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From: Director, U. S. Naval Research Laboratory, Washington, D. C. 20390
To: Chief, Bureau of Naval Weapons

Subj: Gravity Gradient Stabilization Experiment (U)

Ref: (a) BuWeps ltr RTOS-1 Ser 0096 of 15 Jan 1964

Encl: (1) Description of NRL Gravity Gradient Stabilization Experiment

1. Enclosure (1) is forwarded herewith.

2. A more formal stabilization description and results will be available after a complete data review.

W. R. FAUST
By direction

Unclassified when enclosure is removed

[redacted]

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DESCRIPTION OF NRL GRAVITY GRADIENT STABILIZATION EXPERIMENT

Introduction

Many experiments to be flown in both military and civilian spacecraft may best be accomplished with one axis of the orbiting spacecraft aligned vertically. In an effort to have vertical alignment capability in Naval Research Laboratory spacecraft, the Satellite Techniques Branch launched a gravity gradient stabilization experiment on January 11, 1964.

It is the opinion of NRL engineers that the optimistic results of studies performed by General Electric Co., Bell Telephone Laboratories, NASA, APL and others, coupled with the successful gravity gradient stabilization experiment launched by APL prove the feasibility of stabilizing satellites with gravitational torques. However, NRL feels that no system has been sufficiently tested to be accepted as "state of the art".

In general, the stabilization task breaks down into three major problem areas; 1, reducing all satellite tumble and aligning the payload in the desired orientation, 2, extending boom or booms to give a large ratio of pitch and roll axis moment of inertia to yaw axis moment of inertia, and 3, damping the satellite librations to orient the vertical axis within tolerable oscillations. This experiment does not attempt to resolve the initial attitude problem since there is no preferred direction of the plus or minus Z axis of the NRL payload along the local vertical.

Test Payload

The stabilization system will be compatable with a payload described by the following parameters:

Weight -- 70 $\pm$5 lb.

Center of Gravity -- 1 $\pm$1 inch below geometric center

Moment of Inertia -- $I_z = 0.7 \pm .1$ Slug-ft^2

$I_x = I_y = 0.6 \pm .1$ Slug-ft^2

Balance about vertical axis -- Static - .38 oz. in

Dynamic - 10.07 oz. in^2

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Dimensions -- two 20" hemispheres separated by a $3\frac{1}{2}$" equatorial band

Magnetic Moment -- Less than 250 pole-CM

The stabilization systems parameters are:

Boom length -- 28 ft.

Boom erection mechanism wt. -- 1.75 lb.

Damper diameter -- 5 inches

Damper Weight -- 11 lb.

Total stabilization system weight -- 14 ±1 lb.

The total test payload weight is 84.19 lb. and after boom extension the $I_x = I_y$ moment of inertia will have increased to 239 slug-ft^2.

Test Conditions

The gravity gradient experiment was launched on a thrust augmented Thor-Agena vehicle from PMR on January 11, 1964 at 12:20 PST. The experiment was launched into a 69.906° prograde inclination, 497 N. mile perigee, and 508 N. mile apogee orbit. Boom extension was initiated by command from a [redacted] at the start of orbit number 12. Full boom extension was indicated by satellite telemetry 11 minutes later. All visible local noon passes were recorded for approximately the first 260 orbits. The satellite was in steady state oscillation by orbit 54 (42 orbits after rod extension). Periodic checks of damper performance will be made throughout the life of the satellite.

Description of Stabilization System

The use of an extendable boom mechanism to change the satellites mass distribution in orbit is common to all the proposed stabilization systems reviewed by NRL. This is normally accomplished by the extension of a mass attached to an extendable boom mechanism. To date the only source of these mechanisms is the Special Products Division, DeHavilland Aircraft of Canada, Ltd. NRL has had a great deal of experience with several models of the DeHavilland extendable booms in ground tests and considers these units to be flight worthy. Flight of DeHavilland's mechanisms as booms and/or long antennas by Airborne Instrument Laboratory, the Canadian Government, APL and NRL have proven that these units will operate successfully in orbit.

The other component common to all the stabilization system reviewed by NRL was the damper. The damper must remove the energy of oscillation so that the satellite axis of minimum moment of inertia will stabilize along the local vertical. All of the systems reviewed by NRL utilized a different and always unique damper component. The damper selected to be flown on the NRL stabilization experiment is the megnetically anchored viscous damper designed, built and pre-launch tested by the General Electric Co. This damper was selected for (1) simplicity in ground handling, (2) anticipated high component reliability in orbit (3) computer studies indicate good damper performance (4) desirability of testing a system other than the damped spring and mass system successfully tested in orbit by APL and, (5) the General Electric Co. indicates that they can deliver a damper unit by mid November. A detailed description of the boom extension mechanism and the magnetically anchored viscous damper are included in this report.

In the NRL experiment the damper will be extended on the end of a 28 ft. boom. The weight of the damper will serve as the transferable mass necessary to greatly increase the pitch and roll moments of inertia. Figure 1 shows the stabilization system in launch configuration. The boom extension mechanism is mounted inside the satellite skin and attached through a hole in the skin to the damper. The damper is clamped to the satellite skin during launch and the vehicle-satellite separation modes of the flight.

After separation the satellite probably had some tumble resulting from separation tipoff and vehicle motion. Even though the boom is unextended, the damper will remove all the tumble energy as the bar magnet tries to stay aligned with the earths magnetic field. The tumble rate was expected to be a maximum of 3 degrees per second and completely decay before the orbit 12. By ground command the damper was released and the boom deployment process started. The boom extension time was approximately eleven minutes. At the time of boom deployment, the satellite attitude may be considered arbitrary. Therefore, in the worst case the payload must be

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rotated 90° to be correctly oriented. If the worst case is assumed, the oscillation about vertical should be decreased to 33° in approximately 10 orbits after boom deployment. In orbital configuration one time constant is 10 orbits. One time constant will remove 37% of the initial oscillations. Since the best satellite aspect resolution is about 6°, slightly less than 30 orbits should be required for the satellite attitude to appear as steady state. Flight performance data is attached in Appendix I to this report.

Description of Damper*

The magnetically anchored viscous damper, see Figure 2, consists of three elements: (a) viscous damper, (b) magnetic anchor, and (e) magnetic suspension. The device is completely passive, requires no external sources of power for operation, has no rubbing parts and is ideally suited for long life reliable operation in a space environment. None of the elements incorporated represents an advance in the state of the art or represents basically new and untried concepts.

The viscous damper consists of two concentric spheres with a viscous fluid between them. When there is a difference in angular velocity, there will be a viscous shearing action which results in a dissipation of energy. In order to produce a difference in angular velocity of the spheres and to be assured that they do not eventually "lock-up" on each other, the inner sphere is fixed to the earth's field by the magnetic anchor. This is achieved by a bar magnet attached to the inner sphere, which acts essentially as a compass needle, always aligning itself parallel to the earth's magnetic field.

In order to assure the concentricity of the spheres and to prevent any possibility of rubbing under operating conditions, the spheres will be separated magnetically. This separation will be attained by a magnetic suspension in which a diamagnetic material is repelled by a magnetic field. The outer sphere will be made of a diamagnetic material, and the magnetic field will be produced by permanent magnets attached to the inner sphere.

* NRL Experimental Damper Proposal, Sept. 17, 1963 General Electric Company, Valley Forge Space Technology Center, Philadelphia, Pa.

Damping will be obtained by the relative motion of two concentric spheres which are separated by a viscous fluid. The concept of utilizing the motion of concentric spheres to produce damping is not new in the state of the art. It results in a small, lightweight, and most important, a completely passive device.

The magnetic anchor serves to hold the inner sphere fixed while the outer sphere, which is attached to the spacecraft rotates. The magnetic anchor locks the inner sphere to the earth's magnetic field by means of a longitudinally magnetized bar magnet attached to the inner sphere. This bar magnet acts as a magnetic dipole which will be torqued by the earth's field. The perturbing effect of the bar magnet flipping as the satellite crosses the earth's poles will be unnoticeable since it is less than the 6° aspect resolution. The use of a magnetic dipole to orient a satellite is not a new concept; it has been used successfully in Transit 1B and 2A, where an Alnico V bar magnet 4 inches long, and 1 inch in diameter was used.

Boom extension Mechanism*

The boom extension mechanism is depicted in its basic form in Figure 3. The boom elements are formed out of strip material, heat-treated into a natural circular section in such a manner that the edges of the material overlap by approximately 90°, giving the tubular element a strength which is almost equivalent to that of a seamless tube of the same diameter and wall thickness. The boom element, when retracted, is stored in the strained, flattened condition by winding it on a drum. When the boom is retracted, the tubular element is continuously transformed from its natural circular section to the flattened condition by passing it through a suitable guidance system. The boom may be extended or retracted simply by rotating the storage drum in the correct direction. It will be apparent that retracting the boom involves supplying strain energy to the boom material as it flattens from its circular section. The coiled boom, therefore, has a natural tendence to self-extend, thus providing low power extension, the drive motor acting mainly as a governor to limit the extension velocity. The NRL boom had no in-flight boom retraction capability.

*Proposal for 40 ft. Extendable Antenna for Lofti Satellite, DeHavilland Aircraft of Canada, Ltd., Downsview, Ontario

The 28 feet of boom element is stored on a drum and is led through a guide sleeve which supports it as it forms from its strained, flat cross section to its natural tubular shape. Mechanical power transmission to the drum from the electric drive motor is by a spur gear train. Boom extension is automatically stopped when full length is achieved by the action of a microswitch in series with the drive motor being actuated by a slot cut in the tail end of the boom.

Throughout the design of the proposed system, close attention has been given to compactness, low weight and, in particular, extreme reliability. To this end, the design has been simplified wherever possible and use made of proven hardware and techniques. It is considered that the proposed system represents a carefully balanced compromise between the above requirements.

The following sections describe some of the major mechanical features of the boom mechanism:

Boom

The boom element consists of 28 feet of specially heat-treated Beryllium Copper strip, processed to retain a high elastic limit stress. Each element will be 2.0 in. wide and 0.002 in. thick, the thickness being determined by the stresses imposed upon the element as it unfurls from its unstrained circular condition to the flattened condition for storage purposes. The strip will form into a tube of approximately 0.5 in. diameter with 90° overlap. The boom element has been designed so that the flattening stresses are sufficiently below the elastic limit stress of the material to ensure a virtually unlimited element fatigue life. Structural analysis reveals that boom material of this size will easily withstand the bending moments generated by the specified change in vehicle spin velocity.

Drive Motor:

The drive motor is a 12 volt D.C. permanent magnet type, with a 3/4 in. frame size. It is complete with an integral precision gear head providing a 150:1 gear reduction. A final gear reduction is made from the gearhead output shaft to the boom storage drum by external nylon spur gears providing the desired boom extension time of 11 $\pm$1 minutes.

The motor bearings are double shielded, stainless steel ball-races and are lubricated by G.E. 300 low vapour pressure grease, as is the gearhead. This type of motor has undergone extensive testing to prove its ability to operate in a space environment and DeHavilland experience with this type has shown them to be entirely satisfactory. Tests under thermal vacuum conditions up to 200 hours have shows no deterioration in performance.

Guidance System:

The boom material must be guided very precisely as it transforms from the stored condition to its tubular shape in order to ensure smooth reliable extension. Over the years DeHavilland have developed a simple, lightweight, guidance system which exhibits these properties and will be used in the proposed design.

This guidance system employs tangential element take off, with automatic compensation for the decreasing drum diameter as the boom element is extended. Spring belt tensioners are used to restrain the element on the drum.

Structure and Materials:

The boom system is constructed from two fibre glass side plates, correctly located by magnesium and stainless steel spacers. The boom storage drum, guidance system components, and the external spur gears are made from nylon. All materials used have a proven ability to withstand a space environment for long periods of time. Aluminum and magnesium parts will be anodized to MIL-A-8625 and Dow 17 respectively. No other materials used require surface treatment.

Satellite Earth Aspect Instrumentation

It was decided to fly a gravity gradient stabilization experiment as a research and development experiment whose performance would not affect satellite operation. Due to the short lead times involved, it was decided to fly an optical instrumentation system of limited resolution but covering deviation angles from the local vertical from 0° to 45°. This instrumentation system is of such a nature that quick look data reduction is possible without mathematical calculations.

The chief disadvantage of this system is that aspect data is available only when the satellite sees the earth fully illuminated from horizon to horizon around 360°. Thus, when the sub-satellite point is at local noon for any spot on the earth, aspect data is accurate.

It was not known whether the satellite will stabilize top up or top down. Therefore, it was necessary to instrument the satellite for either possibility.

It was decided to use six optical sectors of five detectors each, a total of 60° wide located symmetrically 120° apart on the top and bottom hemispheres of the satellite concerned. The earth's horizon at the desired altitude is at the center of these sectors (the 60° angle) for an earth stabilized satellite.

Available logic circuitry in the satellite makes it practical to sequentically switch B+ power to each of the six sectors. The outputs of these sectors can then be connected together and to the five common level detecting devices (Schmidt Triggers). Thus at any particular time one sector of five sensors (or detectors) has power applied to it and has its outputs routed to the level detectors which are followed by mixing resistors and a subcarrier oscillator. The basic block diagram is shown in Figure 4. A complete frame of data is available every four seconds.

The Earth Aspect output has six discrete levels of "0" V, 1 V, 2 V, 3 V, 4 V, or 5 V which is changed to corresponding frequency variations by the subcarrier oscillator. Given an output reading at a particular time, the output will increase by 1 volt for each sensor that is illuminated. That is, each of the five sensors increases the output reading by 1 volt when it is illuminated by reflected light from the earth.

The detailed optical geometry of a sector is given in Figure 5. Each sector is 1/4" wide, and mounted on a 20" sphere.

By regarding the earth from horizon to horizon around 360°, it appears as a disc of a particular size at a particular altitude. In the same manner

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the hemisphere of the satellite with the three sectors mounted on it can be laid flat and dimensioned to the same scale as the earth. These plane surfaces are shown in Figure 6.

Considering the inside of the earth circle lit up, one can lay it over the satellite template and move it relative to the satellite template. Any sensitive portion of a sensor thus illuminated will add 1 volt to its own sector reading. Thus the output reading of a sector will be 1 volt times the number of its sensors that are illuminated or partially illuminated. By measuring the distance between centers of these two circular templates and using the length-angle ratio necessary to make these templates, one knows the angle from the local vertical to which the satellite pole is pointed once three sector outputs are known. Once these templates are made, one can determine all possible satellite outputs for a particular altitude before the satellite is in orbit. A list of all possible outputs is included in Appendix I

Independent sun sensors are also provided to determine which end of the satellite is pointed earthward and therefore which set of three sectors to read data from.

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Satellite RF Systems Section

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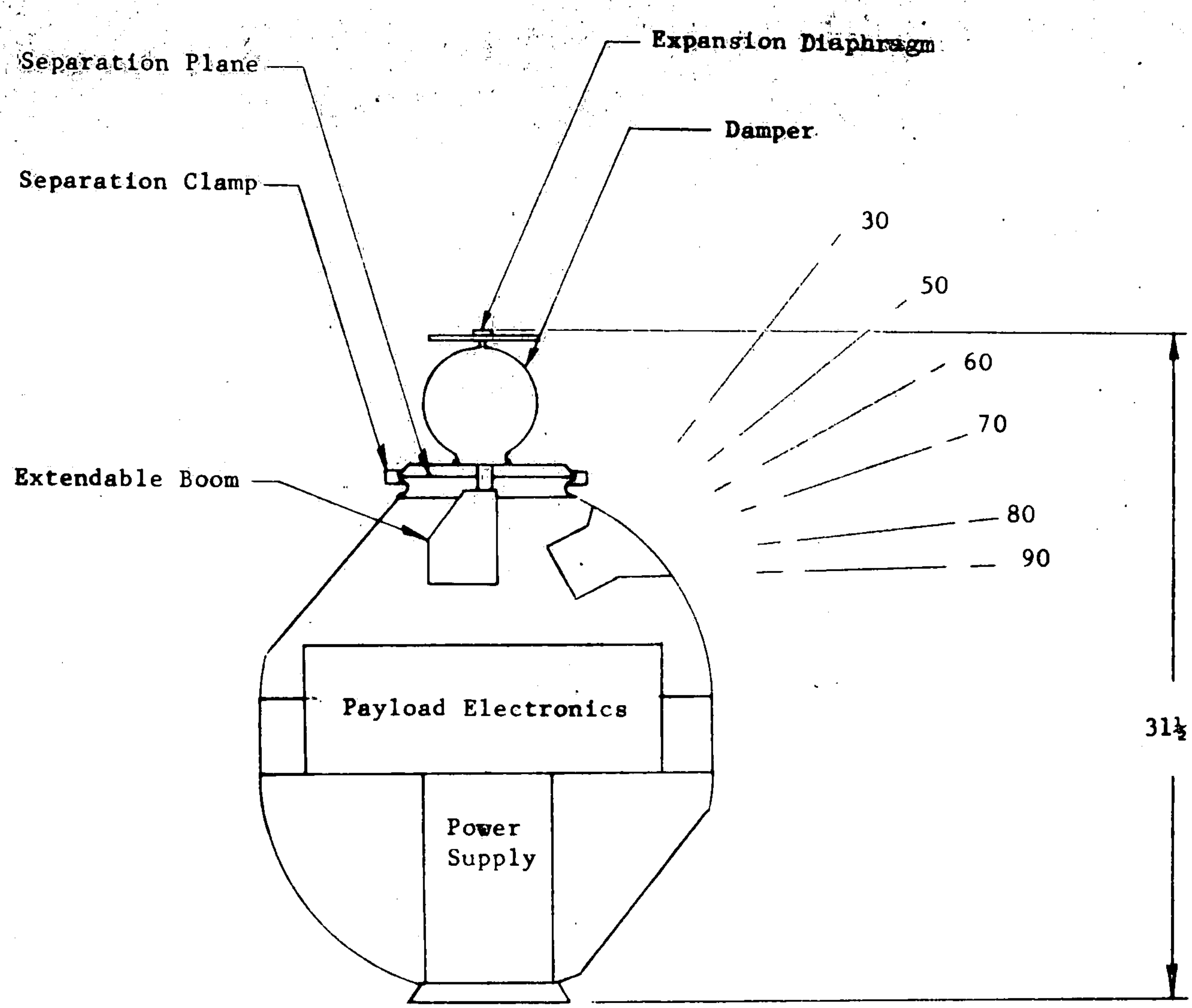
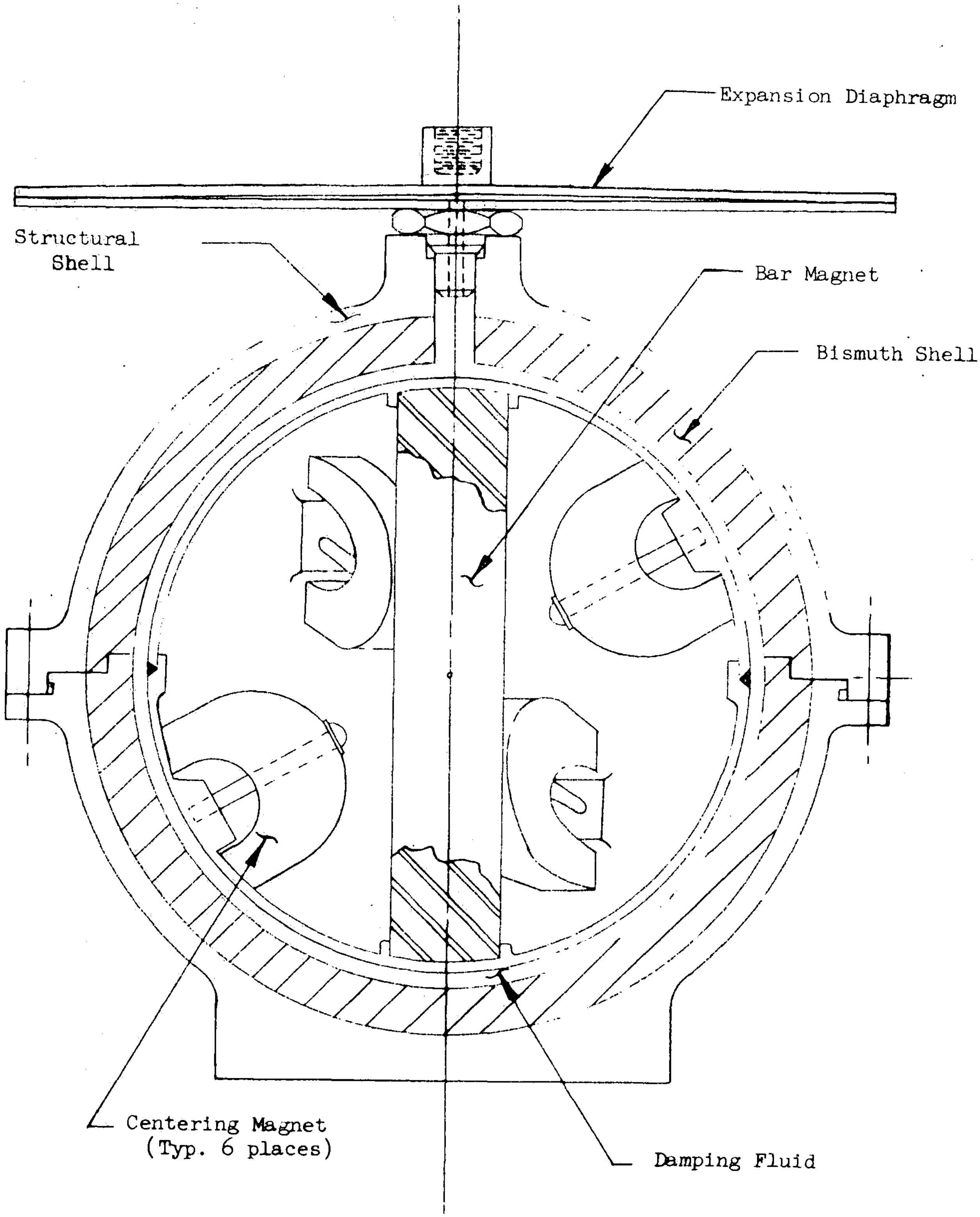


Figure 1

Gravity Gradient Stabilization Experiment Payload

Satellite weight - 70 $\pm$5 lb.
Stabilization system weight - 14 $\pm$1 lb.
Total Satellite weight - 84.19 lb.
Dimensions - two 20" hemispheres separated by a 3½" equatorial band
Before boom extension
Center of gravity - 1 $\pm$1 inch below geometric center
Moment of inertia
$I_z = 0.7 \pm .1$ Slug ft.^{2}
$I_x = I_y = 0.6 \pm .1$ Slug ft.^{2}
After boom extension
$I_x = I_y = 239 \pm 5$ Slug-ft.^{2}



MAGNETICALLY ANCHORED VISCOUS DAMPER

Figure 2

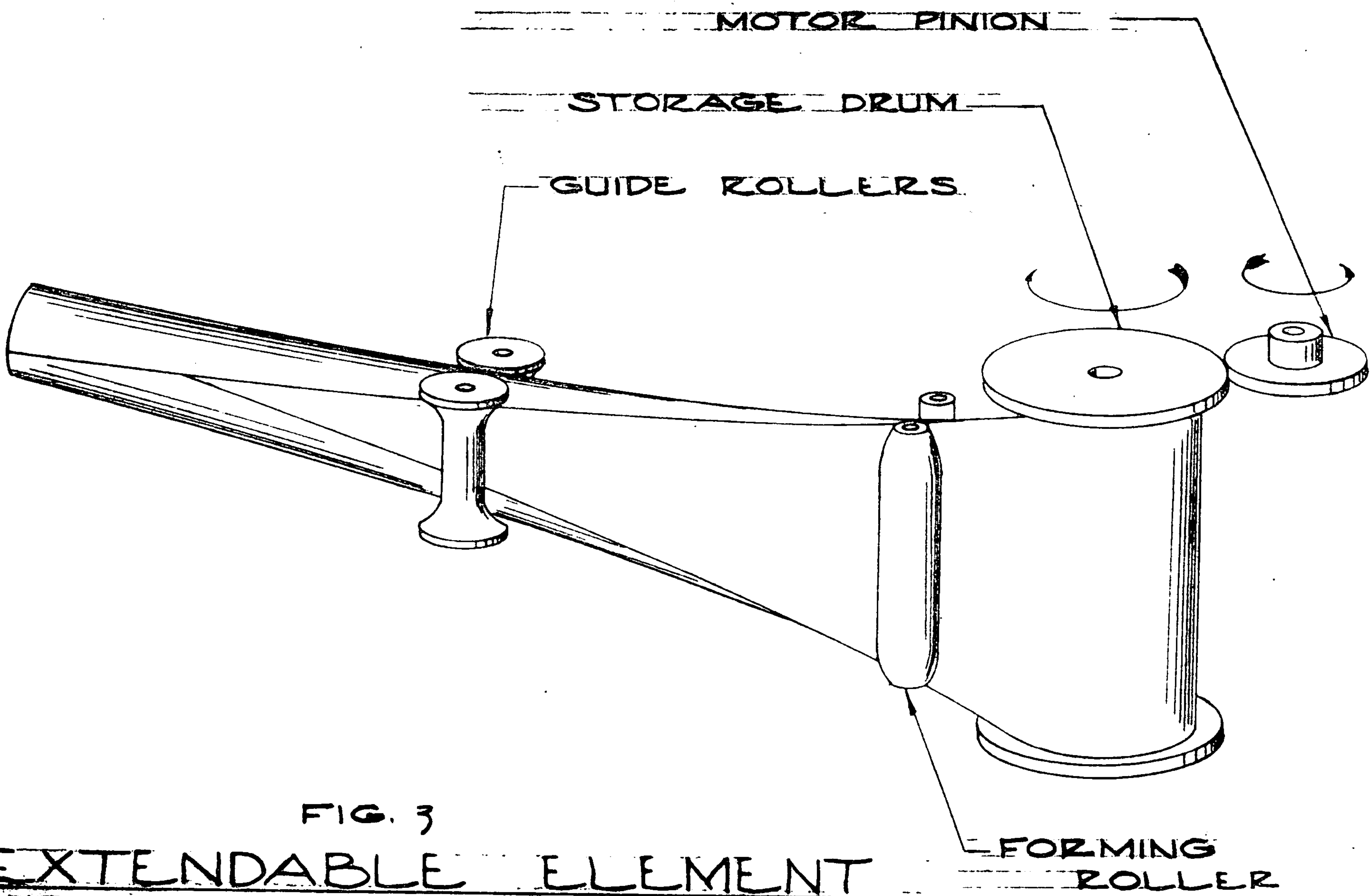


FIG. 3

EXTENDABLE ELEMENT

USING INTEGRAL SPRING ENERGY
AND MOTOR ASSIST EJECTION PRINCIPAL

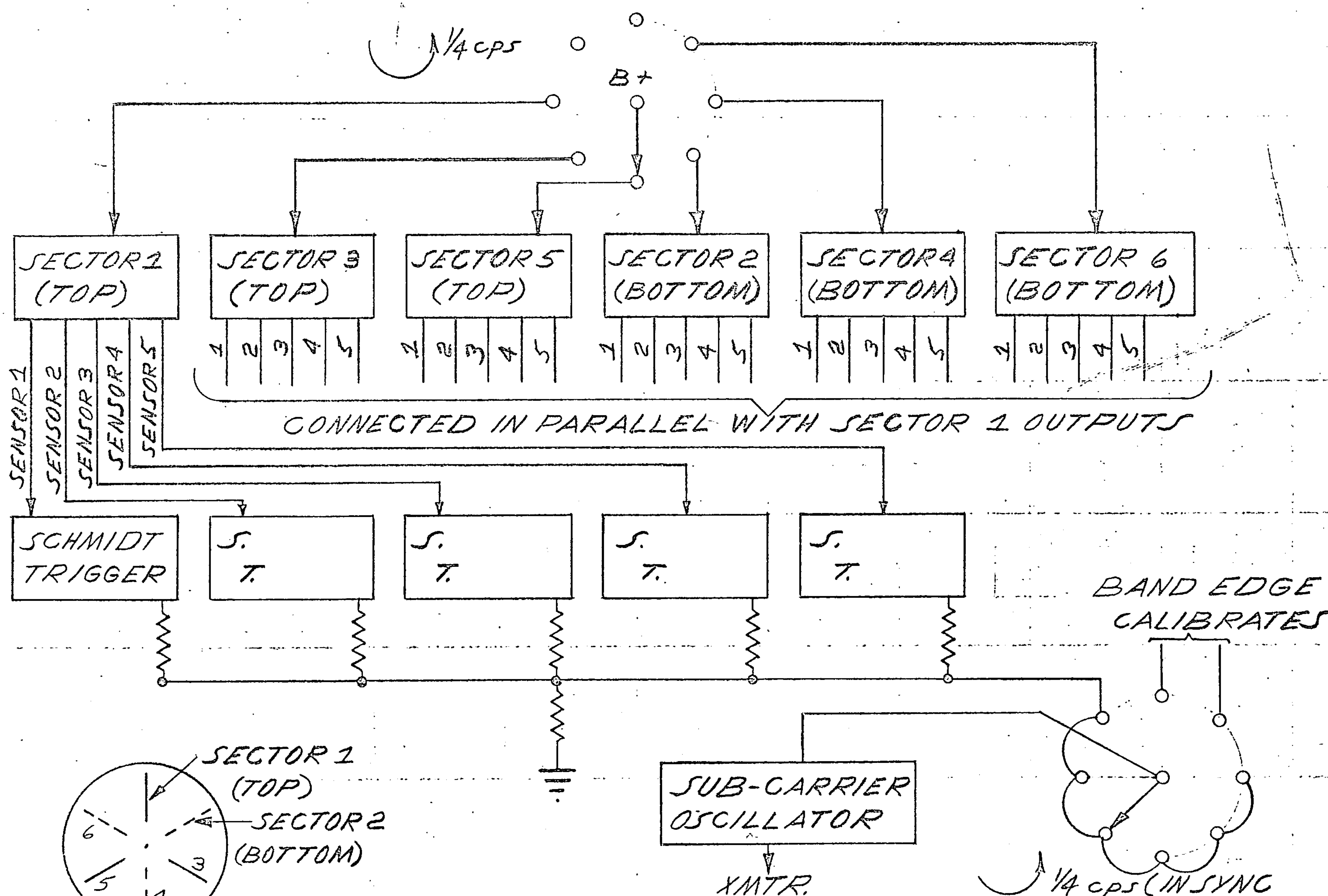


FIGURE 4

EARTH ASPECT INSTRUMENTATION

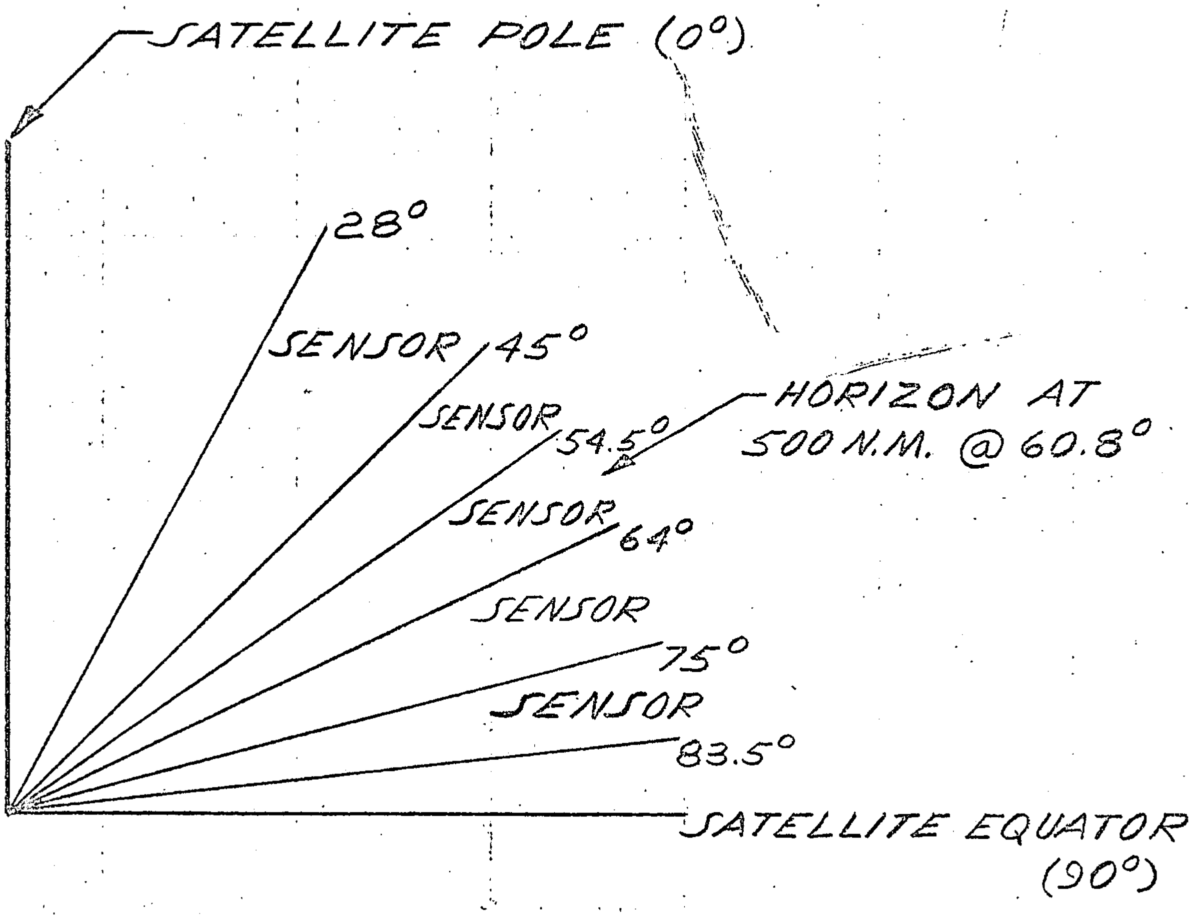
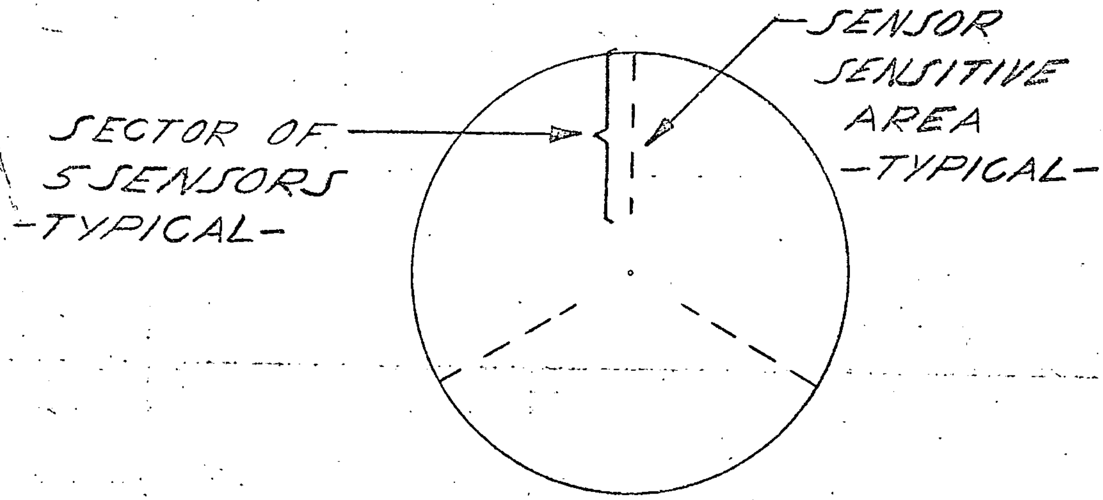
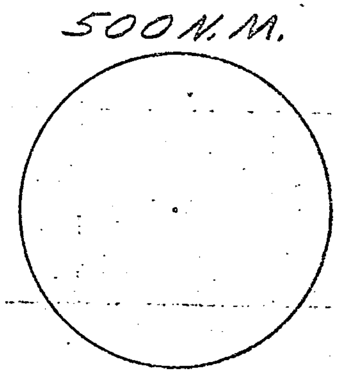


FIGURE 5

SECTOR OPTICAL GEOMETRY



SATELLITE TEMPLATE



EARTH TEMPLATE

FIGURE 6

EARTH ASPECT CALCULATOR

APPENDIX I

INSTRUMENTATION AND ORBIT RESULTS

Visible light sensors sensitive to reflected light from the earth were used to determine satellite attitude. The instrumentation system will be described in detail in a forthcoming NRL report. The instrumentation system cannot individually distinguish roll, pitch or yaw of the satellite but defines the angle of a cone of ambiguity to which the satellite vertical axis is aligned to the local vertical. This information is transmitted in real time by the satellite FM/AM telemetry transmitter.

The instrumentation system can distinguish the following bands of angular deviation from the local vertical:

0° to 6°	17.5° to 34°
3° to 10°	18° to 24°
6.5°	20° to 35°
7°	25° to 42°
7° to 16°	33° to 59°
8° to 16°	34° to 36°
11° to 14°	34° to 58°
14° to 25°	26° to 42°
14.5° to 19°	42° to 89°
16° to 33°	47° to 74°

The gravity gradient rod with the damper mounted on the outboard end was extended 28 feet on orbit number 12. Prior to that orbit, the low tumbling rate of the vehicle indicated that the damper was operating and extracting the energy imparted in tipoff at separation from the booster. During rod extension, the angular deviation from local vertical was between 7 degrees and 19 degrees. Within seconds after completion of rod extension, the reading changed into the 17.5 degree to 34 degree band, indicating that at the time of crossover the angle was 17.5 to 19 degrees. With this initial deviation and inertial rate of essentially zero (which the satellite would have at the end of rod extension) the initial oscillation half amplitude would be between 38 degrees and 42 degrees. The lower hemisphere sensors were indicating earth sensing and the upper hemisphere sun sensor signal confirmed that the rod was pointed upward. The fact that the angle off the vertical increases rather than decreasing immediately following rod extension indicates that the rod was leaning back with respect to the direction in orbit. During the next pass, the angle was in the 18 to 34 degree band. Subsequent posses showed consistantly smaller readings, indicating that a steady-state mode was reached by about the 54th orbit (about 42 orbits after rod extension.)

Most of the data available for evaluation at this time is from the Hybla Valley Station. This information generally covers about 5 to 10 percent of an orbit which is on the order of 10 to 20 percent of a cycle of oscillation and therefore does not necessarily bound the amplitude of the oscillation. Some data tapes are now available from the following stations:

Hybla Valley, Virginia
South Point, Hawaii
Lima, Peru
Woomera, Australia
Quito, Ecuador
San Nicolas Island, California

As these data are examined and patched together the full cycles of oscillation will be better defined, within the resolution constraints of the sensors. A report including the results will be prepared after completion of the data analysis.

The attached appendix gives the aspect readings and the time increments over which they were observed for each tracking station for which data is presently available. Summarizing the data starting at pass 26 and taking the upper limits on the sensor bands shows that the satellite was aligned within less than 6 degrees of the local vertical 47.0% of the total time of data coverage, within less than 10 degrees 84.6% of the time of data coverage, and always within better than 16 degrees during the times of coverage. Although final assessment of performance can be made only after examining all of the data, the information to date indicated that the oscillations decayed approximately as predicted and that the steady-state amplitude is generally less than 6 degrees with possibly an occasional spike over that.

Additional aspect data will be obtained at the ground stations until about orbit number 280. At this time the orbit plane will have regressed to a position where the visibility disc under the satellite will not be fully illuminated by the sun. It will take approximately thirty days for the orbit plane to regress on around to a position which is again favorable for good aspect readings.

Appendix II

Aspect Data Summary-All Stations
Available as of 2/3/64

Data applicable between orbits 26 and 261

Data from 54 individual orbits

333	11,230	0° to 6°	47.0%	84.6% under 10°
334	8,023	3° to 10°	33.6%	
332	949	7°	4.0%	
234	3,219	7° to 16°	13.5%	
242	254	11° to 14°	1.0%	
235	196	14.5° to 19°	0.8%	

Total data time = 23,871 seconds

= 3.85 equivalent orbits out of 54 orbits sampled

Hybla-Quito Data Overlap

(data corrected for overlap)

Orbit	θ		Δ t (sec)
54	0° to 6°	16 min, 54 sec	686
	7°		328
68	0° to 6°	18 min, 46 sec	600
	3° to 10°		486
	7° to 16°		40
95	0° to 6°	13 min, 23 sec	116
	noise		124
	3° to 10°		563
109	0° to 6°	19 min, 48 sec	588
	3° to 10°		472
	0° to 6°		128