

GRAVITY GRADIENT STABILIZATION

Vertical stabilization of a satellite is achievable by means of the earth's gravity gradient. Gravity gradient attitude stabilization is defined as the alignment of one axis of a satellite along the earth's local vertical direction so that a particular end of the satellite always faces in the downward direction. Passive gravity gradient stabilization is defined as the achievement of this orientation, including damping the resulting librations, without use of active control elements such as servo systems, reaction wheels, or gas jets. Passive techniques can include moving parts that utilize the environment of the satellite (such as the gravity gradient itself) to damp oscillations about the local vertical.

There are several benefits to be derived from satellites that are aligned vertically, with the same side continually facing downward. Probably the greatest is that a directional satellite antenna can be utilized to enhance the signal strength of radio transmission both to and from the orbiting satellite. In a similar manner, improved optical tracking of a brilliant flashing light, as used on the ANNA satellite, can be obtained by directing the light only in a downward direction. At the altitude of a synchronous satellite (22,000 n.m.) gravity stabilization is a tremendous asset for efficient communication to and from the satellite.

Gravity gradient stabilization offers many advantages for earth observations by means of cameras on an orbiting spacecraft. For example, the quantity of usable pictures produced from a meteorological or surveillance satellite can be significantly increased when the cameras are always directed toward the earth's surface.

Several scientific experiments to study corpuscular and electromagnetic radiation are more profitably performed on a vertically oriented spacecraft.

A less obvious benefit is that gravity stabilization can be employed to improve the operation of solar-cell power-generating systems. With a system of gravity stabilization it is possible to design the satellite so that the extent of the projected area of the solar cells is inversely proportional to the percent of solar illumination. This assures a constant rate of electrical power generation irrespective of the fraction of the time that the satellite is illuminated by the sun. This same principle of changing projected area can be applied to improving the thermal design of a satellite.

Theory of Gravity Gradient Attitude Stabilization

The principle on which gravity gradient attitude stabilization is based is quite simple,^{1,2,3} although putting these ideas into practice is difficult. However, since June 1963 there have been several in-orbit demonstrations of passive gravity gradient stabilization that show that the engineering problems have been solved.

In simplest terms the principle of gravity gradient stabilization is that an elongated body will tend to align itself along the local vertical; Fig. 1 illus-

¹ R. E. Roberson, "Gravitational Torque on a Satellite Vehicle," *J. Franklin Institute*, 265, Jan. 1958, 13-22.

² W. B. Klemperer and R. N. Baker, "Satellite Librations," *Astronautica Acta*, 3, 1957, 16-27.

³ R. A. Nidley, "Gravitational Torque on a Satellite of Arbitrary Shape," *J. Am. Rocket Soc.*, 30, Feb. 1960, 203-204.

Vertical stabilization of an orbiting satellite by passive means has been accomplished successfully by use of the earth's gravity gradient. By having one end of a satellite constantly pointing downward along the earth's local vertical, radio transmissions to and from the satellite are significantly improved, and other important advantages accrue. This paper discusses the theory of gravity gradient attitude stabilization, procedures for putting it to practical use, and application of the principles in specific R and D satellites designed at APL.

of Earth Satellites

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trates this effect. The mass on the end of the dumbbell closest to the center of the earth is attracted to it by a force that we denote F . The force on the other mass we will denote f . Even if these masses are equal it is easy to see that force F will be larger than f . A torque on the dumb-

bell is thus developed that drives it to alignment with the local vertical. It is a simple matter to show mathematically that even if the masses are not equal, one can still develop substantial gravity gradient torques on the satellite.^{1,2,3}

The meaning here of substantial torques is quite different from that normally encountered by a person living on the surface of the earth where friction is omnipresent. A typical torque of a gravity gradient satellite, say 100 ft long with a mass of 3.2 lb at its end, at an orbital altitude of 600 n.m., would be 0.00026 ft-lb. This is equal to the twisting effect of a force of 0.01 lb at a distance from the pivot point of 0.026 ft (approximately 0.3 in.). Yet this torque, when applied in the frictionless environment of space, is quite adequate to stabilize a body 100 ft long. One should keep in mind, however, how small the forces really are and how careful one must be to eliminate from the satellite anything that might disturb this real, but delicate, balance.

Procedure for Achieving Stabilization

For an earth satellite to achieve passive gravity gradient stabilization, it is necessary to follow certain procedures. While these will, of course, differ somewhat for various satellite missions, some problems that are common to all will be discussed here. We will assume for all cases that the boom required to alter the mass distribution of the satellite is extended after the satellite is in orbit.

The first thing that must be accomplished is to remove virtually all the spin that may have been

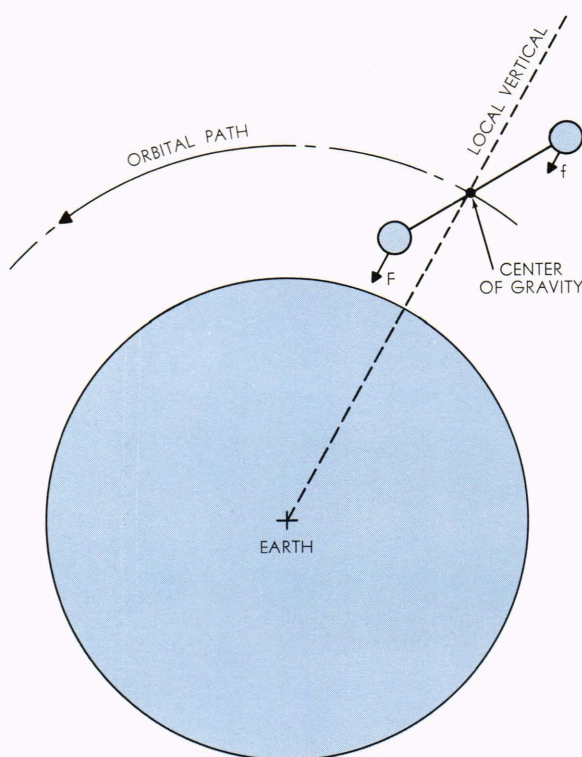


Fig. 1—Gravitational forces acting on a dumbbell-shaped satellite.

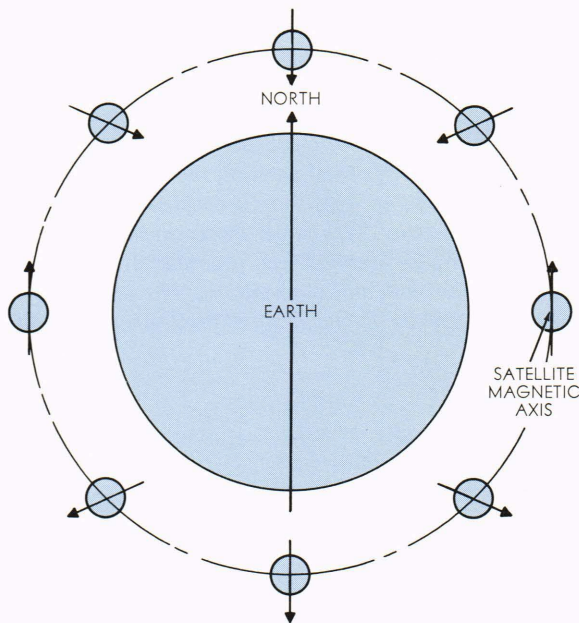


Fig. 2—Motion of a magnetically oriented satellite in a polar orbit.

imparted to the satellite during the launch procedure. A device that rapidly removes the spin energy of a satellite is the so-called “yo-yo,” consisting of two weights attached to cables that are wrapped around the satellite.⁴ When the weights are released they spin out from the satellite, causing a tension in the cables that results in a retarding torque on the satellite. This device has been successfully employed on three APL satellites as well as on several Tiros satellites. To guarantee the very low angular rates that are required when erecting a comparatively weak extensible boom, magnetic hysteresis rods can be employed.⁵ As these rods rotate in the earth’s magnetic field, they remove the spin energy of the satellite because of their magnetic hysteresis loss.

The next procedure is to align the satellite vertically with the correct side facing downward. This can be done by energizing an electromagnet that is rigidly attached to the satellite, causing it to follow the earth’s magnetic field direction in exactly the same manner as a compass needle. The direction of the magnet is along the satellite’s Z (symmetry) axis. It can be shown that the satellite will align this axis along the local magnetic field direction. For a polar orbiting satellite, the motion will then

be as shown in Fig. 2. The magnetic hysteresis rods used to remove the spin energy of the satellite will also damp the oscillations of the satellite about the local magnetic field direction. Since the local magnetic field is vertical at points directly above the earth’s magnetic poles, the optimum procedure is to capture the satellite into gravity gradient attitude stabilization as it passes over one of the poles, having previously stabilized it magnetically with a particular desired face directed toward the earth.

The boom is then erected and the electromagnet turned off by radio command from a ground station. The tumbling rate of the satellite will immediately be reduced by the ratio of the moments of inertia before and after deployment of the boom. For a typical satellite design, the moment of inertia might be increased by a factor of 100, resulting in a decrease in the satellite’s tumbling rate to 0.15 revolution per orbit (rpo). This means that the satellite is essentially stopped in inertial space. To be vertically stabilized the satellite must then achieve a tumbling rate in inertial space of 1.0 rpo. Immediately after the boom is erected, the satellite continues in its orbital motion with its Z-axis essentially fixed in inertial space. As the satellite moves away from the magnetic pole, as shown in Fig. 3, a gravity gradient torque will act upon it, tending to align the Z-axis along the local vertical

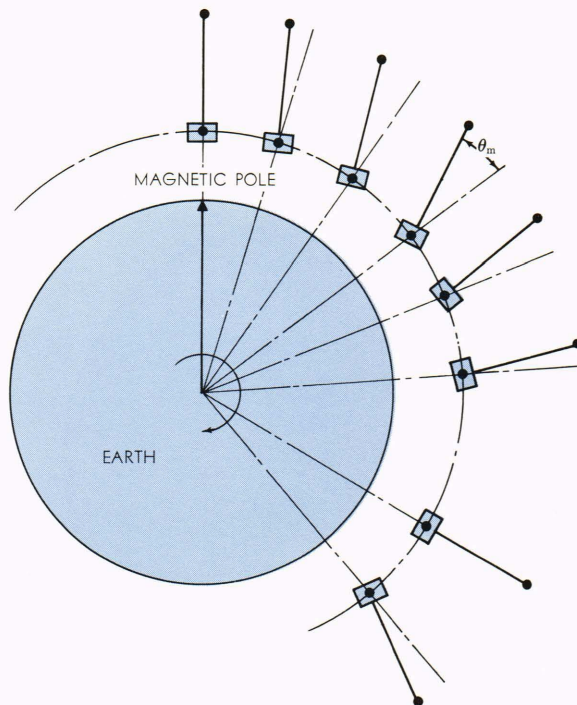


Fig. 3—Initial motion of a satellite after gravity-gradient capture.

⁴ R. B. Kershner and R. R. Newton, “Attitude Control of Artificial Satellites,” *Space Astrophysics*, McGraw-Hill Book Company, Inc., New York, 1961, chap. 14.

⁵ R. E. Fischell, “Magnetic Damping of the Angular Motions of Earth Satellites,” *J. Am. Rocket Soc.*, 9, Sept. 1961, 1210-1217.

direction. The angle with the local vertical will continue to increase until the gravity gradient torque causes the satellite to develop an angular rate of 1.0 rpo. The satellite angle with the vertical will then decrease as the gravity gradient torque continues to act, resulting in a planar libration motion of the satellite.

The maximum angle to which the satellite will swing is of great interest. If this angle is less than 90° , capture of the satellite into gravity gradient attitude stabilization will result. The angle can be calculated rather simply by equating the angular kinetic energy that the satellite must develop (to achieve an angular rate of 1.0 rpo) with the work done by the gravity gradient torque as the satellite moves out to that maximum angle.

Calculation shows that if the satellite is vertical at the time the boom is deployed, then it will swing out to a peak angle of 35.36° . If the satellite is initially at an angle greater than 54° off the vertical, it will swing out to 90° ; this, therefore, is the limiting angle for capture.

The previous discussion describes a capture process for a satellite whose orbit takes it over one of the earth's magnetic poles. This includes orbits with geographic inclinations between 74° and 90° for capture over the north magnetic pole and between 68° and 90° for capture over the south magnetic pole. This capture process can also be accomplished using the method described above for satellites with a considerably lower inclination. In this case, however, oscillations perpendicular to the orbital plane will result and must be damped out just as is the initial oscillation in the plane of the orbit. The technique of initial alignment along the earth's magnetic field is quite practical for orbital inclinations as low as 30° . At 30° N. latitude and 84° W. longitude, a magnetically stabilized satellite would only be 27° off the local vertical direction. After the boom is extended a satellite captured at this point would have an initial cross-orbit oscillation of 27° as well as the initial oscillation in the plane of the orbit of 35.36° .

In an alternate scheme the satellite's Z-axis is allowed to drift in a random manner and the boom is then erected by a command from some station when the Z-axis is observed to be within some acceptable angle, e.g. 30° , with respect to the local vertical. Another possibility is to use a system of reaction wheels or gas jets to obtain the initial orientation that is required for capture.

The next procedure, damping of the satellite librations, is essential to achieve gravity gradient stabilization. Damping removes initial librations and reduces the effect of perturbing torques and

impulses. Several methods for such damping have been suggested,^{6,7} and undoubtedly there are other possibilities for doing so. One highly promising method—the use of an energy-dissipating spring—was suggested by Dr. R. R. Newton of APL. For satellite 1961 $\alpha\eta 2$, damping of the libration motion was accomplished by this ultra-weak spring fastened to the end of a long boom.⁸ An illustration of the motions of the librating satellite with a damping spring is shown in Fig. 4.

As the satellite oscillates about the local vertical, the radial force in the direction of the boom varies because of the difference in gravity gradient force as a function of angle off the vertical plus an additional force resulting from the libration motion. This varying force causes the spring to move in and out, thus absorbing the libration energy by mechanical hysteresis in the spring. This damping has been analyzed in detail by Dr. Newton and also by B. Paul of the Bell Telephone Laboratories.⁹

Another method of damping libration motions of a satellite is by means of magnetic damping rods. While it has been shown that these rods by themselves can damp the oscillations of the satellite, a combination of the spring and the magnetic

⁶ L. J. Kamm, "Vertistat—An Improved Satellite Orientation Device," *J. Am. Rocket Soc.*, 32, June 1962, 911-913.

⁷ "Damping Spring for Gravity Stabilized Satellites," *APL Technical Digest*, 2, Nov.-Dec. 1962, 20-21.

⁸ R. E. Fischell, "The TRAAC Satellite," *APL Technical Digest*, 1, Jan.-Feb. 1962, 2-9.

⁹ B. Paul, "Planar Librations of an Extensible Dumbbell Satellite," *A.I.A.A. J.*, 1, Feb. 1963, 411-418.

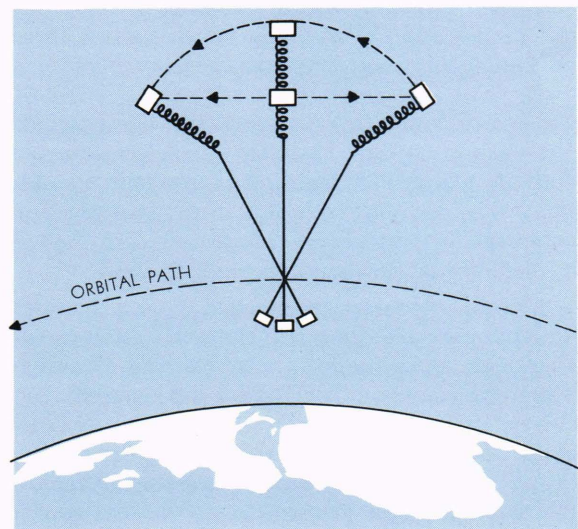


Fig. 4—Action of the damping spring during satellite oscillations.

rods is most effective. This is the technique used on the first successful gravity stabilized satellite—the spacecraft designed and built at APL, launched in June 1963, and bearing the international designation 1963-22A.

Design of Satellite 1963-22A

Pertinent physical characteristics of satellite 1963-22A are the following:

Number of magnetic rods	4
Magnetic rod dimensions	48 in. × 0.110 in.
Total rod volume	1.80 in. ³
Electromagnetic dipole strength (when activated)	2.5×10^4 unit pole-cm
Boom length	100 ft
Damping spring constant	2.14×10^{-6} lb/ft
Zero-force spring length	1.5 in.
Equilibrium spring length	20 ft
Spring dissipation per cycle (γ)	0.50
Weight of end mass	3.85 lb

MAGNETIC DAMPING SYSTEM—Satellite 22A employed four magnetic damping rods aligned perpendicular to the symmetry axis of the satellite. The rod material selected was permalloy with a nominal composition of 47.5% nickel and 52.5% iron. The rods were annealed in a dry hydrogen atmosphere to develop the highest possible value of initial permeability.

The purpose of these rods was threefold: (1) to remove the spin of the satellite about its symmetry axis; (2) to damp oscillations about the local magnetic field direction during the magnetic stabilization phase; and (3) to damp the cross-orbit (roll) oscillations of the gravity stabilized satellite.

MAGNETIC STABILIZATION SYSTEM—The magnetic stabilization system included an electromagnet, with an unannealed, high-purity iron core, in addition to the damping rods described above. By radio command it is possible to cause current to flow in a solenoid that is wound on the iron core.

With the electromagnet turned on and the satellite spin rate less than 0.1 rpm, the satellite will align itself along the local magnetic field direction. When the command is given for the electromagnet current to be turned off, a capacitor mounted across the electromagnet terminals in the satellite causes an alternating, slowly decaying current in the windings. This in turn causes the iron core in the electromagnet to become demagnetized. The residual dipole moment of the electromagnet is less than 100 pole-cm. Since the iron is unannealed

it does not develop a significant dipole moment in the low magnetic field strength experienced by the orbiting satellite.

EXTENSIBLE BOOM—The extensible boom used for this satellite was built by DeHavilland Aircraft of Canada, Ltd. The boom is of the “self-erecting” type, i.e., it is deployed by the energy stored in the wound tape. The tape material is 2-mil-thick × 2-in.-wide beryllium copper. When deployed, the tape forms a cylinder 0.55 in. in diameter and 100 ft long. The boom tape weighs 1.35 lb; the entire unit weighs 3.2 lb.

Deployment of the boom is initiated by a radio command to the satellite that causes detonation of an explosive squib, thus unlatching the boom mechanism and allowing it to deploy.

DESIGN OF THE DAMPING SPRING—The fabrication of a damping spring, and the design of a simple but reliable means of deploying it in orbit, presented an interesting engineering problem. Satellite 22A employed a helical spring having, under zero force, an equilibrium length of 1.5 in. The helical spring was 7.6 in. in diameter and consisted of 70 turns of 0.008-in.-diameter beryllium-copper wire. Since beryllium copper is an excellent spring material, it does not provide sufficient hysteresis loss. To obtain good damping, a 0.0008-in.-thick layer of the mechanically soft material, cadmium, was electrolytically deposited on the outer surface of the beryllium-copper wire. A 0.0002-in. coating of gold was electrolytically deposited over the cadmium to prevent the cadmium from subliming in the hard vacuum of space. When completely fabricated, annealed, and coated, the spring had a constant of 2.14×10^{-6} lb/ft.

To determine effectiveness of the spring under the conditions expected in orbit, a torsional pendulum using the spring material was built and tested in a large vacuum chamber. The period of the torsional pendulum was set at 55 min. to correspond closely to the natural period of libration for the nominal orbit of the 22A satellite. By this method it was determined that the spring had a damping coefficient of 50%; that is to say, 50% of the maximum energy stored in the spring was dissipated on each oscillation. This compares with an energy loss of less than 1% per cycle for the uncoated beryllium-copper wire.

To prevent tangling or other damage to this ultra-weak spring during handling and launching operations it was necessary to encapsulate it in a solid subliming material; the one selected was an aromatic compound known as biphenyl. Biphenyl was also used to hold the spring end mass securely

during extension of the boom. After extension, the biphenyl was to sublime away; first the end mass would be released, then further sublimation of the biphenyl would allow one coil of the spring to extend at a time. Complete deployment of the spring from the subliming material was to be accomplished within a period of one day.

ATTITUDE DETECTION SYSTEM—To determine if the gravity stabilization experiment was successful it was necessary to instrument the satellite with an attitude detection system. For attitude measurements, a system of magnetic-aspect sensing and solar-aspect sensing was employed. Magnetic measurements were accomplished by means of a three-axis vector magnetometer; the angular resolution of the magnetometers relative to the earth's magnetic field was better than $\pm 0.5^\circ$.

Sun sensors were mounted on the satellite to determine orientation relative to a line from the sun. Five sun sensors, each with angular resolution of approximately $\pm 1.0^\circ$, were mounted to determine solar aspect relative to the +Z, +X, -X, +Y, and -Y directions of the satellite. The object of this system was to determine satellite attitude in inertial space. Displacement of the satellite from the vertical, both in-plane and cross-plane, could then be determined. Analysis of magnetometer and sun-sensor data to determine angle with the vertical was performed by J. W. Teener and H. D. Black of APL.

SPRING END MASS—A flashing-light system was used as the end mass for the spring in order to obtain additional information on the performance of the gravity stabilization systems. Separate solar cells powered this unit, providing a flash rate of slightly less than one per minute. Light intensity as measured at the satellite provided information concerning the extension length of the spring. The system was so designed that it could also aid in

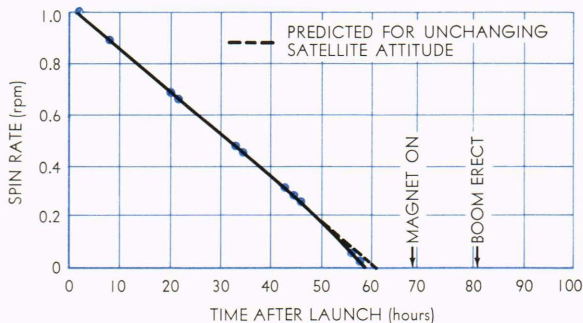


Fig. 5—Spin rate as a function of time after launch for satellite 1963-22A.

determining if the flashing light was within a 5° , 10° , or 20° half-cone angle with respect to the +Z-axis of the satellite.

EXPERIMENTAL RESULTS—Satellite 22A was launched in June 1963 into a near-polar orbit. Some of its orbital parameters are:

Perigee	389.2 n.m.
Apogee	414.5 n.m.
Inclination	90.01°
Eccentricity	0.0032
Orbital period	99.71 min.

For an eccentric satellite orbit the orbital angular rate at perigee is greater than at apogee. Since a vertically stabilized satellite tends to achieve a steady angular rate of 1.0 rpo, the effect of eccentricity is to drive the satellite off the local vertical. The angle to which it is driven off the vertical is approximately the eccentricity expressed in radians. Therefore, for satellite 22A, when fully stabilized and with the initial libration motion damped, the eccentricity of the orbit would provide deviations off the vertical of only 0.18° .

SATELLITE DESPIN—Immediately before separation from the rocket, the satellite had a spin rate of approximately 200 rpm. Several minutes later a "yo-yo" despin was used to reduce the spin rate to 1.02 rpm. The magnetic damping rods then reduced the spin rate to almost zero in 59 hr. Figure 5 is a curve of spin rate as a function of time for this satellite. At 69 hr after launch time the spin rate about the Z-axis was measured as less than one revolution in 120 min.

MAGNETIC STABILIZATION—The electromagnet was turned on 69 hr after injection into orbit, with the satellite nearly 90° off the local magnetic field direction at that time. Satellite 22A then proceeded to oscillate about the local magnetic field direction, with a natural period of 15 min., 4 sec, or within 3% of the theoretical value for this magnetic field intensity, dipole moment, and satellite moment of inertia.

Twelve hours later the magnetic rods had damped this oscillation to a peak value of 16° . This damping agrees very closely with the theoretical value determined by the method of Ref. 10.

BOOM DEPLOYMENT AND GRAVITY CAPTURE—Special precautions were taken to assure that the command for boom extension would be given when the satellite was in the proper orientation,

¹⁰ R. E. Fischell, "Passive Magnetic Attitude Control for Earth Satellites," *Advances in the Astronautical Sciences*, Vol. II (ed. H. Jacobs), American Astronautical Society, Jan. 16-18, 1962 (Western Periodical Co., North Hollywood, Calif.) 147-176.

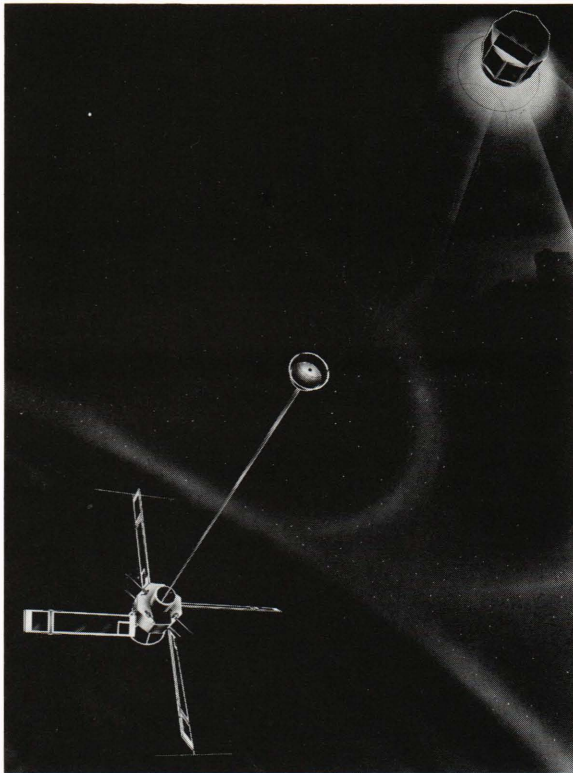


Fig. 6—Satellite 1963-22A, showing the boom, deploying spring, and end mass with the flashing light.

i.e., boom away from the earth and as near vertical as possible to minimize the amplitude of oscillations. The three-axis vector magnetometers aboard the satellite provided a convenient method of determining the satellite orientation relative to the earth's magnetic field. At high latitude the magnetic field approaches the vertical and can be used to indicate satellite orientation.

When the command was given, the boom erected to its entire length of 100 ft. From the telemetry record it was possible to count every turn of the spool as it deployed the flat tape to form a hollow cylinder 0.5 in. in diameter and 100 ft long.

DAMPING SPRING DEPLOYMENT—On the satellite pass immediately following that in which the boom was extended, telemetry indicated that a biphenyl "lock" had not released and that spring deployment had therefore not begun. This was as expected. On a pass 10 hr later the biphenyl lock was observed to have been released, and signals from the flashing light system were received, indicating that the damping spring had started to deploy. The amplitude of the flashing light signals was initially quite low, indicating that either the spring was deployed over 100 ft, or the reflector

was tipped beyond 45° from the satellite and the satellite was therefore receiving a much-attenuated signal from the edges of the flash beam. During the next several days flashing light signals were received regularly with increasing strength, indicating an approach of the spring to its equilibrium extension of 20 ft from the end of the boom. An artist's concept of satellite 1963-22A in orbit with spring extended is shown in Fig. 6.

LIBRATION DAMPING—Damping of the libration motions and proving that this has been done are critical problems in achieving passive gravity gradient stabilization. From the limited field of vision of a single telemetry receiving station at APL, one can only observe the satellite during 10 to 14 min. of its 100-min. orbit during 4 or 5 passes a day. As previously described, solar aspect detectors and vector magnetometers in the satellite provide data from which the satellite attitude in inertial space can be determined. By doing this many times, and observing consistent approach to the vertical and maintenance of that orientation, effective damping can be inferred. Figure 7 shows the average deviation of the satellite from the vertical as a function of time after boom erection.

Libration damping in the 22A was complicated by a comparatively high-frequency oscillation of the satellite that had been observed on every pass at the time the satellite moved from the earth's shadow into sunlight. The cause of this oscillation is the extremely rapid heating of the boom tape on the side of the satellite facing the sun, which causes an impulse to be imparted to the boom and results in the oscillation of the boom and satellite.

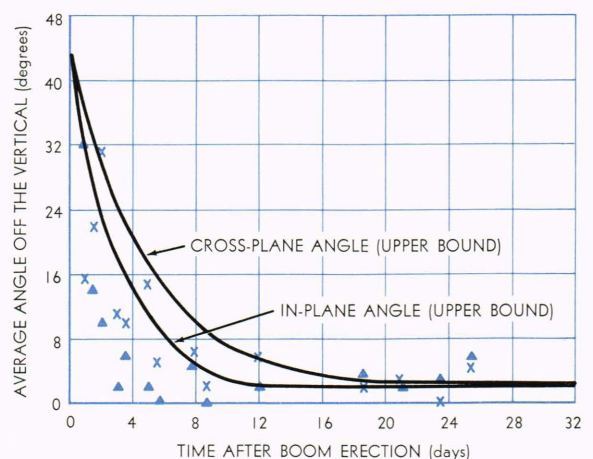


Fig. 7—Damping of a satellite libration, showing the upper bounds for both cross-plane-angle and in-plane-angle librations.

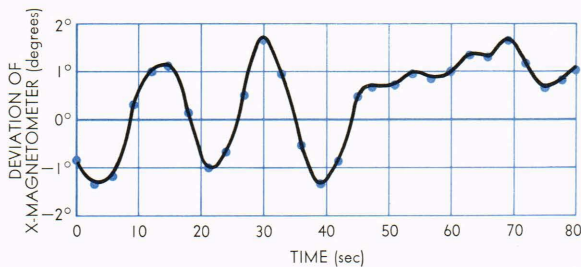


Fig. 8—High-frequency oscillations of satellite 1963-22A.

Figure 8 illustrates this effect as observed 10 days after the boom was erected. Since the satellite is massive compared to the boom, it is believed that the point where the boom joins the satellite is a node for the wave along the boom, causing maximum angular deviations of the satellite at that point. Since beryllium copper is an extremely low-hysteresis-loss material, this motion does not damp out in an orbital period. It is probable that the steady-state thermal bending of the boom, in addition to the dynamic excitation discussed above, prevents this satellite from more closely approaching the vertical.

The objective of gravity gradient stabilization for the 22A satellite was to have the antennas directed downward within 20° of the local vertical at all times. This objective was successfully accomplished by the satellite's passive gravity gradient attitude stabilization system. In fact, the maximum deviation from the vertical was reduced to approximately 10° within 10 days after boom erection.

Satellites 1963-38B and 1963-49B

The technique used to gravity stabilize satellite 1963-22A was later applied to the APL-built satellites 1963-38B and 1963-49B. These were virtually identical to each other in design and external appearance, and also were launched into circular, polar orbits at a 600-n.m. altitude. An artist's concept of these satellites, with boom and spring deployed, is shown in Fig. 9. The principal difference in the external appearance of these satellites (compared to 22A) results from the fact that 22A was powered entirely by solar cells while the 38B and 49B derived nearly all their electrical energy from SNAP-9A, nuclear powered, thermoelectric generators.

Satellite 38B was the second satellite to be gravity gradient stabilized. The initial despin and magnetic stabilization and boom deployment were all completely successful. The satellite was captured into gravity stabilization within 2 days after launch.

However, a serious problem then developed as the spring deployed from the subliming biphenyl. As this material turned into a gas it acted like a rocket, and while the impulse was only on the order of 10 millionths of a pound, at the end of a 100-ft boom it was sufficient to tumble the satellite. This tumbling continued for two weeks before the satellite was "captured"—unfortunately upside down. The result was a drastically reduced radio-signal strength at the surface of the earth.

This perturbing rocket effect did not occur on satellite 22A because the geometry of the 100%-sunlight orbit into which it was launched was significantly different from the orbit of satellite 38B. It can be shown that the biphenyl subliming in a 100%-sunlight orbit does not cause an overturning torque on the satellite.

Satellite 49B was then built with a deflector to reduce the force of the biphenyl subliming sideways. Although this vastly reduced the disturbing effect of the vaporizing biphenyl, there was, nevertheless, just enough force to gently tumble the satellite. This occurred 10 days after the boom was successfully erected. Fortunately a large magnet was installed in this satellite, just in case it was necessary to turn it over. Although the satellite tried to capture upside down on two occasions, the magnet was energized to push against the earth's magnetic field, and the attitude was corrected. After two weeks, when all the biphenyl had sublimed, the magnet was activated to capture the satellite along the local vertical with the correct side facing downward.

The fact that the disturbing torque resulted from the subliming biphenyl was further confirmed by the fact that when this material was present, it provided a net thrust in the direction of satellite motion of approximately 2 millionths of a pound. This caused an increase in orbital period of approximately 0.084 sec per 107-min. orbital period. When the disturbance torque disappeared, the increase in orbital period also disappeared.

Within 10 days after the biphenyl had sublimed, satellite 49B was stabilized along the vertical with a maximum deviation of approximately 15° . It has continued to maintain good vertical stabilization since mid-January 1964.

One advance that was made in the design of both the 38B and the 49B was that the booms were silver plated to reduce the steady-state and dynamic thermal bending. The improvement was most significant. With unplated beryllium copper the 100-ft boom caused the satellite to deviate off the vertical by more than 5° because of steady-state bending, with an additional $\pm 5^\circ$ because of



Fig. 9—Exterior configuration of satellites 1963-38B and 1963-49B.

dynamic bending. With silver-plated booms on the later satellites, steady-state bending was reduced to less than 2° and dynamic bending was reduced to a maximum value of $\pm 0.2^\circ$. This is illustrated in Fig. 10. The silver also acted to damp oscillations of the boom so that dynamic bending was rapidly reduced to less than 0.1° .

Future APL Studies of Gravity Stabilization

Within the next 12 months, APL, under the sponsorship of the Bureau of Naval Weapons, hopes to design, fabricate, and launch from one to three new satellites that will permit additional study of improved techniques for gravity gradient stabilization. Among the new techniques that will be tried is a biphenyl release device of improved design to prevent torque generation due to the sublimation of this material. Also, APL will study the use of passive magnetic damping rods by themselves to damp the librations of the satellite. Several improved dampers of an entirely different type are also being investigated.

Application for Communication Satellites

The techniques for gravity stabilization developed by APL are directly applicable to both medium-altitude and synchronous-orbit communication satellites. Changes would be made in the stiffness of the damping spring and in the techniques for obtaining magnetic damping, but both are well within current capability.

The improved effectiveness of communication satellites using gravity gradient stabilization is best seen in Fig. 11.* Here we have plotted the power

* Derived by W. A. Allen of APL.

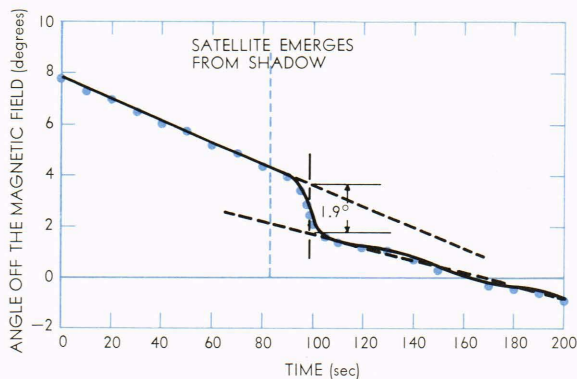


Fig. 10—Thermal bending observed for a silver-plated, 100-ft boom erected in a space environment.

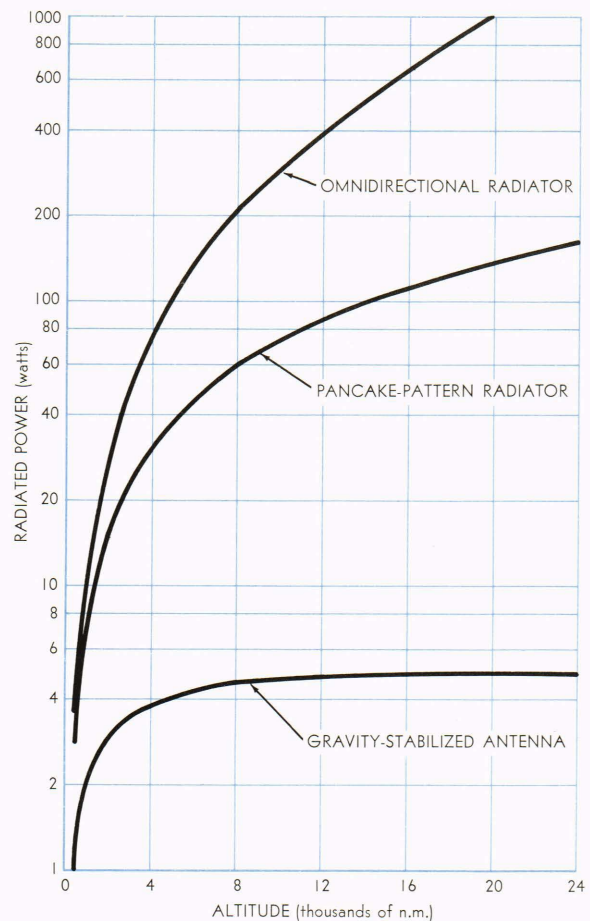


Fig. 11—Radiated power required by three different antenna patterns for constant signal strength at the surface of the earth.

required to operate a satellite transmitter to get a reasonable signal strength at the surface of the earth for three cases: (1) an omnidirectional radiator, (2) a “pancake” pattern (as would be used on a spin-stabilized satellite), and (3) a gravity-stabilized antenna covering the earth from horizon to horizon.

One watt of power radiated by a gravity-stabilized satellite at a 400-n.m. altitude was taken as providing a reasonable signal strength on the ground for high-data-rate communication. From Fig. 11 one can see immediately the advantage of gravity gradient stabilization at very high altitudes. For example, let us assume a transmitter of 30% efficiency in a satellite at synchronous altitude. This would require that the satellite provide 15 watts of electrical power for the gravity-stabilized antenna, 450 watts for a spin-stabilized antenna, and 3300 watts for an isotropic radiator.