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History of Bell Labs Physical Research, 1980–2006

Geophysics, Space Physics, and Communications

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Many of the scientific results from the data produced by the space missions that Bell Laboratory researchers were key participants in during the 1960s and 1970s were covered in Chapter 7 of Millman (1983). That Chapter also relates the partial transition to ground-based studies of Earth's space environment and to collaborative space-based missions in the solar system. The pre-1980 research and its follow-on to the early 2000s is outlined in volume two of my memoir *Way Leads on to Way—Career* (2023). A portion of the ground-based research was reorganized on occasion to address some questions arising related to AT&T cable and satellite communications organizations and to government agency research being conducted at the Bell Laboratories location in Whippany, New Jersey. This essay briefly addresses post-1980 research related to studies of the space environment around Earth and in the broader solar system. It also briefly addresses a number of these research activities that were of relevance and importance to the telecommunications business of AT&T.

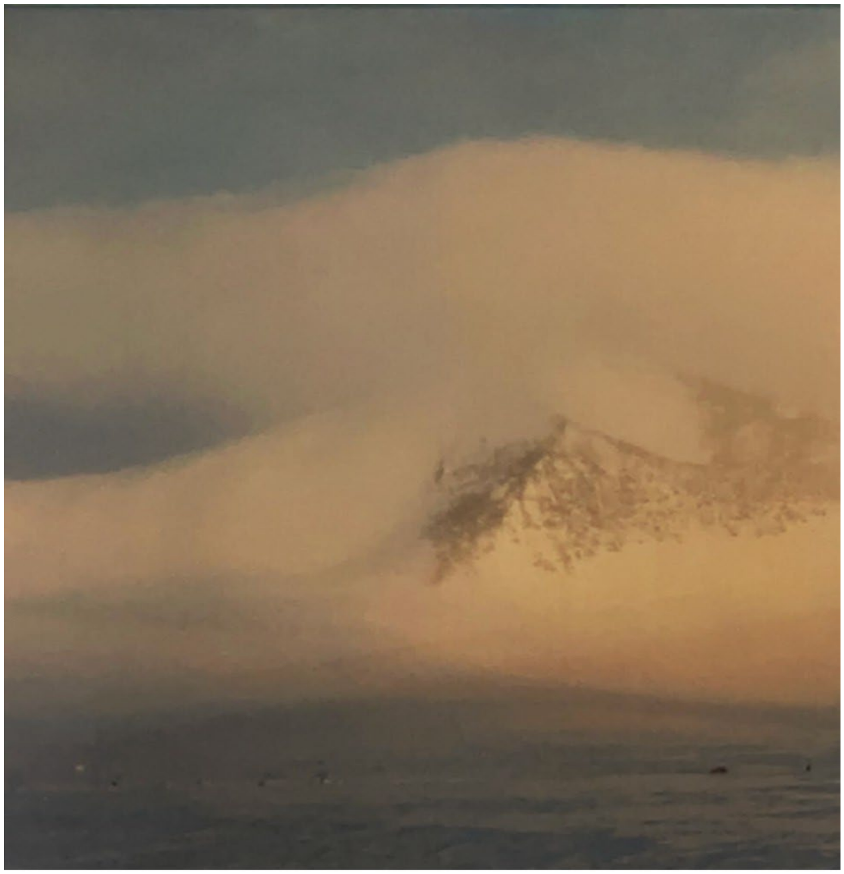
Geomagnetic Research: Antarctica

Chapter 7 of Millman (1983) captures the beginning of research with ground-based fluxgate magnetometers at high northern geomagnetic latitudes and in the Antarctic. In the north, stations were established at Bell Canada locations at Girardville and north of La Tuque, Quebec. In New Hampshire, one location was a New England Bell central office in Pittsburg and a University of New Hampshire field station. Results of this research included important understandings of the effects of plasma gradients in the magnetosphere on hydromagnetic waves, their generation and propagation. As related in that Chapter, essential plasma theory research was contributed by Akira Hasagawa and Liu Chen.

Starting about 1980 the Antarctic research was repositioned and added to. The instrument at Siple Station was moved to the South Pole, in the southern auroral zone. Another instrument was positioned at Arrival Heights near McMurdo on Ross Island, south of New Zealand. In the 1980s one of the instruments in Quebec was relocated to Iqaluit on Baffin Island. South Pole and Iqaluit are located at about 75 degrees west longitude and a geomagnetic flux tube approximately connects them: conjugate stations in the auroral zone. This move provided unique conjugate studies of magnetosphere auroral processes. The magnetic flux tube also passed through the GEO location of AT&T satellite Telstar 402R.

Magnetometer Vault at Arrival Heights, Ross Island

The magnetometer location at Arrival Heights provided data at latitudes inside the magnetosphere polar cusp, with geomagnetic field lines stretching into the interplanetary medium. Both locations in Antarctica included instrumentation from university groups, including riometers, VLF receivers, and photometers at auroral green, yellow, and white light wave lengths. Responsibility for both the South Pole and Arrival Heights stations were assumed in the early 2000s by the Center for Solar-Terrestrial Research (CSTR) of the New Jersey Institute of Technology (NJIT).

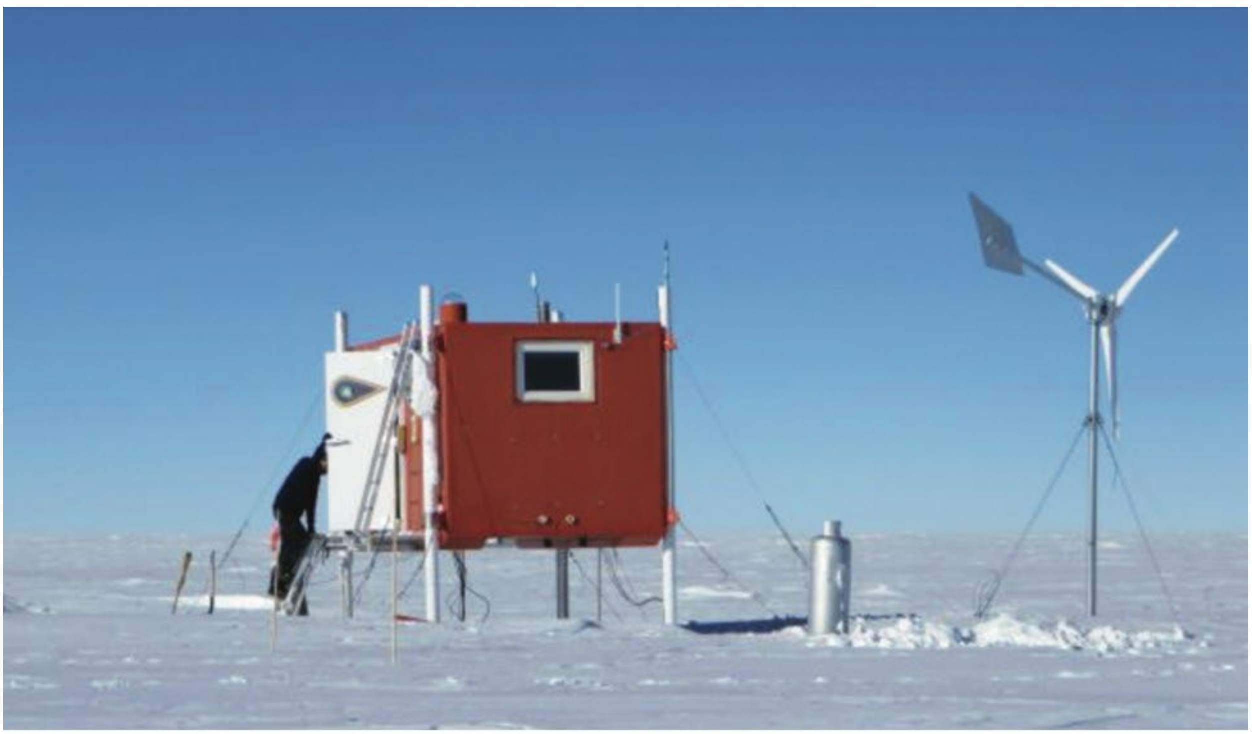


Mount Lanzerotti, 1550m, Sky-Hi Nunataks, Antarctica. Gifted to Louis Lanzerotti by John Dudeney, British Antarctic Survey

In parallel with the research installations at South Pole and then Arrival Heights near McMurdo, we collaborated in the 1980s and 1990s on a major Antarctic project with research groups at the University of Maryland, Stanford University, a Lockheed Research Laboratory group in Palo Alto, and the Space Sciences Laboratory at the University of California Berkeley. The effort was to design, build, and install five unmanned geophysical observatories on the Antarctic plateau: Automatic Geophysical Observatory (AGO).

The geographic layout of the AGOs spanned from the geographic South Pole location to across the south geomagnetic pole. Only the Antarctic continent provides a polar land mass to span such a wide geomagnetic range. Instrumentation at each site consisted of our Bell Labs low power fluxgate magnetometer, imaging riometers of Maryland (Ted Rosenberg), optical imaging of Lockheed and Berkeley (Jack Doolittle and Stephen Mende, respectively), and VLF antennae of Stanford (Robert Helliwell). Excellent data were received and happily analyzed for many years. Of especial interest was monitoring and then understanding of changes in the data under solar-produced disturbances of the magnetosphere. Abrupt differences were found as the magnetosphere compressed and expanded under relaxed and enhanced solar wind conditions. Of considerable interest was the response of the polar magnetosphere to large ejections by the Sun of coronal mass. The unique array of stations spanning the southern polar region provided the first (and only) such data and contributed to theories of magnetosphere structure under differing solar wind driving conditions.

The initial AGO power for winter-over operations was by propane generators. Propane tanks were airlifted in each austral summer. Unfortunately, summer austral visits found the propane power to be down on occasion at a station, due to freeze up of generator exhaust or some other condition. Obviously, such a condition at a station caused the loss of data. Ultimately, after my move to NJIT and the managing of the Antarctic project being assumed by physics professor Andy Gerrard, wind turbines and solar cell power were designed by NJIT technical personnel. This powering combination was installed at each of the four AGOs that could still be accessed above the snow and provided uninterrupted power and data acquisition into the 2010s.



Automatic Geophysical Observatory (AGO) on Antarctic plateau

Geomagnetic Research: North America and Applications

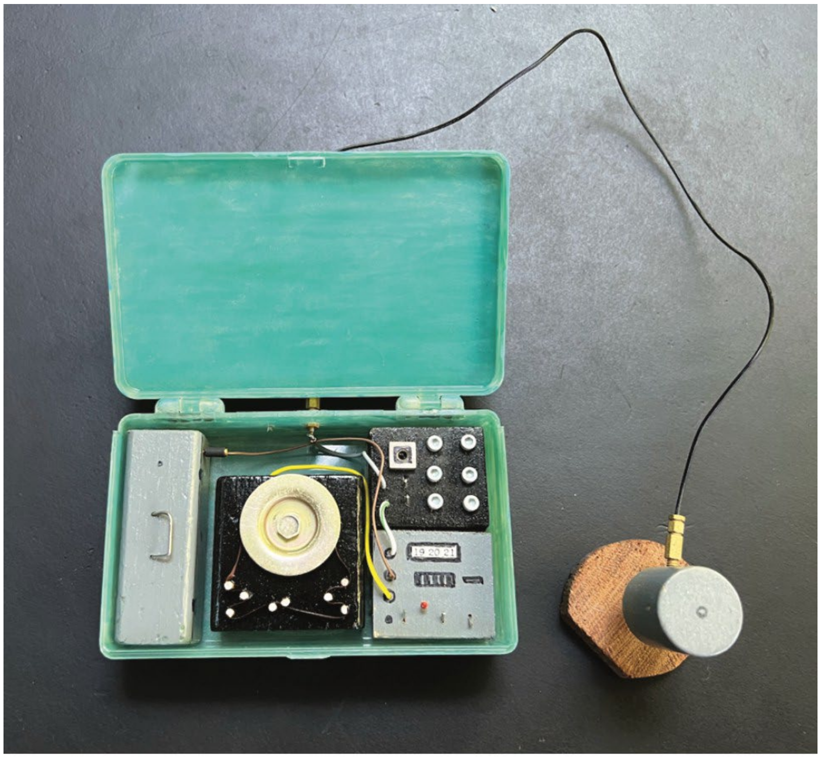
For some time in the mid-to late 1970s we had begun to think about how we might study the azimuthal extent (azimuthal wave numbers) of hydromagnetic waves on the ground, as a complement to the ongoing latitudinal studies with the four stations in New Hampshire and Quebec. We decided that we required instrumentation flexibility for such studies. That is, installing magnetometers at fixed locations in longitude was not the path to follow; the ability to flexibly change azimuthal spacing was needed.

This desire from a research perspective, combined with the results of the ATT long lines L-4 cable outage in Illinois in the August 1972 geomagnetic storm (see below), led us to the conception and design of a portable fluxgate magnetometer system. With such a system we would also be able to travel to Illinois and study the geophysics of the L4 cable route from Plano to Cascade that suffered the 1972 outage. At that time in the late 1970s Bell Labs had developed the MAC-8 (BELLMAC-8) microprocessor that we could use for our planned portable system. Working closely with us on the system was Peter Rosenfeld of the computing area in Building 2, who was centrally involved with the development of the MAC-8.

We incorporated the MAC-8 together with a commercial 9-track, 256-bit tape recorder into a suitcase-sized aluminum carrying case. We purchased four low power fluxgate magnetometers designed to our specifications from Mario Acuna who had developed a business derived from his work at the Goddard Space Flight Center with Norman Ness on spacecraft magnetometers. The fluxgate instrumentation was also included in the carrying case together with a battery that could power the entire system for a month.

An interesting aspect of the 256-bit tape recorder was that the individual recorded bits could be visually identified with an eye loop after sprinkling magnetic dust on the tape. In this way we could importantly verify in the field that the system was working and recording data. Designing and working on the system was Carol Maclennan, Joe Kraus, and Les Medford. Two of the portable magnetometers were deployed at Peacham, VT, and at Saranac Lake, NY. The data obtained from the initial azimuthal array in the early 1980s, together with the data from the fixed Pittsburg, NH, location were excellent. However, the science results from azimuthal studies were never exploited as much as they could have been, largely because of the intrusion and pressure of other research activities.

One portable magnetometer was taken to the Sondrestrom, Greenland, National Science Foundation radar site on two occasions in 1985 for joint data taking with the incoherent scatter radar. This research opportunity arose from the sabbatical year that Bob Hunsucker of the Geophysical Institute at the University of Alaska was spending at Bell Labs, occupying a desk in Les Medford's lab. Bob suggested some joint radar and magnetometer research on hydromagnetic waves, in particular to understand magnetosphere cusp ionosphere plasma densities and the production of hydromagnetic plasma waves. Bob, an expert in incoherent radar studies, had written a proposal to the National Science Foundation to request dedicated time on the radar. Bob programmed the radar to be able to detect hydromagnetic waves in the about 2-minute to 5-minute band, which we could readily measure by the magnetometer. Good data were obtained from both excursions made to Sondrestrom. Carol Maclennan, Bob, and I transported the magnetometer and ourselves on military flights from McGuire Air Force Base in New Jersey, with always a stop at Goose Bay, Labrador.



Portable Magnetometer System Model by Lester Medford

Magnetic storm of August 1972. One of the largest geomagnetic storms of the 20th century occurred in the interval 4-7 August 1972. The Bell Labs instrument on the IMP5 satellite provided excellent measurements of the solar particles emitted by the sun and that were accelerated by the two interplanetary shock waves that impacted Earth. Ultimately a number of research papers resulted from these measurements. Research related to this geomagnetic event led to further related applied and frontier research in the 1980s and 1990s.

Shortly after the storm, I was contacted by Chester Anderson, an employee in a Bell Labs department at Whippany. His department worked on electromagnetic interference problems in AT&T outdoor systems. This department was heavily involved with studies of lightning mitigation on AT&T infrastructure. Chester informed me in his call that an AT&T Long Lines L4 cable in Illinois had suffered an outage from the geomagnetic storm. The segment of cable running from the powering station at Plano, Illinois, to Cascade, Iowa, had been overwhelmed by ground currents that had shut down the power supply at Plano. This outage meant that a major communication line from Chicago to San Francisco was out of use for more than an hour.

Chester wanted to collaborate in order to understand the geophysical situation that produced the outage. An arrangement was made for Chester to work full time at Murray Hill on the analysis of the storm and the outage. Chester spent over a year at Murray Hill, during which time we wrote a scientific paper on geomagnetic induction arrows as well as worked on the geomagnetic storm analysis. Between the expertise of Carol Maclennan and me in geo-magnetic activity and the magnetosphere, including the interplanetary conditions at the time of the storm, and Chester's expertise in electromagnetic ground induction studies, we were able to complete a quite thorough study of the event. In addition to understanding the geophysical conditions, we were able determine the likely magnitudes of the induced ground currents in the cable and thus the impact on the AT&T long lines telephone cable. The analyses had implications for changes needed in communication cable powering systems to mitigate against possible similar solar-produced events in the future. System changes were introduced. A significant paper was published in the *Bell System Technical Journa*l (*BSTJ*) that received much attention in the Bell System and in the wider engineering community.

In the late 1970s into the 1980s, the Bell System came under some pressure from outside companies and the Department of Defense because of the L4 cable outage in the August 1972 geomagnetic storm. Outside professionals well known for their expertise in understanding the electromagnetic pulse from high altitude nuclear explosions pressed on the government that perhaps the Bell System was not robust and that the System did not know how its cable systems operated. In particular, how they might operate under a nuclear explosion, which the geomagnetic storm served as an analog in nature.

The Bell System had already installed many of its cable powering and control systems in deep underground, blast-proof vaults, such as was installed at Plano. As a result of the political pressures from several quarters (including a few outside experts, the Defense Department, and some companies), in the 1980s three portable magnetometers were deployed from Plano to Cascade to carry out research to potentially understand the conductivity structure in the region of the cable. The research did identify some high resistivity regions near the area of Galena, Illinois, that could have routed the ground currents through the cable. The results of this study were reported in a technical paper.

On several occasions I was asked to accompany Sol Buchsbaum, Bell Labs Executive Vice President, to meetings at the Pentagon to engage in discussions of the 1972 L4 cable outage and what the Bell System was doing about the situation. The combination of our *BSTJ* paper, our magnetometer research in the Plano/Cascade region, and the changes that Long Lines made to the cable powering systems on the basis of our analyses and *BSTJ* paper caused the external pressures on the company to be slowly relieved — in so far as I as a researcher discerned.

Sandia program. The portable magnetometer systems became important as well when a Sandia Laboratories employee, Sanders ("Sandy") Dolce, called me in the early 1980s to talk about a possible classified measurement program in Nevada. I had originally met Sandy when he was a graduate student at the Bell/Rutgers tandem accelerator while I was calibrating our ATS and IMP satellite instruments. At the time, Sandia was still being managed by AT&T. Les Medford set up one of the portable magnetometers in California (Barstow) and two in Nevada in support of the Sandia program. In addition to the data that we supplied to Sandy and Sandia for their program, Les, Carol Maclennan, and I used the data for some published scientific studies of hydromagnetic waves at the low geomagnetic latitudes of the sites.

Puget Sound study. A short-term magnetic field campaign was conducted in the 1980s with Bell Labs Whippany personnel in the Juan de Fuca Strait and Puget Sound areas of Washington state. Patricia Gruber was the lead in the Whippany effort in the field campaign. Portable magnetometer instrumentation was situated at several locations on the Olympic Peninsula for the classified program. Data were transferred to Whippany for their analysis and ultimate program use.

Ocean cables. The experience with the AT&T L4 cable outage in Illinois and the subsequent geomagnetic depth sounding study of the region the cable traversed led us to begin to think about the company's long haul cable system. The "Long Lines" element, the trans-ocean cables, was still a part of AT&T after the 1984 divesture. And AT&T was continuing to lay cables across the Atlantic. At this time, AT&T was the only ocean cable carrier from the U.S.

Prior to the divestiture, the U.S.-based Atlantic cable locations were underground bomb-hardened sites (as was the site at Plano, Illinois). The hardening was relaxed after divestiture (e.g., the bomb-proof doors were readily opened). The two sites at Green Hill, Rhode Island, and Tuckerton, New Jersey, as well as Point Arena, California (a non- hardened site), were the locations where we ultimately installed cable monitoring equipment. Magnetometers were sited at Point Arena and St. Joseph Shrine in Stirling, New Jersey. The site at Tuckerton had too much cultural magnetic "noise" from the urban ground currents. The Stirling site, abutting the Great Swamp Wildlife Refuge, was very quiet geomagnetically.

The ocean engineering workforce was based in the office complex on Mt. Kemble Avenue south of Morristown. This was a very convenient location for Les Medford and me to interface with the cognizant personnel. The Labs management and engineering personnel for the design of cables and repeaters were at the Bell Labs Holmdel location.

The station at Point Arena was the location of the first cable between the continent and Hawaii, which landed at Hanauma Bay. The old system, deactivated and unpowered, consisted of two cables, as for the first transatlantic cable (in 1956): one line for voice in one direction, the second for voice in the opposite direction. The trips to Point Arena were always enjoyable, through laid-back social areas of California (including Point Arena itself) and the coastal redwood forests. The drive from Boonville to Point Arena via Mountain View Road through the redwood forests was always a treat for the beauty of the redwoods and for the twists and turns of the road.

The cable data were analyzed in a number of ways. The Hawaii data (with the two unused cables grounded at both ends) were used for statistical studies of the induced voltages, including as a function of geomagnetic activity . A tsunami off Cape Mendocino was detected by the induced current measured in the cables; the analysis technique and results motivated a patent with David Thompson of the math department, Carol Maclennan, and me. Studies of the induced currents during the quietist geomagnetic intervals provided a determination of the electric field at the core-mantle boundary. This research followed an earlier study by Keith Runcorn of the U.K. His and our measurements have not been duplicated since and have played a role in discussions of Earth's structure.

Much of the data from the Atlantic cables were statistically analyzed in terms of probably distributions of induced voltage and current extremes and as functions of geomagnetic activity. The distribution data were characterized in terms of mathematical distribution functions so that determinations could be extrapolated to other possible extremes for possible powering disruptions. Some data from individual geomagnetic storms were also analyzed. The results were shared and discussed with the engineering staff at AT&T Long Lines in the Morristown office.

The laying of the TAT-7 cable from Tuckerton provided the opportunity to do measurements on the first segment laid from the station to just off the continental shelf. Long Lines engineers installed a grounding plate on the cable end off the shelf for us. Data analysis and interpretation surprisingly showed a geomagnetic anomaly off the New Jersey east coast and was reported in a technical paper.

The TAT-8 cable, the first ocean fiber cable, was being monitored at the time of the large 1989 geomagnetic storm that produced an electrical power outage across Quebec. The storm also affected some of the U.S. east coast. A large electrical transformer at a nuclear power station in New Jersey was destroyed by the exceptionally large ground currents. The induced voltage drop measured by our instrumentation on TAT-8 was just under the limits for shutting down the powering system.

A proposal was made to the Bell Labs management engineers in Holmdel involved with cable design, and to Long Lines engineers, to consider incorporating temperature sensors (possibly thermistors) in future cable repeaters in the deep ocean. Such data could be of significant importance to ocean scientists and the cost impacts on cable repeaters would be minimal. It would also be a fine contribution of AT&T to ocean science. While considerable discussions occurred, the idea was not pursued even though Long Lines engineers in the Morristown office were very supportive throughout. Such ideas and implementation for deep ocean monitoring are continuing to be explored by researchers in the context of the large arrays of ocean cables that have been deployed over the last decades. Nokia Bell Laboratories has achieved major advances in this research area, making use of the signaling capabilities of fiber systems and the now large array of systems across the world (e.g., Kamalov and Mazur, 2025).

AT&T Telstar satellites. I began to become involved with the AT&T Telstar 3 satellites when Dean Maurer of Bell Labs and AT&T Skynet approached me on several occasions about radiation effects on solar panels. Dean was responsible for overseeing aspects of the satellite powering systems that were in the AT&T communications satellites that were being built by contractors. Dean asked me to review contractor proposals for the AT&T series 3 and series 4 Telstar satellites in terms of radiation effects, and of radiation effects on solar panels, and thus on likely power degradation over the lifetimes of the spacecraft. These projects for studies of solar panel arrays formed the topic of my first "space weather" paper in 1969.

During some of the discussions related to the Telstar 3 series, I proposed flying surface charge plates on the satellites to monitor surface charging and degradation of solar panels. Dean was very interested, but the idea initially went nowhere with AT&T Skynet management.

Before and after serving as a Mission Specialist astronaut on the shuttle STS 41-C Challenger mission in 1984 (the eleventh shuttle mission), Terry Hart, with degrees in mechanical and electrical engineering, worked at Bell Labs. In the late 1980s he served as the director of the Government Data Systems Division of AT&T in Stockholm, Sweden. Terry returned from Europe in 1991 as the director of Satellite Engineering and Operations for AT&T Skynet. He became the president of Loral Skynet when AT&T sold its satellite division to Loral Space and Communications in 1997. Terry was very interested in the work that Dean Mauer and we at the Labs in Murray Hill were doing related to radiation effects. He encouraged us with financial and moral support. This continued after the sale of Skynet by AT&T to Loral. This interest also resulted in the flying of surface charge monitors on the Telstar series 4 satellites.

Dean, Carol Maclennan, and I, together with several summer students, analyzed these charge plate data. The analyses included examination of geomagnetic activity and data from several of our magnetometer locations around North America and Antarctica. The objectives included understanding the charging conditions with geomagnetic activity on the several surfaces of the satellites where the plates were placed.

Of especial interest and importance to AT&T were our analysis of the failure of Telstar 401 in January 1997 during a geomagnetic storm. We analyzed the charging data from Telstar 402R in the context of the geomagnetic field data from our ground-based instrument locations at South Pole and Iqaluit. These stations were at the foot points in the southern and northern hemispheres, respectively, of the geomagnetic field line approximately through the geosynchronous Telstar 402R. For the first time changes in surface charging on a satellite caused by space plasmas were found to be associated with changes in the electrical currents connecting the magnetosphere to ionosphere currents where the magnetic field changes resulted. The results showed the time history of increases of magnetosphere plasma encountering the satellite and its solar panels.

Bell Laboratories, Telstar 50th Anniversary, July 2012. Seated: Louis Lanzerotti and Walter Brown; Behind Louis and Walter: Carol Maclennan, Ian Ross (past President), Jeong Kim (President), Alice White (CTO)

50th anniversary of Telstar 1. July 2012 marked the 50th anniversary of the launch of the first active telecommunications satellite Telstar 1. Walter Brown and I were invited to give two of the three talks in the small celebratory symposium that was held in the Arnold Auditorium at Murray Hill. Walter spoke of his experiences with Telstar, including his radiation detectors on the satellite. I spoke on space weather effects on communications and some of our related Bell Laboratories research over the years for the Bell System.

NASA Science Missions

Voyager mission to the giant planets and the local interstellar medium. From my current day (2024) perspective looking back on the national space research program, the first decade and more of the program was heavily devoted to understanding the space environment around Earth and in the local interplanetary medium between the Sun and Earth. This research resulted in dramatically new understanding of these regions of space. The research was also required for understanding of the space environment that enveloped spacecraft launched into it, and that could affect humans in space — the ultimately successful program to land humans on the Moon within the decade of the 1960s.

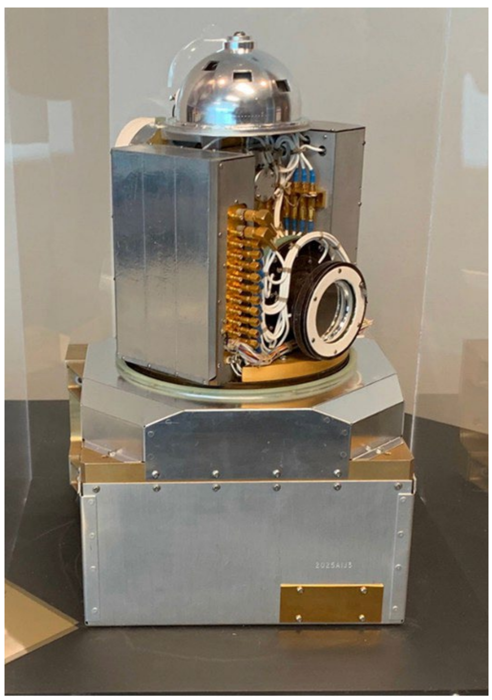
The decade of the 1960s saw the regular launches of satellites into the magnetosphere around Earth and into the solar wind near Earth and the Moon. A considerable learning curve was experienced by scientists and engineers at NASA and in universities as failures of rockets and instruments were expected and often occurred. Successes followed in short order; increasingly sophisticated instrumentation was flown and the return of new data was achieved.

The ambitions of researchers soon began to expand beyond near-Earth space. The outer solar system, both the planets and the interplanetary medium beckoned. In parallel, to achieve such goals meant that missions became more costly and lengthy in time to build before launch. And to reach the outer solar system required years of flight. As such, while the Bells Labs involvement in the NASA Voyager mission began in 1972, science results did not begin until 1979 and into the 1980s. And continued into the 2000s.

In 1969 NASA announced the opportunity to propose instruments for the planned missions by the Pioneer 10 and 11 spacecraft (Pioneers F and G prior to launch, and under the management of the NASA Ames research center) to Jupiter and Saturn. We at Bell Labs, with me as PI, submitted a proposal for particle measurements based largely on the design of our instruments for the late 1960s NASA Interplanetary Monitoring Platform (IMP) 4&5. There were a large number of proposals submitted for a wide range of investigations. I made a presentation at NASA headquarters to the selection panel. Our proposal was not accepted.

NASA announced in 1971 the opportunity for an outer planets mission Mariner Jupiter-Saturn, planned for launch in 1977. This mission, under the management of the Jet Propulsion Laboratory, was originally called Mariner 11 and Mariner 12, and subsequently named Voyager (Voyager 1 and 2) when the design exceeded the Mariner class. Tom Krimigis of the Johns Hopkins University Applied Physics Laboratory (JHUAPL) organized a 6-member team to propose for the mission. I was a member of the team. The instrument that our team proposed, Low Energy Charged Particle (LECP) investigation, was selected for flight. LECP had several unique features for that era of space science, including very thin solid state detectors for the identification of low energy ion species and a mechanical rotating platform for the particle detectors to record 3-D particle distributions in all the space environments to be encountered.

The major Bell Labs contribution to the ensuing decades-long flight performance of each instrument was the thorough calibrations at the Rutgers/Bell tandem Van de Graaf in Piscataway prior to the launch of both Voyagers. I designed and had constructed in Bell Labs shops a special vacuum chamber for the LECP instrument. The chamber was connected to the same tandem beam line that I had used for calibrating prior Bell Labs instruments for the IMP 4 and 5 satellites in the late 1960s. The chamber had feed throughs for instrument powering and for data extraction. An internal platform could rotate the instrument for determining its angular efficiencies for particle detection. I calibrated with protons and the wide range of heavy ions, from N and O up to Fe, that could be produced by the tandem. These calibrations were critical for the subsequent interpretations of received LECP data throughout the mission and to date. The calibrations proved especially important for characterizing the heavy ions encountered in Jupiter's magnetosphere and the fluxes of solar cosmic rays measured to the edge of the heliosphere and in the local interstellar medium (LISM).



LECP Voyager Instrument

Carol Maclennan and I were present for each of the Voyager flybys of the giant outer planets: Jupiter (V1 1979, V2 1979), Saturn (V1 1980, V2 1981), Uranus (V2 1985), and Neptune (V2 1989). For the mission, I recall vividly the press conference in the large room with all the investigation teams when the Voyager 1 pictures of volcanism on the moon Io were shown. For LECP during both Jupiter encounters, the major science discovery was the identification of the hot plasma conditions that dominated the dynamics of the Jovian magnetosphere. Quite unlike Earth's magnetosphere; as if the plasmasphere of Earth dominated its entire magnetosphere. Feature articles in *The New York Times* quoted Krimigis and me on these measurements and their implications for the space environment of Jupiter.

The LECP instrument returned excellent data from the Voyager encounters with the magnetosphere conditions around the other three giant planets. As at Jupiter, hot plasmas that only LECP could measure were found to dominate the magnetosphere of Saturn. As Krimigis and I wrote in *Physics Today*, "A major discovery to emerge from the era of spacecraft investigations of the solar system is the high degree to which planetary magnetic fields organize ionized matter."

Following the Saturn encounter, V1 proceeded outward to the heliosphere termination shock at 94 AU (2004) and the heliopause at 122 AU (2012) into the LISM. After Uranus and Neptune, V2 traveled outward to the heliosphere termination shock, crossing it in 2011 at 84 AU and the heliopause at 119 AU in 2018.

Many publications and presentations with Bell Labs researchers as co-authors and lead authors (largely Carol Maclennan and me, with visitors and students) appeared in the 1980s and into the early 1990s from the Voyager data. Results from crossing the termination shocks and the heliopauses were published with me as a co-author after I was resident at the New Jersey Institute of Technology (NJIT).

Sputtering of ices. One of the more valuable technical and professional aspects of Bell Labs was the daily lunch discussions around a large round table in the cafeteria. Lunches were not to be missed when not on travel. It was at one of these lunch table discussions in late 1978, a few months prior to the March 1979 encounter of Voyager 1 with Jupiter, that I asked the question of those in attendance if anyone had any information on the sputtering rates of charged particles on water ice. I explained the origins of my question: Jupiter had an intense radiation environment that our LECP instrument would soon be measuring. And this radiation was interacting with the large icy moons of Jupiter. How would the surfaces of these moons be affected by the radiation?

Walter Brown was at the table. He immediately responded that he did not have any information on this, that he did not think that any such data existed, and that we should do an experiment using his 1 MeV ion Van de Graaf located at the 1F end of the first floor of building 1. I was elated in his response. John Poate was also at the table that day. The three of us decided to do a "quick and dirty" experiment and see what would result. The lunch-time question resulted in nearly a decade in the 1980s of intermittent experiments of the interactions of ions—largely low energy protons—with ices, both pure ices such as water, ammonia, carbon dioxide, and ice mixtures.

The first major discovery shortly following the lunchtime discussion was the very high sputtering rate found of water ice compared to that expected from classical nucleon-nucleon sputtering. This discovery of "electronic sputtering" of the insulator water ice resulted in a paper in *Physical Review Letters*. Papers were published in *Nature* and *Geophysical Research-Space Physics* using the sputtering results to discuss topics such as the lifetimes of icy grains in the solar system and of ice on the moon, and implications for the icy satellites of Jupiter (and ultimately the icy moons of the other giant planets). Many invitations for talks and invited papers related to charged particle interactions with ices of various types, as well as ice mixtures, were received and accepted. I generally gave talks related to "astronomical" topics while Walter addressed topics more related to implications for the sputtering of insulators, such as the resists used in semiconductor processing.

Galileo mission to Jupiter. I was involved with two proposals made and selected for the Galileo orbiter and probe mission to Jupiter. The Galileo orbiter was a Jet Propulsion Laboratory mission. The Galileo atmosphere entry probe (carried by the orbiter) was managed and built by the NASA Ames center. I was a co-Investigator on the orbiter Energetic Particles Detector (EPD) built at the Johns Hopkins University Applied Physics Laboratory. I was the Principal Investigator for the Lightning (LRD) and the Particle Detector (EPI) instruments for the entry probe. I ultimately had relatively little responsible involvement with the EPD.

My involvement with the Galileo Probe lightning investigation began with an invitation from Ian Axford, the Director the Max Planck Institute for Aeronomy in Katlenburg-Lindau, Germany. At the time, it was well recognized that the atmosphere of Jupiter contained constituent species that some researchers, including Carl Sagan, attributed to the possible formation by lightning in the planet's atmosphere. I was fairly familiar with some of these considerations from the work that I had done on the Bell Labs proposal for the Pioneers 10 and 11 missions and the proposal for the Voyager missions.

Klaus Rinnert, an ionosphere researcher at the Institute, was recruited by Axford to be the Institute lead. Axford, as the managing director of the Institute, could allocate the necessary funding for a lightning investigation. However, any flight participation would require a formal proposal – and then selection – for such an instrument. Further, if Americans were involved, resources from NASA would be needed. Rinnert and I recruited the well known lightning experts Martin Uman of the University of Florida and Philip Krider of the University of Arizona. The full team ultimately consisted of Gerhard Umlauft in Lindau, Gunther Dehmel as RF engineer and Fritz Gliem as digital engineer, both of the University of Braunschweig.

I wrote a NASA proposal, submitted by Bell Labs and the University of Florida for a lightning detector to be incorporated in the Galileo entry probe. The lightning detector was selected for flight. The flight instrument, after the design and the development model, was built at Dornier Systems in Friedrichshafen on the Bodensee. Several weeks of instrument calibration occurred over several different summer months under the summer lightning storms of central Florida, including at the Kennedy Space Center. A number of publications related to characteristics of Earth lightning resulted from these calibrations.

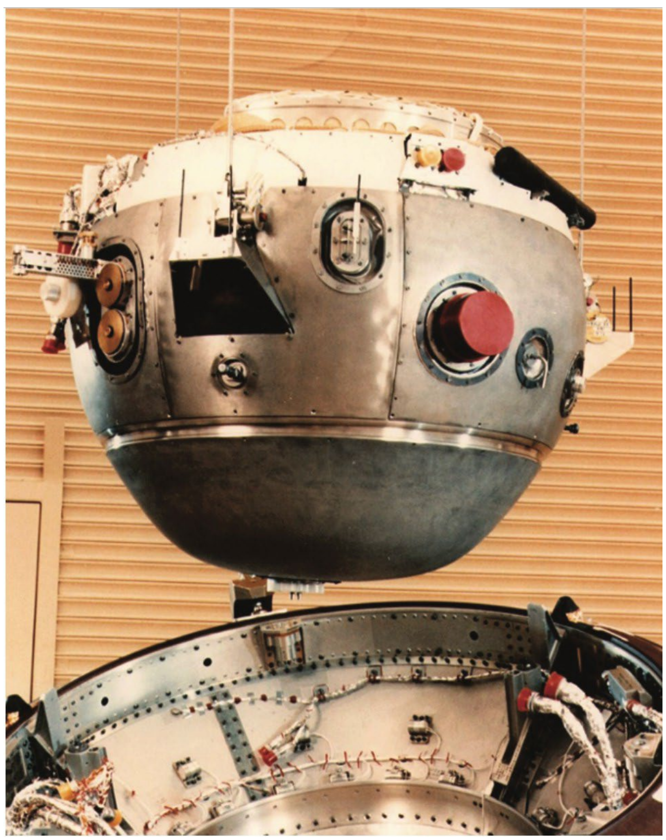
Our lightning team worked intensively with the Probe design engineers at the NASA Ames center. This was necessary to ensure that the design of the heat shield of the entry probe had an appropriate RF transmission "opening" such that lightning RF signals could be detected while still retaining the structural and heat-resisting character of the heat shield.

Under the NASA contract of the lightning instrument, the EPI shared the LRD electronics. The lead participants in this instrument besides myself were Gerhard Wibberenz and Harald Fischer of the University of Kiel, and John Mihalov of NASA Ames. Because of the heat shield, the EPI could only measure quite high energy ions. Calibrations of the EPI were carried out at the Harvard cyclotron laboratory and and at the Bevatron at Berkeley.

Launch of Galileo was delayed until October 1989 because of the shuttle Challenger accident in January 1986. Arrival at Jupiter was on 7 December 1995 after gravitational swing-bys of Venus and Earth (twice). The probe entry on 7 December was into a very dry region of the atmosphere.

During the one-hour descent through the atmosphere, our lightning instrument detected distant and low frequency lightning signals. The LRD results remain quoted to this date as new missions to Jupiter measure RF waves and whistlers in Jupiter's magnetosphere that can be attributed to atmospheric lightning.

The EPI successfully measured high energy ions in Jupiter's magnetosphere to the top of Jupiter's atmosphere. This is a unique set of magnetosphere trapped radiation data that will not be duplicated until another entry into Jupiter's atmosphere is someday executed.



Galileo Probe Descent Module LRD Lightning Instrument Antenna (hlack cylinder on upper right)

Max Planck Institute, Katlenberg-Lindau, early 1980s Guenther Dehmel, Fritz Gliem, Gerhard Umlauft, Louis Lanzerotti, Klaus Rinnert, Joerg Bach

Ulysses mission over the solar poles. Beginning very early in the nation’s civil space program, cosmic ray researchers had been discussing the scientific importance of a cosmic ray mission out of the ecliptic plane. At the time, and for years after, a primary motivation was the determination of the interstellar cosmic ray flux. This type of discussion included debates and discussions of the location of the boundary of the heliosphere, both above the solar poles and in the ecliptic plane, that would result from the interaction of the outward flowing solar wind with the local interstellar medium.

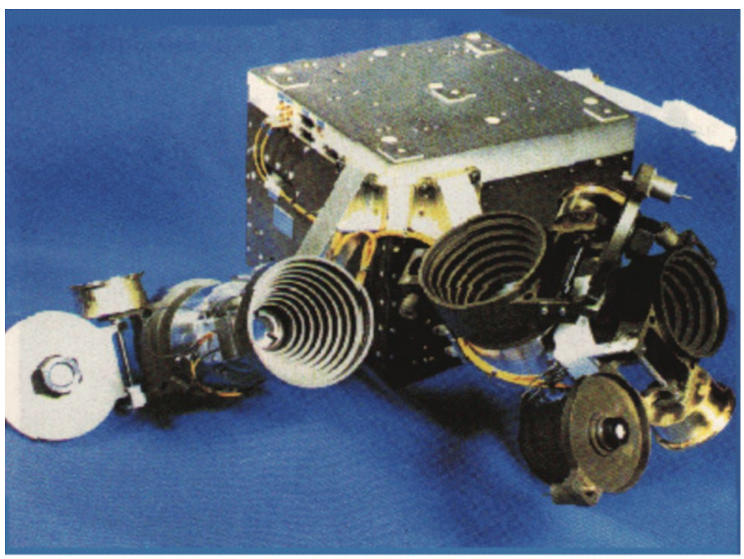
The energy requirements for ejecting a spacecraft directly out of the ecliptic plane to accomplish an “out of the ecliptic mission” over the solar poles, is formidable. In 1974 the European Space Agency (ESA) and NASA began to examine the feasibility of a joint mission that would consist of two spacecraft, one from each national group, to fly out of the ecliptic. An “out of the ecliptic” trajectory would be achieved by using gravity assist from close flybys over the poles of Jupiter.

The mission was defined as the International Solar Polar Mission (ISPM) and was agreed upon between the two agencies in 1977. After launch, the mission was renamed as “Ulysses” in recognition of its long and indirect travel to reach the solar poles. Requests for proposals for instruments on ISPM were issued in the U.S. and Europe.

A low and high energy charged particle instrument, the Heliosphere Instrument for Spectra, Composition, and Anisotropy at Low Energies (HISCALE), was proposed. HISCALE was to be built at the Johns Hopkins University Applied Physics Laboratory (JHUAPL). I was the Principal Investigator with team members Tom Krimigis, Robert Gold, Edmund Roelof of JHUAPL, Thomas Armstrong (University of Kansas), Robert Lin and Kinsey Anderson (UCBerkeley), Manos Sarris (Xanthi University, Greece), Monique Pick (Meudon Observatory, Paris), and George Simnett (Birmingham University, UK).

HISCALE was selected for flight. In the joint agency agreement, NASA and ESA decided that the selected instruments would be distributed between the two spacecraft, with American instruments on the European spacecraft and European instruments on the American spacecraft. Because of the long experience of the Jet Propulsion Laboratory (the lead center for the American spacecraft), the American spacecraft would include a camera system for imaging the solar polar regions. HISCALE was placed on the European spacecraft.

In the selection process, the NASA/ESA committee descoped our instrument to only the four total ion and electron telescopes that were designed to provide directional particle data using the spacecraft spin. Our low energy ion composition telescope (mirroring the Voyager LECP telescope) was descoped. Given our team's view of the importance of the composition telescope for mission objectives, I was determined to find a way to implement ion composition in our investigation. Ultimately we designed a small two-element detector telescope that would be mounted on the side of one of the four proton/electron telescopes. This composition add-on array would use one of the proton/electron detectors as the third detector in the telescope array. We informed NASA and the European project of this move, noting that the cost, power, and weight (300gm) could be accommodated within the previously established spacecraft resource allocations for HISCALE. We stressed the small size of the added telescope, calling it only a "Wart" (officially the Composition Aperture—CA) on the side of one of the existing telescopes. NASA project readily approved. Substantial negotiation with the ESA project ultimately also resulted in the approval of the Wart for flight.



Ulysses Mission, HISCALE Instrument

Because of NASA and other budget problems in the early 1980s, the NASA spacecraft was descoped from the mission. Imaging of the solar poles was thus lost from the mission. Our team was fortunate to have been initially included on the European spacecraft.

The Challenger shuttle disaster of January 1986 postponed the Ulysses launch until October 1990. Ulysses swung by Jupiter in February 1992 for its energy assist out of the ecliptic plane. At the encounter with Jupiter, HISCALE was commanded to close a cover over the Wart that had been designed to protect the thin solid state first detector from radiation damage. The cover also contained a radioactive source for calibration checks on the detectors and instrument.

Ulysses is in an elliptical heliocentric orbit inclined at 80° to the solar equator. Aphelion is about 5.4 AU (determined by the Jupiter gravity assist); perihelion at 1.3 AU. Ulysses crossed the south and north solar poles three times each, finally ending its mission above the ecliptic plane in mid-2008 after the radioactive plutonium power source could no longer keep the hydrazine fuel lines (used for spacecraft orientation) from freezing.

Chios, Greece, HISCALE Team Meeting, 1996. Bell Labs colleagues: Carol Maclennan, David Thomson, Louis Lanzerotti

Ulysses remains today, flying silently in its elliptical out-of-the-ecliptic orbit around the sun. Throughout the mission, the HISCALE instrument provided excellent data on solar particle composition and propagation out of the ecliptic from various source locations on the quiet and disturbed sun.

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