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SPECIAL TEST EQUIPMENT AND FIXTURING FOR MSAT REFLECTOR ASSEMBLY ALIGNMENT

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ABSTRACT

The MSAT Reflector Assembly is a state of the art subsystem for Mobile Satellite (MSAT), a geosynchronous-based commercial mobile telecommunication satellite program serving North America. The Reflector Assembly consisted of a deployable, three-hinge, folding-segment Boom, deployable 5.7 x 5.3-meter 16-rib Wrap-Rib™ Reflector, and a Reflector Pointing Mechanism (RPM). The MSAT spacecraft was based on a Hughes HS601 spacecraft bus carrying two Reflector Assemblies independently dedicated for L-band transmit and receive operations. Lockheed Missiles and Space Company (LMSC) designed and built the Reflector Assembly for MSAT under contract to SPAR Aerospace Ltd. Two MSAT satellites were built jointly by SPAR Aerospace Ltd. and Hughes Space and Communications Co. for this program, the first scheduled for launch in 1994.

When scaled for wavelength, the assembly and alignment requirements for the Reflector Assembly were in many instances equivalent to or exceeded that of a diffraction-limited visible light optical system. Combined with logistical constraints inherent to large, compliant, lightweight structures; "bolt-on" alignment; and remote, indirect spacecraft access; the technical challenges were formidable. This document describes the alignment methods, the special test equipment, and fixturing for Reflector Assembly assembly and alignment.

INTRODUCTION

The MSAT Spacecraft Bus and Reflector Assemblies are illustrated in Figure 1. In operation, the MSAT Satellite consisted of the MSAT Bus with deployed Transmit and Receive Reflector Assemblies. From spacecraft interface to outboard end, the Boom Assembly consisted of 3 hinges, Shoulder, Elbow and Wrist, a Load Absorber Mechanism, and 3 interconnecting graphite-epoxy tubes. Deployed Interface Shims were used in-between the Shoulder Hinge Base and Spacecraft. The Reflector was mounted on the Load Absorber, attached to it by the Reflector Pointing mechanism (RPM), RPM Shim and Spider. The RPM, built and furnished by Hughes, was a two-axis gimbal mechanism for on-orbit reflector-to-spacecraft tip and tilt alignment correction. The Deployed Interface and RPM shims were plane-parallel and for contingency use only.

The Spider was the critical structural element by which Reflector attachment to the Boom Assembly and ground alignment to the Spacecraft were simultaneously achieved. Integrated Alignment was the operation which established and manufactured the Spider to its requisite form: wedge, axial separation, and shear (decenter and clocking) relationship of the Reflector Hub and RPM interfaces. Spider manufacture, free-state characterization of the Boom Assembly and remote site transfer of the spacecraft interface and coordinate system were the challenging aspects of Reflector Assembly alignment and verification. All of these technical challenges were resolved by precision special test equipment (STE) and fixturing.

Reflector Assembly Alignment Overview

The baseline methodology for MSAT Spacecraft alignment required that Reflector Assembly alignments be performed independent of the Spacecraft Bus. Bolt-on alignment interfacing of the Reflector Assembly to the Spacecraft Bus at the end of the project was to be relied upon to 1) accurately orient and position the deployed reflector relative to the spacecraft-mounted reflector feeds, and 2) achieve a less critical stowed fit.

In response, the Reflector Assembly alignment and verification (A&V) was architectured with heavy reliance upon master & slave drill tool pairs; precision templates to establish and transfer spacecraft interface hole patterns. Two sets of master/slave drill tools were used, one set for the Transmit Reflector Assembly and a second for the Receive Reflector Assembly. Each set consisted of two master/slave tool pairs, one for the deployed interface and the other for the stowed interface. Both spacecraft were serviced by these two sets of master/slave tools. For the alignment-critical spacecraft deployed interface, the master/slave tooling was also relied upon to transfer spacecraft coordinate system knowledge from the Spacecraft Bus A&V site to the remote Reflector Assembly A&V site. Reflector Assembly A&V would follow, coordinated to the Spacecraft Coordinate System as-represented by the drill tools.

Master/slave drill tool use was adopted because it was a simple, low tech, low cost, high reliability manufacturing technique for establishing and transferring precision interfaces. Its practicality drove the decision to use master/slave tools for all alignment-sensitive pinned interfaces on the Reflector assembly: LMSC-Hughes interfaces involving the Hughes-supplied RPM and Reflector Assembly (RPM-Spider and RPM-Load Absorber interfaces), and LMSC intrafaces (Reflector Hub-Spider). All STE and fixturing that attached to any master/slave drill tool-controlled interface had their interfaces similarly generated.

An alignment plan and alignment error budgets were generated in accordance with this philosophy, which accommodated constraints associated with offloading large, compliant, lightweight structures; remote spacecraft access; and no practical means to perform end-to-end alignment verification tests. The fundamental elements of the Reflector Assembly alignment plan are detailed in Figure 2. The alignment plan relied upon subassembly-level testing, alignment-repeatable interfaces, high performance STE and fixturing. Stringent attention to manufacturing and test workmanship was required, especially when alignment-critical interfaces were involved. The RSSed error budgets were the principle means of evaluating error propagation, suballocating requirements and incorporating interface "bolt-on" alignment repeatability and other manufacturing tolerances. Two methods of estimating "bolt-on" alignment repeatability were used. The first was by RSS-based hand calculation and the second was computerized variation simulation analysis (VSA). Both methods took into account the geometric tolerancing of component interface features for the two mating parts comprising the interface. Tests on STE, breadboard mock-ups and flight hardware, verified these modeling techniques.

Boom Assembly Alignment And Verification

The Boom Assembly was constructed on the Boom Assembly and Retention Tool (BART), a dual purpose assembly and alignment fixture. Initially, BART was used to mechanically fixture boom components during Boom assembly. Afterward, during Integrated Alignment, it was reconfigured to fixture the Boom Assembly in its free-state condition. BART, detailed in Figure 3, consisted of a three-legged/two-sided 90° "fence" weldment that supported 5 vertical "Smart Plates". Each "Smart Plate" featured a boom component tooling interface and 3 tooling balls that were used to establishing plate manufacturing and alignment datums. BART design was based on modular fixturing concepts, to coordinate and simplify BART manufacturing, assembly and alignment. Boom assembly and alignment consisted of 1) interfacing the 3 hinges, Load Absorber Mechanism and boom stow fitting upon their BART tooling interfaces to establish their required alignment, and 2) installing and attaching the 3 interconnecting graphite epoxy Boom Tubes. Two BART fixtures were made, one for the assembly of Transmit Boom Assemblies, the other for the Receive Boom Assemblies. For Integrated Alignment, the Load Absorber Mechanism, Wrist Hinge and Elbow Hinge interfaces were reconfigured with adjustable boom retention clamps. The Shoulder Hinge tooling interface was not reconfigured.

Measuring and verifying BART alignment stability was a major concern, in particular the flexible 90° sidewall-sidewall configuration. The solution was to kinematically interface BART to the floor and establish accurate and redundant BART coordinate system references. The BART-facility floor interface: The corner column leveling foot was bolted directly bolted to the floor. The 2 end column leveling foot locations rested upon identical single degree-of-freedom translation stages, "soft" axes oriented parallel to the BART walls. BART coordinate system references: Three tooling balls mounted on top of the BART columns in a precise, level, 90° arrangement defined the local BART Coordinate System. The 3 axis-adjustable BART Cube Module cube was accurately oriented orthogonal to this coordinate system. The smart plate balls and Spacecraft Cube Module cube served as redundant coordinate system references. The 3 axis-adjustable Spacecraft Cube Module was used to define nominal spacecraft orientation and was a back-up reference for the Spacecraft Coordinate System cube on the Shoulder Drill Tool. Over the duration of the program (approx. 1 year) no alignment changes could be measured for BART and co-aligned optical cubes. Angular measurement accuracy was ± 3.4 µrad (7 arc sec/0.005 in over 120 in). Position measurement accuracy was ± 0.13 mm (0.005 in) or better.

Reflector Assembly And Verification

The fundamental elements of Reflector assembly and alignment are detailed in Figure 2. Reflector assembly (Figure 4) consisted of attachment and alignment of 16 ribs to the Reflector Hub, surface mesh integration, and concluded with surface contour adjustment to obtain the desired shape and shape alignment. A coordinate measuring theodolite system was used for this final task, measuring approximately 600 surface-mounted targets. All of these assembly and alignment operations, plus Integrated Alignment, were coordinated to optical and mechanical references on the Reflector Reference Tool (RRT). The RRT, shown in Figure 6, was used to establish the Reflector Hub Coordinate System, a local coordinate system orthogonal to the Reflector Hub geometry. Its functional requirements were: Accurate and stable coordinate system references, accurate recalibration and realignment of these references, and repeatable interfacing onto the Reflector Hub Strongback. Each reflector had a dedicated RRT and Reflector Hub Strongback.

RRT references consisted of 4 equally-spaced retro-reflective button targets, 4 equally-spaced tooling balls, a fifth "ambiguity" retro-reflective target (to prevent photographic misinterpretation of targets) and an optical octagon with 3 axis-adjustable mount. The octagon mount consisted of a box flexure stage (tip and tilt) topped by a rocker hinge flexure (clocking) that supported the octagon. Granite table metrology was used to determine the local (X, Y, Z) position of all four (4) balls and five (5) targets. Optical and mechanical runout techniques (air bearing rotary table and granite table metrology) were used to align the octagon orthogonal to the target-defined coordinate system. The octagon was aligned to the to 4.8 µrad (10 arc sec) or better in each degree of freedom and this alignment was maintained for the duration of the program (> 1 year). Alignment repeatability of the RRT on the strongback was 1.5 µrad /0.05 mm (4 arc sec/0.002 in) or better.

Spacecraft Interfaces and Spacecraft Coordinate System Transfer

Master and slave drill tools established the Reflector Assembly-to-Spacecraft deployed and stowed interfaces. The master tool generated the interface on both the Spacecraft Bus and the slave tool. The slave tool generated the interface on the Reflector Assembly. All interfaces were "flange-style": flat and coplanar mating surfaces, fastener clearance holes and shear pin holes. Only the shear pin holes required accurate drilling and reaming, the only precision required of the transfer process. Flat and coplanar mating surfaces were essential on the flight hardware and master/slave tooling, especially where high accuracy bolt-on alignment was expected. Hand lapping was frequently performed to establish flatness and coplanarity better than 0.013 mm over 250 mm (0.0005 in over 10 in).

Spacecraft Interface Transfer: The deployed interface slave tool was mechanically aligned to 'nominal position" relative to the Shoulder Hinge, see Figure 7, and the hole pattern transfer drilled and reamed into the hinge base. The stowed interface slave tool relied upon its deployed interface features (generated using the deployed interface master tool) to mechanically align the stowed

Reflector Assembly. Transfer drilling of holes typically held true-position accuracy of ±0.008 mm (0.0003 in) and diameter accuracy of ±0.005 mm (0.0002 in).

Spacecraft Coordinate System Transfer: The deployed interface master/slave tools were also used to transfer spacecraft coordinate system knowledge to the Reflector Assembly A&V site. At LMSC, the slave tool, the Shoulder Drill Tool (SDT), functioned as a spacecraft simulator. The SDT was calibrated in conjunction with the spacecraft-calibrated master tool, the HAC Tool. The calibration process, shown in Figure 7, was performed with the two tools interfaced to each other. Calibration was always performed horizontally, resting on a foam pad to obtain the "free-state" condition. Both tools had alignment references that consisted of 3 tooling balls and an optical cube. The SDT cube, mounted on a 3 axis-adjustable flexured gimbal stage, was aligned "dead-on" to the Spacecraft Coordinate System. Using a coordinate measuring machine, the SDT tooling balls positions were measured in relation to the HAC Tool tooling balls and transformed into spacecraft coordinates. The measured interfacing repeatability of the HAC Tool and SDT was 4.8-7.3 μrad (10-15 arc sec) and 0.018-.038 mm (0.0007-0.0015 in). Tooling ball calibration measurement accuracy was 0.013-0.018 mm (0.0005-0.0007 in) and 2.4-3.4 μrad (5-7 arc sec) for theodolite-based cube alignments. Cube alignment granularity was approximately 1.5-2.4 μrad (3-5 arc sec) and alignment to the Hac Tool/theodolite-defined Spacecraft Coordinate System was under 4.8 μrad (10 arc sec).

Integrated Alignment: Strain-Free Boom Assembly Operations

Three separate tests were conducted to measure and verify strain-free fixturing of the Boom Assembly on the BART Fixture, the necessary precondition for Reflector-to-Spacecraft Bus alignment. A fourth, independent, test was performed to verify Boom Assembly alignment stability. The STE and fixtures used in these tests, and their relationship to the Boom Assembly are detailed in Figures 8 through 12. The basic procedures for these tests were cube-to-cube angular measurements using optical theodolites and target-target (or tooling ball) position measurements using a coordinate measuring theodolite system. All measurements were made relative to coordinate system established by STE attached to the Shoulder Hinge Base, a Spacecraft Bus structural "ground".

Strain-Free Test #1: Boom Assembly, suspended on cables by the 3 BART-mounted boom offloaders, was "floated-in" relative to BART to mate the Shoulder Hinge Base to the Bart Shoulder Hinge tooling interface and the offloaded SDT. Shoulder Hinge Cube Module (SCM; see Figure 9) cube elevation measurements relative to gravity were made to obtain the free-state attitude of the BART-fixtured Shoulder Hinge Base.

Strain-Free Test #2: The floating "free-state" Boom was characterized by this test. Suspended by 3 boom offloaders, the Boom Assembly was leveled to the exact Strain-Free #1 SCM cube attitude. Orientation measurements of the Load Absorber Cube Module (LACM; see Figure 10) and RPM Cube Module (RPMCM; see Figure 11) cubes relative to the SCM cube were then performed. Position measurements of the RPMCM target and LACM Keel Ball were made relative to the Shoulder Hinge Base tooling balls.

Boom Segment Alignment: The outermost boom segment, Wrist Hinge-to-Load Absorber Mechanism, was "3-1-1-1" kinematically fixtured to BART and aligned to the BART-fixtured Shoulder Hinge per the Strain-Free Test #2 characterization. The Load Absorber Mechanism and Wrist Hinge were constrained by the Load Absorber Clamp (LAC) and the Wrist Clamp Assembly (WCA) respectively. Both tools are detailed in Figure 12. First, Strain-Free Test #1 was repeated to re-attach the Shoulder Hinge to the BART tooling interface and offloaded SDT. SCM cube and Shoulder Base tooling ball coordinate systems were then re-established. A tooling ball was then interfaced to the LAC bushing and the LAC was adjusted to position this ball to the LACM Keel Ball position measured during Strain-Free Test #2. The boom was then adjusted to engage the LACM Keel Ball into the LAC bushing, which kinematically functioned as a cone, to mechanically establish position alignment of the boom outboard end in 3 degrees of freedom. WCA screw adjustments, quantity 3 adjusters, oriented the RPMCM and LACM cubes relative to the SCM cube in 3 angular degrees of freedom; the outermost boom segment pivoting about the Keel Ball/LAC bushing interface. In parallel, the BART-mounted Elbow Hinge jackscrew support point was adjusted until a slight change in LACM and RPMCM cube alignment was detected.

Pre- and Post-Environmental Tests: After completion of Integrated Alignment, Pre- and Post-Environmental Alignment tests were performed on the Boom Assembly to measure boom alignment stability after thermal-vacuum testing. These tests were conducted in a manner identical to Strain-Free Test #2 and included the Spacecraft Interface Cube Module (SICM). The SICM, see Figure 13, was used to establish a local coordinate system at the Deployed Spacecraft Interface. For these tests interface alignment repeatability for the SICM, SCM, LACM and RPMCM was required. The measured angular repeatability for these tools were: SICM ± 2.4 μrad (5 arc sec); SCM and RPMCM ± 4.8 μrad (10 arc sec); LACM ±14.4 μrad (30 arc sec). Position repeatability was less than 0.05 mm (0.002 in) for these tools. SDT-SCM measurements during Strain Free Test # 2 establish Spacecraft Coordinate System traceability to the STE.

Integrated Alignment: Reflector-Spacecraft/Boom Assembly Alignment Operations

Reflector-Spacecraft/Boom Assembly Alignment was conducted in 3 separate operations. The end-item objective of these operations was a completed Spider. The STE and fixtures used in these tests, and their relationship to the Boom Assembly are detailed in Figures 14 through 17. The basic measurement techniques used were cube-to-cube angular measurements using optical theodolites and target-target position measurements using a coordinate measuring theodolite system. Granite table-based mechanical metrology, epoxy replication and jig & fixture machining were used for Spider manufacturing.

Reflector-Spacecraft/Boom Assembly Alignment: The Reflector, supported by the Integrated Alignment Stand (IAS), was first aligned to the Spacecraft

Coordinate System and relative to the free-state fixtured Boom Assembly. The Integrated Alignment Stand (IAS), detailed in Figure 14, was used to support and precisely align the stowed Reflector to the Spacecraft Coordinate System in six degrees of freedom. An adjustable "3-2-1" kinematic platform, the IAS aligned the Reflector Assembly with ±0.5 μrad (1 arc sec) and ±0.025 mm (0.001 in) precision relative to the test equipment and maintained alignment better than 2.4 μrad (5 arc sec) and 0.01 mm (0.004 in. over a 24-hour period. The Spacecraft Coordinate System was defined by the SDT cube (orientation) and tooling balls (position). The RRT octagon, targets and tooling balls similarly defined the Reflector Hub Coordinate System. This alignment operation is shown in Figure 5. Alignment was maintained during strain-free, precision mechanical replication of the RPM-side of the Load Absorber/RPM Interface and the Spider-side of the Reflector Hub/Spider Interface. A secondary mechanical replication operation, performed off-line on a granite table, established mechanical simulation of the Load Absorber-side of the Load Absorber/RPM Interface and the Spider-side of the Reflector Hub/Spider Interface. These two replication operations, and STE, are detailed in Figure 15.

Tooling Spider Fabrication: In this operation, presented in Figure 16, the tooling spider was epoxy-generated using the mechanical simulator. Here the Aft Tooling Spider, RPM and RPM Shim were integrated into the simulator, mechanically aligning the Aft Tooling Spider (RPM-Spider Interface) relative to the Forward Tooling Spider (Reflector Hub-Spider Interface). The Forward Tooling Spider, an integral part of the mechanical simulator, was then epoxied to the Aft Tooling Spider to create the Tooling Spider. The Tooling Spider mechanically represented the required flight Spider in form and feature.

Flight Spider Fabrication: The flight Spider was "cloned" from the Tooling Spider by conventional machining techniques detailed in Figure 17. Forward versus rear interface wedge and clocking, the mechanical form and features that governed Reflector angular alignment, were duplicated to ±0.013 mm over 406 mm (0.0005 in over 16 in) or better. Decenter and axial thickness were duplicated to 0.051 and 0.178 mm (0.002 and 0.007 in) or better, respectively.

CONCLUSION

The STE, fixtures, test equipment and procedures described in this paper were used to successfully ground-align 4 Reflector Assemblies. The budgeted ground alignment requirement for Reflector-to-Spacecraft alignment, as-defined by the Reflector Reference Tool and Shoulder Drill Tool respectively, was ± 29 μrad (1 arc min) in orientation, and ± 1 mm (0.04 in) in position, each degree of freedom. To confirm ground alignment accuracy, Integrated Alignment for the MSAT 1 Transmit Reflector Assembly was independently repeated, including complete Shoulder Drill Tool recalibration to the HAC Tool to re-establish the Spacecraft Coordinate System. The first-replication mechanical simulators generated by these tests were compared and agreed to 87 μrad (3 arc min) and 2 mm (0.080 in) or better. In between these tests the Boom Assembly was subjected to static load testing, which measured Boom Assembly alignment hysteresis of approximately ± 58 μrad (2 arc min) and ± 2 mm (0.08 in).

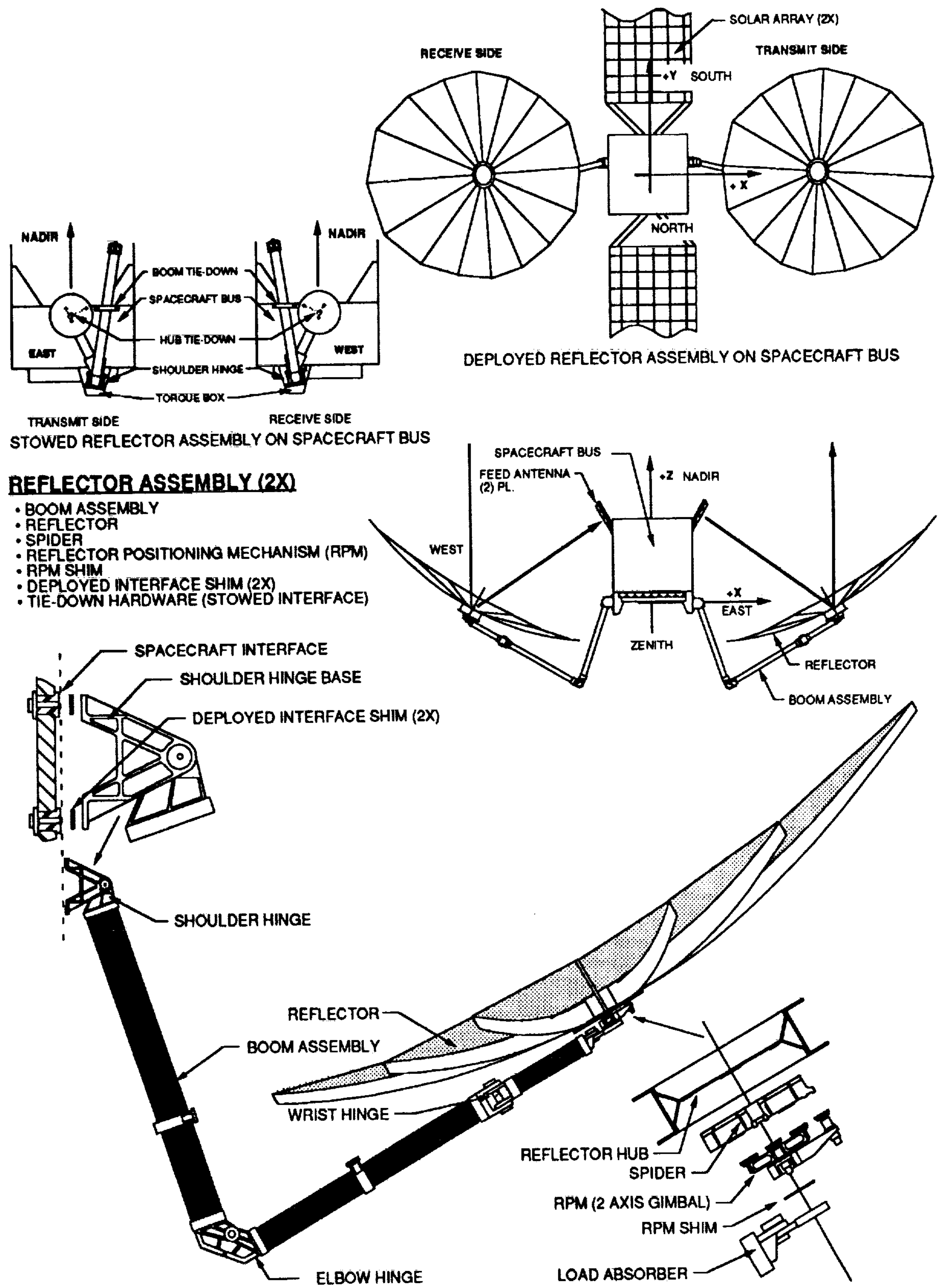


Figure 1 MSAT Reflector Assembly

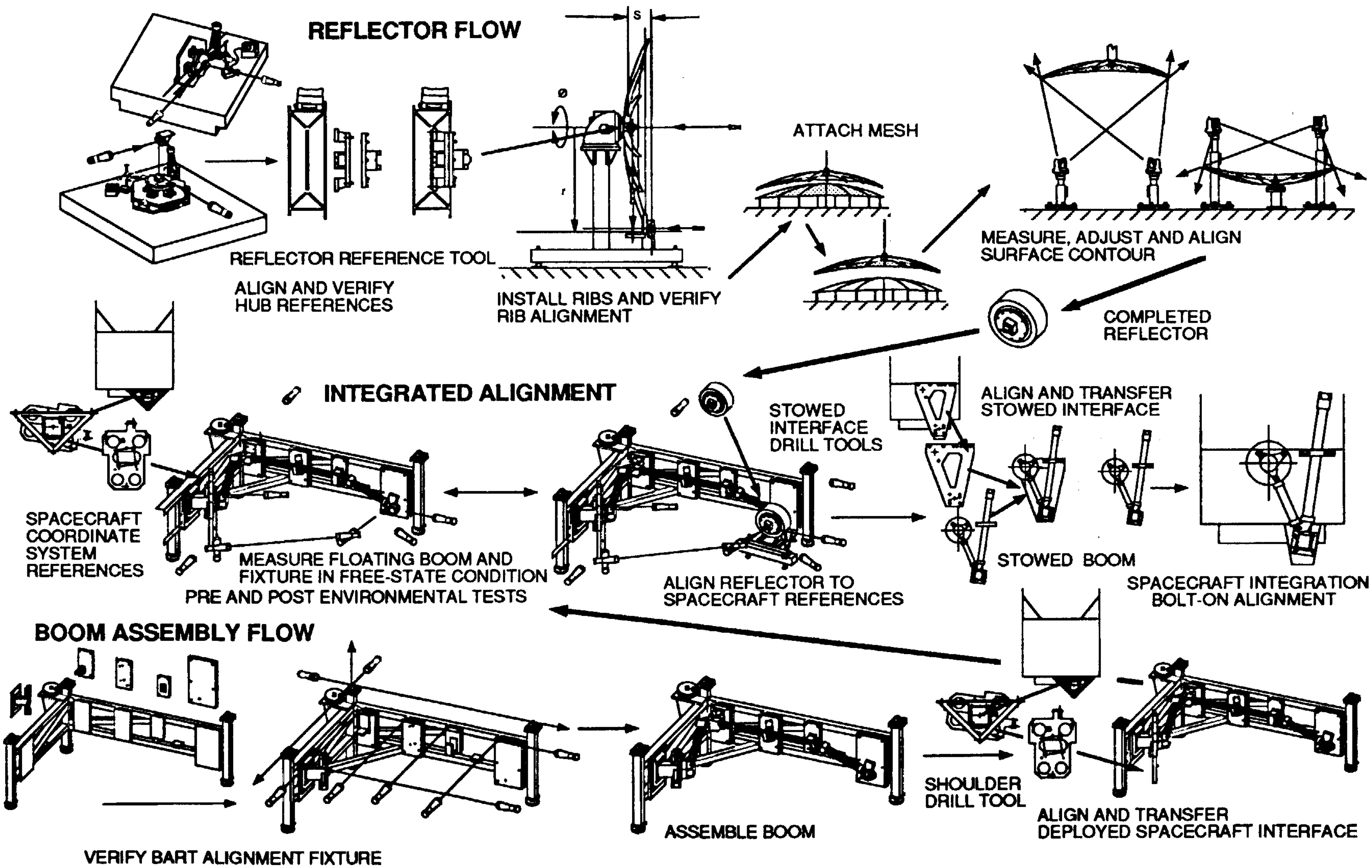


Figure 2 Reflector Assembly Alignment Flow

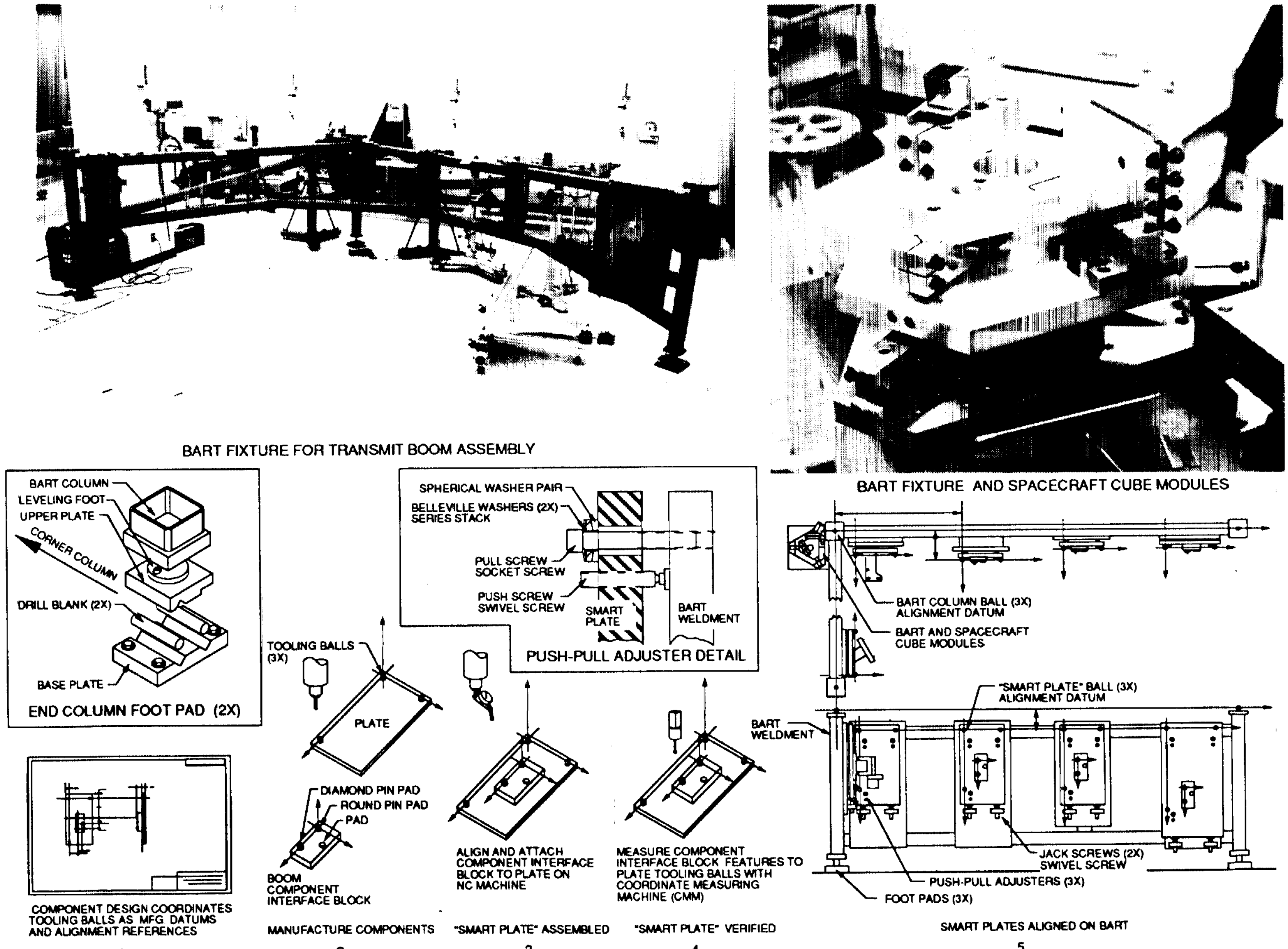


Figure 3 BART Assembly Details

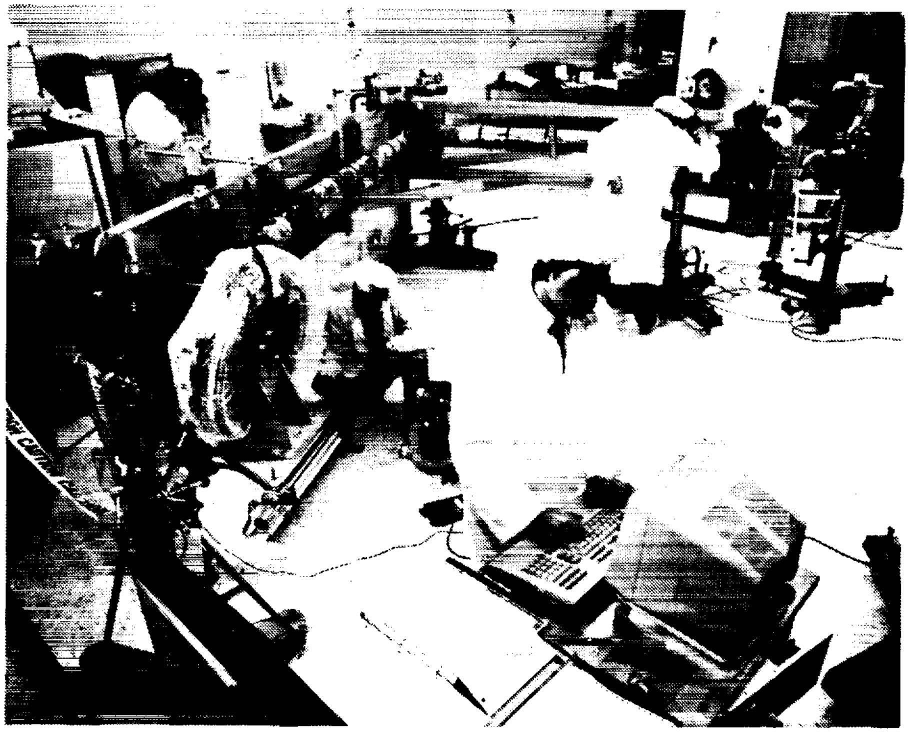


Figure 5 Integrated Alignment, MSAT Receive Reflector Assembly

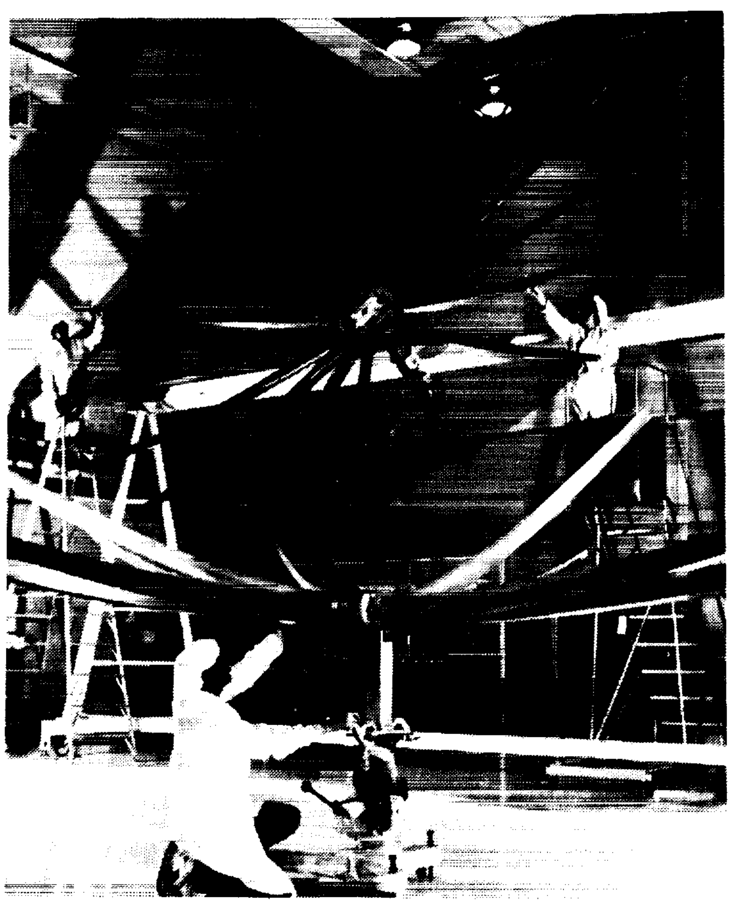
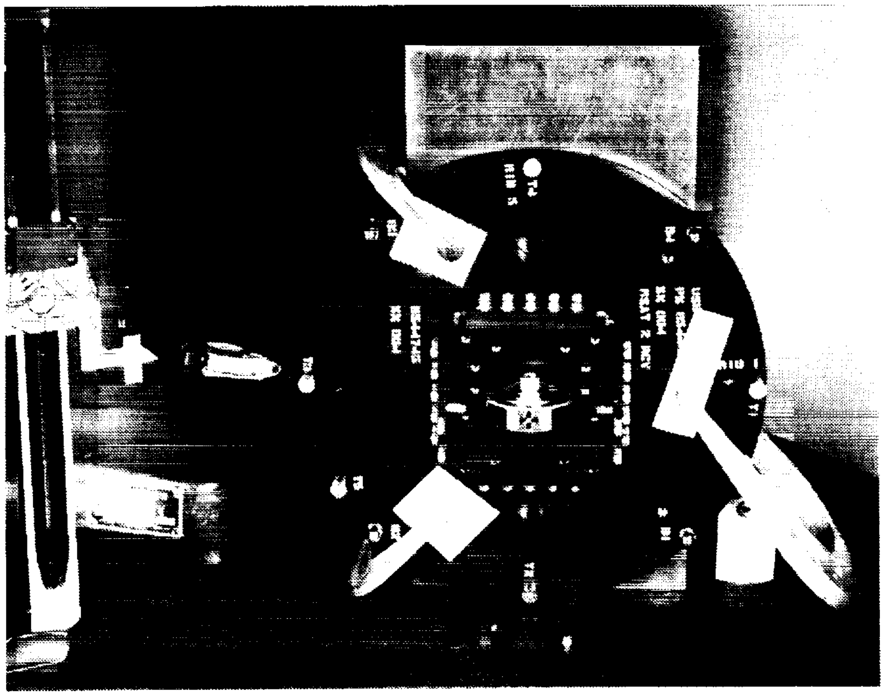


Figure 4 MSAT Reflector During Assembly



Reflector Reference Tool During Calibration

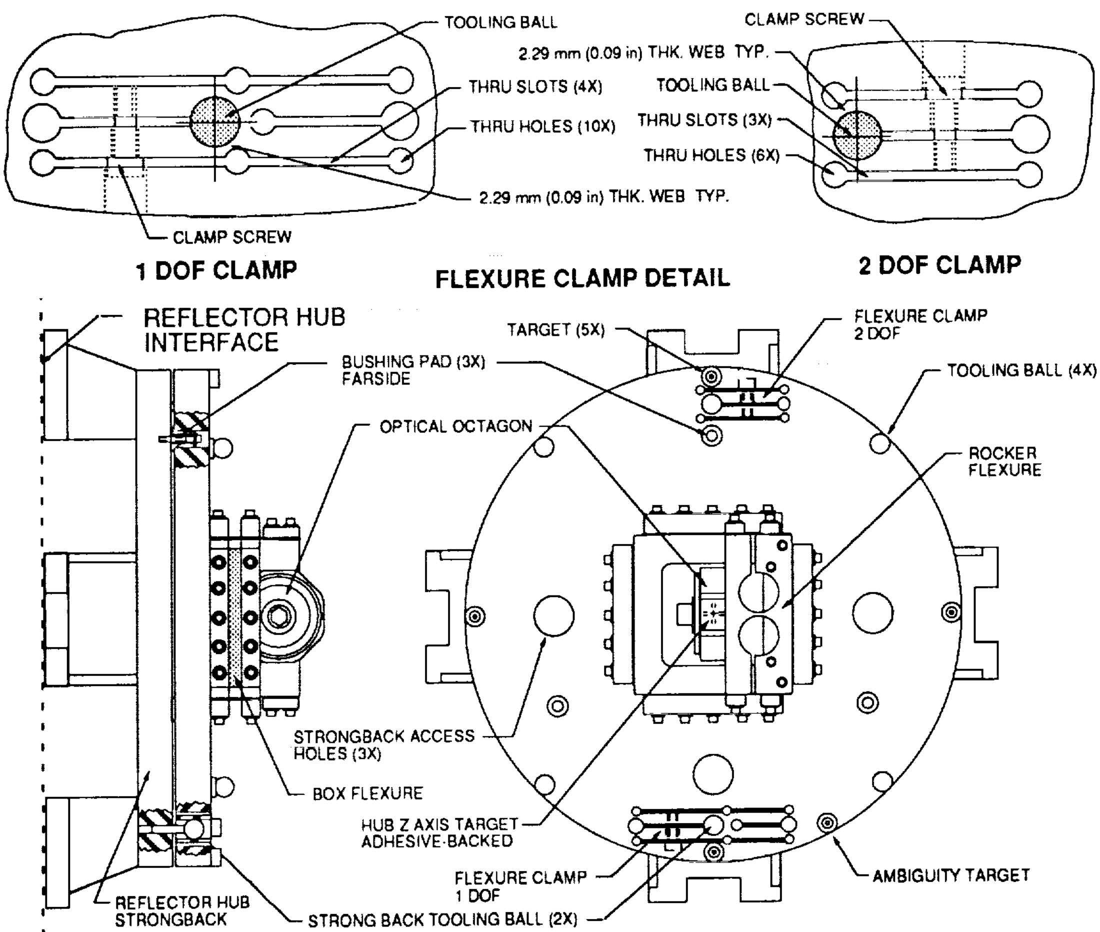


Figure 6 Reflector Reference Tool

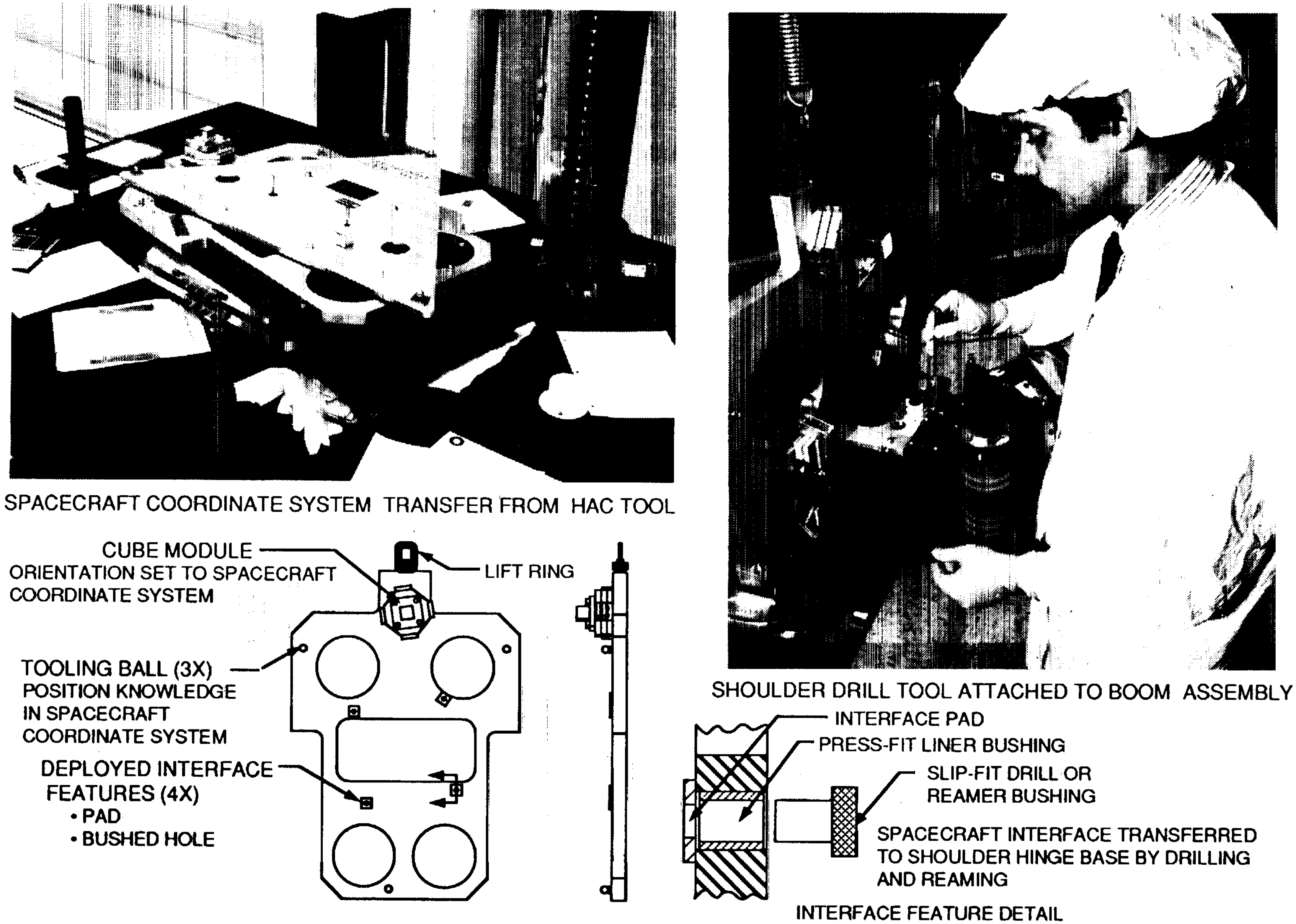


Figure 7 Shoulder Drill Tool

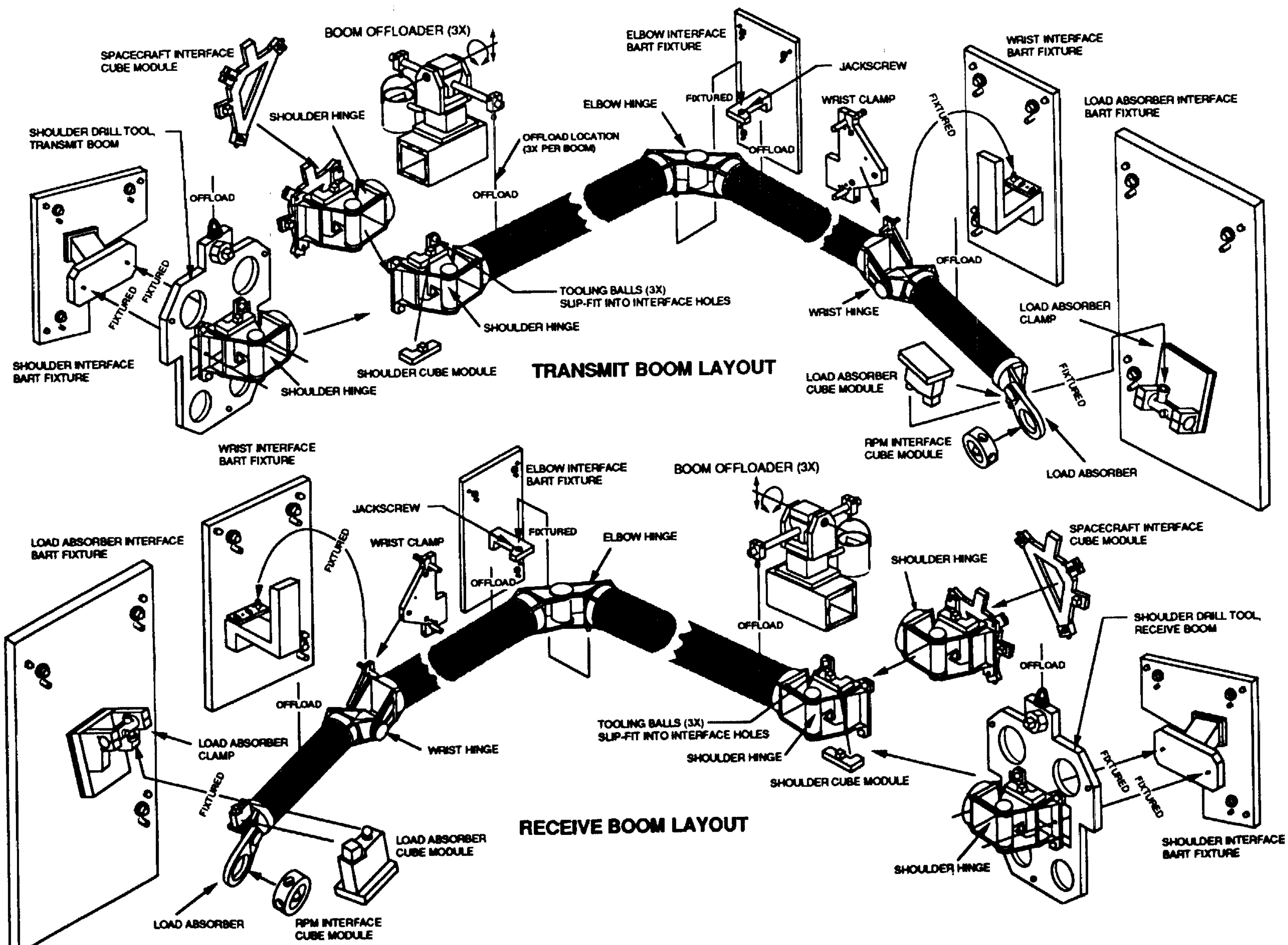


Figure 8 Boom Assembly And Special Test Equipment (STE)

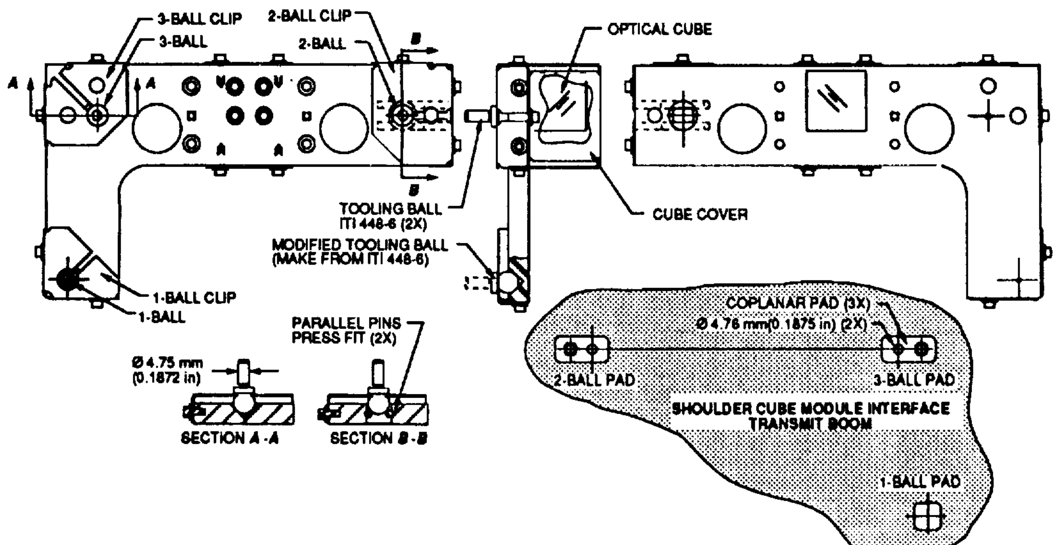
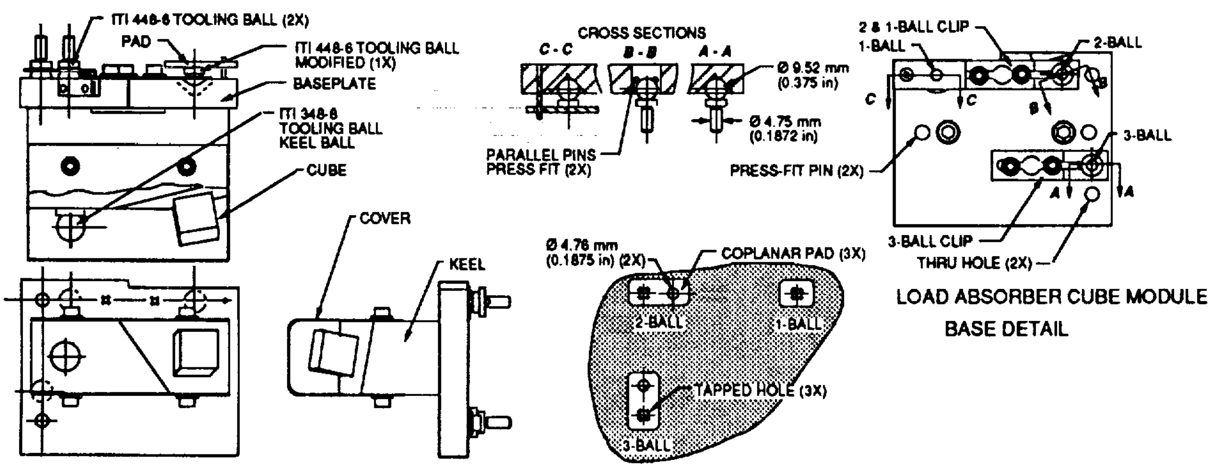


Figure 9 Shoulder Cube Module



LOAD ABSORBER CUBE MODULE BASE DETAIL

LOAD ABSORBER CUBE MODULE, TRANSMIT

LOAD ABSORBER CUBE MODULE INTERFACE

Figure 10 Load Absorber Cube Module

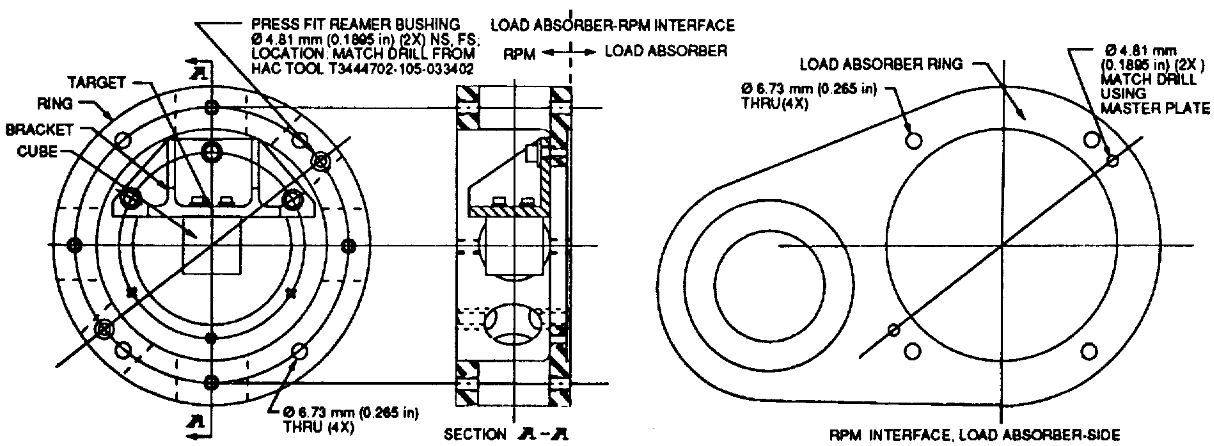
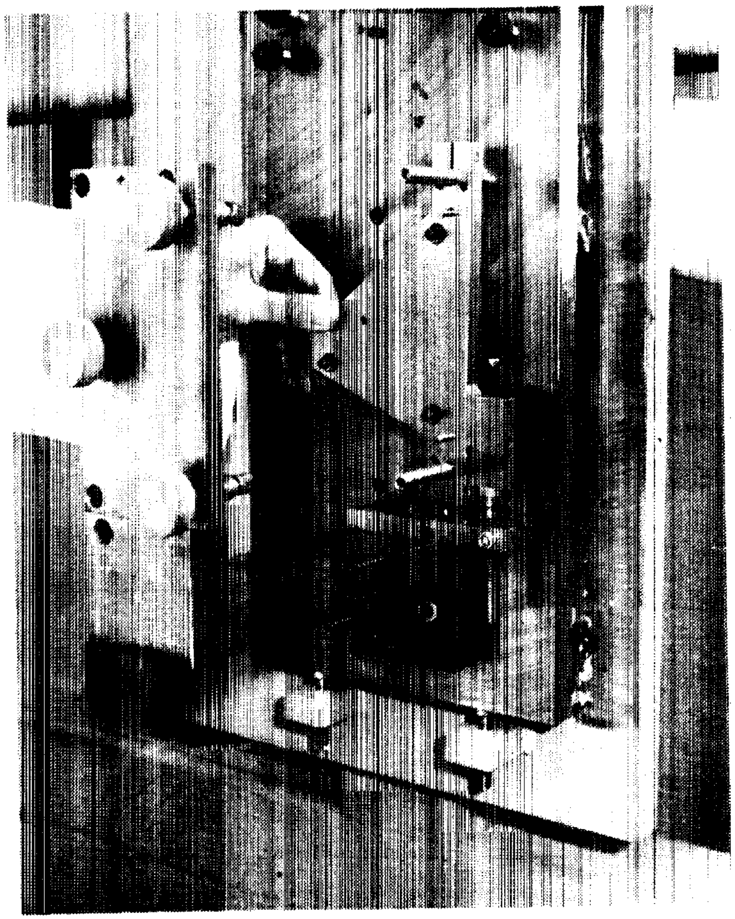
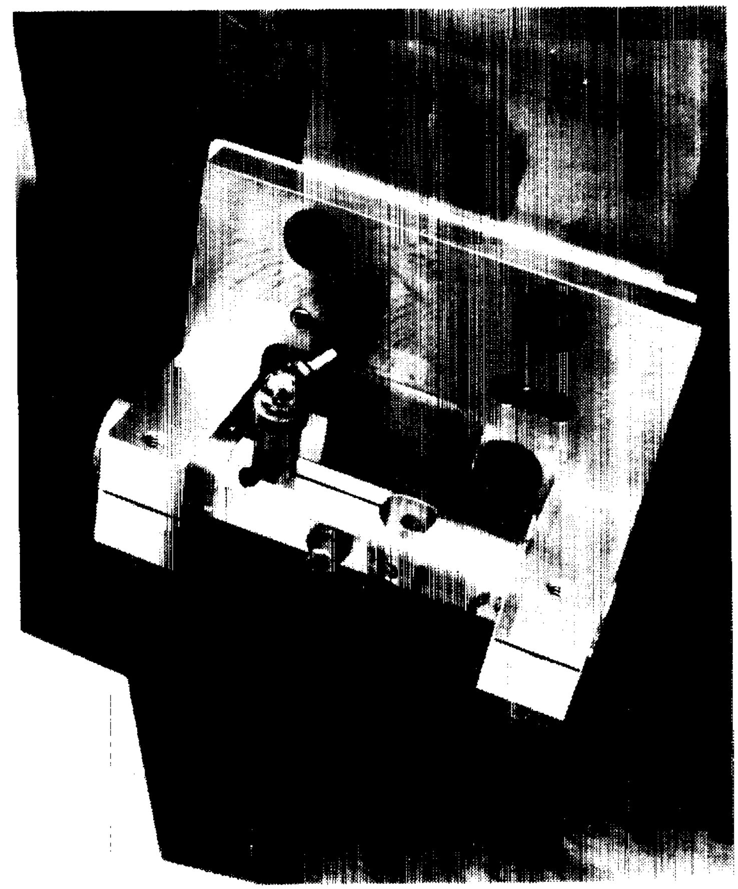


Figure 11 RPM Interface Cube Module



RECEIVE BOOM WRIST CLAMP ASSEMBLY ON BART



TRANSMIT BOOM LOAD ABSORBER CLAMP ON BART

FIGURE 12 ADJUSTABLE BOOM RETENTION CLAMPS

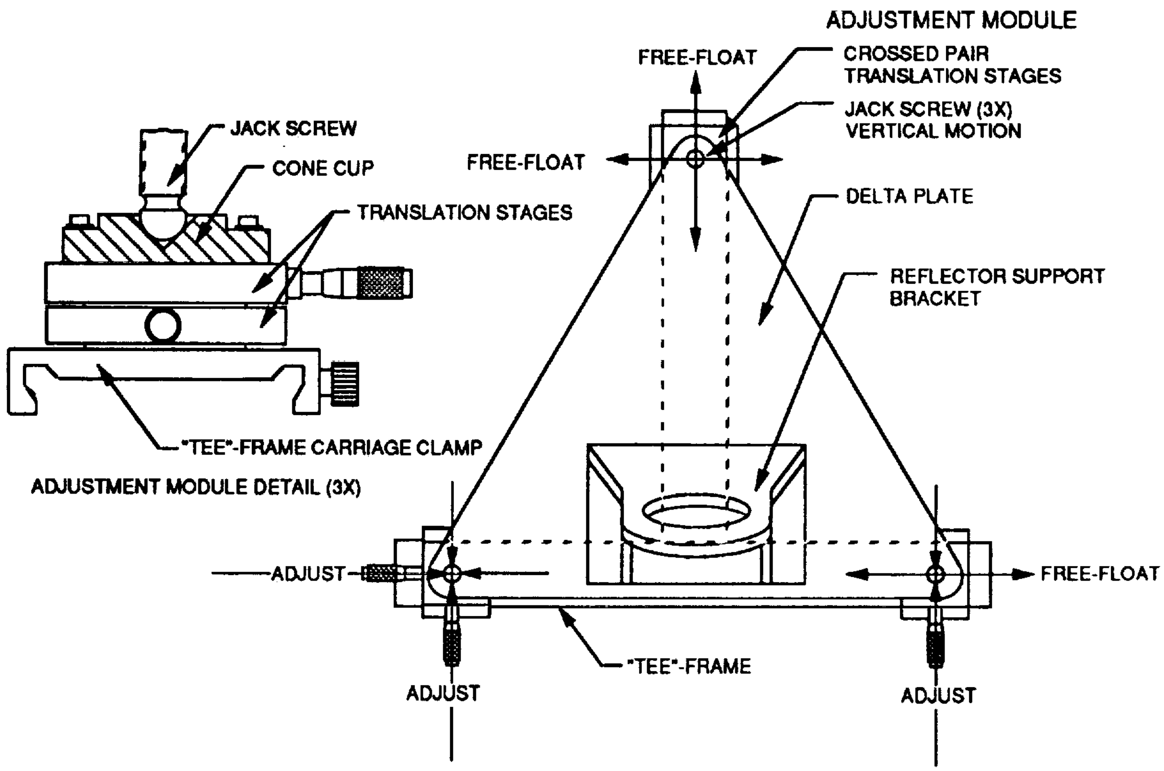


Figure 14 Integrated Alignment Stand

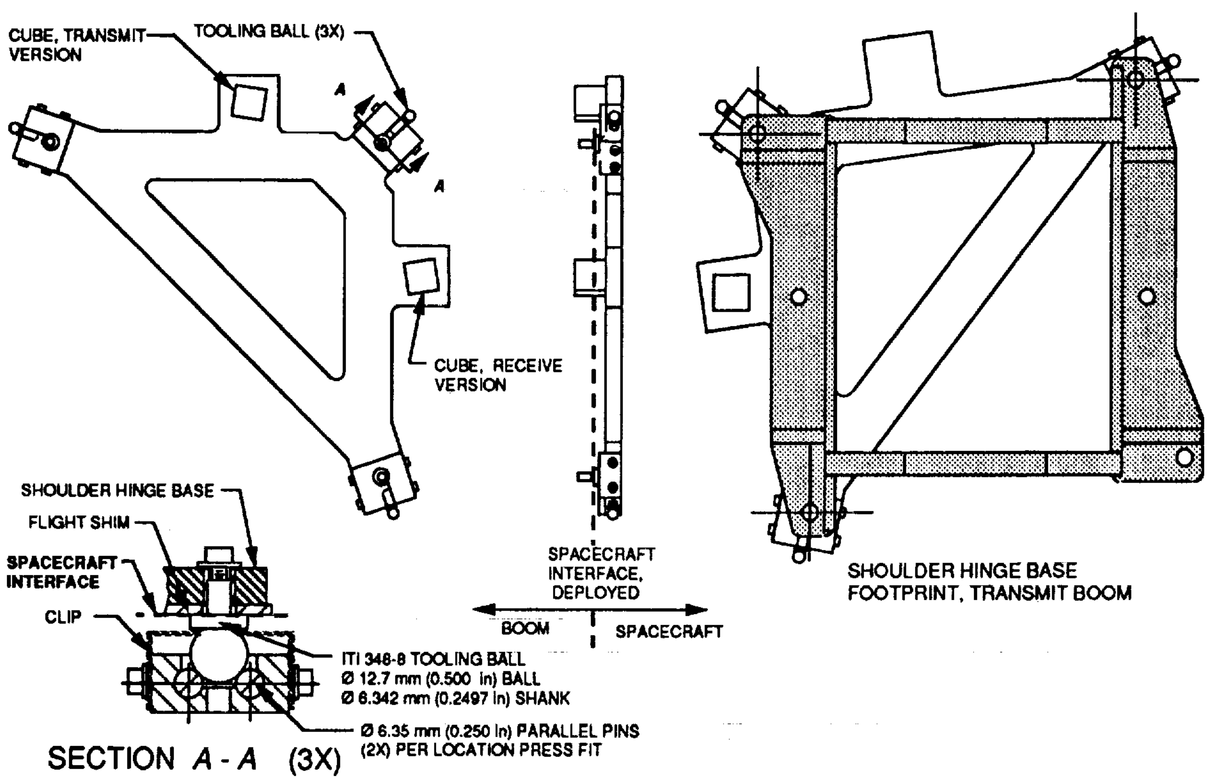
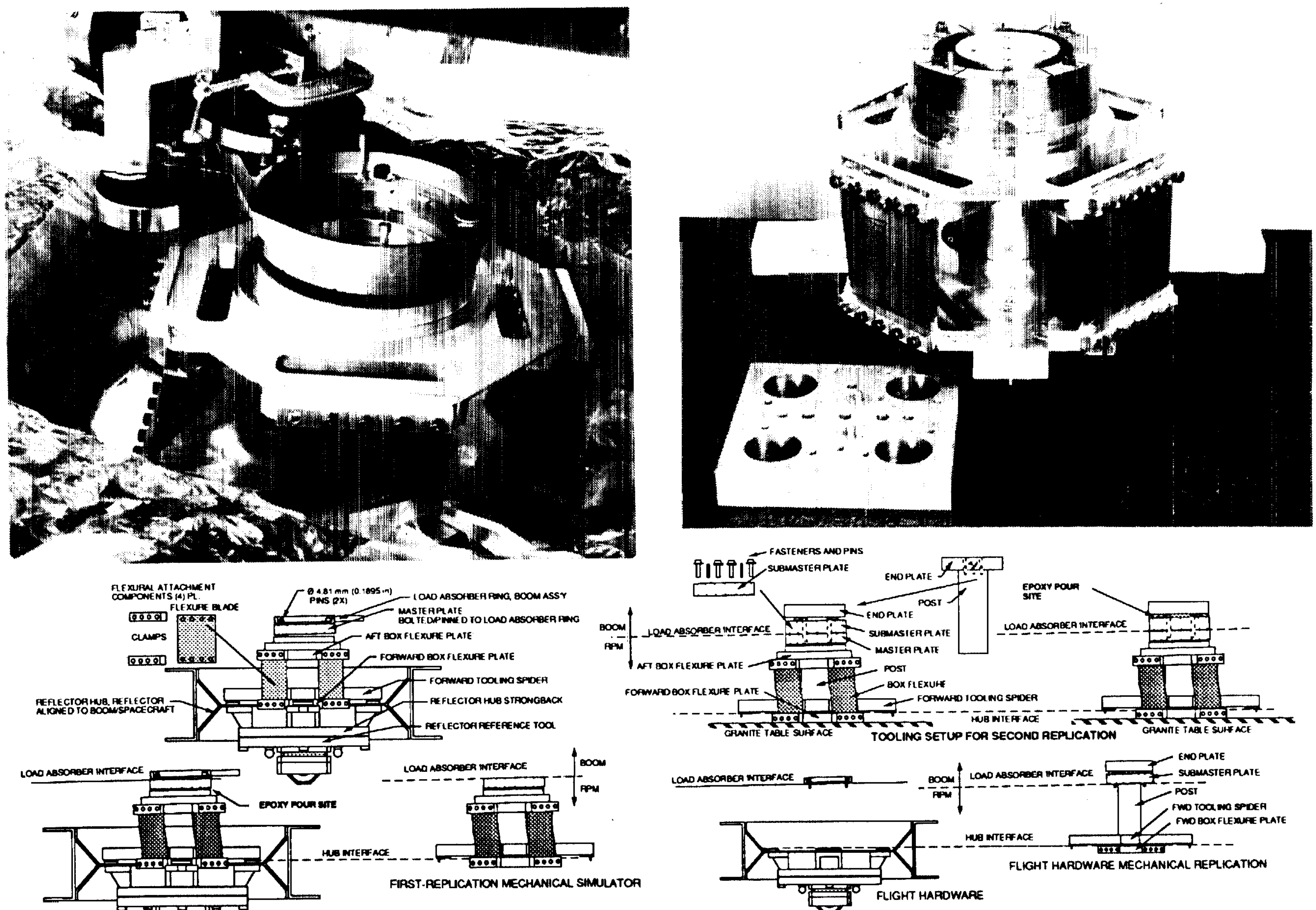


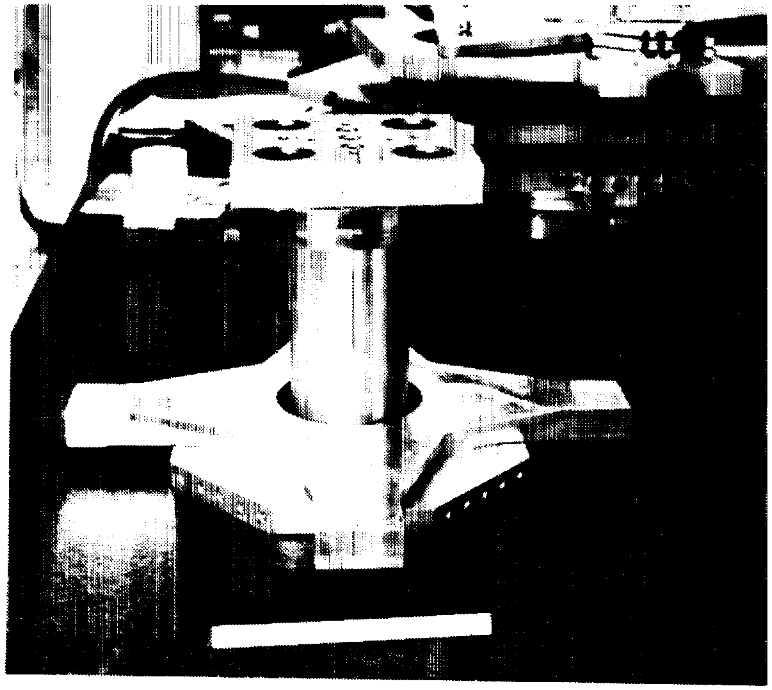
Figure 13 Spacecraft Interface Cube Module

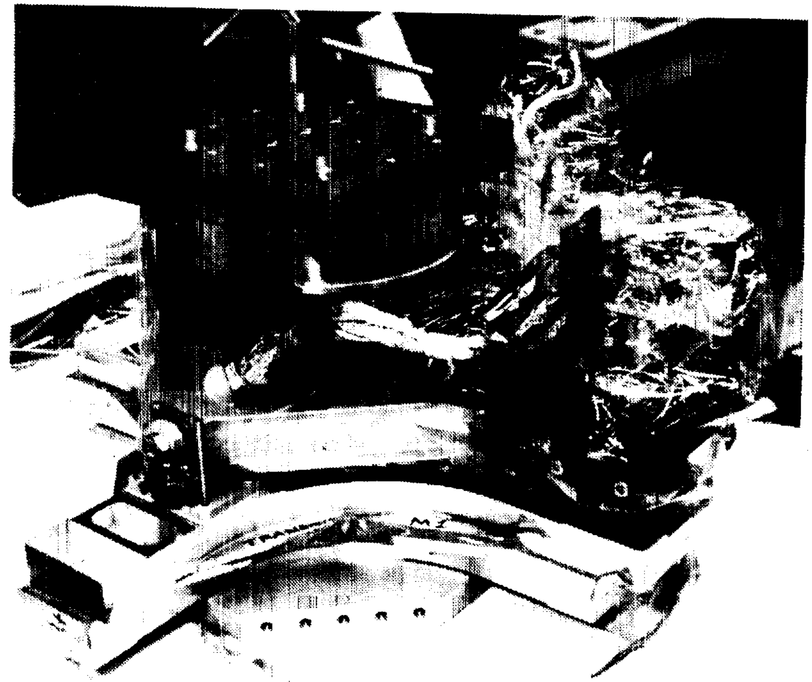


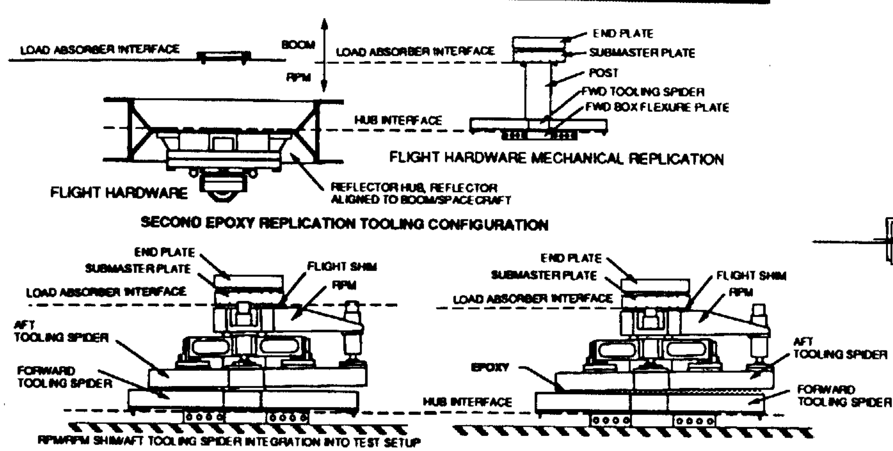
1) FIRST REPLICATION: HUB INTERFACE, SPIDER -SIDE-TO-LOAD ABSORBER INTERFACE, RPM-SIDE

2) SECOND REPLICATION: HUB INTERFACE, SPIDER-SIDE-TO-LOAD ABSORBER INTERFACE, BOOM-SIDE

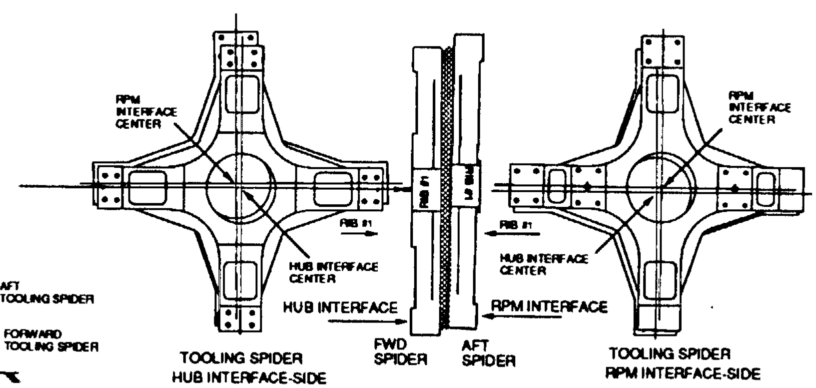
Figure 15 Reflector-Boom Alignment: Reflector Hub-To-Load Absorber Interface Replication







3) THIRD AND FINAL EPOXY REPLICATION: TOOLING SPIDER GENERATION



4) COMPLETED TOOLING SPIDER

Figure 16 Reflector-Boom Alignment: Tooling Spider Generated From Replication Tooling

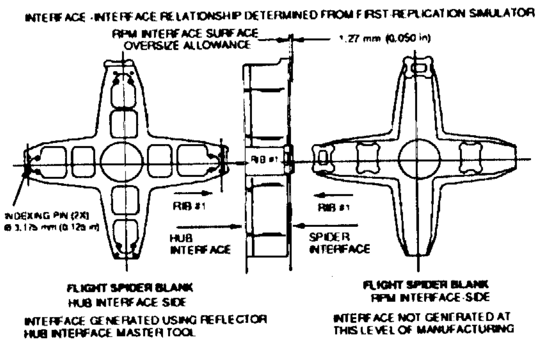


FIGURE A MSAT FLIGHT SPIDER BLANK FABRICATION

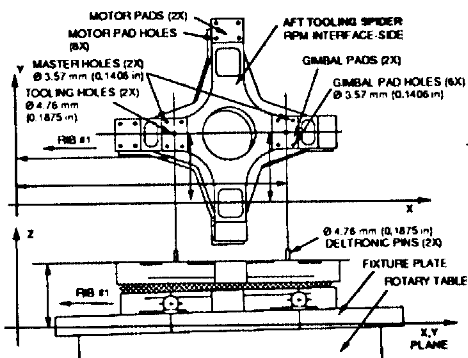
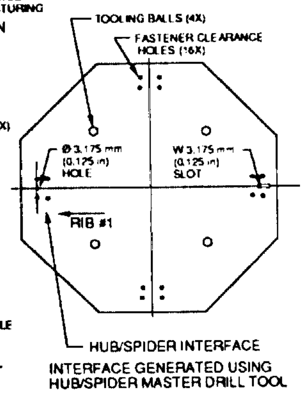
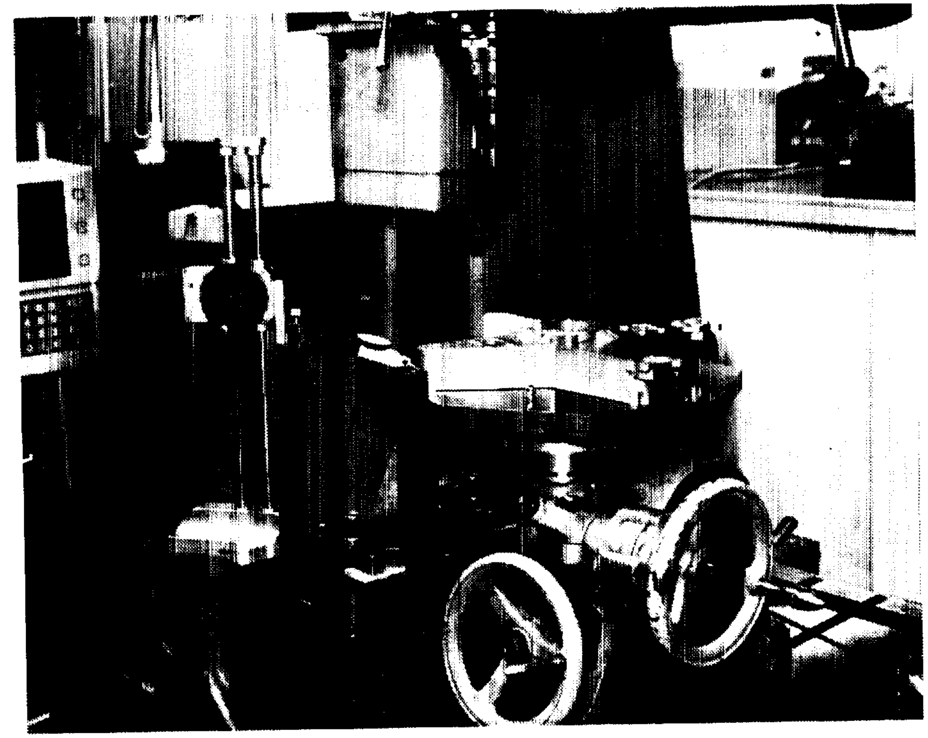


FIGURE B TOOLING SPIDER RPM INTERFACE BASELINE



FIXTURE PLATE



SPIDER MACHINING SETUP: JIG BORER WITH Ø 33 CM (13 IN) ROTARY TABLE AND FIXTURE PLATE

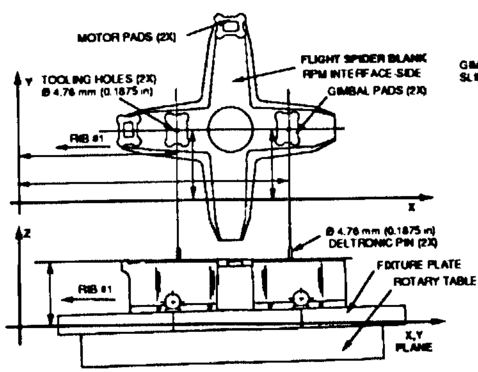


FIGURE C CUT RPM-SPIDER INTERFACE PADS AND BORE TOOLING HOLES TO TOOLING SPIDER BASELINE

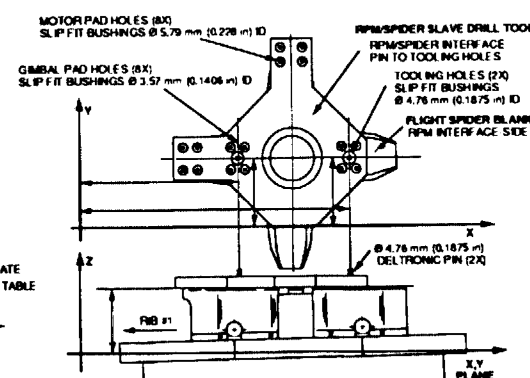


FIGURE D GENERATE FLIGHT SPIDER-RPM INTERFACE HOLE PATTERN

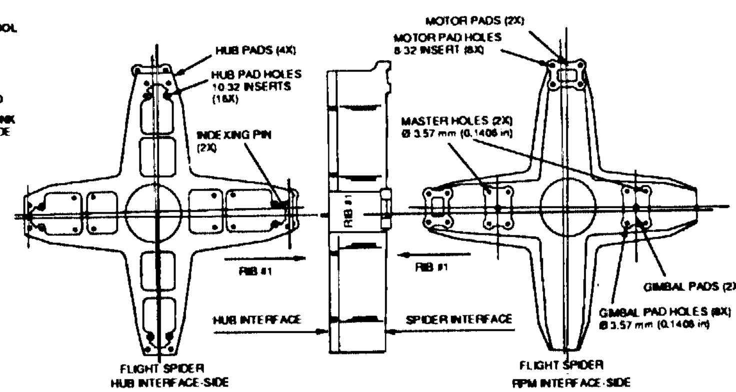


FIGURE E COMPLETED MSAT FLIGHT SPIDER

Figure 17 Flight Spider Manufacturing Process