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SPACECRAFT DESIGN INNOVATIONS IN THE APL SPACE DEPARTMENT

The Applied Physics Laboratory has made several important contributions to spacecraft design in the fields of Doppler tracking and navigation, attitude control, mechanisms, drag compensation, antennas, spaceborne computing, and autonomous satellite positioning. Many of these innovations have since become standard spacecraft techniques. Others are being rediscovered in the light of renewed interest in small, mission-capable satellites.

INTRODUCTION

Since its beginning in 1959, the APL Space Department has designed, built, and launched fifty-four satellites (Fig. 1). Fifty-one were completely assembled at APL; three (the Delta series) were built jointly with McDonnell Douglas. An additional twenty-three satellites were fabricated by government and industry to APL's designs as part of the Navy Navigation Satellite System (Transit) production runs. The Space Department has also provided about seventy scientific instruments and numerous engineering subsystems for launch on non-APL spacecraft.

Despite its relatively small size, the Space Department has been remarkably productive in introducing and implementing simple and effective technical solutions to spacecraft engineering problems. Many of these techniques have become standard spacecraft practice without it being widely known—even by some of our younger staff—that they were invented at APL. Richard B. Kershner, the founding head of the Space Department, described some of these innovations about thirteen years ago.[1] This article is a follow-on to his and presents revisions, updates, and subsequent developments, including some Kershner was perhaps too modest to mention.

DOPPLER TRACKING

Shortly after the launch of the Russian Sputnik-1, APL researchers William H. Guier and George C. Weiffenbach discovered that they could determine the satellite's orbit solely from RF Doppler measurements made on a single pass over APL.[2] Inventing and reducing to practice the use of Doppler signals for tracking and navigation were probably the APL space program's most significant technical advances. These led to the invention of the Transit satellite navigation system and the establishment, in 1959, of what is now called the APL Space Department.

It is not at all obvious that Doppler tracking should work. In general, knowledge of Doppler shift as a function of time is insufficient to completely determine the path of a transmitter. A satellite of the Earth, however, has so many other constraints on its motion that knowledge of the time rate of change of slant range, which is what Doppler shift measures, is sufficient to determine the satellite's orbit. Researchers at other laboratories had thought about this problem, but had oversimplified the analysis, concluding (incorrectly) that the orbit could not be found at all or that it could be found only with low accuracy. Only Guier and Weiffenbach solved the theoretical problem correctly, concluding that a highly accurate orbit could be determined using Doppler data gathered from a single pass.

In March 1958, Guier and Weiffenbach were discussing their Doppler tracking results with Frank T. McClure. It occurred to McClure to invert the problem: if the position of the satellite were accurately known, Doppler data could tell an observer on the ground his unknown position. This new navigation principle could solve a difficult problem then facing the Navy—the worldwide navigation of Polaris submarines. Thus began the Transit navigation system.

By September 1959, APL launched its first satellite, Transit 1-A, to test the Doppler navigation principle. The launch vehicle's final stage failed to fire, so 1-A flew ballistically for only twenty minutes. But Doppler data taken during this partial orbit and compared with independent radar tracking data confirmed that the "orbit" could be determined to about 0.1 nmi, roughly the accuracy of the radar itself.

In 1960 the second Transit (1-B) was launched, and it did achieve orbit. In addition to validating the Transit navigation concept, 1-B supplied data to help settle an important question regarding the shape of the Earth. We expected the satellite's apogee and perigee radii to decrease monotonically because of atmospheric drag. Instead, we were surprised to discover that the radii oscillated about their decreasing mean values with a period equal to the period of perigee precession. This discovery proved that the Earth had a significant north–south asymmetry in its gravitational field, that is, the Earth was "pear shaped." Evidence pointing in this direction had been announced previously by NASA and others, but those findings were not generally accepted. (Another Transit, 4-A, subsequently discovered the ellipticity of the equator.) Transit 1-B showed that improved knowledge of the

Earth's gravitational field would be important to achieve the ultimate potential of Doppler positioning. The inference of the shape of the Earth's field from satellite Doppler measurements became known as *dynamic geodesy*, which supplanted all competing methods. The Laboratory launched the first dedicated geodetic satellite in 1961, ANNA (Army, Navy, NASA, and Air Force) 1B, which also flew the first gallium arsenide solar cell in space. Ultimately, seven APL satellites were launched specifically for geodetic research (Fig. 1).

Doppler positioning was also affected by the refraction of RF signals as they traversed the ionosphere and troposphere. Refraction effects could cause many hundreds of meters of navigational error at 150 MHz. The Space Department began a research program on these effects and eventually built and launched a series of seven ionospheric research satellites for both DoD and NASA (Fig. 1). The Laboratory was the first to demonstrate the dual-frequency method of correcting for these ionospheric errors, and (on the Triad satellite) demonstrated *single*-frequency refraction-free navigation using pseudonoise modulation. Additional satellites and experiments were launched to study the radiation environment, cosmic rays, geomagnetic phenomena, atmospheric drag, and solar radiation, all to collect information to help design the Transit satellites.

Virtually everything used in those first satellites had to be invented or built from scratch, since no space industry existed to supply subsystems or "black boxes." In addition to the innovations discussed in this article, many incidental space engineering "firsts" achieved by APL (Table 1) came from the Transit program: Transit 3-B flew the first electronic memory in space; Transit 4-A was the first satellite to fly a nuclear power supply (six APL satellites were powered this way); and Transit 5A-1 demonstrated the first uplink authentication system.

The increasing lift capability of launch vehicles soon led APL and the Navy to consider launching multiple payloads with a single vehicle. Transit 2-A and the Naval Research Laboratory's Solrad-1 became the world's first multiple payload launch, using piggyback separation techniques demonstrated originally on Transit 1-B. With Transit 4-A, APL had the first triple launch. The multiple launch record may be held by APL's LIDOS (Low-Inclination Doppler-Only Satellite), sent up in 1968 with nine others on a single Atlas. Unfortunately, the heat shield failed to deploy, and all ten satellites were lost. Multiple launch is a routine practice today; eight Transits have been launched in pairs.

One important development required for Transit was a high-quality oscillator. As a rule-of-thumb, a frequency error of 1 part in 10^{11} gives a navigational error of about two meters. Even the first Transits needed a 1000:1 improvement over the state of the art. The Space Department introduced oven-controlled quartz crystal oscillators into space and has continually improved their drift, stability, phase noise, power consumption, radiation hardness, and reliability. Our oscillators have become recognized as the world's best, and we have built hundreds for our own and non-APL spacecraft. The incremental phase shifter and programmable frequency synthesizer carried on the TIP (Transit Improvement Program) satellites allowed for the first time the removal of all long-term drift and maintenance of the satellite's clock to within 40 ns of UTC. The Laboratory's current oscillators provide frequency stability to parts in 10^{-14}, approaching hydrogen maser performance over certain averaging times (Fig. 2).

Satellite reliability was an important consideration for Transit. In Transit 3-A (1960), APL first incorporated a passively redundant battery system that could automatically switch in a backup battery. This began a series of APL innovations in spacecraft redundancy design, particularly in the command, power, and RF systems. Recognizing the importance of temperature control for high reliability, APL flew the first automatic temperature control system (Transit 5A-3) in 1963.

Beginning with the 5-A series in 1962, the Laboratory switched to the less expensive Scout launch vehicle, which dictated a 50% reduction in weight. The use of lightweight composites (and even pure beryllium) was increased, and a series of electronics packaging innovations was started, including electronic cordwood welding, wirewrapping in lieu of connectors, and new potting techniques to compress the electronics into a central body of about one-fourth the previous volume. Steady progress continued in satellite reliability. Our Oscar-13 satellite went on to become the world record holder for the longest-lived, continuously operational satellite, performing its mission for 21.7 years until battery failure shut it down. And this was no fluke—the operational navigation satellites have demonstrated a mean-time-to-failure of more than fourteen years.

The Navy first used the Transit navigation system in early 1964, and the system was declared fully operational in 1966. Since then at least one satellite has always been available for routine use. The present single-pass accuracy is about twenty-five meters (a fraction of the typical Navy ship length), provided the navigator has good knowledge of his own velocity. Stationary users who can average multiple passes do much better than that. Transit today is used not only by the military, but by 100,000 civilian and foreign navigators and surveyors. Guier, Weiffenbach, McClure, and Kershner received numerous awards for their pioneering work in developing Transit.

MAGNETIC STABILIZATION

Until 1959, only two types of satellite attitude control had been demonstrated, the simplest being spin stabilization. If enough spin was imparted to the satellite to provide gyroscopic stiffness, the spin axis remained fixed in inertial space. Of course, this arrangement was extremely inconvenient for satellites that wanted to point toward Earth. Some early weather and communications satellites, in fact, spent most of their time looking away from the Earth. Spin stabilization seemed like a poor choice for a Doppler navigation system, because it would superimpose a spin modulation that would interfere with precision frequency measurement. The other attitude control method, found primarily in the manned space program, was the use of thrusters, which involved expendable fuels, plumbing complexities, and contaminat-

Table 1. Selected APL spacecraft design innovations.

Innovation	Spacecraft	Launch date
Satellite tracking by Doppler	Sputnik-1	4 Oct 1957
Development of satellite Doppler navigation system	—	(1958)
Yo-yo despin mechanism	Transit 1-A	17 Sep 1959
Two-frequency method for correcting ionospheric error	Transit 1-B	13 Apr 1960
First attitude-controlled spacecraft using permanent magnets	Transit 1-B	13 Apr 1960
Solar attitude detectors	Transit 1-B	13 Apr 1960
Hysteresis damping of satellite libration	Transit 1-B	13 Apr 1960
First dual-payload launch	Transit 2-A	22 Jun 1960
First satellite electronic memory	Transit 3-B	21 Feb 1961
First nuclear power supply in a spacecraft	Transit 4-A	29 Jun 1961
Damping of satellite libration by lossy spring-and-mass	TRAAC (Transit Research and Attitude Control)	15 Nov 1961
Sublimation switches	ANNA-1B (Army, Navy, NASA, and Air Force)	31 Oct 1962
First gallium arsenide solar cell experiment	ANNA-1B	31 Oct 1962
First uplink authentication system	Transit 5A-1	19 Dec 1962
Gravity-gradient stabilization	Transit 5A-3	16 Jun 1963
Automatic temperature control of spacecraft	Transit 5A-3	16 Jun 1963
Magnetic spin/despin system	DME-A (Direct Measurement Explorer-A)	29 Nov 1965
First integrated circuits used in space	Geos-A	6 Nov 1965
First yaw stabilization of a satellite using pitch axis wheel	DODGE (DoD Gravity Experiment)	1 Jul 1967
Dual-spin control of satellite pointing	SAS-1 (Small Astronomy Explorer-1)	12 Dec 1970
First satellite compensated for drag and radiation pressure	Triad	2 Sep 1972
Single-frequency refraction-free satellite navigation	Triad	2 Sep 1972
Quadrifilar helix antenna	Triad	2 Sep 1972
First satellite-to-satellite tracking	Geos-3	9 Apr 1975
Delayed command system	SAS-3	7 May 1975
Crystal oscillator with all drift removed by programmable synthesizer	TIP-II (Transit Improvement Program)	12 Oct 1975
First use of pulsed plasma microthrusters in space	TIP-II	12 Oct 1975
Worldwide time synchronization to 40 ns from a single satellite	TIP-II	12 Oct 1975
Satellite-to-satellite tracking by Doppler signals (NAVPAC navigation package)	1977 56A	27 Jun 1977
First microprocessor system in space	Seasat altimeter	27 Jun 1978
Quadrifilar helix antenna with beam shaping to compensate for slant range	Seasat synthetic aperture radar downlink	27 Jun 1978
First attitude and command systems using microprocessors	Magsat	30 Oct 1979
Autonomous satellite navigation using Global Positioning System satellites (GPSPAC)	Landsat-4	20 Jun 1983
Bifilar helix antenna	Geosat-A	12 Mar 1985
First space intercept of an accelerating target	Delta-180	5 Sep 1986

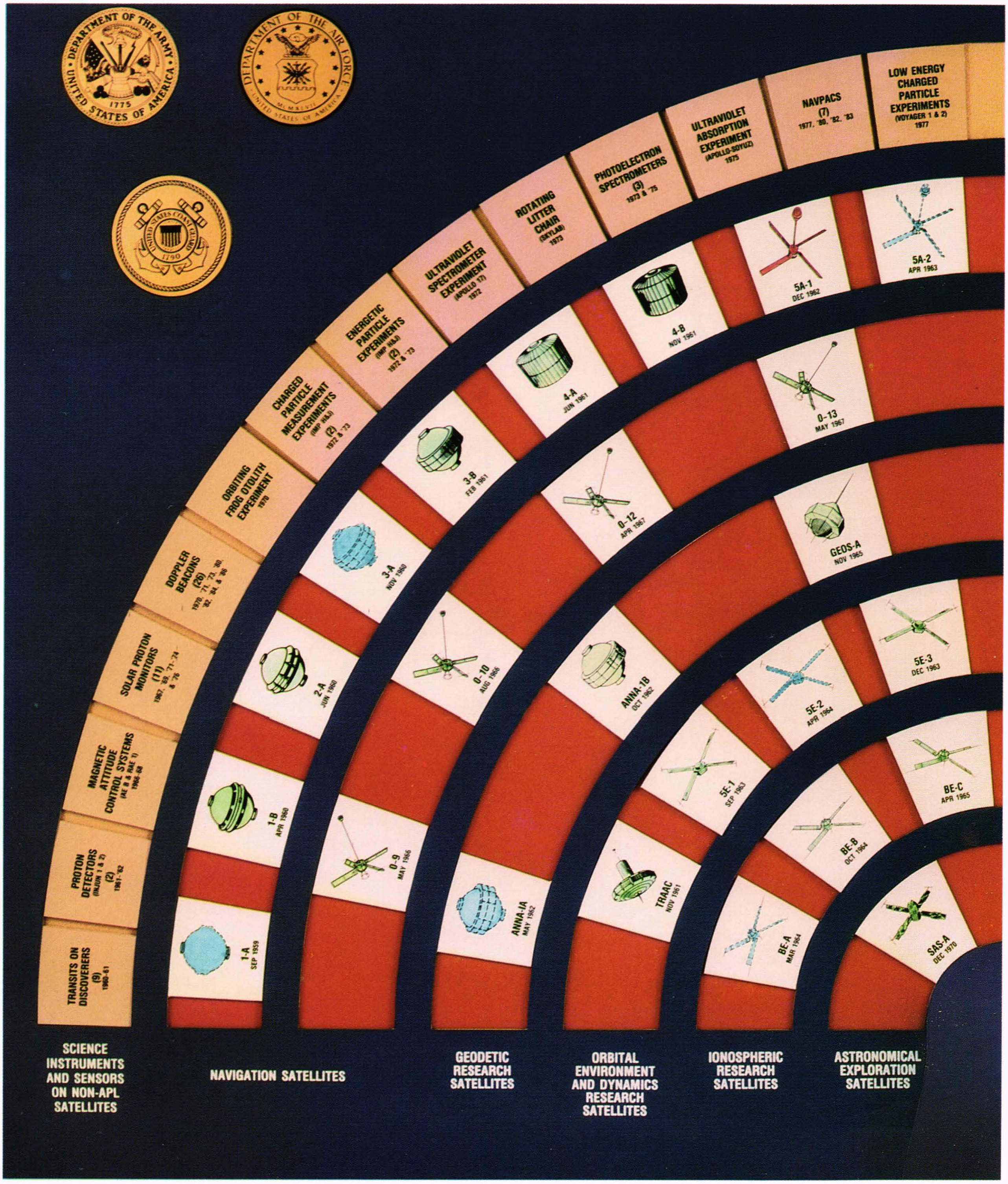

Figure 1. The APL Space Program, 1959–1991 (green, successful; blue, failed to orbit; red, partially successful).

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
U.S.A.
DEPARTMENT OF THE NAVY
UNITED STATES OF AMERICA
STRATEGIC DEFENSE INITIATIVE
DEPARTMENT OF DEFENSE
PARTICLE FLUX MONITOR (IUE) 1978
RADAR ALTIMETER (SEASAT-A) 1978
ION COMPOSITION TELESCOPE 1980
GPSPACS (3) 1983, '84, '86
MAGNETIC FIELD EXPERIMENTS (2) (DMSP & VIKING) 1984, '85
SENSOR MODULES DELTA 180 DELTA 181 DELTA 183 1986, '88, '89
ENERGETIC PARTICLES DETECTOR (GALILEO) 1989
HI-SCALE (ULYSSES) 1990
HOPKINS ULTRAVIOLET TELESCOPE 1990
RADAR ALTIMETER LASER RETRO. ARRAY FREQ. REF. UNIT (TOPEX/POSEIDON)
ULTRA-STABLE OSCILLATOR (MARS OBSERVER)
MAGNETIC FIELD EXPERIMENT (FREJA)
ENERGETIC PARTICLES & ION COMPOSITION (EPIC) (GEOTAIL)
GPS/TM XMTR (GTT) (BPFE)
5A-3 JUN 1963
5BN-1 SEP 1963
5BN-2 DEC 1963
5BN-3 APR 1964
5C-1 JUN 1964
0-4 JUN 1965
0-6 DEC 1965
0-8 MAR 1966
0-14 SEP 1967
TRIAD SEP 1972
TIP-II OCT 1975
TIP-III SEP 1976
0-11/ TRANSAT OCT 1977
GEOS-B JAN 1968
LIDOS AUG 1968
GEOS-C APR 1975
GEOSAT-A MAR 1985
5E-5 DEC 1964
DODGE JUN 1967
MAGSAT OCT 1979
CCE/AMPTE AUG 1984
MSX
DME-A NOV 1965
P76-5 MAY 1976
HILAT JUN 1983
POLAR BEAR NOV 1986
SAS-B NOV 1972
SAS-C MAY 1975

ing by-products. The Laboratory felt that thrusters were incompatible with the goal of achieving a five-year lifetime for a navigation satellite.

Clearly, the time had come to invent a new attitude control method, and our thoughts turned toward using the Earth's magnetic field. Beginning with the second satellite (Transit 1-B), a large, permanent magnet was installed. The magnet was aligned with the symmetry axis, causing that axis to follow the direction of the Earth's magnetic field. This alignment guaranteed that one specific side of the satellite would point toward Earth in the Northern Hemisphere; 1-B became, in fact, the first attitude-controlled satellite. To verify attitude capture, the Space Department also invented and flew the first solar attitude detectors (SAD's); these became the precursors of the digital SAD's widely used today. The fact that the wrong side of the satellite pointed toward Earth at low latitudes was of no consequence for the first few satellites, because APL did not yet have ground stations worldwide. Although Transit soon abandoned passive magnetic stabilization for more advanced methods, the idea has been periodically resurrected for low-cost "cheapsats."[3]

By replacing the permanent magnet with commandable electromagnetic coils, the Space Department found a solution to the "upside-down capture" problem inherent to gravity-gradient stabilization (discussed in a later section). More recently, advances in spaceborne computing, along with better knowledge of the Earth's magnetic field, have led to an APL-proposed active magnetic attitude control system that would be simple and reliable and have no moving parts or expendables.[4]

MAGNETIC DAMPING

Some means of damping was required to make magnetic stabilization reliable. Robert E. Fischell suggested a simple and ingenious solution using long, thin "hysteresis rods." These nickel–iron rods are easily magnetized, even by the Earth's weak field. The rod material also exhibits substantial magnetic hysteresis; that is, the current state of magnetization depends heavily on its former state. The behavior of a rod of high-permeability material with hysteresis, rotating in a magnetic field, is described by Warburg's Law: 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, for an inertia I, the rate of energy loss is proportional to the angular velocity ω, or

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

from which

$$I\dot{\omega} = \text{constant}. \tag{2}$$

By installing such a rod in a satellite, a constant retarding torque is produced that opposes any rotation. Since this opposing torque remains constant, even for very slow rotation, hysteresis damping is effective even at low angular velocities. In comparison, viscous damping becomes less effective as the rotation rate decreases. Hysteresis damping has worked well for many APL satellites and is now a standard technique.

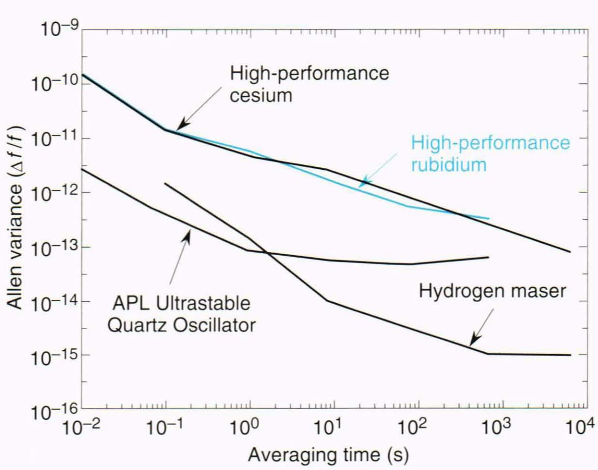

Figure 2. Frequency stability of a modern APL satellite oscillator in terms of Allen variance versus averaging time. Over certain important regions of operation, the APL quartz oscillator compares favorably with more complex oscillators (f = frequency).

THE YO–YO

Many early launch vehicles had spin-stabilized upper stages; some still do. The Transit satellites, therefore, arrived on orbit spinning at up to 160 rpm. Some way had to be found to remove this angular momentum before the solar arrays could be deployed and the satellite stabilized. The Laboratory provided a very reliable and widely practiced solution to this problem by developing the "yo-yo," which was used on APL's first satellite, Transit 1-A (Fig. 3).

Consider a disk-shaped satellite of radius R and inertia I_z spinning about its axis with initial angular velocity ω_0 (Fig. 4). One end of a wire is fastened to the circumference of the disk; it is then wrapped around the circumference in a direction opposite to the direction of spin. A weight of mass m is attached to the other end of the wire and held against the circumference. The initial moment of inertia of the satellite plus weight is therefore $I_0 = I_z + mR^2$. When 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 are used to prevent transverse forces on the spin axis. Most analyses (a thorough one is given in Ref. 5) assume a single weight, however.

By applying conservation of angular momentum and conservation of kinetic energy to the satellite-weight system, the satellite velocity after release of the weight is easily shown[5] as

$$\omega = \dot{\phi} = \omega_0 \frac{I_0 - ms^2}{I_0 + ms^2}, \tag{3}$$

where s is the amount of wire paid out at any given time. Equation 3 shows that the satellite will have zero velocity when a length of wire

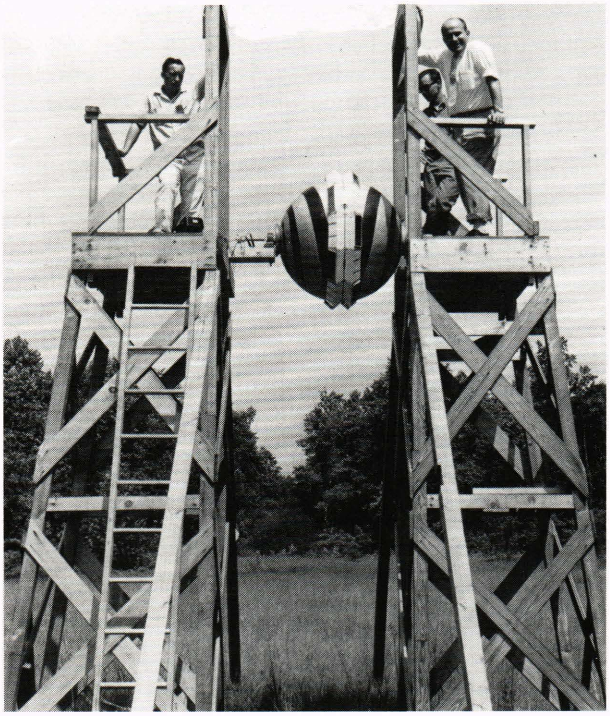

Figure 3. The yo-yo mechanism being tested on APL's first satellite, Transit 1-A. Logarithmic spiral antennas are painted on each hemisphere. James F. Smola (right) is now Spacecraft Manager of APL's fifty-fifth satellite, the MSX (Mid-Course Space Experiment).

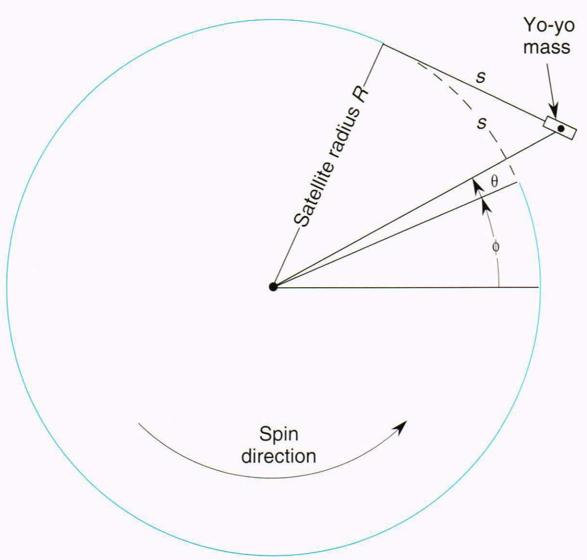

Figure 4. Yo-yo geometry showing the variables used in Equations 3 and 4, which describe the removal of spin by deploying a yo-yo on a wire (s = amount of wire paid out, ϕ = angle turned by the satellite after release of the weight, and $\phi + \theta$ = the polar coordinate of the weight).

$$s = \sqrt{\frac{I_0}{m}} \quad (4)$$

has been paid out. If more wire is paid out, the satellite will actually begin to spin in the opposite direction. If the length of wire s is attached to the satellite with a hook-and-eye release mechanism, the wire and weight will detach and fly away from the satellite when the wire reaches the radial direction. The weight will then fly off into space, carrying with it all of the satellite's initial angular momentum and leaving a totally despun satellite. Significantly, the yo-yo design for total despin does not depend in any way on the initial angular velocity.

Clearly, from Equation 3, the yo-yo can be designed to leave the satellite with any desired fraction—from +100% to −100% —of its initial spin rate. Imperfections in yo-yo design usually leave a small residual spin rate, even when total despin is desired. This residual is easily removed with the magnetic hysteresis rods described earlier. The Laboratory has also used the yo-yo cables to restrain the solar arrays before deployment. One simple device thereby accomplishes two functions.

Many separation and deployment events on the early satellites were controlled by "sublimation switches," another APL invention. These comprised sets of electrical contacts held apart by a plug of material that readily sublimes in the vacuum of space (helped along by the heat of the final stage motor). Beginning with the TRAAC (Transit Research and Attitude Control) satellite in 1961, APL measured the sublimation rates of biphenyl and other substances in orbit and used the data to design separation switches. These served as simple, foolproof separation devices until the electronics state of the art caught up.

Interestingly, the yo-yo was not APL's first concept for despinning a satellite. Our original thought was to increase the moment of inertia by paying out a weight on the end of a wire from the center of the satellite. This technique would have required a payout mechanism and would have only slowed, not stopped, the spin. It then occurred to Richard Kershner that wrapping the wire around the outside of the satellite and allowing centrifugal force to unwrap it would accomplish the same increase in inertia and also apply a retarding torque. The analytical result showing that this technique could bring the satellite to a complete stop, and even reverse its direction, was so counterintuitive that it was greeted with disbelief until a model was demonstrated. After inventing, developing, and perfecting the yo-yo, APL learned that the Jet Propulsion Laboratory had independently (and slightly earlier) invented and demonstrated the same thing. It was, as Kershner said, clearly an idea whose time had come.

GRAVITY–GRADIENT STABILIZATION

The passive magnetic stabilization used on early Transits tumbled the satellites in pitch at a rate of two revolutions per orbit. Operational satellites stabilized this way would have required either isotropic antennas or antenna switching, both undesirable. The Laboratory, therefore, began development of a simple, reliable, and totally passive alternative based on the use of gravity-gradient torques to maintain one side of the satellite pointing toward Earth at all times.

Gravity-gradient stabilization can be understood without equations. Consider a barbell-shaped satellite consisting of two masses separated by a long rod (Fig. 5). Be-

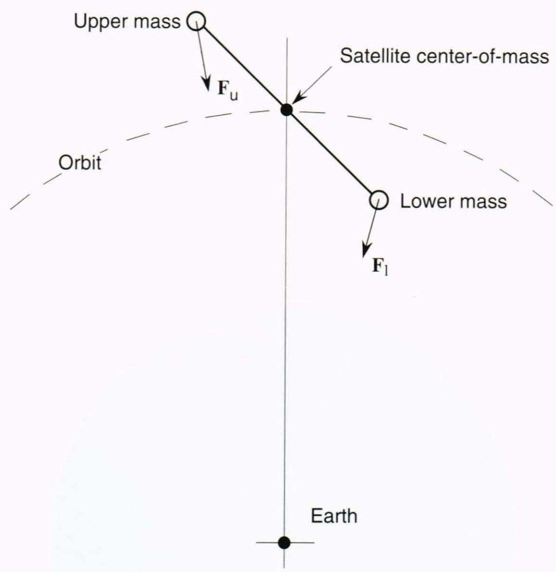

Figure 5. The gravity-gradient concept. The attractive force ($\mathbf{F}_l$) on the lower mass *m* of a barbell-shaped satellite exceeds the attractive force ($\mathbf{F}_u$) on the upper mass. A torque, therefore, arises to align the satellite toward the vertical.

cause the Earth's gravitational attraction falls off as $1/r^2$ (where r is the distance from the center of the Earth), the force on the lower mass is stronger than that on the upper mass. Thus, a torque arises that tends to align the rod to the vertical direction. It had long been understood that gravity-gradient torque is what keeps one face of the Moon pointing toward the Earth.

Because the gravity-gradient torque is so small (5×10^{-5} N·m/deg, typically), the feasibility of using this technique to stabilize satellites was in considerable dispute around 1960. The Space Department recognized the small value of the torque, but argued that if it could be made to dominate all other competing torques (magnetic, aerodynamic, radiation pressure, and so on), then gravity-gradient stabilization could be achieved. The Laboratory's TRAAC satellite flew the first gravity-gradient boom in 1961, but only a meter or so of the 18-m boom deployed, and stabilization was not demonstrated. (The TRAAC satellite did, however, set the record for shortest time from concept to launch of any entirely new spacecraft: 3½ months.) Transit 5A-3 (1963) became the first satellite to achieve gravity-gradient stabilization, and the technique has been widely used since.[6]

A major concern with gravity-gradient stabilization is to provide a damping mechanism so the satellite does not librate 45° or more about the vertical direction. Our first satellites used spring-and-mass dampers in which libration energy was dissipated in the flexing of a helical spring between the end mass and the boom. Transit 5C-1 (1964) demonstrated that the same hysteresis rods used for damping magnetic stabilization were also effective for gravity-gradient stabilization; magnetic damping has been used ever since.

A special problem with gravity-gradient stabilization is that the satellite is 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 recovered. The Laboratory developed two methods to achieve capture. For satellites in polar orbits (e.g., the Transits), an initial stage of magnetic stabilization was used, polarized so that the desired end of the satellite faced Earth over the north magnetic pole. During a suitable pass over the pole, the electromagnet was commanded off, and the gravity-gradient boom was extended. For satellites in low-inclination orbits that did not pass over the pole, APL developed an inversion procedure using boom retraction and re-extension. This method was used on Geos-1, the first NASA gravity-gradient satellite.

The gravity-gradient torque, small even for low-Earth–orbit satellites, falls off as the *cube* of the orbit radius. In 1967, APL launched the DoD Gravity Experiment (DODGE) satellite to determine how well a high-altitude orbit could support gravity-gradient stabilization. The satellite, with ten booms and a variety of dampers, demonstrated that gravity-gradient stabilization could be achieved at near-synchronous altitude—but just barely. A camera flown on DODGE to observe boom deployment and position took the first color picture of the full Earth, a famous photograph that appeared as a foldout in the November 1967 *National Geographic*. The DODGE satellite also carried a constant-speed "momentum wheel" whose spin axis was aligned normal to the orbit plane. The DODGE mission was the first to demonstrate use of the gyroscopic stiffness of a "pitch axis wheel" to stabilize a gravity-gradient satellite in yaw. This simple and reliable method of achieving three-axis control has since been used on many satellites.

Gravity-gradient stabilization, with or without yaw control, is now accepted as a simple and reliable means of achieving Earth-pointing in the altitude range from a few hundred to a few thousand kilometers, where gravity-gradient torques dominate both drag and radiation pressure. This method is a reasonable choice for missions requiring a few degrees of stabilization (e.g., RF missions). Although conceptually simple, gravity-gradient stabilization is full of subtleties; APL has taken a leading role in understanding and applying these subtleties.[6]

MAGNETIC SPIN–DESPIN

The yo-yo and magnetic hysteresis rods provided a convenient way to remove spin from a satellite. In 1963, APL faced the opposite problem: to add spin to a satellite (the Direct Measurement Explorer, DME-A) after it was in orbit. Furthermore, the direction of the spin axis in inertial space had to be controllable by ground command. The DME-A had to spin slowly about an axis normal to its orbit plane so that its instruments could scan ionospheric charged particles from different view angles.

Because DME-A's instruments directly measured ionospheric constituents, contamination concerns ruled out the use of attitude-control thrusters.

Fischell solved this problem by using only the Earth's magnetic field. If three mutually orthogonal electromagnets are placed within a satellite, a magnetic dipole **M** can be established in any direction. The satellite can determine the Earth's field **H** at any moment by means of a vector magnetometer. By activating the electromagnets appropriately in response to the magnetometer measurements, a torque $\mathbf{T} = \mathbf{M} \times \mathbf{H}$ in any direction can be obtained. This torque can be used to spin up the satellite to any desired rate, or to despin it, or to precess the spin axis.

Essentially, APL made the satellite act like the rotor of an electric motor, with the Earth's magnetic field serving as the stator. The DME-A spin system maintained a constant spin rate by supplying energy to compensate for damping losses without requiring commands from the ground. The precession torques were ground-commanded. The spacecraft operators quickly found the torques that would yield a precession rate almost exactly matching the precession of the orbit plane, so a commanded change in torque was needed only about once a week. The entire system worked well on its first attempt and proved a simple, reliable, and accurate method of controlling a spinning satellite; the method has been used many times since. *Industrial Research* selected the magnetic spin system as one of the 100 most significant industrial inventions of 1967.

DUAL–SPIN STABILIZATION

Magnetic spin-axis precession does not require that the entire satellite spin at a high rate. It need only have a large angular momentum vector, which can be achieved by a constant speed momentum wheel within the satellite. With such a wheel providing the gyroscopic stiffness, a magnetic spin/despin system of the type already described can control the angular velocity of the rest of the satellite to any level, including zero or even back-and-forth scanning. This system, suggested by Fischell also, was first used in our Small Astronomy Explorer (SAS-1, 1970). This satellite carried an X-ray telescope to survey the entire celestial sphere. The SAS-1 had to rotate very slowly because of the response time of the telescope. The flexibility and controllability allowed by the dual-spin system were crucial to the astronomical discoveries made by SAS-1, which included the first evidence supporting the existence of black holes.

A particular mode of dual-spin operation arises if the spin axis is placed normal to the orbit plane. Then, if the main satellite body is controlled to a spin rate of one revolution per orbit, an alternative method of Earth-pointing a satellite is available. The rapidly spinning momentum wheel can even include its own outward-looking infrared horizon scanner. Nadir direction can then be accurately determined as the midpoint of the high-temperature Earth region, easily distinguished from the cold space background. By including a fine adjustment in the spin rate of the momentum wheel, the main satellite's spin rate can be made to accelerate or decelerate. This mode of operation was incorporated and successfully demonstrated in SAS-3 (1975). Dual-spin stabilization has been used on many spacecraft, and scanner wheels of the type described are now commercially available.

Earth-pointing capability was included in SAS-3, not to satisfy its primary mission (X-ray astronomy), but to demonstrate the general-purpose capabilities of the SAS design. The first mission to need dual-spin Earth-pointing was the magnetic survey satellite Magsat (1979). This satellite successfully validated operational use of dual-spin stabilization and also demonstrated to NASA the usefulness of a general-purpose scientific satellite bus that could support a variety of bolt-on experiments. This bus concept is now being rediscovered by NASA for small, mission-capable satellites ("lightsats").

THE DRAG–FREE SATELLITE

One of the most challenging technical advances undertaken by the APL Space Department was the development of the "drag-free" satellite Triad, launched in 1972. Triad was the first satellite to fly a completely gravitational orbit, free from all surface forces such as drag and radiation pressure. What made this possible was the Disturbance Compensation Device (DISCOS). This concept, sometimes referred to as a "ball within a box," was invented independently by several people well before the space age (see, e.g., Ref. 7). Its original purpose was to improve the accuracy of ballistic missiles by eliminating aerodynamic drag effects. The concept was considered too difficult to apply to missiles, but was suggested for application to satellites and was first implemented by APL in Triad.

To understand DISCOS, imagine a satellite having a hollow cavity containing a small proof mass (Fig. 6) and some system for sensing the position of the proof mass without disturbing it. A set of six thrusters can propel the satellite in the direction of any of three orthogonal axes. Once in orbit, the proof mass is uncaged, and the thrusters are then fired in such a way as to keep the proof mass centered in the cavity. Since the proof mass is shielded from all external forces, it flies a purely gravitational orbit. The satellite, centering itself around the proof mass at all times, flies the same disturbance-free orbit. This came to be known as a drag-free orbit, since drag is the dominant external force at Transit altitudes.

Although such a disturbance compensation system had never been flown before on either a missile or a satellite, considerable analysis and simulation had been done by the Stanford University Guidance and Control Laboratory under Daniel DeBra. The APL Space Department relied heavily on this work and subcontracted Stanford to assist with the DISCOS portion of Triad. We saw clearly at the outset that the various forces acting on the proof mass had to be well controlled, and Triad had to keep all forces, other than the Earth's gravitational attraction, below $10^{-11}g$.

To keep the magnetic attraction or repulsion low, APL fabricated the proof mass from a special gold–platinum alloy. Measurements by the National Bureau of Standards confirmed that the alloy's magnetic susceptibility was almost unmeasurable. Thermal radiometer forces (the

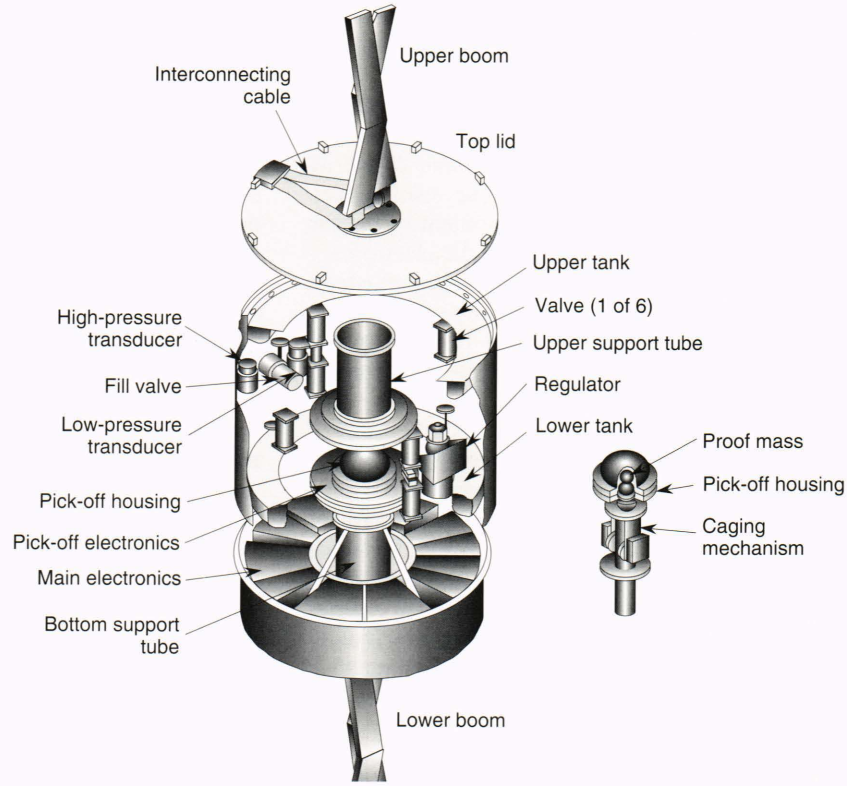

Figure 6. The three-axis DISCOS (Disturbance Compensation Device) portion of Triad. A proof mass within a cavity flies a drag-free orbit. Triad continually centers itself around the proof mass by firing cold-gas microthrusters. For the follow-on TIP (Transit Improvement Program) satellites, APL switched to a single-axis DISCOS and long-lived pulsed plasma microthrusters. An exposed view of the proof mass and housing is shown on the right.

same forces that drive the vanes in a Crooke's radiometer) were eliminated by careful thermal design and by using high-density proof mass material.

The most difficult design problem was to ensure that the gravitational attraction exerted by the rest of the satellite on the proof mass was below 10^{-11} g. Since Triad was to be gravity-gradient stabilized, the satellite was divided into three sections (Fig. 7). Most of the mass was placed in the two end segments of a barbell configuration, well-removed from the central DISCOS section by extendable booms. So although accurate bookkeeping had to be kept of the mass and position of every element of the small DISCOS section, the two outer sections could be treated for gravitational purposes as point masses. Cold-gas impulse thrusters located in the DISCOS section received their fuel from two interconnected tanks to balance the mass of the fuel.

Following launch, Triad quickly achieved gravity-gradient stabilization, and the proof mass was uncaged. Within 400 seconds of activating the system, the proof mass entered the 1-mm dead band and remained there as long as DISCOS was active. The DISCOS operated for 2½ years, until its fuel was exhausted. The effectiveness of the compensation for drag and radiation pressure was tested by comparing tracking data with long-term predictions. In one experiment, the satellite position was predicted ninety days ahead with an error of only 300 m.

The Triad DISCOS data proved that the main external disturbance affecting long-term orbital prediction was the along-track drag force. Thus, for the next two Transit Improvement Program satellites, TIP-2 and TIP-3, DISCOS was simplified to a single-axis unit, developed at APL under Albert Sadilek. The single-axis DISCOS uses a toroidal proof mass suspended around a straight wire and is kept from touching the wire by means of ac eddy current repulsion (Fig. 8). Since a cold-gas thruster system was inconsistent with the ten-year lifetime desired of an operational system, a set of Teflon pulsed-plasma microthrusters was installed. This propulsion technique, in which a tiny impulse is obtained by vaporizing a minute quantity of Teflon with a high-voltage pulse, was used for the first time in space on the TIP satellites. The TIP design was subsequently turned over to industry as the latest operational satellites, Nova, and three are in orbit.

Operational DISCOS data supplied by Triad, TIP, and Nova prompted NASA to propose a DISCOS-like instrument to test a fundamental precept of Einstein's General Theory of Relativity; NASA's Gravity Probe-B mission is now in the advanced development phase.

THE QUADRIFILAR HELIX

The Space Department needed to develop several novel antennas to radiate the Doppler signal to the ground. The first Transits used an APL-invented spherical projection of a logarithmic spiral (Fig. 3). When later spacecraft departed from spherical shape, the design switched to the aptly-named "lamp shade" antenna. That antenna, however, suffered from poor polarization and a null in its gain pattern at nadir. A new antenna was clearly needed—one that could provide broad beam coverage with good circular polarization yet be small compared with the 2-m wavelength and the spacecraft body itself.

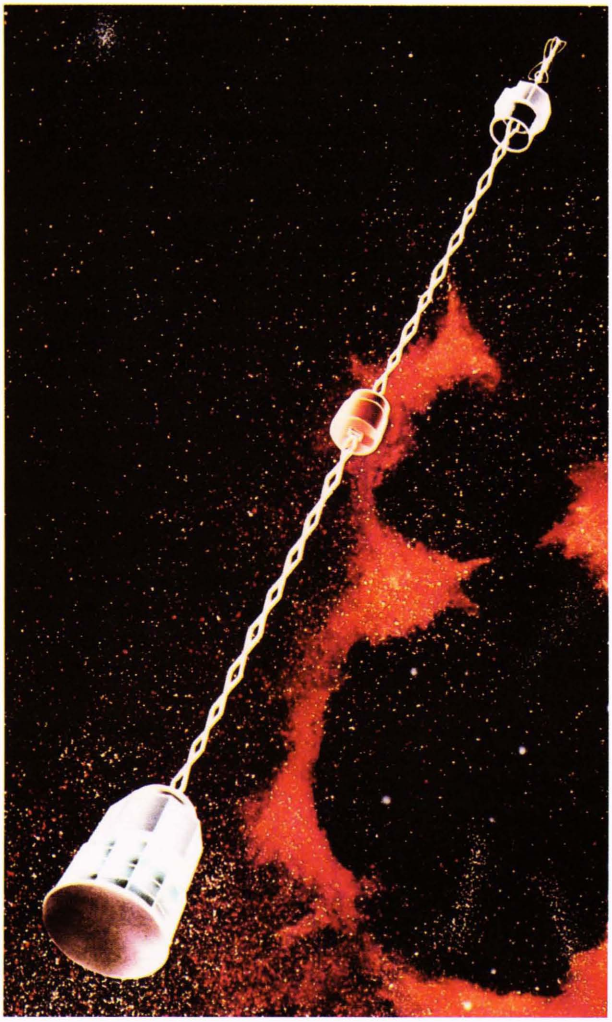

Figure 7. The first drag-free satellite, Triad. The central unit contains the DISCOS (Disturbance Compensation Device). The Earth-pointing portion (bottom) carries nested quadrifilar helix antennas. The top unit contains the nuclear power supply, the last of six flown by APL.

Charles C. Kilgus answered this need by inventing the resonant quadrifilar helix, first flown on Triad (and visible in Fig. 7).[8]

Kilgus's antenna consisted of four elements helically wound into a cylindrical shape and fed with suitable phasing to produce a cardioid gain pattern with excellent circular polarization over the entire visible Earth. Unlike unifilar helices long used for ground stations, the APL design did not need a ground plane. Furthermore, a smaller, higher-frequency helix could be fitted within the empty volume of an outer, low-frequency helix (exactly what was done for the 150 and 400 MHz Transit antennas). Because the antenna resembled a helical spring, it occurred to Charles F. Owen that the antenna could be compressed for launch. The compressed version was flown for the TIP and Nova satellites following Triad. The quadrifilar helix design has since been used on many U.S. and foreign spacecraft.

The small size of the quadrifilar helix posed a possible manufacturing liability as frequencies approached S-band. The Laboratory, therefore, developed a different version, the backfire bifilar helix, which was about twice the size, but simpler to manufacture and tune. Developed originally for an L-band buoy application, the bifilar helix had clear advantages for satellites, and APL first flew one on Geosat-A (1985).

A characteristic of low-altitude orbits is the 10-dB or more variation in satellite-to-ground slant range between horizon and zenith. Most antennas have maximum gain on their boresight, which directs most of the RF power toward nadir, where it is least needed. Our helix antennas lend themselves to easily shaping the gain pattern to compensate for the slant range variation. We flew the first shaped quadrifilar helix on the Seasat synthetic aperture radar data link in 1978. Shaped quadrifilar and bifilar helices are now becoming recognized as ideal lightsat antennas because the 2- to 3-dB improvement in link performance can reduce RF power requirements by up to 50%.[9]

PROGRAMMABLE SPACECRAFT COMPUTER

The Transit navigation concept required the satellite to store its own orbit ephemeris and transmit it to the ground. For the accuracy and duration desired, we needed a substantial (for those days) digital memory. The Laboratory therefore became a pioneer in spaceborne digital data storage, taking it through several technologies, each being the state of the art in its day. This need to store and process digital data ultimately led us to fly one of the first general-purpose computers in orbit and the first microprocessor to operate in space.

The Transit 3-B experimental navigation satellite (1961) carried the first spaceborne digital memory—384 bits of magnetic core shift register. This experiment helped evaluate technology to load and store the tens of kilobits needed to hold the navigation message. By the time Transit 4-A was operational, storage capacity using a magnetostrictive delay line had increased to 2048 bits. This technique was selected over an alternative idea being developed by Westinghouse—a combination magnetic disk drive and momentum wheel. The latter is so appealing, however, that it gets reinvented every few years, most recently as a combination optical disk and wheel.

By 1961, magnetic core storage had been adopted for its nonvolatility, radiation hardness, and reliability. This became the storage method for the 30 kilobits of navigation message in the operational (Oscar) satellites. By the early 1960s, APL was evaluating the first commercial integrated circuits (IC's) for logic applications (they were not yet nearly dense enough for data storage). The Laboratory's Geos-A (1965) is believed to have flown the first IC's in space.

With the Triad mission, control and data collection requirements became too complex for hard-wired logic. We therefore proposed, in 1968, a fully programmable, general-purpose spacecraft computer to act as spacecraft controller. James A. Perschy and Benjamin M. Elder developed this 16-bit machine using the transistor–transistor logic IC's of that era, along with a core memory storage of 4096 words. The computer included several technical innovations to reduce power consumption and pro-

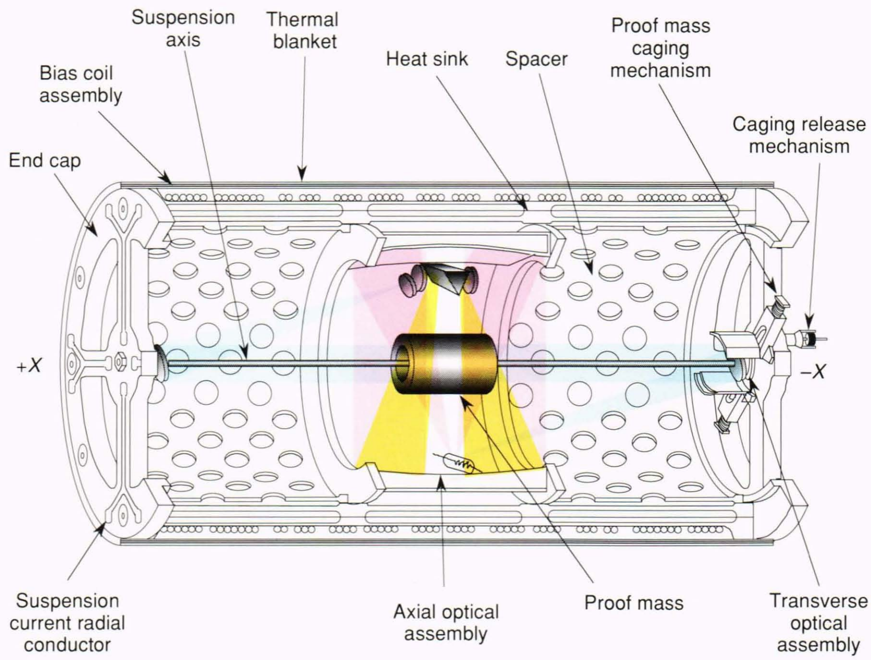

Figure 8. The single-axis DISCOS (Disturbance Compensation Device) suitable for correcting along-track drag effects. Here, the proof mass and cavity are cylindrical rather than spherical. The proof mass is held off the wire by means of eddy current repulsion.

vide extreme radiation hardness. Launched in 1972, this was one of the first reprogrammable computers in orbit.

In 1973, the microprocessor revolution began. The Space Department immediately started evaluating microprocessors for space use and two years later began designing an 8080-based controller/tracker for the Seasat altimeter. Launched in 1978, this altimeter carried the first microprocessor to operate in space. A year later, APL's Magsat satellite carried the first microprocessor-based attitude and command systems, which used radiation-hard RCA-1802 IC's.

The Laboratory continues to operate at the leading edge of spaceborne data storage and processing. New components are systematically evaluated to select those meeting stringent reliability and radiation requirements. For example, only two years after magnetic bubbles were invented in 1969, APL was evaluating them and performing conceptual designs of spaceborne data recorders for NASA. We have even designed our own microprocessor, a reduced instruction set IC, that directly executes the Forth high-level language; it will fly soon in our magnetometer experiment on a Swedish satellite. The MSX (Mid-Course Space Experiment), APL's fifty-fifth satellite (now being integrated), contains more than forty microprocessors; many are interconnected, and some are fabricated using the highly radiation-resistant silicon-on-sapphire process.

AUTONOMOUS SATELLITE POSITIONING

The accurate determination of satellite position and orbit parameters is essential for most near-Earth space missions. The APL-invented highly accurate Doppler positioning technique is still the most widely used for this purpose. This technique entails placing an ultrastable Doppler beacon on board the host vehicle (HV) satellite and collecting Doppler data with a worldwide network of ground stations. Doppler beacon hardware derived from APL's Transit program has flown on countless HV's. Although the spaceborne hardware is relatively simple, this approach does have its drawbacks: high operational costs, delays in delivering the data to a central point, postprocessing expenses, and geographical and political difficulties in optimally locating the stations. Low-altitude satellites are especially troublesome; their small circle of visibility requires many stations, yet they require the most dense set of measurements because of drag.

The need for autonomous satellite tracking was clear. The Laboratory demonstrated the first satellite–satellite tracking with Geos-3 in 1975. By closed-loop tracking through an S-band transponder, the position of Geos-3 was measured relative to the known position of NASA's Applications Technology Satellite-6.

That same year, APL took the next step toward an autonomous spacecraft navigation set with the development of the NAVPAC (Navigation Package) for the Defense Mapping Agency (DMA). The NAVPAC, installed on an HV, automatically collected Doppler data from up to three Transit satellites simultaneously. The raw Doppler data were stored on the HV and dumped to the ground for postprocessing. Six NAVPAC's were successfully launched, beginning in 1977. The NAVPAC performed well, but suffered from the low density of Transit contacts, especially at low latitudes. In addition, it was not fully autonomous since it did not compute the HV's orbit and position on board.

Around this time, the DoD was settling on the Global Positioning System (GPS) as the next worldwide satellite navigation system. The system was to be fully operational by 1983, after which it would replace Transit. Because GPS uses a different principle than Transit (time difference-of-arrival rather than Doppler shift), it requires the viewing of four satellites at once to solve for position.

But GPS was planned as a sufficiently dense constellation (twenty-four satellites originally) so that a low-Earth–orbit HV would always be able to see at least four GPS satellites. The Laboratory, therefore, proposed to DMA that a spaceborne GPS receiver and processor package (GPSPAC) be developed to perform the complete orbit determination and HV position task autonomously.[10] The GPSPAC was intended as a proof-of-concept experiment to settle such system issues as how many GPS satellites to observe, which GPS codes and frequencies were needed, whether to make simultaneous or sequential measurements, and so on.

A joint program was established in which APL had responsibility for overall system engineering and hardware for the GPSPAC, while the Naval Surface Weapons Center took on the challenging software development. The Laboratory wanted to develop the spaceborne receiver subsystem in-house but was urged by the sponsor to subcontract this portion to an outside organization to modify an existing backpack design. After the program was under way, NASA joined as a co-sponsor.

The first GPSPAC receiver/processor subsystem was flown on board Landsat-4 in 1983. The GPS satellite constellation was well behind its planned density at that time, with only four working satellites in orbit instead of the eleven promised by that date. Despite the sparse constellation, the first GPSPAC demonstrated navigational accuracy to better than 50 m over 10- to 30-min arcs on 88% of the revolutions. Three more GPSPAC's were successfully flown on board two military HV's and on Landsat-5. Industry has since followed the lead shown by GPSPAC and has developed spaceborne GPS receivers far smaller, lighter, and lower in power than the GPSPAC receiver/processor, which was based on 1976 technology.

INNOVATION AT THE SYSTEM LEVEL

Establishment of the Strategic Defense Initiative (SDI) in 1984 presented APL with new opportunities to innovate at the system level. The SDI Organization (SDIO) needed a quick and convincing demonstration that plume detection and kinetic kill principles to be used for SDI were valid. The mission was to acquire, characterize, and track a rocket plume in space, and then maneuver onto a collision course with it. Conventional industry estimating and management techniques indicated this mission would require three to five years and cost far more than SDIO could afford. At that point, APL system engineers Michael D. Griffin and John Dassoulas suggested an entirely new mission concept using the launcher's final two stages as the target and chase vehicles. The SDIO gave the go-ahead for this Delta-180 program in May 1985.

The Laboratory played a major role in developing the Delta-180 mission concepts, instruments, and satellite configurations, and in planning the mission operations and data recovery and reduction. One measure of the complexity of this mission is that range support alone involved 170 range assets, including 38 radars, 4 aircraft, and 31 satellite links. We designed a flight ultraviolet instrument, plus data handling, power, command, RF, telemetry, and support systems for our own instrument and for three other sensors. These were then integrated by APL into a 540-kg "science module," which was tested and mated to the remaining spacecraft sections provided by McDonnell Douglas (Fig. 9). Innovative design and management techniques were introduced to expedite this complex mission, resulting in a launch less than sixteen months after authorization to proceed. The mission, SDIO's first space experiment, was an outstanding success.

As Delta-180 was being readied for launch at Cape Canaveral, a follow-on mission, Delta-181, was already being planned. Its objective was to collect background, plume, and discrimination data for SDI's design database,

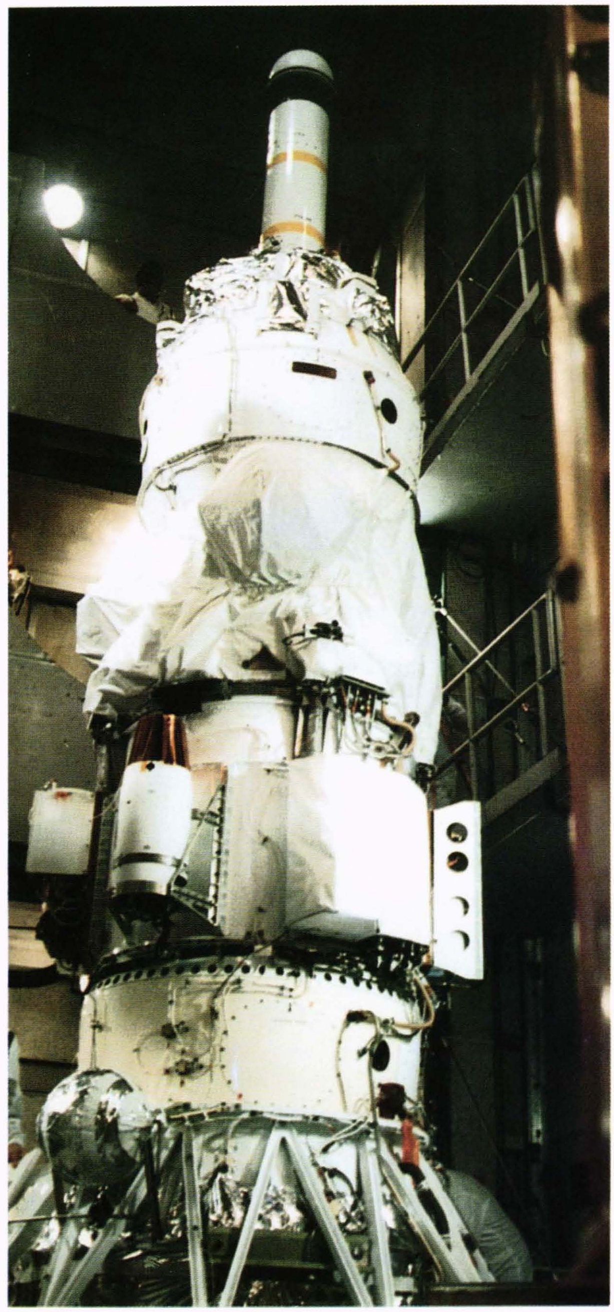

Figure 9. The Delta-180 payload being readied for launch on a Delta rocket at Cape Canaveral. The APL-provided payload is shown just beneath the thermal blankets.

and to test tracking and pointing concepts. The Laboratory again provided the sensor module, this time with seven instruments, plus the support electronics and power system. This spacecraft was even larger and more complex than Delta-180, yet we delivered it to the Cape for launch only nineteen months after go-ahead. A follow-on plumes and background measurements mission, Delta-Star, took advantage of residual Delta-181 spares to deliver a sensor module a mere ten months after go-ahead. (For a complete discussion of APL's SDIO programs, see the companion article by Coughlin et al., this issue.)

The Laboratory responded to the system challenges of the Delta programs with the same kind of creative thinking, innovation, and questioning of assumptions that had led in earlier days to the creation of Transit and the invention of gravity-gradient stabilization. The performance of end-to-end design of complex space system missions remains a major leadership area for the APL Space Department.

INNOVATION, CREATIVITY, AND THE FUTURE

How can one relatively small organization, the APL Space Department, introduce so many satellite design innovations? One might argue that in the beginning of the space age almost everything needed to be invented, since little space industry infrastructure existed. When Transit was conceived, only four primitive satellites had been put into orbit. But although the novelty undoubtedly created more opportunities for invention, it is not the whole answer.

Operating in space provided a mechanical engineer's dream: a weightless, frictionless environment in which small torques could perform useful tasks. It is no coincidence that so many of the earliest innovations came in the field of attitude control. In addition, Transit was one of the first programs scheduled for long-term operational use. The need for long-lived satellites led us to reject expendable fuels and moving parts and to seek out passive methods that took advantage of Transit's natural environment at an altitude of 1100 km. This led directly to the development of gravity-gradient and magnetic stabilization.

The Transit program, from the beginning, was planned as a series of eight (later reduced to seven) technology development satellites, each one testing one or two new concepts needed for the operational system. We thus "built a little, tested a little," and moved forward a step at a time. Some failure was expected along the way.

As the space age progressed, the capability of launch vehicles increased, and satellites became larger. Simultaneously, electronics became more dense. Many instruments and sub-missions could be combined on a single satellite "for economy of scale." As missions became ever more complex—and expensive—tolerance for risk faded. Today, a sponsor often insists on "no new developments" or "no new technology," or requires "maximum heritage" from past programs. Casual, seat-of-the-pants management gave way to formal management. Sponsoring organizations grew larger and established staff dedicated to risk management (which often meant risk avoidance). Appropriate perhaps when human lives or huge budgets are at risk, this environment does not foster inventiveness. As Jack Townsend, former Director of NASA's Goddard Space Flight Center, said, "If it *ever* happened, somebody puts in a rule so that it never happens again. This way, nothing bad ever happens, but nothing good happens either" (banquet address, AIAA/USU Conference on Small Satellites, 1988).

How can innovation prosper in this environment? In 1986, NASA held a Spacecraft 2000 Workshop to deal with the eroding space technology base in the United States.[11] Leaders of NASA spoke of reintroducing inventiveness into their programs by, for example, instituting a policy of allocating a small portion of each satellite for nonmission-critical technological development. It is unclear whether NASA project offices have taken this goal to heart.

Around the same time, the Defense Advanced Research Projects Agency formalized its lightsat initiative for small military satellites. The lightsat philosophy[12] attempts to reverse the spiral by which ever more complex missions lead to more severe reliability and quality assurance requirements (including additional redundancy, which makes the satellite even larger) and so on. Lightsats provide another low-risk way to flight-qualify advanced technologies. For a new subsystem to be considered flight-qualified on the basis of a lightsat flight, however, agreement is needed on reliability and test standards, which are still the subject of some debate.

Innovation can also be encouraged within present management structures. The Laboratory in particular uses multilevel configuration management and reliability and quality assurance systems in which a project's level of control is selected proportional to the consequences of failure. This strategy allows high-risk developmental projects to operate alongside more conservative, high-reliability missions in the same organization. Creativity can also be taught. Brainstorming sessions—in which quantity of ideas is the goal and critiquing is forbidden—are important to creative design. In many ways, brainstorming is the mirror image of a design review, in which critiquing the design is the whole point. Both activities are essential to good design, and our engineers and managers must know how to participate in, and to run, both.

In 1899, the Director of the U.S. Patent Office said, "Everything that can be invented has been invented." That is certainly not true for spacecraft. A close reading of the Spacecraft 2000 report[11] shows dozens of spacecraft developments waiting to be invented and flight-qualified, and more needs have been identified since then. With an inventive staff, a management system that fosters creativity, and enlightened sponsors who encourage new developments, the APL Space Department plans to continue its record of spacecraft innovation.

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ACKNOWLEDGMENTS: This article draws heavily on the work of Dr. Richard B. Kershner and is dedicated to his memory. I am also grateful for valuable conversations with Robert J. Danchik, Benjamin M. Elder, Robert E. Fischell, Charles C. Kilgus, Stamatios M. Krimigis, Jerry R. Norton, James A. Perschy, Reginald M. Rhue, James F. Smola, and Robert K. Stilwell.

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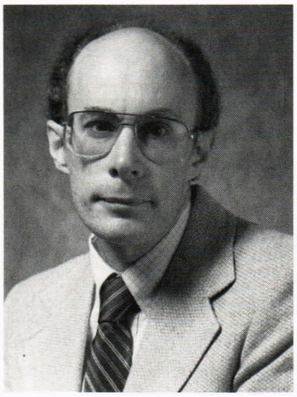

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