, equivalent to 6,370 km.

Electron Cyclotron Frequency	The frequency at which an electron will cycle or gyrate in a magnetic field; also known as the gyrofrequency.
Electron density	Electron number density, usually signifying the number of free electrons per cubic centimeter.
ESRO	European Space Research Organisation, later renamed the European Space Agency (ESA).
F layer	The most prominent layer of ionization in the ionosphere.
F-layer critical frequency	The lowest radio frequency that will penetrate through the ionospheric F layer without reflection.
Geomagnetic field	The magnetic field of the Earth.
GHz	Gigahertz, a unit of frequency in the radio spectrum, equivalent to one billion (10^9) hertz.
GSFC	Goddard Space Flight Center (NASA).
Hertz	A unit of frequency in the radio spectrum which, at one time, was termed *cycle per second.*
HF	High frequency; designates a portion of the radio spectrum used for communication via ionospheric reflection; usually applies to the radio band from 3 to 30 MHz.
Hydrazine	A liquid, carried in tanks on a spacecraft, for use in the jet thrusters.
ICS	Interdepartmental Committee on Space
Ions	Electrically charged particles; may be positively and/or negatively charged atoms or groups of atoms.

Ionogram	An ionosonde recording that shows the range from which echoes are received as a function of frequency.
Ionosonde	An HF transmitter-receiver combination used to *sound* the ionosphere.
Ionosphere	A region in the upper atmosphere where free electrons and positive ions are found in significant concentrations.
ISIS	International Satellites for Ionospheric Studies.
kHz	Kilohertz, a unit of frequency in the radio spectrum, equivalent to 1,000 hertz.
LeRC	Lewis Research Center (NASA).
Magnetosphere	An elongated mantle or cavity about the Earth, rather like a comet in general appearance formed by the interaction of the solar wind with the Earth's magnetic field.
Magnetotail	The long tail of the magnetosphere, which extends in direction opposite to that of the sun.
MHz	Megahertz, a unit of frequency in the radio spectrum, equivalent to one million (10^6) hertz.
NASA	National Aeronautics and Space Administration (USA).
NRC	National Research Council (of Canada).
OECA	Ontario Educational Communications Authority.
Plasma	A gaseous collection of electrons and positive ions, that may also include some neutral particles.

Plasma frequency	The frequency at which electrons, if displaced from their equilibrium position in a plasma, will oscillate in the process of re-establishing equilibrium. This frequency is proportional to the square root of the electron density.
Plasma sheet	The central, apparently flat or planar, portion of the magnetotail (see Figure 10).
Plasmasphere	A region in the inner magnetosphere where the plasma density is relatively high (see Figure 10).
RMS	Remote Manipulator System, sometimes identified as the Canadarm; developed for the Space Shuttle.
SARSAT Program	Search and Rescue Satellite program.
SCOPO	Space Communications Program Office at CRC.
Solar wind	Outward flowing plasma from the sun.
Sputnik 1	The first artificial satellite of the Earth, launched by the USSR on October 4, 1957.
STEM	Storable Tubular Extendible Member, manufactured by Spar Aerospace Ltd.
STEP	Satellite Tele-Education Program (BC).
TCTS	TransCanada Telephone System.
TVRO	Television receive-only.
UHF	Ultra high frequency; usually applies to the radio band from 300 - 3,000 MHz.
VLF	Very low frequency; usually applies to the radio band from 3 - 30 kHz.

World Data Center Set up for the international collection, preservation and exchange of scientific geophysical data in accordance with principles established by the International Council of Scientific Unions, an autonomous body that comes under the aegis of the United Nations' Educational, Scientific and Cultural Organization (UNESCO). Centres for ionospheric data are at Boulder in the USA, Moscow in the USSR, and Tokyo in Japan. The main centre for satellite data is at GSFC.

Chronology

October 4, 1957	Launch of Sputnik 1, the first artificial satellite of the Earth.
December 31, 1958	Canadian proposal for top-side sounder submitted to NASA.
March 11, 1959	NASA approval in principle for top-side sounder.
November 18, 1959	Letter of Agreement between NASA and DRB re Alouette.
December 16, 1959	Letter of Agreement between DRB and NASA re Alouette.
September 29, 1962	Launch of Alouette 1.
May 23, 1963	Memorandum of Understanding between DRB and NASA re ISIS.
May 6, 1964	Exchange of Notes between US and Canada, confirming ISIS Memorandum of Understanding.
November 29, 1965	Launch of Alouette 2.
January 30, 1969	Launch of ISIS 1.
September 1, 1969	Telesat Canada created.
March 31, 1971	Launch of ISIS 2.
April 20, 1971	Letter of Agreement between DOC and NASA re Hermes.
May 18, 1972	Protocol agreement between ESRO and DOC re Hermes.
September 30, 1972	Termination of Alouette 1 operations.
November 9, 1972	Launch of Anik 1.
April 20, 1973	Launch of Anik 2.
May 7, 1975	Launch of Anik 3.

August 1, 1975	Termination of Alouette 2 operations.
January 17, 1976	Launch of Hermes.
May 21, 1976	Formal inauguration of Hermes experiments.
January 17, 1978	First extension of Hermes experimental program.
December 15, 1978	Launch of Anik B.
November 24, 1979	Termination of Hermes operations.

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