RELIABILITY BREAKTHROUGH: AN ANTENNA DEPLOYMENT/ POSITIONING MECHANISM WITH ELECTRICAL AND MECHANICAL REDUNDANCY

By M. C. Olson, L. W. Briggs and J. B. Pentecost
Hughes Aircraft Company

ABSTRACT

An Antenna Positioner Mechanism (APM) has been developed for deployment of an antenna reflector and for fine granularity closed loop tracking of the antenna in response to RF beacon error signals. By utilizing permanent magnet stepper motors, spur gearheads, irreversible single thread worm/wheel assemblies and a miter gear differential, full electrical and mechanical redundancy has been realized. Two versions of this design have been generated: one is a weight-optimized design with a clutch for overload protection and one is a more rugged unit without a clutch.

INTRODUCTION

The SBS (Satellite Business Systems) and the Anik C (Canadian Communications Satellite) spacecraft employ 1.8 meters (6 feet) diameter antennae which are restrained during launch by pyrotechnic devices and after orbit injection are deployed approximately 70° to their operating position. (See Figure I.) This deployment as well as the fine grain on-orbit steering are performed by the Antenna Positioner Mechanism shown in Figure II. Except where noted, all descriptions, test programs, etc. presented in this paper apply to the initial weight-optimized design. This unit because of the light weight features required a slip clutch to protect the gears from on-orbit backdriving loads from the antenna and from the full stall torque capability of the stepper motor. After completion of the development effort on this weight-optimized unit, a more detailed computer model revealed a torsional stiffness requirement an order of magnitude greater than that measured. Several quick-fix solutions were abandoned in favor of a complete redesign to satisfy the new stiffness requirements. The ruggedized version that evolved from this redesign effort is described briefly at the end of this paper. With the exception of the clutch, which because of the larger gears became unnecessary for load protection, the basic designs of the two versions are identical. Both contain the full electrical and mechanical redundancy features.

DESIGN REQUIREMENTS/CHARACTERISTICS

The key design requirements and characteristics of the APM are summarized in Table I. The output shaft motion granularity of 0.0025 degrees for each 45° motor step determined the overall gear ratio of 18000:1. For one of the failure modes, described later in this paper, the output step increment becomes 0.005 degrees which is still acceptable. During deployment the step rate is 25 steps per second while typical operation for antenna pointing is about 1 step every 18 minutes.

The torsional stiffness about the APM output shaft was initially undefined when the weight optimized unit was conceived, designed and developed. When this parameter was established, it was an order of magnitude higher than the value measured on the qualification unit and, of course, necessitated a redesign.

The antibacklash torque is the torque required at the output shaft to prevent pointing errors due to backlash in the gears. Normal in-orbit loads due to spacecraft wobble and nutation dictate this requirement.

DESIGN DESCRIPTION

The APM gear train layout is shown in Figure III and is illustrated in schematic form in Figure IV. Redundant permanent magnet stepper motors drive through reducing gearheads into worm/wheel sets and a miter gear differential. The revolving trunnion shaft of the differential carries a serrated tooth, spring loaded clutch as shown in Figure V. The differential gear system permits either motor to drive the output shaft. Rotation of the non-powered half of the system is prevented by the irreversible feature of the single thread worm/wheel gears supplemented by the permanent magnet detent of the motor acting through the gearhead and worm/wheel ratios.

Any failure in the motor, gearhead or worm/wheel components is overcome by switching to the standby system. In the case of a jammed bevel gear in the differential, both motors are energized simultaneously. This operating mode causes the entire differential to rotate as a common member and actually reduces the gear ratio by 1/2 to 9000:1. Step size at the output is increased to 0.005 degrees, but since both motors are driving, the output torque is the same as for normal operation.

The clutch, located between the output shaft and the fixed bevel gear of the differential, is spring loaded to slip at approximately 8.16 Newton-meters (6 ft-lbs) of torque. This value prevents damage to the mechanism in the event of high backdriving torques from the antenna due to spacecraft maneuvers, etc. It also is sized to limit the amount of amplified motor torque seen by the gearbox and thus permits use of smaller and lighter components. A fixed stop external to the APM prevents antenna overtravel to about 1 degree beyond the operating range when the clutch is activated.

A conductive plastic, infinite resolution potentiometer is mounted on the APM output shaft to provide telemetry information. Since it is not necessary for mission success, it is not redundant. For applications where position data is necessary for closed loop pointing, a redundant unit could easily be provided. This custom-made frameless potentiometer has an electrical angle of 75°. In order to obtain high resolution in the operating region, an off-center tap is provided. With 5 volts applied at the potentiometer ends and 0 volts at the tap, the sensitivity over the first 65° from the stowed position is about 77 millivolts/degree while in the remaining 10°, which includes the normal operating region, it is about 500 millivolts/degree.

Spring biasing of the output shaft is used to eliminate backlash or dead zone in the gear system. This spring starts at essentially zero torque in the stowed position and winds up over the 70° deployment angle to provide about 12 in-lbs in the operating region.

All bearings supporting the worm/wheel gears and differential are preloaded angular contact type. Ground shims are provided to set the proper wavy spring preload forces. Except for the main output shaft bearings, failure of any bearing in the system is overcome by switching to the standby motor/geartrain or to simultaneous stepping by both motors. The main output bearing redundancy is achieved by applying thin sputtered MoS_2 film to the close tolerance slip fits of bearing to shaft and bearing to housing. In effect this creates journal bearings at these interfaces that allow operation if the output bearings fail.

APM LIFE & LUBRICATION DESCRIPTION

The APM design life consists of the following combination of test and flight operating cycles:

1.	Unit Test	162,000	motor steps
2.	Spacecraft System Test	284,000	" "
3.	In-Orbit Deployment	28,000	" "
4.	In-Orbit Pointing	292,000	" "
	Total test & mission steps	766,000	

The in-orbit positioning requirement was determined from the following assumptions:

- An average daily correction of ± 0.05 degrees, corresponding to 80 steps per day.
- A correction frequency of 1 step every 18 minutes, representing a correction of .0025 degree
- An in-orbit life of 10 years.
  (10 years X 365 days X 80 = 292,000)

The extremely large numbers of oscillatory cycles due to spacecraft nutation or wobble are not a factor since the magnitude of the torque loads is less than 1/10 that necessary to overcome the antibacklash spring on the APM output shaft. The in-orbit operational life can be expressed as 3650 cycles (365 days X 10 years) at a very low rate (1 step every 18 minutes) with an average amplitude as follows:

at motor	± 900° (± 20 steps)
at output of gearhead & the worm gear	± 12°
at worm wheel and input to bevel gears	± 0.1°
at output shaft	± 0.05°

The gear and bearing lubrication and processing are tabulated in Table II. A significant feature of the lubrication system is the extensive use of sputtered MoS_2 and ion plated lead for bearings and gears. The 2000°A lead film was chosen for the gearheads to be compatible with the small clearances and tight tolerances required for reliable operation. The sputtered MoS_2 on the bearing races and balls provides an extremely tenacious, uniform film for initial lubrication while the Duroid 5813 (primarily teflon & MoS_2) provides a space-proven replenishment system for long life. A bonded MoS_2 was employed for the difficult worm/wheel lubrication task because of the extensive previous experience in similar space applications and superior performance in tests where sliding friction occurs.

QUALIFICATION/LIFE TESTS

After completing a series of in-process functional/electrical tests, the weight-optimized unit was subjected to a design qualification test program. The key performance parameters evaluated during the tests included the following:

- Total excursion versus motor steps as measured by the control logic input pulse register and a mirror/autocollimator setup (performed for each of the redundant motor/gear systems).
- Small angle (± 1 degree and ± 0.1 degree) step accuracy using the autocollimator system for each motor/gear system.
- Clutch release torque and antibacklash spring values.
- Torsional and cross-axis stiffness characteristics.

The unit environmental tests consisted of the following exposures:

- Qualification level random vibration of 21 g's rms overall along each of 3 axes.
- Qualification level thermal tests with a representative inertia load attached to the output shaft.

The unit performed flawlessly during all phases of the test program. In addition, an inspection after completion of unit and qualification spacecraft tests showed the gears and bearings design/lubrication to be compatible with the life requirement.

Since the life travel distance requirement was most severe for the gearheads, an additional special life test was conducted on a motor/gearhead combination driving a representative inertia load. For this test, the motor was programmed (at a rate of 25 pps) for continuous cyclic operation (7000 pulses CW and CCW each followed by a 4 second pause) for a total of one million pulses. After completion of the cyclic life test the gearhead was disassembled and visually inspected for lube wear and gear tooth damage. The results of this inspection revealed no gear tooth damage with the ion-plated lead film intact and in excellent condition.

ALTERNATE DESIGN DESCRIPTION

The cross-section of the alternate design developed to provide additional torsional stiffness is shown in Figure VI. Because of the larger shaft and gears needed to satisfy the requirement for an order of magnitude increase in stiffness, a clutch was not required for overload protection. This feature along with some minor design improvements has simplified the assembly procedures and reduced the overall complexity. The qualification model of this design, after completion of functional and environmental testing, will be subjected to a life test program.

CONCLUDING REMARKS

The APM for the SBS/Anik C programs was developed with the goal of achieving high reliability through full mechanical and electrical redundancy. The final configuration required a redesign effort in order to satisfy all the system requirements as well as the reliability goal. Although the initial weight-optimized unit proved the basic design concepts and will, of course, be valuable for future applications, an earlier definition of stiffness requirements could have eliminated this extra design iteration.

TABLE I - APM DESIGN REQUIREMENTS/CHARACTERISTICS
(WEIGHT-OPTIMIZED VERSION)

Parameter	Requirement/Characteristics
Deployment Travel Range	70 degrees
Deployment Time	19 minutes
Operating Travel Range	± 1.0 degrees
Positioning Increment	0.0025 degrees/step (0.005 deg/step acceptable)
Step Rate	1 - 25 steps/second
Power Required	15 watts (28 V, 25°C)
Load Inertia	1.632×10^{8} gm-cm^{2} (12.0 slug-ft^{2})
Torsional Stiffness	Requirement Undefined - unit achieved 9.52 Newton-meters/degree (7.0 ft-lbs/degree)
Antibacklash Torque	16.32 Newton-meters (12.0 in-lbs)
Clutch Slip Torque	8.16 Newton-meters (6 ft-lbs)
Temperature Range	-51°C to 66° (-60°F to + 150°F)
Weight	1.59 kgms (3.5 lbs)
Redundancy Required	Electrical & Mechanical

TABLE II - APM LIFE/BEARING/LUBRICATION SUMMARY

ITEM	DESIGN LIFE (REVOLUTIONS)	LUBRICATION/PROCESSING	
Motor Bearings	77,500	Duroid 5813 retainers - Bearings (in motor) run-in in controlled atmosphere (GN_2)	
Gearhead Bearings	1,025 to 27,000	Duroid 5813 Retainers	Bearings and Gears (in gearhead) run-in in controlled atmosphere
Gearhead Gears	1,025 to 27,000	2000 Å ion plated lead	
Worm & Wheel Gears	1,025 (worm) 8-1/2 (worm wheel)	Lubeco 905 (Bonded MoS_2) Run-in in controlled atmosphere	
Bevel Gears	8-1/2	Lubeco 905 - Run-in in controlled atmosphere	
Bevel Gear Bearings	8-1/2	Duroid 5813 retainers. Sputtered MoS_2 on balls & races. Run-in in controlled atmosphere.	
Output Shaft Bearings	4-1/4	Duroid 5813 retainers. Sputtered MoS_2 on balls & races. Run-in in controlled atmosphere.	

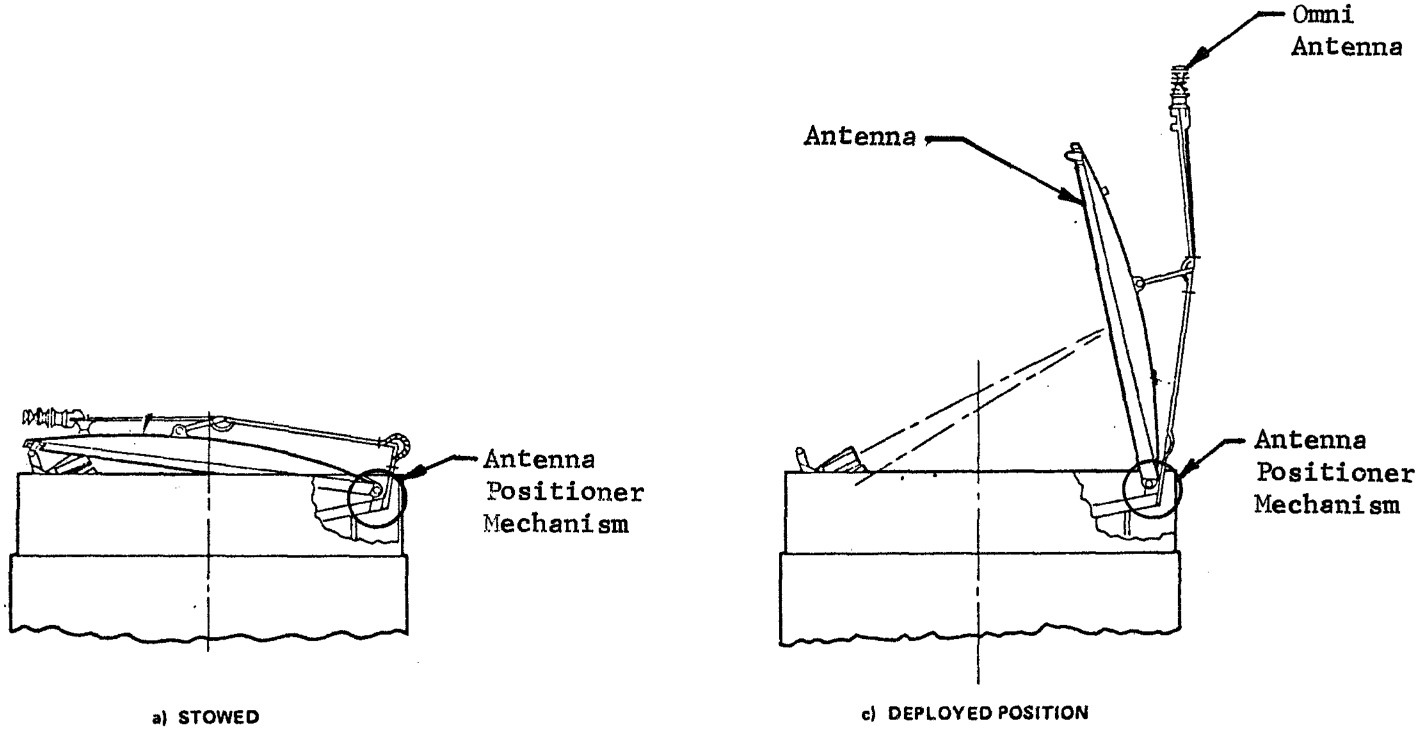

Figure I - SBS/Anik C Antenna Arrangement

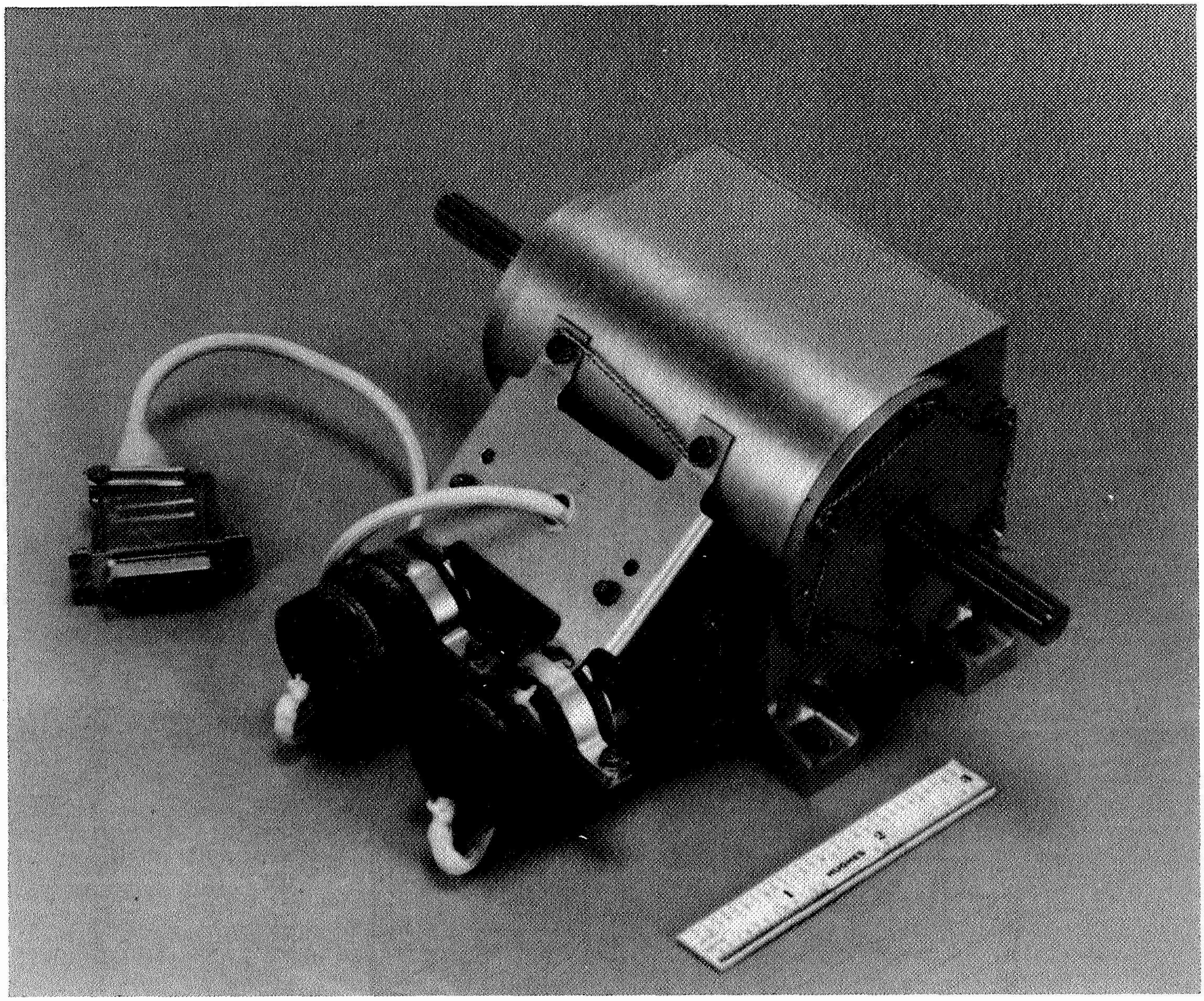

Figure II. Antenna Positioner Mechanism-Weight-Optimized Version

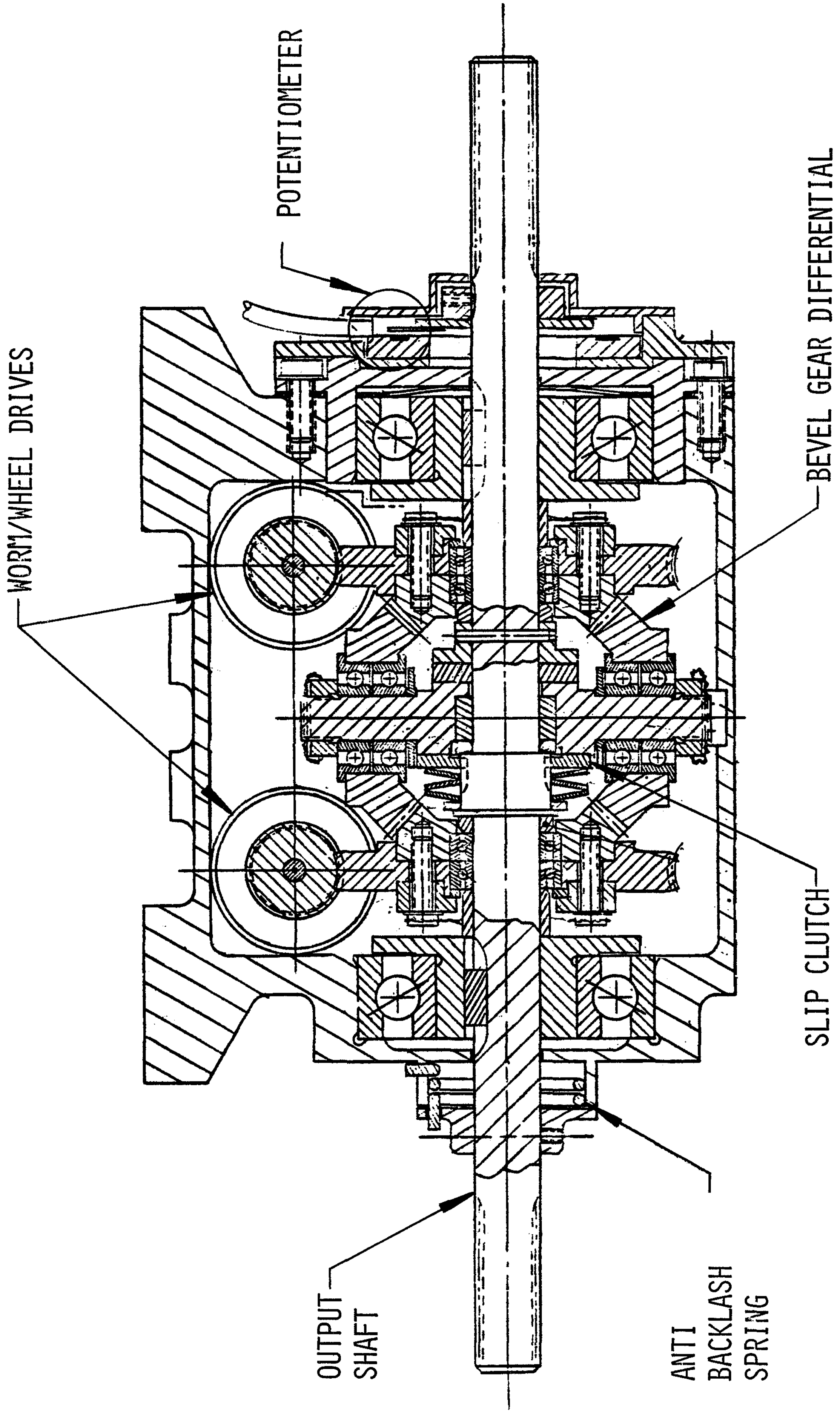

Figure III - Cross-Section of Weight-Optimized APM

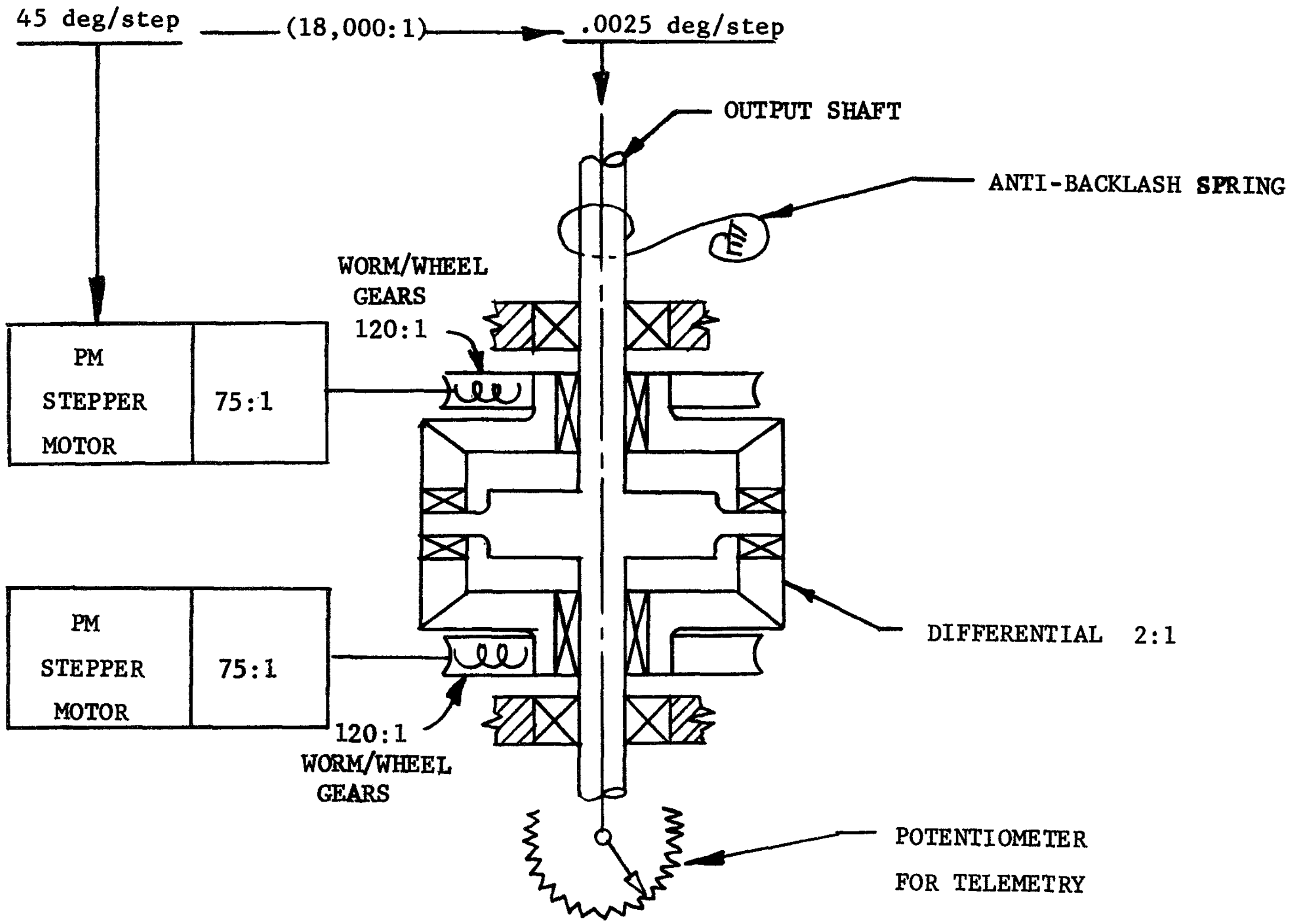

Figure IV - APM Mechanical Schematic

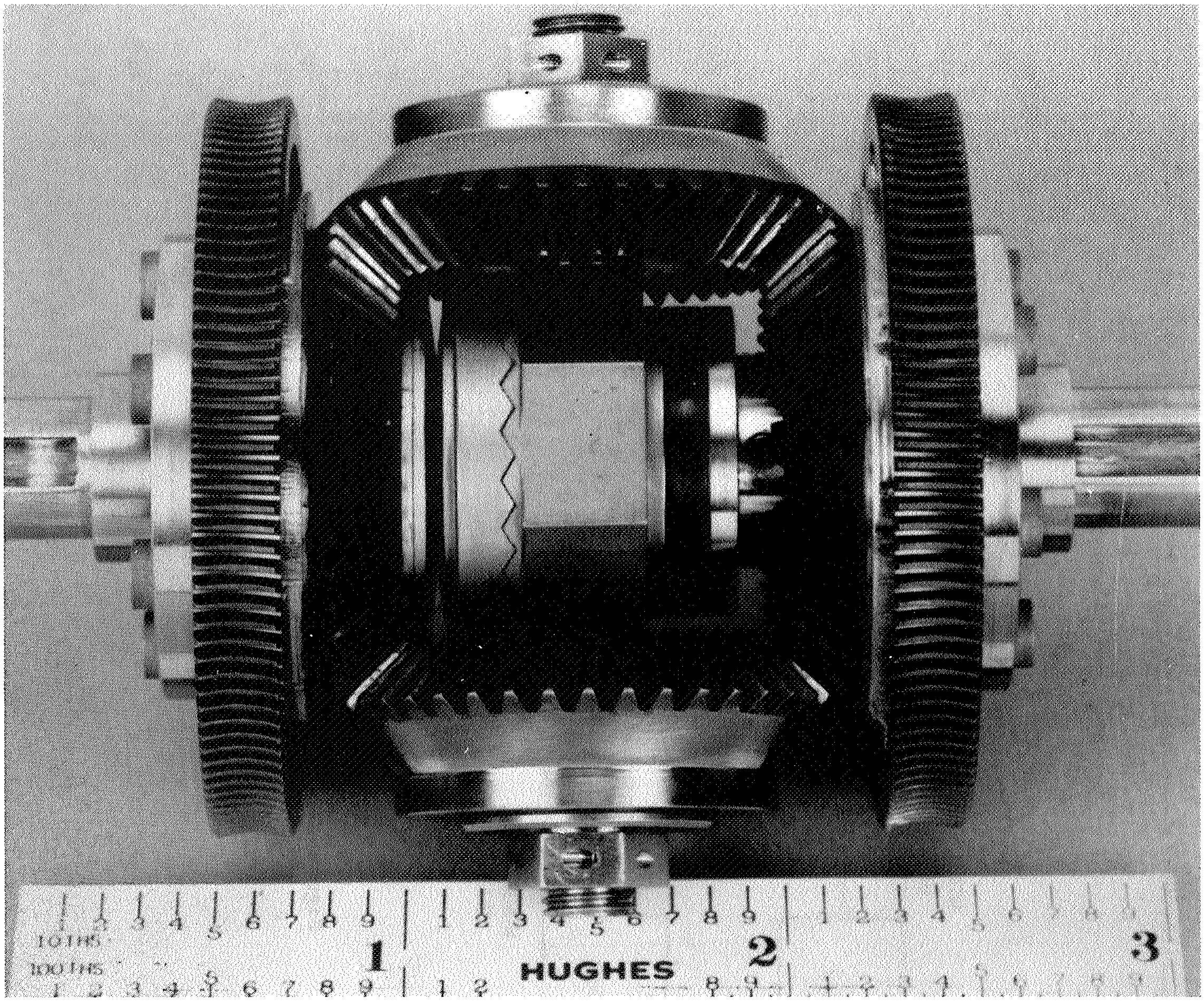

Figure V. APM Differential/Clutch System-Weight-Optimized Version

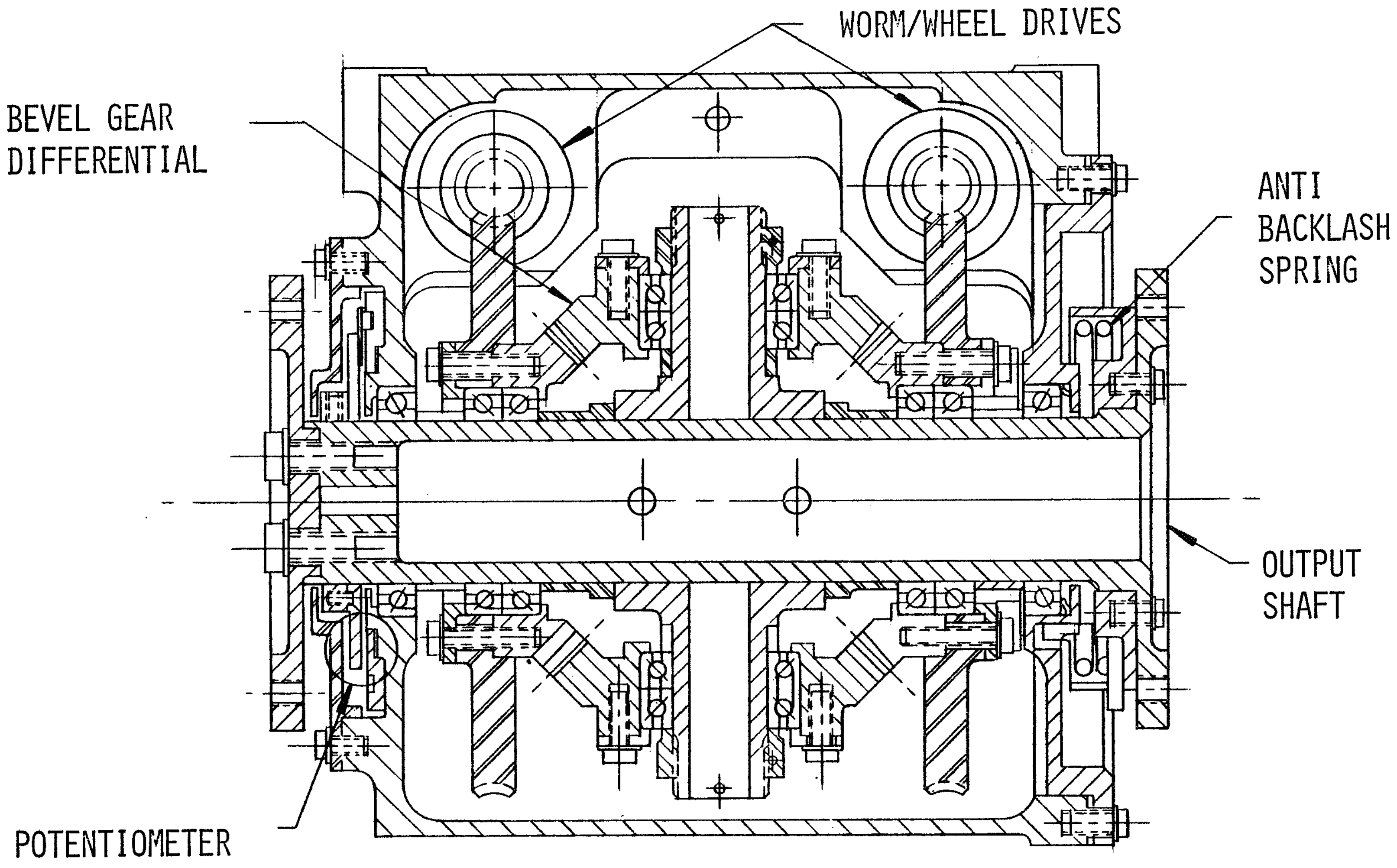

Figure VI - Cross-Section of Ruggedized APM