FOCAL PLANE TRANSPORT ASSEMBLY
FOR THE HEAO-B X-RAY TELESCOPE

By

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ABSTRACT

The High Energy Astronomy Observatory - Mission B (HEAO-B) is an earth orbiting X-ray telescope facility capable of locating and imaging celestial X-ray sources within one second of arc in the celestial sphere. (1)

The Focal Plane Transport Assembly is one of the basic structural elements of the three thousand pound HEAO-B experiment payload. The FPTA is a multi-functional assembly which supports seven imaging X-ray detectors circumferentially about a central shaft and accurately positions any particular one into the focus of a high resolution mirror assembly. A drive system, position sensor, rotary coupler and detent alignment system are all an integral part of the rotatable portion which in turn is supported by main bearings to the stationary focal plane housing.

INTRODUCTION

The High Energy Astronomy Observatory X-Ray Telescope is shown in Figure 2. Major components are the High Resolution Mirror Assembly, Optical Bench, and Focal Plane Transport Assembly (FPTA). On the left hand side appears the FPTA in its fully assembled state attached to the optical bench. The Focal Plane Transport Assembly has been designed and fabricated to satisfy a wide variety of structural, scientific, and environmental requirements. Among these are chiefly:

- To physically maintain each detector focal plane within prescribed limits as defined by the high resolution mirror focus criteria.

- To withstand launch environments induced by Atlas-Centaur launch vehicle.
- To maintain alignment during on-orbit temperature excursions.
- To rotate one of many detectors into and out of the telescope field-of-view upon ground command, and maintain the detectors in position.
- To maintain structural factors of safety of two on yield and three on ultimate strength.
- To provide complete redundancy in all moving systems including drive system, position sensing and detent alignment system.

The major constituents of the (FPTA) are delineated in Figure 1 and those appearing in solid lines will be discussed individually.

DRIVE SHAFT ASSEMBLY

The Drive Shaft Assembly is the central most feature of the FPTA. It provides support to all X-ray detecting instruments by way of an Instrument Support Structure, which is hard mounted to the drive shaft at four circumferential locations. Both the Drive Shaft itself and the Instrument Support Structure are made from Invar LR-36. This material possesses a low coefficient of thermal expansion ($\sim 1.0 \times 10^{-6}$ in/in/^{o}F) which is a near perfect match to the remaining structures that control the mirror focus, namely the High Resolution Mirror itself, made from quartz primarily, and the Optical Bench which is made from a graphite/epoxy composite.

The Drive Shaft Assembly also houses (centrally within itself) the Position Sensor Assembly, Rotary Coupler, and Harmonic Drive Assembly, all of which are statically connected to the shaft. The shaft mounts to the main support bearings on which the whole FPTA rotates.

Some of the imaging X-ray detectors which are mounted to the FPTA use a special gas, in order to function properly, which is also stored on the rotating assembly. This gas is stored in 3000 psi titanium spheres which contain enough gas for two years consumption in orbit. However, the gas does flow through the detectors and therefore, must be vented to space. To accomplish this, the FPTA provides several separate rotary plenum chambers whereby gas lines can be plumbed directly to the rotating portion of each plenum chamber and likewise from the static portion where it can then be directly connected to the spacecraft vent panel. This method allows for five continuous separate vent paths across the main support bearings, handling one of three gases or gas mixtures, without the use of cumbersome flexible vent lines since available volume is a real premium in this area. In addition to the aforementioned gas usage, another instrument contains solid ammonia and methane which are used to cool detectors for proper operation. These solids have a finite life at certain low pressures resulting from sublimation. This sublimation also needs to be vented across the main support bearings; however, interface pressures must not exceed 8.0 Torr for CH_4 nor 0.065 Torr for NH_3. The calculated interface pressures resulting from the actual hardware configuration are 0.76 torr for CH_4 and 0.054 torr for NH_3, well below the triple point of the substances.

A variety of O-rings are used to seal the integral plenum chambers, VITON which is compatible with methane, argon, CO_2 and xenon, NITRILE which is compatible with both methane and ammonia, and BUTYL which is compatible with ammonia. All seals are liberally lubricated with Braycote (2) 3L-38 RP, an inert, low vapor pressure perflourinated polyether stable grease. Life tests have been conducted on all these seal materials with grease in the design configuration and found to have a margin of 4.9 over the intended usage. Figure 3 shows the completed drive shaft with the welded Invar Instrument Support Structure attached. The ISS is painted while the drive shaft is nickel-plated, thus the difference in appearance for the same material.

FOCAL PLANE HOUSING

This member is that static portion which houses the fixed halves of the main support bearings. Additionally, it provides the static connection for the Harmonic Drive Assembly as well as a reference for the Position Sensor Assembly. The FPH is made from two materials. On the forward portion where the interface is made to the graphite epoxy optical bench (a low coefficient of thermal expansion material) Invar is used. This provides good lateral control of thermal growth of detector positions with respect to the optical axis, as well as a good α match to the bench. The completed FPH is shown in Figure 5 while the integration of the circumferential shear tie between the forward bulkhead of the FPH and the optical bench is shown in Figure 4. The remainder of the housing is made of aluminum which is a riveted-and-epoxied construction, thereby reducing the overall weight, increasing the specific stiffness and minimizing thermal gradients.

The axial positioning of all detectors mounted to the FPTA, as well as the structural support during launch, is maintained through the forward main bearings. These bearings are preloaded back-to-back as a duplex pair capable of taking both radial and thrust loading. The aft main bearings provide support in the radial direction only. The FPH also provides a mounting interface for two of the four telescope mounting points to the Spacecraft.

HARMONIC DRIVE ASSEMBLY

The Harmonic Drive Assembly (HDA) is used to rotate the entire array of X-ray detectors along with the associated support equipment and structure. The rotating mass is approximately 800 pounds and volumetrically occupies approximately 60 ft.^3 The HDA is packaged within the central main shaft at the aft end. This is also where the static connection is made to the Focal Plane Housing through the center of the rear support bearings. The connection extends radially outward and attaches to the stationary aft bearing support.

Two redundant drive systems are so arranged in a single assembly such that one drive relies on the other to complete the drive path from static connection to output shaft. Both drives are completely independent of one another for functional operation. The basic arrangement of each functional section is a Brushless DC Gearmotor(3) which drives a Harmonic Drive Transmission(4) and is shown in Figure 6. The purpose of this arrangement is to develop substantial torque through a large mechanical advantage using relatively little power. The brushless DC motor operates at approximately 8500 rpm and drives the input stage of a three stage planetary gear box resulting in a speed reduction of 170:1 and a torque multiplication of 144:1. The planetary is then the input to the single stage Harmonic Drive Transmission.

The Harmonic Drive is a constant ratio mechanical drive system used for power transmission, angular positioning or other motion conversion. It is comprised basically of three components namely the wave generator which in this case is the input member, the flex spline which is the output member, and the circular spline which is the fixed member. A continuous deflection wave generated in a flexing spline element achieves high mechanical leverage between concentric parts. That is, rotation of the wave generator produces radial deflection and tangential motion of the flexible spline. Essentially, the circular spline (fixed member) is a fine toothed internal gear while the flexible spline is a fine toothed external gear which meshes with the circular spline at two regions diametrically opposite on the major axis of the ellipsoid when radially deflected. Teeth of the two splines clear at the minor axis. The wave generator creates this elliptical shape inside the flexible spline. Without the radial deflection of the flexible spline, there would be no effective gear mesh since there are slightly fewer teeth on the flexible spline than on the circular, however, teeth on both splines are cut to the same circular pitch. To allow engagement at two diametrically opposite regions, the tooth arrangement must be symmetrical. In this case, the system has two regions of tooth engagement, therefore the difference in the number of teeth is an integral multiple of two regions. The calculation for mechanical advantage is then:

$$R=\frac{N_f}{N_f-N_c}$$

where R = gear ratio
N_f = number of teeth on flex spline
N_c = number of teeth on circular spline

A negative value for R indicates output is in opposite direction from input.

The Harmonic Drive used here has a speed reduction of 200:1, in series with the 170:1 of the planetary resulting in a 200 x 170 or 34,000:1 speed reduction. The FPTA then rotates 8500/34,000 or 0.25 rpm.

The drive system torque summary is shown in Figure 8 while the primary and redundant drive components are shown in Figure 9.

Several unique advantages are derived from using the Harmonic Drive. Among those include:

- A high-ratio speed reduction in a single stage.
- Many spline teeth are in simultaneous engagement to carry high torque loads. Teeth adjacent to load-bearing teeth are in near engagement and provide reserve capacity to accommodate shock overloads.
- Low tooth friction losses due to almost pure radial motion at contact.
- Regions of tooth engagement and application of load torque are diametrically opposed, and result in a force couple that is symmetrical and balanced.
- In-line relationship of input and output elements where space is limited, resulting from concentric orientation and minimum diameters provides a desirable package.

A cross section through this assembly is shown in Figure 6. It becomes obvious how the primary drive and the redundant drive interact. Figure 7 describes the torque vs. various failure modes associated with this model of the Harmonic Drive, as well as the FPTA operating points.

BRUSHLESS DC GEARMOTOR

The brushless DC gearmotors used in this application drive the input stage of both the primary and redundant drive. This is shown in Figure 6 also in two respective places. The brushless aspect was chosen for a number of reasons. Primarily, the operating lifetime of a conventional brush motor in hard vacuum of space is very limited. The requirement for our application is ~760 hours operation over a mission life of one year in-orbit, plus much ground operation, checkout, and margin. Nowhere was it obvious that there was a brush motor to perform reliably under these conditions. The drawbacks of conventional brush type motors are well-known. The brushless DC Motor has three basic components: housing, rotor shaft and electronics assembly, including magneto-resistors and solid state logic. All switching circuits are handled external to the motor assembly.

The housing contains the stator windings where any heat generated passes directly to the housing unlike conventional motors where heat generated in the rotor windings must pass through an air gap to the housing, a relatively high resistance thermal path. The rotor shaft then contains the permanent magnet as well as the targets necessary to change the sensor magnetic field. Essentially, this sensed change in magnetic field causes a level change in the input signal to the logic circuit. What we have basically is a motor shaft proximity sensor which indicates when to energize each stator winding. The rotor position sensors are speed independent and non-contacting. There is no physical contact between rotor and stator except through the bearings.

POSITION SENSOR ASSEMBLY

Knowledge of the angular position of the FPTA is important in that the drive electronics needs positional information for CW and CCW sequencing. In order to accomplish this, there is mounted to the stationary member two types of potentiometers, a ten turn and a single continuous turn giving 3600° and 360° electrical degrees respectively. The pot shafts are driven through an anti-backlash gear set whereby the follower gear is pot mounted and the driver gear is FPTA mounted in a 9:1 speed increasing arrangement. That is, the potentiometer shafts are rotating 9 times the speed of the FPTA thereby maximizing the resolution. Effectively, we are using the large majority of the 3600° electrical degrees for one equivalent revolution of the FPTA while the single turn potentimeter provides a vernier reading to the less accurate 10 turn. This arrangement is located just behind the Harmonic Drive Assembly and can be seen in Figure 6.

ROTARY COUPLER ASSEMBLY

In order to provide the necessary signal and power leads to the X-ray detecting instruments on the rotating FPTA, it became obvious that the best route would be directly down the shaft center of the FPTA at the opposite end from the harmonic drive and position sensor. Since the FPTA rotates through only approximately 300° absolute, moving CW and CCW, the wire bundle need only twist plus and minus through half that angle. Approximately 750 wires are serviced through this Rotary Coupler. They are so arranged relative to one another such that they provide minimal torque resistance when rotated as well as minimize routing problems at either end.

Figures 10 and 11 show the life test set up and also the rotary coupler in the revolved state respectively. One can readily see from the wire twist variations, that emphasis was placed on axial separation of potted ends, surface friction coefficient of inside guide tube and wire orientation to produce a satisfactory operating rotary coupler. A mock-up of this design was fabricated and life-tested for an equivalent of 5 years of normal operation.

DETENT ALIGNMENT SYSTEM

In order to locate each detector in the focal plane properly, a simple over center toggle mechanism is employed. On the rotating portion exists several position detents which are dedicated to each instrument viewing position. They are complimented by the over-center toggle assembly which is located on the stationary Focal Plane Housing. The symbolic arrangement of the Detent Alignment System is shown in Figure 12. When a viewing position is desired (instrument in the telescope focus) the FPTA is driven in a CW and/or CCW specific sequence and the rotating position detents physically drive up against the toggle mechanism and reach a physical stall condition. Meanwhile, the brushless DC gearmotor is current limited to a predetermined value (1.5A) which effectively limits the torque applied. In order to reconfigure to any other instrument viewing position, the sequence must start by rotating CW away from the toggle previously positioned against.

The design of the toggle mechanism itself is such that it is equally stable in the full open or full closed position but not so half way. If a position detent on the CW rotating FPTA moves by the toggle, the geometry is such that the toggle will spring return to its original location ready to provide the necessary location for the next viewing position. In order to rotate substantially (more than one viewing position) in the CCW direction, one must first rotate CW to the end position where reset cams move the toggle into the full-open position where it will stay until reset at the opposite end of rotation. The need for rotational position sensing becomes more obvious at this point since the drive electronics is so designed to handle this rather complex CW/CCW driving logic automatically. That is, the logic is "built-in" to reconfigure from any one of 11 detent positions to any one of the other remaining positions. Several different sequences are necessary depending on what position is current in the viewing position and what position is desired. Figure 13 shows the electronics block diagram describing the aforementioned interaction.

TEST AND INTEGRATION ACTIVITY

The entire FPTA with its support electronics in the fully integrated condition has been functionally tested at AS&E. The HEAO-B X-ray telescope was successfully tested in vacuum for 41 days at Marshall Space Flight Center during the summer of 1977. The FPTA performance was satisfactory over a range of temperatures from -10°C to 30°C. The entire X-ray telescope has since been shipped to TRW in Redondo Beach, Ca., integrated with the spacecraft, and awaiting further environmental testing. The entire spacecraft and experiment payload will then undergo vibration testing, acoustic testing and a thermal balance test in vacuum in preparation for launch in late 1978.

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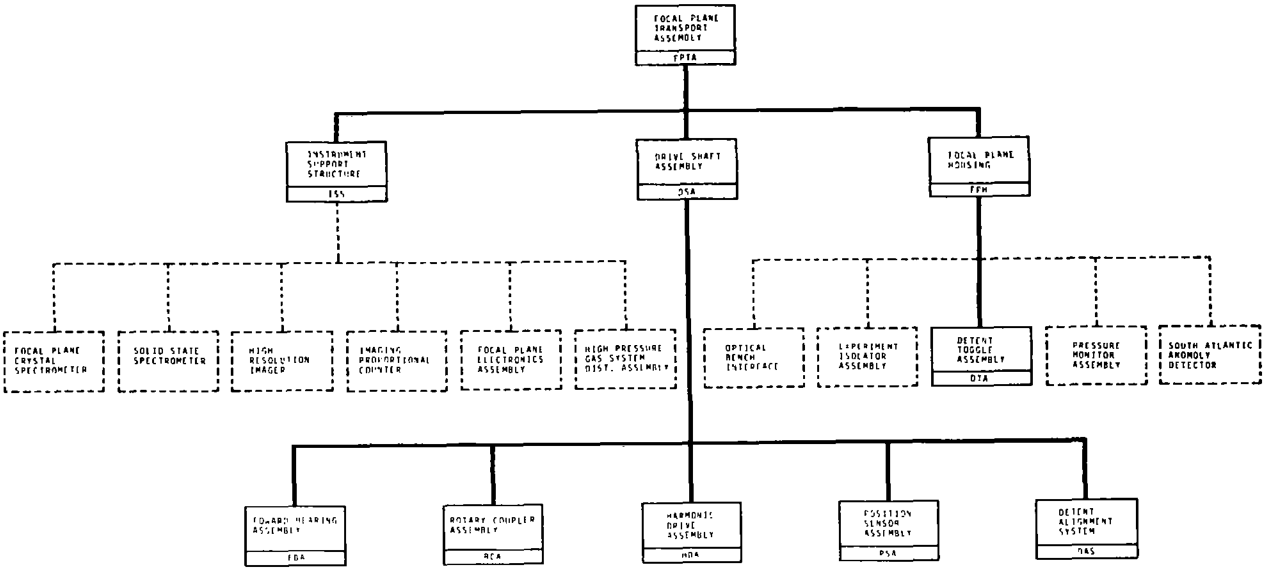
REFERENCES

(1) HEAO-B is a NASA program managed by the Marshall Space Flight Center. Scientific requirements were established by a consortium consisting of Smithsonian Astrophysical Observatory, Massachusetts Institute of Technology, Columbia University, and NASA Goddard Space Flight Center. Dr. Riccardo Giacconi of SAO is Principal Investigator. TRW, Inc. is the Spacecraft prime contractor and AS&E is the X-Ray Telescope prime contractor under contract NAS8-30750;

(2) Product of Bray Oil Co., Los Angeles, Ca.

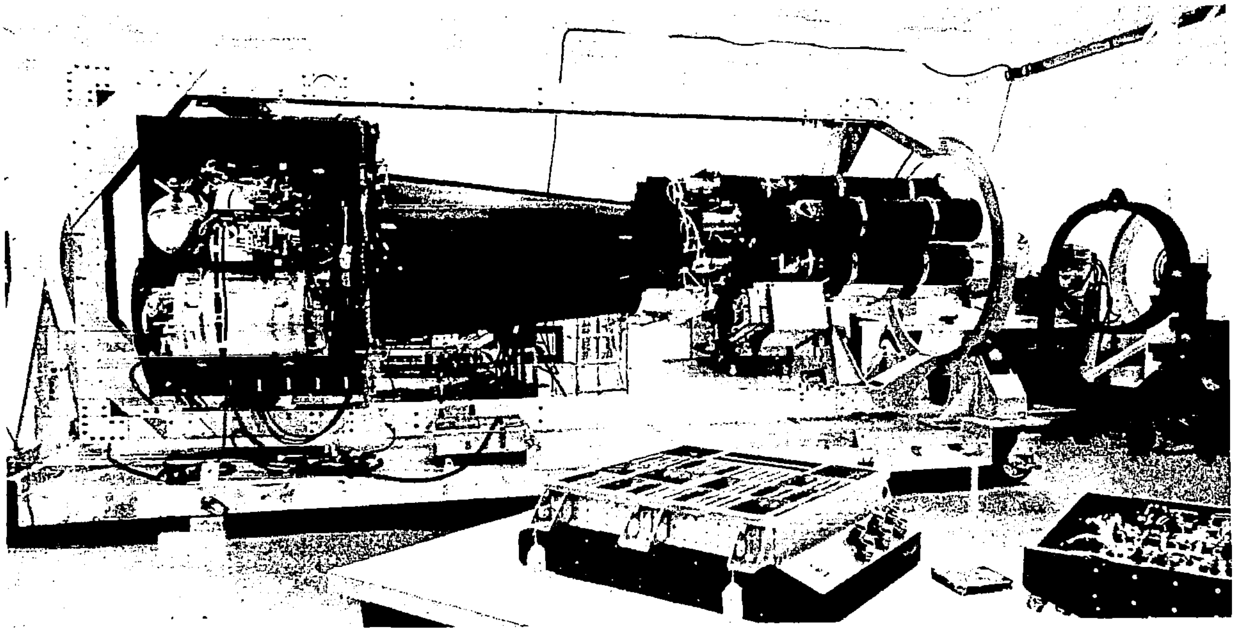
(3) Provided by Aeroflex Laboratories, Inc., Plainview, L.I., N.Y. under contract to AS&E.

(4) Component parts provided by USM Corporation, Woburn, Ma. under contract to AS&E.



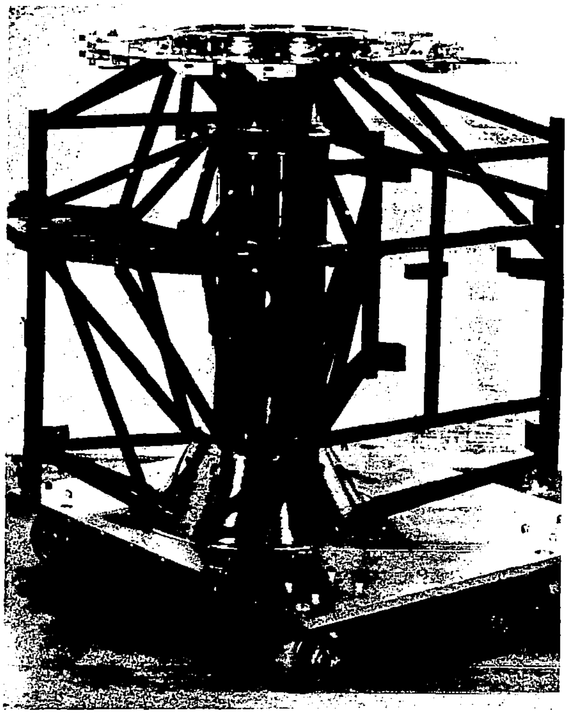
FOCAL PLANE TRANSPORT ASSEMBLY BREAKDOWN

Figure 1



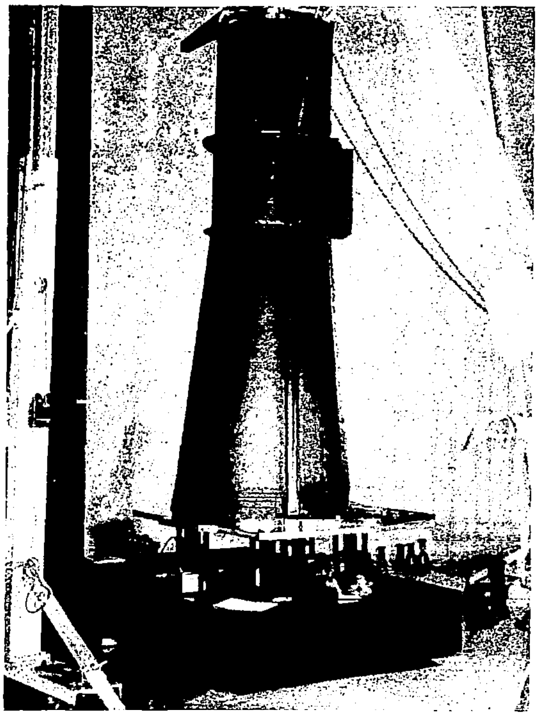
HEAO-B X-RAY TELESCOPE

Figure 2



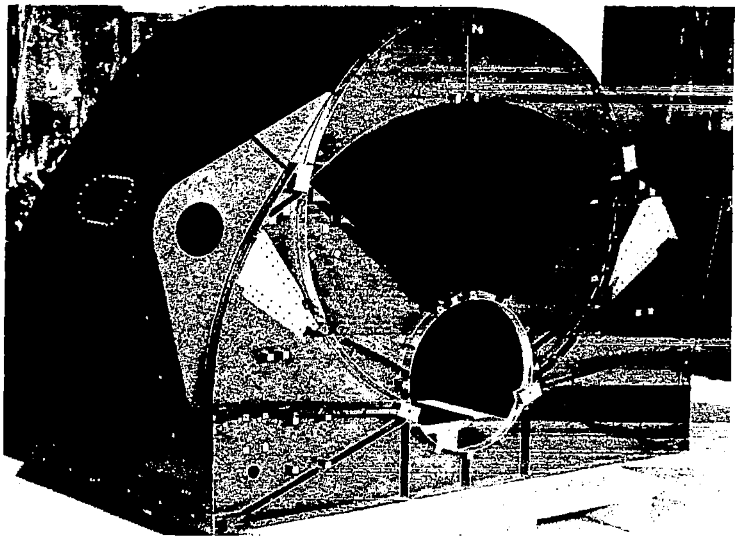
INSTRUMENT SUPPORT STRUCTURE

Figure 3



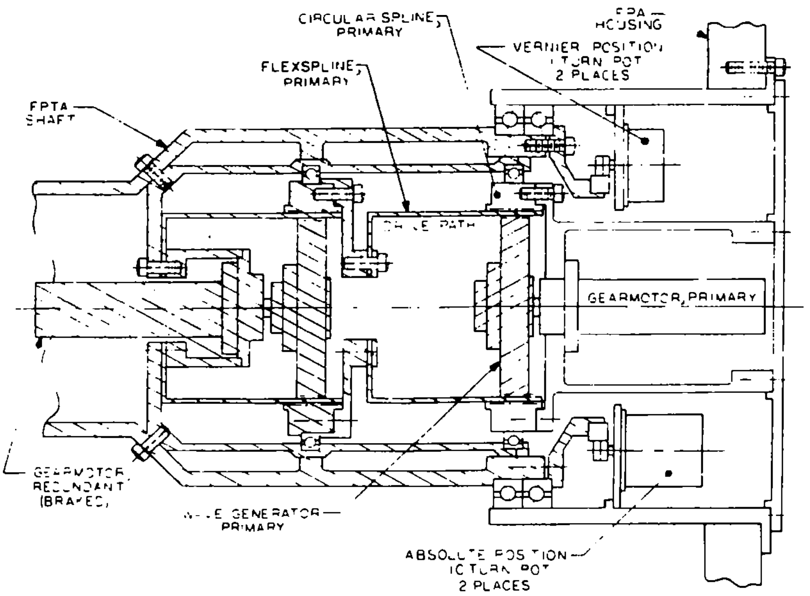
OPTICAL BENCH/FOCAL PLANE HSG.
BULKHEAD INTEGRATION

Figure 4

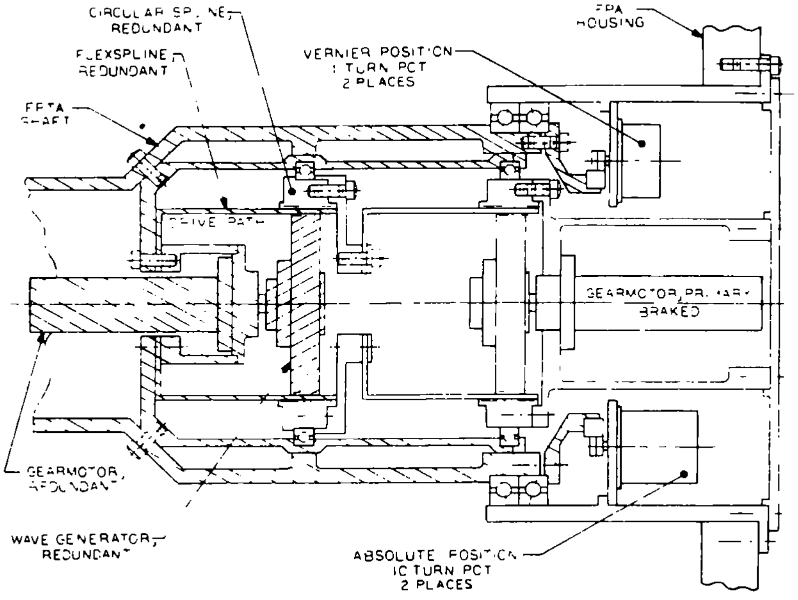


FOCAL PLANE HOUSING

Figure 5



HARMONIC DRIVE PRIMARY



HARMONIC DRIVE REDUNDANT

HARMONIC DRIVE ASSEMBLY CROSS SECTION

Figure 6

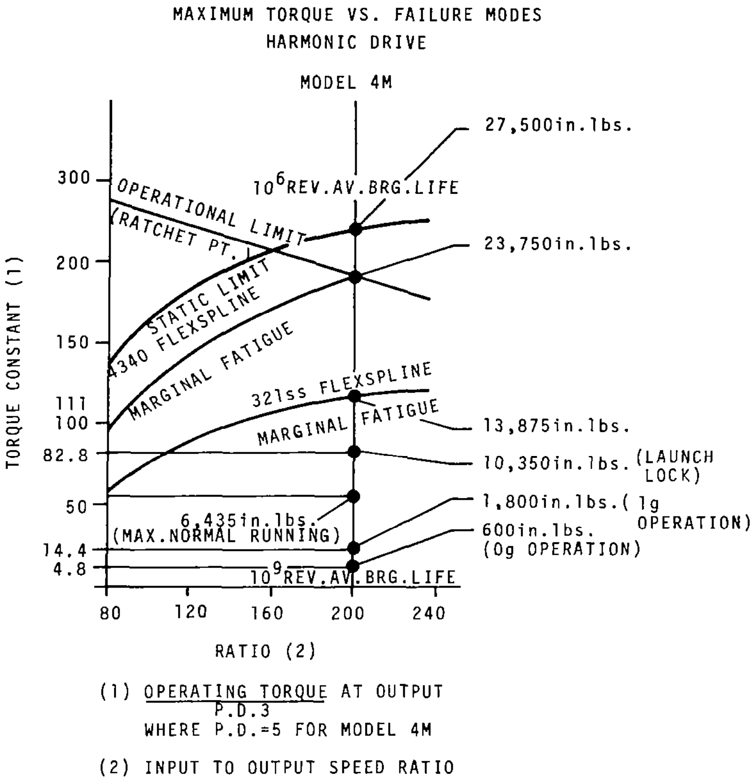


Figure 7

<u>1g OPERATION</u>

APPLIED:	unbalance moment	=	1,200	in. lbs.
	system friction	=	600	in. lbs.
	total:	=	1,800	in. lbs.
AVAILABLE:	DC gearmotor current limit condition			
@1.5A	715 oz in x $\frac{200 \times .72}{16}$	=	6,435	in. lbs.
@2.0A	975 " "	=	8,531	in. lbs.
TORQUE MARGIN (Normal):				
	6435/1800	=	$\boxed{3.6}$	
TORQUE MARGIN (Max):				
	8531/1800	=	$\boxed{4.7}$	

<u>0g OPERATION</u>

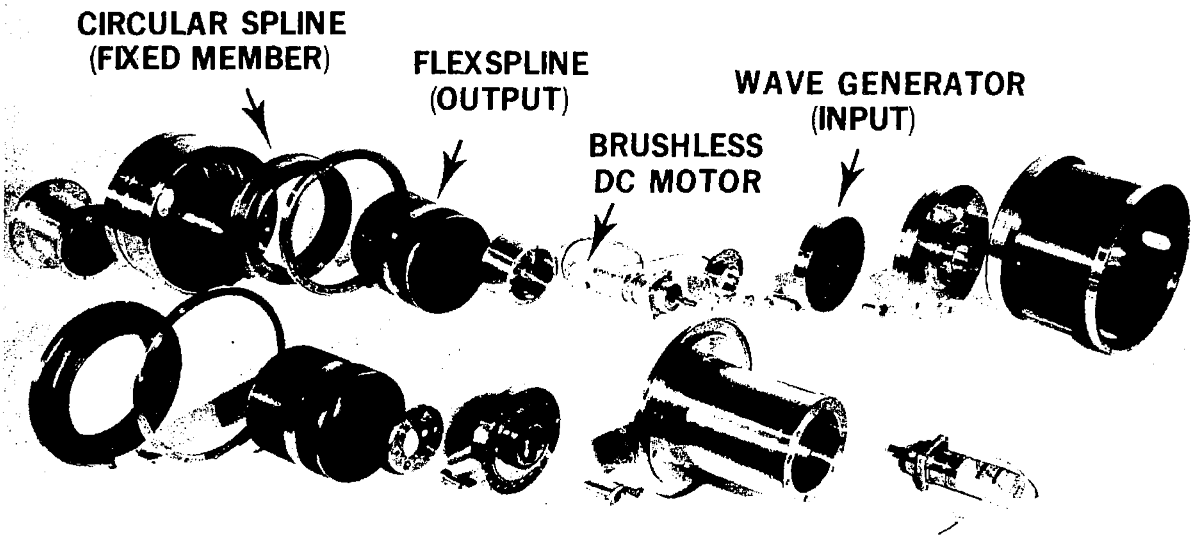
APPLIED:	system friction	=	600	in. lbs.
AVAILABLE:	DC gearmotor @ 1.5A current limit condition	=	6,435	in. lbs.
TORQUE MARGIN (Normal)		=	$\boxed{10.7}$	
TORQUE MARGIN (Max)		=	$\boxed{14.2}$	

<u>LAUNCH LOCK CONDITION</u>

TORQUE PRELOAD:	1150 in.oz. $\frac{200 \times .72}{16}$	=	10,350	in. lbs.
	System Friction	=	600	in. lbs.
	System resisting torque	=	10,950	in. lbs.
MECO INDUCED TORQUE		=	8,563	in. lbs.
TORQUE MARGIN:	10,950/8563 design goal 1.25	=	$\boxed{1.28}$	

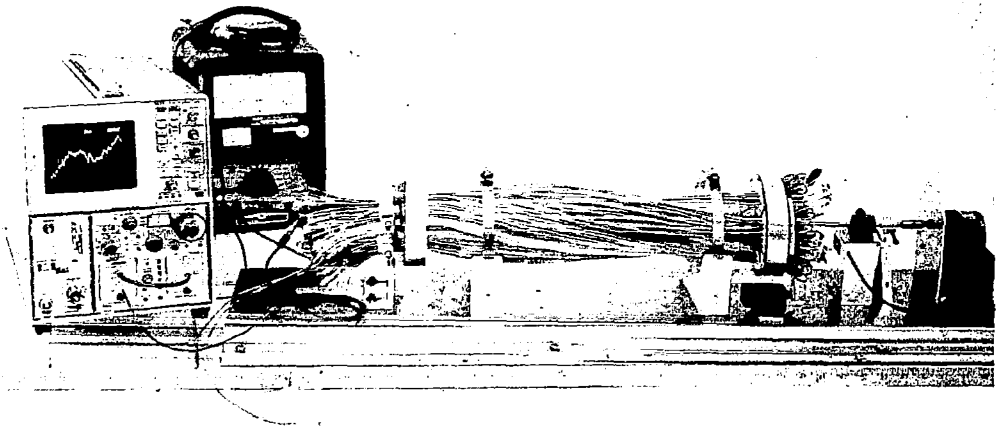
DRIVE SYSTEM TORQUE SUMMARY

Figure 8



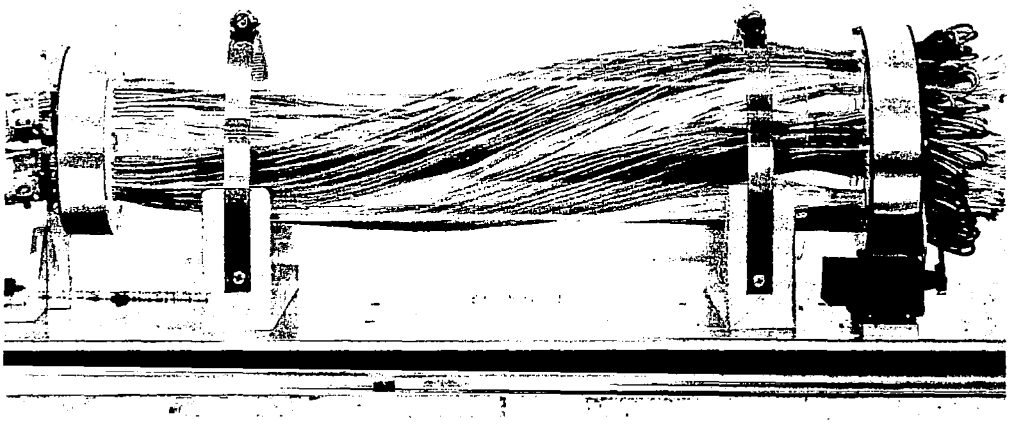
PRIMARY AND REDUNDANT DRIVE COMPONENTS

Figure 9



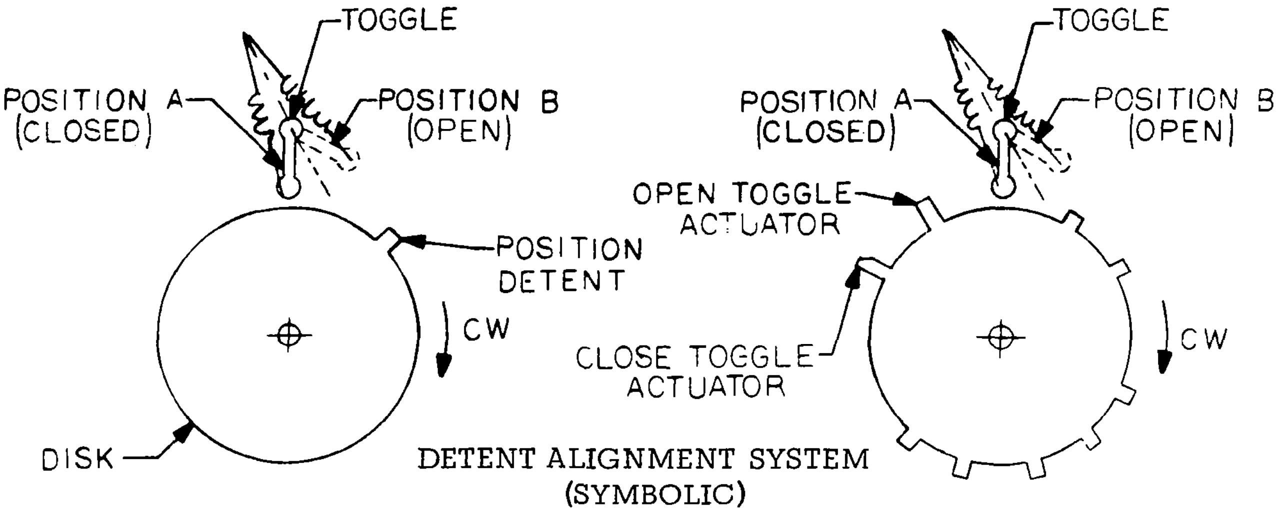
ROTARY COUPLER LIFE TEST

Figure 10



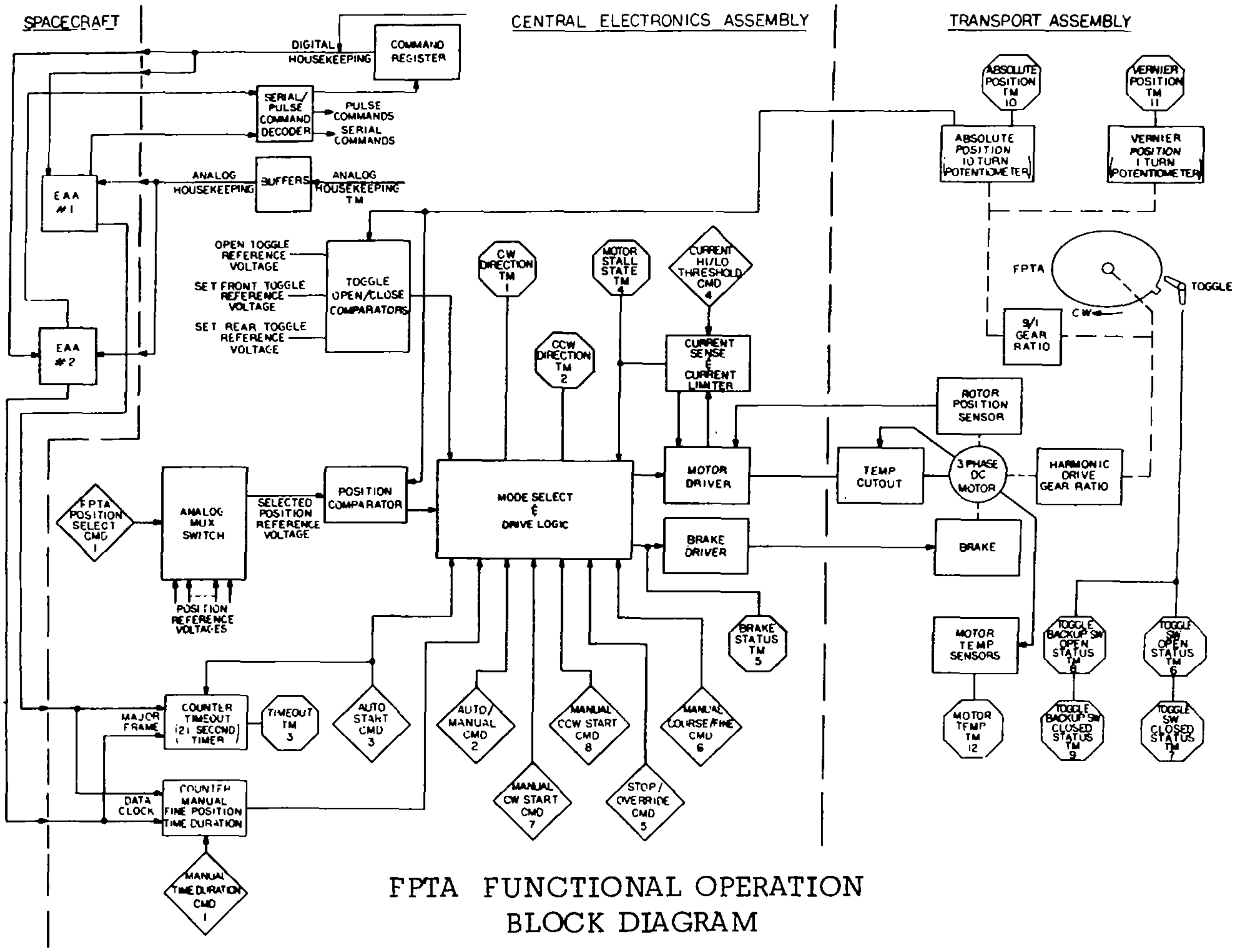
ROTARY COUPLER REVOLVED

Figure 11



DETENT ALIGNMENT SYSTEM (SYMBOLIC)

Figure 12



FPTA FUNCTIONAL OPERATION BLOCK DIAGRAM

Figure 13