Decade of Improvements to Orbiting Solar Observatories

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Solar research in space preceded the satellite age by more than ten years. The NASA Orbiting Solar Observatory Program began in 1959 and was designed to extend a solar physics program which used balloon and sounding rockets as research platforms. The OSO satellites are an adaptation of the gyroscopically stabilized biaxial pointing system first used on the rockets in 1950. OSO-1, launched March 7, 1962, was the most stable orbiting solar research platform of its day with short-term pointed instrument jitter of only 0.5 arc-min. OSO-7 is today's most stable platform with residual spin axis coning of one arc-min and pointing jitter of only one arc-sec. The paper describes improvements which have greatly increased OSO capabilities and which have helped make dual-spin stabilization an attractive option for a wide variety of missions.

Introduction

SOLAR research in space preceded the satellite age by about ten years. Scientists, eager to make observations above the "sensible atmosphere," used balloons and sounding rockets in the late forties. A biaxial pointing control system was developed which allowed instruments to be pointed with an accuracy of about 0.1°, in spite of large balloon pendulum and sounding rocket coning motions. The first NASA observatory program was started in 1959 and was based upon a proposed orbital application of the rocket design.

The first Orbiting Solar Observatory (OSO-1) was launched on March 7, 1962.[1-3] It was the most stable orbital research platform of its day with spin-axis coning angles less than 0.05° and pointed-instrument jitter of less than 0.5 arc-min. This observatory demonstrated the orbital feasibility of dual-spin stabilization. This principle was used for six more OSOs and has been recently used on several communications and meteorological satellites. Figure 1 shows the evolution of the design of the solar research platforms.

OSO-7, launched Sept. 29, 1971, represents a decade of improvement in the original satellite design. With residual spin-axis coning angles of about one arc-minute and short-term (5 min) pointed-instrument jitter of about one arc-second, OSO-7 is the most stable orbital solar research platform to date.[4] This paper describes the design improvements that are of special interest for dual-spin satellites, by comparing OSO-1 with OSO-7.

Physical Comparison

Each observatory consists of three gimbaled bodies. (See Fig. 2.) The "wheel" spins to provide gyroscopic stabilization and

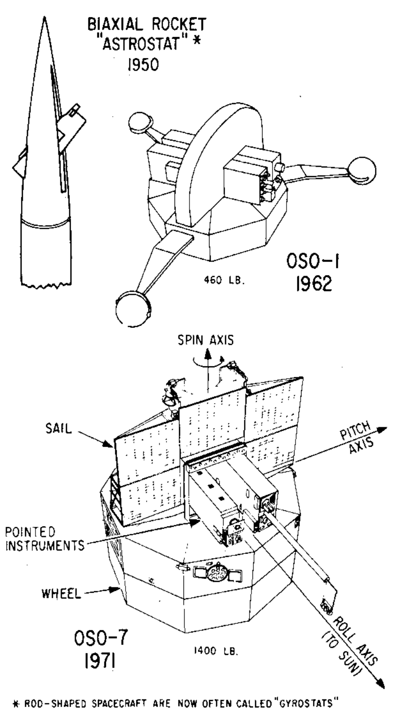

Fig. 1 OSO design evolution.

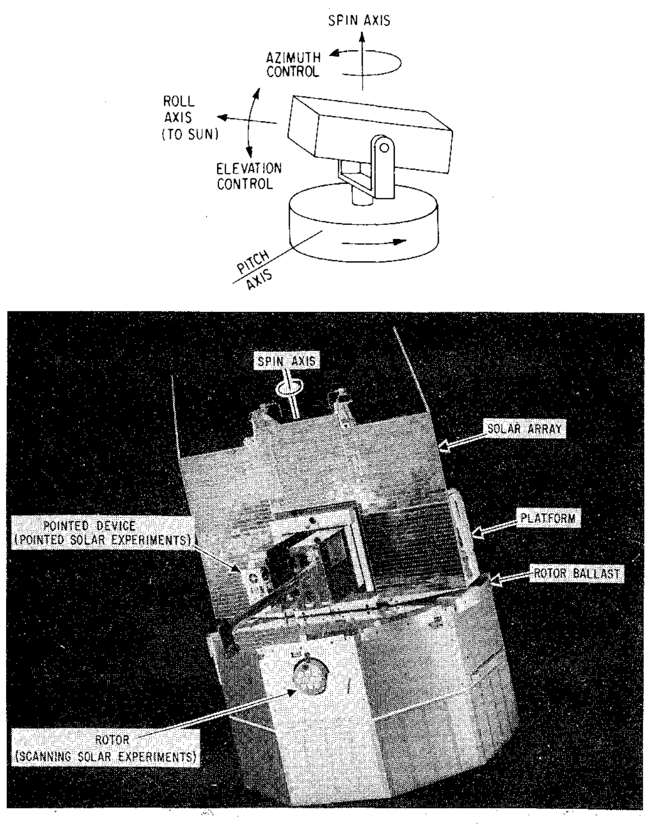

Fig. 2 OSO-7.

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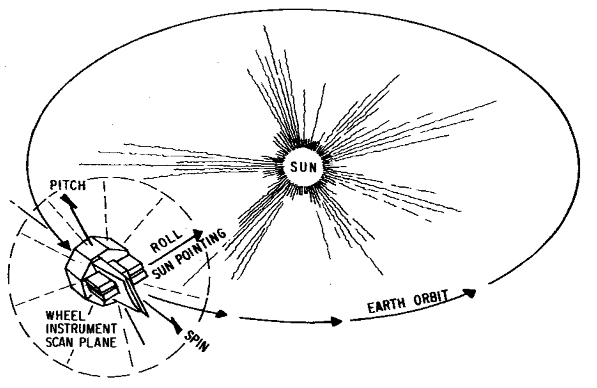


Fig. 3 OSO pointing and scanning capabilities.

accommodates scanning scientific instruments. The "sail" provides a mount for the solar array and is despun and pointed at the sun. The pointed instruments are pointed accurately by the combined action of the azimuth and elevation servos.

OSO-7 is more than twice as heavy as previous observatories, and carries more than twice the weight of scientific instruments. Mechanically, OSO-7 was simplified by eliminating the deployable ballast arms used on previous observatories. The wheel was enlarged from 44 to 57 in. in diam to accommodate larger scanning instruments. The elevation gimbal was enlarged from 9 by 9 in. to 15 by 15 in., to accommodate larger pointed instruments. The solar array was enlarged to increase power from 30 to 97 w.

Pointing and Scanning Capabilities

The dual-spin design used on all seven OSOs evolved from a biaxial pointing control ("astrostat") used on inertially rod-shaped sounding rockets in the early fifties. The OSOs are uniquely suited for solar research and accommodate a group of scanning scientific instruments. The azimuth (or despin) servo despins and orients the sail for maximum power output from the solar array. The elevation gimbal decouples the pointed instrument assembly (PIA) from spin-axis coning motions.

Figure 3 defines the pitch and roll axes of the observatory. The roll axis is the line to the sun. The spin axis can be rotated about the line to the sun without interfering with pointing. This changes the celestial plane scanned by the wheel instruments. The spin axis is usually rolled into the ecliptic plane after launch, as shown in Fig. 3. For this orientation, the spin axis, which must remain perpendicular to the Earth-sun line, pitches through 360° in a year, allowing the scanning instruments to map the entire celestial sphere every six months.

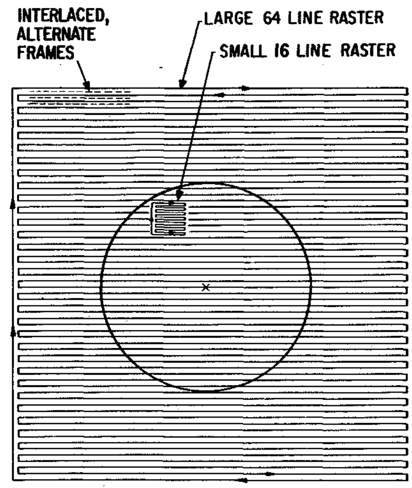


Fig. 4 OSO pointing capabilities.

Although OSO-1 only pointed at the center of the sun, the biaxial servo permitted excellent flexibility in pointing the PIA.[5] On later OSOs, offset point commands and scan patterns were fed to the servos. On OSO-7, this allows experimenters to point at regions of special interest, scan a 60 by 60 arc-min, 64-line raster pattern (128 lines when interlaced), and finely scan specific regions using a five by five arc-min 16-line pattern. (See Fig. 4.)

Disturbances

The wheel on OSO-7 spins at 30 rpm, resulting in a spin angular momentum of 200 Nm-sec. In a 555 km altitude orbit, the external disturbance torques are of the order of 10^{-5} Nm. The resulting precession drift is only about 0.01° per orbit and the nutation amplitude is negligible. The magnetic precession control system is sized to provide 10 to 20 times this precession rate, and

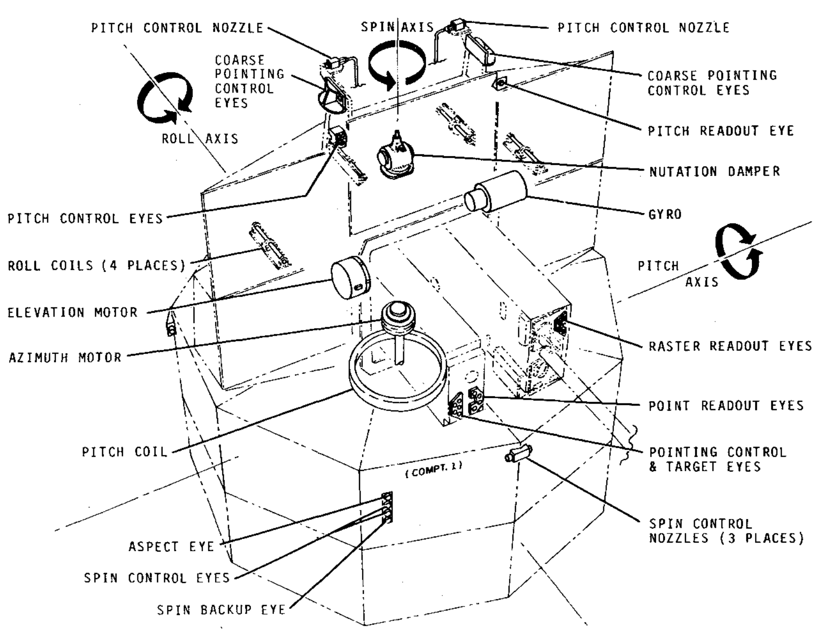


Fig. 5 OSO control system components.

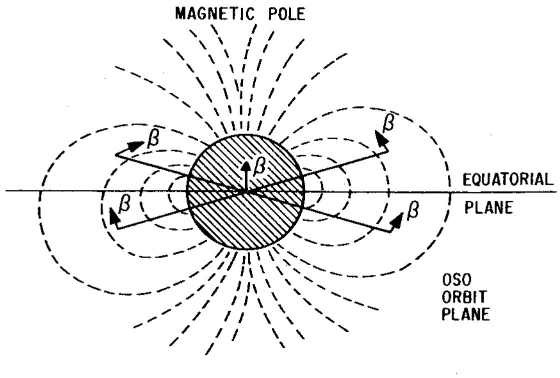


Fig. 6 Geomagnetic field for the OSO orbit.

the cold gas system is sized for about 2000 Nm-sec. Thus, large deviations in external torque are tolerable.

The pointing disturbance on the PIA is dominated by changes in azimuth and elevation gimbal friction of the order of 0.02 Nm. Therefore, external disturbance torques 10^3 larger than those expected would not significantly degrade pointing performance.

The large margins for disturbance torques prevented loss or degradation of the OSO-7 mission even though a launch vehicle malfunction placed the observatory in a 330 by 575 km altitude orbit instead of the planned 555 km circular orbit.

For the nominal orbit, the most difficult disturbance to control to the 10^{-5} Nm level is the reaction of observatory magnetic dipole moments with the geomagnetic field. OSO-1 experienced undesirable spin rate fluctuations as a result of this interaction. Precise measurement and control of dipole moments is achieved by using a "magnetotropometer" to measure directly the reaction of the assembled spacecraft to the influence of the Earth's field.[6] The BBRC fixture, designed in 1962, has resolution of about 30 gauss-cm^{-3}.

Control Systems Functions

The control systems control the precession and spin rate drift caused by external torques, damp nutation, and point the pointed instruments in the desired direction in spite of wobble and nutation coning. Figure 5 shows the control system components on OSO-7.

Precession and Spin Rate Control

On OSO-1 the wheel spin rate could only be controlled by actuating wheel-mounted nitrogen jets. For pitch angle errors larger than $\pm 3°$, jets mounted on the sail provided closed-loop precession control. On OSO-7, electromagnets on the wheel and sail provide additional spin rate and precession control. Magnetic torquing increases the life expectancy of the observatory and makes it convenient to vary the roll angle to change the celestial scan plane of the scientific instruments in the wheel.

The magnetic control torque is generated by interaction between the satellite dipole moment and the geomagnetic field (see Fig. 6). The rotation of the tipped Earth dipole axis and the rotation of the orbit plane cause daily and bimonthly fluctuations in magnetic torquing geometry. However, the secular components of the field enable adequate open-loop control by periodical adjustment of the strength of magnets with dipole moments along the spin and roll axes. This eliminates the expense and complexity of programed or closed-loop actuation of the magnets.

In Fig. 7, attitude time histories for OSO-6 show that the combination of magnet torquing and open-loop gas jet actuations can be used to control pitch angle and spin rate much closer than the normal $\pm 3°$ and $\pm 13\%$ nominal closed-loop limits. At the same time, large changes in roll angle were made to accomplish the wheel experiment scientific objectives. The first plot shows that spin rate was controlled to $\pm 4\%$. The second shows pitch angle was controlled to $\pm 1°$. The next two plots show how the spin and roll axis magnetic dipole moment was switched by ground command. The last plot shows how the desired roll maneuver was made.

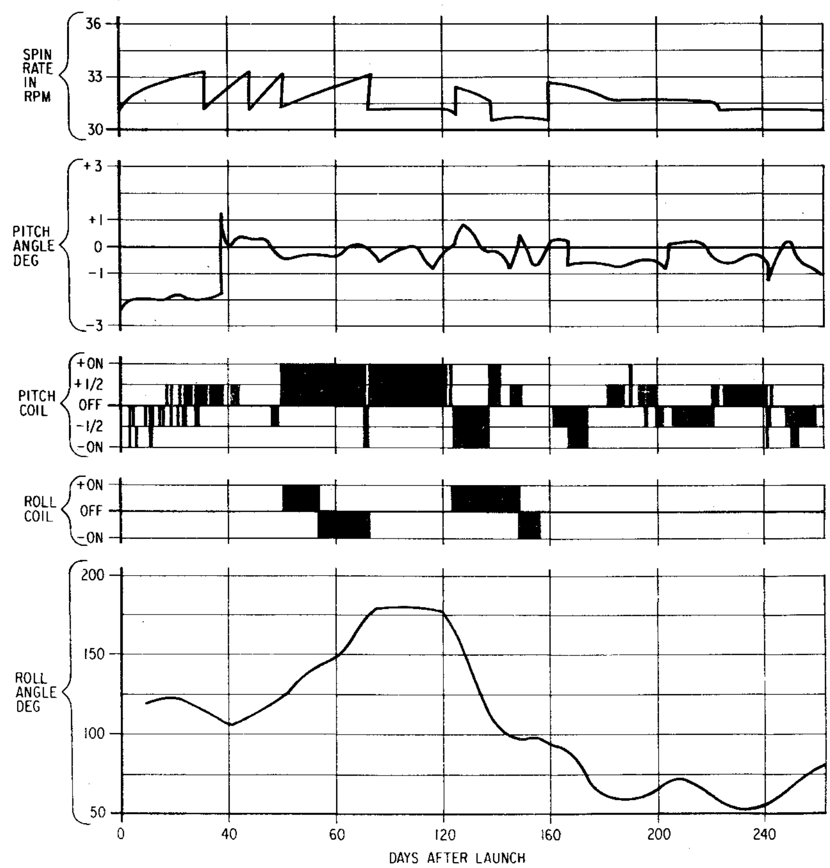


Fig. 7 Magnetic control on OSO-6.

Nutation Control

All the OSOs were made inertially disk-shaped so they would be unconditionally stable. Passive dissipations in the wheel, therefore, tend to damp rather than drive nutation. This reduces the analysis and testing required to ensure against nutation problems like those exhibited by Explorer 1[7] and TACSAT I.[8]

Nutation is damped by a simple passive damper.[7] The cantilevered-bob is driven by the coning motion and the excess kinetic energy of nutation is dissipated by motion of the bob in a viscous fluid. The nutation damper, shown in cross-section in Fig. 8, is compact, easily caged during launch, and not incapacitated by sliding or rolling friction for small nutation amplitudes. The damper on OSO-7 has a decay constant of about 2 min, and is nearly identical to that used on the smaller OSO-1 where the decay constant was about 30 sec.

On OSO, elevation servo interactions are the principal source of nutation.[9] On OSO-7, these interactions are smaller than on OSO-1 because of higher servo gains and better damping. On OSO-7, interaction caused by raster scan resets is reduced to about 0.03° (from about 0.5° on previous OSOs) by applying the raster reset command through a lag circuit.

Wobble Control

The residual wobble angle due to wheel mass imbalances is given by

$$\theta = u/(I_s - I_t)$$

where u is the equivalent dynamic imbalance about the spin-bearing axis, I_s is the rotor spin moment of inertia, and I_t is the over-all transverse inertia. For a nearly spherical satellite like OSO-7, wobble is particularly critical.[4]

For most satellites, $I_s - I_t$ is accepted, as determined by other conditions, and wobble is controlled by balancing the wheel to sufficiently small u. For OSO-7, wobble was controlled by controlling both u and $I_s - I_t$. For a given value of u, $I_s - I_t$ was made sufficiently large by ballasting the upper rim of the wheel

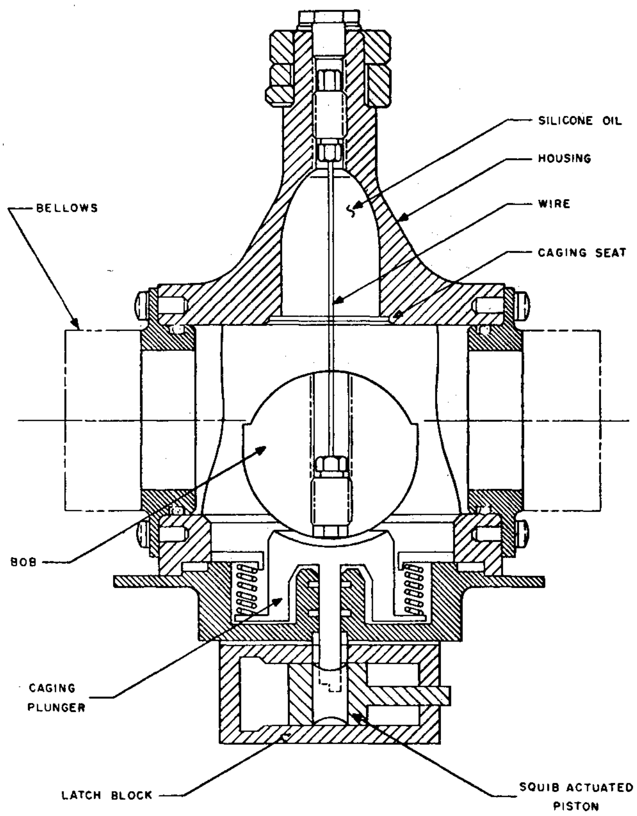


Fig. 8 OSO nutation damper.

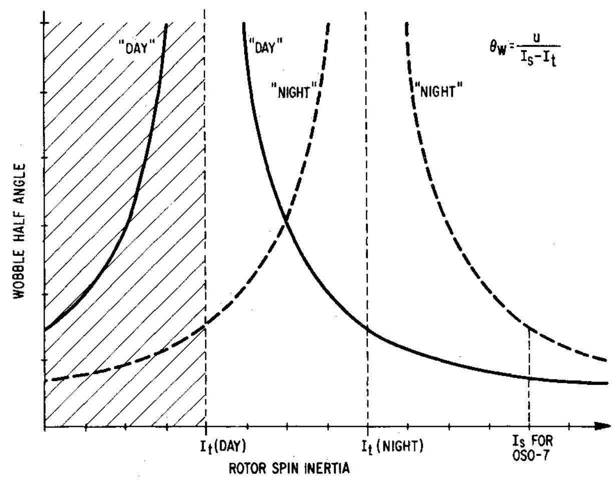


Fig. 9 Wobble angle variation with I_s.

with fixed weights. Figure 9 shows how the wobble angle varies with I_s for fixed u. Two pairs of curves are shown because the effective value of I_t changes when the PIA is uncontrolled (night curve) instead of oriented with respect to the sun (day curve).

The fixed ballast used on OSO-7 offers two advantages when compared to the extendable arms used on previous observatories. First, the ballast extension failure mode is eliminated. Second, the fixed ballast eliminates the large imbalance changes caused by small angular displacements of extendable arms. This made it feasible to control wobble to 1 arc-min as for previous observatories. The disadvantage of the fixed ballast approach is that greater nonfunctional weight was required.

A soft mount balancing machine was used on OSO-1–6. The dynamic balancing precision was about 0.37×10^{-2}kg-m^2 (200 oz-in^2). For OSO-7, a more versatile Ball Brothers hard mount machine was available. This machine achieves higher precision (about 0.18×10^{-2}kg-m^2 or 100 oz-in^2) at spin rates as low as 60 rpm by a novel use of synchronous excitation of strain gauges. This is the dynamic imbalance precision for a worst-case concurrent static imbalance. The machine can detect a *pure* dynamic imbalance as small as 1.8×10^{-4}kg-m^2 (10 oz-in^2).

Biaxial Pointing Servo

The biaxial servo has two azimuth modes. During sun acquisitions, the coarse mode uses error signals from silicon cell sun sensors to despin the sail. A sun target sensor is used to switch out the coarse error signal and initiate fine azimuth control. Only one mode is used in elevation.

Because gimbal friction is by far the largest pointing disturbance, OSO pointing accuracy is largely unaffected by external torques. The servos are biased to eliminate the error caused by the average torque. Variations in gimbal friction and solar sensor drift caused long-term pointing drift of up to 2 arc-min on OSO-1 over the life of the observatory. The offset point capability on the last two OSOs allows in-orbit adjustment of the offset bias. This enables compensation of pointing errors resulting from long-term drift of the friction level and the sensor null.

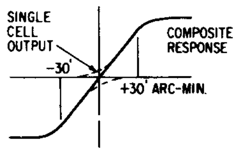
The sun-center pointing drift during an orbit has been reduced from about 15 arc-sec on OSO-1 to less than 2 arc-sec on OSO-7. This improvement resulted from decreasing the drift of the sensor null by improving the thermal design of the sensor and sensor assembly. When pointing at the edge of the solar disk, pointing drift is about twice as large as center pointing drift because the sensor scale-factor drift causes an additional error.

Figure 10 shows sun sensors on the front of a pair of pointed instruments and summarizes the performance improvements.

The high-frequency gimbal friction variation has ranged between 0.02 and 0.03 Nm. Friction variation due to spin-axis coning motions caused pointing jitter of about 0.5 arc-min on

PERFORMANCE IMPROVEMENTS
(ARC SECONDS)

	OSO-1	OSO-7
ONE YEAR DRIFT	30	3
ONE ORBIT DRIFT	15	2
PHOTON NOISE	0.01	0.01
PREAMP NOISE	0.1	0.1



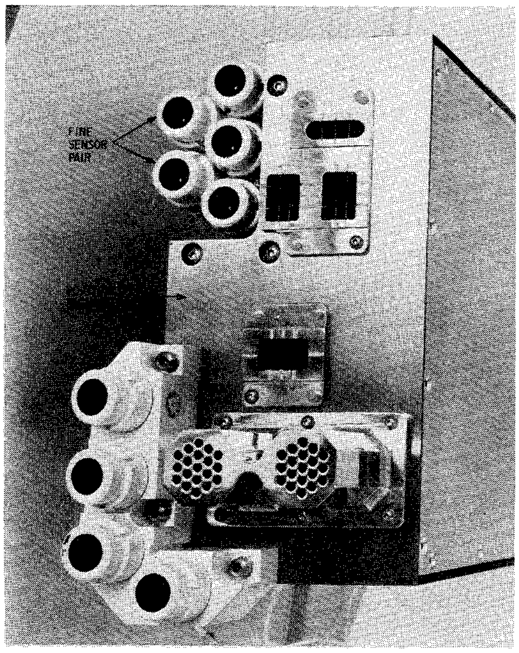


Fig. 10 Fine sun sensors and performance.

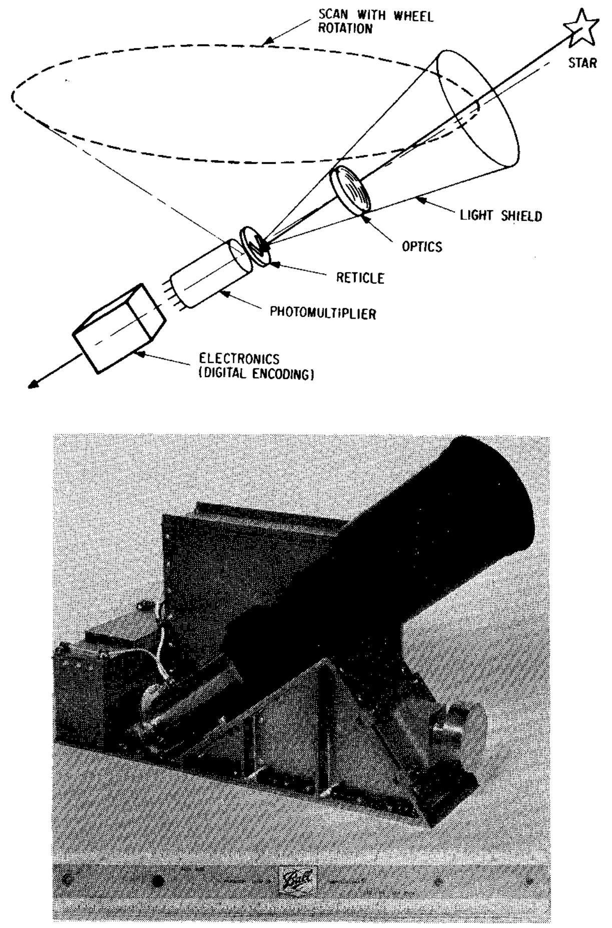


Fig. 12 Star scanner and its operation.

OSO-1. The short-term jitter amplitude on OSO-7 is less than 1 arc-sec. Figure 11 compares orbital data from a read-out sensor on OSO-1, 3, and 7. All the errors are in arc-sec.

The reduction in jitter resulted from increasing the servo bandwidths from 10 rad/sec on OSO-1 to 30 rad/sec on OSO-7 and from reducing the effect of a dead zone caused by the pulse width modulated motor drive. The increase in bandwidth was made feasible by raising the observatory mechanical resonance frequencies. Jitter could be further reduced by a factor of 10 or so, by using smaller bearings, and more complex servo compensation.

The total power consumed by the OSO biaxial servo pointing control is less than 6 w.

Aspect Determination

OSO-1 had only sun sensors for pitch angle and spin rate determination. A magnetometer was incorporated on OSO-2–6.

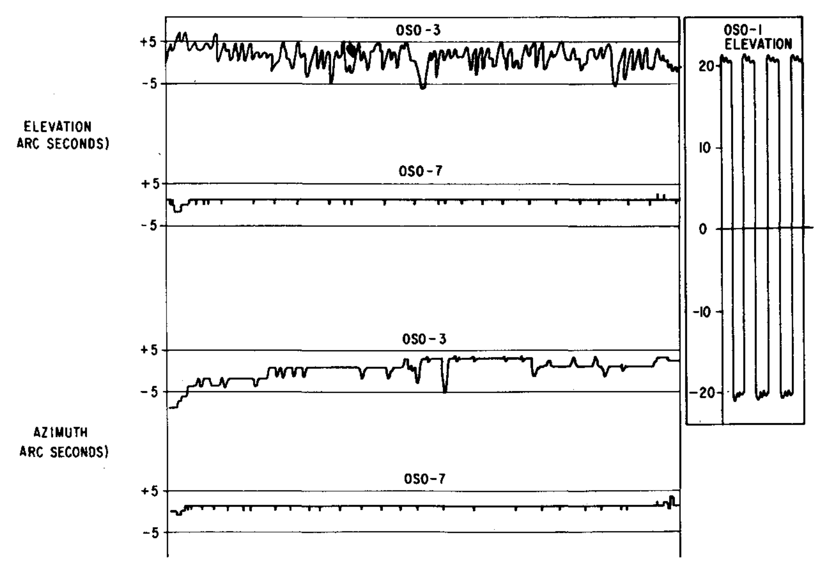


Fig. 11 Pointing jitter on OSO-1, -3, -7.

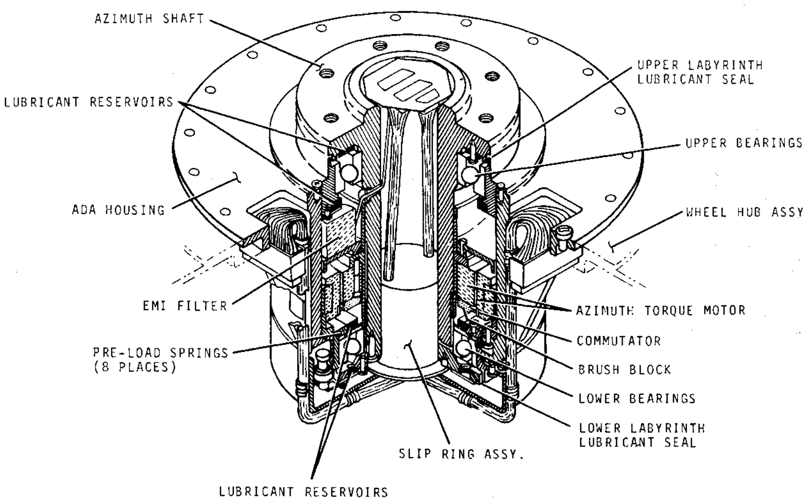


Fig. 13 OSO azimuth drive assembly.

This allowed roll angle determination to an accuracy of 2° and gave a measure of night-time drift.

Attitude determination was greatly improved on OSO-7 by incorporating a sail-mounted rate integrating gyroscope, an azimuth gimbal encoder, and a wheel-mounted scanning star sensor. Coarse attitude determination was improved by incorporating a wide-angle sun sensor.

The star sensor is mounted in the spinning wheel and so does not require separate mechanical or electrical scanning. Star transit times across two slits in a fixed reticle are telemetered in digital form for ground data reduction. The reticle pattern design eliminated much of the noise that has caused trouble on other scanners. Figure 12 shows the flight hardware and a schematic representation of its operation. This system permits three-axis attitude determination to about one arc-minute through orbit day and night.[10]

The gyroscope output is used to keep the sail despun at night. In addition to making attitude determination easier, this eliminates the dawn reacquisition required on previous OSOs and simplifies large angle spin-axis attitude corrections.

Thermal Control

By carefully selecting the optical properties of key surfaces, temperature is controlled without resorting to mechanical shutters, electrical heaters, or heat pipes. Passive temperature control has given excellent results on all seven observatories. This passive approach is not subject to electro-mechanical failures. Degradation of optical properties and tolerances in their measurement cause temperatures to vary from the analytical values, but these variations have been acceptably small.

Temperatures of the wheel hub indicate the thermal balance achieved between the satellite and the sun, Earth, and space. By comparing design goals with orbital data, Table 1 shows how successful passive control has been throughout the OSO program.

Table 1 Performance summary—hub temperatures

OSO	Max-°C	Min-°C	Avg of extremes °C	Predicted avg at equinox
3	22.5	12.5	17.5	15.4
4	22.2	12.2	17.2	15.4
5	19.8	7.2	13.5	14.1
6	17.6	9.0	13.3	15.4
7	14.8	12.5	13.7	12.9

Bearing Lubrication

Prior to launching OSO-1 it was widely believed that an unsealed bearing would cold weld in space. Gimbal design, lubricants, and application procedures have been developed to the

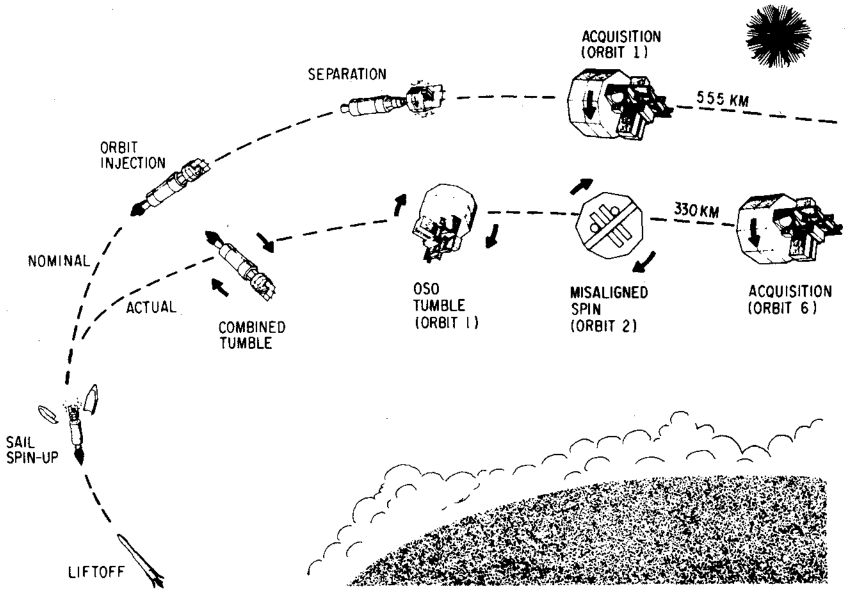


Fig. 14 OSO-7 nominal and actual launch sequence.

Table 2 Performance summary for OSO-1–OSO-7 (as of Dec. 1972)

Performance data	OSO-1	OSO-2	OSO-3	OSO-4	OSO-5	OSO-6	OSO-7
Launch date	March 7, 62	Feb. 3, 65	March 8, 67	Oct. 18, 67	Jan. 22, 69	Aug. 9, 69	Sept. 29, 71
Observatory weight	460	547	635	604	642	635	1415
Experiment weight	180	215	246	242	255	219	497
Wobble angle, arc-min p-p	10	6	10	3	3	12	3
One year pointing drift, arc-sec p-p	120	12	20	10	30	6	3
One hour pointing drift, arc-sec p-p	40	10	7	5	18	3	2
Jitter, arc sec p-p	20	10	5	4	3	2	1.5
Performance anomalies	• Spin up for short time to speed where it could not acquire • Badly degraded solar array due to "star fish" atomic test • Tape recorders failed after 3 months because of spurious commands causing power cycling	• Excessive dipole moment	• Dynamic unbalance twice that expected • Tape recorders failed after 18 months • Az motor current 2X normal after 27 months • Excessive sensor degradation (4.7%/yr)	• Tape recorders failed after 7 months			• One tape recorder failed due to abnormal launch
Life (months)	15	9	58	51	47—Still Operating	40—Still Operating	15—Still Operating
Life ended by	Degraded solar array from "star fish" radiation	Gas depletion due to excessive dipole moment	Put in stand-by mode and left unattended	Put in stand-by mode and left unattended	Still Operating	Still Operating	Still Operating

point where Ball Brothers now builds "Vac Koted" drive assemblies with 10-year life expectancy.[11,12] The development of this lubrication technology is the greatest single breakthrough in dual-spin satellite technology. Bearings, motor brushes, and slip rings are not life limiting components on OSOs.

Figure 13, a cross section of the OSO-7 azimuth drive assembly, shows the range of lubrication tasks that must be performed. Slip ring technology has progressed from the modest 18-circuit unit on OSO-1 to a vacuum-proved 350-circuit unit for general space applications. Furthermore, 5 amp power handling, 50kc frequency handling, and 5 μv noise for 10 ma signals (with typical 5 v peak levels) have been demonstrated.

OSO-7 Launch Sequence

New large angle acquisition procedures and sensors made it easier to recover OSO-7 from a 60 rpm end-over-end tumbling motion and 70° misalignment of the initial angular momentum caused by a launch vehicle malfunction.[13] Figure 14 compares the nominal and actual launch sequences. The $-11g$ acceleration during the 60 rpm tumble increased the azimuth bearing friction level enough to stop the sail from spinning. Spin gas torque was applied immediately after separation and the spin axis started erecting toward the positive angular momentum vector. In spite of close control (to 0.3%) of the difference between the wheel transverse moments of inertia, erection with correct spin direction may have only been an accident. This is because of gyroscopic cross-coupling of the large tumble angular velocities.

The 70° attitude correction required 8 hr of open-loop ground command operation. The large initial attitude error caused abnormally low gyroscope temperature and high drift rate, and the electrical power was limited to that stored in the batteries because the solar array was not directed at the sun.

Since the initial recovery action, the observatory has performed flawlessly with spin-axis coning angles of about 1 arc-min and short-term pointing jitter of about 1 arc-sec.

Perspective

Table 2 summarizes OSO performance from 1962 to 1972. These achievements can be placed in perspective by reviewing stabilization results of the sixties and considering present trends. OSO achievements together with those on other programs have made dual-spin a competitive stabilization option for a wide variety of missions. The main satellite stabilization techniques applied during the sixties include gravity gradient, single-spin, multiple momentum wheels and mass expulsion (limit-cycle) systems. The characteristics of various systems and orbital results for the sixties are summarized below.

Gravity Gradient

For satellites which must point along the planetary nadir there is no simpler stabilization technique. It was realized at the outset that the technique is relatively sensitive to disturbances. In the early sixties, attention was given to means of achieving initial stabilization, damping libration, and providing yaw stabilization. With a libration damper and a pitch-axis momentum wheel (which is often used for yaw stiffness) the technique loses part of its advantage in simplicity.

Unexpected engineering design problems with extendible gravity gradient booms caused a number of satellites to behave erratically. These problems resulted from boom deformations induced by thermal and gravity gradients. While the boom deformation problems may now be largely eliminated, the technique has lost some of its early appeal.

Gravity gradient pointing accuracies range from 1° to 5° and the technique is sensitive to variations in orbit parameters.

Actively articulated booms have been proposed for higher pointing accuracy but the complexity of such a system is comparable to that of a multiple momentum wheel system. Hybrid applications using the gravity gradient torque to help dump accumulated momentum (viz., Nimbus and Skylab) are currently considered attractive.

Single-Spin

The first U.S. satellite, Explorer 1, was a single spinning body. This has been the most widely used stabilization technique for U.S. satellites. In the early sixties active and passive systems were devised to control nutation. Mass expulsion and magnetic torquing systems were developed to control spin rate and orientation. Inertially disk-shaped spin stabilized satellites have had an excellent record. The record of the rod-shaped satellites is spotty (including the misbehavior of Explorer 1). Currently, single bodies are only spin stabilized about the minimum axis of inertia for short periods.

The principal drawback to spin stabilization is that only the spin-axis has a fixed orientation. Also, it is usually only practical to change spin-axis orientation slowly through small angles.

Dual-Spin

Dual-spin satellites have generally shared the reliability record of the simpler single-spin satellites. This is partly due to the low spin rate of a single relatively large momentum wheel. The pointing flexibility is far greater than for single-spin satellites and highly accurate pointing, not anticipated in 1960, has been demonstrated. Excellent flight results of OSOs, later Intelsats and ITOS, have made dual-spin the glamour stabilization concept of the late sixties.

Dual-spin satellites have a preferred scanning axis (about the spin axis). The early communications and meteorological satellites only needed to despin their payloads about the orbit normal and keep the spin axis aligned with the orbit normal for these applications. During the sixties, only the OSOs used a pitch-axis cross-spin gimbal to provide two-axis pointing in the arc-sec range. No existing satellite has an additional roll-axis cross-spin gimbal, but this is a natural extension which would provide extreme accuracy in three axes.

Multiple Momentum Wheels

A typical three-axis system has a rate sensing gyroscope and electrical servo which drives a reaction wheel or CMG for each axis. A momentum dumping system is also required. High-accuracy three-axis stabilization is achieved but the system is considerably more complex than the others mentioned. Three small high-speed wheels are used in place of the single large low-speed wheel used for dual-spin satellites. For extreme accuracy, six wheels are used in the inner and outer control loops. The higher wheel speed and added complexity is partly responsible for the modest reliability record of early systems. Gyroscope and momentum wheel hardware development is reaching the point where added cost and electrical power are the principal drawbacks to the technique.

Mass Expulsion

Systems which depend only on released gas, etc., for control are simple and have excellent operating flexibility. Lifetime considerations have prevented application for missions that require both high accuracy and long life. The system has worked well for high accuracy and short life on sounding rockets, for moderate accuracy and life-time manned missions, and for moderate to low accuracy on long-life interplanetary spacecraft. Bang-bang control is used to produce mass-saving "limit-cycles" about the desired pointing direction. New low-thrust and high-impulse mass-expulsion systems should extend the capabilities of this method.

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