

TECHNICAL INNOVATIONS IN THE APL SPACE DEPARTMENT

This article discusses several APL contributions to spacecraft design, viz., Doppler tracking, magnetic torquing, yo-yoing, gravity-gradient stabilization, magnetic spin-despin, dual-spin stabilization, and DISCOS.

Since its earliest beginnings in 1958, the APL Space Department has designed and built 44 complete satellites (Fig. 1). In addition, it has provided scientific instruments and other special devices for a number of satellites that were primarily designed by others. In this latter category are numerous Doppler beacons, a large variety of particle detectors, ultraviolet spectrometers, and a precision radar altimeter for the Seasat program. Finally, in connection with the development and establishment of the Navy (NNSS; also known as Transit) Navigation Satellite System, which was the original *raison d'être* for the Department, it has designed and built ground stations and user navigation equipment in a variety of styles.

Most of this work, particularly NNSS and its scientific results, has been amply documented.¹ The scientific experiments have been particularly productive in contributing to an understanding of the solar wind and its interaction with the magnetic fields of the earth and Jupiter and of the source of other hot plasmas in the near-Jovian space.²

For a relatively small organization and budget, the program of the APL Space Department has been remarkably productive in introducing and reducing to practice a considerable variety of simple and effective (though not widely known) technical approaches to the solution of spacecraft problems. It is the purpose of this article to describe some of these techniques and place in perspective their significance to space technology as a whole.

DOPPLER TRACKING

Probably the single most significant technical advance produced by the APL space program was inventing and reducing to practice the use of Doppler measurements by ground stations of signals received from near-earth satellites as a means of determining the orbits of the satellites. In fact, the discovery by W. H. Guier and G. C. Weiffenbach that they could determine the orbit of the Russian Sputnik from Doppler measurements made on a single pass over a receiver at APL led to the invention (by F. T. McClure) of the Transit concept and the establishment of the APL Space Department.

It is not true, in general, that a specification of the Doppler shift as a function of time is sufficient to determine the path of a transmitter moving through space. A transmitter in an aircraft, for example, has basically three degrees of freedom for its path, and the Doppler shift determines only the rate of change of the direct line-of-sight distance between the transmitter and receiver and thus poses a single constraint on the three degrees of freedom of motion. However, an artificial satellite of the earth already has a large number of constraints, implicit in the statement that it is an earth satellite. For example, its path must lie (nearly) in a plane that also contains the center of mass of the earth. A complete orbit of a satellite is determined by specifying a time; the coordinates x , y , z of a point in space that the satellite occupies at the given time; and the components \dot{x} , \dot{y} , \dot{z} of the velocity vector at that point. These parameters adequately specify a set of initial conditions for the solution of differential equations governing the motion of the satellite (Newton's law of motion).

What Guier and Weiffenbach did was to choose arbitrarily a set of initial conditions, i.e., a set of values (x , y , z ; \dot{x} , \dot{y} , \dot{z}); numerically solve the differential equation of motion; calculate the rate of change of the line-of-sight distance between the satellite position and the position of the receiver on the ground; and then repeat this process with other assumed initial conditions until a best agreement was reached between the calculated and measured Doppler shift. Neither the existence of a convergent process nor the uniqueness of the answer is obvious, and the validity of such a technique remained controversial for some years in spite of well-demonstrated success. NASA in particular, was reluctant to believe these results. It was only some years later that they introduced a system that employed Doppler measurements of near-earth satellites but then only in conjunction with range measurements in the so-called Goddard range and range-rate system. This is even more surprising in that the NASA group at the Jet Propulsion Laboratory who had responsibility for interplanetary probes did, indeed, recognize the convenience and accuracy of Doppler measurements for determining the orbits of these deep-space objects with extraordinary precision.

Perhaps the reason for the slow acceptance of Doppler tracking for near-earth satellites was that there was one very important class of satellites where the technique did not work well, namely, the so-called stationary or geosynchronous satellites that have been so important in satellite communications systems. In the particular case of a purely equatorial satellite with an exact sidereal-day orbit period, the satellite appears to hover over a fixed spot on earth and the Doppler shift is to zero. While it establishes that the satellite is geosynchronous, it gives no information on the specific location of the satellite or of the subsatellite point. However, it can now be stated unequivocally that Doppler tracking has proved the cheapest, most convenient, and most accurate method for determining the orbit of a spacecraft that is either substantially below or substantially above the geosynchronous altitude of 19,320 nautical miles.

The accuracy of Doppler tracking was not generally recognized for a number of years. A major reason for this slow recognition was the lack of an alternate method with an established accuracy to use as a reference. The basic NASA Minitrack system was not intended for high accuracy, and errors in prediction of position at a fixed time were measured in tens or even hundreds of kilometers. The Air Force was firing very low altitude classified satellites (Discoverer series) with a reasonably accurate tracking system and carried out some tests with Doppler tracking with comparable but not clearly superior results.

We now know the reason for the somewhat disappointing results of these early tests. First, there is the fact that at altitudes of only a few hundred miles the air density (and hence the drag effect on the satellite orbit) is widely variable and unpredictable. Air density at these altitudes varies by more than an order of magnitude in response to unpredictable changes in solar activity. Second, a satellite very close to earth responds to the variation in density or shape of the earth (gravitational field variations), which proved to be much more complex than was generally expected. It took about five years to determine a mathematical model of the earth's gravitational field that was sufficiently accurate to permit orbit determinations by Doppler measurements to meet consistently our initial goal of quarter-mile navigation accuracy with Doppler tracking.

The results of the very first APL satellite, Transit 1-A, were extremely encouraging in spite of the fact that a launch vehicle failure precluded a long-term orbit. Transit 1-A was fired from Cape Canaveral northward off the United States east coast on a trajectory making a 50° angle with the equator, and it reached the intended operational altitude. At this point a final launch-phase rocket was supposed to fire to provide a sufficient velocity increase to circularize the orbit at that altitude. It failed to fire, and the satellite reentered the earth's atmosphere and burned up somewhere off the Irish coast. Thus Transit 1-A was short-lived. But for about 20 minutes from the end of rocket thrust to reentry into the

atmosphere it was technically "in orbit," i.e., in a ballistic trajectory, controlled primarily by gravitational attraction of the earth. During these 20 minutes, Doppler data were obtained at APL and at a receiving station established at Argentia, Newfoundland. A 20 minute segment of Transit 1-A's "orbits" could be determined by an analysis of the Doppler data as measured at two ground stations. Best of all, during most of this period there was a quite independent and relatively accurate means of determining the satellite position, namely, tracking radar from Cape Canaveral. The Doppler analysis was done, and the satellite position determined in this way was found to agree with the radar tracking data to about 0.1 mile, which was roughly the accuracy expected of the radar data. This was highly encouraging and demonstrated the fundamental soundness of the Doppler tracking concept.

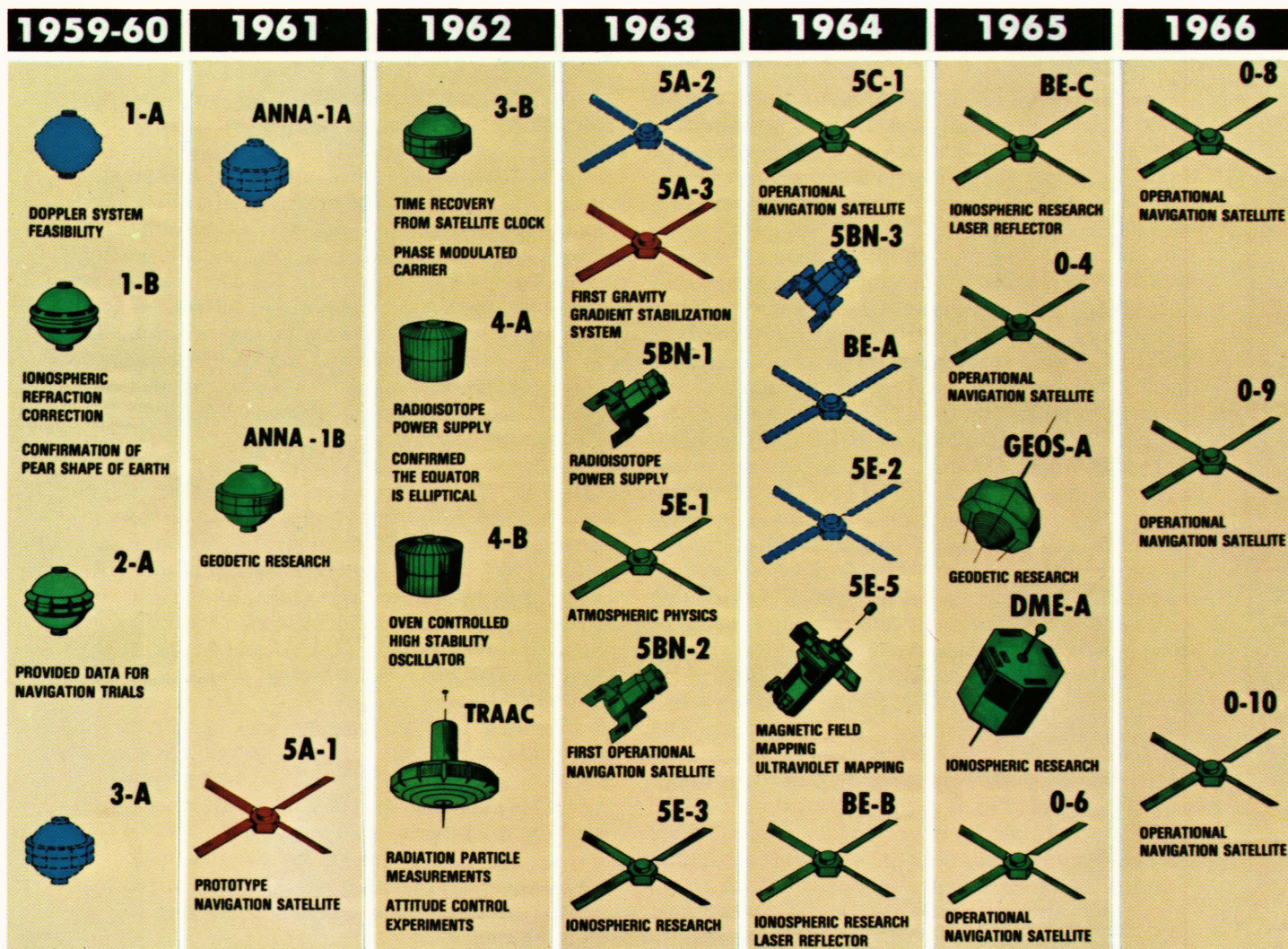
In April 1960, the second Transit (1-B) was launched, and this time it achieved an orbit that did not intercept the earth. Although it had the very low perigee of 382 km and an apogee of 760 km, it functioned perfectly for 89 days before a thermostat failure destroyed the power system. By this time there was a substantial ground network of tracking stations including Austin, Tex.; Las Cruces, N. M.; Seattle, Wash.; and Farnborough, England, in addition to APL and Argentia.

Data were reported regularly back to APL, and an orbit was determined every day or two. At first the results were very disturbing. Changes of as much as 1 km in apogee radius occurred in as little as 2-day time periods, which seemed surprising even with the very low perigee. Worst of all, for the first month the apogee radius persisted in increasing, changing from 7125 km in late April to a high point of over 7128 km a month later.

A satellite with a low perigee should suffer substantial loss in velocity due to drag as it swings through perigee, thus reaching a lower apogee radius the next time around. What we expected was a gradual, relatively slow decrease in the apogee radius. There was no immediate explanation for an increasing apogee radius. Fortunately, continued tracking clarified the situation, as seen in Figs. 2 and 3. The apparent apogee radius increase during the first month was only the rising side of a sinusoidal oscillation in apogee radius fluctuating around the expected linear decrease due to drag. Specifically (Fig. 4), the semimajor axis showed a steady decrease. There was thus no mysterious force adding energy to the orbit. All that was happening was a redistribution of the division of the major axis into a perigee radius and an apogee radius due to a sinusoidal motion of the focal point of the ellipse, reflecting an oscillatory variation in eccentricity of the ellipse.

The most revealing fact that emerged from almost three months of tracking was the period of the sinusoidal variation. It corresponds exactly with the period of the precession of perigee, i.e., the period of the tumbling of the major axis in the orbit plane.

Spacecraft Designed and Built by APL



Instrumentation on Spacecraft not Designed by APL

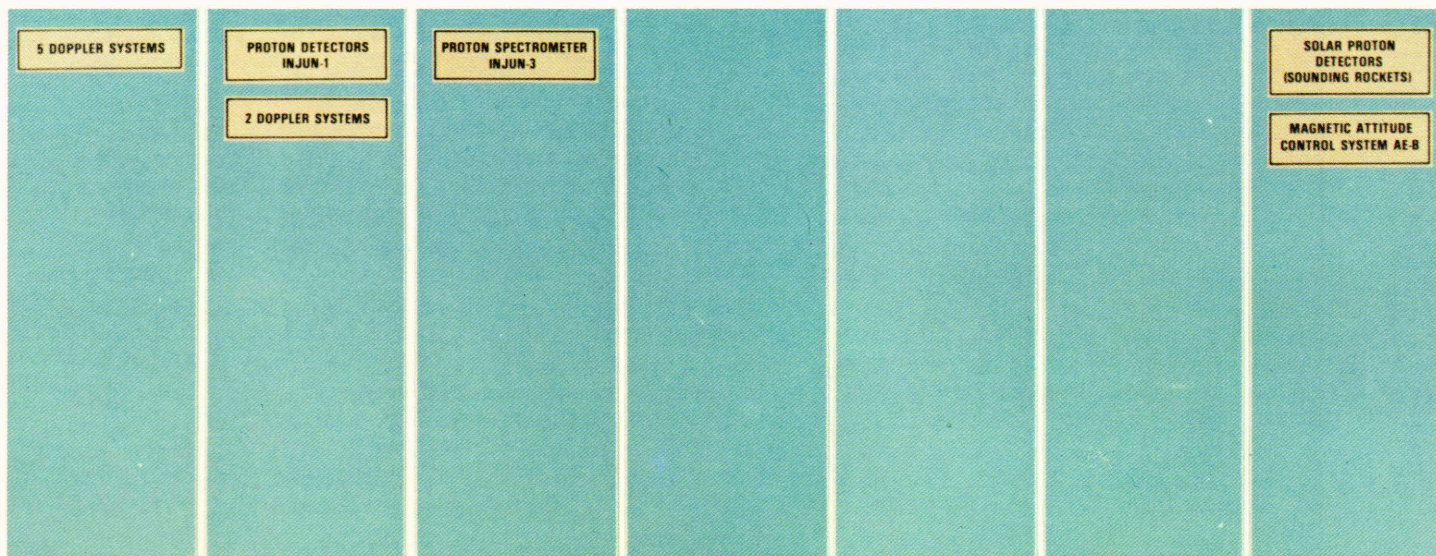
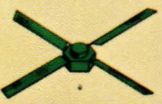
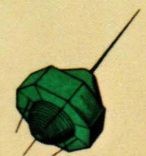



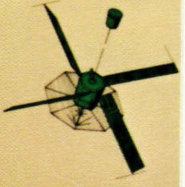
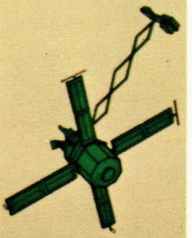
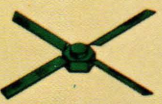



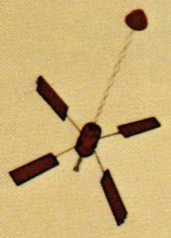
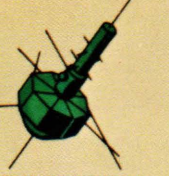
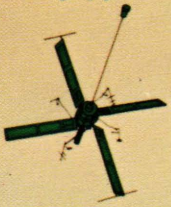
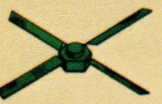



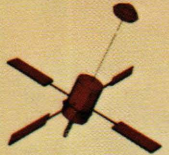


Fig. 1—APL Space Department satellite program, 1959-1979.

1967	1968-69	1970-71	1972-73	1974-75	1976-77	1978-79
<p>0-12</p>  <p>OPERATIONAL NAVIGATION SATELLITE</p>	<p>GEOS-B</p>  <p>GEODETIC RESEARCH</p>	<p>SAS-A</p>  <p>X-RAY MAP OF CELESTIAL SPHERE</p>	<p>TRIAD</p>  <p>ATMOSPHERIC DRAG COMPENSATION NAVIGATION BY RANGING IMPROVED TIME AND FREQUENCY CONTROL RADIOISOTOPE POWER SUPPLY</p>	<p>GEOS-C</p> 	<p>P76-5</p> 	<p>MAGSAT</p>  <p>MEASURE NEAR-EARTH GEOMAGNETIC FIELD</p>
<p>0-13</p>  <p>OPERATIONAL NAVIGATION SATELLITE</p>	<p>LIDOS</p> 		<p>SAS-B</p>  <p>GAMMA RAY MAP OF CELESTIAL SPHERE</p>	<p>SAS-C</p> 	<p>TIP-III</p> 	
<p>DODGE</p>  <p>NEAR SYNCHRONOUS ORBIT 3 AXIS GRAVITY GRADIENT STABILIZATION SYSTEM FIRST COLOR PICTURE OF FULL EARTH</p>					<p>TRANSAT 0-11</p> 	
<p>0-14</p>  <p>OPERATIONAL NAVIGATION SATELLITE</p>	<div style="border: 1px solid black; padding: 5px;"> <p>  SUCCESSFUL  FAILED TO ORBIT  PRINCIPAL OBJECTIVE NOT MET </p> </div>			<p>TIP-II</p> 		

<p>SOLAR PROTON MONITOR IMP F</p> <p>MAGNETIC ATTITUDE CONTROL SYSTEM RAE-1</p>	<p>SOLAR PROTON MONITOR IMP G</p>	<p>SOLAR PROTON MONITOR (ITOS-1 (TIROS-M), NOAA-1 (ITOS-A), IMP-1, NOAA-2 (ITOS-B))</p> <p>6 DOPPLER BEACONS</p> <p>ORBITING FROG OTOLITH EXPERIMENT OFO-1</p>	<p>CHARGED PARTICLE MEASUREMENT EXPERIMENT IMP H, IMP J</p> <p>ENERGETIC PARTICLE EXPERIMENT IMP H, IMP J</p> <p>SOLAR PROTON MONITOR NOAA-2 (ITOS-D), ITOS-E, NOAA-3 (ITOS-F)</p> <p>ULTRAVIOLET SPECTROMETER EXPERIMENT APOLLO 17</p> <p>3 DOPPLER BEACONS</p> <p>ROTATING LITTER CHAIR SKYLAB 1</p> <p>PHOTOELECTRON SPECTROMETER AE-C</p>	<p>4 DOPPLER BEACONS</p> <p>SOLAR PROTON MONITOR NOAA-4 (ITOS-G)</p> <p>ULTRAVIOLET ABSORPTION EXPERIMENT APOLLO SOYUZ</p> <p>PHOTOELECTRON SPECTROMETER AE-D, AE-E</p>	<p>4 DOPPLER BEACONS</p> <p>SOLAR PROTON MONITOR NOAA-5 (ITOS-H)</p> <p>NAV PAC-1</p> <p>LOW ENERGY CHARGED PARTICLE EXPERIMENT VOYAGER 1, VOYAGER 2</p>	<p>PARTICLE FLUX MONITOR IUE</p> <p>NAV PAC-2</p> <p>RADAR ALTIMETER, SYNTHETIC APERTURE RADAR DATA LINK, LASER RETROREFLECTOR ARRAY, DOPPLER BEACON SEASAT-A</p>
---------------------------------------------------------------------------------	-----------------------------------	----------------------------------------------------------------------------------------------------------------------------------------------------------------	-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------------------------------------------------------------------------------	----------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------------------------------------------------------------------------------------------------------------------

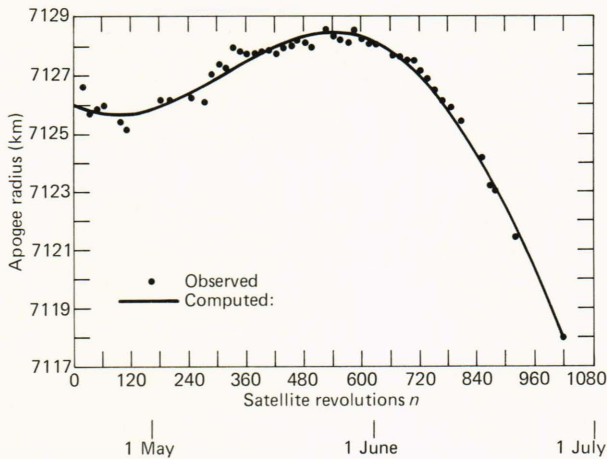


Fig. 2—Apogee radius from the center of the earth for Transit 1-B. Each dot in this figure is based on an independent determination of the orbit derived from data spanning the specific time period. The data are reasonably approximated by the smooth curve that is a graph of the empirically determined equation,

$$R_A = 7131.79 - 0.151n + 6.03 \sin 0.004079(n - 314).$$

Thus the variation of apogee can be described as a linear decrease with a superimposed sinusoidal variation.

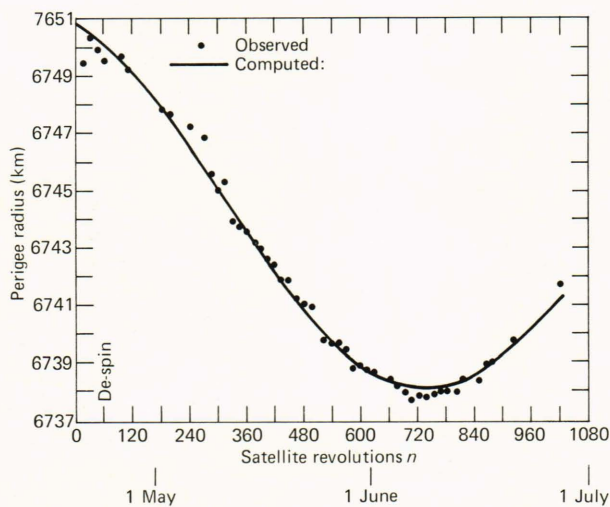


Fig. 3—Perigee radius from the center of the earth for Transit 1-B. As in Fig. 2 each dot is based on the results of an independent orbit determination. The smooth curve represents the empirical formula,

$$R_P = 6745.57 - 0.00297n + 5.41 \sin 0.004079(n + 456).$$

This fact clearly demonstrated that the orbit behaved differently when perigee was in the northern hemisphere than it did when perigee was in the southern hemisphere.

It could be most plausibly explained by assuming a north-south dissymmetry in the earth's gravitational field. In fact J. O'Keefe of NASA/Goddard Space Flight Center (GSFC) had announced a few months earlier, based on long-term tracking of NASA satellites, evidence of such a north-south dissymmetry in the form of a pear-shaped term in the earth's field. To understand what this means, one should start with the fact, known since the time of Isaac Newton,

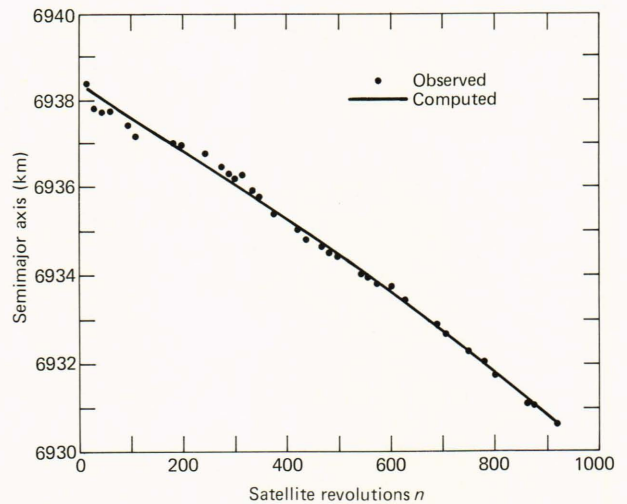


Fig. 4—Semimajor axis of Transit 1-B. This curve is an average of the curves in Figs. 2 and 3 (the semimajor axis is one-half the sum of the apogee and perigee radii). The sinusoidal variation almost disappears, and the change in semimajor axis is a nearly linear decrease with time, due to drag.

that the earth is very nearly an oblate spheroid, a body of revolution formed by rotating an ellipse about its minor axis. O'Keefe's pear-shaped term reflected a slight departure from a perfect oblate spheroid that featured a slightly depressed north pole, a somewhat increased radius at mid-northern latitudes, a decreased radius at mid-southern latitudes, and a slightly elevated south pole. Actually such a departure from north-south symmetry had been earlier detected by Worzel of Lamont from a study of extensive gravimeter data, but his findings were not generally accepted. This refinement of the earth's gravity field explained the seemingly strange Transit 1-B tracking data beautifully; in fact, we were able to improve slightly on O'Keefe's quantitative determination of the pear-shaped term in the earth's shape.

The Transit 1-B results proved two crucial facts: (a) accurate determination, and especially prediction of satellite orbits, required a greatly improved determination of the earth's gravitational field; and (b) the tracking of low altitude satellites provided an unprecedented and powerful means of making this needed improvement.

At that time (circa 1960) there was fairly widespread recognition that artificial satellites provided a powerful new attack on the ancient problems of geodesy. But there was by no means any consensus on the most fruitful technical approach. The Army Map Service outlined an ambitious program to determine the location of a very large number of benchmarks — globally distributed — using satellites only as simultaneously intervisible points to span wide bodies of water and using a specific electronic ranging method (known as SECOR for SEquential COLLation of Range) as the measurement technique. The Air Force favored a system of photographing satellites (contain-

ing a flashing light) against a star background and using angle measurements, again using the satellites only as simultaneously intervisible objects. Shortly thereafter laser ranging (more accurate than SECOR) was introduced. Only the Navy program and some NASA efforts tried to determine the earth's field by observing its dynamic effect on satellite orbits (this became known as *dynamic geodesy*). A number of satellites (most of them built by APL), such as Anna 1-A and Anna 1-B in 1961, Geos-1 in 1965, and Geos-2 in 1968, were launched to determine which of these techniques would yield the best results. It turned out that dynamic geodesy using Doppler tracking proved the most powerful. It was not obvious that this would be so. Some of the alternate methods, particularly laser ranging, provided individual measurements of greater accuracy, but the great virtue of the Doppler approach was that every pass of a satellite over every ground station provided a wealth of data of very good accuracy without any weather or time-of-day limitations. Laser ranging required ideal skies. The flashing-light photography required clear skies at night. Such limitations tended to bias the data.

By 1964, APL had developed a sophisticated model of the gravitational field of the earth in the form of an expansion in spherical harmonics (a three-dimensional analog of a Fourier series) that was sufficiently accurate to make possible our goal of better than 0.1 mile navigation at sea. This model was based solely on the analysis of Doppler tracking of a variety of APL satellites. At that point the gravitational-field knowledge was no longer a limiting factor in the navigation accuracy achieved at sea, which instead was dominated by orbit prediction errors caused by the inherent unpredictability of drag and the effect of errors in the estimate of ship's velocity. Continued geodetic work would not contribute to our primary task of providing at-sea position fixes for the Polaris submarines. At this point, responsibility for future geodetic refinements was transferred to NSWC/Dahlgren (which had already been working in this area in parallel with APL).

By 1972, the various geodetic efforts of the armed services were merged, creating the Defense Mapping Agency. Dynamic geodesy, based on Doppler tracking and Transit navigation, had become the official standard for geodetic progress. Today it is recognized internationally as *the* standard means for global survey. International disputes, such as the line through the North Sea separating Norwegian oil well claims from those of the British Isles, are settled by Transit surveys. At a meeting in Las Cruces in 1976, the only serious dispute was one between those who thought that the accuracy of the Transit survey position was 1 meter and those who thought it was 30 cm. To put this in perspective, it should be mentioned that in 1959, at the start of the Transit program, the location of Australia was wrong by several thousand meters.

Starting in 1959, the accuracy of Doppler tracking

was recognized by the Air Force, which was launching a large number of very-low-altitude classified satellites for which they needed very accurate orbits. Then APL was asked to provide Doppler beacons to be carried by these satellites and simplified ground receiving stations, called Geoceivers, to be dispersed in critical locations. Since that time, APL has provided 20 Doppler beacons for Air Force host vehicles and other low altitude satellite programs. Still more recently we have developed for the Defense Mapping Agency a satellite-borne Transit receiver that measures Doppler from as many as four Transit satellites simultaneously and relays the data to the ground, enabling an orbit determination without the effort and expense of a Geociever network. Doppler tracking has truly come of age.

MAGNETIC TORQUING

Until 1959, only two types of attitude control had been demonstrated for artificial satellites. The first and simpler of the two was spin stabilization. When enough spin was imparted to the satellite to provide gyroscopic stabilization, the direction of the spin axis was fixed in inertial space. This was used even for the early meteorological satellites even though it meant that most pictures taken failed to show the earth. The other system, used primarily in the manned space program, was the use of attitude control jets to provide appropriate torques to obtain the desired attitude.

APL felt that the use of control jets was incompatible with our goal of a five-year lifetime. Our choice of Doppler tracking as the primary measurement technique ruled out spin stabilization since spin would impart a modulation and, hence, a frequency sideband indistinguishable from the Doppler shift. As a stopgap, our early satellites after Transit I-A were magnetically stabilized by incorporating a fixed magnet in the satellite that would cause it to line up along the earth's magnetic field lines. This had the virtue of pointing one specific side of the satellite toward the earth in the northern hemisphere. It is true that the other end would point earthward in the southern hemisphere, but, since at that time no ground stations were located in the southern hemisphere, magnetic stabilization served our purposes for a while.

Some means of damping was required to make magnetic stabilization stable. At the suggestion of R. E. Fischell, this problem was solved very simply and ingeniously by the use of "hysteresis rods," i.e., long, thin rods of a readily magnetizable material that exhibits substantial magnetic hysteresis. This means that the present state of magnetization is partly controlled by its former state so that there is a tendency to reflect the magnetization of the earth's field where the satellite has recently been. For such materials, if the rod is slowly rotated through a complete revolution, the torque will not be zero on average but instead will have a specific nonzero value and a direction that depends on the direction of rotation

of the rod. The basic law governing the behavior of a rod of high-permeability material with hysteresis, rotating in a magnetic field, is that, for every complete revolution of the rod, a fixed amount of energy is dissipated in the rod. This amount of energy is the area of the standard hysteresis loop. Thus the rate of energy loss is proportional to the angular velocity, or

$$\frac{d}{dt} \left(\frac{1}{2} I \omega^2 \right) = \text{const.} \times \omega ,$$

whence

$$I \dot{\omega} = \text{const.}$$

It is seen that incorporation of such a rod in a satellite produces a constant retarding torque opposing any rotation. The fact that this opposing torque remains constant in value even for very slow rotation makes the use of hysteresis damping very effective at low angular velocities. Magnetic stabilization worked extremely effectively in our early satellites.

THE YO-YO

A special problem was posed for the early Transit satellites by the fact that the launch vehicle had a spinning final stage. The satellite was placed into orbit with a substantial spin rate, and it was necessary to find some means to remove this spin angular momentum before magnetic stabilization could be accomplished. The device chosen to accomplish this received the name "yo-yo."

Consider a disk-shaped satellite spinning about the axis of the disk. Assume that a wire has one end fastened to the circumference of the disk; it is then wrapped about the circumference in a direction opposite to the direction of rotation. A weight is attached to the outer end of the wire and held against the circumference. At a given instant the weight is released. It swings out under centrifugal force and, through the wire, exerts a retarding torque on the satellite. In practice, two diametrically opposite weights and wires are released simultaneously to avoid transverse forces on the axis of the disk. However, for simplicity we will consider the case of a single weight and assume the disk axis is fixed.

The geometry of the situation after release of the wire is shown in Fig. 5, where ϕ is the angle turned by the satellite after release of the weight, R is the radius of the satellite, s is the amount of wire paid out, and r and $\phi + \theta$ are the polar coordinates of the weight. Clearly, from the geometry,

$$\theta = \frac{s}{R} - \tan^{-1} \frac{s}{R}$$

$$r = \sqrt{s^2 + R^2} . \quad (1)$$

Let I be the moment of inertia of the satellite

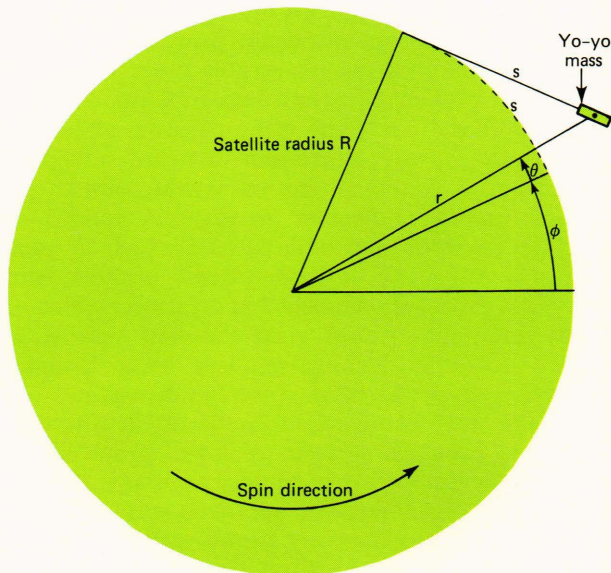


Fig. 5—Yo-yo geometry. This illustrates the variables required to establish the equations covering the removal of spin energy by the deployment of a yo-yo mass.

(without the yo-yo weight) and m the mass of the weight, so that $I_0 = I + mR^2$ is the initial moment of inertia of the satellite before release of the weight. Let ω_0 be the initial angular velocity.

The equations expressing the conservation of angular momentum and kinetic energy are

$$I \dot{\phi} + mr^2 (\dot{\phi} + \dot{\theta}) = I_0 \omega_0 \quad (2)$$

and

$$I \dot{\phi}^2 + mr^2 (\dot{\phi} + \dot{\theta})^2 + m \dot{s}^2 = I_0 \omega_0^2 .$$

Now if r , θ , \dot{r} , $\dot{\theta}$ are expressed in terms of s , \dot{s} by means of Eq. 1, then Eq. 2 becomes

$$(I_0 + ms^2) \dot{\phi} + \frac{ms^2}{R} \dot{s} = I_0 \omega_0 , \quad (3)$$

and

$$(I_0 + ms^2) \dot{\phi}^2 + \frac{2ms^2}{R} \dot{s} \dot{\phi} + \frac{m}{R^2} s (\dot{s})^2 = I_0 \omega_0^2 . \quad (4)$$

If Eq. 3 is multiplied by $\dot{\phi} + (\dot{s}/R)$ and subtracted from Eq. 4, the result is

$$\dot{s} = R \omega_0 , \quad (5)$$

and this, substituted in Eq. 4, immediately yields

$$\dot{\phi} = \omega_0 \frac{I_0 - ms^2}{I_0 + ms^2} . \quad (6)$$

Equations 5 and 6 can be immediately integrated with the obvious boundary conditions to give

$$\dot{s} = R\omega_0 t,$$

and

$$\phi = 2\sqrt{\frac{I_0}{mR^2}} \tan^{-1} \left(\omega_0 \sqrt{\frac{mR^2}{I_0}} t \right) - \omega_0 t. \quad (7)$$

However, most of the important features of the yo-yo operation are more easily obtained directly from Eqs. 5 and 6 without integration. For example, from Eq. 6, it is clear that $\dot{\phi} = 0$ when

$$s = \sqrt{I_0/m}. \quad (8)$$

Thus when the amount of wire given by Eq. 8 has been paid out, the satellite will have been brought to rest, and, if any further wire is paid out, the satellite will begin to turn in the opposite direction. The limiting value, for infinite s , is also obvious from Eq. 6, namely, $-\omega_0$ (the same angular speed as the initial speed but the opposite sense of rotation). If the wire is arranged to detach from the satellite after a length s , given by Eq. 8, has paid out, the satellite will be left without angular velocity and the weight will depart into space carrying the entire angular momentum of the system with it.

It is particularly interesting that Eq. 8 does not contain the initial angular velocity ω_0 . Thus if the yo-yo is properly designed, with a mass m and length of wire s satisfying Eq. 8, its operation will remove whatever angular velocity exists. However, while it is not necessary to know what the angular velocity will be to design a yo-yo to remove it, it is necessary to know the direction of the angular velocity.

It may be of interest to relate how the invention of the yo-yo at APL came about. Actually it was more of an accidental discovery than an invention. It was obvious that the spin rate of a spinning satellite could be reduced to any desired fraction simply by increasing the moment of inertia of the satellite by a corresponding ratio; for example, by paying out a weight on the end of a cable from the center of the satellite. It occurred to me that wrapping the cable around the outside of a (spherical) satellite and allowing centrifugal force to unwrap the cable would accomplish the desired increase in the moment of inertia and in addition apply some retarding torque. The primary motivation for the study of this possibility was the mechanical simplicity as compared to some controlled feedout mechanism. Accordingly, I asked George Munro to set up and, if possible, solve the differential equation controlling this deployment process. The next day he told me the equations were readily integrable and showed the rotation being brought to a complete halt with a relatively small amount of cable deployed, and with further cable deployment the satellite was spun up in the direction opposite to the initial rotation. This did not seem at all intuitive to me, so I checked all the mathematics carefully and

could find no error. I also talked to most of the physicists in the Laboratory and, to a man, they found the results implausible. John Garrison was particularly intrigued by this unlooked-for behavior, and as a result he and I spent that evening in his basement workshop building a demonstration model. Sure enough, the yo-yo worked exactly as the equation said it should, and we immediately planned for its incorporation in the satellite.

APL had all the fun of inventing the yo-yo, developing it, (including the development of ground-test capability), and seeing it work beautifully before we received a report from Jet Propulsion Laboratory showing they had quite independently and at a slightly earlier time invented and demonstrated the yo-yo. Clearly it was an idea whose time had come.

Due to an imperfection in the release mechanism, the spin rate is generally not reduced precisely to zero, but the magnetic hysteresis rods described above rapidly accomplished the removal of what little spin is left.

GRAVITY-GRADIENT STABILIZATION

The use of magnetic stabilization for early Transit satellites was clearly not optimum for an operational navigation system. Since a magnetically stabilized satellite tumbles twice per orbit, it is necessary either to transmit signals as nearly as possible isotropically or to use multiple antennas and antenna switching during the orbit. Fortunately there was an ideal alternative available in the form of gravity-gradient stabilization that would keep one end of the satellite always pointed at the earth and allow an antenna to be placed at this end without wasting RF energy by radiating it into the sky. This is the stabilization system responsible for keeping one face of the earth's natural moon always turned toward the earth; the torque responsible for it had been well understood for a long time.

It is possible to understand the source of the gravity-gradient torque without writing any equations if one remembers that, for a satellite at any given orbital altitude, there is a unique velocity that corresponds to a circular orbit at that altitude. At this velocity and orbital radius the centrifugal force at the center of gravity exactly balances the gravitational attraction. Since gravity attraction varies as $1/r^2$, the appropriate circular orbit velocity is lower for higher altitude satellites and higher for lower altitude satellites. If the satellite is moving faster than this circular orbit velocity, it swings out in an elliptic path to a larger radius, losing speed as it climbs against gravity; if it is moving too slowly to maintain a circular orbit, it swings inward on an elliptic path, acquiring speed as it falls.

Now consider a satellite in the shape of a barbell, consisting of two separate masses on opposite ends of a rather long bar. Suppose the entire device is in orbit and that the axis of the bar is at 45° with the vertical, i.e., the direction toward the center of the earth. If

there is the proper balance by the centrifugal force and gravitational attraction at the center of gravity for the entire device, it is clear that one end of the barbell — the end at the larger radius — is going too fast and will attempt to swing outward, while the other end at the lower radius is going too slow and will want to drop. Thus there is a net torque in the direction to cause the bar to approach the vertical. The torque arises from the variation in the level of gravity across the vertical dimension of the satellite. It is easily seen that the torque vanishes as the barbell becomes strictly horizontal, but this is an unstable equilibrium condition, whereas the vertical position is stable.

The feasibility of gravity-gradient stabilization of artificial satellites was a matter of considerable dispute about 1960. Many felt that the available torques were too small to provide a reliable engineering solution to attitude control. The APL Space Department recognized the very small value of the torque but argued that, if all other competing torques (magnetic, gyroscopic, aerodynamic, radiation pressure, etc.) were at substantially lower levels, the “best” torque would win. A more serious problem was the provision of a damping mechanism. Several were tried in APL satellites launched in the early 1960’s until it was confirmed that the same magnetic hysteresis rods used for damping in the early magnetically stabilized satellites also provided adequate damping in the gravity-gradient mode.

A special problem with gravity-gradient stabilization is that the satellite is precisely as stable upside down as it is right side up. In fact one early satellite was turned over by a form of outgassing and was not recoverable. Two separate solutions to this problem were found. For the Transit satellites that are in polar orbit, we used an initial stage of magnetic stabilization just as we had in the earliest satellites. This stabilization is polarized, and the satellite was designed so that the desired end was pointed earthward over the north magnetic pole of the earth. After magnetic stabilization was sufficiently damped, we chose a pass in which the satellite would pass over the north magnetic pole, at which point it was conveniently in line of sight from APL; we sent a signal commanding (a) that the magnet (an electromagnet) be turned off, and (b) that a boom be extended to produce the barbell configuration required to provide the gravity-gradient torque.

Now consider the tumbling rate of the satellite through this period. When it settled down to a pure magnetically-stabilized mode, it was tumbling at two revolutions per orbit in inertial space. When the boom was extended there was a huge increase in the moment of inertia that effectively brought the tumbling rate to zero in inertial space. If the extension occurred when the boom axis was vertical, there was no immediate gravity-gradient torque. However, as the satellite proceeded around its orbit with the boom direction frozen in inertial space, it quickly departed from vertical and a gravity-gradient torque built up

rapidly. Calculation (confirmed by experience) shows that it is in fact captured by the gravity-gradient torque before it reaches the horizontal and is reliably captured right side up. This technique has been used successfully on about nine Transit satellites built by APL and others built by Naval Avionics Facility, Indianapolis (NAFI) and RCA. Notice that this method works only for satellites with high enough inclination to pass over the north magnetic pole.

On one satellite, the Geos-1, a different technique was used that eliminated the need for an initial magnetically stabilized mode and, more importantly, will work for any orbit inclination, even for an equatorial satellite. It required a motorized boom that can be retracted as well as extended. With this technique, after satellite angular motions have been sufficiently damped (e.g., by hysteresis rods), the boom is extended and the satellite is allowed to gravity-gradient stabilize with either end up, as it chooses. If it happens to be right side up, well and good. If it happens to be upside down, there is a simple inversion maneuver that can be accomplished easily. This maneuver depends on the fact that a gravity-gradient stabilized satellite has a tumble rate of exactly one revolution per orbit. Retracting the boom causes a huge decrease in the moment of inertia and a corresponding increase in the tumble rate that is very accurately calculable. When the satellite has turned exactly 180° (usually after just a few minutes), the boom is reextended, the tumble rate returns to the desired one revolution per orbit, and the satellite is right side up. This has been demonstrated to work and in fact is just as easy as it sounds, although the equations that calculate the time taken to retract and extend the boom and the variable moments of inertia during these periods are slightly more complicated than I have indicated. But first-year calculus suffices.

Gravity-gradient stabilization is now accepted as a simple and reliable means of achieving an earth-pointing satellite in the altitude range from a few hundred to a few thousand miles. At lower altitudes, aerodynamic torques exceed the gravity-gradient torques. At very high altitudes, where the gravity-gradient torques fall off rapidly, radiation pressure torques may dominate. But for many satellites, where earth-pointing is desirable, it provides the only system that has, as in the case of the moon, a proven lifetime measured in billions of years.

MAGNETIC SPIN-DESPIN

The use of the yo-yo and magnetic hysteresis rods provided a convenient means of removing the spin from the satellite. In 1963-64, we were faced with the challenge of designing a satellite that could have spinning added after it was in orbit. Furthermore, it was required that the direction of the spin axis in inertial space be controlled by command from the ground. The satellite involved was called DME-A and was launched in 1965. Its objective was a survey of the composition of the ionosphere. It was desired that

the satellite should rotate (tumble) in the orbit plane, i.e., rotate about an axis orthogonal to the orbit plane. The experiments that were placed around the rotating circumference thus scanned all possible angles of attack and made it possible to obtain information on the vector velocities of the charged particles comprising the ionosphere. The use of reactor jets, which was the typical means of obtaining satellite spin-up in orbit, was undesirable because of polluting the environment being sampled.

A solution to this problem was found by R. E. Fischell using only the earth's magnetic field. If three electromagnets, at mutually right angles, are included within the satellite, it is possible to establish within the satellite any desired magnetic vector. If the satellite contains a vector magnetometer, it is possible to determine the earth's magnetic field vector at any moment. By activating electromagnetic coils appropriately in response to the vector magnetometer measurement, a torque in any desired direction can be obtained. This torque can be used to spin up the satellite to any desired spin rate. If it is desired to use a specific fixed axis in the satellite as a spin axis, then only two electromagnets and two vector magnetometers are required that are mutually orthogonal and orthogonal to the desired spin axis. Essentially what was done was to make the satellite act like the rotor of an electric motor with the earth's magnetic field serving as the stator. Provision can easily be made to provide an additional magnetic torque that will serve to precess the spin axis once the satellite is spinning and gyroscopically stabilized. The satellite spin system was designed to hold a constant spin rate, by putting in energy to make up for damping losses without requiring commands from the ground. The precession torques were ground-commanded. However, torques that would provide a precession rate almost exactly equal to the precession of the orbit were found very quickly, and a change in command was necessary only about once a week. The entire system worked beautifully on the first attempt and proved a remarkably simple, reliable, and accurate method of controlling the attitude of a spinning satellite. R. E. Fischell was awarded one of the coveted *IR 100* awards (for the one hundred most significant industrial inventions of the year) for his invention of the magnetic spin system in 1967.

There is a restriction on the mass distribution (the ellipsoid of inertia) of a spin-stabilized satellite that must be observed. The spin axis must be chosen as the shortest axis of the ellipsoid of inertia, i.e., the axis about which the moment of inertia is maximum. The reason is that for the closed system containing the satellite, both total energy and angular momentum must be maintained constant. In fact, angular momentum can be altered only by ejecting material (jets, yo-yo, etc.) or by applying torques (e.g., magnetic torquing). On the other hand, energy can be transformed readily into heat and then radiated. Consequently, a satellite that is set spinning about an axis about which the moment of inertia is not maxi-

mum has a strong tendency to seek a state in which it has the same angular momentum with a lower total energy of rotation. The minimum energy is clearly obtained at the minimum angular velocity, which occurs when the moment of inertia is maximum. For short periods of time, particularly with little internal damping, this rule can be violated, as it is with artillery shells. But for long periods of time it is necessary to design a spin-stabilized satellite so that the moment of inertia about the spin axis is maximized.

DUAL-SPIN STABILIZATION

It is reasonably obvious that the technique of magnetic spin-axis precession does not require that the entire satellite be spinning at a high rate. All that is required is that it have a large angular momentum vector that could be provided by including within the satellite a momentum wheel (flywheel) that can be spun by an ordinary electric motor. With the angular momentum for gyroscopic stabilization provided by such a momentum wheel, it is possible to control the angular velocity of the rest of the satellite to any level, including zero, by the magnetic spin system described above. This system, suggested by Fischell also, was first used in SAS-1 launched in 1970. This satellite carried an x-ray telescope and had the mission of surveying the celestial sphere in search of x-ray sources. The requirement was that the satellite rotate, but only very slowly because of the response time of the telescope. A momentum wheel was incorporated to provide the gyroscopic stabilization. Magnetic spin-axis precession was provided, and the spin rate of the overall satellite was independently controllable by a magnetic spin-despin system. The flexibility and controllability of this system proved crucial to the spectacular astronomical discoveries of this satellite. For example, many x-ray pulsars were identified, and it was the ability to vary the satellite spin rate to match the pulsar repetition rate that made this system particularly convenient. The satellite could even be commanded to scan back and forth over a limited region of the sky instead of rotating at a given rate.

The dual-spin attitude control system of SAS-1 was used again in SAS-2, launched in 1972, which carried a gamma-ray telescope provided by NASA/GSFC. It worked equally well although, unfortunately, the gamma-ray telescope itself had a rather short life.

One particular mode of operation of the dual-spin system arises if the spin axis is placed normal to the orbit plane. Then, if the main satellite is controlled to have a spin rate of one revolution per orbit, you have an alternative method of obtaining an earth-pointing satellite. However, in this case, a refinement is possible that overcomes some of the limitations of gravity-gradient stabilization. First, the momentum wheel (which, of course, is also rotating at a high rate about an axis normal to the orbit plane) can include an infrared detector, looking out radially, that responds to the large temperature difference between the earth

and outer space and so recognizes the horizon. Thus the direction of the earth is accurately determined as the midpoint of the high temperature portion of each scan. In addition, the spin rate of the satellite can incorporate a fine adjustment (about the average rate of one revolution per orbit) by accelerating or decelerating the momentum wheel, causing a corresponding deceleration or acceleration in the spin rate of the main satellite. This mode of operation was incorporated and successfully demonstrated in SAS-3 launched in 1975. As compared to gravity-gradient stabilization, it can provide much greater accuracy of earth-pointing, especially with highly eccentric orbits and at very low altitudes. With eccentric orbits, the gravity-gradient torques are too weak to provide the angular accelerations and decelerations necessary to follow the earth-pointing direction. At low altitudes aerodynamic torques compete with the gravity-gradient torques and make accurate earth-pointing very difficult. These problems are easily handled by the dual-spin system described above.

The primary mission of SAS-3, another x-ray telescope, did not require the earth-pointing mode. Nevertheless it was provided as an optional mode and was demonstrated to establish the suitability of SAS-3 as a multipurpose vehicle. The first mission for which this dual-spin mode of earth-pointing was ideally suited was the Magsat satellite, launched in 1979. Magsat was designed to survey the earth's magnetic field from as low an altitude as possible. A star camera was used to determine the attitude of the satellite with great precision. Unfortunately, the star camera is inherently magnetic. To avoid degradation of the magnetic field measurements, the magnetometers had to be removed a substantial distance from the star camera by an extendable boom. In order to relate the attitude of the vector magnetometers to the attitude of the star camera, an attitude transfer system was used. This system involved a light beam originating near the star camera and reflecting off a mirror system mounted at the magnetometer end of the boom so that yaw, pitch, and roll deflections of the boom could be measured accurately. The entire system worked throughout the life of the mission, and the satellite met all its objectives. The data are still being reduced.

DISCOS

In many ways, the most challenging and demanding piece of technical wizardry that the APL Space Department undertook was embodied in the Triad satellite launched in 1972. This is a device frequently referred to as the "ball in a box" or the "drag-free device." It was invented independently by a number of people well before the space age and was intended for application in ballistic missiles. The objective was to force the missile to follow a pure ballistic (gravitationally determined) trajectory even after the missile reentered the atmosphere, improving its accuracy by eliminating the variable aerodynamic effects on the trajectory. The name "drag-free" was intended to

suggest that it followed the same trajectory as if drag were not acting on the missile.

The concept was considered too difficult to apply to ballistic missiles but was suggested³ for application to satellites and was first implemented by APL in the Triad satellite. Suppose that within the satellite there is a hollow box or other enclosure within which is a small proof mass. There is required some means of detecting the position of the proof mass within its container without applying any force on the proof mass. At least six jets are required that are capable of providing thrust force on the satellite in either direction along each of three mutually perpendicular axes. Once in orbit, the proof mass is released and, from then on, the jets are fired in such a way as to prevent the proof mass from coming in contact with the walls of the container. This is basically a collision-avoidance system that keeps the proof mass suspended in the center of its container. Thus the satellite is forced to follow the trajectory of the proof mass quite accurately. If this is successfully accomplished, the proof mass is itself a satellite but is shielded from any aerodynamic forces and in that sense is drag-free.

The term "drag-free" is really misleading on two counts. First, the overall satellite is not free from drag forces but is slaved to a proof mass that is protected from drag forces. The jet forces provided to the satellite must compensate exactly for the drag forces. Second, not only drag forces but any other external forces, such as radiation pressure, are equally compensated. For this reason, the APL Space Department has preferred to use the word DISCOS (for DISTurbance COMPensation System) in referring to this device.

Although there was no attempt to implement the DISCOS system either in ballistic missiles or satellites before APL undertook the design of the Triad satellite, there was substantial development, both analytical and with a two-degree-of-freedom simulator (using an air cushion-levitated device) by the staff of the Guidance and Control Laboratory of Stanford University under Dr. Daniel DeBra. APL relied heavily on this work and placed a major subcontract with Stanford University to assist in the design and fabrication of the Triad satellite. The detailed design of the Triad satellite can best be understood in the light of a discussion of the various forces that can act on the proof mass and that must be kept very small. Specifically, the object of the Triad program was to reduce all forces other than the gravitational attraction of the earth to the level of 10^{-11} g.

Radiometer Forces

Most readers will have seen radiometers, which consist of an evacuated glass globe within which a primitive merry-go-round rotates. The merry-go-round is a balanced cross piece with a vertical axis in the center and enlarged flat plate ends that are black on one side and white or silvered on the other. It will spin when placed in strong sunlight and is commonly believed to demonstrate the existence of radiation

pressure. Actually its functioning has nothing to do with radiation pressure. The device works only because the glass ball is not too well evacuated. The easiest way to see this is to note the direction in which the device turns. With the black sides of the end plates facing in a counterclockwise direction, if radiation pressure were the motivating power, the device would turn counterclockwise since the radiation pressure on a reflecting surface is greater than that on an absorbing surface and the absorbing (black) surfaces would be driven backward. What actually drives the device is that the absorbing surface becomes hotter than the reflecting surface and transfers this heat to the molecules of the residual gas in its immediate proximity, causing a somewhat higher pressure against the black surface than against the reflecting surface and producing a consequent clockwise rotation. This force, caused by thermal inhomogeneity in a rarified gas, is referred to as the "radiometer force." In Triad the radiometer acceleration was kept very small by making sure that the proof mass and the cavity containing it were excellent thermal conductors, that surfaces were uniform in emissivity and absorptivity, and that the proof mass was quite heavy (high density).

Magnetic Forces

Considerable care was taken in keeping magnetic attraction or repulsion of the proof mass below the 10^{-11} g level. The earth's magnetic field was no particular problem, since the gradient of the earth's field across the dimensions of the proof mass is, indeed, negligible. However, it is difficult to assure the same lack of gradient from fields that arise from either magnetic material or current loops within the satellite itself. For this reason it was decided to seek a material of low magnetic susceptibility. Since we desired very high density, we investigated the possibility of using an alloy of para- and diamagnetic materials so that the magnetic susceptibilities would cancel each other out. It was found⁴ that an alloy of 70% gold and 30% platinum had an exceedingly small magnetic susceptibility (Fig. 6). Such a proof mass was made and its susceptibility pronounced almost unmeasurably small by the National Bureau of Standards.

Self-Gravitation

The most difficult design problem was to ensure that the gravitational attraction exerted by the rest of the satellite on the proof mass was reduced below the 10^{-11} g goal. Since the attraction that the entire earth exerts on the proof mass produces only 1 g acceleration (by definition), it might be thought that the mass attraction of the rest of the satellite could be neglected, but the problem is that gravitational attraction varies as $1/r^2$. For the attraction of the earth, the appropriate r is the relatively large distance from the proof mass to the center of the earth, whereas there are parts of the satellite that, of necessity, are quite close to the proof mass.

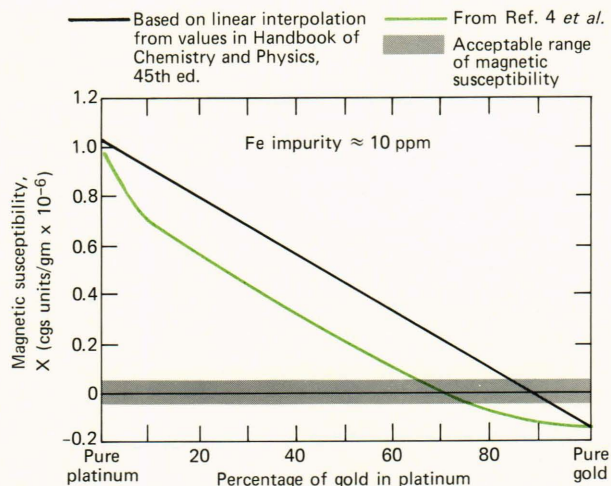


Fig. 6—Magnetic susceptibility of platinum/gold alloys. This figure, based in part on Ref. 4, shows experimentally determined magnetic susceptibility for alloys of platinum and gold. Note that the actual susceptibility departs very markedly from a linear interpolation.

Design Features

We turn now to a discussion of the design features of the Triad satellite and the fabrication techniques used to ensure that the self-gravitational force was reduced to the 10^{-11} g level. First it was desired that the Triad satellite be gravity-gradient stabilized, which suggests a barbell configuration, and thus it was easily possible to concentrate most of the mass of the satellite in one of the two ends that could be removed a substantial distance from the proof mass by extendable booms.

In the relatively small central section were concentrated only those elements intimately involved in the functioning of the DISCOS device itself. This was a great convenience since the large end masses could be treated gravitationally as point masses and only the location and distribution of masses within the DISCOS section had to be controlled with extreme precision. Propulsion was provided by cold gas released in short bursts through the electrical activation of pneumatic valves in a "bang-bang" servo system. Particular care had to be taken with the fuel storage tank since the gravitational attraction exerted by the fuel tanks had to remain small as the total amount of mass changed from the initial full tanks to the eventual empty condition. This problem was solved by the use of a pair of toroidal tanks equidistant above and below the proof mass and interconnected so that the pressure and hence the mass of fuel remained the same in each tank (see Fig. 7).

The proof mass was very accurately spherical and the "box" that shielded it from external forces was a hollow sphere. Utmost care had to be taken to ensure the uniformity of thickness and density of this hollow sphere. Fortunately, the gravitational attraction exerted by a uniform-density spherical shell on any object inside the cavity is zero. Some electronics had to be placed in close proximity to the proof mass, and

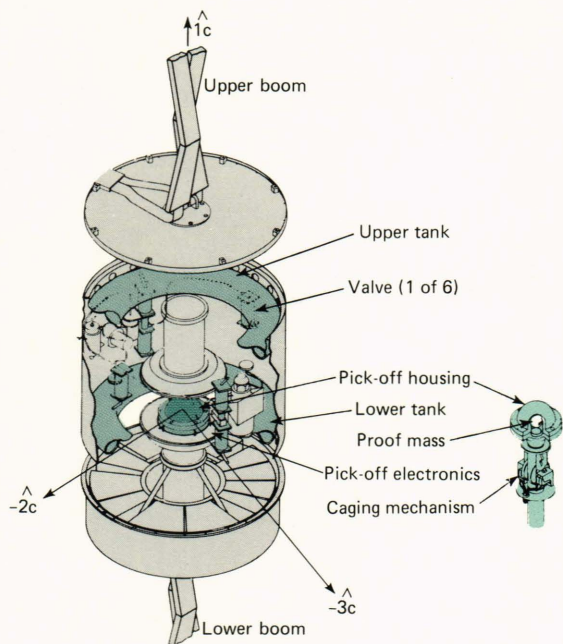


Fig. 7—Disturbance compensation system of Triad. This figure shows that the central section of Triad contained only the components required for operation of the DISCOS device: cold gas tanks and associated valves and nozzles; and the proof mass, its housing, and the electronics required for pick-off, that is, for determining the position of the proof mass within its housing.

an elaborate bookkeeping system was initiated in which the location and mass of every piece of wire, every component, and even every solder joint were carefully noted so that the total gravitational attraction could be ultimately compensated.

The satellite was launched September 2, 1972. Gravity-gradient stabilization was achieved quickly, and the DISCOS proof mass was uncaged. The system was activated, and the behavior of the proof mass is shown in Fig. 8. It is seen that within 400 seconds the proof mass was in the dead band (1 mm) and remained there as long as the DISCOS system was active. Typical proof mass activity within the 1 mm dead band is shown in Fig. 9. On some occasions when an external force was acting, the behavior was a typical one-sided limit cycle. On other occasions or for other axes, it was a two-sided limit cycle. It should be noted that the thruster firing produced a fixed impulse, and the variation in required thrust level was obtained by varying the interval between thruster firings. This approach has the great advantage of providing for a very large dynamic range for the system. It operated for over a year without interruption, after which it was intentionally turned off and thereafter operated whenever desired until the gas was exhausted. The effectiveness of the compensation for drag and radiation pressure was tested by comparing tracking data with long-term prediction. This required some refinement in our long-term prediction computation in-

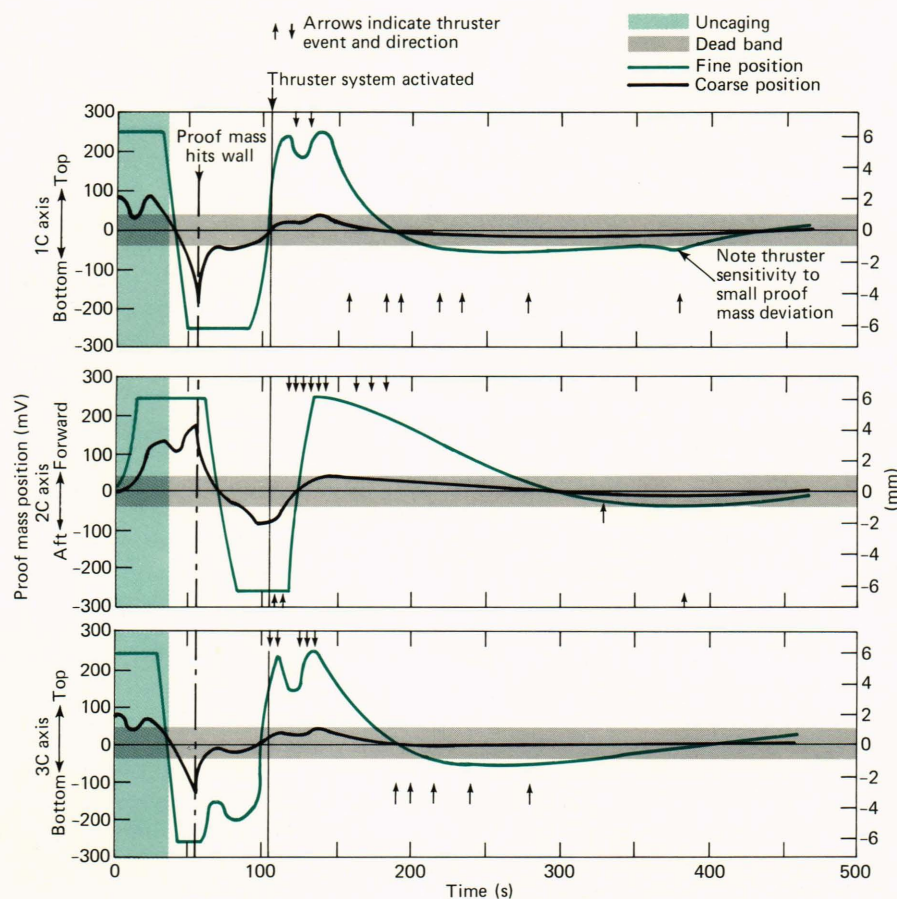


Fig. 8—DISCOS proof mass motion after uncaging. This figure shows on two different scales the motion of the proof mass on all three axes after the proof mass was uncaged. The coarse position scale (solid line) is used to follow early motion because the fine position scale (dotted line) saturates. The short vertical arrows indicate independent (impulsive) thruster firings. The large cluster of firings on the 2C axis reflects the substantial rate at which the proof mass was moving and provides some insight into the large dynamic range provided by this type of servo system.

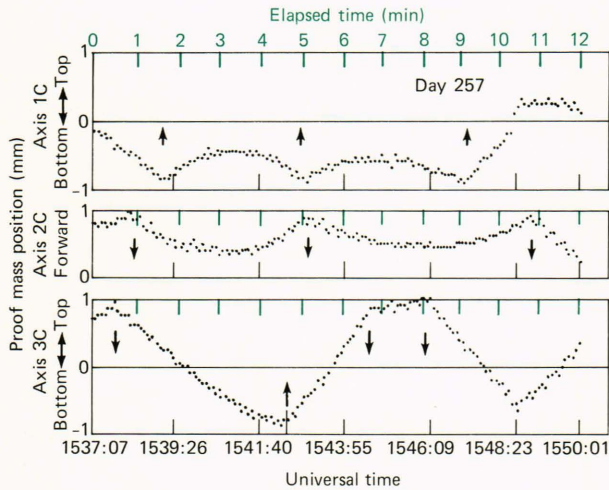


Fig. 9—Typical proof mass activity in the 1 mm dead band.

cluding the gravity field model but, when accomplished, showed that agreement could be reached on the assumption of an along-track force on the proof mass of 5×10^{-12} g.⁵

MOTIVES FOR INNOVATION

It may seem surprising that so many innovative techniques in the design of near-earth satellites were introduced by one relatively small organization, the APL Space Department. The reason is partly historical and partly a matter of attitude. Historically, the Transit Program was one of the very first satellite programs scheduled for prolonged operational use, with the corresponding emphasis on long-lived satellites and minimum-cost launch vehicles. We decided from the beginning that the long life could be achieved most readily by avoiding either expendables (as in jets) or moving parts. Thus it was natural to study carefully all available sources of torque to accomplish attitude control without either. The magnetic or gravity-gradient torques emerged as the most powerful at the intended operational altitude of the Transit satellite (600 nautical miles). In later missions when more short-lived satellites would meet the requirements, we found that an optimum design could be achieved with the use of a momentum wheel. We subsequently found that, if properly designed, momentum wheels could have extremely reliable lives in orbit. In recent years we have been less reluctant to make use of this one simple moving part.

But in some ways our approach to the design of a satellite differs from that of most satellite design organizations in the same way that the attitude of a settler in a new country differs from that of an explorer. The explorer, like the early Spanish explorers in South America, brings with him the resources to dominate the new, strange environment by sheer power of technology. The settler prepares himself to live on the resources that he finds in the new environment. Thus the earliest approach to satellite attitude control used jets that could apply torques larger than

any that would be exerted by the environment; our approach was to look at the various torques the environment would necessarily impose and specifically design the satellite so that one of these torques would dominate or could be made to dominate and then use this torque to accomplish our objective. I have stated elsewhere that this difference in attitude can be considered as the difference between engineering and applied physics.

THE FUTURE

The specific interest in drag-free satellites that led to the Triad demonstration was the fact that the Transit satellite currently requires a new orbit determination every day or two because of the unpredictability of drag effects. However, in the future this technology opens up many exciting possibilities. In particular, it appears possible to operate satellites at very low altitudes, perhaps as low as 150 km, for long periods of time. It is true that the high air density at this altitude means that very substantial propulsion capability must be provided, requiring very large satellites, but they would not need to be expensive since the greater part of the mass would be simple fuel tanks. The Shuttle program is ideally suited to putting very large masses into low altitude orbits at a remarkably low cost per pound. Some of the implications of this possibility are given in the article by Fischell and Kershner in this issue.

REFERENCES and NOTES

- ¹The current status of the Transit system is well covered by "The Transit System, 1977: Performance, Plans and Potential" by H. D. Black, *Phil. Trans. R. Soc. London Ser. A* **294**, pp. 217-236 (1980). This paper includes a substantial bibliography.
- ²Transit 5E-1 (1963-38C) produced a number of papers on solar particle access to the magnetosphere and produced a complete description of the inner radiation zone and its time history:
 - C. O. Bostrom, D. S. Beall, and J. C. Armstrong, "Time History of the Inner Radiation Zone, October 1963 to December 1968," *J. Geophys. Res.* **75**, p. 1246 (1970).
 Even more significant, Transit 5E-1 produced the first observation of magnetic field-aligned (Birkeland) currents in the magnetosphere — observations that were followed up by comprehensive measurements with the Triad satellite:
 - T. A. Potemra, "Observations of Birkeland Currents with the Triad Satellite," *Astrophys. Space Sci.* **58**, p. 207 (1978); T. A. Potemra, T. Iijima, and N. A. Saflekos, "Large-Scale Characteristics of Birkeland Currents," *Dynamics of the Magnetosphere* (S.-I. Akasofu, ed.), D. Reidel, Dordrecht, Holland, p. 165 (1979).
 A series of particle detectors of increasing complexity was flown on Injun-1 and Injun-3, IMP-6, -7, and -9, the Ito spacecraft, and IMP-8 and -9, producing measurements of energetic solar and magnetospheric particles and resulting in attempts to synthesize data from many spacecraft into a coherent picture of particle acceleration and transport:
 - E. C. Roelof and S. M. Krimigis, "Analysis and Synthesis of Coronal and Interplanetary Energetic Particle, Plasma, and Magnetic Field Observations over Three Solar Rotations," *J. Geophys. Res.* **78**, p. 5375 (1973); S. M. Krimigis, J. W. Kohl, and T. P. Armstrong, "The Magnetospheric Contributions to the Quiet-Time Low Energy Nucleon Spectrum in the Vicinity of Earth," *Geophys. Res. Lett.* **2**, p. 457 (1975); S. M. Krimigis and E. T. Sarris, "Energetic Particle Bursts in the Earth's Magnetotail," *Dynamics of the Magnetosphere* (S. I. Akasofu, ed.), D. Reidel, Dordrecht, Holland, p. 599 (1979).
 Photoelectron spectrometers flown on AE-C, -D, and -E in collaboration with The Johns Hopkins University established the characteristics of the photoelectron flux and spectrum in the earth's thermosphere and measured the low-energy portion of the auroral fluxes:

W. K. Peterson, J. P. Doering, T. A. Potemra, and C. O. Bostrom, "Characteristics of 1-500 eV Electrons Observed in the Earth's Thermosphere from the Photoelectron Spectrometer Experiment on the Atmosphere Explorer Satellites," *Dynamical and Chemical Coupling* (B. Grandal and J. A. Holtet, eds.), D. Reidel, Dordrecht, Holland, p. 353 (1977).

Most recently APL led the team that provided the low-energy particle instrumentation on the Voyager spacecraft to Jupiter, Saturn, and beyond:

S. M. Krimigis, T. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, G. Gloeckler, L. J. Lanzerotti, E. P. Keath, R. D. Zwickl, J. F. Carbary, and D. C. Hamilton, "Hot Plasma Environment at Jupiter: Voyager 2 Results," *Science* **206**, p. 977 (1979); S. M. Krimigis, J. F. Carbary, E. P. Keath, C. O. Bostrom, W. I. Axford, G. Gloeckler, L. J.

Lanzerotti, and T. P. Armstrong, "Characteristics of Hot Plasma in the Jovian Magnetosphere: Results from the Voyager Spacecraft" (submitted to *J. Geophys. Res.*); J. F. Carbary and S. M. Krimigis, "Encounters with Jupiter: The Low Energy Charged Particle Results of Voyager," *Johns Hopkins APL Tech. Dig.* **1**, No. 1, p. 60 (1980).

³B. Lange, "The Drag-Free Satellite," *AIAA J.* **2**, No. 9, pp. 1590-1606 (1964).

⁴D. W. Budworth *et al.*, "The Thermal and Magnetic Properties of Some Transition Alloys," *Proc. R. Soc. London Ser. A* **257** (1961).

⁵A more complete description of the Triad results is given in "A Satellite Freed of All but Gravitational Forces: Triad-1," AIAA Paper No. 74-215, prepared by the Applied Physics Laboratory and the Guidance and Control Laboratory of Stanford University.