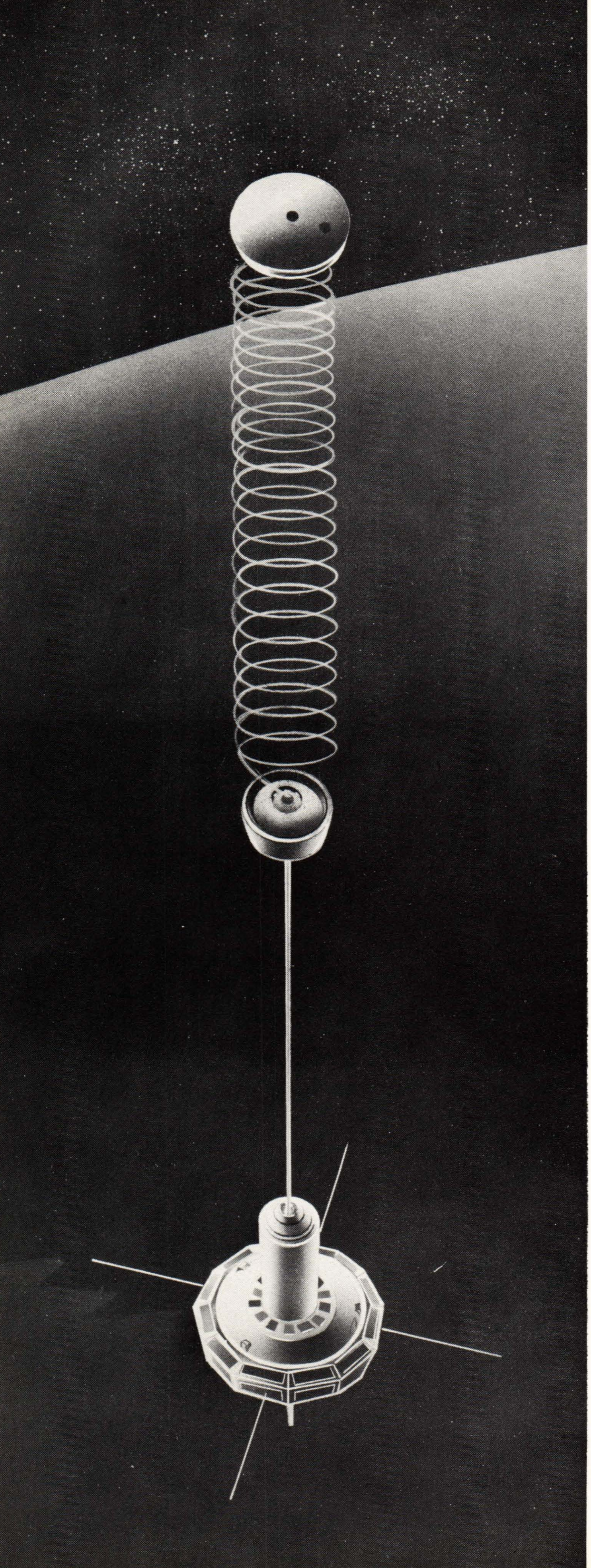

the TRAAC satellite

R. E. Fischell

The TRAAC satellite was primarily an experiment to use the earth's gravitational field for controlling the attitude of an orbiting satellite. Although the gravity stabilization experiment was not realized, TRAAC has provided significant scientific and engineering data which further insure the success of Transit and other satellites.

At 5:25:39.1 PM EST, on Nov. 15, 1961 the Transit 4B and TRAAC satellites were launched from Cape Canaveral, Florida, by means of a Thor-Ablestar launching vehicle. The Transit was one more in a series of steps toward developing an all-weather, worldwide navigation system for the Navy. The TRAAC satellite (Transit Research And Attitude Control) embodied many experiments which will directly contribute to the fulfillment of the objectives of the Transit program. It is also providing a considerable amount of engineering and scientific information which will help to advance the "state of the art" of space technology.

Although theoretical discussions of gravity-stabilized satellites, the moon being a prime example, have been presented in technical journals for several years, the problem of damping the oscillations of an artificial satellite by passive means is so difficult that no other group has yet actually attempted to employ this most useful attitude control system.

The TRAAC satellite came into being at the request of the Bureau of Naval Weapons when it was decided that the Naval Research Laboratory auxiliary payload (the GREB satellite)[1] could not operate profitably in the low-inclination orbit that was required for Transit 4B. This gave APL the opportunity to provide its own auxiliary payload to ride a-top the Transit 4B. Authority to provide such a payload was given to APL in mid-July 1961.

The first reaction of the Space Development Division, in July 1961, was that, for a launching on Nov. 15, only a "simple" payload could be designed and fabricated. By early August it was decided that the most useful purpose of such a payload would be to perform an experiment in gravity-gradient attitude stabilization. The system subsequently designed was incorporated as the principal experiment in the TRAAC satellite. Employing this stabilization system offers considerable advantages for many space applications. For example, the operation of weather satellites is considerably improved when observation devices always face the earth. A directional antenna radiating only in a downward direction provides improved transmission to and from the satellite. Many scientific experiments using satellites are best accomplished on a vertically-stabilized vehicle.

In addition to the gravity-gradient stabilization experiment, several other experiments were included in the satellite. In particular, fairly complete equipment for particle detection was included. There were also experiments on attitude detection and an experiment to determine the rate at which solder sublimes, or erodes, in the space environment.

The Theory of Gravity-gradient Attitude Stabilization

The principle on which gravity-gradient attitude stabilization is based is quite simple, but putting it into practice is a difficult engineering problem. Figure 1 shows a satellite which is essentially in the shape of a "dumbbell." For this discussion, assume that the c.g. of the system is contained within the major satellite instrumentation denoted mass "A." Extended a considerable length outward from the satellite c.g. is mass "B" attached to mass "A" by a boom. The c.g. of a satellite is in a stable orbit when the centripetal acceleration due to the satellite motion in a curved trajectory is precisely equal to that called for by the gravitational force resulting from the attraction of the mass of the earth, assumed to be a point mass.

If we let F_g be the gravitational force at the c.g. of the satellite and F_c be the centrifugal force at the c.g., then a stable, circular orbit is defined by

$$F_g = F_c, \tag{1}$$

and for $(L/R)^2 \ll 1$ (on the order of 10^{-10} for TRAAC),

$$F_g = \frac{G\,M(m_A + m_B)}{R^2}, \tag{2}$$

and

$$F_c = (m_A + m_B)\,\omega_o^2\,R. \tag{3}$$

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[1] G. F. Pieper, "Injun, A Radiation Research Satellite," *APL Technical Digest*, 1, 1, Sept.-Oct. 1961, 3-7.

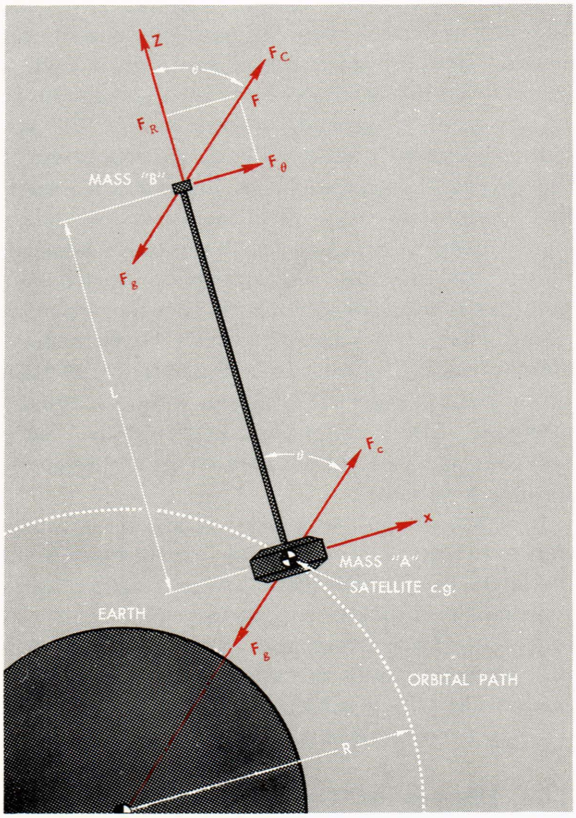

Fig. 1—Gravitational and centrifugal forces acting on a satellite with a "dumbbell"—shaped mass distribution.

The forces are given in dynes and the symbols represent:

G = gravitational constant ($\mathrm{cm^3\,gm^{-1}\,sec^{-2}}$),
M = mass of the earth (grams),
m_A = mass of the satellite (grams),
m_B = end mass (grams),
R = orbital radius (cm),
L = distance from the satellite c.g. to the mass "B" (cm),
ω_o = orbital angular rate (rad/sec),
and θ = angle of the satellite symmetry axis with the local vertical.

When $\frac{d\theta}{dt} = 0$ (see Fig. 1),

the forces on the mass "B" are given by

$$F_g^B = \frac{G\,M\,m_B}{(R + L\cos\theta)^2}, \tag{4}$$

and

$$F_c^B = m_B\,\omega_o^2\,(R + L\cos\theta). \tag{5}$$

Since $F_g = F_c$ defines a stable orbit, it therefore readily follows that

$$F_c^B > F_g^B, \tag{6}$$

and there is a net outward force on mass "B" given by

$$F = m_B\left[\omega_o^2(R + L\cos\theta) - \frac{G\,M}{(R + L\cos\theta)^2}\right]. \tag{7}$$

The satellite would stabilize equally well with m_B downward from the c.g. of the satellite. For this case the force on m_B is merely the negative of the value of F given by Eq. (7). The component of F along the length of the boom causes a tension in the structural member attaching the mass "B" to the satellite body. When $\frac{d\theta}{dt} = 0$, this tension force is given by

$$F_R = m_B\left[\omega_o^2(R + L\cos\theta) - \frac{G\,M}{(R + L\cos\theta)^2}\right]\cos\theta. \tag{8}$$

When $\frac{d\theta}{dt} = 0$, there is an additional contribution to F_R due to the angular rate of the mass "B" about the c.g. of the satellite.

The force perpendicular to the longitudinal axis is the desired restoring force and results in a restoring torque (for $\frac{d\theta}{dt} = 0$) given by

$$\tau = F_\theta\ L = m_B\left[\omega_o^2(R + L\cos\theta) - \frac{G\,M}{(R + L\cos\theta)^2}\right] L\sin\theta. \tag{9}$$

More generally it can be shown [2] that for a "dumbell"-shaped satellite with moments of inertia I_x and I_z, the torque is given as

$$\tau = \frac{3}{2}\ \omega_o^2(I_x - I_z)\sin 2\theta, \tag{10}$$

where I_z = moment of inertia about the longitudinal (symmetry) axis ($\mathrm{gm\,cm^2}$),
and I_x = moment of inertia about an axis perpendicular to the Z-axis ($\mathrm{gm\,cm^2}$).

In order to develop a substantial torque, it is necessary that I_x be very much greater than I_z. We also see that the gravity-gradient torque is less effective for satellites at very high altitudes where the orbital period is very great and therefore ω_o^2 is very small.

Investigations at APL have shown that the natural period of oscillation (libration period) of a gravity-stabilized satellite is given by

$$T_{\parallel} = \frac{2\pi}{\omega_o\sqrt{3(1 - I_z/I_x)}}\ \text{(sec)}, \tag{11}$$

in the plane of the orbit; and by

$$T_{\perp} = \frac{\pi}{\omega_o\sqrt{1 - I_z/I_x}}\ \text{(sec)} \tag{12}$$

in the plane perpendicular to the orbit. For a satellite having an orbital period of 100 min and with $I_x \gg I_z$ we find that $T_{\parallel} = 57.8$ min and $T_{\perp} = 50.0$ min. These very long libration periods, when combined with the small torques that are available, make damping of the satellite oscillations a difficult problem.

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[2] R. A. Nidley, "Gravitational Torque on a Satellite of Arbitrary Shape," *ARS Journal*, **30**, 2, Feb. 1960, 203-204.

Plan of the Experiment

The TRAAC satellite was to be launched into a circular orbit of a 550-nautical-mile altitude with the orbital plane inclined to the equator at 32.5°.

To perform the gravity-gradient experiment it is first necessary to damp the spin of the satellite. This is done by magnetic despin rods that absorb the angular kinetic energy of the satellite by means of hysteresis loss.[3] When the spin is sufficiently damped—a period of approximately two days—a powerful electromagnet is activated within the satellite to align an axis along the local direction of the earth's magnetic field.[4] For the TRAAC satellite, an alignment within 10° of the local magnetic field direction is accomplished within 7 days. In the region of 75° W longitude and 32° N latitude, the TRAAC satellite is at its highest magnetic latitude and is simultaneously at its closest proximity to the APL command injection station. The dip angle of the earth's magnetic field in this region causes the satellite axis to incline only 25° from the local vertical. At this point, with a particular face of the satellite directed downward, the electromagnet is turned off and a boom with an end mass is extended outward to a length of 60 ft. The satellite will then have the proper mass distribution for gravity stabilization.

To keep a particular satellite axis facing downward it is necessary to damp out the oscillations about the local vertical discussed above. This is accomplished by an ultra-weak spring fastened to the end of the boom. This spring, with its own associated end mass, is held rigidly to the end of the boom in a block of subliming material during the launch phase and magnetic stabilization period. After the boom is erected, this material starts to sublime. First to be released is the mass attached to the end of the spring; the unbalanced centrifugal force then acts on this mass and tends to pull the spring out. The subliming material permits only one coil to be released at a time. Although the spring has zero length in its equilibrium position in a zero g field, the gravity-gradient force acting on the end mass causes it to have a nominal length of approximately 40 ft.

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 the angle θ plus an additional force contribution due to the $\frac{d\theta}{dt}$ term originating from the libration motion. This varying force causes the spring to move in and out. The libration energy is then absorbed by mechanical hysteresis in the spring. It has been shown by J. L. Vanderslice of APL that the TRAAC satellite would be aligned with the local vertical, to an angle of less than 5°, within 15 days after turning off the magnet.

If TRAAC had achieved vertical stabilization, an electromagnet mounted perpendicular to the symmetry axis would have been activated to align the satellite's X-axis in the magnetic north direction along the *horizontal* component of the earth's magnetic field.

Satellite Design

The best way to discuss the particular design features of the TRAAC satellite is through reference to the exploded cutaway view shown in Fig. 2. Only the most pertinent design features of the satellite will be briefly discussed.

ELECTRICAL POWER SYSTEM—The TRAAC electrical power system consists of solar cells charging nickel-cadmium secondary batteries. The minimum power-generating capability of the satellite in the orbits of least illumination is approximately 16 watts.

In addition to the main battery, which provides power for all systems when TRAAC is in the shadow of the earth, a separate command receiver battery has been provided. In the event of a short-circuit failure of some piece of satellite equipment, the command battery can supply sufficient power to operate the command system for slightly over three days. During this time, attempts would be made to repair the fault by switching out the short-circuited load.

DOPPLER SYSTEM—The TRAAC satellite contains a standard type of Transit doppler system[5] which includes a 3-mc ultra-stable oscillator plus frequency multiplier, and 54-mc and 324-mc transmitters. This system makes it possible for TRAAC to be used as a back-up for geodetic studies which would normally be conducted using the Transit 4B satellite.

MAGNETIC DESPIN—Magnetic despin rods are employed on TRAAC to remove any residual

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[3] R. E. Fischell, "Magnetic Damping of the Angular Motions of Earth Satellites," *ARS Journal*, 31, 9, Sept. 1961, 1210-1217.

[4] R. E. Fischell, "Passive Magnetic Attitude Control for Earth Satellites," Paper 62-8, *8th Annual National Meeting of the American Astronautical Society*, Washington, D. C., Jan. 16, 1962.

[5] J. W. Hamblen and J. B. Oakes, "Instrumentation and Telemetry of Transit Navigational Satellites," *Electronics*, 34, 32, Aug. 11, 1961, 148-153.

spin rate that might occur during the launching process. The satellite is not intentionally spun during the launching, but operation of the Thor-Ablestar second-stage control system usually results in some spin. Only four magnetic despin rods were employed as compared with 16 on Transit 3B. Fewer rods were used because it was felt that the interaction of these rods with the earth's magnetic field might perturb the vertical stabilization condition.

MAGNETIC ORIENTATION—To align TRAAC along the local direction of the earth's magnetic field, it was decided to employ four electromagnets directed along the symmetry axis of the satellite. Each of the electromagnets consisted of a solenoid of 3600 turns of copper wire wrapped around a core of unannealed, high-purity iron. The magnetic dipole moment produced by each

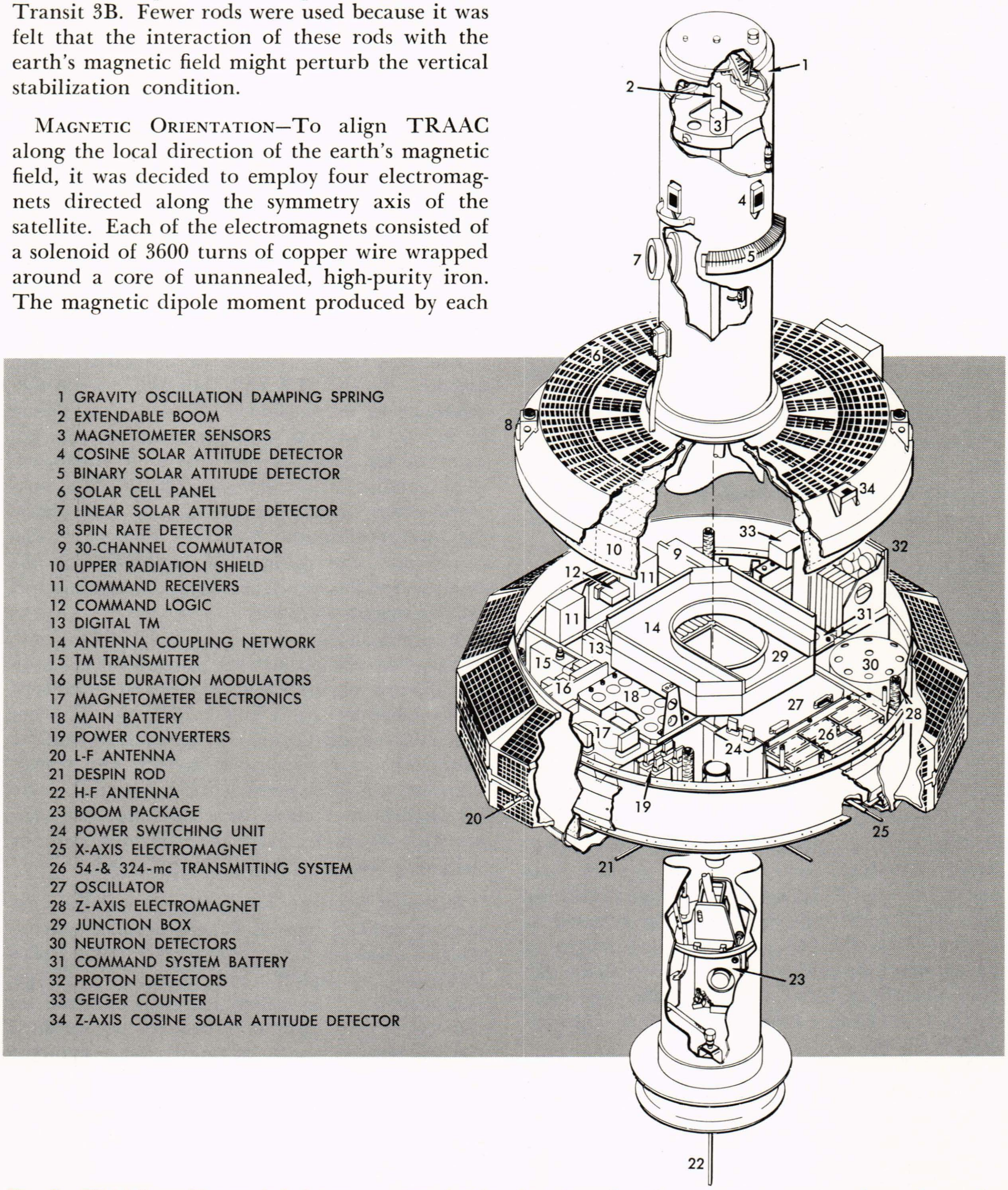

Fig. 2—TRAAC satellite exploded cutaway view showing location of major components. Attaching flange for mating the TRAAC and Transit 4B satellites during launch is at the bottom.

electromagnet was 1.5 x 10^4 unit-pole cm. The large number of turns was required to reduce the operating power of the electromagnets to only 3 watts. When it is desired to transfer from magnetic attitude control to gravity-gradient stabilization, it is necessary to stop the current from flowing through the electromagnet windings and to demagnetize the iron core. This is accomplished by means of a large capacitor in parallel with the electromagnet, which causes a decaying oscillation of the electromagnet current when power is commanded off. This system operated most effectively for demagnetizing the electromagnets.

EXTENDABLE BOOM—The 60-ft extendable boom used in the TRAAC satellite is seen in Fig. 3. The boom, shown in its retracted position, is of 2-in.-wide by 0.002-in.-thick beryllium copper tape. In its retracted position, with the tape rolled onto a hub, the outer diameter is 2.5 in. When a motor is activated to drive the tape off the hub, the tape material forms a 0.45-in.-diameter cylinder 60 ft long when fully extended. Total weight of the boom tape is only 13 oz.

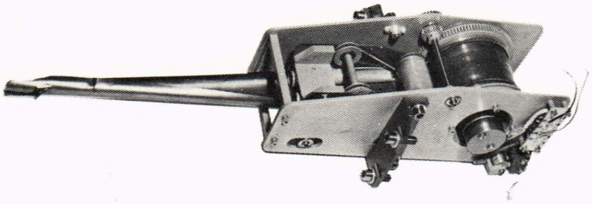

Fig. 3—Extendable boom package shown in its retracted position, i.e., with most of the beryllium-copper tape wound on the hub.

Measurements of the extension rate of the boom and of its straightness were accomplished by extending the boom in a horizontal position. Helium-filled balloons attached to the boom at 5-ft intervals allowed it to "float" in mid-air to simulate the zero g orbital condition. These measurements showed that the boom erected in 1 min, 45 sec and was within 1.5° of being aligned along the symmetry axis of the satellite.

DAMPING SPRING AND MASS—At the outer end of the extendable boom was attached an ultra-weak, energy-dissipating spring with a 5-lb mass connected to its outer end. When extended, the damping spring has the shape of the surface of a frustrum of a cone. The spring is heat-treated in a flat (unextended) position, the inside diameter being 4 in. and the outside diameter 7.25 in. The spring consists of 142 turns of 0.007-in.-diameter beryllium-copper wire. Beryllium-copper can be deformed without significant energy loss; therefore, to obtain good damping, an 0.0008-in.-thick layer of the mechanically soft material, cadmium, was electrolytically deposited on its outer surface. To prevent the cadmium from subliming in the hard vacuum of space, a 0.0002-in. coating of silver was electrolytically deposited on its outer surface. When completely fabricated, annealed, and coated, the spring had a constant of 1.5 x 10^{-6} lb/ft.

In a gravitational field of 1 g, such a spring is incapable of supporting even one of its turns without exceeding the elastic limit of the material. In order to prevent any tangling of the spring or other damage during handling and launching operations, it was necessary to encapsulate the spring in a solid subliming material; a compound of the benzene family, biphenyl, was selected for this purpose. After the spring was formed, it was placed on a conical holder and the biphenyl was poured on it. The biphenyl was also used to hold the end mass securely during erection of the boom. After erection the biphenyl sublimed, first releasing the weight which then pulled away due to gravity-gradient force, and then, by gradually subliming around the conically-formed spring, allowing the spring to extend one coil at a time.

ATTITUDE DETECTION—Two systems for attitude detection were incorporated in TRAAC. The first was to determine the attitude of the satellite relative to the sun. For this purpose four cosine solar attitude detectors, one linear solar attitude detector, and one binary solar attitude detector were employed on the satellite (Fig. 2). The cosine solar attitude detectors were essentially solar cells whose output is proportional to the cosine of the angle of incidence of the sun.

The linear solar attitude detector consisted of a circular solar cell mounted in the bottom of a well so that its output was linearly proportional to the angle of incidence of the sun over a range from normal incidence to 30° off normal.

The binary solar attitude detector was a series of 40 diodes mounted at the bottom of 2-in. slits, each 2.25° wide. When the sun shines into one of these slits, the photo diode conducts and registers a "one" signal through the binary telemeter system; when the sun does not shine on the photo diode, a "zero" signal is transmitted When the satellite undergoes slow angular motions so as to go from one slit to another, one can interpolate the attitude of the satellite with respect to the sun with a resolution considerably better than 1°.

The second system of attitude detection employed three vector magnetometers oriented along the *X*, *Y*, and *Z* axes of the satellite. These magnetometers, mounted at the upper end of the cylinder, provided information on the attitude of the satellite relative to the earth's magnetic field; and, if the satellite had been gravity stabilized, they would also have provided information on the earth's magnetic field intensity.

Spin Rate Detection—The TRAAC satellite included four devices for measuring the rates of roll, pitch, and yaw of the satellite (Fig. 4). This is accomplished by means of a series of slits in an aluminum housing under which is mounted a photo diode. As the satellite rotates, the slits in the aluminum housing cause the sun to illuminate the photo diode intermittently at the base of the detector. By counting the rate at which the light from the sun is chopped by the slits, one can determine the angular rate of the satellite.

Particle Detection—In addition to the experiments on attitude control and detection, the TRAAC satellite included several experiments for the detection of corpuscular radiation. One purpose of the experiment was to measure the neutron albedo of the earth, which is a particularly significant experiment for a vertically-oriented space vehicle. In addition, there are several highly significant experiments on the measurements of charged particles of different energy levels.[1]

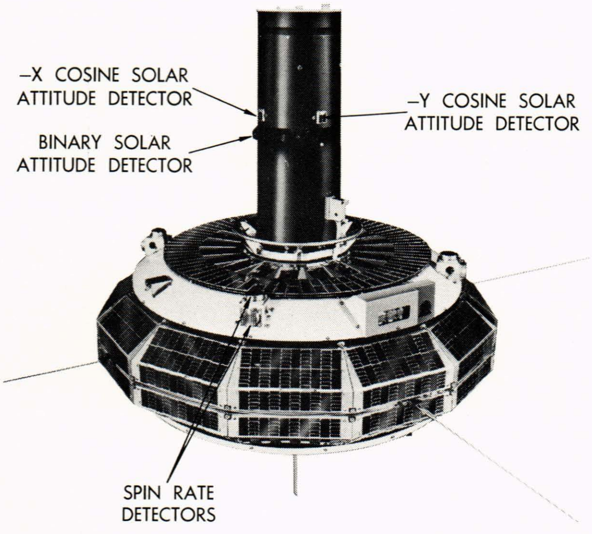

Fig. 4—Exterior of the TRAAC satellite, with three of the four low-frequency antennas shown.

Solder Sublimation Experiments—To verify whether solder would sublime or erode in the space environment, two samples of a 60-40 solder were vacuum-deposited on glass slides and then mounted on the exterior of the satellite. The voltage produced across these resistive samples by a 0.5-ma current flowing through them was monitored by telemetry to obtain an indication of the depletion of the material.

Launching Operations

The TRAAC satellite arrived at Cape Canaveral six days before it was to be launched. The first three days were occupied with extensive in-hangar tests of the satellite and in final preparation of the countdown procedure. One significant and successful test, run for the first time at the Cape Canaveral APL facility, was a radio-commanded extension of the boom with its attached weight. For this experiment the TRAAC satellite was hung horizontally from the peak of the hangar building, with the weight at the end of the boom suspended by a string approximately 40 ft long. The boom was then extended 5 ft by radio command while all satellite functions were observed by telemetry.

Results in Orbit

Once the TRAAC satellite was in orbit, it became apparent that the doppler transmitters were interfering with the ability of the satellite to receive commands. Although this created some early difficulties, it was possible, by repeatedly commanding the satellite with the most powerful transmission available, to turn off the doppler transmitters. It was then easily possible for the satellite to receive the commands required to put the gravity-gradient apparatus into operation.

Two days after launch, when the spin rate of the satellite was approximately 0.55 rpm, the Z-electromagnet was commanded on. Figure 5 illustrates the approach of TRAAC to magnetic stabilization. The ordinate represents the angle that the *Y*-axis of the satellite makes with the direction of the earth's magnetic field. On Nov. 17, just before the Z-electromagnet was activated, satellite rotation caused the *Y*-axis to undergo 60° excursions with respect to the normal direction of the earth's magnetic field. One day after the electromagnet was turned on, the

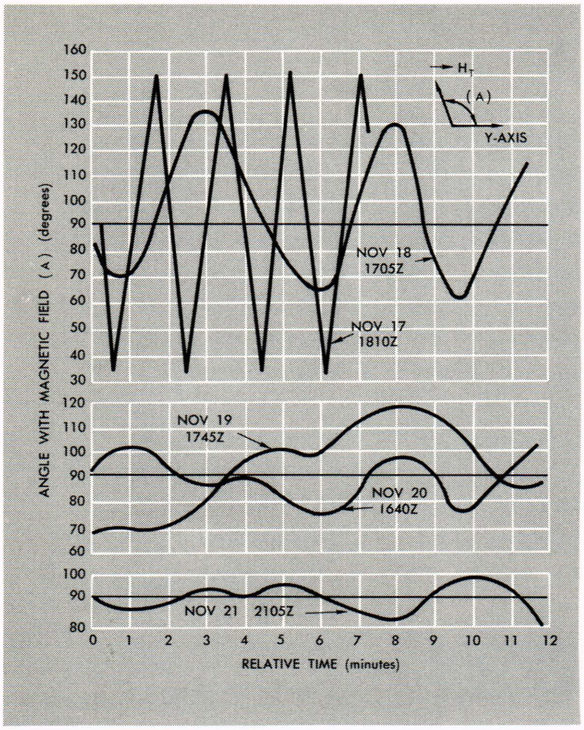

Fig. 5—Approach of the TRAAC satellite to alignment along the local direction of the earth's magnetic field.

character of the satellite motion was completely changed. By Nov. 19, the satellite was aligned within 30° of the direction of the earth's magnetic field. By Nov. 21, the maximum deviation of the satellite from the direction of the local magnetic field was less than 10°. Also by that date, the satellite spin rate was reduced to 0.17 rpm. However, even this slow spin rate caused a complex oscillation and precession motion of the satellite, as can be seen from the curves in Fig. 5.

On Nov. 24, the Z-electromagnet was commanded off, and the boom was commanded to erect. However, the boom motor drew stall current for a period of approximately 5 min, at which time it was commanded off. It is difficult to determine why the boom did not erect; extensive tests had shown that it should operate satisfactorily under the conditions to which it was exposed. A possible explanation for the malfunction is that the flight fairing covering the payloads during launch did not release properly and, by slipping down on top of the TRAAC satellite, caused a malfunction of the erection system. There is other evidence to indicate the possibility of fairing damage to the payload, though it is not certain that this caused the malfunction.

Approximately 20 days after the attempt to erect the boom, when the satellite spin rate was reduced to 0.025 rpm, the electromagnet was again commanded on. This was done at a time when the satellite's magnetic dipole axis (the *Z*-axis) was 60° off the local direction of the earth's magnetic field. Although calculations indicated that at least four or five days should be required to damp the resulting oscillations to less than 10°, this was accomplished in one satellite orbital period of approximately 100 min. This excessive damping could only have resulted from deployment of the spring and mass from the end of the TRAAC cylinder. Further evidence of this deployment and of sublimation of the biphenyl material has come from measurements of the natural period of oscillation of the magnetically stabilized satellite. By Jan. 18, 1962, TRAAC was aligned along the local direction of the earth's magnetic field with a maximum angular oscillation of 0.4°.

A great deal has been learned from the TRAAC experiment. The magnetic despin rods performed as expected; the Z-electromagnet aligned the satellite along the earth's magnetic field; virtually all the attitude detectors worked as planned; the biphenyl sublimed and released the spring in a satisfactory manner; and the spring showed that it was an effective damper of satellite oscillations. Furthermore, the particle detection experiments are yielding most useful results. In 80 days under orbital conditions the solder sublimation experiments indicate no detectable erosion of these speciments, a factor of significance in the design of future satellites.

Additional experiments on gravity stabilization will be incorporated on subsequent Transit satellites. In lieu of the motorized extendable boom, a self-erecting device will be employed. One end of this new extendable structure will be attached to the satellite, and a hub containing the wrapped-up beryllium-copper tape will be ejected outward by means of the energy stored in the tape itself. By eliminating motors and gearing, the weight of the boom unit is decreased and the reliability of this device should be improved.

The extensive knowledge and experience gained from the TRAAC satellite will be of invaluable assistance in designing a gravity-gradient attitude control system for future Transit satellites.