DEVELOPMENT OF A HIGH STABILITY POINTING MECHANISM FOR WIDE APPLICATION

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ABSTRACT

A recurrent requirement of spaceborne instruments and communications equipment is that of accurate pointing. This need is recognisable in such diverse applications as Star Sensor trimming, Momentum Wheel gimballing, in-orbit adjustment or alignment of equipment, inter-satellite communication and Antenna Pointing.

As part of the ESA Advanced Supporting Technology Programme, British Aerospace is developing a pointing mechanism of novel design having several advantages over the more conventional gimbal, centre-pivoted or cross axis pointing concepts currently state-of-the-art.

INTRODUCTION

The 1977 World Administrative Radio Conference (WARC) stipulated that accuracies better that ±0.1° should be achieved on communications beamwidths of typically 1° to 2°, and as a consequence gave rise to an operational requirement for Antenna Pointing Mechanisms (APMs) capable of around ±0.01° pointing accuracy, thus relieving the satellite AOCS from the difficult, if not impossible, task of achieving this accuracy for multi-antenna systems.

Experience with thermal vacuum testing has shown that these high accuracy requirements are very difficult to achieve, particularly when the APM is operating in 'Open Loop' mode (see Ref. 1). Nonlinearities, build errors, non-orthogonality effects and, particularly, thermal expansion effects combine to reduce the accuracy until, typically, an accuracy of around ±0.025° limits the performance of conventional gimbal systems.

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Better 'Closed Loop' performance (i.e. when the APM is responding to an external error signal such as that derived from an RF sensor) can normally be obtained providing that the movement resolution of the actuators is high enough and that mechanism backlash and control response are adequate. (Ref. 2, 3).

The objective of the APM development programme was therefore to achieve an APM design which offered, in addition to other attributes, an improved stability of pointing. Following trade-offs covering the range of existing pointing mechanism concepts, a radically new concept was chosen based on an idea developed at ESTEC. This concept, and its derivatives, is the subject of an ESA patent application.

THE SWASH-PLATE PRINCIPLE

The new mechanism utilises the swash-plate or rotating wedge principle in order to achieve and maintain the pointing vector. Figure 1 shows the operating principle. The device contains 4 main structural elements, A,B,C and D. B and C are wedge-shaped and enabled to rotate about the z-axis by means of bearing systems located at 1, 2 and 3. If mutual z-axis rotation between A and D is prevented by, for example, a bellows E, and the bearings at 1 and 2 are driven, then the device becomes a polar coordinate pointing mechanism.

When B and C are rotated by equal amounts, one clockwise the other anti-clockwise, there results a tilting of the pointing vector away from the z-axis (nodding). If B and C are now rotated together, the vector sweeps around the z-axis at the angle previously achieved. Figure 2 illustrates this by showing the circular paths traced by the pointing vector on a target, due to the rotation of B and C and the combination B + C.

It can readily be seen that if either of the two swash-plates is prevented from rotating, then the pointing vector can be re-aligned with the z-axis by the rotation of the other swash-plate alone. In principle any two of the three bearings may be driven, but it is advantageous to drive bearings 1 and 3 since the actuators may then be mounted on the base and top plates. If the actuators prevent back-driving of the two sections by virtue of their detent positions, then the pointing vector is maintained without the application of power.

MECHANISM DESCRIPTIONS

A cross-sectional view of the BAe High Stability APM is shown in Figure 3. The two swash plates, having a swash angle of 2.15 degrees, can be seen supported by single bearings and the two motors supported off the top (payload) interface and the bottom (satellite) interface, respectively. Figure 4 shows additional views with the installation of the positional encoders.

Main Bearings

The three main bearings are Kaydon four-point contact (Gothic Arch) bearings of 7 inches diameter having a minimal preload within the bearings. This preload, and the thermal design of the mechanism, necessitated careful analysis in order to avoid on the one hand, bearing clearance which would, in principle, result in degraded pointing accuracy, and on the other hand excessive preload and consequent increased torque.

The four-point contact bearings are well suited to the concept allowing a compact design whilst at the same time having a high load-carrying capacity (13,600N radial, 34,000N axial, quoted manufacturer's value for static loading). Substantial mass and dimensional savings are achieved over the use of duplexed pairs of angular contact bearings.

The bearings are lubricated with a low-vapour-pressure oil. The use of a liquid lubricant increases the thermal conductivity of the bearing, reducing the thermal gradients which would otherwise contribute to preload changes. The bellows allow the possibility of hermetic sealing, if required by the application.

Structure

The material selected for the four main structural components of the mechanism is Beryllium. The advantages offered by this material are:

- Extremely low mass
- Thermal expansion close to that of the bearing steel
- Good thermal conductivity
- High specific heat.

The three latter features, combined with the cylindrical nature of the structure and the externally mounted bellows, provide a protected environment within the mechanism, leading to an exceptionally high thermal stability.

The four main structural sections, with the interconnecting bearings, constitute the load path through the mechanism. The large diameter of 180mm is significant in that high strength and stiffness can be obtained for very low mass. The mechanism can typically support unaided a mass of up to 10kg through an Ariane launch, the strength limitations being those of the main bearings having a load capacity as given above. In Figure 4 it can be seen that the central part of the mechanism is free from obstruction. Thus, when desired, an aperture of up to 40mm dia. can be provided through the mechanism for the passage of cables, flexible waveguides, or payload hold-down mechanisms.

Actuators

The actuators, shown mounted off each of the two end sections, are comprised of 15° permanent magnet stepper motors driving through a spur gear train onto ring gears mounted on each of the swash-plates. The motors have an in-line double stacked arrangement such that each motor has a double length rotor and a full set of redundant windings.

The gear ratio is 701:1 from motor shaft to ring gear which, in conjunction with the swash-plate geometry, gives a typical output step size of 0.0008° for each motor step. This high gear ratio also provides a high output torque (>350Nm), permitting a slew rate of 0.24°/sec to be applied to a load of 50kg m^2. The fact that the mechanism is stiff as well makes it suitable for the pointing of complete antennas incorporating relatively stiff 'flexible waveguides'.

Since the actuators prevent back-driving even during launch conditions, no launch lock is needed. As a consequence no pyrotechnics are needed.

Position Sensors

Two-pin contact encoders mounted off the end-plates allow the position of the swash-plates to be determined. The encoders mesh with the ring gears on the swash-plates via a two-pass gear and have a resolution equivalent to 2 motor steps. In addition to the contact encoders, two pairs of redundant optical pick-offs identify the '(0.0)' reference position (where the pointing vector is aligned with the z-axis). These sensors have an accuracy equivalent to ±3 motor steps and provide back-up information in the event of encoder failure or an alternative means of datum identification for applications where encoder information is not required.

THERMAL DESIGN

Pointing mechanisms are normally mounted in exposed conditions, and while the base of an APM may benefit from the relatively controlled temperature of the satellite body, the payload or antenna interface was taken as -170°C to + 120°C and that of the satellite top floor as -20°C to -50°C.

For a satellite-mounted application, the thermal control is completely passive. Thermal insulation is placed between the mechanism and the payload and the mechanism is surrounded by multi-layer insulation. Thermal straps assist the dissipation of heat from the motor so that in the extreme case gradients are limited to:

- 6°C through the main bearings
- 10°C between adjacent swash-plates or end-plates
- 2°C radially across the APM.

For a boom-mounted application, without power supplied to the motors the mechanism can reach very low temperatures. In that case it is necessary to employ heaters either to retain acceptable 'start up' temperatures, or to provide a warm-up capability prior to a re-pointing activity. The motors may act as heaters. In operation the variation in temperatures is expected to have very little impact on the mechanism performance.

OPERATIONAL CHARACTERISTICS

As already described, the High Stability Pointing Mechanism operates in an essentially polar-coordinate fashion such that where the rotation of the two swash-plates is defined by the angles θ_1 and θ_2 the pointing angle of the mechanism in cartesian coordinates is defined by:

$$x = \alpha(\sin\theta_1 - \sin\theta_2)$$

$$y = \alpha(\cos\theta_1 - \cos\theta_2)$$

where α is the swash angle on each of the rotating sections.

For simple open loop repointing it is quite straightforward to calculate the values of θ_1 and θ_2 required and drive the swash-plates to the desired positions on command from the ground. However, in closed loop operation where an RF sensor is employed, it is necessary to respond automatically to the error signals generated in the cartesian axes of the sensor. In this case a number of command strategies are possible.

In a generalised case, where an APM is required to trim about a number of alternative RF beacons, use is made of the quasi-orthogonal nature of the nod and sweep motions. These motions are inclined to the RF sensor axes and an on-board microprocessor is employed in the control electronics to perform the necessary conversion. This is greatly simplified by the use of the algorithm:

$$\Delta\theta_1 = Ae_x + Be_y$$

$$\Delta\theta_2 = Ce_x + De_y$$

where e_x and e_y represent the errors in x and y directions and A, B, C and D are four constants inputted to the electronics by telemetry. These depend on the location of the trimming position within the pointing range and can either be obtained from the encoders or estimated independently. The encoders are not necessary for trimming operations.

This technique allows trimming at any point within the pointing range other than at the centre or at the edge. These 'no-go' areas exist because of reduced slew rates at these positions due to the harmonic character of the pointing vector movement. For a mechanism with a pointing range of 4.3° radius and slew rate requirements of 0.1°/sec. of the boresight the operating range is within an annulus of between 0.7° radius and 4.2° radius.

In a more realistic situation, the trimming position required is fixed and known in advance. Referring to Figure 2, the intersection of the B locus and the C locus at point P represents a point where the two motors, acting independently, comprise their own quasi-cartesian coordinate system. These axes may be chosen to be coincident with the RF axes and thus a simple control system can be achieved. This control philosophy is currently proposed for the European Communication Satellite L-SAT.

While, for trimming operation, the nominal pointing direction is obliged to be off-set from the centre of the range, for re-pointing duty it is advantageous to make the nominal pointing direction coincident with the z-axis or zero reference position. This permits the added feature of a controlled 'return to zero' capability with a single actuator. Since with power off the mechanism will remain fixed, all pointing mechanisms on a spacecraft can be controlled by one electronics unit which multiplexes between them.

TEST RESULTS

A prototype model of the High Stability Pointing Mechanism has been constructed and tested by British Aerospace. It was constructed using commercial standard, off-the-shelf, components for the main bearings and motors. The structural elements were made from aluminium.

Typical results of the test are given in Table 1. Given that the clearance present in the commercial standard bearings employed is theoretically capable of contributing an error of up to ±0.028° without taking into account other error sources such as bearing and housing runout, the results show that the design is inherently highly accurate. In these tests the preload exerted by the bellows tends to compensate for the effects of bearing clearance. Based on these results and supporting analyses, the expected accuracies are given in Table 2. The prototype HSAPM is shown in Figure 5.

PERFORMANCE

Table 3 summarises the main features of the High Stability Pointing Mechanism and its performance. The present design utilises a 2.15° swash angle and 7 inch diameter bearings. However both of these parameters may very easily be changed, thus allowing the pointing range to be greatly extended and the strength and stiffness of the mechanism to be increased dramatically.

The ability to provide a central aperture is a significant advantage for some payloads and, in the case of a steerable antenna dish, is ideally suited to the use of a cassegrain-type feed where defocussing due to re-pointing is avoided.

The incorporation of the pin contact encoder is optional. This is primarily an instrumentational feature since it is not essential for either the trimming or re-pointing duty. A significant reduction in both mass and complexity of the mechanism, compared with other concepts, has been gained by obviating the need for a launch-lock device and a separate fail-safe, return-to-zero facility.

CONCLUSIONS

The High Stability Pointing Mechanism is a new conceptual design which provides a simple and rugged mechanical interface between two structures (see Figure 6) and which is capable of orientating those structures relative to one another on demand. With its high strength, high-stiffness torque output and accuracy the mechanism has been designed to suit a wide variety of applications including antenna pointing for which the mechanism is to be employed on L-SAT (see Figure 7). The pointing range will be increased to 8.6° radius for the L-SAT application.

REFERENCES

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   by B. Hubert and P. Brunet, Proc. 15th Aerospace Mechanisms
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TABLE 1 - EXPERIMENTAL POINTING ERRORS

$E\theta_x$	$E\theta_y$
0.002	0.007
0.016	0.001
0.016	0.023
0.010	0.041
0.007	0.017
0.012	0.000
0.005	0.007
0.008	0.004
0.002	0.005
0.008	0.012
0.017	0.000
0.001	0.015
0.002	0.005
0.000	0.000
0.003	0.001
0.018	0.022
0.010	0.020
0.033	0.029
0.015	0.005
0.007	0.013
0.003	0.015
0.006	0.008
0.005	0.009
0.002	0.010

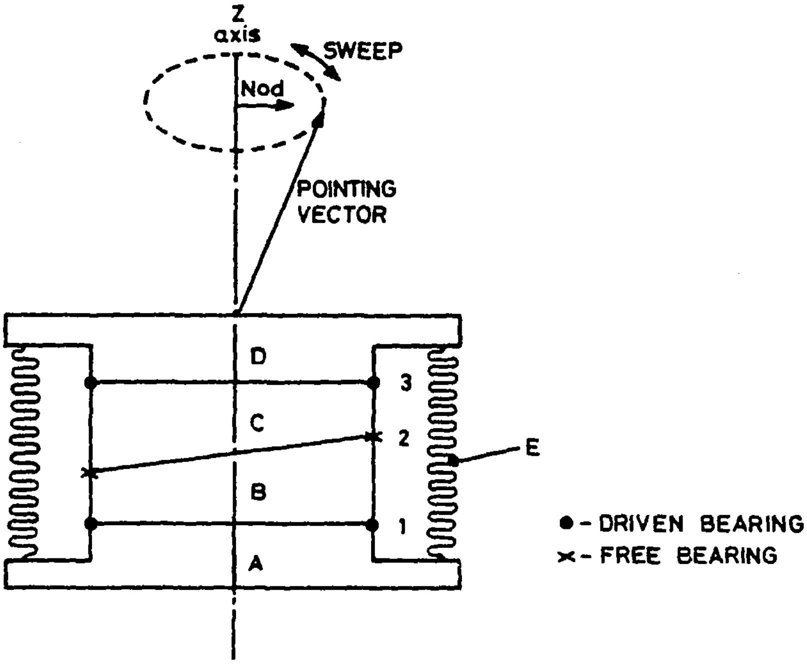
TABLE 2 - HSAPM POINTING ACCURACIES

MODE	ACCURACY
Trimming mode with RF sensor	± 0.006°
Repointing using encoder	± 0.0080°
Repointing (open loop) with encoder set datum	± 0.0085°
Repointing using pipper	± 0.01°
Steady state pointing	± 0.0080°
Launch configuration (relative to interface)	± 0.0080°
Failsafe mode using encoder	± 0.0080°
Failsafe mode using pipper (This assumes use of the encoder on the failed section).	± 0.0094°

For all modes other than the trimming mode the pointing accuracy will be governed by structural component accuracy, bearing run-out, thermal distortion, system backlash and motor step size. The accuracy for these modes is, therefore, dependent on whether it is the encoder or pipper that is used.

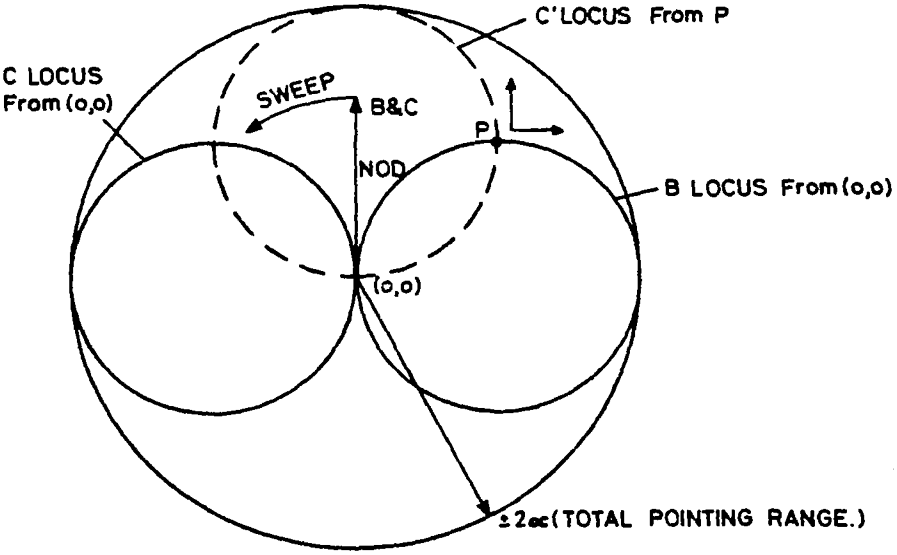
TABLE 3 - HSAPM PERFORMANCE CHARACTERISTICS

Mass	:	< 4.2kg , depending on configuration
Dimensions	:	100mm height 235mm diameter
Interface fixation	:	6, M5 bolts on 190mm PCD (antenna) 6, M5 bolts on 215mm PCD (Spacecraft)
Design life	:	10 years continuous trimming duty
Position sensors	:	Pin contact encoder (non-redundant) ± 0.008° Optical datum (redundant) ± 0.01°
Pyrotechnics	:	None
Control aperture	:	Up to 40mm
Load capability (individually applied)	: :	20,000 N axial 8,000 N radial 450 Nm cross axis moment
Ground running capability (individually applied)	: :	4,000 N axial 1,800 N radial 60 Nm cross axis moment
Payload inertia	:	Up to 50kgm²
Stiffness	:	140×10^6 N/m longitudinal 120×10^6 N/m lateral 450×10^3 Nm/rad cross axis rotation 730×10^3 Nm/rad torsional
Output torque	:	>350 Nm
Swash angle	:	2.15 deg. (4.3 deg for L-SAT)
Pointing range	:	Radius of 4.3° (8.6 deg for L-SAT)
Step size	:	0.0008° from each swash-plate
Slew rate	:	Up to 0.24°/sec.
Accuracy	:	See Table 1
Power consumption	:	Trimming 4W/motor Repointing 4W/motor Steady State pointing 0W/motor
Failsafe return to zero	:	Available for repointing applications



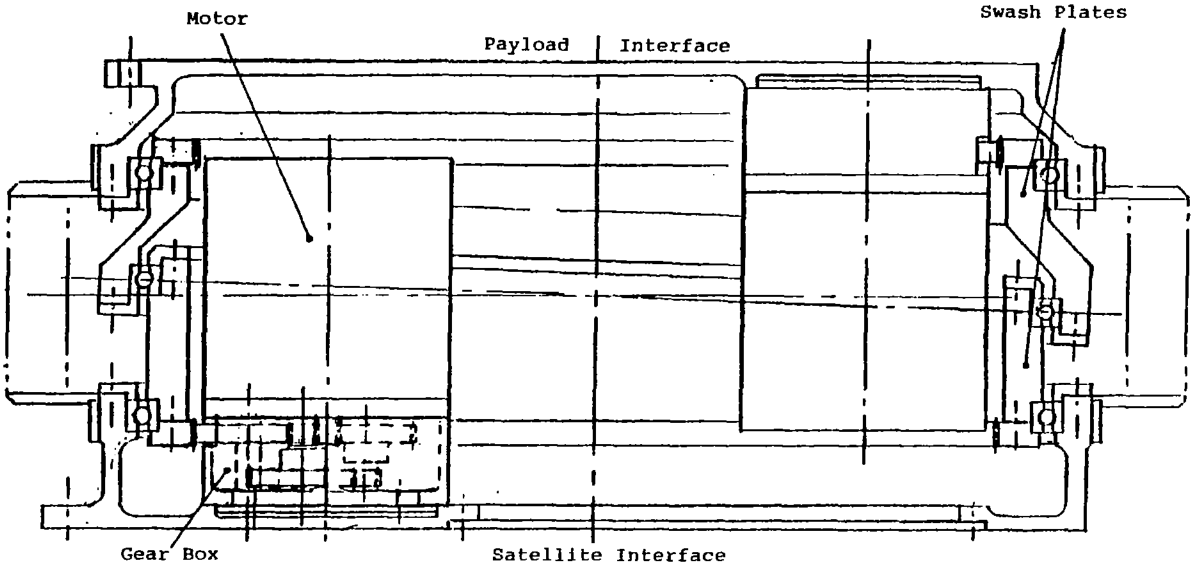
SWASH PLATE POINTING MECHANISM
PRINCIPLE OF OPERATION

FIGURE 1

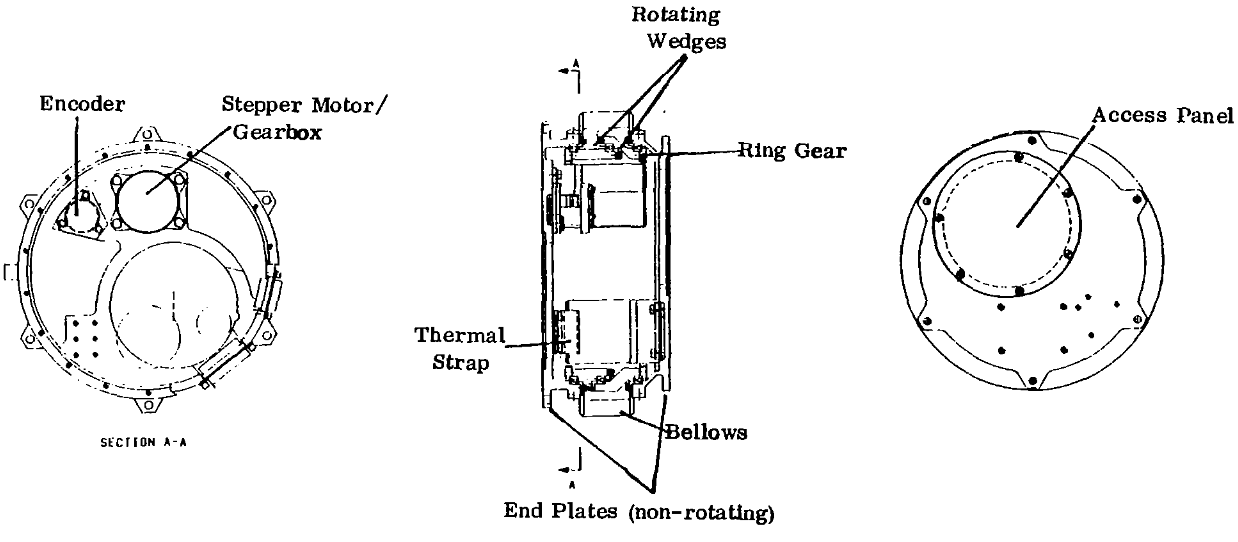


LOCUS OF POINTING VECTOR DUE TO ROTATION
OF SWASH PLATE

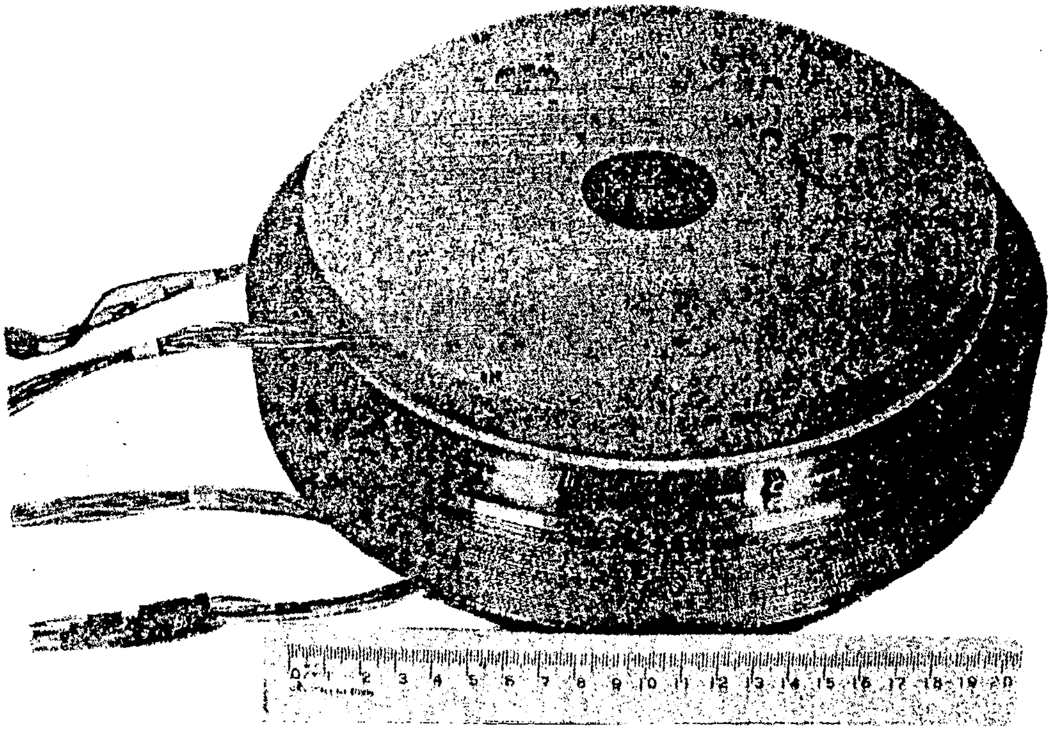
FIGURE 2



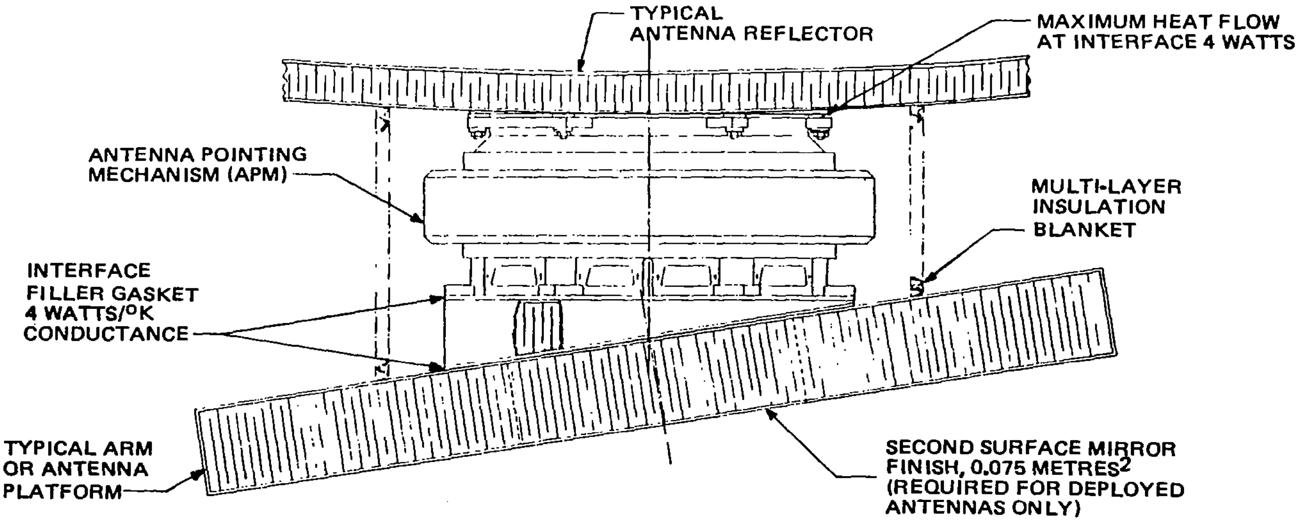
CROSS SECTIONAL VIEW OF HSAPM FIGURE 3



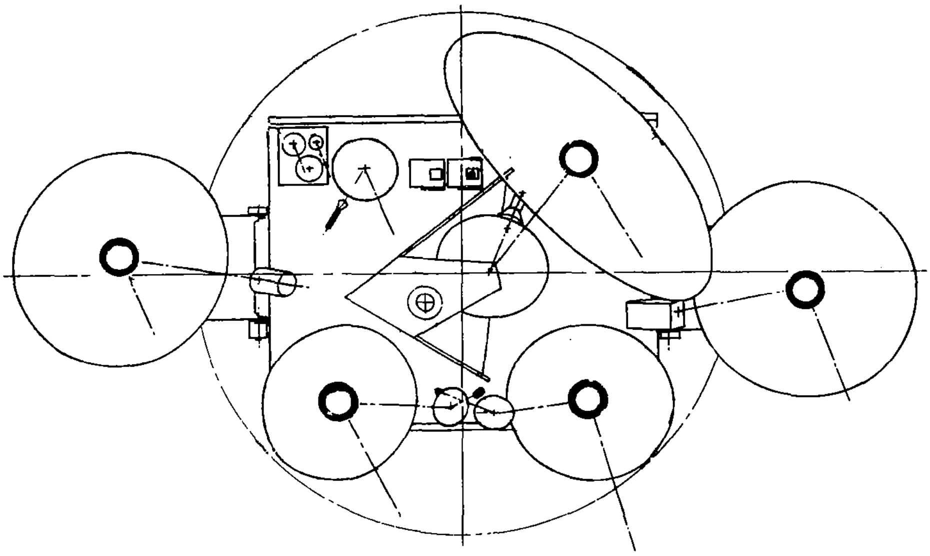
HIGH STABILITY ATTITUDE POINTING MECHANISM FIGURE 4



PROTOTYPE HASPM FIGURE 5



TYPICAL HSAPM INSTALLATION FIGURE 6



L-SAT CONFIGURATION (5 APM's SHOWN) FIGURE 7

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