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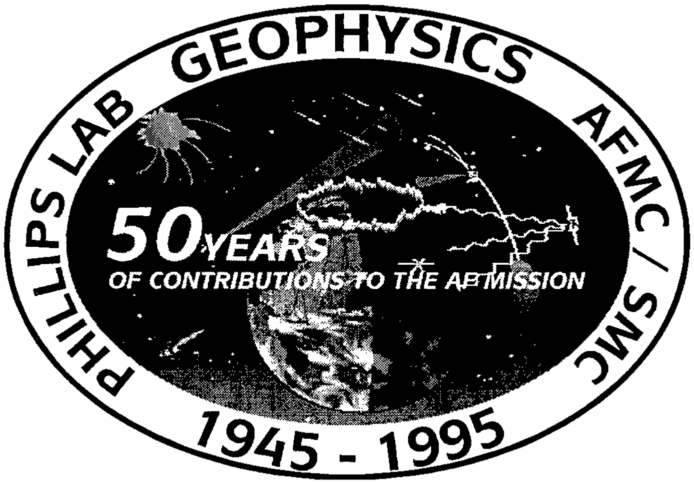
AIR FORCE GEOPHYSICS
1945 - 1995

Contributions to Defense and to the Nation



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This report surveys the contributions made to science and to defense and national security by the Air Force's Geophysics Directorate between the end of World War II and the present. After an introductory section on the historical context of these contributions, a discussion of the technical content follows. The Directorate's contribution falls into two main areas: forecasting the operational environment and resolving atmospheric issues for detection and targeting systems. In addition, the Directorate developed seismic technology for the monitoring of nuclear test ban treaties, and it contributed to engineering and technical support for geophysics. The report is intended to provide an overview for government agencies, other organizations, and the general public.

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AIR FORCE GEOPHYSICS

1945-1995

Contributions to Defense and to the Nation

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Air Force Geophysics: Contributions to Defense and the Nation

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Introduction

In the fifty years of its existence since 1945, the Air Force's organization for Geophysical Research and Development has made significant contributions to the nation. Some of these contributions are specific to requirements for military operations and, more broadly, to national security. Because of the nature of the geophysical sciences, many of the contributions represent generic or dual/use technology that benefits the civilian and commercial, as well as the military, sectors. Especially in the first decade after 1945, the military was the principal source of Federal funding for university research in geophysics. Air Force support expanded the United States academic infrastructure in this area and also contributed some important new facilities for scientific research. Although it was primarily military funding for electronics research that spurred the development of the Boston area as a center of science and high technology after WWII, Air Force funding for geophysics has added an increment to this regional growth.

This essay will first sketch the context in which the Army Air Forces started to sponsor meteorological research before and during WWII and the institutionalization and expansion of this sponsorship at the end of the war to cover a broad sweep of geophysical disciplines. To conclude this section there will be a brief discussion of general forces that shaped the direction of this enterprise over the course of the Cold War era. The main body of the essay will highlight some of the Air Force's geophysical programs that produced significant contributions in this period. It will close with a prospectus for the role of military geophysics in the post-Cold War era.

The Context

The Air Force's support of geophysical research emerged after the end of World War II both from concerns specific to its day-to-day operations and from the broad vision of an expansion of the role of science and engineering in warfare. The first glimmerings of this technical vision had emerged already during World War I and were represented by the Army Signal Corps' Science and Research Division.[1] The interwar years saw the Army and the Navy sponsoring applied research in fields related to their operations. Both services did work on radio communications, the Army at its Signal Corps Laboratories in Fort Monmouth, NJ, and the Navy at the new Naval Research Laboratory outside Washington, DC. The Navy extended its radio propagation work into ionospheric studies.[2]

The new Air Corps within the Army had an inherent technological orientation focused around the development of aircraft. During the 1930s, Brigadier General Henry H. ("Hap") Arnold, soon-to-be Chief of the Air Corps,[3] kept abreast of technological novelties of possible interest to the Corps through his contacts at the California Institute of Technology. He was particularly interested in the potential of weather forecasting to improve flying performance, and he supported the controversial ideas of Irving Krick for making extended weather forecasts (weeks and months ahead rather than the usual one or two days).[4] As of 1937, the Air Corps obtained Army authorization for a new Air Weather Service to provide forecasts for itself and for the Army's ground forces. The responsibility for developing new meteorological equipment remained with the Army Signal Corps.[5]

The second World War witnessed a massive intensification of applied scientific research for the war effort. In the United States, the Army had charge of accomplishing the Manhattan Project, and it worked on ballistic trajectories and proximity fuzes. The Navy developed sonar and coordinated military efforts to improve radio communications, while radar was developed within the framework of a wartime university laboratory--the Massachusetts Institute of Technology's Radiation Laboratory.

The Army's Air Corps (after March 1942 reorganized under the Army Air Forces) mobilized academic meteorology to support the war effort. The five major faculties of meteorology in American universities in this period--Massachusetts Institute of Technology, New York University, California Institute of Technology, University of Chicago, and the University of California at Los Angeles--offered a rigorous, nine-month, postgraduate training program in meteorology for aviation cadets to become "weather officers." A parallel short course was offered for Air Corps enlisted personnel to train them as "weather observers." About 6200 officers and 19,000 enlisted personnel were trained in these programs and then sent out to make forecasts in support of Allied operations in the European and Asian theaters. Several of the AAF weather experts were key players in the intensive forecasting effort for the invasion of Normandy. The University of Chicago also undertook extensive climatology studies in support of Army Air Forces bombing missions.[6]

Wartime operations led to an increased awareness of various atmospheric effects. There were periodic difficulties with high-frequency radio communications, and it was recognized that these were linked to solar activity. Pilots flying on bombing raids across the Pacific encountered unexpected winds at high altitudes, while radar was sometimes "spooked" by atmospheric effects, leading to false warnings of air attacks. It was also realized that, under certain conditions, the atmospheric medium (whether liquid or gaseous) could enhance the transmission of signals.[7]

Toward the end of the war, the impact of radar and the atomic bomb, together with an appreciation of the German breakthroughs in missiles and jet propulsion, all combined to spur the American military services to make long-term investment in science a part of their postwar military strategy. Both the Army and Navy began to make plans to realize this technical vision. The Army Air Forces, which emerged as a separate military service in September 1947,[8] was a third major participant in this enterprise.

By the end of the 1940s, the three services and their new governing body, the Department of Defense (DoD), had either established a set of new organizations and mechanisms, or adapted existing ones, to continue the wartime partnership with civilian scientists and engineers. At the highest DoD level, the new Research and Development Board was charged with coordinating the services' research and development projects to avoid duplication. Military funding supported the services' in-house laboratories, new university-affiliated laboratories like the Applied Physics Laboratory of Johns Hopkins University,[9] and individual researchers at universities. Civilian boards were set up to advise the services as a whole or specific military organizations, and new agencies like the Office of Naval Research were dedicated to administering funds for universities.[10]

The Army Air Forces' general plans for post-war research, unlike those of the other services, were laid out in a single, comprehensive report which its commander, General H.H. Arnold, had commissioned in 1944.[11] At Arnold's request, his longtime adviser on technical issues, Dr. Theodore Von Karman of the California Institute of Technology, organized a large group of expert consultants to create a three-part report entitled, Toward New Horizons. Von Karman wrote the first two sections, Where We Stand (an assessment of the current state of military technology) and Science, the Key to Air Supremacy (a blue-print for organizing future AAF research). The third section consisted of 32 monographs authored by the consultants on their specific technical areas. The list of monograph topics included materials and propellants for aircraft and guided missiles, radar, aviation medicine, explosives, guidance systems--and weather.[12] The short monograph on "Weather and Warfare" was authored by Irving Krick. It compared the German and American weather services during World War II, and it made recommendations for developing better weather data collection, forecasting techniques, communications, and coordination in order to be prepared for a possible future war.[13]

Although Arnold was forced by ill health to retire early in 1946, a group of general and field officers in the Army Air Forces inspired by the Arnold-Von Karman vision worked to realize the ideas proposed in <u>Toward New Horizons</u>. Some of the key individuals in this group, who were attached mainly to the Air Staff, the Air Materiel Command or the Air Weather Service, were Lt Gen Laurence Craigie, Gen Donald Putt, Gen Donald Yates, Col (later Brig Gen) Benjamin Holzman, Col Marcellus Duffy, and Col Oscar Maier.[14] The Air Materiel Command headquartered at Wright Field implemented the creation of a group of new or expanded laboratories, development centers, and test centers which were in place by the early 1950s. This included the Geophysics Research Directorate and the Electronics Research Directorate under the Air Force Cambridge Research Laboratories, the Air (later the Aerospace) Research Laboratory, an Aeromedical Laboratory, the Rome Air Development Center, the Wright Air Development Center, the Arnold Engineering Development Center, and the test facilities at Edwards Air Force Base.[15] The Air Force established a permanent Scientific Advisory Board at headquarters level to coordinate and evaluate research programs throughout the service.

In the case of the Geophysics Research Directorate, the Army Air Forces issued a directive on 20 September 1945 to recruit wartime personnel with expertise in electronics, radar, and geophysics for postwar employment in military research. This call coincided with the disbanding of the Radiation Laboratory at the Massachusetts Institute of Technology and of the Radio

Physics Laboratory at Harvard University. By 1948 the newly-independent Air Force had established both an Electronics Research Directorate (ERD) and a Geophysics Research Directorate (GRD) in Cambridge, MA. (Figure 1). The electronics directorate had drawn in a large contingent from MIT's Radiation Laboratory and a smaller one from Harvard's Radio Physics Laboratory. The geophysics directorate combined one large group from the Radiation Laboratory with the personnel of the new Atmospheric Laboratory at the AAF's Watson Laboratories in Red Bank, NJ.[16] The umbrella organization for the two directorates, originally called the Cambridge Field Station, was renamed the Air Force Cambridge Research Laboratories (AFCRL) in 1949. It is under the name of AFCRL that the geophysics organization was known during the 1960s and 1970s.

The whole organization moved out from their initial headquarters next door to MIT to new permanent quarters at Hanscom Air Force Base in Bedford, MA, in the mid 1950s. The geophysics and electronics components of AFCRL were separated in 1976, with the latter being attached to the Rome Air Development Center. The geophysics divisions were then renamed the Air Force Geophysics Laboratory (AFGL). It was known under this name until 1989 when its name was revised to Geophysics Laboratory (AFSC). In December of the following year, 1990, the organization was merged with the Air Force's Weapons and Rocket Propulsion Laboratories to form a new Air Force "superlaboratory," acquiring its current name and status as the Geophysics Directorate of Phillips Laboratory.[17]

The programs instituted by the original Geophysics Research

The original headquarters of the Geophysics and Electronics Research Directorates next door to the Massachusetts Institute of Technology at 224 and 230 Albany St., Cambridge, MA.

Directorate in the late 1940s are best understood as part of a larger Department of Defense effort in this area. The Research and Development Board sponsored a Committee on Geophysical Sciences as one of its 16 committees for different technical areas.[18] In 1948 the Committee undertook two important projects. The first was a long pamphlet published by the Research and Development Board entitled Geophysics and Warfare to explain "why the military departments should be sponsoring research work in the field of geophysical sciences." Authored by the well-known climatologist, Dr. Helmut E. Landsberg, then deputy executive director of the Committee, the pamphlet surveyed the impact of the environment on warfare in recent history. It discussed how all the major sub-fields in the geophysical sciences from geology and hydrology to terrestrial magnetism and electricity could contribute to military capability.[19]

The Committee's second important project was to conduct a survey of "scientists engaged in geophysical researches" in the United States in 1948. It concluded that the area was understaffed to meet military and civilian needs in the postwar era and recommended that funding be allocated to universities to address this deficiency. Similar surveys by the Committee's panels that focused specifically on meteorology and oceanography came to the same conclusion.[20] These recommendations set in motion funding for programs, including capital investments for new geophysical facilities. To augment research efforts, the Committee coordinated joint programs with civilian agencies like the Weather Bureau and the U.S. Geological Survey.

The geophysics programs run by each of the military services under the aegis of the Research and Development Board differed significantly both in terms of research areas sponsored and in terms of their organization. They tended to group around areas that reflected the operating spaces and challenges of particular concern to each service. While the Navy's sea operations resulted in a special emphasis on oceanography and on ionospheric studies for improving fleet communications, the Air Force's flying requirements gave a priority to meteorological research and especially to weather prediction. In its turn, the Army focused on sciences related to battlefield terrain, such as hydrology and soil mechanics. In some of these areas, there was a fair amount of overlap between service programs and, in a few cases, strong competition for DoD approval and resources. This was particularly true of the services' parallel efforts to develop guided missiles.[21] The rivalries in this area also extended to the related research on the upper atmosphere.[22]

The organization of each service's programs also varied. In the Navy, the well-funded new Office of Naval Research (ONR) began a large program to sponsor university research in the areas of geophysics relevant to its operations, above all oceanography. ONR support enabled the older Naval Research Laboratory to add to its applied research a large program of basic research in the fields of ionospheric physics and solar spectroscopy.[23] The new Air Force had no funding agency which functioned at the same level as the Office of Naval Research in the first years after 1945. It was not until the mid-1950s that the Air Force Office of Scientific Research (AFOSR) began to play a major role in funding geophysics, supporting basic research both at universities and at the Geophysics Research Directorate. During the first postwar decade, the new geophysics directorate served as the core agency for funding university research in areas of geophysics in which the Air Force had an interest. At the same time the directorate worked to build up its in-house capability.

Both of these military services utilized high-level civilian advisory boards to review their research programs. ONR had its own very prestigious advisory board. In 1946 the Air Force created a general Scientific Advisory Board (SAB) with panels to review all of its basic research programs. During the late 40s and early 50s, the SAB's Geophysics Panel, headed by Joseph Kaplan of UCLA, played an important role as technical mentor to the fledgling GRD. Members of the Von Karman group, particularly Colonel Holzman, also lobbied at higher levels within the Air Force and DoD to ensure support and funds for the directorate.[24]

The new Geophysics Research Directorate had received its formal mandate in March of 1947, when Air Force headquarters delegated to the Air Materiel Command the "responsibilities for research and development in meteorology and related geophysical fields."[25] In the Air Force directorate, these related geophysical fields were broadly defined so as to encompass a wide range of earth sciences and upper atmosphere phenomena. The initial group of programs that GRD set up in the late 1940s reflected the breadth of the directive. It consisted of theoretical and applied research in meteorology, upper atmosphere, and solar studies, together with programs in ionospheric and seismo-acoustic propagation.[26] In the late 1950s, the directorate added programs in space physics and optical/infrared studies, followed shortly by geodesy and gravity. Supporting these research areas was an engineering program that developed experimental meteorological equipment, sounding rockets and balloons, and scientific payloads for satellites and the Space Shuttle.

The resulting group of geophysical program areas supported by the Air Force--space and ionospheric physics, atmospheric and earth sciences, optical/infrared physics, plus aerospace engineering--has been in place since the 1960s. In these areas, a long-standing network of relationships has developed between the directorate, other military and civilian government agencies, university research groups, and specialized industrial suppliers. Recently, the increasing cost of geophysical programs, particularly those using platforms in space, has intensified the trend toward interagency and international cooperative efforts.

The specific programs in these areas have evolved considerably over the course of the Cold War era in tandem with new technology and with changing military requirements. Geophysical research immediately after the war was enlarged by the wartime technical breakthroughs in radar, sonar, and rocketry.[27] As of the 1960s, the new technologies of satellites and computers began to revolutionize the geophysical sciences. While it is hard to quantify the extent of their contributions, the military contributed to the development of both these new technologies and, consequently, to the growth of geophysics.

Changing military requirements similarly shaped the direction of research and development. Each of the various theaters of war, potential and actual, from the Arctic region and central Europe to Korea and Vietnam, generated requirements for geophysical information about the particular region. The ongoing Cold War made for a continuing emphasis on the operational environment of the polar and auroral regions, in which, and over which, military activity would presumably occur. For example, before the technology of air-to-air refueling became established, the directorate pursued a large research program over the decade of the 1950s to study the Arctic ice islands. In the early 1950s, Maj Joseph Fletcher, the second chief of GRD, won fame by manning a station on a floating island (T-3) that was later named after him. The follow-on to this program demonstrated techniques for creating usable landing strips for aircraft on the islands in case of war with the Soviet Union.[28]

Similarly, the design of new Air Force systems and politically-related technical issues led to new programs. In the 1960s, for instance, the call for increasingly accurate targeting of the new ballistic missiles gave rise to Air Force research efforts in geodesy and gravity. The Air Force's responsibility to monitor compliance with nuclear test ban treaties in effect, or under negotiation, enlarged its seismology programs. More recently, the increasing sensitivity of optical systems and the susceptibility of miniaturized electronics in space have necessitated a correspondingly-scaled reassessment of the environment in which they operate.

It is in this historical context, where postwar military and political forces interacted with science and technology, that the directorate has made some significant contributions to defense and the nation.

Contributions

Over the course of the Cold War era, the directorate has made both a general contribution to the growth of the geophysical sciences in the United States and a number of specific contributions to defense and national security. Because of the generic nature of much geophysical research and development, many of the contributions to defense have also benefited the civilian and commercial sectors. They represent intellectual capital and resources transferred to civilian governmental agencies and universities, as well as new scientific products developed cooperatively with specialized industries.

The directorate contributed to the growth of the geophysical sciences in the postwar United States in a number of ways. It conducted in-house research and development programs, funded university research, created new research facilities, sponsored conferences in areas at the frontiers of the geophysical disciplines, underwritten the compilation of reference works, and developed geophysical engineering expertise to enhance experimental capabilities. Having access to an international network of military bases, to aircraft and logistical support, and to both military and civilian satellites, the directorate was able to develop major data-sets of regional and global geophysical observations. Its cooperative international scientific programs also supported geophysical research in Europe and Asia.[29]

The directorate's funding of American university research was particularly important in the first decade after World War II when the military was the primary source of Federal grant funding. In 1950, for instance, the

U.S. Weather Bureau's budget for extramural research was $90,000 while GRD had research contracts valued at about $5 million.[30] At this time the academic geophysical establishment was fairly small. Its professional organization, the American Geophysical Union, numbered about 3000 members. The fields its members represented were primarily subfields of earth science such as geology (including commercial oil exploration work), hydrology, oceanography, geodesy, and meteorology. In late 1945, the American Meteorological Society had almost 2900 members.[31] The directorate's research contracts underwrote expanding university faculties and programs and supported graduate students, while its growing in-house programs provided some graduates with jobs. GRD, together with the Office of Naval Research (ONR), contributed significantly to expanding the academic infrastructure in meteorology and to establishing the newer areas of atmospheric physics and solar-terrestrial studies. Later in the 1960s, the directorate provided major support for the development of explosion seismology. It also provided considerable funding for university research in the areas of molecular and infrared spectroscopy.

The funding scene for geophysics changed greatly in the mid-1950s becoming both considerably expanded and much more diversified with support from new Federal civilian agencies. Bridging the initial postwar decade and this subsequent period were two major geophysical events in 1957--the International Geophysical Year (IGY) and the launch of the first artificial satellites. In the area of meteorology, the United States Weather Bureau started to increase its research programs. Two new civilian federal agencies with responsibilities in geophysical and space sciences appeared--the National Aeronautics and Space Administration (NASA) in 1958 and the National Oceanic and Atmospheric Administration (NOAA) in 1969. The National Science Foundation (NSF) established in 1951 became the key civilian federal agency for funding basic research. Another important new player on the geophysical scene was the National Center for Atmospheric Research (NCAR), whose creation NSF sponsored in 1960.[32]

Because the total federal research budget in the post-Sputnik period was on the upswing, the military (including the Air Force) remained a major patron of basic research at universities throughout most of the 1960s. In the atmospheric and space sciences, however, the new mission responsibilities of NASA and NOAA had the effect of narrowing the scope of research programs undertaken by the Air Force's geophysics directorate. During the Vietnam era, the Mansfield Amendment had a similarly limiting effect. As military funding for research and development became tighter in the 1970s, the directorate to some extent shifted its focus to programs more closely tied to military applications. It also periodically conducted cooperative programs with the new civilian agencies as well as with universities. In recent years, the increasing cost of geophysical programs, particularly those using platforms in space, has intensified a general trend towards cooperative efforts by broadly-based interagency and international consortia.

The directorate's contributions to defense and national security have been primarily to enhance the design and operation of Air Force and DoD systems--both weapons and related surveillance, communication, and navigation systems. Its military contributions have taken the form of prediction codes, models, atlases, data bases, design and test standards, feasibility studies, software, tactical decision aids, and prototype hardware. They are transferred to the Air Force's system program offices for use by system designers or to the major commands for use in operations. Many geophysical products for the major operating commands have been regularly channeled through the Air Weather Service, although specific troubleshooting assignments are often done on a direct consulting basis.

There are two broad technical areas in which the directorate has made significant contributions to defense: forecasting the operational environment and resolving atmospheric issues for detection and targeting systems. The environmental forecasting area, in its turn, has consisted of two research and development efforts. First, the directorate has made contributions to improving the forecasting of traditional "weather" in the troposphere. Secondly, it has initiated efforts towards future forecasting of so-called "space weather," that is, disturbances in the Earth's upper atmosphere and in near-Earth space which are largely caused by the Sun. This second effort has only now begun to be feasible after several decades of upper atmosphere and solar-terrestrial research in which the directorate has participated extensively.

The second area of resolving atmospheric issues for detection and targeting systems is also very broad because issues of this kind arise in connection with nearly all aspects of military operations, from intelligence and surveillance activities to theater and global missions. The directorate has produced important data bases and predictive models to address some key

In the early 1950s, staff operated the first GRD computer used for making weather forecasts. Meteorological data were keypunched for processing on a Remington Rand machine.

issues. A third area of contributions, smaller in scope but key for national security, has been developing seismic technology to support the monitoring of nuclear test ban treaties. Finally, there have been a number of directorate contributions to engineering and general technical support for geophysics.

Weather Forecasting

The Army Air Forces' interest in improved weather forecasting, already increasingly in evidence during World War II, continued in the context of its stated postwar goal of becoming an all-weather flying force. The new technology of jet engines entailed understanding of weather patterns and turbulence at higher altitudes and, later on, the aerial refueling of bombers carrying nuclear warheads meant stringent forecasting requirements for this demanding military exercise. Consequently, the Air Force's new Geophysics Research Directorate made meteorological studies and particularly weather forecasting its first priority. (Figure 2).

The directorate supported and expanded postwar academic meteorology by continuing contract programs with the "wartime five" departments mentioned above--UCLA, Cal Tech, Chicago, MIT, and NYU. By 1948 its list of university contractors in meteorology and atmospheric sciences extended to University of Alaska, Columbia, Princeton's Institute for Advanced Study, Florida, Johns Hopkins, New Mexico, Penn State, and Stanford. In order to ensure dissemination of advances in the field, the directorate contracted with the American Meteorological Society to produce a new series of Meteorological Abstracts, which started in 1950, and a large new reference volume for the discipline, the Compendium of Meteorology

(1951). It also co-sponsored and assisted in the technical preparation of a widely-used handbook, the Glossary of Meteorology (1959).[33]

In the area of weather forecasting, the directorate made a major contribution to two important new forecasting techniques, namely, numerical weather prediction and weather radar. It also had a significant role in the initial development of satellite meteorology. The products from its research in these areas have been transferred to the Air Weather Service, the Air Force's operational weather forecasting agency for use at the Air Force Global Weather Central (AFGWC). They have also been transferred over to the nation's civilian weather agencies--the U.S. Weather Bureau (after 1970 the National Weather Service) and the National Severe Storms Forecast Center. More recently, the directorate has developed forecasting software products for specific military operations.

Numerical weather prediction is a technique for deriving forecasts through the use of mathematical models assisted by computers. GRD and ONR underwrote a project to develop this technique which was conducted at Princeton University's Institute for Advanced Study in the late 1940s. GRD's Capt Philip Thompson was a key player in the project, both technically and as a facilitator. He helped to augment the Princeton group headed by John von Neumann, being instrumental in bringing both Jule Charney and Arnt Eliassen into the project.[34]

During the early 1950s, GRD's in-house numerical weather-prediction program under Thompson systematically tested the most promising mathematical models on a month-long series of synoptic data. On the strength of these statistically significant test results, a joint agency NWP unit was established in 1954. This unit was a proto-operational forecasting activity sponsored by the Air Force, Navy, and Weather Bureau. In 1961, Thompson published the book Numerical Weather Analysis and Prediction, a landmark text for over two decades. Later work carried on under GRD's Ralph Shapiro improved the NWP methods, and these results were then transferred over to the National Weather Service.[35]

The term "weather radar" signifies the application of radar techniques to the detection, analysis, and forecasting of meteorological phenomena, particularly weather hazards like severe storms, hurricanes, and tornadoes. The potential of microwave radar for weather applications had become apparent to military meteorologists during World War II. The British used radar experimentally in 1941 to track a rain shower over the English Channel.[36] As of 1943, the U.S. Army Air Forces began to use harbor and air defense radars for weather surveillance. After the war, military and civilian agencies in the United States jointly undertook a major field program, Project Thunderstorm, to analyze this weather hazard and to explore further radar and other techniques for detecting it.[37]

In 1948, the Geophysics Research Directorate set up a Weather Radar Branch under its Ionospheric Laboratory in order to conduct ongoing research and development. The branch chief was David Atlas, a wartime "weather officer" and radar expert, who had participated in Project Thunderstorm. Under Atlas's direction, the group made what have been generally recognized as pioneering advances in the area of weather radar.[38] Attention was first focused on observing the constituents and structure of precipitation. At the same time, the group explored the puzzling and controversial issue of radar backscatter occurring in a visually clear atmosphere. The question of whether these echoes arose from "point targets" (birds and insects) or from refractive index fluctuations due to turbulence was hotly debated for more than a decade. By the late 1960s coordinated radar and airborne measurements made by the directorate had demonstrated that many of these echoes were due to turbulence in the clear atmosphere.[39]

In the early 1960s, the work of the Weather Radar Branch started to focus on developing radar, and particularly Doppler radar, techniques for detecting features of severe storms. A member of the branch, Edwin Kessler, transferred this expertise over to the National Severe Storms Laboratory, which was established in Norman, OK, in 1964 with Kessler as its first director. By the end of the decade another branch scientist, Ralph Donaldson, had demonstrated the value of a single Doppler radar for identifying the precursor of a tornado. During the 1960s and 1970s, the group worked to adapt the "pulse pair" signal processing technique developed by Bell Laboratories to compute the Doppler mean velocity in storms at all sample ranges in real time. This capability is essential to understanding air motion within storms and wind-related weather hazards. They also developed procedures for automated real-time analysis together with computerized color displays of Doppler radar data. Taken together, these advances served to make Doppler weather radar usable for everyday weather observation and forecasting.[40]

Building on this work, at the end of the 1970s the Weather Radar Branch participated in the Joint Doppler Operational Project in Oklahoma. This project led to the creation of the Next Generation Weather Radar (NEXRAD) Program sponsored jointly by the Departments of Commerce, Defense, and Transportation. Its purpose was to replace existing weather surveillance radars operated by the National Weather Service and the Air Force that were based on 1950s technology. They measured only the reflectivity of storms and incorporated little or no automated data processing. The new system developed under the NEXRAD Program, designated WSR-88D, which has now been deployed nationwide, is a Doppler radar and signal processor with a radar product generator.

The new radar system incorporates a set of meteorological algorithms, arithmetical problem-solving procedures, that were developed principally by the Air Force's geophysics directorate and by NOAA laboratories. Nine of the nineteen algorithms included in the first units of the WSR-88D system were directorate products. These included techniques for storm tracking, storm position forecasting, hail detection, and tornado detection. Recently a mesocyclone-detection algorithm was transitioned to the WSR-88D Operations Support Facility (OSF) for incorporation into the system. This algorithm detects severe rotation in thunderstorms and provides an assessment of the likelihood and probable intensity of tornadoes.[41] These products contribute not only to the protection of Air Force assets in the so-called "Tornado Alley" of the midwest and southwest but also to the forecasting of weather hazards nationwide.

A final area of contributions to weather forecasting relates to the creation of satellite meteorology. In the late 1950s, prior to the launch of the first weather satellite, Tiros I, the directorate sponsored Project Satellite Cloud Photo to evaluate the potential meteorological utility of televised images from a satellite vehicle and then to devise procedures for application. Subsequently GRD's John Conover acquired samples of photos that duplicated the satellite geometry by piggybacking a camera on a ballistic missile launched from the Eastern Test Range. The camera capsule was engineered to separate from the missile at altitude, take photos and descend on a parachute, after which the film was retrieved from the Atlantic ocean.[42] When Tiros I was launched in April 1960, Air Force personnel from GRD and the Air Weather Service created the first satellite-derived analysis of cloud cover (nephanalysis) that was distributed to meteorologists. Thus the directorate contributed substantially to establishing the methodology for satellite meteorology.

The newly-formed NASA had been assigned responsibility for the TIROS Program and for developing more advanced weather satellites, and the U.S. Weather Bureau began to administer the new cloud forecasting activity.[43] Military cloud studies conducted in the later 1960s under the classified Defense Meteorological Satellite Program (DMSP)[44] focused on operations in Southeast Asia. It was not until after the DMSP program was declassified in 1973 that geophysics directorate scientists started projects to improve meteorological instrumentation for satellites and to advance techniques for cloud analysis. In the area of instrumentation, they developed software for the microwave temperature and moisture sounders currently flown on DMSP satellites. In cloud analysis technology, they recently completed a new model which achieves a much more accurate and timely assessment of global cloud cover. Integrating data from both polar and geostationary weather satellites at hourly intervals, it provides cloud amounts both in toto and by layer, cloud top heights, and cloud types. The new model will increase cloud forecasting capability at the Air Force Global Weather Central.[45]

During the 1980s, the directorate began to package its accumulated forecasting expertise for tactical military applications. A new advanced development program worked to combine weather data and forecasts together with optical codes in software for tactical operations in Europe. Its Tactical Decision Aids, as the products were called, were developed to maximize the performance of precision-guided munitions. By combining data on upcoming meteorological and optical background scene conditions with models of sensor performance, TDAs predicted the relative performance of different electro-optical sensors paired with the munitions. Thus they helped mission planners to choose the most effective weapons for a given military exercise. Most importantly, they enabled pilots to calculate acquisition and lock-on range to selected targets. By the early 1990s the fully developed version of the software, which was called the Electro-Optical TDA (EOTDA), was in full operational use by weather support units.

Defining the Upper Atmosphere and Near-Earth Space

The Geophysics Directorate has made significant contributions, first, in mapping and characterizing the Earth's upper atmosphere and secondly, in exploring the immense region between the Earth and the Sun, which is variously called near-Earth space, geospace, or the solar-terrestrial environment. In the late 1940s, the directorate's most highly funded contract programs were its upper-atmosphere studies.[46] At that time, the Air Force defined "upper air research" pragmatically in terms of observing platforms. It was the study of the physics of the atmosphere above the level of approximately 100,000 feet (about 31 km or 19 miles) where balloons could not reach, going up to about 160 km (100 miles). This was the expected range of the captured V-2 rockets.[47] For purposes of study today, these regions above the troposphere are generally divided into the middle atmosphere (stratosphere and mesosphere) starting at about 12 km (7 miles) and the upper atmosphere (thermosphere and exosphere) starting at about 85 km (53 miles) up.

One of the first missions of the original Geophysics Research Directorate was to explore this largely-unknown environment, which would be the operational arena for future guided missiles and supersonic aircraft. While prewar studies had mapped out the basic layers of the ionosphere (the partially-ionized regions of the middle and upper atmosphere which permit radio communications), knowledge of the physical and chemical features of these regions was not as advanced.[48]

Recognizing that the sun exerted a controlling influence on these regions, the directorate promptly began a large effort in solar research as part of its new Upper Air Program. In 1952, it dedicated a new solar coronagraphic observatory at Sacramento Peak, NM. The large coronagraph

The vacuum tower telescope (top center) at the Sacrmento Peak Observatory, NM. Completed in 1969, the instrument is one of the highest-resolution telescopes in the world for observing small-scale processes on the sun. In the lower foreground, the solar coronagraph facility.

(the second to be built in the U.S.) was designed and constructed in collaboration with the Harvard College Observatory.[49] In the later 1960s, the Air Force enlarged the Peak's facilities adding a new vacuum tower telescope. (Figure 3). Sac Peak, today a section of the National Solar Observatory, represented a major addition to United States capabilities in solar optical research, contributing to astronomy, astrophysics, and solar-terrestrial studies.

Directorate studies of the middle atmosphere were pursued using ground-based instruments, balloons, and a variety of aircraft--including a high-altitude U-2. In the late 1950s and early 1960s, important ground-based studies of atmospheric particles were conducted in-house and under contract with Harvard University. A GRD meteorologist, Christian Junge, gave his name to the layer of aerosols that he had discovered in the stratosphere.[50] During the mid 1960s, the directorate's Ozone Network collected a large data base on the climatology of the ozone layer, and balloon-borne experiments in the later 1970s contributed to the analysis of solar ultraviolet radiation in the stratosphere. The applied research for the Kwajalein Missile Range in the 1970s (described in the section on issues for targeting below) spurred the development of a new system for measuring atmospheric particles, which is now widely used for applications from clean rooms to planetary probes.[51]

Upper atmosphere research blossomed in the mid-1950s when the directorate started large-scale field programs using sounding rockets and, later, satellites. Dr. Hans Hinteregger started a series of sounding rocket and, later, satellite experiments to make scanning photoelectric measurements of the sun's extreme ultraviolet radiance that creates the Earth's ionosphere.

Hinteregger's measurements on the Atmospheric Explorer satellites in the 1980s provided the basic data on solar ultraviolet irradiance for all upper atmospheric models.[52] His field programs were complemented by vacuum ultraviolet studies in the laboratory started under Dr. Kenichi Watanabe and Dr. Yoshio Tanaka, who gave his name to a band system in nitrogen. In another group of programs started in the later 1950s, Dr. Kenneth Champion began a long program of rocket and satellite measurements of atmospheric density using the new "falling sphere" technique originally created by the University of Michigan. These measurements similarly provided another set of basic data for models of the neutral upper atmosphere.[53]

The directorate also played a key role in codifying and modeling these major new atmospheric data sets from its own and other agencies' experimental programs. The data were used to enlarge standard and reference atmospheres, incorporating the new values for density, temperature, and other features at higher altitudes. Starting in 1953, GRD's Norman Sissenwine was the driving force in organizing successive editions of the U.S. Standard Atmosphere, a widely used model of the vertical structure of the atmosphere presented in globally- and temporally-averaged values. An acknowledgement of his long-term contribution prefaced the 1976 edition of the Standard Atmosphere.[54]

The directorate pioneered a new technique for probing the upper atmosphere, using small-scale releases of various chemicals from sounding rockets to elucidate chemical composition and physical features like winds. The first such experiment in 1956, using a release of nitric oxide gas to study photochemistry, tried at the suggestion of Dr. David Bates of Queens University, was accomplished by Murray Zelikoff and Fred Marmo.[55] From the late 1950s into the middle 1960s, under the umbrella name Project Firefly, hundreds of small rockets were launched applying this very successful technique. Optical studies of the upper atmosphere, both ground-based and rocket-borne, imaged the aurora and updated the fourth Lord Rayleigh's work on the airglow.[56]

The region of the lower ionosphere (the D and lower E regions) at the base of the upper atmosphere, between 60 to 120 km (about 38 to 75 miles) is a difficult region to study. Rocket experiments can be significantly affected by vehicle contaminants. Moreover, because of the relatively high pressure, active experiments which involve sampling (such as a mass spectrometer) can be affected by condensation and recombination on surfaces.[57] The directorate has made several important contributions to the understanding of this region. It is an instance where basic research was developed in conjunction with very specific military concerns. The military goal was to understand the effects of high-altitude nuclear blasts on the upper atmosphere in order to assess communications and targeting capabilities in a post-nuclear scenario. This entailed characterizing the impact of the nuclear debris on conductivity in the lower ionosphere and on the production of atmospheric background radiances at different wavelengths.

During the era of atmospheric nuclear testing, through the 1950s and early 1960s, the directorate made aircraft and rocket measurements of the upper atmosphere following high-altitude test blasts. Since the passage of the

Atmospheric Test Ban Treaty in 1963, the directorate has conducted various kinds of programs to provide more data for ongoing modeling of the post-nuclear environment. Scientists have made measurements of intense auroras, a natural phenomenon which shares some optical characteristics with the post-nuclear atmosphere. They have also conducted experiments in the laboratory and the atmosphere which simulate some post-nuclear features. One major program of this kind was the rocket-borne Precede/EXCEDE program which developed a mother-daughter payload combination in order to propagate a high-powered electron beam and then measure the local atmospheric effects.[58]

Starting in the early 1960s, the directorate also conducted basic research on the lower ionosphere. One key group of sounding rocket programs directed by Dr. Rocco Narcisi collected vastly improved mass spectrometer data. He found that hydrated oxonium (water cluster) ions were the major positive ions in the D region and that metals (from meteors) were important in its natural ion chemistry.[59] Narcisi's results overturned previous notions about the simplicity of the region's features. Directorate scientists then began long-term laboratory programs to ascertain accurate reaction-rates for the ion chemistry under varying thermal regimes. Metal ions were given special attention because they play a dominant role in the exotic chemistry of the post-nuclear environment. The early results of this research were transformed into a complex computer code (the Keneshea code), which was used for E-region models and for Nuclear Weapons Effects codes.[60] This ongoing area of work helped to clarify military planning for post-nuclear scenarios during the Cold War period, and it has contributed significantly to the understanding of atmospheric chemistry.

The directorate also contributed to the development of another significant area of atmospheric studies. Starting in the 1950s it began to develop basic research programs in molecular spectroscopy and, in the 1960s, it sponsored an extensive program of basic research in infrared spectroscopy through contracts with universities. This led into work on the infrared physics of the upper atmosphere. Aided by the great expansion of computing power, by the 1970s Fourier spectroscopy had become a feasible technique for everyday use, allowing great improvements in analyzing infrared sensor data. AFCRL sponsored the pioneering Aspen International Conference on Fourier Spectroscopy in 1970 to advance the state-of-the art in this area.[61]

In subsequent experimental programs initiated under Dr. A. T. Stair, Jr, it conducted an extended sounding rocket program (the ICECAP Program), making the first-ever spectral scans of auroral infrared excitations. More recently, measurements of infrared background radiances made by the directorate's Cryogenic Infrared Radiance Instrumentation for Shuttle experiment in 1991 revealed the previously-unsuspected presence of "super hot" rotationally excited species (OH and NO) in the mesosphere and lower thermosphere. Supporting these field experiments were the ongoing laboratory programs on infrared spectroscopy. Like the ion chemistry research discussed above, this work had relevance for military operations in post-nuclear scenarios. It also formed the basis for applied research on the Strategic Defense Initiative discussed below in the section on detection and targeting.

The "filling in" of the immense regions between the Sun and the Earth's atmosphere, aided by research satellites and manned spacecraft, has been one of the great achievements of the geophysical sciences since the late 1960s. It has involved developing an understanding of complex solar activity, the solar wind, the interplanetary space and magnetic field, the Earth's magnetosphere and ionosphere, and the linkages between all these regions.[62] Solar-terrestrial physics, or space physics, as this now-established field of research is often called, has made major strides in sorting out the complicated strands of the Sun's effects on the Earth's upper atmosphere. However, the broader area of solar-climate-weather studies has continued to present great difficulties and lagged far behind.[63]

The directorate participated in the growth of solar-terrestrial physics, and it has made some notable contributions both to space sciences and to spacecraft engineering. The contributions in these areas have rested on an extensive program of sounding rocket, satellite, and Space Shuttle experiments carried on since the 1950s, together with ground-based observations and theoretical work.[64] As new upper atmosphere and near-Earth space data became available, the directorate started to publish reference works in this area in the same way it did earlier for meteorology. In 1965, it began the Geophysics and Space Data Bulletin, putting together a number of its own solar-related data sets for the use of the community. The directorate's original Handbook of Geophysics for Air Force Designers (1957) was a compilation of the "anticipated natural environment of USAF weapons systems" that included new data on upper-atmospheric constituents, geomagnetism, and solar radiation.[65] Subsequent editions of the Handbook, incorporating the latest data on the areas of geophysical and space sciences covered by the directorate, appeared in 1960, 1965, and 1985. Technical data from the Handbooks were condensed in a large Aerospace Wall Chart issued in 1961, 1976, and 1989. These reference works have been used extensively throughout both the military and civilian geophysical communities.

In its researches on solar-terrestrial physics, the directorate has studied primarily the phenomena that bracket solar-terrestrial interactions, that is, the initiating solar activity and the concluding disturbances in the Earth's magnetosphere and ionosphere due to the arrival of a variety of solar-generated emissions and outflows. Basic research has gone hand in hand with a focus on solar-induced disturbances in near-Earth space because the latter create hazards for Air Force operations. These hazards have created an impetus for the directorate to generate specific techniques for monitoring and providing timely warning of them. This applied research is discussed below in the section on space weather forecasting.

The solar research carried out at the Sacramento Peak Observatory has contributed to an understanding of basic solar processes, particularly magneto-convection at the solar surface, the basic interaction between gas flows and magnetic fields that leads up to solar activity.[66] Other longterm research has significantly advanced knowledge of the structure and activity of the solar corona, as well as the production of solar flares, including the rare phenomenon of white-light flares.[67]

Research at Geophysics Directorate headquarters has focused more on the emissions accompanying solar activity. During flare activity, hazardous electromagnetic radiation (ultraviolet and X-ray) is emitted into interplanetary space. This radiation only takes eight minutes to effect a change in the Earth's ionosphere and to disrupt communications (the sunlit ionospheric disturbance). Flares are also sources of energetic particles. These range from high-energy (GeV level protons and alpha particles) to lower energy (KeV protons and electrons) particles. The most energetic particles reach earth in about ten minutes, while the transit time for a 10 MeV proton is about one hour.

Within the last decade, directorate scientists have played a key role in recognizing the importance of ejections of solar material and their embedded magnetic fields in creating interplanetary disturbances. These so-called "coronal mass ejections" take from 15 to 100 hours to propagate to the earth. They are linked to the most intense, sporadic, geomagnetic storms and to the largest solar particle events. Contributions have also been made to the understanding of the sources of recurrent geomagnetic storms. The initial peak of these storms originates in the interaction between high-speed wind flows from dark regions in the solar corona, so-called "coronal holes," and low-speed flows from adjacent bright streamers.[68]

The directorate's magnetospheric studies have dealt with the energetic protons, electrons, and cosmic rays, and the lower-energy protons and electrons (solar plasma) arriving from the sun. They have focused on determining the incidence, energy levels, and distribution of these particles under varying natural conditions. These studies, in turn, have led to broader investigations of interactions between the particles, on one hand, and waves and fields in the magnetosphere, including the population of the Van Allen radiation belts.[69] The directorate's Space Radiation Effects (SPACERAD) experiments flown on the joint Air Force/NASA CRRES satellite in 1990-1991 collected data that revised the standard NASA (Vette) models of the radiation belts that are used by satellite designers. CRRES also had the great fortune to record the creation of a long-lasting, third radiation belt (a second inner belt of protons) around the Earth following the major geomagnetic storm of March 1991. The existence of such a belt had been hinted at in early data but never confirmed.[70]

Directorate research in magnetospheric-ionospheric interactions has yielded contributions to the understanding of key linked processes in these two regions. Programs have focused on the regions above the Earth's polar cap, the auroral zone, and the equator. These regions happen to be very relevant from a political-military point of view--the polar cap and the auroral zone for the Cold War and the equator for the Third World. They are also are very prone to natural irregularities. The polar cap is the point of entry for energetic particles into the high-latitude magnetosphere and ionosphere. Scientists have made measurements of the cross-polar cap potential, which influences the transfer of magnetic flux from the dayside to the nightside of the magnetosphere and affects the generation of magnetospheric substorms.[71] Other studies since that time have explored the still-not-fully-understood substorms, exploring the physical mechanisms responsible for their onset and their diversion through the ionosphere.[72]

Another group of programs has made major contributions to characterizing the auroral region. Directorate scientists participated in work during the 1960s that described the continuity of the auroral oval. More recently, large statistical studies have mapped the distribution and equatorward boundary of electrons that give rise to auroras as they precipitate down from the magnetosphere into the ionosphere. These latter programs have utilized a suite of incrementally improved space sensors that the directorate has flown as adjunct sensors on the Defense Meteorological Satellite Program (DMSP) vehicles since 1977.[73]

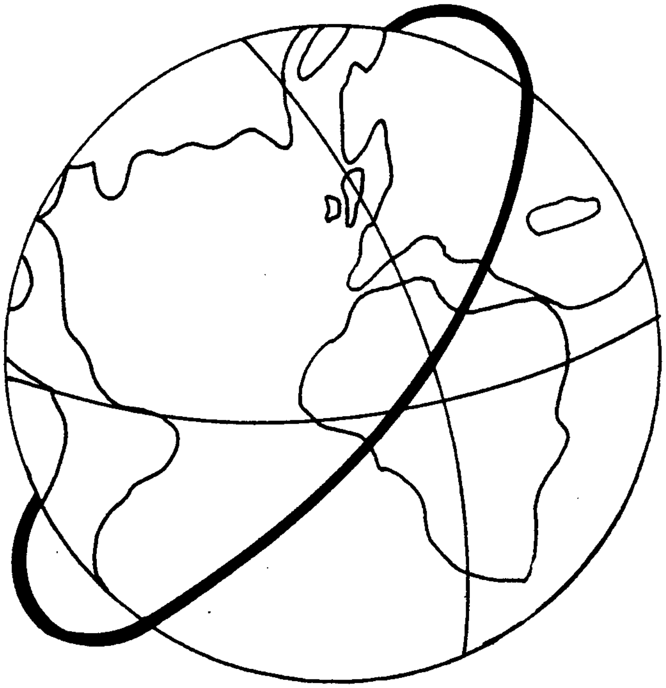
The directorate's programs on the ionosphere have studied its structures, dynamics, and irregularities in connection with military requirements for communications. For experimental programs, scientists have developed techniques for optical and radio measurements, many of them made using GRD's Airborne Ionospheric Observatory, together with measurements from ground-based radar and sounding rockets, and sometimes satellites. During the 1970s, GRD's ionospheric physicists extensively analyzed the irregularity known as "equatorial spread F." The latter affects HF radio communications, and also satellite navigation and radar, near the equator on a daily basis. They went on to revise the notion of the polar cap ionosphere as a quiet unstructured region, revealing instead an alternating pattern of highly-structured plasma patches and Sun-aligned arcs (auroras).[74]

The structure and dynamics of the ionosphere operates across a broad spectrum of spatial scales. Air Force scientists initially focused on the smallest-scale, sub-kilometer irregularities, because it is these which create radio disturbances called "scintillations." These in turn produce amplitude and phase fluctuations in satellite-ground communications. GRD's Dr. Jules Aarons was an authority on transionospheric propagation and the morphology of scintillations.[75] Recent directorate programs have explored the processes by which these small-scale irregularities are generated within the large-scale dynamics of the ionosphere. They have also contributed important data on features of the neutral upper atmosphere for general circulation models and for military requirements.[76]

In addition to these contributions to solar, space, and upper atmosphere research, the directorate has conducted engineering-oriented research that relates to practical issues of spacecraft design and operation. Immediately after the first Sputnik was launched, the geophysics and the electronics directorates at Hanscom set up ad hoc techniques for satellite tracking. First dubbed Project Harvest Moon, then Project Spacetrack (Figure 4), these activities gradually developed into the Air Force's operational satellite tracking facilities. During the 1960s, both the civilian and military agencies who had started to fly spacecraft became concerned about the survivability of satellites in space, the protection of satellite-ground communication links, and, above all, astronaut safety. In all these areas which require measurements of spacecraft-environment interactions, the directorate has made major contributions since the 1960s.

Since the 1970s, the directorate has flown several space experiments which gathered data bases, both large in size and gathered under controlled conditions, on issues related to spacecraft design. The Spacecraft Charging

SATELLITE TRACKING



PROJECT SPACE TRACK

GEOPHYSICS RESEARCH
DIRECTORATE

AIR FORCE CAMBRIDGE
RESEARCH CENTER

BEDFORD, MASSACHUSETTS

12 FEBRUARY 1958

at High Altitudes (SCATHA) Program launched in 1978 addressed electrical charging of satellites at geosynchronous orbit and led to the development of a new passive device to mitigate it. A prototype Charge Control System is now being tested on a Defense Satellite Communications System (DSCS-3) satellite. The Space Radiation Effects (SPACERAD) Program, launched in 1990 on the joint USAF/NASA CRRES satellite, and the Photovoltaic Array Space Power plus Diagnostics (PASP Plus) experiment, launched in 1994, tested space environmental effects on microelectronics and on solar cell arrays.[77] The data bases and models resulting from these programs have improved standards for radiation shielding and verified the choice of new materials, designs, and operating voltages for solar arrays.

"Space Weather" Forecasting

"Space Weather" is a short-hand term for a range of disturbances in the Earth's atmosphere which derive from solar emissions. They include sudden ionospheric disturbances, solar proton events, and major geomagnetic storms. Each of these disturbances, in turn, has a number of practical consequences. Major geomagnetic storms, for instance, heat up the upper atmosphere, which increases the drag on satellites, pulling them down from their orbits and making them difficult to track. They also increase electrical currents in the atmosphere which can couple into regional power grids and cause major outages. Solar protons were recognized early as the source of communication blackouts in the Arctic region. Their influx greatly enhanced the D and E regions of the polar ionosphere. More recently, they have been found to damage microelectronics and star-sensor orientation devices in spacecraft.[78]

All these "space weather" phenomena have implications for military planning and operations. During the Cold War, for instance, Arctic communications blackouts would pose operational difficulties in the event of a confrontation with the Soviet Union. Damaged or misplaced satellites have a variety of military consequences, ranging from loss of surveillance capability to degradation of Ballistic Missile Defense scenarios. Thus it has been important for Air Force scientists to work to identify and monitor these events, and then to develop techniques to provide advance warning of them.

The directorate was one of the earliest players in the development of "space weather" forecasting in the US, starting in the 1960s. It started efforts early on to identify specific "precursors" of solar flares which could provide some ability to forecast their occurence.[79] Other programs looked for the "signatures" of the solar flares that released high-energy protons in order to provide some advance warning of disturbances that would occur at Earth within minutes or a few hours. One event often associated with flares, a radio burst with a U-shaped spectrum, was discovered by GRD scientists in the mid 1960s. More recently, long-duration, soft x-ray bursts have proven to be more reliable signatures associated with large particle events. Computer algorithms to predict the occurrence and arrival time of solar energetic particles at the Earth were developed for the Directorate's Proton Prediction Model. The latter became an operational space weather tool at the Air Force Global Weather Central at the end of 1987.[80]

As in other areas, directorate scientists worked to coordinate and advance international efforts. In the later 1970s the Air Force strongly supported NOAA in co-sponsoring a new Solar-Terrestrial Predictions Workshop, the first of several held since 1979.[81] The Directorate also conducted research on signatures for major geomagnetic storms and substorms. While the major storms are sporadic and occur much less frequently than the recurrent smaller substorms, the damage they can do to satellites and to electric power grids may be crippling. The directorate's Ground-based Magnetometer Network, active in the 1980s, worked on identifying these storm signatures. Most recently, in 1995, space physicists have started to utilize solar wind data available from NASA's Wind satellite launched on November 1994 in order to develop algorithms for predicting the strength of incoming storms.

A related long-time activity in the "space weather" area has been the directorate's contributions to specifying the state of the ionosphere for military communications, navigation, and tracking and surveillance systems. In the communications area, scientists have provided data and short-lead forecasts for both ground and satellite based communications systems. To assist the Air Weather Service in providing operators with data for adjusting transmitting frequencies, the directorate sponsored the development of new world-class ionosondes. Its contractor, the Lowell Center for Atmospheric Research, produced this improved instrumentation, which is now an operational network of 17 stations, the Digital Ionospheric Sounding System (DISS), run by the Air Weather Service.[82] At the beginning of the Gulf War, the directorate produced a handy reference guide to ionospheric effects on C^3I for commanders and communications officers. Another more recent effort has been the development of a call-up system enabling commanders to obtain forecasts of scintillation activity within a theater of operations.[83]

The directorate has also made a number of key contributions to navigation and tracking systems. Since variations in the total electron content (TEC) of the ionosphere delay transmission of signals, an appropriate correction has to be made for this effect, in order not to introduce errors into calculations of position coordinates. For the newly-completed Global Positioning System (GPS), the directorate contributed algorithms for both single-frequency and dual-frequency GPS receivers. These are widely used and essential to the high precision of the system.[84] Air Force Spacetrack Systems also make use of similar algorithms. The new Transionospheric Sensing System (TISS) to measure TEC in realtime in order to meet Air Force system requirements was developed with the technical assistance of ionospheric physicists at the directorate.

An essential component for forecasting space weather is the continuous monitoring of solar emissions. In the future, this function may be performed by a dedicated satellite orbiting around the sun. For the last twenty years, however, monitoring of different solar emissions (optical, radio burst, ultraviolet, and X-ray) has been shared by a group of agencies--NOAA, NASA, and USAF. They forward the data to U.S. civilian and military space forecast centers. In the early 1970s, AFCRL physicists and engineers created the prototype instrumentation for ground-based stations to monitor solar optical and radio emissions.[85] A group of these observing stations spaced around the globe were then linked together to make the operational Solar Electro-Optical Network (SEON), which is run by the Air Force's Space Command. Technical support for SEON upgrades and assistance with operational problems is still provided periodically by the directorate.

The directorate has also supported the long-term development of space environment models. Its Space Physics Division funded the early development at Rice University of what has now become the Magnetospheric Specification and Forecast Model (MSFM). Ionospheric physicists at the directorate have worked on developing models for their region, of which the Parameterized Realtime Ionospheric Specification Model (PRISM) is the latest version. PRISM is now operational at the 50th. Weather Squadron, providing timely reports on global ionospheric parameters to all DoD customers.

An emerging goal of research is to develop a comprehensive "space weather" model linking the solar wind and the Earth's environment. It is only in the last few years that the feasibility of this goal has become generally accepted in the scientific community. In 1994, a proposal for a new national space weather organization was floated, and more elaborate plans and programs are now underway.[86] The directorate's models will be major components of a future comprehensive "space weather" model, which is essential to achieve the long-range goal of a true predictive capability in this area.

Atmospheric Issues for Detection and Targeting

The atmospheric issues that affect these two basic modes of military operation have very diverse sources. In some instances, they involve phenomena of the lower atmosphere like clouds, rain, fog, or winds which, in addition to their general role in weather, also have specific effects on detection and targeting. In other instances, they derive from upper-atmosphere disturbances like auroral activity. These phenomena can degrade, confuse, or block signals from different wavelengths used for detection systems. Similarly, both atmospheric effects such as winds, together with "hard-earth" effects such as gravity field anomalies and insufficiently-precise position and distance coordinates, can pose difficulties for achieving accurate targeting of ballistic missiles.

The directorate's contributions in this area have generally consisted of finding solutions to atmosphere-related issues or ways to work around the problems. In a few instances, however, the atmosphere and its processes create new possibilities for detection of military objects of interest. The first major geophysics program that the Army Air Forces started early in 1946, before the directorate was formally organized, drew impetus from such a possibility. This was Project Mogul, managed out of the AAF's Watson Laboratories and headed by Capt Albert Trakowski.[87] The concept of Project Mogul was to explore the feasibility of using balloon-borne acoustic sensors for long-range detection of potential Soviet missile launches and atomic tests. It derived from a suggestion of Professor Maurice Ewing of Columbia University that one might find acoustic ducts in the atmosphere analogous to deep sound channels underwater.[88]

Although this approach did not prove fruitful, the newly-established Geophysics Research Directorate at Watson Laboratories started a follow up program, MSX-968, early in 1948 to explore radiological, acoustic, and seismic techniques for long-range detection. Work on the radiological technique, originating under a Watson Labs contract with Tracerlab, Inc. in Cambridge, MA, developed airborne measurements of post-nuclear particles that diffused through the atmosphere. It led to a successful identification of the first Russian nuclear explosion in 1949.[89]

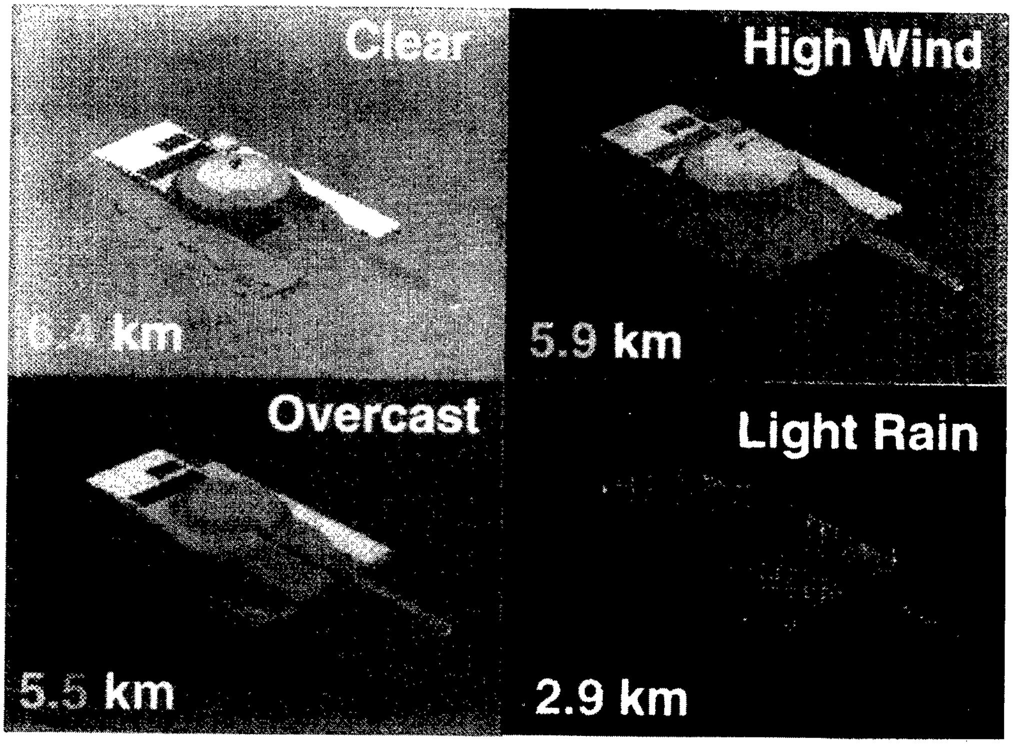
Another program that utilized natural atmospheric processes was over-the-horizon radar. The concept was to extend the range of radar that surveyed aircraft over the oceans for United States continental defense by bouncing beams off the ionosphere. Air Force geophysicists contributed ongoing technical assistance to the Over-the-Horizon Backscatter System Program Office at the Electronic Systems Division following the office's creation in 1970. They provided models of the high-latitude environment for radar designers, automated and deployed environmental sensors for daily frequency management, and flew dedicated missions as an aircraft target for the radar during testing of the experimental and operational versions of the CONUS OTH-B Radar System in the 1980s.[90]

In the more usual situation of atmospheric effects on systems that need to be mitigated for optimum performance, the directorate has made some major contributions to military operations. Cloud-free lines of sight are a basic requirement for detecting and targeting in tactical operations, especially air-to-ground missions. Given the fact that, on average, clouds will cover about one-half of the Earth's surface, it is not surprising that cloud studies have been an ongoing area of research and development at the directorate.

Clouds block detection systems at most wavelengths, not only visible but also those for infrared and laser transmission. During the late 1970s, directorate meteorologists accomplished a 2-year data collection program, gathering a quarter of a million observations on the incidence of clouds in the northern hemisphere. The resulting statistical model giving the probability of clear, cloudy, or hazy conditions for specified angles at different altitudes is still used by designers of infrared and laser systems.[91]

Infrared sensors were developed for a variety of military missions in both strategic and tactical arenas during the Cold War. These sensors present special atmospheric issues because they yield thermal images of targets relative to their natural backgrounds. The variability of conditions for optical transmission and background radiances means that images of a single target scene can vary widely (Figure 5). In tactical applications, such as air-to-ground engagements, this makes for uncertainties in the performance of the infrared sensors that are used to direct costly precision-guided munitions. Airborne infrared surveillance of other aircraft can have difficulties with backgrounds in the middle atmosphere. In the strategic application of satellite surveillance, the challenge is to discriminate just-launched ballistic missiles from the varying infrared clutter of the atmosphere above the Earth's horizon, especially during auroral activity. In the Strategic Defense Initiative in the mid-1980s, this earlier surveillance mission for satellite-borne infrared sensors was enlarged to include tracking and kill assessment of the missiles, thereby raising the level of performance requirements.

The directorate's ongoing programs to develop optical transmission and



A T-62 tank against a soil background presents a very different image under clear, overcast, windy and rainy conditions. Variations in the optical and meteorological environment for a mission result in different target acquisition distances for a specific electro-optical weapon system.

radiance codes to assist infrared and visual sensors to discriminate targets against their natural backgrounds have been highly successful. In 1978, LOWTRAN (the simplified code for the lower atmosphere) and FASCODE (the high-resolution code for optical/laser systems), together with HITRAN (the supporting molecular spectroscopy data base), were designated as the standard transmission models for the Department of Defense. An improved version of LOWTRAN, entitled MODTRAN, has been under development since the 1980s and is gradually replacing LOWTRAN for applications requiring somewhat higher resolution.[92] These codes have been integrated with weather forecasting data in the tactical decision aid software discussed above in order to maximize the performance of precision-guided munitions. They are widely used by government agencies and by the scientific/industrial community for a variety of functions. The LOWTRAN code has become ubiquitous. A new code dubbed SPIRITS which the Directorate developed for airborne-middle atmosphere surveillance can be utilized by private aerospace firms in designing new aircraft.

The directorate developed an analogous group of radiative and transmission codes for the upper atmosphere. These supported the operational missile early-warning system called the Defense Support Program (DSP), and they contribute to improving the design of planned launch-warning and target tracking systems. In terms of civilian applications, these codes have relevance for modeling ozone depletion and global climate change. Most recently, optical physicists in the directorate have linked up all these different codes under one computer interface called PLEXUS in order to present a single, user-friendly package for military customers.

In research relating to targeting, the directorate has focused on difficulties caused by atmospheric phenomena like clouds and wind, while its research on "hard-earth" issues has dealt with the effects of gravity anomalies and deficiencies in geodetic requirements for precision targeting. Both clouds and winds were discovered to have an impact on the new ballistic missiles intended for strategic missions. In early tests of ballistic missiles during the later 1950s, missiles launched from the Eastern Test Range at Patrick AFB, FL, were either becoming unstable or veering off course due to wind shear below and above the jet stream. Directorate scientist Norman Sissenwine developed a fine-scale model of the vertical wind profile which was then used by missile designers to overcome this effect.[93]

The impact of clouds on reentering ballistic missiles was discovered during tests at Kwajalein Missile Range in the 1970s when reentry trajectories unaccountably varied. Directorate meteorologists who had been assigned to forecast the weather for these tests investigated using coordinated radar and instruments to measure particle size distribution and particle types in clouds (snow crystals, ice, etc.). They discovered that liquid particles associated with stormy weather caused severe erosion (ablation), and occasionally even destruction, of the carbon nose-cone. When the erosion occurred asymmetrically, it changed the trajectory of a missile. These data provided guidance to military contractors in addressing this design problem. The particle-measuring techniques developed by a directorate contractor, Dr Knollenberg, for this program have since been applied to many other areas, including monitoring of particles in clean rooms and planetary probes.[94]

"Hard-earth" issues for targeting of intercontinental ballistic missiles have been the subject of directorate research. Accuracy in targeting implies a corresponding accuracy in the location and distance data fed into guidance systems, the degree of accuracy required being specified by the acceptable Circular Error Probable (CEP) for the missile. In the 1960s geodesists at AFCRL began to develop triangulation techniques using new points of reference available in space (artificial satellites and mirrors on the moon's surface) to increase the precision of geodetic data for operational requirements. Another group of programs addressed tiny variations in the Earth's local gravity field in launch site areas. These can create small offsets in the trajectory of ballistic missiles towards their targets. Research in airborne and balloon gravimetry research, the most recent programs utilizing GPS position data, have reduced errors of this type.

Nuclear Test Detection

Seismic technology in support of nuclear test ban treaties is an area where a relatively small, but continuous, program in the Directorate since the late 1940s has made an important contribution to national security. The Army Air Forces began to explore techniques for detecting potential Soviet missile launches and nuclear tests in 1946. As discussed above, the staff at the AAF's new Watson Laboratories investigated acoustic, radiological, and seismic approaches, starting with Project Mogul described above.[95] Late in 1947 Watson's newly-formed Geophysics Research Division hired Dr. Norman Haskell, a brilliant Harvard-trained seismologist. Throughout the 1950s

Haskell pursued nuclear-related acoustic and seismic studies, and in 1958 he served as one of the technical experts for the U.S. at the Geneva Talks.[96]

In 1959, the Department of Defense started an ongoing research and development program to improve monitoring of all types of nuclear tests. The program, under the management of the new Advanced Research Projects Agency (ARPA), was called Project Vela. Vela Uniform was the initial name for the section devoted to monitoring underground tests. With the ratification of the 1963 Nuclear Test Ban Treaty, which outlawed all but underground nuclear tests, seismic techniques for nuclear detection became central. AFCRL became a lead agency under Project Vela Uniform for managing test-related research by universities and other organizations, with Haskell as the contract manager.[97] The Vela Uniform contracts supported the growth of a new discipline, explosion seismology.

Since the early 1960s, the directorate has been one of the handful of government agencies that has provided continuity and direction for the research in this area. After Haskell's retirement in 1968, the Air Force Office of Scientific Research took over its contract research programs (both with universities and companies) until 1985. Then the management of these contracts was returned to the Geophysics Directorate. Research sponsored in the 1970s and 1980s focused on seismic techniques for verifying compliance with the Threshold Test Ban Treaty which, although not ratified by the U.S. Senate until 1990, was considered unofficially binding.[98] Directorate scientists participated in the first U.S./Soviet Joint Verification Tests in 1987. Their efforts since then have focused on providing the enhanced seismic capability that would be required to monitor a future Comprehensive Test Ban Treaty.

Engineering and Technical Support

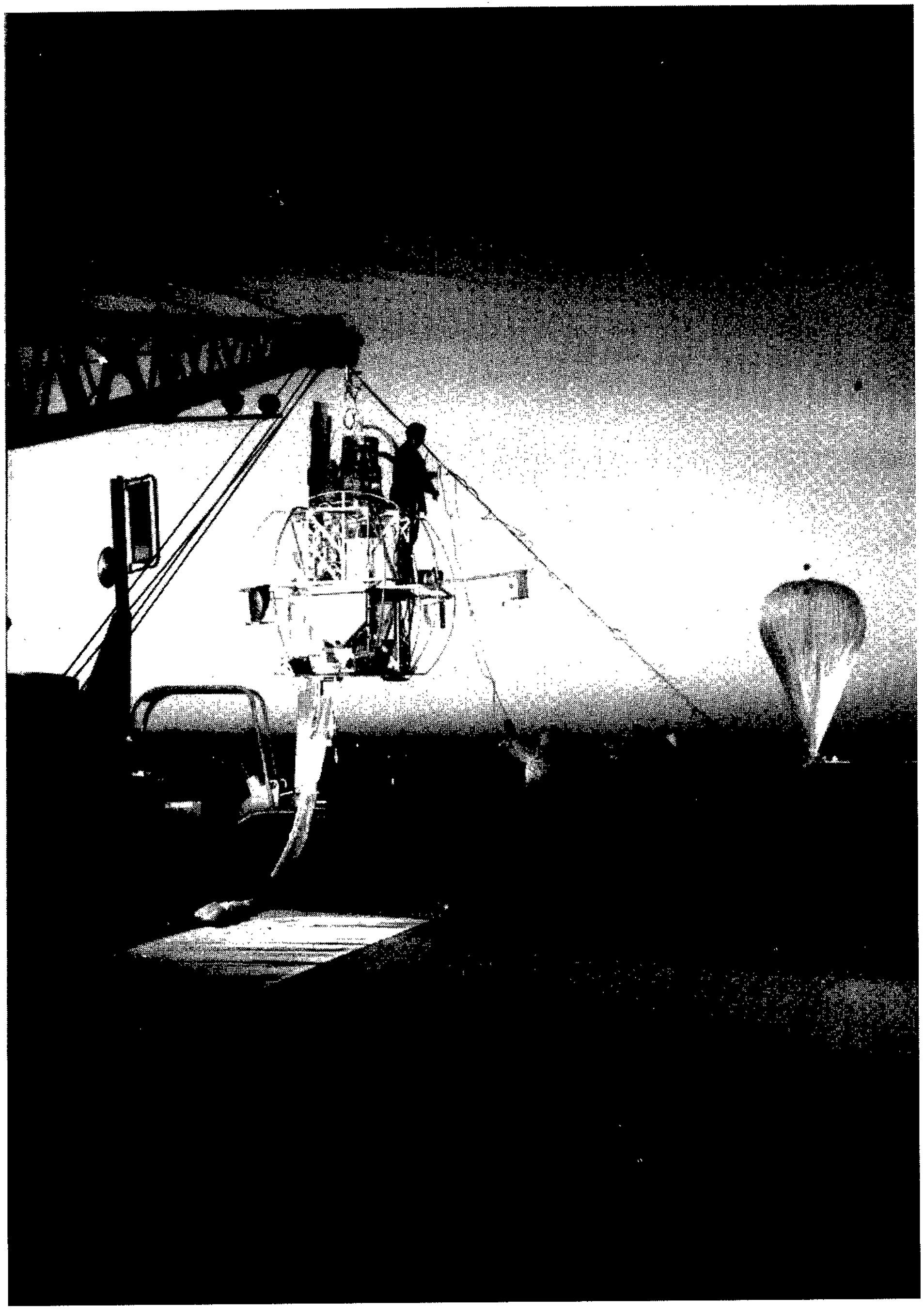
In addition to its scientific contributions, the Directorate has made notable contributions to engineering and technical support for geophysics. Some of these have come about in areas where the Department of Defense has delegated specific technical responsibilities to the directorate. Others have derived from the need for platforms and data processing that are part of the geophysical enterprise.

In 1951 DoD transferred responsibility for developing experimental meteorological equipment from the Army Signal Corps to the Air Force and specifically to the Geophysics Research Directorate.[99] In the 1960s development meteorologists created a new series of meteorological sounding rockets, some of which went into operational use at the National Meteorological Ranges. The directorate also improved the utilization of balloons for meteorology. Its staff members patented a number of meteorological measuring devices, including a rain rate meter and apparatus for particulate measurements, as well as several innovations in data processing.[100]

The directorate has had responsibility for several of the formal Military Standards and Handbooks that govern system acquisition. In 1967, it became the technical focal point for updating DoD's Military Standard 210, "Climatic Extremes for Military Equipment," which had first been issued in 1951. It coordinated the tri-service preparation of MIL STD 210B, which appeared in 1973, and of MIL STD 210C, which was published in 1987. This last edition adopted a new approach of flexible guidelines for applying the standard.[101] In the 1980s, the directorate's new advanced development space program (Space Systems Environmental Interaction Technology) participated in the formulation of military standards for the design and testing of space systems, MIL STD 1809, which was issued in February 1991.

The broadest area of engineering contributions made by the directorate has been in the development of improved research platforms for field measurements. Starting in 1946, its engineers conducted and sponsored work concurrently on both unmanned balloons and sounding rockets. Project Mogul pioneered the use of large single polyethylene balloons, developed by New York University, to replace the current clusters of rubber balloons. This technology for zero-pressure, free-flying balloons was then taken up by the Navy in its Skyhook program.[102] In the early 1950s the directorate was given technical responsibility for balloon research and development in the Air Force, and later it was directed to provide balloon launch facilities for the whole Department of Defense. Its main balloon launching facility was located at Holloman AFB, NM (Figure 6).

Over the years directorate engineers sponsored industrial research to improve the quality of the polyethylene balloon envelopes, setting records in the early 1970s for the size, payload weight, and altitude attained by these free-flying balloons. In the 1970s they began to experiment with improving the design and altitude obtained by tethered balloons, and they also set some records in this area. They also pursued ongoing efforts to improve techniques for launching and for commanding both the balloons themselves



Directorate engineers and technicians prepare a zero-pressure balloon carrying a geophysical experiment for launch at Holloman AFB, NM.

and the instruments carried on their gondolas. Through the movement of personnel, some of this expertise was transferred to NCAR and the new balloon launch facility that it established in the 1960s at Palestine, Texas, which later was transferred to NASA. Between 1963 and 1978 the directorate hosted a series of Symposia on Scientific Ballooning whose proceedings disseminated advances in the state-of-the-art.

In addition to its main responsibility to support geophysical research, the balloon group provided a variety of testing services. Anchored balloons (tethered aerostats) were particularly suited to suspend targets for testing weapons systems under development. Over the years balloon engineers have assisted in conducting many such tests. Probably the most unique services performed were the drop-tests for NASA of the re-entry systems for lunar and planetary probes. Starting with drop-tests in 1965 from a tethered aerostat for the Surveyor Lunar Lander, the engineers went on to drop-tests from free-flying balloons in 1966 and 1972 for the Voyager and Viking probes of Mars, in 1977 for the Pioneer probe of Venus, and lastly in 1982 for the recently successfully-completed Galileo probe of Jupiter.[103] The drop-test for the planetary probes were technically very demanding because the enormous balloons required to carry the heavy probe had to be commanded to a location high above the observing ground stations and then to perform a complex sequence of parachute openings to simulate the probe descent.

In sounding rockets, the directorate made contributions in a similarly broad program. Its characteristic approach to rocket vehicles was to adapt surplus operational missiles for scientific experiments. This was initially done by all the services with the captured V-2s immediately after the war. After the Navy developed the liquid-fueled Aerobee sounding rocket in the later 1940s, the directorate cooperated with the Navy in expanding its range and payload capability into the 1970s. In the 1950s the directorate moved into solid-fuel engines and returned to an adaptive approach, utilizing obsolete Nike and later Minutemen III second-stage boosters to achieve economical vehicles tailored to experimental requirements. Its engineers significantly expanded the capability of sounding rockets in the later 1970s by introducing recycled boosters with guidance systems and increased weight-carrying ability.[104]

The first fifteen years of postwar scientific experiments on sounding rockets performed by the Geophysics Research Directorate, the Naval Research Laboratory, and other groups established "a technical culture" of space experimentation, as DeVorkin has put it. They developed the basic scientific instrumentation (spectrometers, coronagraphs, solar pointing controls) that was then flown on satellites. Thus the directorate contributed to laying the foundation for space sciences.[105]

Prospectus for Military Geophysics in the Post Cold War Era

The Cold War era shaped the assumptions and the emphasis of the Air Force's geophysical research in the forty-five years after World War II. The directorate's contributions to national security and to science ranged from specific responses to an evolving range of military issues related to the Cold War to broader basic research that advanced areas of geophysics of interest to the Air Force.

With the dismantling of the Iron Curtain and the beginnings of reform in the Soviet Union, much of the previous context of military geophysics started to fade. The balance of terror between two world superpowers gave way to a global scene of multiple players with rising new powers in Asia and significant regional armed conflicts. Terrorism, sharp local-ethnic tensions, and the global challenge of nuclear proliferation have become major international issues. Despite the grandiose hope/fear of a "new world order," the reality has been more one of uncertain groping towards new arrangements and conflict-solving mechanisms.

Since military geophysics tends to be responsive to current and planned strategy and operations, the present Geophysics Directorate is regrouping around reformulated doctrines and procedures as they emerge in the post Cold War era. Some signposts for new directions in geophysics appeared during the course of the Gulf War. A key Cold War satellite resource, the Defense Support Program (DSP), was used to provide warning of short-range, rather than intercontinental, ballistic missile launches. The recently-completed installation of Global Positioning System (GPS) satellites, used with a commercial receiver, provided position location and navigation for infantry units in the desert. These innovations helped to break down the Cold War distinction between strategic-nuclear-long-range and tactical-conventional-short-range spheres of operation. The space-to-ground configuration envisioned for future theater operations, including the revised concept of theater missile defense, requires more emphasis on all the solar/atmospheric issues connected with spacecraft survivability and reliability and with the use of satellites for communications, surveillance, and navigation. More generally, it implies the need to integrate previously separate areas of research on the upper, middle, and lower atmosphere.

To cover all the potential areas of future regional conflict, advances in global satellite meteorology and new regional climatological studies are called for. The threat of nuclear proliferation and the effort to achieve a Comprehensive Test Ban Treaty carry with them new challenges for seismology. In particular, these involve developing techniques to detect the very small tests that are likely to be conducted by first-time proliferators.[106] While the seismology of the U.S. and the Soviet Union has been explored extensively, for other regions of the world these data are sparse or nonexistent. Developing accurate and reliable seismic predictions for such regions is a difficult but essential task. Thus, in this transformed global context, there is a range of major new military issues which require input from technical areas in which the Geophysics Directorate has long-standing expertise. The directorate has been refocusing its programs to deal effectively with the new challenges for military geophysics.

While these major shifts in the international scene have been in process, other major domestic developments are affecting the prospectus for military-sponsored geophysics. The first is a group of political initiatives (not necessarily consistent) to downsize the Federal workforce and budget, to shift government-run research to universities and the private sector, and to devote more Federal funding to applied research and engineering in order to make the nation more competitive in the global economy. This last initiative has spurred a reassertion of the value of basic research, civilian and military, to the nation. A second major domestic development is the growing public concern with environmental issues, ranging from global warming and the ozone layer down to local pollution and land-use.

While the first of these domestic developments has led to the downsizing of military geophysics, the second gives it some potential new opportunities. The directorate can make a contribution to addressing these pressing environmental issues. For instance, in recent Shuttle and satellite experiments, its scientists have expanded their defense-related missions to include atmospheric chemistry measurements that provide significant data for ozone and global warming studies. During the Cold War, the Directorate made significant contributions to a wide range of defense-related issues, and it augmented the national stock of resources in the field of geophysics. Now it is adapting its resources to bring them to bear on an equally vast set of new challenges in the post Cold War era.

NOTES

1. Michael H. Gorn, The Universal Man: Theodore von Karman's Life in Aeronautics (Washington, DC: Smithsonian Institution Press, 1992), 81-82. See also John Fuller, Thor's Legions: Weather Support to the U.S. Air Force and Army, 1937-1987 (Boston, MA: American Meteorological Society, 1987), chap. 2.

2. Bruce Hevly, Basic Research Within a Military Context: The Naval Research Laboratory and the Foundations of Extreme Ultraviolet and X-Ray Astronomy, 1923-1960 (PhD Dissertation: Johns Hopkins, 1987).

3. Between 1933 and 1940, Arnold rose from the rank of Colonel to Major General and became first the assistant chief (1935) and then the chief of the Army Air Corps (1938); Thomas M. Coffey, Hap, Military Aviator: The Story of the U.S. Air Force and the Man Who Built It, General Henry H. "Hap" Arnold (New York: The Viking Press, 1982), 6, 166, 169, 182.

4. Gorn, Theodore von Karman, 81-86; Fuller, Thor's Legions, 30-32, 39-42. Krick's own, and according to Fuller, unreliable account of his research is presented in Victor Boesen, Storm: Irving Krick vs. the U.S. Weather Bureaucracy (New York: G.P. Putnam's Sons, 1978).

5. Charles C. Bates and John F. Fuller, America's Weather Warriors, 1814-1985 (College Station, TX: Texas A&M University Press, 1986), 46-48.

6. Bates and Fuller, Weather Warriors, chaps. 4-6; TSgt William M. Rhodes, "Tracing Chanute's History in Weather Training," Observer (Special Edition), Air Weather Service (1993): 4.

7. Donald Menzel, Our Sun (Philadelphia: The Blakiston Co., 1949), ; Fuller, Thor's Legions, 201-203.

8. Herman S. Wolk, Planning and Organizing the Postwar Air Force, 1943-1947 (Washington, DC: Office of Air Force History, 1984).

9. Michael A. Dennis, "Our First Line of Defense: Two University Laboratories in the Postwar American State," ISIS, Vol. 85, No. 3 (September 1994), 427-455.

10. Silvan S. Schweber, "The Mutual Embrace of Science and the Military: ONR and the Growth of Physics in the United States after World War II," in Everett Mendelsohn et al., eds. Science, Technology and the Military (Dordrecht, Holland: Kluwer Publishers, 1988), Vol. I; Harvey Sapolsky, Science and the Navy: The History of the Office of Naval Research

(Princeton, NJ: Princeton University Press, 1990); For the Research and Development Board, see Steven L. Rearden, History of the Office of the Secretary of Defense: Vol. I, The Formative Years, 1947-1950 (Washington, DC: Office of the Secretary of Defense, 1984), 96-103

11. Henry H. Arnold, Global Mission (1949; reprint, PA: Tab Books, Military Classics Series, 1989). See also Gorn, Theodore von Karman (1992), chaps. 5 and 6.

12. The two essays from Toward New Horizons are reprinted in Prophecy Fulfilled: "Toward New Horizons" and Its Legacy, ed. Michael Gorn (Washington, DC: Air Force History and Museums Program, 1994). The accompanying monographs are deposited in the archives of the Air Force Materiel Command History Office, Wright-Patterson AFB, OH.

13. Although Krick alluded briefly to the possible use of controlled atomic energy for weather modification, he made no mention of the meteorological potential of artificial satellites. A 1951 classified RAND report on the feasibility of satellite meteorology received no immediate response, according to Bates and Fuller, Weather Warriors, 174. See also Charles C. Bates, Thomas F. Gaskell, and Robert B. Rice, Geophysics in the Affairs of Man: A Personalized History of Exploration Geophysics and Its Allied Sciences of Seismology and Oceanography (Oxford, UK: Pergamon Press, 1982), 140-42.

14. Gorn, Theodore Von Karman, chap. 7; Thomas A. Sturm, The USAF Scientific Advisory Board: Its First Twenty Years, 1944-1964 (Washington, DC: USAF Historical Division Liaison Office, 1967).

15. Published histories or chronologies exist for most of these organizations.

16. Thomas W. Thompson, "Rome Laboratory: A Brief History," The Rome Laboratory Technical Journal, Vol. I, No. 1, 1-2. For the initial organization of the Atmospheric Laboratory at Watson Labs as of January 1947, see The Roswell Report: Fact vs Fiction in the New Mexico Desert, Headquarters USAF, 1995 (Washington, DC: Government Printing Office, Superintendent of Documents), McAndrews Attachments, #2.

17. Ruth P. Liebowitz, Chronology: From the Cambridge Field Station to the Air Force Geophysics Laboratory, 1945-1985, AFGL-TR-85-0201 (Hanscom AFB, MA: Air Force Geophysics Laboratory, 6 September 1985).

18. Rearden, Office of the Secretary of Defense, I, 100. The Committee continued the work of the earlier advisory Committee on Geophysical Sciences, set up in 1946 under the Army-Navy Joint Research and Development Board, the predecessor to the RDB.

19. Helmut Landsberg, Geophysics and Warfare, Office of the Assistant Secretary of Defense (Research and Development), March 1954: Phillips Laboratory, Geophysics Directorate, Hanscom AFB, MA (henceforth cited as PL/GP), History File. The 1954 publication is the unclassified version of a 1948 piece, no copies of which seem to have survived.

20. National Military Establishment, Research and Development Board, Survey of Scientists Engaged in Geophysical Researches, Digest Series 11, June 25, 1948: A copy is in the RDB archives at the National Archives and Records Administration, Washington, DC (henceforth cited as NARA), Records Group (henceforth R.G.) 330, Box 228, Folder #62. For the Committee on the Geophysical Sciences'discussion of the manpower shortage, see NARA, R.G. 330, Box 228, Folder 77, Item 7.

21. Michael A. Dennis, "Bushwhacked! Vannevar Bush and the Dilemmas of Science Policy," presentation to the American Physical Society Meetings, 19 April 1994, Washington, DC. A discussion of Air Force missiles under development is given in Jacob Neufeld, Ballistic Missiles in the United States Air Force, 1945-1960 (Washington, DC: Office of Air Force History, 1990), chaps. 2 and 3. For scientists' interest in guided missiles, see David DeVorkin, Science with a Vengeance: How the Military Created the US Space Sciences (New York, NY: Springer-Verlag, 1992).

22. See the heated and unresolved debate in 1949 in the RDB Committee on Geophysics and Geography's Panel on the Atmosphere over which service should be assigned these programs: NARA, R.G. 330, Box 72, Folder 108.

23. For sources on ONR, see above, note 10. For ONR's postwar support of NRL and the impact on the laboratory, see Hevly, Basic Research, 70-93, 262, and David Van Keuren, "Government Science in the Wake of War: The Reorganization of the Naval Research Laboratory after World War II," in David Van Keuren and Nathan Reingold, eds., Science and the Federal Patron (Cambridge, England: Cambridge University Press, forthcoming).

24. Col Frederic Oder, Chief, Geophysics Research Directorate from 1949-1951, interview by Ruth Liebowitz, 27 April 1982. For an example of Holzman's intervention to protect GRD programs, see his troubleshooting at the RDB to avoid difficulties for the planned Upper Air Observatory at Sacramento Peak: NARA, R.G. 330, Box 113, Folder 112GG.

25. The 26 March 1947 directive from General Spaatz, signed by Curtis LeMay, is reproduced in Liebowitz, Chronology, Appendix D. The directive ended some previous controversy over where in the Army Air Forces the meteorological R&D function should be located: see Fuller, Thor's Legions, 216, 230 .

26. Starting in 1949 the directorate published the results of its programs in the series, Geophysical Research Papers. More applied work starting in the early 1950s was reported in the series, Air Force Surveys in Geophysics, initiated in 1952. A fair number of the Surveys were issued as classified reports.

27. Bates, Gaskell, and Rice, Geophysics, chaps. 4 and 5; DeVorkin, Science with a Vengeance.

28. A.P. Crary and I. Browne, Probable Ice Island Locations in the Arctic Basin, January 1954, Air Force Surveys in Geophysics, No. 50, AFCRC-TN-60-455 (Geophysics Research Directorate, Bedford, MA, May 1954).

29. The organization handling the scientific exchange programs in Europe since 1952 has been the Air Force Office of Scientific Research's European Office of Aerospace Research and Development (EOARD). In 1992 AFOSR established an Asian Office of Aerospace Research and Development (AOARD).

30. For the Weather Bureau figure, see Ronald Doel, Solar System Astronomy in America: Communities, Patronage, and Interdisciplinary Science, 1920-1960 (Cambridge University Press, 1996), 64. The figures for the GRD budget in fiscal year 1951 are in the records of the RDB's Committee on Geophysics: NARA, R.G. 330, Box 59, Folder 106GG.

31. Bates and Fuller, Weather Warriors, 298, note 5. The current membership of the AGU is more than 30,000, an order of magnitude larger.

32. For the impact on ionospheric studies, see C.S. Gillmor, "Federal funding and knowledge growth in ionospheric physics, 1945-1981," Social Studies of Science 16 (1986), 105-133.

33. Glossary of Meteorology, ed. Ralph E. Huschke (Boston, MA, American Meteorological Society, 1959). It was co-sponsored by the U.S. Weather Bureau, Air Weather Service, GRD, the Army Signal Corps, and ONR. Compendium of Meteorology, ed. Thomas F. Malone (Boston, MA, American Meteorological Society, 1951). The Committee on the Compendium, chaired by H.G. Houghton, consisted of H.R. Byers, H.E. Landsberg, H. Wexler, B. Haurwitz, A.F. Spilhaus, and H.C. Willett. The contracts with the American Meteorological Society for the abstracts and the compendium have the numbers AF 19(122)-82 and W28-099 ac-399.

34. "Necrologies: Philip D. Thompson, 1922-1994," Bulletin of the American Meteorological Society, Vol. 76, no. 4 (April 1995), 570-72. For Thompson's scientific contributions, see John M. Lewis, "Philip Thompson: Pages from a Scientist's Life," Bulletin of the American Meteorological Society, Vol. 77, No. 1 (January 1996), 107-113.

35. Chankey Touart, retired director of the Meteorology Laboratory, interview by Ruth Liebowitz, May 1995; Fuller, Thor's Legions, 222-23.

36. M.G. H. Ligda, "Radar Storm Observation," Compendium of Meteorology, 1265-1282.

37. Project Thunderstorm sponsors included the Army Air Forces, the U.S. Weather Bureau, the Navy, and NACA: Bates, Weather Warriors, 58-59, 139-40.

38. James I. Metcalf and Kenneth M. Glover, The Fortieth Anniversary History of Weather Radar Research in the U.S. Air Force, AFGL-TR-89-0032: Air Force Surveys in Geophysics, no. 452 (Hanscom AFB, MA: Air Force Geophysics Laboratory, 30 January 1989), 2-4. An abridged version of this Metcalf and Glover report appeared under the title, "A History of Weather Radar Research in the U.S. Air Force," in Radar in Meteorology, ed. David Atlas (Boston, MA: American Meteorological Society, 1990), 32-40. See also R. J. Donaldson, "Vortex Signature Recognition by a Doppler Radar," Journal of Applied Meteorology, Vol. 9, 661-70.

39. K.M. Glover, R.J. Boucher, et al., "Simultaneous radar, aircraft, and meteorological investigations of clear air turbulence," Journal of Applied Meteorology 4 (1969), 634-40. These results were fundamental to the eventual development of Doppler radar wind profilers.

40. Metcalf and Glover, Weather Radar Research, 4-31.

41. Metcalf and Glover, Weather Radar Research, chaps. 5 and 6; Paul R. Desrochers and Ralph J. Donaldson, "Automatic tornado prediction with an improved mesocyclone-detection algorithm," Weather and Forecasting 7 (1992), 373-387; James I. Metcalf, interview by Ruth Liebowitz, 12 February 1996.

42. The GRD scientist in charge of the Cloud Photo study was Arnold Glaser. See John H. Conover, The Blue Hill Meteorological Observatory: The First 100 Years, 1885-1985 (Boston, MA: American Meteorological Society, 1990), 307, 320; John H. Conover and James Sadler, "Cloud Patterns,"Bulletin of the American Meteorological Society, Vol.41 (June 1960), 291-97.

43. Bates and Fuller, Weather Warriors, 174-176.

44. For the evolution of the DMSP program, see Walter D. Meyer, "The Defense Meteorological Satellite Program: A Review of Its Impact," in Monitoring Earth's Ocean, Land, and Atmosphere from Space, ed. Abraham Schnapf, Vol. 97: Progress in Astronautics and Aeronautics, (New York: American Institute of Aeronautics and Astronautics, Inc., 1985), 129-149.

45. Maj Michael Remeika, Atmospheric Sciences Division, interview by Ruth Liebowitz, 1 April 1995; James Bunting, Atmospheric Sciences Division, interview by Ruth Liebowitz, 5 January 1996.

46. The contract budget for the Upper Air Laboratory headed by Marcus O'Day ran close to $3.5 million as of December 1949; "Index to Electronic and Geophysical R&D Projects, 31 December 1949," Prepared by MCREE02 Electronic Subdivision, Engineering Division, Air Materiel Command, Wright-Patterson AFB, OH: PL/GP, History File. For documentation on the whole GRD budget at this time, see above note 30.

47. Briefing at the Pentagon, Colonel Marcellus Duffy, Chief of the Engineering Division, Air Materiel Command, March 1948: PL/GP History File.

48. For pre-war ionospheric studies, see C.S. Gillmor, "Threshold to Space: Early Studies of the Ionosphere," in Space Science Comes of Ages: Perspectives in the History of the Space Sciences, Paul A. Hanle and Von Del Chamberlain, eds. (Washington, DC: Smithsonian Institution Press, 1981), 101-114. For the status of upper atmospheric research as of the end of World War II, see David H. DeVorkin, Science with a Vengeance: How the Military Created the US Space Sciences (New York: Spring-Verlag, 1992), chaps. 3 and 4.

49. Ruth P. Liebowitz, "The Creation of the Sacramento Peak Observatory: An Air Force-Harvard Collaboration," (article in preparation).

50. C.E. Junge and J.E. Manson, "Stratospheric Aerosol Studies," Journal of Geophysical Research, Vol. 66 (July 1961), 2163-1183. See also Conover, Blue Hill, 325, 334,337.

51. Interview with Dr. Arnold Barnes, Atmospheric Sciences Division, 27 Nov 95. For studies of solar ultraviolet and the stratosphere, see G.P. Anderson and L.A. Hall, "Stratospheric Determination of O_2 Cross Sections and Photodissociation Rate Coeffecients: 191-215 nm," Journal of Geophysical Research, Vol. 91, No. D13 (December 20, 1986), 14509-14514.

52. For the Atmospheric Explorer program, see Eric Burgess and Douglass Torr, Into the Thermosphere: the Atmosphere Explorers (Washington, DC: NASA, Scientific and Technical Information Division, 1987). See also H.E. Hinteregger, "Rocket Spectra of the Chromosphere," in The Solar Spectrum: Proceedings of the Symposium held at the University of Utrecht, 26-31 August 1963, ed. C. De Jager (Dordrecht, Holland: D. Reidel, 1965), 179-206.

53. Dr. Kenneth Champion, taped interview by Ruth Liebowitz, Hanscom AFB, MA, 22 December 1994: PL/GP, History File.

54. US Standard Atmosphere, 1976 (Washington, DC: NOAA, NASA, and USAF, October 1976).

55. Frederick F. Marmo, Jerome Pressman, et al., "Formation of an Artificial Ion Cloud; Photoionization of NO by Solar Lyman Alpha at 95 km," The Journal of Chemical Physics, Vol. 25, No. 1 (July, 1956), 187.

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57. Dr. Edmond Murad, Ionospheric Effects Division, interview by Ruth Liebowitz, 27 February 1996.

58. R.R. O'Neil, "Summarized Results of the Artificial Auroral Experiment, Precede," Journal of Geophysical Research, Vol. 83, No.A7 (July 1, 1978), 3273. For the final EXCEDE III Program, see Duane E. Paulsen, EXCEDE III Flight Report, PL Technical Report, publication forthcoming (Hanscom AFB, MA).

59. R.S. Narcisi and A. D. Bailey, "Mass spectrometric measurements of Positive Ions at Altitudes from 64 to 112 Kilometers," Journal of Geophysical Research 70 (1965), 3687; R.S. Narcisi,"Processes Associated with Metal-Ion Layers in the E Region of the Ionosphere," Space Research VIII (Amsterdam: North Holland Publishing Company, 1968), 360-69.

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81. The first four of these conferences, co-sponsored by NOAA and the Air Force, were held in 1979, 1984, 1989, and 1992. The most recent one, in January 1996, was sponsored by the Japanese.

82. John Klobuchar, Ionospheric Effects Division, interview by Ruth Liebowitz, 18 December 1995. The Lowell Center for Atmospheric Research is affiliated with the University of Massachusetts at Lowell.

83. Keith Groves, Ionospheric Effects Division, Memo on the RTS^2 System, November 1995.

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86. G. Siscoe, E. Hildner, T.L. Killeen, et al., "Developing Service Promises Accurate Space Weather Forecasts in the Future," EOS, August 2, 1994, page 353; National Space Weather Program: Strategic Plan, Office of the Federal Coordinator for Meteorological Services and Supporting Research (FCM-P30-1995), Washington, DC: August 1995.

87. Much detailed information on Project Mogul is presented in The Roswell Report cited above, note 16. This new Air Force report deals with an alleged UFO incident and subsequent coverup that Project Mogul inadvertently gave rise to.

88. During World War II, Ewing had developed the Sound Fixing and Ranging (SOFAR) technique to exploit the underwater channels for detection purposes: Bates, Gaskell, and Rice, Geophysics, 15.

89. Memo from Capt Albert Trakowski to AFOAT-1, subj: Mogul and MSX-968, 10 December 1948, Geophysics Directorate History File, Hanscom AFB,

MA. For these programs, which originally were classified Top Secret, see Charles A. Ziegler and David Jacobson, Spying without Spies: Origins of America's Secret Nuclear Surveillance System (Westport, CO: Praeger, 1995), esp. chs. 3-7. Also Bates, Gaskell, and Rice, Geophysics, 87-88. As the memo above indicates, the Tracerlab contract was transferred from Watson Labs to AFOAT-1 later in 1948.

90. Ruth P. Liebowitz, "Historical Brief: AFGL Technology Supporting the CONUS Over-the-Horizon Backscatter Radar," PL/Hanscom, Geophysics Directorate History File.

91. The measuring instrument was a clinometer designed by Gene Bertoni, and the measurements were done by airline pilots in a voluntary program; Interview with Donald Grantham, Atmospheric Sciences Division, 28 Nov 95.

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93. N. Sissenwine, Development of Missile Design Wind Profiles for Patrick AFB, Air Force Surveys in Geophysics, No. 96, Geophysics Research Directorate, (Bedford, MA: Geophysics Research Directorate, March 1958); N. Dvoskin and N. Sissenwine, Evaluation of AN/GMD-2 Wind Shear Data for Development of Missile Design Criteria, Air Force Surveys in Geophysics, No. 99 (Bedford, MA: Geophysics Research Directorate, April 1958); D. Grantham, interviewed by R. Liebowitz, 30 January 1996.

94. Originally at the University of Chicago, Dr Knollenberg spun off his own company, Particle Measuring System (PMS, Inc.): Dr. Arnold Barnes, Atmospheric Sciences Division, interview by Ruth Liebowitz, October 16, 1987.

95. Ziegler, Spying without Spies, chap. 2, and also 189-81. A lengthy document on the whole DoD effort, "Long Range Detection Plan for FY-1951," is in the RDB records at NARA, R.G. 330, Box 228, Folder 71.

96. For Haskell, see Vincit Veritas: A Portrait of the Life and Work of Norman Abraham Haskell, 1905-1970, ed. Ari Ben-Menahem, American Geophysical Union, Washington, D.C., 1990.

97. For additional information on Vela Uniform, see Bates, Gaskell, and Rice, Geophysics, 59-176. Also The Vela Program: A Twenty-Five Year Review of Basic Research, ed. Ann U. Kerr, DARPA, 1985.

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99. RDB records in NARA, R.G. 330, Box 59, Folder 106GG.

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102. Ziegler, Spying without Spies, 217-18.

103. AFGL Report on Research for the Period January 1981-December 1982 AFGL-TR-83-0198, (Hanscom AFB, MA: August 1983), 50-51; Newstory, "Phillips Lab Program Finally Gets Results," The Hansconian, January 5, 1996, page 2.

104. Edward McKenna, Aerospace Engineering Division, interview by Ruth Liebowitz, 13 February 1996. See also DeVorkin, Science with a Vengeance, 82-84.

105. DeVorkin, Science with a Vengeance, Conclusions, 341-46.

106. Gregory E. Van der Vink, Nuclear Testing and Nonproliferation: the role of seismology in deterring the development of nuclear weapons (Arlington, VA: The IRIS Consortium, February 1994). The report was prepared at the request of the Senate Committee on Governmental Affairs and the House Committee on Foreign Affairs.