THOMAS A. POTEMRA, FREDERICK F. MOBLEY, and LEWIS D. ECKARD

THE GEOMAGNETIC FIELD AND ITS MEASUREMENT: INTRODUCTION AND MAGNETIC FIELD SATELLITE (MAGSAT) GLOSSARY

The earth's magnetic field, its measurement by conventional methods, and the specific objectives and functions of the Magsat system to obtain precise absolute and directional values of the earth's magnetic field on a global scale are briefly described.

EARLY HISTORY

The directional property of the earth's magnetic field has been appreciated by the Chinese for more than 4500 years. Records indicate[1] that in 2634 B.C. the Chinese emperor Hoang-Ti was at war with a local prince named Tchi-Yeou and that they fought a great battle in the plain of Tcho-Iuo. Tchi-Yeou raised a dense fog that produced disorder in the imperial army — a forerunner of the modern smokescreen. As a countermeasure, Hoang-Ti constructed a chariot on which stood the small figure of a man with his arm outstretched. This figure, apparently free to revolve on its vertical axis, always pointed to the south, allowing the emperor to locate the direction of his enemy's retreat. Tchi-Yeou was captured and put to death.

The first systematic and scientific study of the earth's magnetic field was conducted by William Gilbert, physician (later promoted to electrician) to Queen Elizabeth, who published in 1600 his proclamation "*Magnus magnes ipse est globus terrestrius*" (the earth globe itself is a great magnet) in his *De Magnete.*[2] This treatise was published nearly a century before Newton's *Philosophiae Naturalis Principia Mathematica* (1687), and it has been suggested that Gilbert invented the whole process of modern science rather than merely having discovered the basic laws of magnetism and of static electricity.[3] Gilbert's efforts may have been inspired by the need for Her Majesty's Navy to improve (if not understand) the principal means of navigation — the magnetic compass. This fact is evident from the frontispiece of the second Latin edition of *De Magnete*, (Fig. 1) published in 1628.

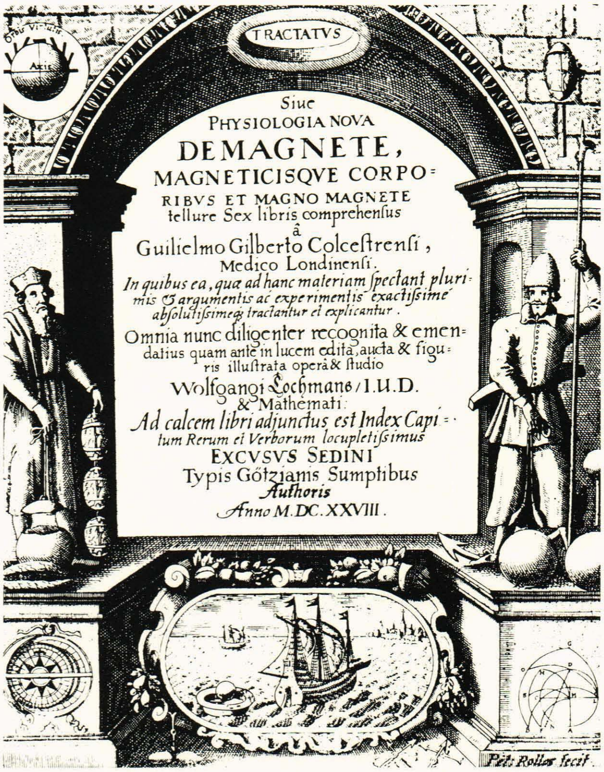
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Fig. 1—The engraved title page from the second Latin edition of Gilbert's *De Magnete*. It shows lodestones, compasses, and a terrella (a small spherical magnet simulating the earth, in the upper left corner). In a vignette at the bottom is a ship sailing away from a floating bowl compass with a terrella at the center. The first edition of *De Magnete* was published in 1600, and copies have become extremely rare.

An understanding of the earth's magnetic field and its variations is still of great importance to navigators. (More recently the U.S. Navy has "inspired" APL to develop and improve a more advanced satellite system for navigation.) The geomagnetic field also plays an important practical role in searching for possible resources beneath the earth's crust and in stabilizing artificial satellites. Major disturbances to the geomagnetic field — called "magnetic storms" — induce large, unwanted effects in long-distance telephone circuits and sometimes cause widespread power blackouts. The geomagnetic field and its interaction with the continuous flow of ionized gas (plasma) from the sun (the solar wind) provide the basic framework for the complicated space environment of the earth, including the Van Allen radiation belts and auroral zones. The distorted configuration of its geomagnetic field is called the "magnetosphere." Many APL-built spacecraft have made major contributions to an understanding of the geomagnetic field and associated magnetospheric phenomena during the past 15 years. Magsat is the latest one to do so.

GEOMAGNETIC FIELD DESCRIPTION

The geomagnetic field can be thought of as being produced by a huge bar magnet imbedded in the earth, with the axis of the magnet tilted away slightly from the earth's rotational axis. The poles of this magnet are located near Thule, Greenland, and Vostok, Antarctica (a U.S.S.R. research station). To a good approximation, the geomagnetic field can be represented by a simple dipole, but there is a significant contribution from nondipole components and from a system of complicated currents that flow in the magnetospheric regions surrounding the earth. The most accurate representation of the geomagnetic field is provided by a series of spherical harmonic functions.[4] The coefficients of such a series representation are evaluated from an international set of spacecraft and surface observations of the geomagnetic field and are published for a variety of practical uses in navigation and resource surveys. A principal goal of Magsat is to provide the most accurate evaluation of the geomagnetic field model in this manner (see the article by Langel in this issue).

MAGNETIC UNITS AND TERMINOLOGY

A wide variety of units and symbols are currently in use in the many scientific and engineering fields involved with magnetism. The following definitions are offered in hope of clarifying some of these for a better understanding of the following discussions.

Classic experiments have shown that the force acting on a charged particle moving in a magnetic field is proportional to the magnitude of the charge. A vector quantity known as the "magnitude induction" is usually denoted by $\vec{\mathbf{B}}$ which characterizes the magnetic field in a manner similar to that done for electric fields by $\vec{\mathbf{E}}$, for example. This unit of induction, $\vec{\mathbf{B}}$, is 1 weber per square meter (1 $\mathrm{Wb/m^2}$); it is the magnetic induction of a field in which 1 coulomb of charge, moving with a component of velocity of 1 m/s perpendicular to the field, is acted on by a force of 1 newton. In SI units, 1 $\mathrm{Wb/m^2}$ = 1 tesla.

In studies of planetary fields, where very small fields are involved, the nanotesla (nT), formerly the "gamma" (γ), is used where 1 nT = 10^{-9} tesla = 10^{-9} $\mathrm{Wb/m^2}$ = 1 γ. (The cgs unit of magnetic intensity is the gauss, where 1 tesla = 10^4 gauss.) The intensity of the surface geomagnetic field varies from about 30,000 nT at the equator to more than 50,000 nT at high latitudes near the magnetic poles.

SECULAR VARIATION

It has been known for over 400 years that the main geomagnetic field is not steady but experiences global secular variations. In fact, from a study of the paleomagnetic properties of igneous rocks, it has been determined that the geomagnetic field has reversed polarity several times over the past 4.5 million years (Fig. 2).[5]

The behavior of the geomagnetic field over a shorter time scale is shown in Fig. 3. That figure shows the positions of the virtual geomagnetic pole since 1000 A.D. based on the assumption that the geomagnetic field is a centered dipole.[6]

The following five features of the secular variation have been determined:[7]

1. A decrease in the moment of the dipole field by 0.05% per year, indicating that the present geomagnetic field may reverse polarity 2000 years from now. Preliminary analysis of Magsat data has revealed that this variation may be more rapid than was suspected from previous observations, and that the field may reverse polarity in only 1400 years;
2. A westward precessional rotation of the dipole of 0.05° of longitude per year;
3. A rotation of the dipole toward the geographic axis of 0.02° of latitude per year;
4. A westward drift of the nondipole field of 0.2° of longitude per year;
5. Growth and decay of features of the nondipole field with average changes of about 10 nT per year.

Although these secular variations necessitate continual corrections to magnetic compasses they pro-

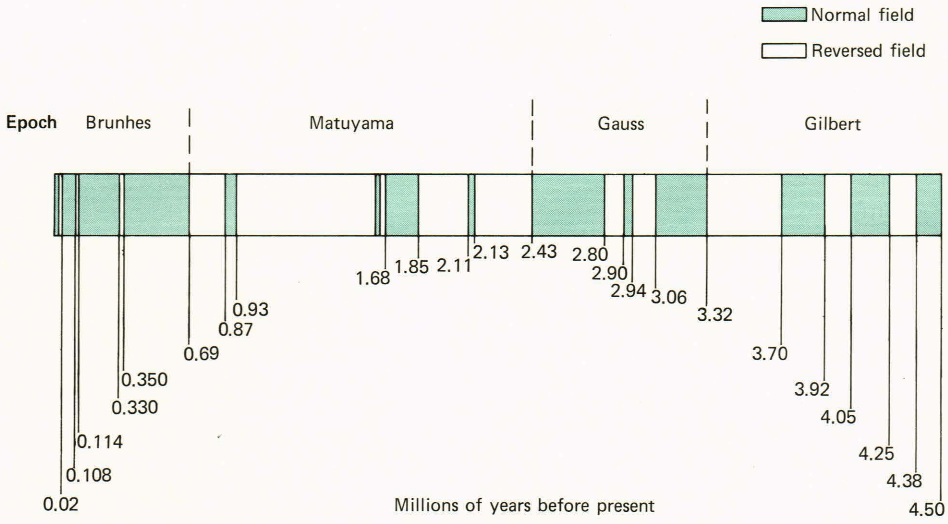

Fig. 2—The polarity of the geomagnetic field for the past 4.5 million years deduced from measurements on igneous rocks dated by the potassium- argon method and from measurements on cores from ocean sediments (from Ref. 5).

vide some clues to the internal source of the geomagnetic field.

GEOMAGNETIC FIELD SOURCES

If the average westward drift of the dipole field in item 2 above is representative of the rate of motion of the field, then the corresponding surface velocity is about 20 km per year. This is a million times faster than the large-scale motions of the solid part of the earth deduced from geological observations and considerations. Seismological evidence reveals a fluid core for the earth that can easily experience large-scale motions, and it is presumed that the geomagnetic secular variation — and indeed the main field itself — is related to this fluid core. Furthermore, geochemical and density considerations are consistent with a core composed mainly of iron — a good electric and magnetic conductor. Therefore, the study of the earth's internal magnetic field draws in another discipline — magnetohydrodynamics, which involves moving fluid conductors and magnetic fields.

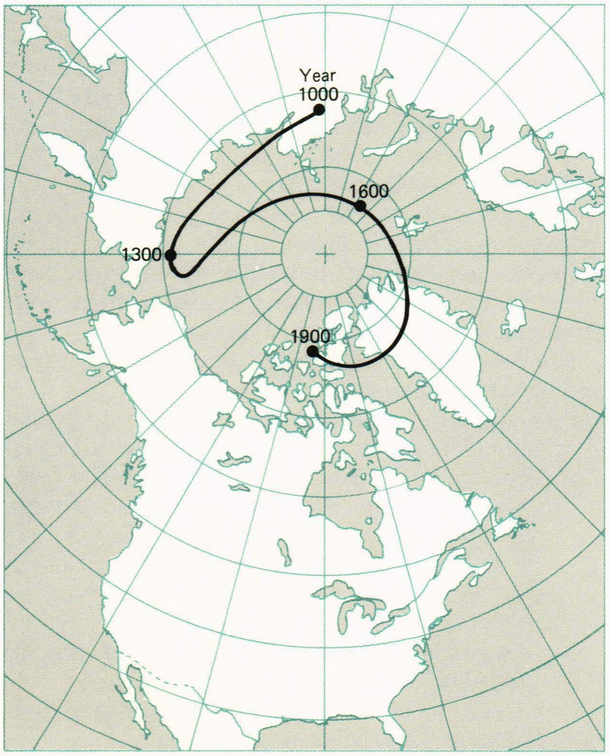

Fig. 3—The virtual geomagnetic pole positions since 1000 A.D., which correspond to the secular variations at London if one ascribes the geomagnetic field entirely to a centered dipole. The London variations were deduced from magnetic field orientations of samples obtained from archeological kilns, ovens, and hearths in the southern half of Britain (from Ref. 6). The present virtual pole is located near Thule, Greenland.

Modern theories of the geomagnetic field are based on the original suggestion of Larmor that the appropriate internal motion of a conducting fluid could cause it to act as a self-exciting dynamo.[8] To visualize this, assume the moving core to be an infinitely good conductor. Any primordial magnetic field lines, outside the core, for example, will be dragged around by the currents within the core as if they were "frozen" into the core. If the core rotates nonuniformly with depth, the field lines will become twisted around the axis of rotation in a way that opposes the initial field. The twisting action packs the magnetic field lines more closely, causing the field intensity to grow. This growth can neutralize the original field and produce an even larger reversal field. The concept of magnetic field amplification by the differential rotation of conductors has been used by astrophysicists to explain the magnetic fields of stars (including the sun), Jupiter, and Saturn. Many theories exist, but the precise generation mechanisms for the internal geomagnetic field are still unknown.[8]

MAGNETOSPHERIC CURRENTS

When viewed from outer space, the earth's magnetic field does not resemble a simple dipole but is severely distorted into a comet-shaped configuration by the continuous flow of plasma (the solar wind) from the sun (depicted in Fig. 4). This distortion demands the existence of a complicated set of currents flowing within the distorted magnetic field configuration called the "magnetosphere." For example, the compression of the geomagnetic field by the solar wind plasma on the day side of the earth must give rise to a large-scale current flowing across the geomagnetic field lines, called the Chapman-Ferraro or magnetopause current (see Fig. 4).

The magnetospheric system includes large-scale currents that flow in the "tail"; "Birkeland" currents that flow along geomagnetic field lines (see the article by Potemra in this issue) into and away from the two auroral regions; the ring current that flows at high altitudes around the equator of the earth; and a complex system of currents that flow completely within the layers of the ionosphere, the earth's ionized atmosphere. The intensities of these various currents reach millions of amperes and are closely related to solar activity. They produce magnetic fields that vary with time scales ranging from a few seconds (micropulsations) to 11 years (corresponding to the solar cycle).

Widespread magnetic disturbances sometimes observed over the entire surface of the earth are known as magnetic storms. These storms are associated with major solar eruptions that emit X rays, ultraviolet and extreme ultraviolet radiations, and particles with energies from 1 keV to sometimes over 100 MeV. The solar plasma accompanying solar eruptions causes a magnetic storm when it collides with the earth's magnetosphere. Minor magnetic storms can occur every few weeks during the peak of the 11-year solar cycle (the peak of the present cycle is thought to have occurred in 1980), whereas "super" magnetic storms that so severely distort the geomagnetic field as to move the entire auroral zone to lower latitudes are a much rarer event (the last super storm occurred on August 2, 1972, when an aurora was observed in Kentucky). Besides the evaluation of models for the internal geomagnetic field, Magsat, launched in October 1979, provided the most sensitive measurements yet of the magnetospheric current system.

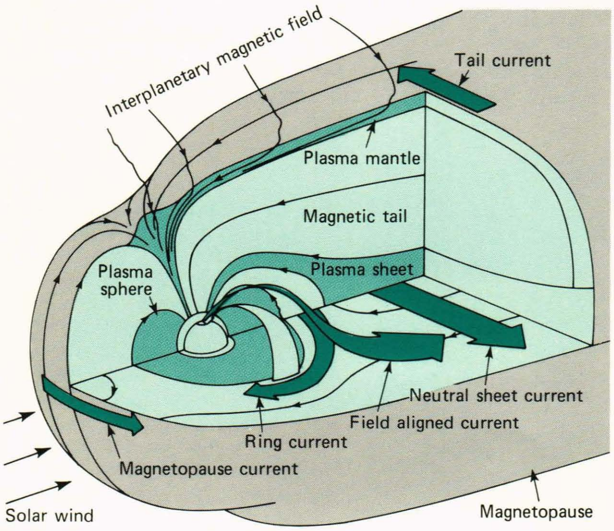

Fig. 4—The configuration of the earth's dipole magnetic field distorted into the comet-like shape called the magnetosphere. The various current systems that flow in this complicated plasma laboratory are labeled. The interplanetary magnetic field is the magnetic field of the sun, which has a modulating effect on the processes that occur within the magnetosphere.

MAGNETIC FIELD MEASUREMENTS

The technique of using airplanes for magnetic field surveys for geological prospecting became well established in the 1950's. Airplanes make their surveys at altitudes of 1 to 5 km, whereas satellites orbit the earth at 200 km or higher. Thus it was somewhat of a surprise when scientists discovered from the data of the Orbiting Geophysical Observatory satellites in 1972 that useful information about the structure of the earth's crust could be derived from satellite data — information that would be very difficult to detect in airplane survey data. Ideas for a satellite devoted to this objective were discussed for a number of years, finally leading to the Magsat program, which had the additional objective of measuring the "main" field for making new magnetic charts.

MAGSAT SPACECRAFT

Preliminary discussions among APL, NASA, and the U.S. Geological Survey (USGS), commencing in the mid-1970's, culminated in conceptual studies of a spacecraft dedicated to the task of completing a global survey of the earth's geomagnetic field. NASA and the USGS subsequently entered into an agreement to conduct such a program on a cooperative basis. The Goddard Space Flight Center (GSFC) was selected by NASA as the lead laboratory for this endeavor. Numerous trade-off design studies were undertaken, with emphasis on flying an adaptation of an available spacecraft design, launched from an early Space Shuttle, as against flying a small spacecraft on a NASA/DoD Scout launch vehicle. However, in view of the uncertainties surrounding the availability of the Shuttle, and in light of the desire of USGS to incorporate satellite magnetic field data into their 1980 map updates, the decision was made by early 1977 to proceed with a Scout-launched spacecraft.

In April 1977, after a successful preliminary design review, APL was funded to proceed with the Magsat design and development effort with the goal of launching the spacecraft by September 21, 1979, at a projected cost of about ten million dollars.

The Small Astronomical Satellite (SAS-3) had been designed and built by APL and launched in

1975. Many of the features of SAS-3 seemed ideally suited to the magnetic field satellite mission. It was a small spacecraft capable of being launched by the inexpensive Scout rocket, it had the world's most precise tracking system (i.e., position determination) in its Doppler tracking system (a derivative of the APL Transit system), it had two star trackers that could provide attitude determination to 10 arc-s (1 arc-s = 0.00028) accuracy, and its attitude control system used an infrared earth-horizon scanner/momentum wheel assembly that was ideally suited for Magsat. A critical problem, which was quickly identified, was the excessive weight of Magsat. Tape recorders with a larger capacity for data storage were needed, and new S-band transmitters were required for the high data rate during tape recorder playback. Compromises in the solar cell array were necessary to keep the weight down to 182 kg, the maximum that the Scout rocket could launch into a 350 by 500 km orbit.

MAGSAT ORBIT

An orbit was needed that would give full earth coverage and as little shadowing by the earth as possible. A polar orbit would be ideal for earth coverage, but because the orbit plane would remain fixed in space, the motion of the earth about the sun would cause shadowing of the satellite within 30 to 60 days after launch. Also, it would be difficult to find star camera orientations that would not present problems with direct sunlight. However, for an orbit inclination of 97°, the orbit plane precesses at the rate of 1°/day, just the right amount to make the orbit plane follow the sun. (This precession is due to the bulge in the earth's gravity field at the equator.) This sun-synchronous orbit (Fig. 5) gives nearly 100% earth coverage and many months of full sunlit orbits. The star cameras could be placed on the dark side of the satellite to avoid direct sunlight.

Even in this case, as the sun approaches the highest latitudes of +23° on June 21, the orbit would be shadowed in the south polar region. Shadowing was expected to begin in April so a launch date of September 1979 was chosen, which would allow six months of fully sunlit orbits. Launch actually occurred at the end of October 1979, so 5½ months of fully sunlit orbits were obtained.

THE SPACECRAFT

Magsat was intended to measure the vector components of the earth's field to an accuracy of 0.01%; this meant that the orientation of the vector sensors must be known to 15 arc-s accuracy. The star cameras were good to an accuracy of 10 arc-s, but they had 2 kg of essential magnetic shielding that would distort the magnetic field. An extendable boom was needed to put the vector sensors 6 meters away from the magnetic disturbance caused by the star cameras. But it was not possible for the boom to be mechanically stable to 5 arc-s. A system was needed to measure the orientation of the vector sensors relative to the star cameras. This system, the Attitude Transfer System (ATS), used an optical technique involving mirrors attached to the vector sensor to make the necessary measurement (see the article by Fountain *et al.* in this issue).

The elements of the ATS and the two star cameras had to be tied together mechanically in some permanent and extremely stable fashion. The structure to achieve this was the optical bench, a built-up assembly of graphite fiber and epoxy resin that provided a near-zero coefficient of thermal expansion. The bench was attached to the satellite at five points, two of which were released by pyrotechnic devices after the satellite was in orbit. The

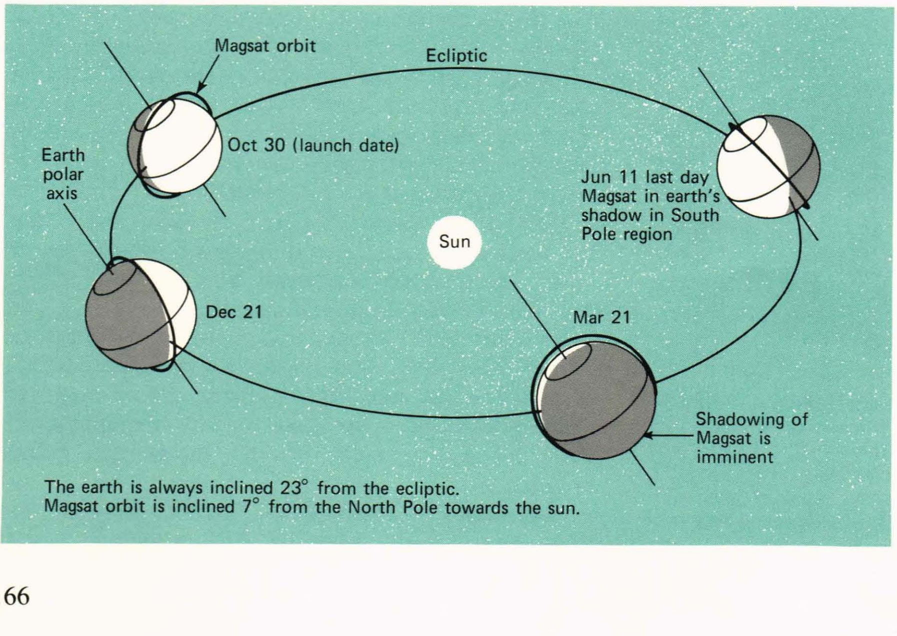

Fig. 5—The precession of the Magsat orbit plane with time. The Magsat orbit plane makes an angle of 97° with the earth's equatorial plane. At this inclination (and at the altitude of Magsat), the equatorial bulge of the earth causes the orbit plane to rotate above the polar axis at 1°/day, just the right amount to turn the orbit plane toward the sun as the earth proceeds in its orbit about the sun. Unfortunately, the 23° tilt of the earth polar axis adds to the 7° tilt of the orbit plane in June, causing shadowing of the southern portion of the orbit by the earth. This shadowing began in mid-April for Magsat.

three remaining support points did not apply stress to the bench. Heaters and temperature sensors at eight places stabilized the bench temperature at 25°C.

At the end of the 6 meter extendable boom were the vector magnetometer sensor and a scalar magnetometer sensor (see the articles by Acuna and Farthing). The vector sensor consisted of three small toroidal cores of highly permeable magnetic material with platinum wire windings used to sense the components of the field. They were mounted on a very stable ceramic block, and the temperature was controlled at 25°C. The scalar magnetometer measured the field magnitude very accurately, but not its direction. It used Zeeman splitting of energy levels in cesium-133 gas as a technique for measuring the field. The scalar data provided redundancy and an independent check on the calibration of the vector magnetometer.

Magsat was the latest and most complex of the satellites built by APL. The command system featured its own dual computers, which permitted storage of 164 commands, to be implemented at desired times (see the article by Lew *et al.*). This was very helpful because the low altitude of Magsat meant that a ground station had only 9 to 10 minutes in which to send commands, receive the data played back by the tape recorders, and make decisions about managing the satellite's health. The command system was also designed to accept commands from another on-board system, *viz.*, the attitude control system. The attitude control system also used a small computer to manage the satellite attitude. When it decided that commands were needed, a request was sent to the command system, which then implemented the command.

TESTING

Fabrication and test of components and subassemblies commenced during the winter of 1977-78 and were completed in 1979. The instrument module was assembled in December 1978 and exposed to a thermal balance test in vacuum. The base module was assembled in January and February 1979, and a critical test of the attitude control system was performed to verify various design and performance parameters. Development difficulties delayed availability of the magnetometer boom assembly until May 1979. The base module and instrument module were assembled without the boom and taken to GSFC for the star camera and ATS alignments.

The alignment and calibration of all the optical elements mounted on the optical bench was an especially difficult task. It was done with the fully assembled satellite mounted inside an aluminum cage, using the optical test laboratory at GSFC. Since the calibration was done in the gravity field of the earth (i.e., 1 g), the weight of the star camera and ATS components would distort the optical bench. But in orbit, the satellite continuously experiences zero g, these distortions would disappear, and our ground calibrations would be invalidated. To solve the problem, we made a second calibration with the satellite upside down, thereby reversing the direction of the weight force (i.e., -1 g) and producing distortions equal and opposite to those of the initial calibration. We then presumed that the zero-g calibration must be exactly midway between the two results. This technique has been confirmed with our flight results.

The spacecraft was returned to APL where the two modules were separated so that the magnetometer boom assembly could be installed. A series of boom extension tests was performed to verify ATS performance and alignment and to calibrate the boom deployment telemetry channels. In June 1979, the spacecraft was reassembled and, after a preliminary weight and balance determination, was returned to GSFC for initial magnetics tests and radio frequency interference tests aimed at verifying that all subsystems could operate in the orbital configuration without interfering with one another. Upon its return to APL, there followed detailed electrical performance tests, establishing the baseline for future reference.

During August 1979, the spacecraft was exposed to launch phase vibration and shock excitation tests followed by two weeks of combined thermal vacuum and thermal balance testing. In September the spacecraft was once again taken to GSFC for final weight, center-of-gravity location, and moment-of-inertia determinations; final magnetic tests; and post-environmental verification of the optical alignment of the star cameras and ATS. Upon its return to APL, a final vibration exposure (single axis) was performed to ensure that all components were secure. This was followed by a short electrical test.

LAUNCH AND POST-LAUNCH EXPERIENCES

The spacecraft, ground station, and supporting equipment were trucked from APL to Vandenberg Air Force Base, arriving on the morning of October 8, 1979. Intensive field operations followed, including electrical tests, assembly to the fourth stage rocket, and final spin balance. The spacecraft fourth stage rocket assembly was then mounted on the main rocket assembly, the heat shield was installed, and all-systems tests were performed. On October 27, 1979, a dress rehearsal was conducted, leaving all in readiness for launch, planned for October 29 at dawn. The countdown began on the evening of October 28 but had to be suspended just prior to terminal countdown because of extremely high winds at about 10,000 ft altitude. The launch operation was resumed on the evening of October 29 and culminated in a successful launch at 6:16 A.M. PST, October 30, 1979. All stages fired correctly and the spacecraft was injected into a 352 by 578 km sun-synchronous orbit.

Data were recorded until the satellite burned up at low altitude on June 11, 1980. A large amount of vector and scalar magnetometer data was collected, and scientific results are beginning to become available. We experienced some operational problems because of earth shadowing in the latter portion of Magsat's life, primarily caused by an unexpected loss of battery capacity that forced some compromises in data collection. The sunshades of the star cameras showed light leaks, which caused the loss of some data. On the whole, however, the Magsat satellite has been very successful, and all mission objectives should be accomplished when the data are fully processed.

The articles that follow describe the developments that led to the Magsat program, and the mission objectives, and summarize early flight events. Subsequently, details of the spacecraft components are discussed. The concluding articles describe the scientific results and on-going studies.

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A GLOSSARY OF MAGSAT COMPONENTS

Aerotrim Boom — A motorized extendable boom consisting of a pair of silver-plated beryllium-copper tapes, 0.002 inch thick, rolled on a pair of spools. When extended the tapes formed a tube 0.5 inch in diameter up to 12 meters long. The air drag on the boom was used to balance the aerodynamic torques in yaw.

Attitude Control System — The system that controlled the satellite attitude; in Magsat it held the satellite properly oriented with respect to the earth and the orbit plane. It consisted primarily of a momentum wheel with an integral infrared earth horizon scanner, magnetic torque coils, gyro system, and associated electronics.

Attitude Transfer System (ATS) — An electronic and optical system for measuring the orientation of the vector magnetometer sensor relative to the star cameras. Two optical heads of the ATS were mounted on the optical bench near the star cameras. One of the heads transmitted a beam of light to a plane mirror on the back of the vector magnetometer. The beam was reflected back into the same head where its angular deviation was measured and two angles of the plane mirror were determined. The second head sent a beam of light to a dihedral mirror also on the back of the vector magnetometer. The light was reflected to a dihedral mirror on the optical bench, and then via the first dihedral mirror back to the optical head. The position of the reflected beam was used to measure the twist angle of the vector sensor.

Command System — The apparatus aboard the satellite that accepted the digital bit stream from the receiver portion of the transponders, decoded it to recover the command words transmitted from the ground, and routed the words to the destinations designated by the address codes contained in each word. At destination, the word was further decoded and the specific element of the satellite addressed was placed in the mode designated by the word.

Data Formatter — The portion of the telemetry system that took the various science and housekeeping digital data bits and arranged them in a predetermined sequence for modulation onto the carrier frequency of the transmitter as well as for recording by the tape recorders. The predetermined sequence permitted decoding of the signals by ground-based computers.

Despin/Separation Timer — One of a pair of devices mounted on the head cap of the fourth-stage rocket motor. It was intended to initiate despin followed by spacecraft separation at predetermined times following the completion of firing of the fourth-stage rocket motor.

Horizon Scanner — The momentum wheel had within its structure an optical system capable of detecting radiation from the earth in the infrared (IR) at 15 micrometers. The field-of-view was a narrow beam rotated to form a 90° cone as the wheel spun. When the beam intersected the earth, the IR radiation was detected; an electronic system derived the pitch and roll angles of the satellite from this information.

Magnetic Coils — Magsat had X-, Y-, and Z-axis coils for torquing by interaction with the earth's magnetic field. A coil consisted of many turns of aluminum wire mounted on the outer skin of the satellite. When energized with a steady electric current, the coils experienced torques from the earth's magnetic field that were used for attitude control.

Magnetometer Boom — A collapsible structural element composed of seven pairs of links in a scissors or "lazy-tongs"-type arrangement intended to move the sensor platform from its caged, launch-phase position to a position 6 meters away from the instrument module.

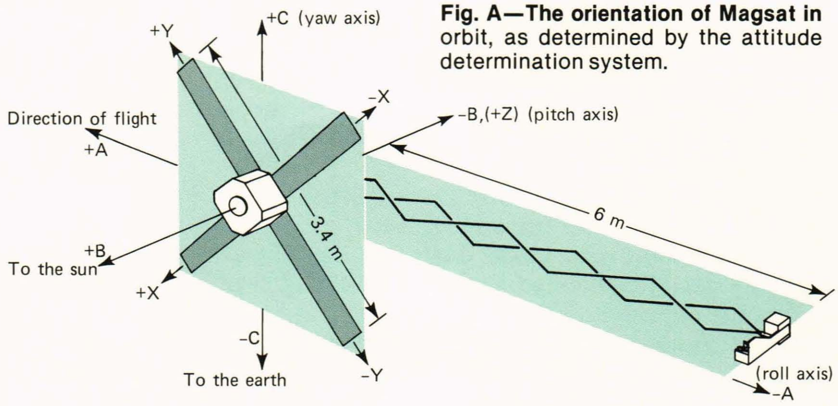
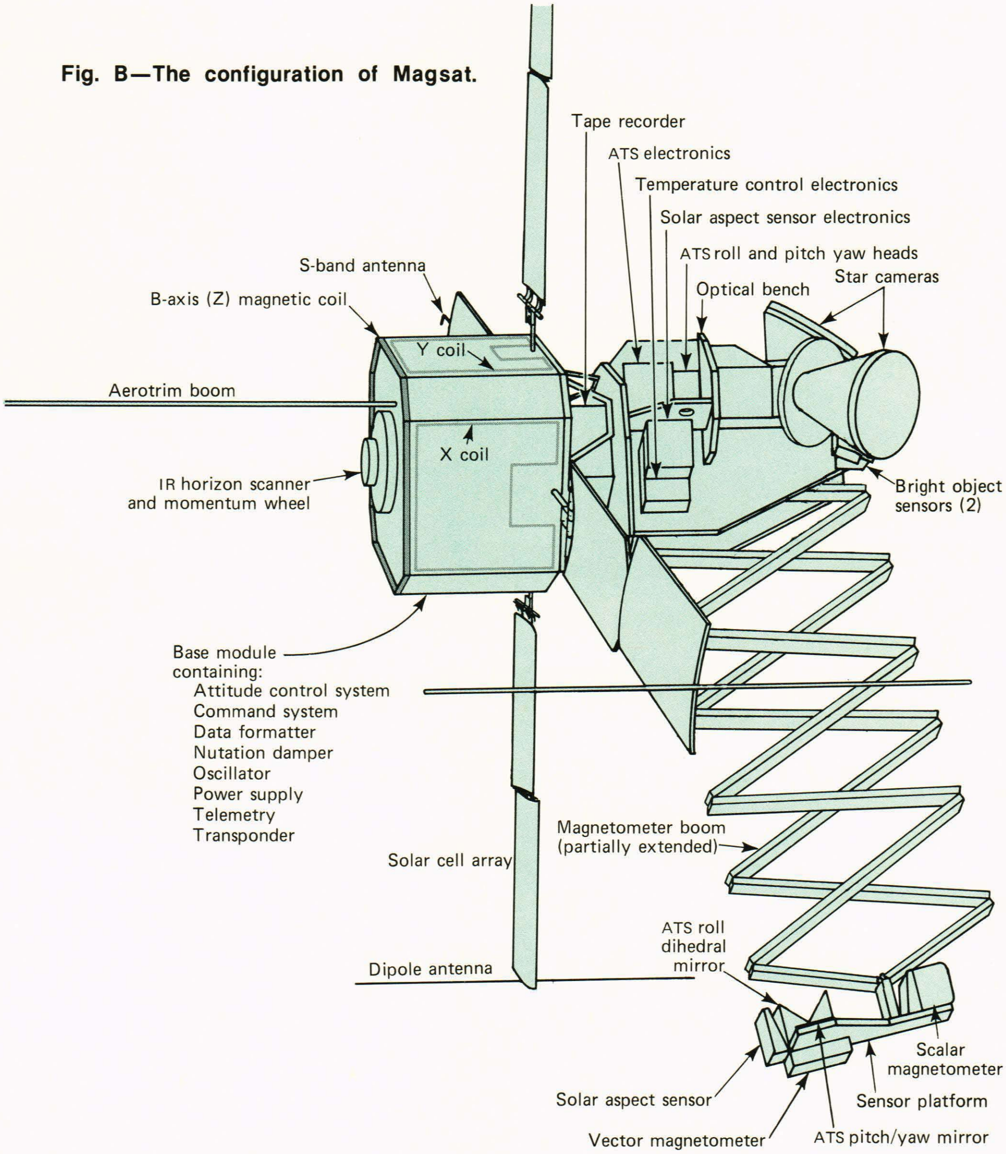


Fig. A—The orientation of Magsat in orbit, as determined by the attitude determination system.

Magnetometers — The scientific in-

Fig. B—The configuration of Magsat.



struments of Magsat consisted of a three-axis vector magnetometer and a scalar magnetometer for measuring the magnetic field of the earth. The vector magnetometer sensor had three small magnetic elements, each sensitive to one component of the earth's field. The scalar magnetometer measured only the magnitude of the field by optical pumping of atomic excitation states in cesium-133 gas.

Momentum Wheel — Magsat had an internal tungsten wheel that spun at about 1500 rpm. This rotation provided angular momentum that gave the satellite a form of gyroscopic attitude stability. This was a key feature of the attitude control system.

Nutation Damper — When a disturbance torque is applied to a gyro-stabilized satellite such as Magsat, the attitude motion includes nodding or wobbling. After the torque is removed, this nodding ("nutation") persists unless damped. In Magsat, damping was accomplished in two ways: by a pendulous mechanical damper that used magnetic eddy currents for damping, and by the closed-loop attitude control that modulated the momentum wheel speed to damp nutation.

Optical Bench — A structural platform constructed of a graphite fiber-epoxy-laminate honeycomb that was designed to provide a very stable surface for mounting the star cameras and ATS components. The properties of the material were used to ensure that the exact angular relationship was maintained between the star cameras and ATS components irrespective of instrument-module temperature fluctuations.

Oscillator — An ultrastable quartz crystal oscillator producing a 5 MHz output used as the source for the 162 and 324 MHz Doppler signals. The 5-MHz signal was also used to synchronize the various DC-DC converters aboard the spacecraft to avoid developing spurious beat frequencies that could be a source of interference to the various electronic devices. The stability of the oscillator was achieved by placing the crystal inside a double-oven arrangement, providing a high degree of thermal isolation from the fluctuations experienced by the base module, and by using a cut quartz crystal selected so that its turnover temperature and the oven temperature were precisely matched. This permitted operation with virtually no temperature effect on the oscillation frequency.

Power Supply — The system consisted of the following elements: solar cell arrays to generate electricity; a battery mounted in the base module to store the electrical energy for use during any shadowed portions of the orbits and to meet peak power demands; battery voltage limiter devices to control battery charging; and DC-DC converter regulators to condition power to the voltages needed by each user.

Solar Aspect Sensors — Several types were included in Magsat. Of special interest was the "precision" solar aspect sensor, mounted near the vector magnetometer sensor, which measured the angles to the sun with an accuracy of 5 to 10 arc-seconds.

Star Cameras — Two star cameras were mounted rigidly on the optical bench. Each camera had a 4-inch-diameter lens that focused the stars on the front end of an "image-dissector" electronic tube. Inside the tube, in the vacuum, was a very sensitive surface that emitted electrons wherever starlight fell upon it. These electrons were directed by magnetic coils to pass through a small hole into an electron multiplier where a cascade of electrons was generated, finally accumulating enough effect to be a measurable electric current. With magnetic coils driven in a predetermined manner, the surface of the tube was searched for sources of electrons (i.e., starlight). When a source was found, the magnetic coils "locked" onto it for a few seconds and the position was recorded.

Tape Recorder — A device used to store telemetry data until the satellite was over or near a ground station. The signals were recorded magnetically on iron-oxide-coated Mylar tape running between a pair of coaxially mounted reels. Two tape recorders were mounted on the deck between the base module and instrument module.

Telemetry — The process by which the scientific (magnetometer) data and information concerning the satellite attitude, load currents, bus voltages, temperatures, and other "housekeeping" data were transmitted to the NASA STDN ground stations.

Transponder — A combined radio receiver and transmitter operating at S-band, used for receiving command signals transmitted from the NASA STDN ground stations and for transmitting the telemetry signals from Magsat to the same ground stations. This NASA Standard Near-Earth Transponder could also be used as a range/range rate transponder for satellite tracking and orbit determination. Magsat, however, used the much more precise Doppler beacons in conjunction with the DMA tracking network.

Vehicle Adapter — The conically-shaped transition section bolted to the fourth-stage rocket to which the spacecraft was clamped. The two halves of the clamp were fastened together at each end by bolts passing through pyrotechnically operated cutters. Separation of the spacecraft from the launch vehicle was achieved by actuating the bolt cutters by a stimulus from the spacecraft battery initiated by the despin/separation timers. When the bolts were cut, the two clamp halves moved apart, allowing small springs to force the spacecraft away from the adapter/fourth-stage assembly.