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POINTING MECHANISMS FOR THE SHUTTLE RADAR LABORATORY

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ABSTRACT

The Shuttle Radar Laboratory (SRL) is scheduled for launch in December of 1993 on the first of its two missions. The SRL has three major radar instruments: two distributed phased-array antennas, which make up the Spaceborne Imaging Radar-C System (SIR-C) and are capable of being electronically steered, and one X-Band Synthetic Aperture Radar (X-SAR), which is pointed mechanically by a suite of mechanisms. This paper will describe these mechanisms and summarize the development difficulties that were encountered in bringing them from the design stage through prototype development and protoflight testing.

INTRODUCTION

The Shuttle Radar Laboratory (SRL) is a Space Transportation System (STS or Space Shuttle) borne imaging radar laboratory that will be used in global scientific studies in geology, hydrology, ecology, oceanography and meteorology. The radar laboratory is the most massive flight instrument system ever designed, fabricated and assembled at the Jet Propulsion Laboratory (JPL). The SRL's mass is 10,400 kg, including electronics, and it measures 12 meters by 3.5 meters (Figure 1). It is made up of three integrated radar instruments:

- o Two U.S. radars, designated the Spaceborne Imaging Radar (SIR-C), which are fixed to the main Antenna Core Structure (ACS). These phased array antennas are fixed relative to the Space Shuttle coordinate system and are electronically steered.
- o The X-Band Synthetic Aperture Radar (X-SAR), which was developed jointly by the German Space Agency and the Italian Space Agency. This antenna is steered mechanically.

Early Mechanisms and the SRL Systems Design

The SRL has its roots in two prior STS instrument laboratories called SIR-A and SIR-B which were launched in 1982 and 1984, respectively (Figure 2). These instruments were smaller than the SRL and and the last, SIR-B, was constructed so that the panels could be folded up onto a pallet, thus saving space in the STS bay for additional

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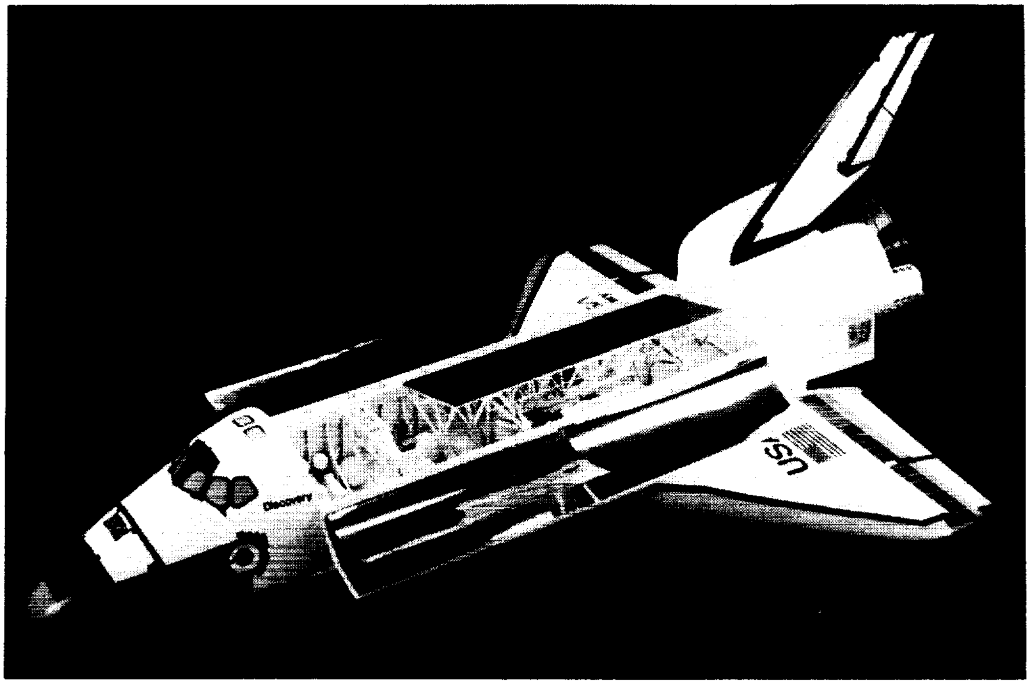


Figure 1. Model of the Shuttle Radar Laboratory Integrated Into the STS Bay

payloads. The forward and aft leaves deployed 180 degrees from their stow position and then the tilt actuator would point the antenna to the desired angle. It was decided that a similar design approach would be followed for the SRL. Significant difficulties were encountered, however, because of several differences between it and the earlier laboratories and because of new, post-Challenger STS constraints.

The SRL is considerably larger than the earlier Laboratories. The total area of its radar panels is 42 sq. meters in comparison to SIR-B's 14.9 sq. meters, and the total masses are 10,400 kg and approximately 3,500 kg, respectively. Simply scaling the hardware would not be sufficient since the stiffness and strength did not increase as quickly as the mass.

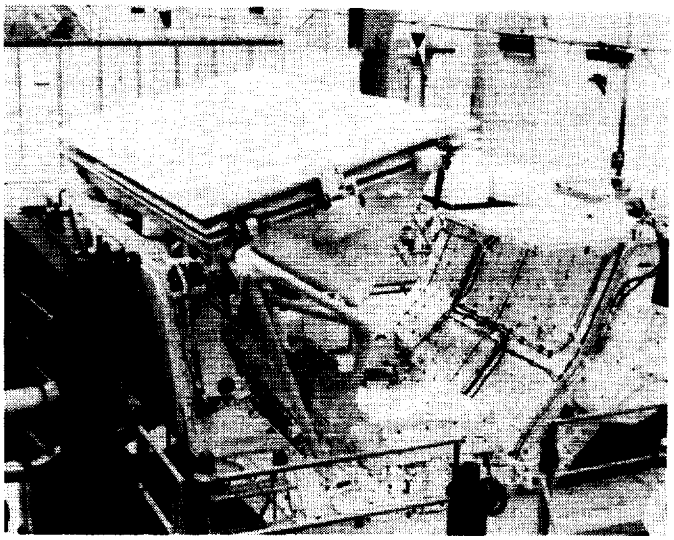


Figure 2. The SIR-B Antenna Assembly

As the work progressed, it quickly became apparent that the structure holding the SIR-C radar panels was not sufficiently stiff to prevent contact between the folded, inner leaf panels and the fixed and outer leaves under launch and landing loads. Since the inner leaves were sandwiched between the fixed and outer leaves, there was little room to increase the stiffness of the supporting structure. It was decided that the least costly change would be to introduce springs with hardstops between the panels in an effort to control the deflections. Many sizes and placements of the springs were tried until the dynamic model confirmed that a configuration had been found that would control the deflections adequately. As these springs became progressively stiffer, the latching mechanisms required to preload them became larger. In addition, the original hinges were found to have inadequate stress margins and the tilt actuators too low a torque margin.

Estimated completion costs were escalating rapidly. The total number of mechanisms and their relative positions can be seen in Figure 3. Finally, it was determined that the number and position of the springs that were necessary to prevent contact between the radar panels were very sensitive to minor changes in the structure; changes that would probably be necessary as the design work progressed. Thus, not only were the present costs high, but we would be chasing the design downstream with potentially large schedule and cost risks. The folded design was considered too risky, and we began a parallel investigation to determine the feasibility of an unfolded design that would allow us to add considerable structural supporting members to the panels and eliminate some of the mechanisms. The initial results looked promising, and with that assessment, we traveled to NASA headquarters with the proposal. It was accepted and we were given permission to start over and develop an unfolded design that would take up nearly the entire STS bay for the mission. (A small volume was still available in which the ASTROS Instrument would fly.)

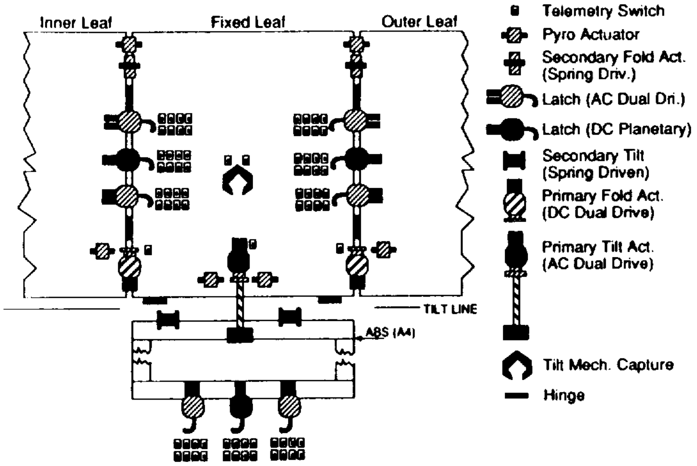


Figure 3. Baseline Mechanism Schematic for the Folded Design

This change in the system configuration reduced the required number of mechanisms from a total of 29 (9 different types) to a total of 12 (7 different types). They were, however, going to be massive in order to tilt such a large antenna and latch it securely in place for launch and landing.

It was then determined that the SIR-C antennas could be rigidly fixed within the shuttle bay at a 14° inclination. They could be electronically steered in this orientation without significant loss of science, and only the long, narrow X-Band antenna would need to be tilted.

The X-Band antenna would still violate the dynamic envelope of the shuttle bay doors when operated through the data collection range of tilt angles. It thus would still need to be pointed by a suite of mechanisms that would have to carry the designation of "STS

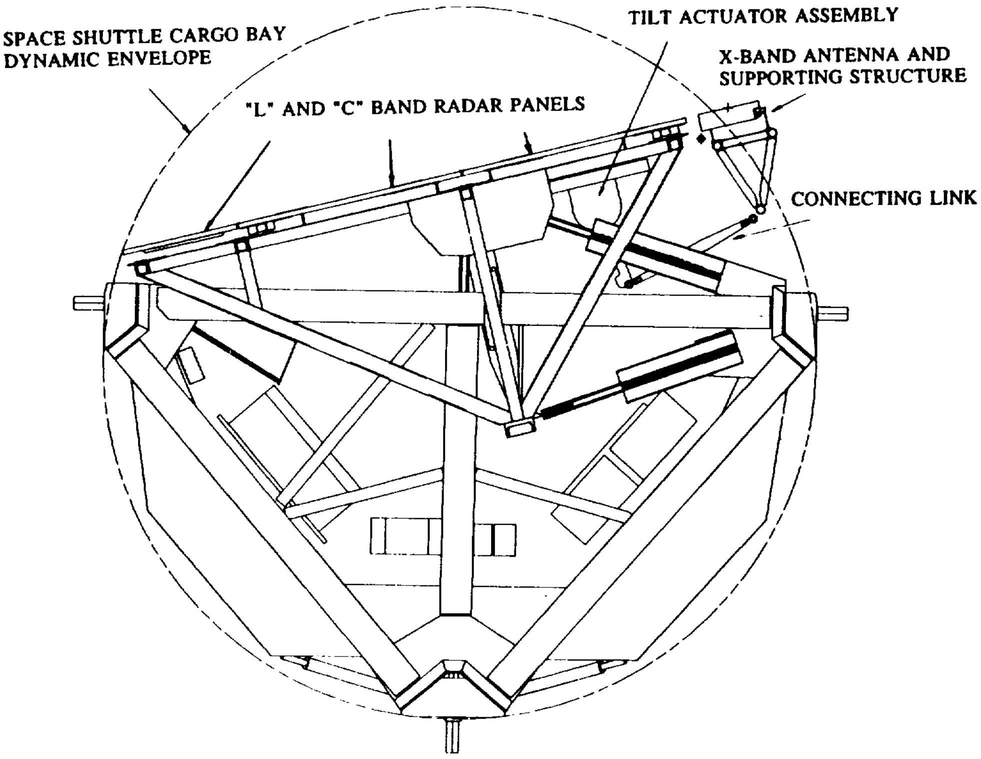


Figure 4. SRL Intrusion Into the Shuttle Door Radiator Dynamic Envelope

Safety Critical" (Figure 4). Now, however, they were fewer in number and could be smaller.

The antenna needed to be capable of being successfully stowed away even if two independent failures were to occur. Douglas Packard, who developed the JPL Dual Drive Actuator, proposed using the same technology in a larger, triple redundant drive that he called the Tri-Drive. This actuator would have three independent and redundant drives instead of two. A single actuator assembly could now be used, eliminating all of the devices that were required to switch from one stowing mechanism to another.

DEVELOPMENT OF THE FLIGHT MECHANISMS

The mass of the X-Band antenna and its supporting structure is about 318 kg, with a center of gravity offset of 26 cm (10 in.), producing an 805 N-m (7210 in.-lb) maximum torque in a 1 G field. The maximum pull-out torque is about 90 N-m (800 in.-lb) during launch and landing. The maximum hinge-line torque was estimated to be about 34 N-m. We had the choice of designing and building separate latching and pointing mechanisms or designing a tilt actuator that could fulfill both functions. We decided to take the latter approach and implemented it by combining the Tri-Drive dual fault-tolerant actuator with a four-bar linkage arrangement that would put the crank in a bottom dead-center position at stow (Figure 5). This protects the gear train of the actuator from significant launch or landing loads and reduces the possibility of accidental deployment. Ground support equipment costs and complexity were reduced further by designing an actuator that could articulate the antenna in 1 G to support ground testing of the radar and easily verify that the safety-critical mechanisms functioned properly immediately before launch.

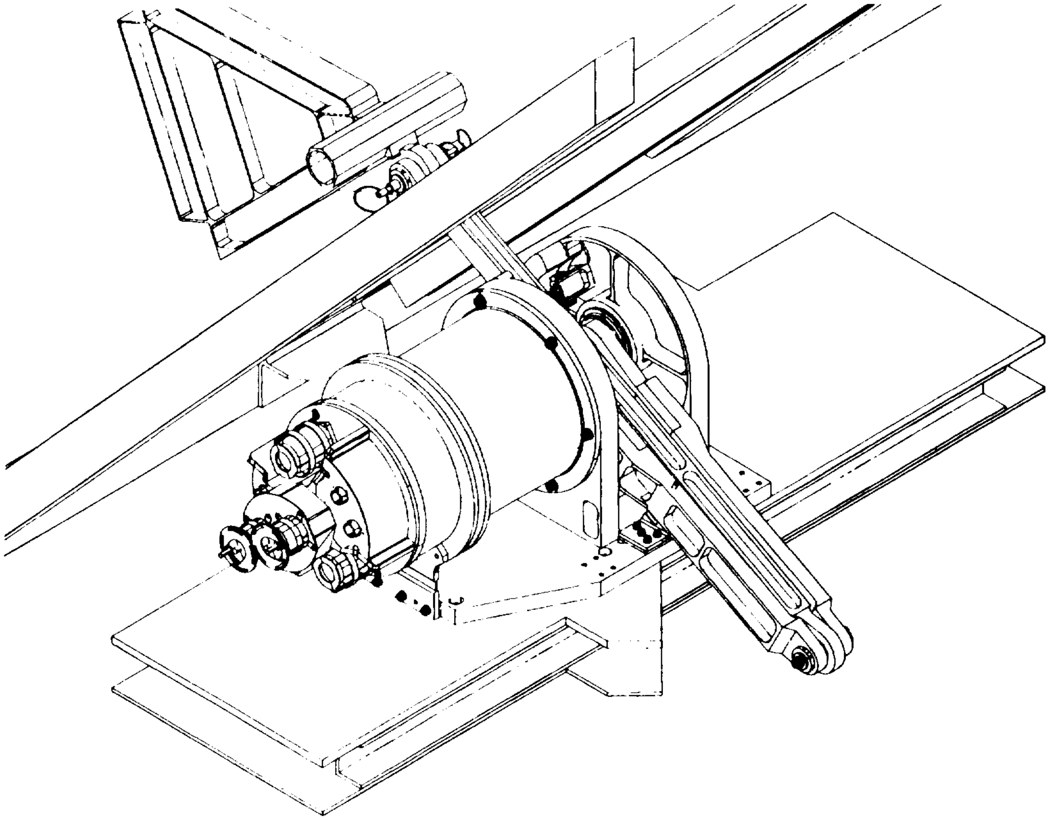


Figure 5. Tilt Actuator in Stow Position

The only other mechanisms needed once this decision had been made were the hinges and a backlash eliminator that would eliminate linkage play (lost motion). Figure 6 shows the positions of the final suite of mechanisms that were developed for the SRL. Table 1 lists some of the other requirements imposed on the mechanisms subsystem.

Table 1. Requirements Summary

Maximum Tilt Control Error	0.5°
Tilt Angle Knowledge	0.1°
Minimum Angular Velocity Between Data Takes	0.9°/s
Fault Tolerance of Safety Critical Mechanisms	Dual
Fault Tolerance of Mission Critical Mechanisms	Single
Tilt Actuator Flight Allowable Temperature Range . . .	-45°/35° C.
Hinge Subsystem Flight Allowable Temperature Range	-75°/45° C.

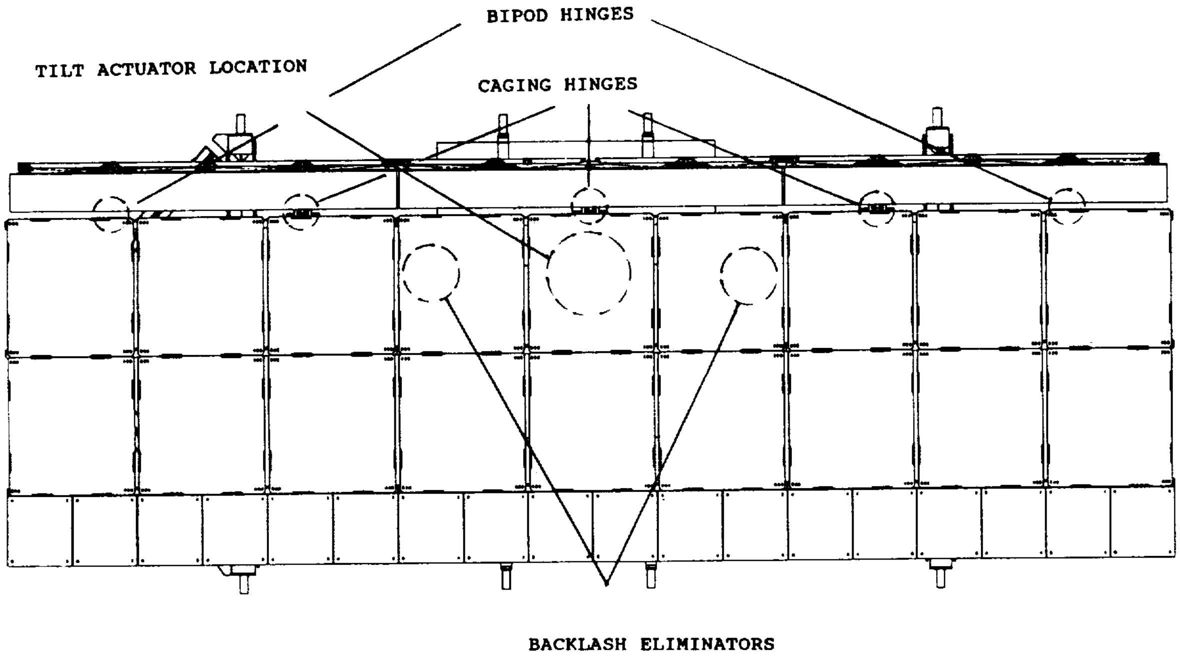


Figure 6. Locations of Mechanisms on the SRL Structure

The X-Band antenna can tilt between 20° and -68° relative to the SIR-C panels. Except for the Backlash Eliminator, all of the mechanisms are classified as STS safety critical. As such, the mechanisms must be dual fault-tolerant to credible mechanical or electrical failures. Other designs for STS safety critical mechanisms are described in references 1, 3 and 4.

Tilt Actuator Assembly

The 156 kg (343 lb) Tilt Actuator Assembly is comprised of two major subsystems: (1) the "Tri-Drive," and (2) the Crank and Linkage Assembly.

Tri-Drive

The following major subassemblies comprise the Tri-Drive (Figure 7):

1. 319.5:1 Size 50 harmonic drive stack.
2. Spur gear box assembly.
3. Three clutch assemblies.
4. Dual-Drive Assembly (DDA) (motor 'C').
5. Two AC motor assemblies (motors 'A' and 'B').

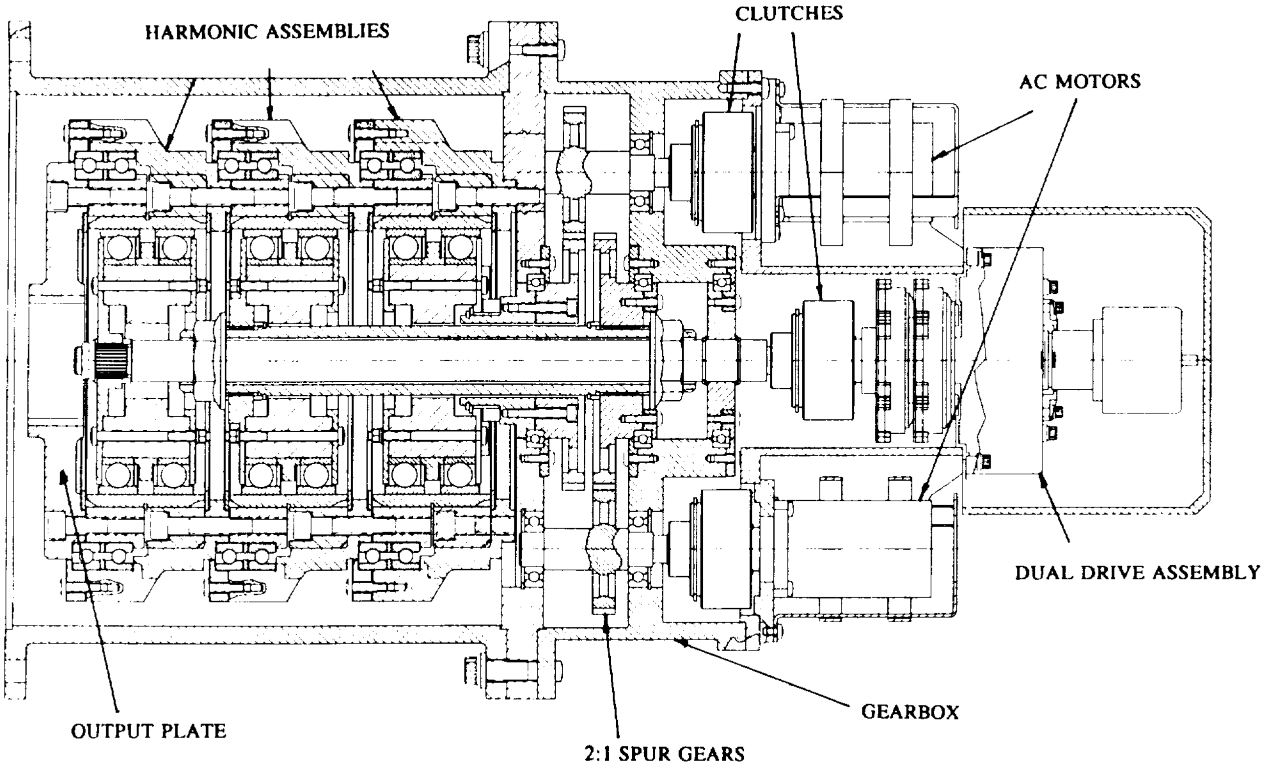


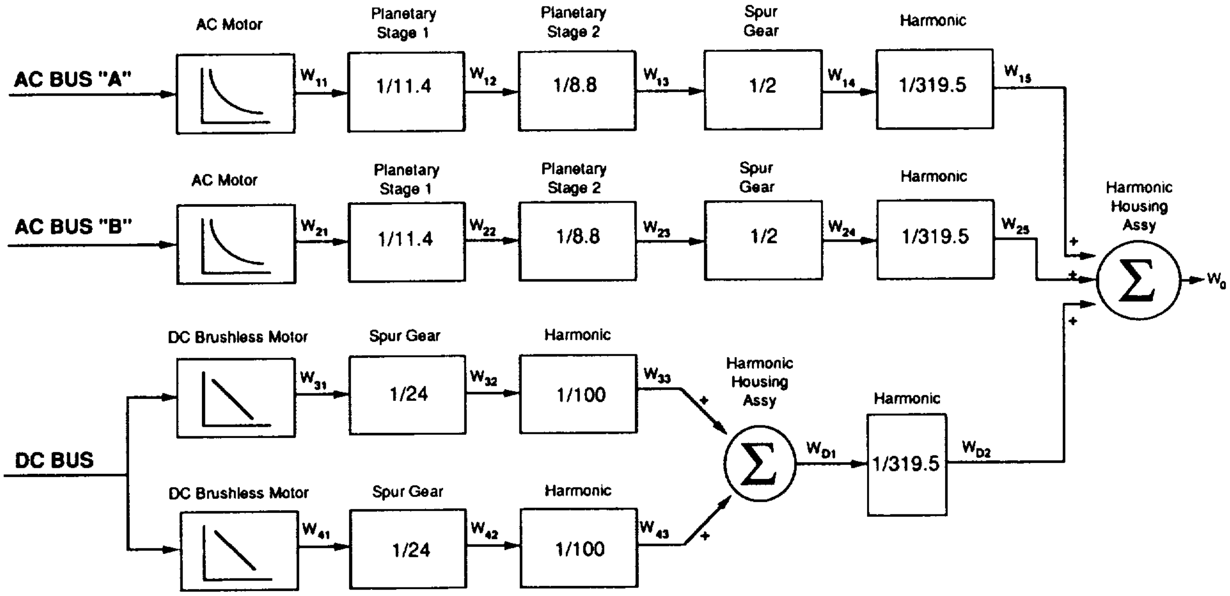
Figure 7. Tri-Drive Assembly Cross-Section

The Tri-Drive is a triple redundant, two-fault-tolerant actuator that can tolerate any two separate mechanism failures in which a gear or bearing interface is jammed or motors fail. Redundancy is also maintained electrically by the use of three independent drives: two AC motors and one DC driven actuator, a Dual-Drive Assembly. Each drive is supplied through three independent STS power supplies via separately routed cables and connectors. Those load paths in the Tri-Drive which are not two-fault-tolerant are designed to satisfy shuttle safety-critical-structure design criteria. Table 2 lists some of the Tri-Drive's principal operating characteristics.

Table 2. Tri-Drive Specifications

Output Torque Capability	782 N-m (7,000 in.-lb)
Angular Velocity (data collection range)	0.9°/s
Mass	97 kg (214 lb)
Stall Power (DC)	30 W
Stall Power (AC)	130 W
Nominal Stop and Hold Torque	339 N-m (3,000 in.-lb)

Figure 8 is a block diagram of the actuator transfer function, neglecting the electrical dynamics of the system and focusing on the gear ratio amplifications and driving sources. As can be seen, each motor independently drives one of the actuator's stages. The angular excursions and angular velocities sum together if all inputs rotate in the same direction. The principle of operation is similar to the Dual-Drive Actuator mechanism described in reference 2.



$$W_0 \doteq W_{D2} + W_{15} + W_{25}$$

Figure 8. Tri-Drive Actuator Block Diagram

The motors may be operated concurrently by switching any two or three of them on together at the STS SP-1 panel, which is operated by the astronauts. In normal operation, ground control will issue a command to slew the X-Band antenna to a desired tilt angle. The Tri-Drive will rotate the antenna until telemetry received from the hingeline encoder indicates that the angle has been reached. Coast-down of the antenna system is less than 1 degree.

The core of the Tri-Drive is made up of dual-ratio, single-output harmonic drive assemblies (Figure 9) that have a gear ratio of 319.5:1. Each of the three harmonic gear sets is independently driven by an AC or DC actuator.

Our prior experience with Dual-Drive actuators that we built and tested for other

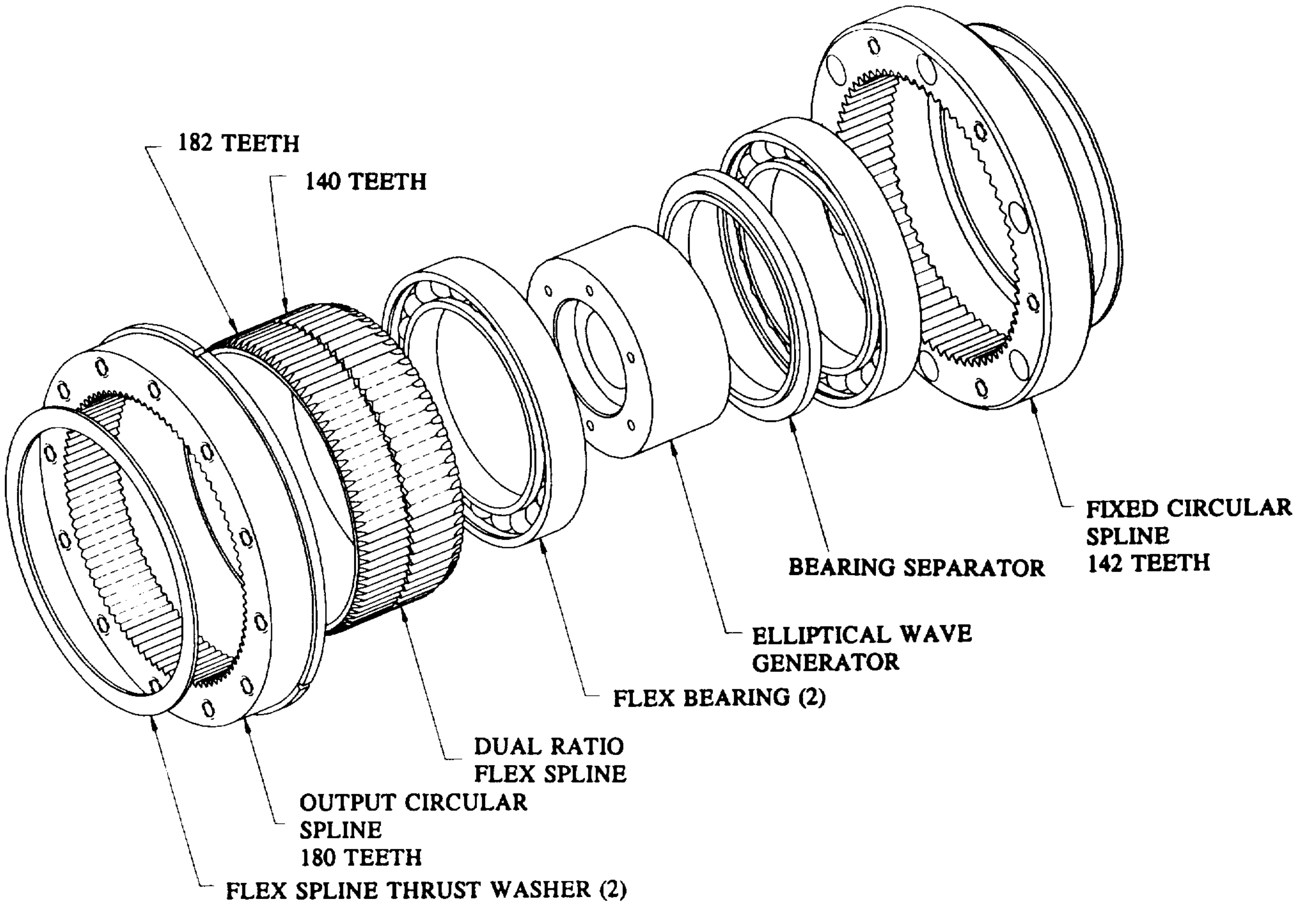


Figure 9. Harmonic Drive Exploded View

programs has shown us that Size 14 1110:1 ratio and Size 20 605:1 ratio units would not backdrive but that Size 14 110:1 ratio units would. We did not know at what gear ratios the backdriving would occur in the Size 50 units. It was necessary to prevent the non-driven harmonic gears in a dual or triply redundant harmonic drive actuator from rotating backwards and thus lowering the actuator output torque or angular velocity.

A development unit was built and tested extensively. It was discovered that the Size 50 319.5:1 ratio harmonic gears would, in fact, backdrive. Backdriving was most pronounced at higher temperatures, as expected. As a consequence, the stop and hold torque of the actuator was low and we could not rely upon the actuator to keep the crank arm preloaded against the hard stop during launch or landing. Thus it was necessary to develop a method of maintaining that preload in some other way. We developed the Detent Device, to be described later, to accomplish this.

The backdrive threshold is dependent on drivetrain friction (which decreases slightly with wear-in) and temperature. We determined that the units are non-backdriveable to a limit of about 782 N-m (7,000 in.-lb) for the AC motors and only 223 N-m (2,000 in.-lb) for the DC Dual Drive Actuator, which runs at 10% of the speed of the AC motors. However, at the high end of the torque range, backdriving will reduce the output velocity of the Tri-Drive. Since the maximum expected resistive torque under mission operations will be about 27.9 N-m (250 in.-lb), no reduction in output velocity during mission operations should be seen. In some ground testing orientations, the Tri-Drive will not be able to hold the antenna in place after it is turned off, but this is acceptable.

The AC motor output is geared down by a factor of 2:1 in the gearbox. The DDA output is passed unchanged through the gearbox. Even without a need for gear reduction, the gearbox would be necessary in order to offset the drive centers to allow mounting of the three motors on the unit. The gearbox and its cover are a precision match drilled assembly.

Tri-Drive AC Actuators

Considerable budget and schedule costs could have been incurred by procuring a space-qualified AC motor/gearbox actuator for the Tri-Drive. For the limited duty cycle required, it seemed reasonable that a high quality aircraft motor/gearbox might suit our purposes well. Therefore we procured some development units from the Astro Instrument Corporation in Deerfield, Florida. The assembly includes a high-performance, four-pole AC motor attached to a 100:1 two-stage planetary gearbox (Figure 10).

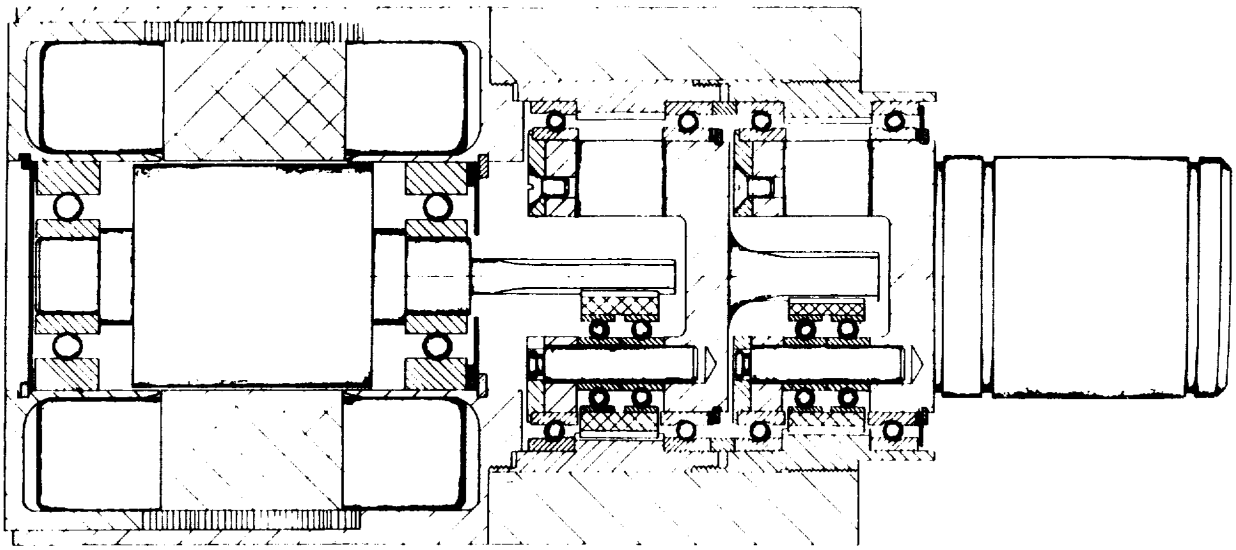


Figure 10. AC Motor Actuator Cross-Section

Table 3 lists some of the actuator's important specifications.

Table 3. AC Actuator Specification

Actuator Stall Torque	6.70 N-m (60in.-lb) at 60°C
Motor Stall Torque	>0.095 N-m (8.5 in-oz)
Stall Current	<0.85 A/Winding
Stall Power	130 W
Backdrive Torque	<0.279 N-m (40 in-oz)
No Load Output Speed	110 RPM

We disassembled one of the early development unit actuators that we procured. A thorough examination, including the generation of an engineering layout of the assembly and reverse engineering the gearbox planetary design, taught us much about the product. The gearbox is a precision-fabricated, well-designed mechanism. We also conducted life tests in air on the gearbox assembly, running it continuously at a medium load for about 72,000,000 input cycles without incident. A post-test examination revealed no unusual wear.

Astro Instrument considered the grease to be a vendor proprietary product. They did, however, reveal to us what the lubricant was. After obtaining a sample, talking with the manufacturer, and running a vacuum condensibles and outgassing test, we became convinced that the lubricant was adequate to meet our needs.

Rigorous thermal vacuum tests on the motor revealed that high torque conditions coupled with high motor ambient temperatures would cause the rotor to expand enough to contact the inner surface of the stator and seize. The first seizure took place after the motor had run for over 1.5 hours in a vacuum against a 5.0 N-m (45 in-lb) load and with a motor mounting interface temperature of 60°C. The peak recorded motor housing temperature was 109°C. Upon cool-down, the motor ran normally.

We proposed to the vendor that the problem could be reduced or alleviated by increasing the air gap in the motor. However, after some motor efficiency calculations, it was determined that more harm than good might come of such a change. Although the efficiency degradation from the increased air gap was minor, the rotor would tend to run even hotter, which would somewhat offset the gap improvement under nominal conditions. Worse yet, the motor might be permanently disabled by an eventual seizure. This is because it would have to grow more and thus have a higher temperature before the actuator shut down. Of course, no motor seizure was acceptable, but it was better to have a robust design.

Thermal tests were conducted on a disassembled prototype to determine the interface heat transfer coefficients for a computer model. Evaluation of this model showed that altering the emissivity and absorptance of the stator bore and rotor diameter would not appreciably lower the rotor temperature until the rotor temperature was too high in a stall condition.

Now that we had determined the limits of the motor's operation, we reduced the severity of the tests to levels that could be used in qualifying the motors. No further seizures occurred when the motors were limited to running a duty cycle of 5 minutes on and 45 minutes off against a 5.0 N-m resistance (45 in-lb).

Two short-duration flights with the SIR-C instrument are planned. Each flight will subject the actuator to intermittent operation of no more than 3 minutes on for every 45-minute operating window, for a total accumulation 1.5 hours of operation over the seven-day period. We experienced no further degradation in performance in the actuator motor or gearbox during the remainder of our development or qualification tests.

Tri-Drive Clutches

We are wary of operating an AC motor for any significant time in a stalled condition in a vacuum, believing that the rotor could be damaged by high temperatures. Therefore, we have included a breakaway roller clutch (Figure 11) in the design which will prevent the motor from stalling should the Tri-Drive output shaft be prevented from rotating for some reason.

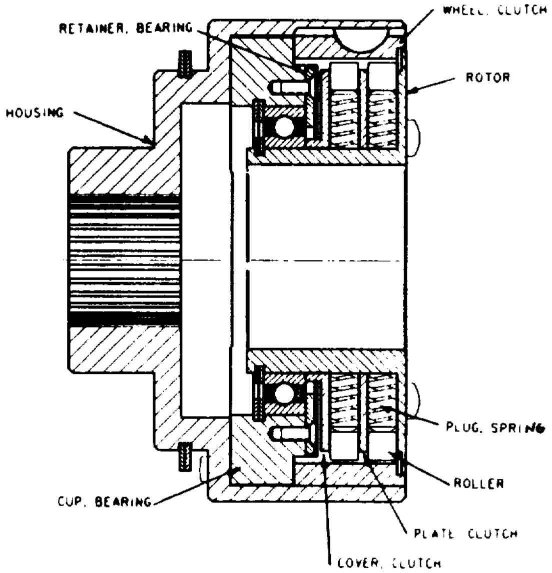


Figure 11. Tri-drive Clutch Assembly Cross-Section

The two AC motor clutches are set to ratchet at about 3.91 N-m (35 in.-lb), whereas the DDA clutch ratcheting level is about 7.26 N-m (65 in.-lb). These units have undergone significant development testing that has demonstrated their durability and consistency in ratchet level (+/- 10%).

Tri-Drive Dual Drive

The tertiary drive system must use the STS DC power supply. Instead of procuring a costly new DC drive unit, we incorporated the SIR-B Dual Drive Actuator, originally used to fold the leaves, into the design. The development and flight units were rebuilt using new spur gears. The harmonic gears were changed from 1110:1 to 100:1 to increase the velocity, and the output plate was changed to provide an interface with the clutch. Both output motors run simultaneously, drawing power from a single DC bus, because no redundancy is required at this level.

For details concerning the Dual Drive, see reference 2.

Crank and Linkage Assembly

The Tri-Drive is mounted to the Crank and Linkage Assembly (Figure 12). Crank torques produced by launch and landing translational vibrations are minimized by a counterweight that balances out the mass moment of the crank and connecting link. Mallory 2000 tungsten alloy was used to increase the mass with a minimum of volume within the counterweight. Torques that might otherwise act on the crank due to pushing or pulling of the X-Band Antenna Assembly are eliminated by stowing the antenna in a bottom dead-center position. This leaves only the rotational accelerations acting to produce a "back-out" torque during launch. We had hoped that the stop and hold torque of the harmonic gears in the Tri-Drive would be sufficient to resist this. However, as previously mentioned, the backdrive level was too low. Upon further reflection, it would have been difficult to characterize the stop and hold level without running vibration tests on the unit.

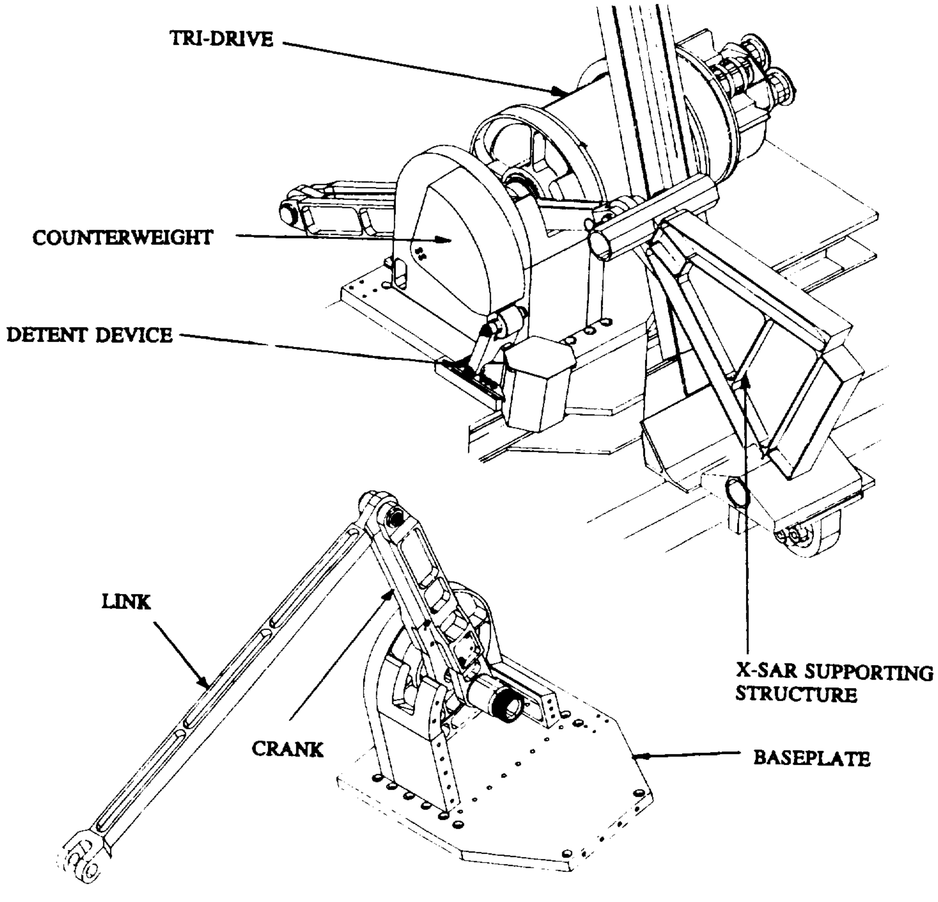


Figure 12. Crank and Linkage Assembly

Detent Device

Therefore, we developed the Detent Device (Figure 13), which automatically preloads the mechanism in the stow position with 268 N-m (2,400 in.-lb) of torque. The device consists of a cam, rollers, pivot, cable assembly, spring and housing. The critical spring is not guided. Instead, we kept the aspect ratio (free height to diameter) low (2:1) and minimized side loads to eliminate any possibility of buckling. A multi-strand cable with double fittings connected between the spring cup and a lever arm provides precise control of the virtual load points for compression of the spring. By minimizing the cable length and lowering the fitting points as much as possible, we gained additional margin for buckling resistance. Deflections as high as 12.7 mm (0.5 in) were detected at the top of the spring during transverse vibration tests, but the assembly was not damaged, compression was maintained and no buckling occurred.

The detent roller rides against a steep, 45° ramp while in the stow position to produce the 268 N-m (2,400 in.-lb) preload. The ramp slope then reverses, producing a torque of about 25 N-m (225 in.-lb) tending toward deployment. This ramp is an involute and gradually drops off until the roller is no longer in contact during mission data-take operations.

Caging Hinges

The X-SAR supporting structure does not have sufficient rigidity to be kinematically supported by only two hinges along the tilt axis during launch and landing. On the other hand, a kinematic support is desired for mission data collection to eliminate redundant load paths in the structure and higher bearing friction/stiction in the hinges. The Caging Hinges were specially designed to meet this requirement.

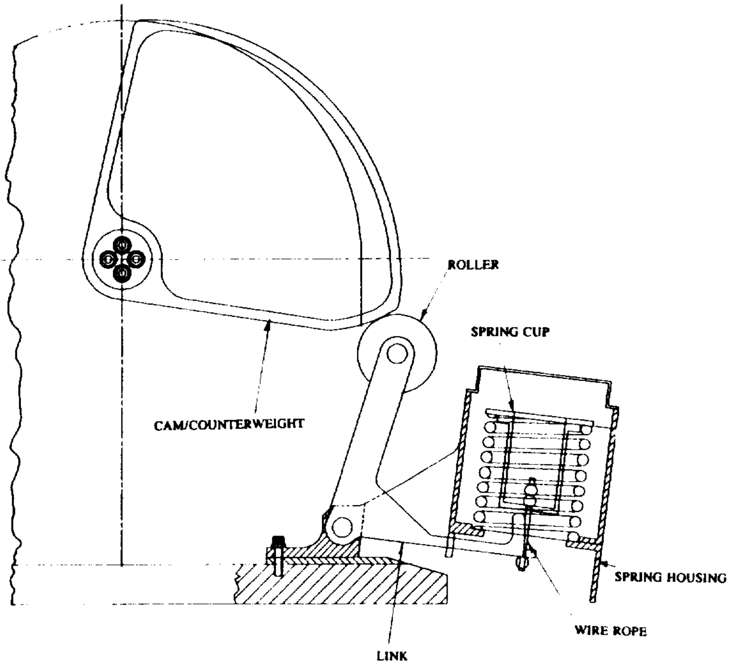
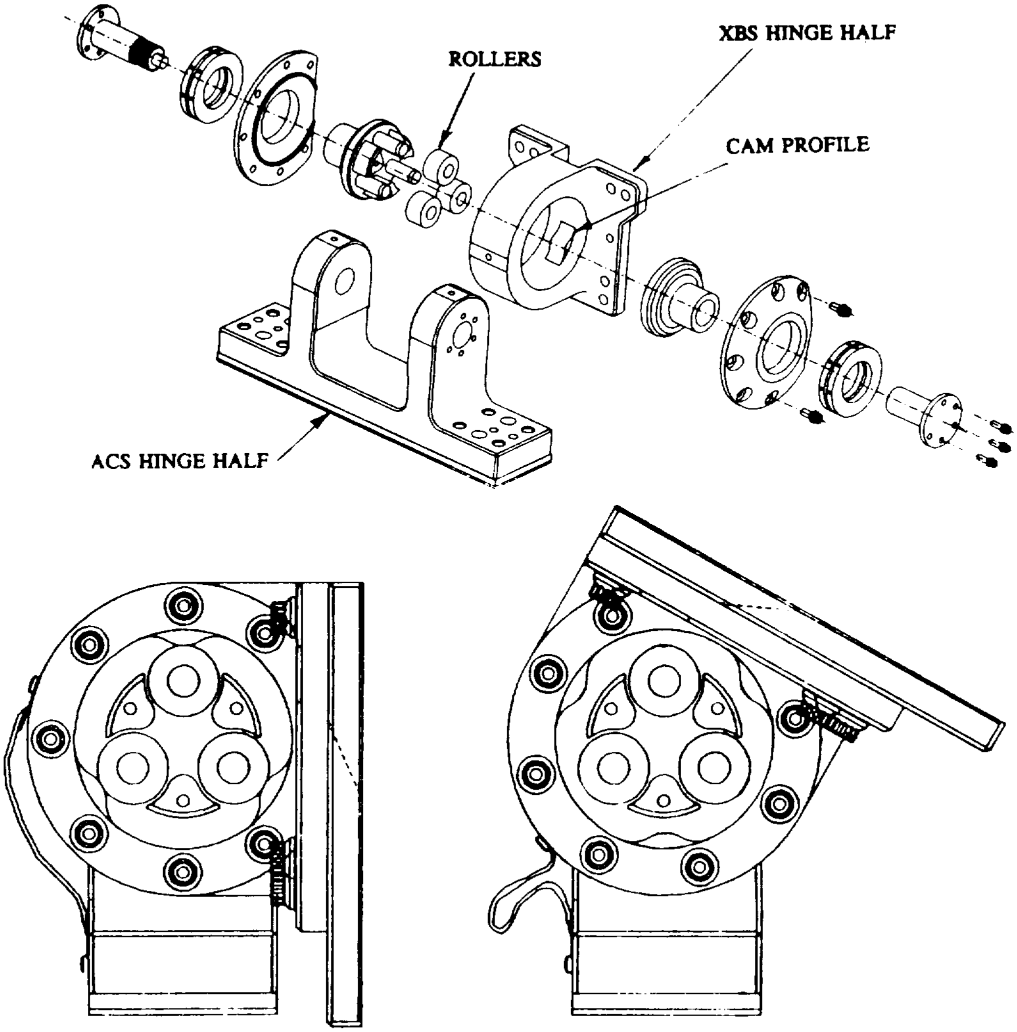


Figure 13. Detent Device

They are located in the positions described in Figure 6. The Caging Hinges are subjected to a maximum of 1090 N (4800 lb) radially and 860 N (3800 lb) axially in launch and landing. The two outer hinges are mounted to swiveling bipods attached to the X-SAR support structure. These hinges constrain the antenna in the Y-Z plane only. The center hinge is rigidly mounted to the XBS and provides a translational constraint in X-Y-Z. Each hinge is identical in all other respects.

Figure 14 shows an exploded view of the hinge and a cross section in stowed and deployed positions. The rollers are in contact with the lobes of the cam when the X-SAR is stowed. Upon deployment, there is a gap of about 6.4 mm (0.25 in.) freeing up the interface in the STS Y-Z plane.



STOWED

$\theta_{XBS} = -66°$

PARTIALLY DEPLOYED

$\theta_{XBS} = -6°$

Figure 14. Caging Hinge

Since there is no contact with the cam rollers when the antenna is deployed, redundant bearing surfaces are not required. The thrust surfaces on either side, do, however, incorporate redundancy and verification spanner wrench holes.

Bipod Hinges

The Bipod Hinges are shown in Figure 15 and are located on the ACS as shown in

Figure 6. They are mounted on XBS bipods, much as the two Caging Hinges are, and thus carry only Y-Z plane forces, which have a maximum value of 500 N (2,200 lbs). Each hinge makes use of a spherical bearing to prevent any binding that might otherwise occur due to small local angular misalignments. The hinge encoders, used for X-SAR position telemetry, are mounted to these hinges using a flexible bellows coupling.

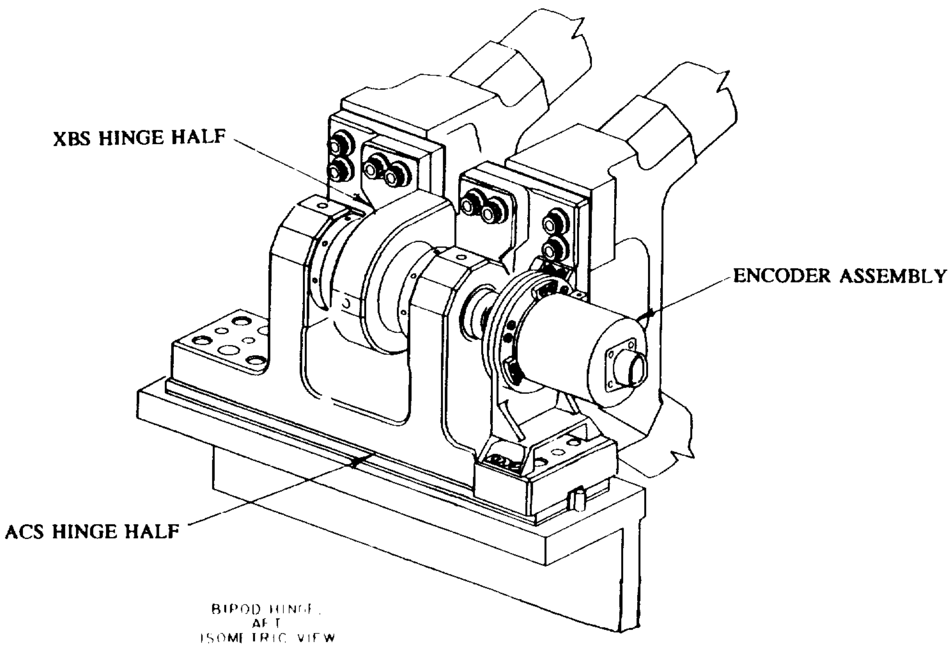
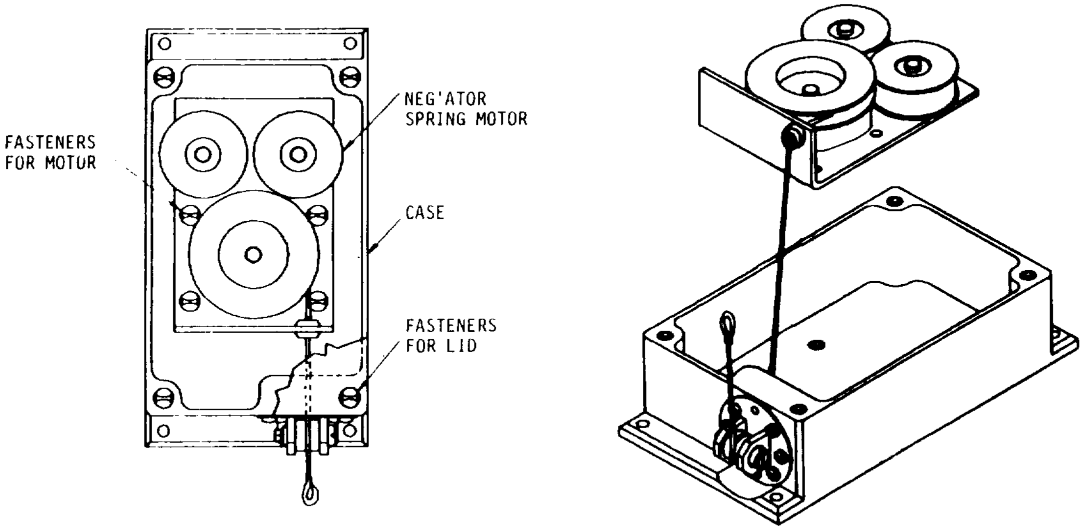


Figure 15. Bipod Hinges

Backlash Eliminator

The Backlash Eliminator's purpose is to eliminate the lost motion or "play" in the tri-drive harmonic gears and the linkage joints (Figure 16). The device is a commercially manufactured mechanism procured from AMETEK Hunter Spring Products Company that has been mounted in a specially designed enclosure in order to meet STS mass containment requirements.

The major components of the device consist of a cable, spool, constant force spring and enclosure. One end of the cable is attached to the X-SAR antenna substructure and the other to the spool. The negator spring keeps the cable at a nearly constant 1.1 N (5 lb) tension regardless of the extension length. This produces approximately 5.58 N-m (50 in.-lb.) of torque about the tilt axis per unit. Should the cable somehow break and then snag and act against the tilt actuator torque, the Tri-Drive has adequate torque at 670 N-m (6,000 in.-lb.) (F.S. of 40) to break the cables and continue to operate. Some pointing control accuracy would be lost, however, due to the extra play.



TOP VIEW
(Lid removed)

EXPLODED VIEW
(Lid not shown)

Figure 16. Backlash Eliminator

CONCLUSIONS

All of the mechanisms described in this paper have been built, tested and integrated. The system has successfully passed the Johnson Space Center Shuttle Safety Review - Phase II. The phase III review is scheduled for Spring of 1993.

Some lessons learned include the following:

- Designs cannot always be extrapolated into a larger scale. Early attention should be paid to dynamic analysis of deflections and stresses when doing so, before additional significant resources are expended in detailed design of mechanism subsystems.
- As usual, friction is not there when you need it. Do not rely heavily upon the nonbackdriveability of gear trains.
- Aircraft-quality AC motors can be qualified for use in spacecraft mechanisms.
- It is possible to design and develop a truly dual fault tolerant actuator for use in a Space Shuttle safety critical application.

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