GEORGE C. WEIFFENBACH, ELLA B. DOBSON, and STAMATIOS M. KRIMIGIS

SOME WORK IN PROGRESS IN APL's SPACE DEPARTMENT

This article describes some of the activities of current interest in APL's Space Department. There has been a tendency in *Johns Hopkins APL Technical Digest* articles to focus more attention on the development of instruments and spacecraft than on the results obtained from them at a later time. With this review, we hope to bring our reporting into better balance. We consider here the operational longevity of our oldest satellite, OSCAR 13, and a status report on our newest, Geosat, together with a listing of current analytic efforts using Geosat data. Finally, we review recent scientific results obtained from Magsat and update current Space Department research activities.

OSCAR 13

We note with satisfaction that OSCAR 13, launched May 18, 1967, is still functioning as the oldest operational satellite in the Transit navigation satellite system, exceeding by far the lifetime predicted when we built this satellite more than two decades ago.

GEOSAT

The newest APL-built satellite, Geosat, containing an APL-designed high-precision altimeter,[1] has been operating satisfactorily since launch in the spring of 1985 and, by November 1985, had produced two complete geodetic data sets. When sufficient data have been collected for an accurate (10-centimeter) geoid determination (probably near the end of 1986), Geosat will be formally dedicated to its secondary mission of oceanography, with a modest orbit adjustment to enhance its oceanographic usefulness. The preferred orbit is one in which the ground track repeats exactly every 3 days. However, one need not wait for this formal change of mission; the data in hand are already the most comprehensive and most accurate satellite altimetry data set that is available for both geodesy and oceanography.

An important design improvement was made in the Geosat altimeter to avoid a problem seen in the Seasat altimeter (launched in 1979), i.e., a steady decrease in the peak power output of the altimeter's traveling wave tube (TWT). The 2000-watt initial peak power dropped by about 10 percent during the 90-day operating life of Seasat. Laboratory tests to find the cause of the

power loss were inconclusive, but it was thought to be a result of high cathode current density in the TWT. For this reason, we decided that it was necessary to abandon the 2000-watt TWT and use a tube that operates at much lower power levels. The Geosat altimeter's TWT generates a much lower peak power of 20 watts and is a modification of a standard tube used in commercial communications satellites. To date, there has been no observable drop in peak power output. The measured in-orbit altimeter precision is 3 centimeters, compared to 5 centimeters for Seasat.

Geosat data are being processed at the Naval Surface Weapons Center in Dahlgren, Va., for geodetic purposes and at the Navy Oceanographic Research and Development Activity in Bay St. Louis, Miss., for oceanography. The oceanographic products obtained at the latter are forwarded to the Fleet Numerical Oceanography Center in Monterey, Calif., for distribution to the Fleet. Geosat data are also being used for oceanographic research by NASA and the National Oceanic and Atmospheric Administration.

At APL, the data from the Geosat altimeter are being analyzed in three areas:

1. Initialization and validation of mesoscale ocean circulation models.
2. Empirical characterization of ocean surface topography.
3. Validation of wave height and wind speed measurements.

The first of these efforts is supported by Independent Research and Development funds and represents a joint effort with APL's Submarine Technology Department. The second and third are Space Department efforts supported by the Office of Naval Research

Dr. Weiffenbach is a senior fellow at APL and was formerly head of the Space Department. E. B. Dobson is a senior mathematician in the Space Geophysics Group. Dr. Krimigis is chief scientist of the Space Department.

and the National Oceanic and Atmospheric Administration, respectively.

The circulation modeling is being pursued in two phases. The first involves implementation of an ocean circulation model that was developed at Harvard University by Prof. A. Robinson. The second phase involves the development of a three-dimensional "primitive equation" model, which has reached the stage where a two-dimensional prototype has been tested against simulated data. Both models give descriptions of currents, fronts, and eddies. The first model represents a gross approximation to these characteristics at mesoscale levels, and the second is intended to provide better accuracies.

The Geosat altimeter will provide estimates of dynamic wave heights and wind speeds that will be used as initial condition inputs to both models. In addition, it is intended that the altimeter height measurements be used to check model accuracy and to improve the models themselves. For example, Robinson's model can be initialized at time t_0 using derived ocean surface wind speeds obtained from measured height gradients. It can then be run for a time Δt, and the subsequent result can be compared to the altimeter measurement at time $t_0 + \Delta t$.

The empirical determination of surface topography uses the altimeter database in a hindcasting mode, in contrast to its use for forecasting in the model cases.

Altimeter measurements unavoidably contain orbit errors, instrument biases, and geoid uncertainties in addition to the oceanographic signatures under investigation. One method for removing the errors is to difference the height data at the intersection points of ascending and descending passes of the satellite. This is called the crossover method, and it provides a measure of ocean surface variability.

Another method that is being investigated is the variance method, in which the variance of the altimeter heights is differenced in time. The assumption is that once the variance of the geoid is established in an area, it will not change with time. Consequently, any change in variance with time is a reflection of a change of oceanographic topography. The crossover and variance methods are being investigated with the Geosat data set in an area where the geoid is known with high precision, and the subsequent analysis should determine the accuracy of both methods for mapping ocean features.

The aim of the validation of Geosat wave height and wind speed measurements is to extract wave height and wind speed values from the Geosat data and to compare these measurements with those obtained from buoys operated by the National Data Buoy Center (an agency of the National Oceanic and Atmospheric Administration). The altimeter wave height is derived from the received pulse shape, and wind speed is obtained from the ocean radar cross section. This analysis will establish

1. An improved algorithm relating altimeter cross section to wind speed (buoy determined).
2. Spatial, diurnal, and seasonal distributions of wind and wave fields.

3. An estimate of the accuracy of the altimeter wind and wave measurements.

RECENT RESULTS FROM MAGSAT

Polar orbiting satellites have been remarkably productive sources of geophysical data. A notable example can be seen in Magsat, which was designed and built at APL under the sponsorship of NASA's Goddard Space Flight Center. Launched in October 1979 into a low-altitude dawn-dusk sun-synchronous orbit, the satellite collected vector and scalar magnetometer data until it reentered in June 1980.

The February 28, 1985, issue of the *Journal of Geophysical Research* is the second special issue that has resulted from analysis of Magsat data (the first was the April 1982 issue of *Geophysical Research Letters*). In his introduction to the second special issue, R. Langel of Goddard Space Flight Center writes that

> By almost any measure the [Magsat] project has been a success: launch was within budget and on time; the data acquired exceeded prelaunch quality requirements even though the instrumentation encountered some problems; with the publication of this issue, the number of related scientific papers is near 100.[2]

A characteristic of the geomagnetic field is that it exhibits substantial temporal variations, with time scales ranging from milliseconds to tens of millions of years, the latter being complete polarity reversals. The slow changes are associated with the earth's internally generated main field. The rapid changes are produced by sources external to the earth, not surprisingly termed the external field. The field also varies geographically as it is modified by the heterogeneous distribution of magnetic material in the earth's crust; this is called the crustal anomaly field.

The primary mission of Magsat was to update information on the direction and intensity of the main field. The fact that a magnetic compass in a fixed location does not align itself in the same direction from year to year has been known since the 17th century. Aside from the westward drift of the nondipole field, this secular variation is not predictable. Consequently, it is necessary to update magnetic charts periodically by actual measurements, preferably every 10 years. In the 1985 special issue, Langel and Estes presented the field in 1980 based on data from Magsat and 91 magnetic observatories to an accuracy of 20 nanoteslas (about 1 part in 2000) at the earth's surface.

The origin of the main field remains something of an enigma. There is general agreement that the source is a dynamo of some kind in the earth's liquid conducting outer core, but the intractability of dynamo theory and the impossibility of direct observations of the core have frustrated the development of a satisfactory dynamo model. (It should be noted that a solution of the earth dynamo problem would be widely applicable in astrophysics.)

Under the circumstances, there is much interest in any measurements that can shed light on the earth dynamo problem. To this end, Magsat models are being

used in studies of the small-scale field structure at the core-mantle boundary. The models are also being used to adduce evidence that the frozen flux hypothesis (Alfvén's theorem that magnetic flux contained within in an element of a perfectly conducting fluid will be transported unchanged with the fluid element) is valid in the earth's outer liquid core for time scales of at least 10 years.[3]

Previous issues of the *Technical Digest* have reported on the use of satellite magnetometer data in studies of the external field by members of APL's Space Physics Group. Only the Magsat data have contributed to that research.

The use of Magsat data for investigating the crustal anomaly field has been inhibited by inadequate spatial resolution of the Magsat measurements, a result of the 300- to 500-kilometer altitude of the satellite. That orbital altitude for Magsat was the lowest that would produce an acceptable mission lifetime in the face of atmospheric drag. Despite that limitation, most of the articles in the *Journal of Geophysical Research's* special issue address the topic, a result of the particular interest in crustal anomalies.

The Space Department has been engaged for several years in design studies for the Geopotential Research Mission (GRM), which could improve the Magsat spatial resolution by more than a factor of 2. The GRM spacecraft are planned to orbit at a 160-kilometer altitude, with on-board rocket thrusters to maintain this altitude for at least 6 months. Because resolution is roughly equal to altitude for these measurements, GRM data would have a (horizontal) resolution of 160 kilometers on the ground, with the added advantage that all measurements would be taken at the same altitude, rather than at the constantly decreasing altitudes experienced by Magsat. Unfortunately, NASA has not set a firm date for a GRM launch.
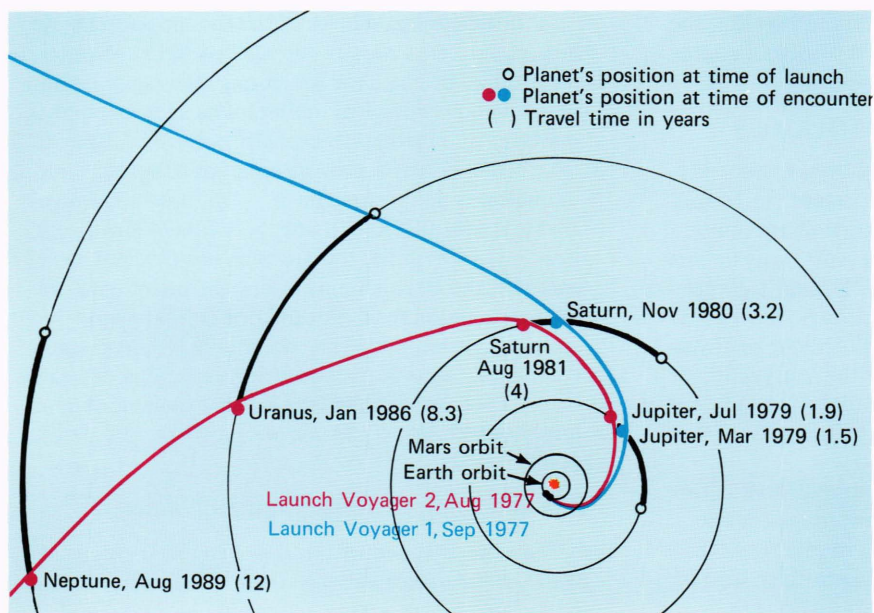
VOYAGER

Voyager 2 began its long flight to Uranus in August 1977, reaching Jupiter in July 1979 and Saturn in August 1981. It is now approaching Uranus; the closest approach will be January 24, 1986.

The Uranus encounter should provide decisive answers to questions that are of particular interest to planetary scientists: Does Uranus have a magnetic field, and, if so, what is the nature of its magnetosphere? The APL Low Energy Charged Particle (LECP) instrument on the spacecraft will help to answer these questions. It uses a variety of solid-state detectors to measure electrons (22 kiloelectronvolts $\leq E_e \leq$ 20 megaelectronvolts) and ions (30 kiloelectronvolts $\leq E_i \leq$ 150 megaelectronvolts) in several energy intervals with good energy, species, and time and spatial resolutions.

The LECP detectors on Voyager 1, which had encounters with Jupiter and Saturn but is now on its way out of the solar system without passing Uranus, and on Voyager 2 have already provided Jovian data that have raised questions relevant to the Earth's magnetosphere.

IONS UPSTREAM OF THE EARTH'S BOW SHOCK

For a number of years, spacecraft have observed ions ($\leq$ 30 kiloelectronvolts) upstream of the Earth's bow shock ($\approx$ 70,000 kilometer altitude) that were thought to be accelerated from the supersonic solar wind as it encounters the Earth's magnetic field. The detailed process of acceleration was assumed to be the original Fermi mechanism[4] that had been applied to the acceleration of cosmic rays almost 40 years ago. A large body of theory and associated observations has developed in support of this in situ acceleration model.

○ Planet's position at time of launch
●● Planet's position at time of encounter
( ) Travel time in years

Saturn, Nov 1980 (3.2)
Saturn Aug 1981 (4)
Uranus, Jan 1986 (8.3)
Jupiter, Jul 1979 (1.9)
Jupiter, Mar 1979 (1.5)
Mars orbit
Earth orbit
Launch Voyager 2, Aug 1977
Launch Voyager 1, Sep 1977
Neptune, Aug 1989 (12)

The flight trajectories of Voyagers 1 and 2 showing the dates of closest-approaches to the outer planets.

LECP instruments on Voyagers 1 and 2 produced the first evidence that the in situ hypothesis might be wrong. The LECP detected energetic ions *upstream* of Jupiter's bow shock, the majority of which consisted of ionized oxygen and sulphur. These ions could only come from inside the Jovian magnetosphere—not the solar wind—since they are unique components of Jupiter's magnetospheric population that have their origin in the volcanic eruptions from the satellite moon, Io.

The similarity in the morphology and spectra between the cases at Jupiter and Earth has led to a re-examination of the data upstream of the Earth's bow shock. In a recent paper,[5] data were examined from three Earth-orbiting spacecraft making simultaneous observations of one of these ion events. Two of the spacecraft were located upstream of the Earth's bow shock, while the third was located on the night side of the Earth, within the extended plasma sheet. The observations showed that ions were present within the Earth's plasma sheet *before* any of the increases were observed in the upstream region outside the magnetosphere. Further, the energy spectrum of the ions upstream was similar to that observed within the plasma sheet, and the intensities within the plasma sheet were greater than those observed upstream. Based on these observations, the authors suggest that ions observed upstream of the Earth's bow shock are not accelerated in situ via the Fermi mechanism, but rather leak out of the Earth's magnetosphere where there is an abundant supply of such ions most of the time.

This result is of particular importance in the context of ion acceleration in solar flares and in astrophysical shocks. The reason is that the Fermi mechanism, thought to be operating upstream of the Earth's bow shock, was used by theorists to suggest that the same mechanism accelerates ions in both solar flares and cosmic rays. Thus, this latest set of observations renders a large body of theoretical work questionable. The authors are in the process of examining several more cases and report that, in all cases examined so far, the Earth's plasma sheet appears to be the principal source of the upstream ions.

THE MAGNETOSPHERE OF URANUS

In February 1984, a workshop sponsored by the Voyager Project was held to establish a scientific framework within which to plan the Voyager 2 encounters with Uranus and Neptune. Three presentations at this workshop have special relevance to APL magnetospheric research. One paper[6] was presented by S. Durrance[7] of The Johns Hopkins University Department of Physics and Astronomy and J. Clarke of the University of California at Berkeley. A second[8] was by T. W. Hill of Rice University and a third[9] by A. Cheng of APL's Space Physics Group.

Durrance and Clarke reported on International Ultraviolet Explorer (IUE) satellite observations of unexpectedly intense and variable hydrogen Lyman alpha (1216 angstrom) emissions from Uranus, which they suggest is the first evidence of Uranian auroras and therefore the first experimental indication that Uranus has a significant magnetic field. The presence of a strong geocoronal background Lyman alpha complicates this type of measurement, but this is alleviated by the high IUE apogee altitude of about 45,300 kilometers. Durrance and Clarke took advantage of this fact by selecting observing times at apogee.

It should be noted that, alone among the planets, Uranus' rotation axis lies in the ecliptic plane (more precisely, the inclination of Uranus' equator to its orbital plane is 97 degrees 53 minutes). This results in a unique "pole-on" magnetosphere twice each Uranian year, which will be the situation during the encounter in January 1986. The pole-on orientation also prevailed at the time of the IUE Lyman alpha observations from March 3, 1982, through September 2, 1983 (a consequence of the long Uranian sidereal period of 84 years), and the resulting slow motion of 4.3 degrees per year of the planet's pole relative to the sun. Voyager 2 will thus provide the first in situ measurements of this unusual magnetospheric configuration.

At the Voyager workshop, Hill[8] and Cheng[9] presented two divergent models of the Uranus magnetosphere and suggested how Voyager 2 measurements could be used to determine which model is correct. Hill states that "corotation in the magnetospheres of Uranus and Neptune would probably exclude solar-wind driven convection as an important driver of global magnetospheric dynamics, as it does at Jupiter and Saturn. Unlike at Jupiter and Saturn, however, the magnetospheres of Uranus and Neptune probably lack sufficient internal sources of plasma (with the possible exception of Neptune's satellite Triton) to produce significant levels of rotationally-driven convection." Hill then suggests ". . .an alternative model in which solar wind motion is coupled directly to the rotation of the ionosphere to establish a dynamo circuit which generates Birkeland currents and polar-cap aurora."[8]

Cheng suggests

> . . .that the magnetospheres of Uranus and Saturn may be very similar. Charged particle sputtering of water ice surfaces on the Uranian moons may maintain an oxygen ion plasma torus similar to the heavy ion plasma torus at Saturn. Atmospheric cosmic ray albedo neutron decay may sustain an inner radiation belt with omnidirectional proton fluxes ~ 300 cm^{-2}s^{-1} above 80 MeV near 2.7 R_U. If the > 100 keV ion fluxes near 7 R_U are similar to Saturnian ion fluxes at such energies, the Uranian aurora may be maintained by ion precipitation from the radiation belts at nearly the strong diffusion rate. This mechanism would predict comparable aurorae over both magnetic poles of Uranus, in contrast with the Faraday disc dynamo mechanism, which powers an aurora only over the sunlit pole.[9]

In a joint note,[10] Cheng and Hill state:

> We agree that neither an Io-like source (associated with tidally-induced vulcanism) nor a Titan-like source (associated with a dense satellite atmosphere) is likely

at Uranus. We have diverged on the question of the likely presence [Cheng] or absence [Hill] of a heavy-ion plasma torus maintained by charged particle sputtering of the icy satellites. Sputtering of Saturn's icy satellites (e.g., Tethys and Dione) is considered an important source of heavy-ion (oxygen) plasma in Saturn's inner magnetosphere. A major unresolved question is whether this sputtering process does [Hill] or does not [Cheng] depend on the pre-existence of magnetospheric heavy ions derived from another source, namely Titan.

This question can be resolved at Uranus, which has analogs to the small icy satellites of Saturn, but no analog to Titan. Our separate arguments presented above suggest two critical observations that Voyager can perform at Uranus to resolve this question: (1) a search for a heavy-ion torus in the inner magnetosphere (within about 20 planetary radii), and (2) a comparison of UV auroral emissions between the day side and the night side. A significant internal plasma source would produce a magnetically conjugate Jovian-type aurora on closed, internal magnetospheric field lines, whereas in the absence of a significant internal plasma source the aurora would be largely restricted to the day side polar cap.

Voyager observations at Uranus can thus close a major gap in our understanding of the plasma source mechanisms operating at Saturn. The resolution of this question will, in turn, determine whether the magnetosphere of Uranus represents a third example of the Jupiter-Saturn type dominated by internally-driven convection (Cheng) or the first example of a new class of magnetosphere dominated by the proposed disc dynamo interaction (Hill).

Note added in proof, January 27, 1986. Voyager 2 experienced closest approach on schedule on January 24, 1986. The spacecraft revealed the surprising fact that the planet's magnetic dipole axis is offset 55 degrees from its rotation axis, with an intensity of 0.25 gauss at the equator. (For comparison, the offset of the earth's magnetic dipole is about 11 degrees, with a strength of 0.31 gauss at the equator.) The Uranian magnetic field appears to be pure dipole, in contrast to the earth's field, which has substantial nondipole components.

On January 27, Voyager's ultraviolet instrument detected a strong ultraviolet hot spot on the dark side of the planet, indicating vigorous auroral activity. This observation supports Cheng's prediction[9] and is inconsistent with Hill's hypothesis.[8]

The APL Low Energy Charged Particle Detector observed heavy ions upstream of the Uranus (magnetic field) bow shock and abundant ions within the magnetosphere, about at the intensities expected.

REFERENCES and NOTE

[1] C. C. Kilgus, J. L. MacArthur, and P. V. K. Brown, "Remote Sensing by Radar Altimetry," *Johns Hopkins APL Tech. Dig.* **5**, 341-345 (1984).

[2] R. A. Langel and R. H. Estes, "The Near-Earth Magnetic Field at 1980 Determined from Magsat Data," *J. Geophys. Res.* **90**, 2495-2510 (1985).

[3] D. Gubbins and J. Bloxham, "Geomagnetic Field Analysis III, Magnetic Fields on the Core Mantle Boundary," *Geophys. J. R. Astro. Soc.* **80**, 695-713 (1985).

[4] E. Fermi, *Phys. Res.* **75**, 1169 (1949).

[5] G. C. Anagnostopoulos et al., *J. Geophys. Res.* **91** (in press, 1985).

[6] S. Durrance and J. Clarke, "Lyman-Alpha Aurora," *Uranus and Neptune*, NASA CP2330, 559-572 (1984).

[7] Dr. Durrance is scheduled to be an astronaut on the Shuttle Astro Mission in 1986. The APL-designed Hopkins Ultraviolet Telescope is one of three instruments on the flight.

[8] T. W. Hill, "Magnetospheric Structures: Uranus and Neptune," *Uranus and Neptune*, NASA CP2330, 497-525 (1984).

[9] A. Cheng, "Magnetosphere, Rings and Moons of Uranus," *Uranus and Neptune*, NASA CP2330, 541-556 (1984).

[10] A. Cheng and T. W. Hill, "Do the Satellites of Uranus Control its Magnetosphere?," *Uranus and Neptune*, NASA CP2330, 557-558 (1984).