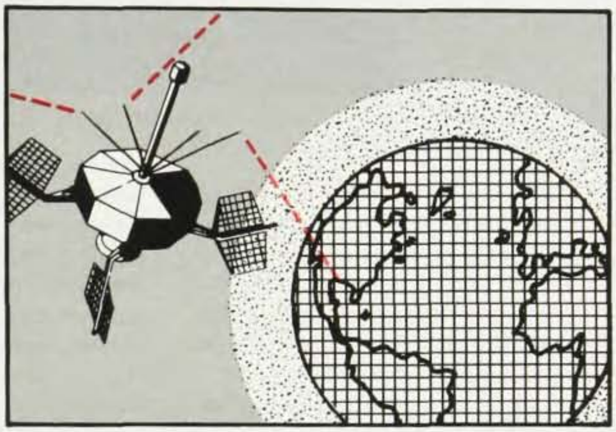
Geophysics Instrumentation

AFCRL adapts instrumentation from the laboratory to studies of the earth's atmospheric environment. Primary interest is in improved instrumentation for balloons, rockets and satellites.

by John N. Howard



IN MANY WAYS geophysical experiments are like space research, requiring major logistic efforts and expensive vehicles to carry even a simple instrument to the remote and largely inaccessible environment. To the general public, geophysical studies seldom have the glamor or excitement of an experiment in space: our launches are seldom televised, and our successes (or failures) are chronicled in the drier pages of scientific journals. But to the geophysicist the research offers many challenges: there are still many mountains to be climbed and mysteries to be solved. Only after we better understand the physical mechanisms of our environment will we have any hope of controlling it. Then, perhaps, people will no longer say that everybody talks about the weather but nobody does anything about it.

Most of us, whatever our discipline, tend toward a Ptolemaic view of the rest of science as revolving about our own particular interest. For example, one of my friends (a laser man) recently asserted that there are really only two kinds of physics: laser physics and nonlaser physics. Similarly, those working in geophysics quote a definition of it as comprising all phenomena from the center of the earth to the outermost reaches of the natural environment.

In this paper we attempt a more modest scope: We discuss some of the instrumentation used for geophysical studies at the Air Force Cambridge Research Laboratories, which is the leading in-house laboratory of the Air Force for environmental studies. Our principal research aim is to elucidate the physical mechanisms in the atmosphere of the earth and the surrounding near-space environment, as well as in a few specific research areas such as geodesy, gravimetry and seismology that include the solid earth itself. We do not explore for oil reserves or study oceanography or dig holes through the crust of the earth, nor do we propose to describe the research instrumentation for geophysics developed by colleagues in other geophysics-oriented groups such as the ESSA and NASA laboratories, the Naval Research Laboratory and the National Center for Atmospheric Research. We quickly found that these other groups would prefer that we describe our own efforts and not theirs; perhaps later they can describe their own research instrumentation.

As a final caveat, we include only a selection of our geophysical instrumentation. We omit, for example, all of our laboratory studies and concentrate on a discussion of physics instrumentation designed to leave the laboratory and measure some environmental parameter in situ, either from the ground or borne aloft by aircraft, balloon, satellite or rocket. First we describe some general characteristics of geophysical experiments with these research vehicles and then give a more detailed example of one or two experiments in each category.

AIRCRAFT STUDIES

Almost since the organization of AFCRL some 20 years ago there have been some research studies from aircraft. At times we have had as many as six aircraft assigned to us; at present we have five. The principal advantage of the airplane over such other environmental probes as balloons, rockets, and satellites is that in general the investigator can accompany the experiment and check the calibration and results as the experiment progresses. The laboratory bench has simply been put in an airplane. The airplane is also highly portable and can carry tons of equipment and electronics to remote and inaccessible locations such as the Antarctic or an eclipse site in the South Pacific. It can also remain on station for several hours at a time.

Unfortunately, there are many practical drawbacks to this flying laboratory: the electrical power available on the airplane is ordinarily 28 volts dc or 110 volts 400 Hz and not well stabilized, and the experiment also must be isolated from the strong mechanical vibrations of the engines. The cabin of the plane is heated and pressurized; so for many experiments a window or port must be cut through the aircraft skin. In a high-performance aircraft, the insertion of such a port requires an expensive restressing of the fuselage. If the sensor is designed for external mounting, it may require an aerodynamic shield and must be either heated or capable of operating at temperatures down to -50°C. We discovered by unhappy experience that even after a successful flight the cold windows of hygroscopic infrared-transmitting material become covered with moisture condensation when the plane returns to lower altitudes. All of these difficulties can be surmounted, however—if one can afford the cost—to yield flying laboratories for geophysical research throughout the world.

A KC-135 INTERIOR has participated in all eclipse expeditions all over the world during the past several years. —FIG. 1

One such flying laboratory is the AFCRL C-130 instrumented for cloud physics research. Operating at altitudes up to 11 km (35 000 ft), it carries devices for sampling atmosphere liquid-water content, including that in supercooled clouds (clouds consisting of liquid-water droplets at temperatures below freezing), and for measuring atmospheric humidity. It also has various temperature probes, electric field meters and ducts for sampling atmospheric refractive index at microwave frequencies. Most of this instrumentation is mounted externally. In addition the aircraft carries three cameras for mapping terrain and horizon-to-horizon cloud cover and four 16-mm time-lapse cameras used to record the growth of clouds. These cameras take one frame every 3 sec.

Another C-130 is instrumented for airborne geological surveys. The basic instrumentation is a multispectral camera that records nine simultaneous photographs in discrete regions of the optical and infrared spectrum. The aircraft also contains a variety of conventional aerial cameras and spectrographic equipment. During a survey last summer in the Mediterranean and Middle Eastern countries, where the mission was to explore natural landing areas, archeologists from the University of Pennsylvania asked that airborne surveys be made over places where they suspected that ancient cities might be buried. The expedition also accommodated a request by the Italian government for surveys over certain geothermal regions of Italy that might provide a source of energy for steam-generating plants.

Higher and faster

For several years AFCRL also operated a U-2 aircraft instrumented for studies of cloud growth, atmospheric electricity and atmospheric ozone profiles. This aircraft was operated up to about 22 km and could photograph and measure the electric field strength of thunderheads as well as photograph the eyes of hurricanes from above. Extensive photography of clouds from above (beyond the altitude capability of ordinary aircraft) was very useful in establishing the feasibility of the TIROS weather satellite. In the early days of the US space program, this aircraft was also used to gather cloud data for predicting weather in the reëntry area for the Mercury series of satellites. What was then a research project has now become, with TIROS, almost a rou-

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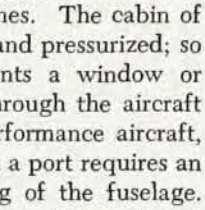


tine weather-satellite function.

Another versatile research aircraft is the KC-135 (a military version of the Boeing 707, originally intended as a refueling tanker). One of these at AFCRL is instrumented for ionospheric studies (see figures 1 and 2); the other has been used for optical research and gravimetry studies. The speed of this aircraft is sufficiently great that at high latitudes, flying east to west, the plane can keep up with the sun (Ptolemaically speaking), thus preserving a fixed geometry between the sun and earth while measuring parameters such as atmospheric airglow and aurora. The ionospheric-research aircraft, together with a similarly equipped Convair 990 operated by NASA, has also participated in every solar total eclipse during the past four years.

INSTRUMENTED AIRCRAFT can quickly transport heavy instruments. This aircraft is equipped for atmospheric optics research. —FIG. 2

Optical-infrared research

Infrared spectral measurements of aurora and airglow are difficult. Radiant sources are relatively weak compared with visible daytime sky. One must contend with the natural atmospheric thermal emission background, and, at the longer wavelengths (greater than 3 microns), one must overcome emission from the instrument environment and even from the instrument itself. Rockets and artificial satellite platforms afford a means for circumventing thermal emission from lower atmosphere regions. But they do not permit large instrumentation payloads and extended data gathering at any one time and geographical location. Data recovery is not simple. The high-performance jet aircraft provides an instrumentation platform without some of these difficulties.

The optical-infrared research aircraft is a KC-135 jet equipped for 15 simultaneous experiments on natural aurora and airglow. Because of the night sky's weak emission, conventional spectrometers are at a severe disadvantage for such applications. They require long integration times leading to uncertainty in the data. Therefore, wherever possible, we have invoked the light-gathering ability of interferometry and Fourier spectroscopy.

As already mentioned, one of the problems in infrared spectroscopy is the thermal radiation from the immediate instrument environment or even from the instrument itself. One could minimize this problem by cooling the instrument and the immediate environment, but this is not always easily done in the field. For one type of interferometer designed to observe from the aircraft airglow emissions in the 1–15-micron region, a new approach has been to mount a liquid-nitrogen-cooled chopper outside the aircraft window. Then the sky emissions modulated at the chopper frequency can be electronically differentiated from the dc (unchopped) emissions from the aircraft window, cabin environment and interferometer. This technique also permits instrument operation at aircraft cabin temperatures and ready accessibility to the operator. Previously such an external chopper had not been attempted successfully. Behind the chopper is mounted a three-barreled optical tracking system slaved to a master tracker operating in the visible for visual target tracking. The output of each barrel feeds a separate interferometer to cover the spectral ranges 1–3 microns (InAs), 3–5.5 microns (InSb) and 5–15 microns (Ge:Hg). The two lower wavelength units are cooled with liquid-nitrogen Joule-Thomson cryostats, and the Ge:Hg is cooled with a helium-nitrogen combination. The resulting interferograms are recorded on analog magnetic tape with an Ampex CP-100 14-track recorder. The Fourier transform is performed after return with the AFCRL 7090/7044 direct-couple computer. This system provides a spectrogram of 5-cm^{-1} resolution with a 30-sec scan time. We anticipate that a signal-to-noise ratio of 10 can be achieved in the airglow by coherently adding 500 spectra.

Measuring gravity

What we call gravity, or terrestrial gravitation, is the gravitational attraction of the earth's mass for bodies at or near its surface modified by the centrifugal force owing to its daily rotation. Gravity increases with increasing latitude because of the earth's ellipsoidal shape and rotation. This pronounced change in gravity ranges from about 978 gals (cm/sec^2) at the equator to about 983 gals at the pole. Superimposed on this fundamental latitude variation are variations caused by elevation changes of about 1-milligal decrease in gravity for each 3-meter increase in elevation, local variations caused by mass irregularities within the earth, and very minor variations attributed to varying positions of the moon and sun causing different attraction. Two different types of gravity measurements are made: absolute measurements of the true gravity value at a site and relative measurements of gravity differences between sites. Absolute measurements provide data needed for inertial guidance and establishment of several physical standards.[1]

FEED MECHANISM of 84-ft dish for studies of ionospheric scintillations. —FIG. 3

The pendulum is one of the oldest means of determining the absolute gravity value. Gravity is determined from pendulum data with the equation $g = 4\pi^2 l/p^2$ (l = pendulum length $= k^2/y$, k = radius of gyration about the oscillation point, y = distance from oscillation point to pendulum center of gravity, p = complete pendulum period). AFCRL designed and built a reversible pendulum apparatus that can be swung about two adjustable oscillation centers. The pendulums are made of fused quartz 12 cm long and oscillate on synthetic-sapphire knife edges. During measurement the pendulum-case interior is maintained at 40 ± 0.005°C and 10^{-6} torr.

When the periods about the two oscillation centers are equal, the distance between the centers is precisely the length of a mathematical pendulum needed for data reduction. This distance is measured with the pendulums stopped in place in the measurement environment by the Fabry-Perot method of spectroscopic measurement. The pendulum period is measured electronically with precision crystal oscillators compared with very-low-frequency time signals. Recent measurements have been made at L. G. Hanscom Field, Bedford, Mass., and Weston Observatory, Weston, Mass. Additional measurements, including the fundamental gravity site in Washington, D. C., are planned. We expect a 1-milligal accuracy.

Another absolute gravity apparatus developed jointly by AFCRL and NBS uses a freely falling rotation-insensitive corner cube as one element of an optical interferometer. Three sets of light fringes are generated as it falls through an effective distance of 1 meter. A 0.1-milligal accuracy is expected from distances between the fringes measured interferometrically to $\pm$ 0.5 microns and corresponding time intervals measured photoelectrically to ± 2 or 3 nanosec. Pressure during the drops is about 10^{-7} torr. Test measurements were made this spring at Wesleyan University, and additional measurements are planned at the fundamental sites in Washington, D.C., Teddington, England, and Sèvres, France, during the remainder of the year.

The third AFCRL absolute gravity apparatus is being completed by the Martin Marietta Corp. Measurements of 100-micron-diameter, aluminum-coated, hollow glass charged particles are made while they are in a free rise and fall trajectory of about 15-cm amplitude. Photomultipliers detect passage of the particles past upper and lower slits in a quartz bar whose slit spacing has been measured interferometrically. A laser source illuminates the particles for detection by another photosensor. This photosensor triggers the accelerate-decelerate system that gives the particles the proper trajectory and slows them down for a servo capture-and-hold system. A system with a 0.1-milligal accuracy is expected to be completed late next year.

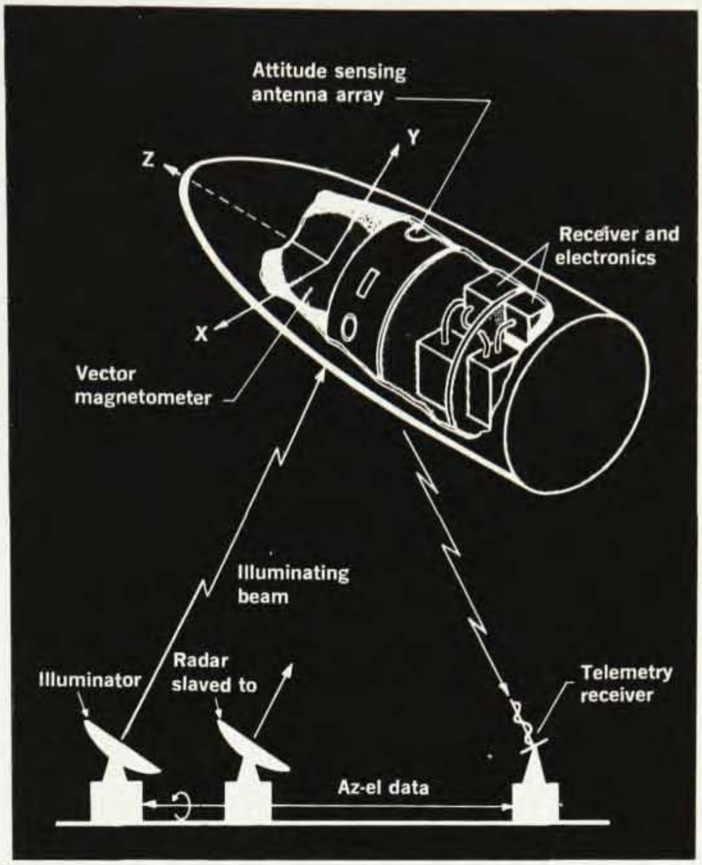
Relative measurements

AFCRL has also made relative land gravity measurements with pendulums and spring gravimeters. For the relative pendulum measurements, operating environment is carefully controlled; so pendulum length can be considered the same at both end sites of a gravity interval. Then the gravity ratio between the two sites is equal to the reciprocal ratio of the squares of the measured pendulum periods. As with absolute pendulums, the design requires meticulous care for pressure and temperature control and stability, precision knife edges, stability of knife-edge position when pendulums are started or in motion, flat and coplanar knife-edge bearing surface, leveling precision, minimizing seismic effects, support flexure, timing, pendulum-length stability, dissipation of electrostatic charges and magnetic shielding or compensation.

Most AFCRL gravimeter measurements have been made with a LaCoste and Romberg meter. It has a zero-length spring with a tension proportional to its full length rather than only the change in length. The meter suspension is adjusted to a near-equilibrium condition that produces a near-infinite period with very high sensitivity. Measurements are also made with a LaCoste and Romberg earth-tide meter. It consists of an accurate land meter with a photosensor system that produces a voltage proportional to departure from the null setting corresponding to equilibrium between gravity and spring tension. The voltage operates a servo system that rotates a measuring screw to the null setting. Changes in gravity are obtained from a recording of the measuring screw. For the problem of measuring gravity gradients AFCRL is developing a gravitational mass sensor through Hughes Research Laboratories. The gradient force to be measured induces dynamic forces in the sensor with a frequency twice the rotation frequency of the sensor, while inertial effects caused by acceleration or vibration of the sensor induce forces with a frequency near the rotation frequency. The gradient force is found by frequency selection techniques.

The land gravimeters requiring adjustment to a null condition do not work for measurements made in aircraft because of the rapidly changing acceleration conditions. The main LaCoste and Romberg modification providing for measurements in moving vehicles is to air damp beam motion beyond critical damping so that acceleration is sensed as beam velocity. Incremental acceleration values with respect to the meter settings are computed from the beam velocity recording.

The Askania-Graf airborne gravimeter is similar to the LaCoste and Romberg except that magnetic damping is used and the signal corresponding to beam position is modified to produce a direct acceleration readout. The Worden airborne gravimeter is a standard Worden land meter modified for airborne use. Metallic rings are added to the beam opposite impulse coils fixed to the gravimeter case above and below the beam. Departure from null position is sensed by a photosensor, and correction pulses are sent through the coils to return the beam to its null position. Because acceleration conditions are continually changing, the coils are continually pulsing the beam up and down. The rate of pulse change is proportional to the desired incremental value of gravity.



BASIC SYSTEM for measuring components from rockets. —FIG. 4

BALLOONS AND ROCKETS

Between altitudes of about 10 km (the ceiling altitude of ordinary aircraft) and about 200 km (the practical minimum orbit for a long-lived satellite) there is a large region of the upper atmosphere sometimes termed the "ignorosphere" because our techniques for probing this region are so scanty. From the ground we can study the ionosphere layers by the transmission of radio waves, and we can measure the spectrum and intensity of high auroras. By using the laser as an optical radar we can infer the aerosol content of the atmosphere up to approximately 100 km; but, in general, to study this region we must resort to balloon-borne and rocket-borne instrumentation.

Large research balloons can, more or less routinely, lift payloads of about 350 kg to 30 or 40 km (above more than 99% of the total atmospheric mass) and can remain at altitude for several hours. Sun seekers or star trackers establish the orientation of the payload, and the data are either telemetered to the ground or the payload is dropped by parachute and recovered. The launching of such research balloons is a science in itself. Because of the possible hazard to people living below (and also commercial air traffic), the launch sites are in sparsely populated areas, and launch times are carefully controlled. The balloon itself has a very delicate skin—ordinarily Mylar 10 to 50 microns thick—and is easily torn; so the launch is subject to the frustration and delays of unpredictable weather and the vagaries of ground level and upper-atmosphere winds. AFCRL maintains balloon-launching groups at Alamagordo, N. M., and Chico, Calif., and in 1966 launched 141 research balloons (not counting the small balloons routinely launched for weather data). The other principal launch site in the US for large research balloons is the NCAR facility at Palestine, Tex.

Earlier this year *Applied Optics* devoted an entire issue[2] to several papers on balloon-borne optical and astronomical studies by most of the groups currently active in the US, Canada and the USSR, and here we do not attempt to summarize those efforts except to state that the present principal research interests of these ten or twelve groups are the measurement of sky and terrain radiance, sky polarization, profiles of water vapor and ozone content with altitude, aerosol distribution, and atmospheric radiation flux and flux divergence. Three or four of these groups are not so much interested in the atmosphere itself as in getting above most of it with a platform for solar, planetary and other astronomical studies.

Rockets

The various types of research rockets are perhaps less temperamental to launch than the research balloon. Some of them are capable of achieving altitudes of 700 km at apogee, but the payload is considerably less (an average rocket will carry a payload of about 70 kg to an altitude of about 150 km). It remains at altitude only a few minutes. An entire rocket flight is ordinarily over in about 15 to 20 minutes. Rockets also must be launched in desolate areas, generally near deserts or oceans, to avoid damaging people or property. Most data are telemetered to the ground. With special equipment a payload can be recovered, repaired and used again. AFCRL research rockets are launched from Eglin Air Force Base, Fla., or Wallops Island, Va., where they fall into the sea, or from Holloman Air Force Base, N. M., and Ft Churchill, Manitoba. Since AFCRL launched its first rocket (an early V-2) in August 1946, the laboratories have launched a total of 670 rockets with scientific payloads.

Many relatively conventional instruments have been modified for rocket-borne experiments: Langmuir probes, impedance probes, mass spectrometers, monochromators, radiometers, Lyman-alpha detectors, positive-ion detectors, retarding potential analyzers and so on. Rockets are also used to drop instruments from altitude such as spheres containing internal accelerometers and small inflated balloons for measuring atmospheric density. Such rockets have been used to modify the ionosphere by releasing chemicals at altitude. With some chemicals deeply ionized areas can be created, or the ionosphere can be depleted of charged particles by chemicals that induce the recombination of positive and negative ions. Chemicals used include nitric oxide, carbon disulfide, trimethyl aluminum and barium compounds. The glows produced when these are released at altitude can be studied and tracked by cameras and telescopes on the ground to determine upper-atmosphere effective temperatures, densities and winds.

Magnetic fields from rockets

Most rockets instrumented to measure the earth's magnetic field during an auroral event are launched from the Ft Churchill range located in the center of the auroral zone and near the north magnetic pole. Earlier magnetic-field measurements from such rockets measured only the total intensity from which could be determined the height, intensity and thickness of auroral magnetic distrubances. Improved payloads permitted also the measurement of the components of the magnetic field perpendicular and parallel to the vehicle axis. More recently, charged-particle measurements have been combined with vehicle-oriented magnetic measurements to obtain the angular distribution of the charged particles with the vehicles as the reference frame. The latest generation of this experiment will allow fairly accurate measurements of the magnetic-field components in a geodetic-referenced coördinate system.[3] This measurement permits the evaluation of the line integral of the scalar product of the magnetic field and the displacement along the path, thus giving the ionospheric current enclosed by the path.

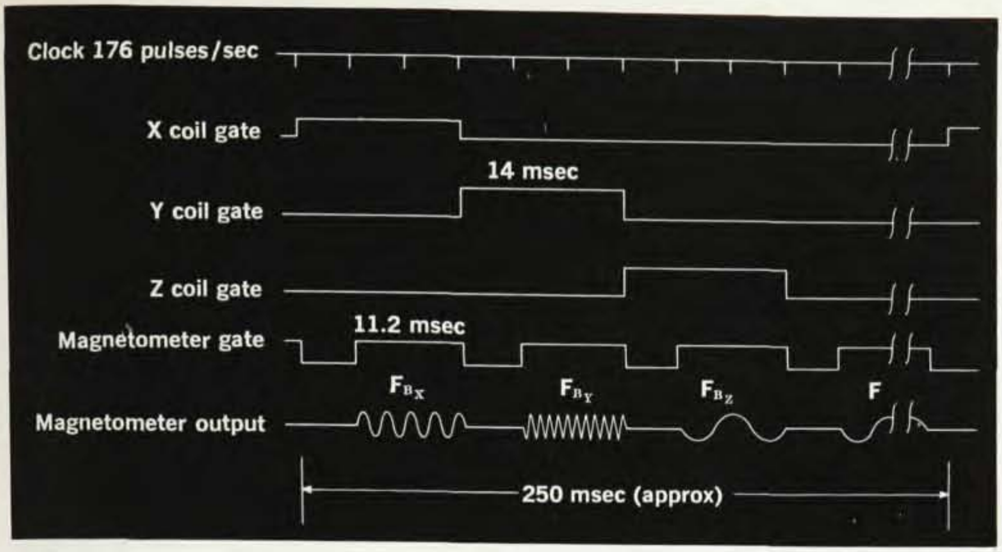
The design elements of a system for component measurements can be summarized as follows: First, the entire payload should be such that it can be made nonmagnetic by eliminating all objects having permanent magnetization or an equivalent dc current loop or a surface or volume that could give rise to induced magnetization. Next the system should be all-weather—unaffected by cloud cover, temperature and winds—and independent of natural references such as the sun, the horizon or a particular geographic location. It should be easily transformable to a geodetic coördinate system, and payload complexity should be minimal to allow for the use of high-acceleration launching vehicles and long periods of holding at full-launch readiness before auroral firings.

Systems involving stabilized platforms, gyro-referenced platforms, stabilized vehicles and combinations of these features have been studied and rejected. We are now using the system shown in figure 4. The total field F and three vehicle-referenced orthogonal elements X, Y and Z are measured and transmitted sequentially to ground. Simultaneously, the vehicle attitude with respect to the cw illuminating beam is obtained in terms of θ and ϕ. The radar beam to which the illuminating beam is slaved is referenced to geodetic coördinates. Its information is combined with the magnetometer and attitude information in a machine program that yields the total intensity and component magnetic field as functions of geodetic position.

Total and component magnetic information is obtained by a Varian model 4969 cesium magnetometer and a three-axis McKeehan coil. When there is no current in the coil, the magnetometer measures the total external field F. When coil current is applied sequentially to each axis (with the coil axes parallel to the x, y and z axes, respectively), the magnetometer measures a different total field, where the x, y, z components of the additional field are known. From those data the vector components of the external field can be computed. Figure 5 shows the timing of events in this process. The payload master clock provides for gating the coil biases sequentially, synchronizing the magnetometer to the bias and applying the resultant information to the telemetry transmitter. The total time for a complete set of measurements is just under 0.25 sec.

Payload problems

The attitude of the payload is obtained from the relative signal strength received by a series of eight antennas illuminated by a cw transmitter slaved to the beacon-tracking radars. These antennas, which feature four equispaced longitudinal slots alternating with four annular slots, are arranged circumferentially. This configuration, chosen after a series of antenna range tests performed on a number of likely arrangements, confirmed its effectiveness and showed a nearly uniform circular error probability. To



TIMING SEQUENCE for current in three McKeehan coil axes. From magnetometer measurements of total field (external plus induced) components of external field can be computed. —FIG. 5

minimize rf interference the cw beam operates at a frequency just below that of the tracking beacons, the narrow bandwidth and narrow beamwidth, thus providing good stability with minimum error. This combination also allows sequential scanning of selected antenna triads, thereby simplifying payload hardware.

In practice, each payload is attached to the appropriate, empty, final-stage motor case, illuminated by a cw beam and calibrated on a range capable of simulating free space. Complete antenna patterns are obtained on each payload in its actual flight configuration and are recorded on magnetic tape. Thus when the real data from an actual flight are processed by the appropriate counting and recording devices, the data can be combined with the calibration, trajectory and beam-angle information in a machine program that will yield the desired magnetic-field information.

Anticipated errors are of two major types: angular and magnetic. Angular errors include those caused by the shaft-position indicators of the tracking radar, others that are attributable to the beam intensity over the scanning time of the receiving antennas and some that originate in the preparation of the calibration tapes and light trajectories. Assuming a clean payload, magnetic errors arise mainly from vehicle motion during the period of measuring each component.

Because the accuracy of a given measurement in even a stationary payload is limited by the combination of time and telemetry bandwidth available to make the measurement (here the actual payload is certainly not stationary), a necessary compromise led to the design of a two-stage despin mechanism to be used for slowing vehicle rotation to a minimum value consistent with coning stability. Preliminary tests on a Javelin rocket nosecone mockup have shown that system accuracies with 0.5–1.0 deg are obtainable for each component. With proper despinning, combined with good signal-to-noise ratios over the signal path, accuracies within 0.1 deg are anticipated from iterative time-dependent corrections based on vehicle data analysis using successive sets of 30 datum points each.

The data-processing, calibration and reduction systems are complex but fully amenable to computer-assisted solutions that can be performed after the flight, repeated and modified as required. The actual flights will use only proven components and simple techniques, ensuring high reliability.

A series of rocket flights using four-stage, solid-propellent, Javelin sounding rockets will be launched this summer from the Ft Churchill rocket range. For a gross payload of 75 kg the peak altitude will be about 700 km and the flight duration 15 minutes.

Each payload is contained within an ogive (arch) 48 cm in diameter and about 1 meter long, with a cylindrical extension section about 33 cm in length. The maximum longitudinal acceleration will approach 40 g during fourth-stage burn. The total intensity of the magnetic field at liftoff will be about 0.6 oersteds and the expected value at peak altitude about 0.4 Oe. Because the magnetic declination at Ft Churchill is near zero and the field nearly vertical, most of the field will be represented by its vertical component. However, it is expected that large, rapid changes will be seen in the horizontal components as the payloads approach and penetrate auroral activity.

Infrared-horizon rockets

Infrared radiometers can be used to measure the infrared emission of the atmosphere near the horizon from high altitudes.[4] One of the most common methods of determining satellite altitude with respect to the earth has been the use of optical or infrared devices to sense the position of the earth's horizon relative to the vehicle. It has become apparent that a principal limitation of the accuracy is the presently little known structure of the earth's horizon as seen from satellite altitudes.

The contrast between the radiations from earth and space in the near vicinity of the earth limb is highly variable and strongly dependent on the wavelength and spectral bandwidth of observation as well as on many local factors such as the presence or absence of clouds in the atmosphere, time of day, season and geographical location. Experience and theory have generally indicated that sensors operating at about 15 and 30 microns (in the carbon-dioxide band and the pure rotational band of water vapor, respectively) would be most practical. Consequently, AFCRL initiated a program to investigate effects of these parameters with a radiometer equipped with interference filters to isolate different spectral regions, a selection of judicious rocket firing times to provide diurnal and seasonal variations, and a launching of rockets from both high and low latitudes. The basic instrumentation for the horizon observations consists of the infrared radiometer, stellar aspect sensors and a vehicle attitude control system (ACS).

All vehicle motions after sustainer burnout are controlled by the ACS. This device obtains its attitude reference data from an inertial unit consisting of two free gyros and three rate gyros. The primary functions of the ACS are to despin the rapidly spinning rocket, erect its roll axis to within 2 deg of the true vertical and generate programed roll maneuvers at a roll rate of 20 deg/sec. Each roll starts and stops at a fixed direction, at which time the vertical reference is reëstablished and signals are generated to change radiometer filters. The rotations are programed to take place from 90 km through peak altitude (about 150 km) and back down to 90 km. At the end of the ninth revolution the vehicle is left in the roll mode until it reënters the atmosphere, and a parachute is deployed that gently lowers the payload to the ground for recovery.

Of primary concern to the horizon-definition experiment is an accurate determination of vehicle attitude and instrument line of sight. Stellar transits observed with a simple star-mapping device constitute the basic attitude reference. In brief, the stellar aspect sensor consists of a lens, an *N*-shaped focal-plane mask and a ruggedized photomultiplier. The device is strapped to the rocket. Rotation of the rocket in its roll mode causes star images to track across the *N*-shaped slits in the focal-plane mask. One of the slits is bore-sight-referenced to the infrared-horizon radiometer. Measurement of the time of a star transit on this slit gives directly the star azimuth in the rocket coördinate system. The relative time intervals between the three pulses generated by the star's passage across the entire *N* determine the elevation of the star in the rocket system.

The infrared radiometer is a single-channel instrument employing an immersed thermistor detector and rotating spectral filter wheel. The collecting optics is a Cassegrain telescope with a 14-cm primary mirror obscured by an 8.1-cm secondary. The mirror surfaces are gold-coated for good reflectivity over the wavelength region of interest. Depending on the flight, the spectral filters (three for each flight) correspond to the 10-micron atmospheric window, the 15-micron carbon-dioxide band, the 9-micron ozone absorption band and the spectral region dominated by the rotational absorption band of water vapor (wavelengths longer than about 20 microns). The field of view of the radiometer is scanned normal to the horizon by means of a large flat mirror located in front of the Cassegrain telescope.

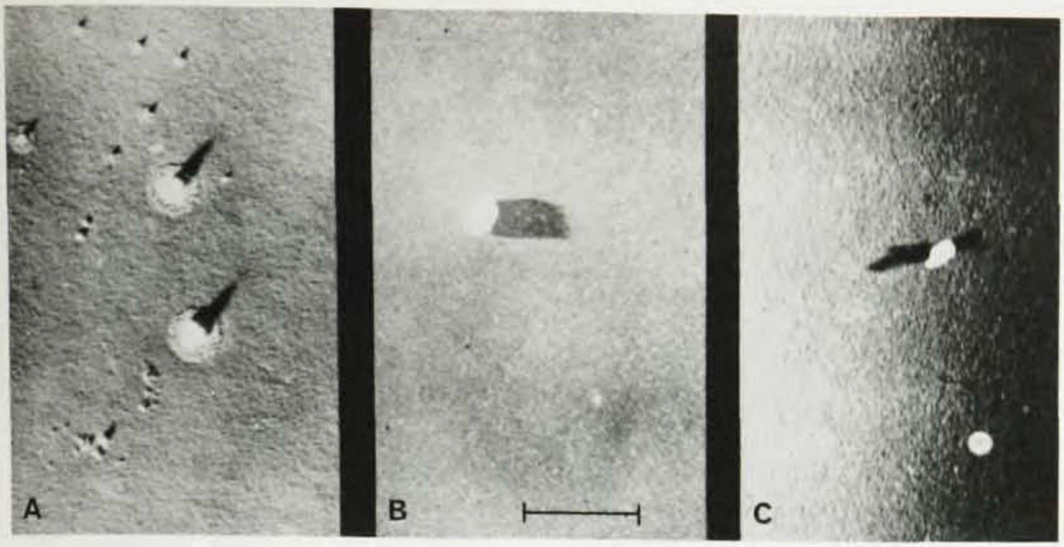
Solar XUV radiation

Solar extreme ultraviolet and soft x radiation (between 0.1 and 170 nm, usually called the "XUV") is known to be absorbed very strongly in the upper parts of the terrestrial atmosphere. Therefore its measurement requires experimentation at altitudes high above the earth's surface.[5] The specific altitude at which the optical depth of the atmosphere above becomes less than a certain value, for example unity, depends not only on the wavelength and the solar zenith angle but also on many other physical parameters. A quantitative description of all these parameters requires knowledge of diurnal, seasonal, latitudinal and other variations in the upper-atmosphere structure. Indeed, rocket-borne measurements of solar XUV absorption in the atmosphere are an invaluable source of such information.

Laboratory-calibrated spectrophotometers (monochromators) equipped with solar-pointing instrumentation are flown on (Aerobee-150) rockets to altitudes of approximately 220 km. Depending on the diffraction grating and detector used in a particular instrument, the solar spectrum is scanned in the wavelength ranges between 170 and 31 nm. Data are telemetered to the ground and, after reduction, yield information on extreme ultraviolet spectral absorption lines, intensities, alteration by the earth's atmosphere and other solar-radiation effects on the aerospace environment. Associated experiments are usually flown as integral parts of the monochromator, such as x-ray proportional counters for measurements in the spectral range of 0.1 to about 1.2 nm, and retarding potential analyzers or other types of electron and ion detectors which yield additional information on electron temperature, rates of ion formation and the magnitude of photoelectron emission from solids exposed to XUV solar radiation.

The basic instrument used to measure the intensity of XUV solar radiation is a telemetering monochromator instrumented for photoelectron or photoionization detection. Data are transmitted directly to the ground receivers on a continuous basis throughout the rocket flight. Recovery of the instrumentation is not required for a successful flight except for postflight examination and reuse of the equipment. The monochromator, which is a unique instrument developed and continually being improved by AFCRL scientists, is pointed at the sun during flight by a biaxial pointing control. Precise acquisition of the sun is accomplished by azimuth and elevation control of the scientific package. Open-structure photomultiplier detectors or thin-window, gas-filled counters permit measurement of a wide dynamic range of solar intensities.

On 12 March 1959 the first successful performance of a telemetering solar XUV rocket spectrometer (scanning the wavelength range from 25 to 130 nm in about 10 sec per scan and capable of resolving about 1.2 nm) was accomplished. Since that time, 105 Aerobee-150 rockets have been launched, all from White Sands Missile Range, N. M., with the exception of two from Eglin Air Force Base, Fla. Fourteen other XUV space experiments have also been flown on Javelins, Astrobees, Nikes and orbital vehicles. The overall rate of complete experimental successes has been very high; failures generally have been due only to missile and operational problems such as improper nose-cone ejection and defective solar-pointing controls. Of the Aerobee flights 29 have been instrumented with XUV mono-



ELECTRON MICROGRAPH of (A) cloud collecting surface, (B) noncloud collecting surface and (C) control surface. (Scale = 1 micron.) —FIG. 6

chromators, and 23 have been successful. Ten more are scheduled for the next two years.

Venus Fly Trap

The conflicting data resulting from different types of micrometeoroid detectors on rockets and early satellites prompted the suggestion that perhaps a more direct approach, namely particle collection, should be attempted in an effort to resolve some of the discrepancies.[6] (See figure 6.)

The first such particle-collection rocket, the Venus Fly Trap, was designed at AFCRL and flown in the summer of 1961. The nose cone of the rocket was instrumented with particle-collection surfaces that could be studied later with either an electron microscope or an optical microscope. These clean collection surfaces were sealed within the nose cone and were not exposed until the rocket reached an altitude of 75 km. At that point the outer skin of the nose cone was elevated and eight arms were extended, exposing the collection surfaces. The rocket reached an apogee of about 170 km. On the downward portion of the trajectory, at about 88 km, the arms were retracted and the outer skin lowered and sealed. A parachute recovery system returned the payload safely to the ground. The particle collection surfaces were examined in the laboratory, and the particles captured were reported as extraterrestial particles. Various types of particle-collection surfaces were used, some intended for electron microscopic examination, some for optical microscopy. One of the more successful surfaces was a thin nitrocellulose film, shadow-coated with a thin layer of aluminum and mounted on an electron-microscope support screen.

Since this first flight other rocket-borne particle-collection systems have been designed and flown and have met with varying degrees of success. Some of these utilize the Venus-Fly-Trap concept of extensible arms whereas some have adopted other methods.

In this experiment a great deal of attention must be given to cleanliness. The first Venus Fly Trap was not prepared in a "clean room," and a definite contamination problem existed. Now all of the particle-collection payloads are prepared in Federal Standard 209, Class 100, clean rooms. Unfortunately even these precautions have not ensured sufficient cleanliness, and efforts are being made to improve the cleanliness to even lower limits. The problem is basically one of signal-to-noise ratio. If one wishes to look for large meteoroid particles, that is, of the order of microns, one must expose large areas and spend a great deal of time scanning.

If one looks for smaller particles, the number of these is greater, but, unfortunately, so is the number of contamination particles. Present methods can control contamination down to about 0.5 microns, but we hope this can be lowered by two orders of magnitude.

Several other changes have been introduced into the more recent Venus-Fly-Trap designs such as a moving shutter to measure the number of particles as a function of altitude and an in-flight shadowing system that evaporates a thin coating of metal on the collection surface immediately before and after exposure to facilitate contamination identification. In this way even water or ice particles collected from, for example, high-altitude noctilucent clouds can be measured by their "shadows," although they vaporize before the rocket returns to earth.

The analysis of a particle-collection experiment is a long and tedious process, but the results have begun to remove some of the ambiguity of the satellite-borne measurements.

SATELLITE GEOPHYSICS

The first US satellite, 1958 Alpha, launched in Jan. 1958, carried an AFCRL experiment—a microphone-type micrometeorite detector. Since that time satellite studies have grown in complexity and reliability: As of May 1967 AFCRL had placed payloads aboard 99 different satellites. At first most of our experiments were piggy-backed, carried aloft for a free ride on someone else's vehicle, as NASA and the Air Force perfected various booster rockets. Even now we ordinarily share a ride with other experiments, but some satellite experiments have been budgeted and scheduled specifically for our experiments. One almost disadvantageous characteristic of a satellite experiment is the immense amount of data that can be measured even in a single orbit. The

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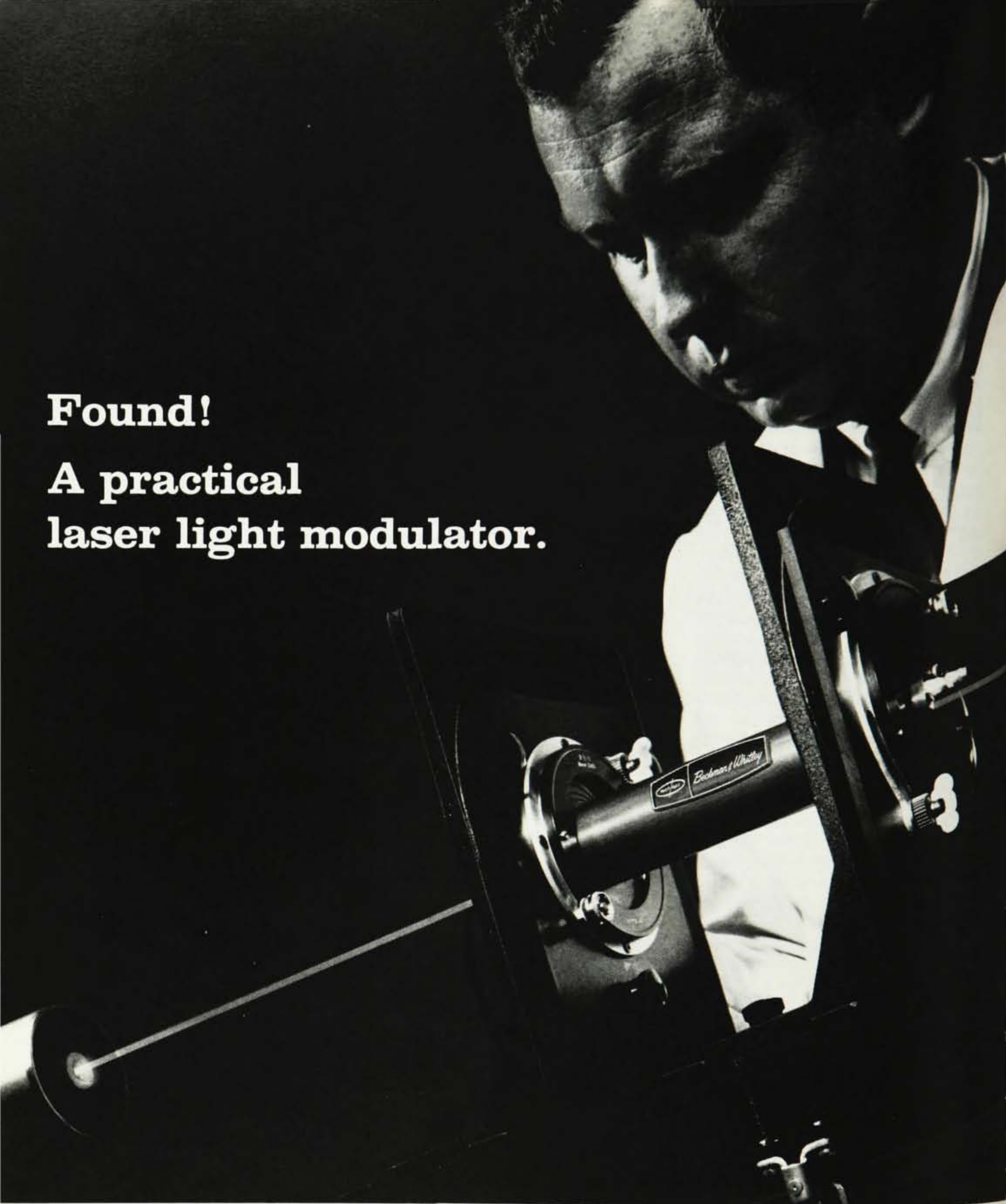

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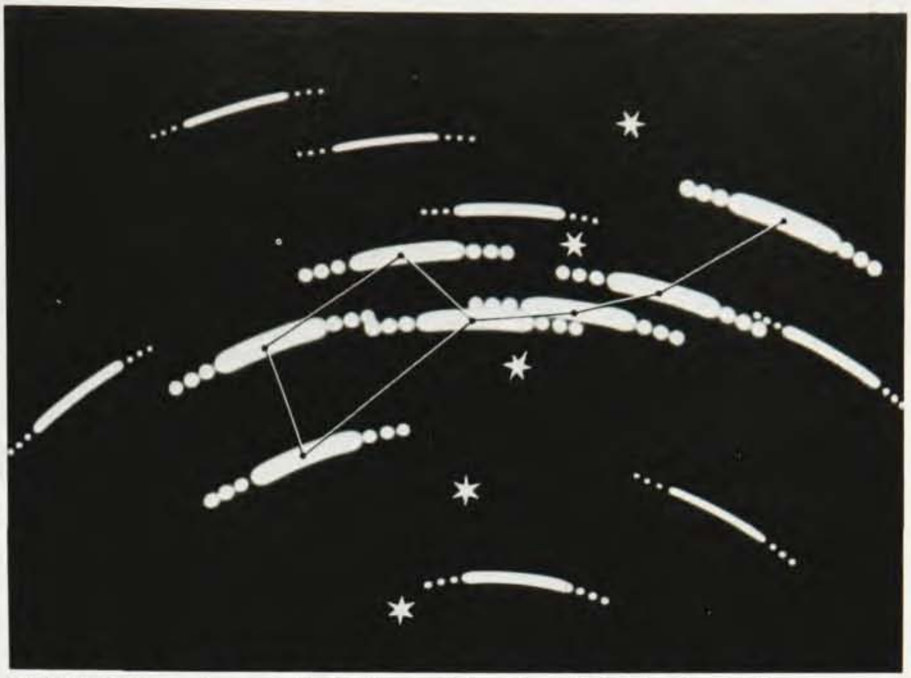
data accumulated from a long-lived satellite can overwhelm an investigator, even if armed with a very large computer.

Reference satellite

The ANNA-1B satellite, the first designed specifically for geodetic experimentation, was successfully orbited on 31 Oct. 1962. The AFCRL part of the Army-Navy-NASA-Air Force payload consists of four high-intensity flash beacons, located on the equatorial band of the spherical satellite, with two lights facing each pole of the satellite and firing simultaneously. (As of June 1967, the satellite's lights are still flashing.) The experiment is demonstrating the feasibility of using a satellite-borne optical beacon as a photographable point source against a stellar background (figure 7).[7] Simultaneous photographic observations of this source by several widely spaced (1000 + km) cameras provide data for a photogrammetric triangulation to determine relative positions of observing sites. Observations to date have produced 1104 plates with flash images. From these data, AFCRL has been able to compute relative positions of observing sites to an accuracy better than one part in 100 000 linearly when compared with NAD 1927 geodetic positions for the sites.

The 24-kg beacon payload is made up of four Edgerton Germeshausen and Grier, Inc., XFX-40 flashtubes and reflector assemblies, four trigger circuits, one sequence controller, one converter, one capacitor bank, one power relay and one cable harness.

Power (12–14 volts) is supplied by 11 nickel-cadmium cells in series that are charged by solar cells located on the equatorial band of the satellite. The flash sequences have been triggered either by programmed pulses from the satellite's main memory or by signal from an alternate ground transmitter that can be used whenever the satellite is within line of sight. (For example, one line-of-sight transmission from Bedford, Mass., successfully flashed the beacons when the satellite was over the Yucatan Peninsula. Flashes were confirmed by a photograph taken at Curacao.) Each flash has a duration of 1 msec at one-third amplitude points and has an intensity of 8000 candle sec on axis tapering to 3500 candle sec about 85 deg off the satellite axis. A sequence is five flashes at 5.6-sec intervals. The timing of flash events was formerly controlled by an on-board clock, but present triggering is timed by an oscillator and clock built into the alternate manual transmitter. Flash times are preselected to make maximum use of observing geometry. These preselected times are transmitted with camera-aiming directions to all participating camera stations. At these stations, for each event there is a precalibration of the photographic plate consisting of four precisely timed shutter openings and closings, exposure for the event and a postcalibration of four more shutter cycles. The precisely timed interruptions of the star trails provide a time and positional reference from which the space position of the satellite can be determined.



SATELLITES against a stellar background for triangulation in determining distances and directions between points on the earth. —FIG. 7

A second active satellite, the GEOS-1, was launched by NASA on 6 Nov. 1965 and yielded much useful data. Unfortunately, however, the optical beacons aboard this satellite malfunctioned on 1 Dec. 1966.

GROUND-BASED PROBING

Not all environmental studies require research vehicles; many important studies can be made from the ground. Radiometers, spectrometers and interferometers can be attached to telescopes to study the atmosphere, airglow, aurora or other environmental parameters. It is popular these days to call this sort of measurement "remote sensing," and many conference proceedings and books with this title have recently appeared, as if this were some basically new technique, but astrophysicists and atmospheric physicists have employed remote sensing since their science began. Several major "remote-sensing" observatories are operated by AFCRL: chiefly the Sacramento Peak solar observatory at Sunspot, N. M., and the Sagamore Hill radio observatory at Hamilton, Mass. In addition an observatory at Strawberry Hill, Concord, Mass., is engaged in lunar studies, and with the National Science Foundation AFCRL has sponsored the construction of a 1.5-meter astronomical observatory in Chile at one of the best "seeing" spots in the world for southern-hemisphere studies.

Our radio astronomy is conducted primarily at Sagamore Hill, where the principal antennas are the 46-meter alt-azimuth telescope and a 26-meter parabolic dish (whose instruments can also be operated together as an interferometer); however, the group is also actively engaged in a continuous monitoring of solar-burst activity, iono-

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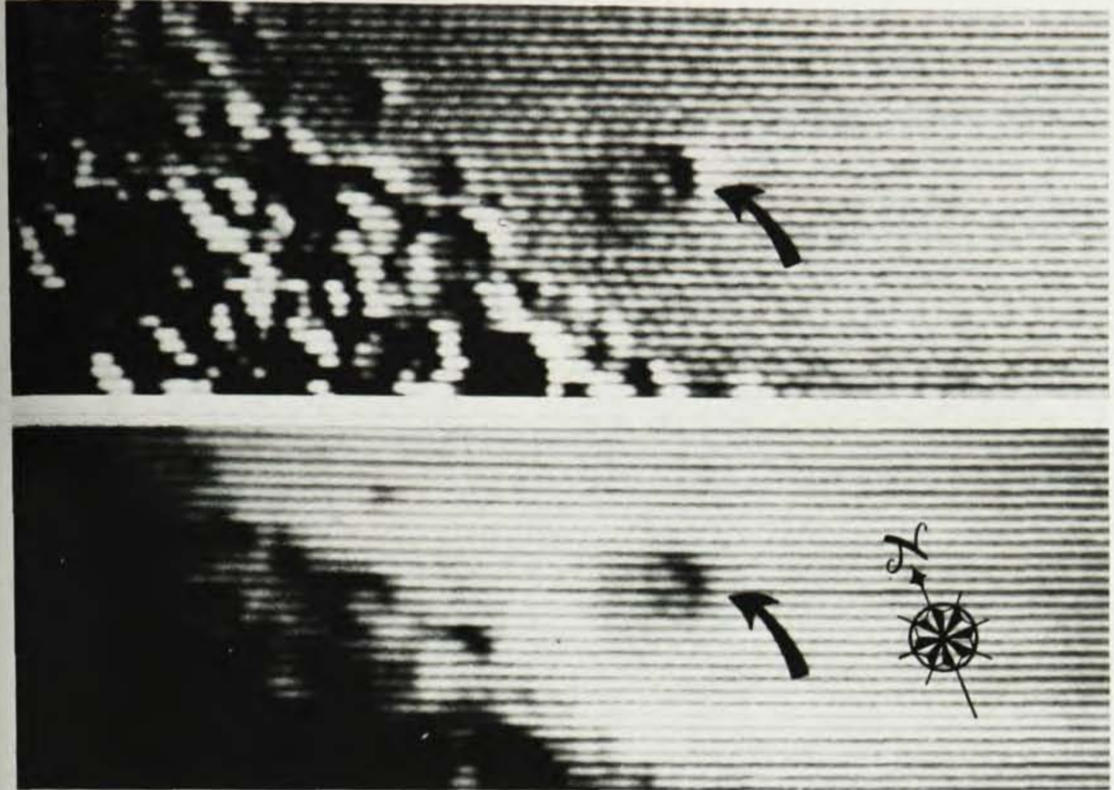

INFRARED IMAGES of Tycho (arrow) obtained by conventional radiometry (lower panel) and thermal enhancement (upper panel).—FIG. 8

spheric total electron content and ionospheric scintillation by means of a network of ground stations throughout the world. One attractive feature of these monitoring stations is that the equipment of the individual stations need not be elaborate or expensive, consisting of fairly simple radio receivers and recorders. Researchers in such improbable locations as Kenya, the Philippines, Peru and Greenland are all actively participating in our solar-flare patrol.

AFCRL operates a second radio observatory on Prospect Hill, in Waltham, Mass., the primary instrument being an 8.4-meter alt-azimuth telescope. This precision instrument operates at a wavelength of 8.6 mm. It has a one-half power beamwidth of 4.2 minutes of arc on a projected area approximately one sixtieth the sun's. Communications studies are being conducted with this telescope, most of which involve the measurement of atmospheric attenuation as a function of zenith angle. Interaction between the lower atmosphere and millimeter waves can be used to obtain information on clear-air turbulance, atmospheric temperature, pressure and water-vapor profile. The telescope is also used to plot contours of warm and cool regions moving over the solar disk corresponding to the slowly varying components of the 8.6-mm solar radiation. Typically warm regions exhibit core temperatures 200°C above the background; but on occasion these regions have remained as much as 800°C above background for an entire day.

Lunar studies

One of our newest tools for lunar studies is an infrared camera designed to operate in the focal plane of the 61-cm reflecting telescope located at Strawberry Hill, Concord, Mass.[8] This camera produces visible images of lunar and planetary radiance patterns and permits the study of variations in the composition of the lunar surface. (See figure 8.)

The telescope optics serve as the energy-gathering and focusing element for the radiometer. The system consists of an infrared detector (either PbS, Ge:Cu, or a thermistor bolometer, depending upon the wavelength region of interest) for sensing and transducing the incoming radiation, an optical chopping assembly to modulate and direct the incoming radiation and processing electronics synchronously to rectify the signal and to convert it to a video signal. The instrument is mounted on an X-Y table that can be driven along the X and Y axes of the telescope to accomplish a fully automated, electromechanical scan of the telescope image in the wavelength of interest. Part of this scanning instrument is an intensity-glow tube, operating from the processed detector output signal, which builds up a pictorial image on a stationary, photographic camera back to permit storage of the image data on film in video format. Both direct and processed detector outputs are stored on magnetic tape. The optical and electronic characteristics have recently been described elsewhere.

The instrument permits several modes of operation:

- thermal or radiance mapping, in which the incoming signal is referenced against a constant blackbody source
- enhancement of small radiance differences, in which the incoming signal is referenced against the attenuated signal coming from the adjacent and partially overlapping target element
- compositional data with spectrum matching, in which the incoming signal is reflected from a polished plate of a mineral of known composition and

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Dark Noise: 32 photoelectrons $\Sigma =$ 1 photoelectron	2.4×10^4	1.5×10^4	7.7×10^4	2×10^4	5×10^4	1.5×10^5
Electron Transit Time (ns @ 1500 V)	20	27	27	59	65	110
Anode Pulse Rise Time (ns @ 1500 V)	1.8	2.3	2.3	12	14	18
Pulse Height Resolution (%)	8.5	8.5	9	7.5	7.5	7.5

referenced against a blackbody

• differential spectrum matching, in which the incoming signal reflected from one reststrahlen plate is referenced against the same signal reflected from another reststrahlen plate of different composition

• conventional spectroscopy, in which the scanning is not performed but in which the incoming signal from any target element passes through a scanning circular variable wedge filter and is spectrally dispersed.

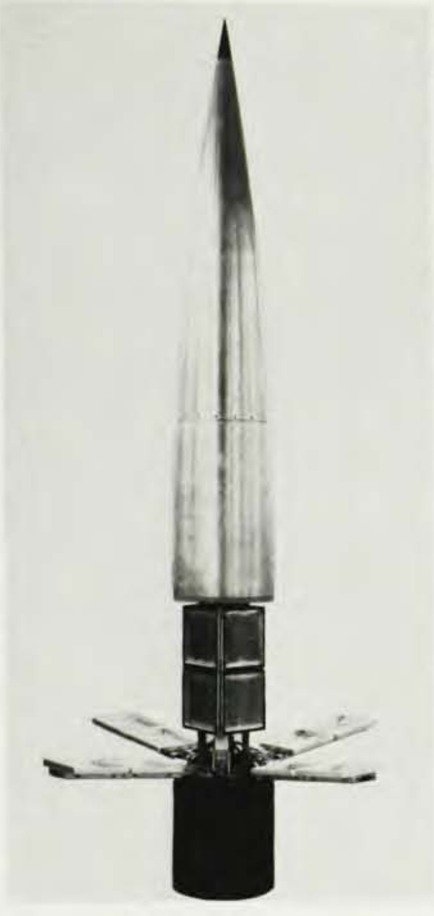
In all of the above modes except the last maps of the lunar or planetary areas investigated are obtained.

Solar magnetic fields

One of the most important research efforts underway at the Sacramento Peak observatory (as well as at other solar observatories) is the study of solar flares and prominences. Flares, which usually develop from active centers on the sun, are sudden outbursts of radiation as large as 100 000 km in diameter, can last 20 to 60 minutes and sometimes give off proton showers that constitute a hazard to men and equipment in space. Many books and papers have been written about the remote sensing of solar magnetic fields, and many instruments have been developed since George Ellery Hale first showed in 1908 at Mt Wilson that the magnetic field of sunspots could be measured by means of the Zeeman splitting of Fraunhofer lines.[9] In 1952 the Babcocks developed the photoelectric magnetograph for the measurement of small longitudinal fields. Accuracies have been achieved approaching 0.1 gauss even on the undisturbed solar surface, where fields averaged over 7500 km^2 are more or less random with rms values somewhat less than 1 gauss.

The Babcock instrument measures the field in only one surface element of the sun at a time. The construction of a detailed chart of field strengths therefore requires long observing periods. To overcome this particular difficulty, Robert B. Leighton of the California Institute of Technology modified the Mt Wilson spectroheliograph into a spectroheliomagnetograph. A coworker has since further modified it into a spectroheliokinematomagnetograph. A jocularity among solar astronomers is that the next step should obviously be a stereospectroheliokinematomagnetograph.

In the fall of 1964 another instrument, the Doppler Zeeman Analyzer (DZA), was developed and operated in Saramento Peak. This instrument permits the study of strong latitudinal magnetic fields in sunspots and active centers. In this instrument, the spectral radiation from a region of the solar surface passes through a polarizing beam splitter that physically separates the right- and left-handed polarized light; these two components are held on the slits of a Babcock detector by a servo-operated line shifter. The positions of the line shifters can be combined to yield signals proportional to both the Doppler shift and the Zeeman splitting. Such a system is independent of the light intensity and is not saturated by the magnetic fields of several thousand gauss that spring up in active centers. The accuracy is similar to that of the Babcock magnetograph, of which it is a modification. After much unexpected initial difficulty with the modulation and servo system, the DZA has been attached to a spectrograph on the 8.2-meter spar in the big dome at Sacramento Peak, with a 41-cm telescope all its own. The sensitivity of this instrument is about 1 gauss in the determination of the longitudinal magnetic field from the Zeeman splitting, about 5 meters/sec in the determination of velocity from the Doppler shift and it has a time constant of about 0.2 sec—all for a 1500-km^2 viewing region on the sun. This should prove to be a powerful new tool for solar studies of active centers.



ROCKET NOSE CONE used to collect micrometeorites and noctilucent cloud particles. —FIG. 9

* * *

The principal author of this paper was John N. Howard, Chief Scientist of the Air Force Cambridge Research Laboratories, Bedford, Mass., who is responsible for all errors of omission, emphasis, interpretation or fact. He is indebted to many colleagues at AFCRL for many details, and in particular to the following who contributed material for some specific sections: Hervey P. Gauvin (aircraft), Bela Szabo (gravimetry), Robert O. Hutchinson (magnetic fields), Charles W. Chagnon (XUV), Robert A. Skrivanek (micrometeorites), Theodore E. Wirtanen (geodesy), Graham R. Hunt (lunar studies), and John W. Evans (solar magnetometry).

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