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MSFC Three Point Docking Mechanism Design Review

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Table of Contents

1.0	Introduction	1-1
2.0	Missions for the Three Point Docking Mechanism	2-1
2.1	Description of NASA/MSFC TPDM Mission Scenarios	2-1
2.2	Nominal Mission Scenario Description	2-2
2.2.1	Propulsion vehicle/TPDM deployment	2-2
2.2.2	Rendezvous	2-3
2.2.3	Proximity Maneuvers (up to initial capture position and pre-rigidization)	2-3
2.2.4	Stabilization (initial capture position/pre-rigidization to rigidization)	2-3
2.2.5	Rendezvous with On-orbit Support System	2-4
2.2.6	Release of Target Vehicle	2-4
2.2.7	Chase Vehicle/TPDM Stowage	2-4
3.0	Requirements	3-1
3.1	Requirement Information from Document Review	3-1
3.2	Requirements Derived From Tumbling Satellite Retrieval Study (TSRS)	3-8
4.0	TPDM Latching Sequence Analysis	4-1
4.1	TPDM Assembly Description	4-1
4.1.1	Latch mechanism	4-1
4.1.2	Auto docking sensor	4-6
4.1.3	Structure and vehicle mounting interface	4-7
4.1.4	Target Satellite Interfaces	4-7
4.2	Auto Docking Sensor Tolerance Study	4-13
4.2.1	Application to TPDM Orientation	4-13
4.2.2	Case 1 - Explorer Platform	4-15
4.2.3	Case 2 - Hubble Space Telescope	4-24
4.3	Alternate Capture Sensor/Capture Mechanism Concepts	4-29
5.0	Flight Issues	5-1
5.1	Health monitoring Information/abort Criteria	5-1
5.2	Recognition of Target Vehicle ARAD Targets	5-4
5.3	Target Vehicle Movement Due to Chase Vehicle Jet Plume Effects	5-4
5.4	Chase Vehicle Thrust Vector Stability	5-4
5.5	Chase Vehicle Orientation Update Based on ARAD Sensor Data	5-4
5.6	TPDM Latch Closure Criteria & Speed	5-5
5.7	Two Body Dynamics	5-5
5.8	Target Vehicle Centering Criteria	5-5
5.9	Target Vehicle Handoff	5-5
6.0	TPDM Issue Resolution	6-1
6.1	Design & Analysis	6-1

Table of Contents (continued)

6.2	Computer Simulation	6-4
	6.2.1 Dynamic Modeling	6-5
	6.2.2 Controls Simulation	6-5
6.3	Ground Test Simulation	6-5
	6.3.1 Flight Robotics Laboratory	6-6
	6.3.2 MSFC 6-DOF Motion Simulator Facility	6-7
6.4	Suggested TPDM Development Program Logic	6-8

Appendix A - Documents Transmitted for Use and Review	A-1
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Table of Illustrations

<u>Fig. No.</u>	<u>Title</u>	<u>Page</u>
3-1	Requirements Identified From Documentation	3-2
3-2	Requirements Derived From TSR Program	3-10
4-1	Three Point Docking Mechanism	4-2
4-2	TPDM Latch Assembly	4-3
4-3	Nominal Trunnion Movement Envelope Within A Latch Assembly	4-4
4-4	Nominal Latch Arm/Trunnion Position At First Contact	4-5
4-5	Trunnion Pin Dimensional Description	4-8
4-6	Nominal Position Of Trunnion Within TPDM Latch (Docked)	4-9
4-7	Towel Bar Dimensional Description	4-10
4-8	Nominal Position Of Towel Bar Within TPDM Latch (Docked)	4-11
4-9	Towel Bar In Docked Position, Showing Clearances	4-12
4-10	Position Of ARAD Sensor & Target Relative To TPDM	4-14
4-11	Summary Of Alignment Errors Applied To Trunnion	4-16
4-12	Latch/Trunnion Position With Alignment Errors Applied 12:00 Location	4-17
4-13	Latch/Trunnion Position With Alignment Errors Applied 4:00 Location	4-18
4-14	Latch/Trunnion Position With Alignment Errors Applied 8:00 Location	4-20
4-15	View of TPDM Latches Showing Composite Effect Of Alignment Errors Applied To Trunnions	4-21
4-16	Position Of 12:00 Trunnion For Case When "First-In" EO Sensor Activates TPDM Latch Logic	4-22
4-17	Variation Of Alignment Error Versus Sensor Position	4-23
4-18	Latch/Towel Bar Position With Alignment Errors Applied 12:00 Location	4-25

Table of Illustrations (continued)

<u>Fig. No.</u>	<u>Title</u>	<u>Page</u>
4-19	Latch/Towel Bar Position With Alignment Errors Applied 4:00 Location	4-26
4-20	Latch/Towel Bar Position With Alignment Errors Applied 8:00 Location	4-27
4-21	View Of TPDM Latches - Composite Effect Of Alignment Errors Applied To Towel Bars	4-28
5-1	Identification Of TPDM Issues And Effected Mission Elements	5-2
5-2	TPDM Issues And Postulated Functional Allocation	5-3
6-1	Identification of TPDM Issues And Potential Resolution Approaches	6-2
6-2	Identification of TPDM Support System Issues and Potential Resolution Approaches	6-3
6-3	TPDM Development Path - Resolution of Flight Issues	6-9

1 - Introduction

In the next few decades, we will be launching expensive satellites and space platforms that will require recovery for economic reasons, because of initial malfunction, servicing, or repairs, or out of a concern for post lifetime debris removal. The planned availability of a Three Point Docking Mechanism (TPDM) is a positive step towards an operational satellite retrieval infrastructure.

This study effort supports NASA/MSFC engineering work in developing an automated docking capability. The work was performed by Grumman Space & Electronics Group as part of Amendment 13 to Contract NAS8-36641, Part 2, Concept Evaluation/Test for the Tumbling Satellite Retrieval Kit. Simulation of a TPDM capture was performed in Grumman's Large Amplitude Space Simulator (LASS) using mockups of both parts (the mechanism and payload). Similar TPDM simulation activities and more extensive hardware testing was performed at NASA/MSFC in the Flight Robotics Laboratory and Space Station/Space Operations Mechanism Test Bed (6-DOF Facility).

2 - Missions for the Three Point Docking Mechanism

The TPDM provides the capability for the capture and release, on-orbit, of a payload having latch pins (trunnions) which enables berthing of the payload with the STS Flight Support System (FSS). The payload will be generically called the "target vehicle" in this report; existing vehicles (payloads) which possess latch pins (trunnions) as an integral part of their structure are the NASA Explorer Platform spacecraft and the Hubble Space Telescope.

The TPDM is fastened to a space vehicle having propulsion and navigation capability. The space vehicle will be referred to as the "chase vehicle" in this report; an example of a chase vehicle is the Orbital Maneuvering Vehicle (OMV), now canceled, and the Cargo Transfer Vehicle (CTV), now in the planning stage. Boosters, launched from earth or those stationed on orbit can also be configured as chase vehicles.

NASA/MSFC has modified the prior TPDM design, both in configuration and selection of hardware elements. This study effort performs an analysis of the present NASA/MSFC in-process configuration that also includes an automatic rendezvous and docking (ARAD) capability using a sensor located on the chase vehicle and alignment targets on the target vehicle. Navigation information, based on signals generated from the sensor illuminating the target, guide the chase vehicle towards the target vehicle at the correct orientation for docking.

Once docked, the TPDM may have an integrated refueling probe assembly that extends out to the target vehicle interface. Electrical interfaces are also planned. These operations mandate that docking occur within prescribed tolerances.

The NASA/MSFC TPDM design is based on two specific missions. These are described in more detail in the following paragraphs.

2.1 Description of NASA/MSFC TPDM Mission Scenarios

Mission 1 - Automated Rendezvous and Capture Flight Experiment

This mission, that of capturing an free flying target, is to use a yet undefined propulsion unit. For purpose of analysis, the propulsion unit is to have a mass of 1000 to 3000 pounds; this unit could be a Multi-Mission Spacecraft (MMS) type unit. The target weighs about 8000 pounds. This mission requires the chase vehicle, with TPDM attached, to be carried into low earth orbit in the shuttle, be placed in space by the RMS from the shuttle cargo bay, and then, with the chase vehicle/TPDM under supervised automated control, rendezvous with and capture the target vehicle. The capture operation would involve use of a sensor on the chase vehicle illuminating targets on the target platform together with chase vehicle navigation and control algorithms to direct chase vehicle orientation and

maneuvering. Manned supervision would be limited to an override mission abort function only, based on screen display information; no provision would be available for performing the mission using teleoperation.

One potential target is the Explorer platform which was launched on June 7, 1992 using a Delta launch vehicle. The Explorer platform is equipped with a GPS and docking targets, placed on the satellite before launch.

The capture demonstration mission is tentatively planned for 1996.

Mission 2 - Cargo Transport Vehicle Capture of the Hubble Telescope

This mission postulates use of the CTV to deliver a payload to the space station using a strong-back cargo container and front-end propulsion assist pod. After delivery, the CTV would jettison the strong-back and propulsion pod into the atmosphere then perform a re-orbit maneuver to become available for satellite retrieval missions. The jettison action would make the TPDM available on the surface of the CTV. For purpose of analysis, the CTV propulsion unit is to have a mass of 30,000 pounds. The target satellite, the HST, weighs about 30,000 to 40,000 pounds. This mission would be performed using supervised automation. The CTV, using its guidance and navigation and radar tracking system, would rendezvous with the HST. Final closure and capture operations would involve use of a sensor system illuminating targets on the HST. This sensor system, together with CTV navigation and control algorithms, will direct CTV RCS jet firings to orient the CTV to perform the capture operation. Manned supervision would be limited to an override mission abort function only, based on on-line screen display information; no provision would be available for performing the mission using teleoperation.

2.2 Nominal Mission Scenario Description

The following describes a nominal mission scenario that identifies the essential step operations for using a TPDM to perform target vehicle capture. This nominal mission discussion will be used in this study effort to aid identification of TPDM requirements, analyze off-nominal latching sequences, and identify issues requiring earth-based laboratory simulations.

It is assumed that the chase vehicle with the TPDM attached is placed into position beyond the range of the TPDM docking sensor's capability to interact with the target vehicle docking aids. If it is placed within range, steps 2.1.1 and 2.1.2 may not apply.

2.2.1 Propulsion vehicle/TPDM deployment

The TPDM is assumed to be rigidly affixed to the propulsion vehicle which provides electrical, mission command, communications and data interface, and mechanical interfaces. TPDM features and executable functions are monitored and checked out via the chase vehicle systems. The composite structure is physically deployed without dependence on the TPDM system.

2.2.2 Rendezvous

This task is purely a chase vehicle task. TPDM health data is repeatedly monitored. The chase vehicle is responsible for placing the composite system within 50 meters of the target spacecraft in an attitude favorable for the TPDM ARAD system. It is assumed that the GPS information in conjunction with the chase vehicle rendezvous and tracking radar will perform this function.

2.2.3 Proximity Maneuvers (up to initial capture position and pre-rigidization)

This task includes all maneuvering required to establish the initial capture position with the target spacecraft. Initial capture position is defined as having all three target vehicle interfaces (trunnions) within their associated latch capture boundaries in a non-escapable configuration.

When the chase vehicle rendezvous and tracking radar system determines that it is within 50 meters of the target spacecraft, a hold point is established, during which the relative movement between the chase vehicle reference and target spacecraft is monitored. If the relative movement is within established criteria and the operator receives display data that the ARAD system has "seen" the target, the ground operator enables the capture command and the chase vehicle (and attached TPDM) moves into capture position using ARAD sensor signals. The initial capture process continues based on chase vehicle maneuvering jet firings via logic authority established by the ARAD system. A preprogrammed approach vector profile which minimizes thrusting in the direction of the target spacecraft is used. Hold points are envisioned during the maneuvering process. If operator abort action is not taken, this mission sequence proceeds until latch actuation sequences occur and the vehicles attain the initial capture position.

The TPDM latch closure motion is automatically actuated by LED sensors located locally to each latch. These indicate when the target vehicle trunnions pass through the plane of the latch sensors.

Present plans call for latch actuation movement to reach initial capture position within three seconds of receipt of the inboard LED sensor signals from any two of the three latch mechanism assemblies. At this point only those two latch arms begin to move; the third latch mechanism arms will move only when its inboard LED sensor provides an interrupt signal. Once two of the latches reach the initial capture position, the chase vehicle propulsion system is shut down, and the two latches continue to move slowly until they reach a fully contained, non-rigid position, which also forces the third fitting fully into capture.

2.2.4 Stabilization (initial capture position/pre-rigidization to rigidization)

Upon establishing that all three latches have reached their pre-rigidization position (on the latch seat), the three latches restart their movement. This movement sequence concludes with application of forces to rigidize the

trunnions against their respective mating fittings. At this time, signals at each latch location confirm that the final position has been attained and the target spacecraft is stabilized and ready for transport.

2.2.5 Rendezvous with On-orbit Support System

The chase vehicle propulsion system is then reactivated by ground operations and propels the mated vehicles to the rendezvous location.

2.2.6 Release of Target Vehicle

The chase vehicle is assumed stable at the transfer location. To execute release of the payload from the chase vehicle, the TPDM latches are activated to the full open position. After a full open position signal is received, the TPDM is deactivated in the full open position.

2.2.7 Chase Vehicle/TPDM Stowage

The TPDM remains deactivated and plays no role in this task.

3 - Requirements

Based on the NASA/MSFC TPDM design information and the documents received for review, we compiled the following requirement information:

- list of requirements identified in the documentation,
- tailoring of previously developed top level requirement information from tumbling satellite retrieval application for TPDM use.
- discussion of requirement information relative to current application.

The most significant difference between the design basis of the previous TPDM implementation and the current NASA/MSFC plan is the use of a sensor to automate the mission tasks of approach and attaining initial capture of the target spacecraft. This requires new requirements for system health diagnostics, nominal mission status diagnostics and establishing the level of desirable interaction between the ground control monitor and the ongoing TPDM mission implementation.

- What information and level of diagnostics are required to provide a basis for mission abort decisions?
- When and how many decision points (mission event times) should be given to the ground control monitor to decide on continuing or aborting the mission?

It is suggested that many of these operational type procedures will evolve from operator response data and 'lessons learned' generated from 'remote' ground simulations. These simulations are assumed to include the fidelity of quasi real-time dynamics (motion and force interaction between the two vehicles).

3.1 Requirement Information from Document Review

Figure 3-1 lists the requirements identified from the documents reviewed. Most of the entries were compiled from the Reference 3 document *Preliminary Design Review for the Three Point Docking Mechanism Latch Assembly*. The list represents detailed requirement information and can be used as a checklist to review the current NASA/MSFC design basis and develop test performance parameters. When detail requirement statements were not available, general entries were included due to their importance as a basis for continuing TPDM development. In other cases, the OMV PDR presentation documentation contained very detailed technical design data which should be consulted directly. Refinements in the latch assembly/sensors requirements were made subsequent to the OMV PDR and are reflected in Section E of Fig. 3-1.

Stand alone equipment specifications *Equipment Specification Three Point Docking Mechanism* (Reference 6) and *Equipment Specification Mechanical Control Electronics (MSE)* (Reference 15) are available. These documents are in a very usable form and have not been recompiled since the OMV PDR.

Figure 3-1, Sheet 1 of 6

Requirements Identified From Documentation

Summary of Categories

<u>Assigned number</u>	<u>Category and Requirement Description</u>
A	TPDM System
B	Latch Mechanism Assembly
C	Motor
D	Latch Assembly/EVA Drive
E	Latch Assembly/Sensors
F	Thermal
G	Materials and Process Requirements
H	Latch Assembly/Capture Arms

A **TPDM System**

- A1 The TPDM provides a means by which the propulsion vehicle can capture and dock with a payload on-orbit.
- A2 The TPDM provides the structural interface between the propulsion vehicle and payload with a standard flight support system (FSS) docking interface.
- A3 In use, the TPDM latch assemblies mounted to the front face of the propulsion vehicle. The latches shall be equi-spaced with each latch being capable of being positioned to within a given angular tolerance to ensure alignment with the corresponding berthing pin (trunnion) on the payload.
- A4 The TPDM shall be capable of accommodating a means of electrically interfacing with a payload, as required.
- A5 The mechanisms are electrically redundant and are controlled by the mechanism control electronics (MCE) located in the propulsion vehicle.

B **Latch Mechanism Assembly**

- B1 The latch structure and mechanism shall be capable of withstanding the applied loads including momentary loads applied during the containment operation with a factor of 1.1 on yield stress and of 1.4 on ultimate stress.
- B2 The entire in-board surface of the latch shall be continuous in order to accommodate any contact with the payload while docking

Figure 3-1, Sheet 2 of 6

- B3 The latch width shall not exceed 3" maximum in the region of 8.95" to 16.41" above the mounting surface of the latch with the structure ring. The outboard surface of the latch shall be continuous over this region in order to accommodate any contact with the payload while docking.
- B4 EVA access shall be via a fiberglass cone and shall be perpendicular to the in-board surface and parallel to the vehicle Y-Z plane.
- B5 The latch structure shall provide protection to the capture arms and locking pawls in their retracted position.
- B6 The three latches shall be capable of being driven simultaneously or independently with power supplied from the MCE.
- B7 The latches are required to operate on the ground and on-orbit, but not during launch and landings.
- B8 Each latch is required to remain in a fully closed position without continuous application of power.
- B9 Each latch is required to remain at the containment position when driven by the MCE latch servo while on the ground and on-orbit.
- B10 The TPDM latch is required to capture a payload trunnion of 1.5020 inches in diameter within the area specified on the source control drawing.
- B11 The TPDM latch backlash as measured at the latch arms shall not exceed 1.0 degree.
- B12 Each latch shall be capable of being operated via an EVA back-up drive with given input torques:
 - from the fully open to the closed and preloaded condition
 - from the closed and preloaded condition to the fully open condition.
- B13 Each latch shall exert a minimum preload of 335 pounds on the captured trunnion in the locked and preloaded position.
- B14 The TPDM latch drive system shall have a torque margin of 100% minimum for the worst case conditions when operating under non-impact load conditions and preload applications.
- B15 The TPDM latch drive motors and commutation sensors, position sensors and the electro-optical proximity sensors shall be redundant.
- B16 Each latch shall incorporate redundant two-beam electro-optical proximity sensors to sense a payload trunnion within the latch capture envelope

Figure 3-1, Sheet 3 of 6

- B17 Each latch shall be driven by a 3-phase reversible, DC brushless, motor with given performance characteristics and motor parameters.
- B18 Each latch shall be capable of mating with a trunnion that is 165 degrees C hotter or 240 degrees C colder than the TPDM latch mating surface.
- B19 The TPDM latch shall provide space for location of heaters and thermostats.
- B20 Each latch shall be designed with an adequate strength, stability and fatigue resistance to preclude failure during all mission phases for a minimum life of 10 years of orbital operations and 20 STS launches and landings with maintenance.
- B21 The TPDM latch shall be capable of 500 latch-release cycles without maintenance.
- B22 (assumed requirement) Each latch shall be capable of removing the preload from the trunnion prior to letting go of the trunnion to ensure a zero-energy release of the payload from the propulsion vehicle.
- B23 Combined in-plane and out-of-plane impact load of \pm TBD pounds and \pm TBD pounds.
- B24 Capture arm containment load TBD in-lb.
- B25* Maximum width of 3" above a point TBD from the latch mounting surface
- B26* In-board surface to be flat and continuous.
- B28 Redundant electro-optical sensors.
- B29 Enable unobstructed trunnion entry when arms fully open
- B30 Successfully pull in trunnion from anywhere within capture envelope
- B31 Pull trunnions through locking pawls
- B32 Provide over travel capability to ensure preload engagement without arms being part of load path, i.e. no contact with trunnion from hardpoint to fully closed position.

* These requirements may be driven by future payloads.

Figure 3-1, Sheet 4 of 6

C Motor

C1 Brushless D.C., samarium cobalt magnets, Hall effect (latching) commutation, 28 V operation, 4 quadrant drive, operation temperatures of -25 to +71 degrees C

D Latch Assembly/EVA Drive

D1 EVA backup procedures as per MSFC - STD -512 - assume ratchet type socket wrench

D2 Provide EVA backup for electrical failures not mechanical

D3 Operate latch via EVA backup from fully open to closed and pre-loaded condition, and from closed and pre-loaded condition to fully open condition

D4 Minimum torque to operate ratchet - 24 in. oz.

D5 Maximum tool torque - 25 ft. lb.

D6 Minimize number of turns

D7 Assume full rotation (360 degrees) of tool available

D8 Assume trunnion within capture envelope.

D9 EVA access and drive nut requirements as specified on TBD.

E Latch Assembly/Sensors

E1 The Three Point Latch Trunnion Sensing (TPLTS) equipment requires an electro-optical approach, two beams per redundant side (assumed parallel), one detector and one emitter per beam, redundancy provided for by four beams on the latch, and protection from trunnion impact.

E2 Sense that the trunnion is in the initial capture position.

E3 500 latch/release cycles.

E4 Electro-optical proximity sensor redundancy **

E5 Operate while exposed to direct sunlight per (NASA JPL SP43-38 VOL. 1 (Solar Array Design Handbook) **

E6 Operating environment (TBD)**

Figure 3-1, Sheet 5 of 6

- E7 Capability of trunnion to break both beams at one discrete position i.e. 'make before break' **
- E8 Bottom beam breaks when the trunnion enters and is completely inside the capture envelope **
- E9 (derived) No critical emitting wavelengths - re: potential interference, both radiated and susceptible **
- E10 (derived) No critical emitting modulation frequencies - re: potential interference as above **
- E11 (derived) Operating life of 1000 hours **
- E12 (derived) No extraneous light sources **

** revised after OMV PDR

F Thermal

- F1 component temperature limits: non-operating (-65 to +80 degrees C); qualification (-34 to +71 degrees C); acceptance (-24 to +61 degrees C)

G Materials and Process Requirements

- G1 Metallic: corrosion (MSFC-Specification-250); stress corrosion cracking (MSFC-Specification-522)
- G2 Non-metallics: thermal vacuum stability (SP-R-0022); flammability (NHB 8060.1)

Figure 3-1, Sheet 6 of 6

- H** **Latch Assembly/Capture Arms**
- H1 Provide translational movement to the trunnion spring preload assembly to exert a minimum preload of 335 pounds.
- H2 Maintain minimum preload throughout the thermal extremes experienced by latch and trunnion
- H3 Maintain latch capture arm in fully closed position with no power applied to motor.
- H4 Synchronize capture arm rotation to spring assembly travel to ensure no interference to trunnion entering seat
- H5 Maintain minimum torque margin of 100% over entire drive rotational range
- H6 Maintain minimum resistive torque to operate EVA tool

3.2

Requirements Derived From Tumbling Satellite Retrieval Study (TSRS)

Figure 3-2 presents the requirement information from the tumbling satellite retrieval report tailored for TPDM use. This information is of a preliminary nature for a tumbling satellite mechanism nature and as such may not be specifically relevant for the design basis definition of the MSFC/TPDM. It reflects higher level information from which technical issues that need resolution can be identified and detailed performance requirements can be derived. Based on directed TPDM program objectives (i.e., what class of satellite is to be included and what level of off-nominal condition or configuration is to be considered within the capture envelope, i.e. spin, nutation) and simulation test data, some of the requirement statements may be challenged and modified.

We have also included the mission requirements identified at the February 12, 1992 technical interchange meeting in the Figure 3-2 entries.

The requirements have been categorized as follows:

1. Mission
2. Safety
3. Operational
4. Functional (as pertinent to the TPDM subsystems)
 - Structure
 - Latch assembly
 - Docking guidance sensor
 - Electrical support subsystem
 - Data management subsystem
 - Thermal
5. Interfaces
 - Target vehicle
 - Remote Operations
 - Ground Control Station
 - Shuttle
 - Space Station
 - Ground Support Equipment
 - Chase vehicle

These categories were selected to support the functional allocation planning process between the chase vehicle and the TPDM hardware. We have provided additional discussion in some of the entries (in italics) to identify issues that require resolution in the design process. These issues relate to the areas of:

- definition of target satellite envelope characteristics
- available and consistent target aid location
- standoff distance of TPDM and target vehicle to avoid damage potential to chase vehicle
- capability definition of TPDM to capture non-stationary satellites

- design load capability of TPDM/chase vehicle pertinent to jettison loads and moments
- need for conducting analysis to minimize loads imparted to the target satellite
- should any EVA intervention be designed into the TPDM
- a very important focus on TPDM health status monitoring and mission parameter analysis for automated abort decision making
- the need for tailored control station consoles.

Figure 3-2, Sheet 1 of 6

Requirements Derived From TSR Program

<u>Assigned Number</u>	<u>Top Level TPDM Requirements by Category</u>
1.	<u>Mission</u>
1.1	The TPDM is to support capture of a target satellite having an approximate mass of 8,000 pounds when attached to a propulsion unit having a mass of 1,000 to 3,000 pounds. This mission calls for the TPDM to be attached to the propulsion vehicle while being carried into LEO in the shuttle.
1.2	The TPDM is to support capture of a 40,000 pound payload when attached to a 30,000 pound propulsion unit. This mission calls for the TPDM to be capable of long term, multi-mission on-orbit operability, attached to the propulsion vehicle in space.
1.3	<p>The TPDM shall be capable of retrieving target vehicles having the required capture interfaces: latch pins enabling berthing with the STS Flight Support System and a specific alignment target, and a specified movement envelope specification.</p> <ul style="list-style-type: none">• <i>The TPDM has to be designed based on a class of target vehicles, but still with some off-nominal center of mass/movement flexibility to account for partially deployed solar panels, appendages, etc.</i>• <i>Different satellites may have limited space available for the target sensor, and probably not the same location; perhaps a future integrated trunnion/target is possible with the sensor embodied in each latch assembly.</i>
1.4	<p>The TPDM shall be capable of disposal (controlled transfer or jettison) or retrieval of target vehicle that have been augmented with the required capture interfaces.</p> <ul style="list-style-type: none">• <i>The operational issues of controlled transfer between two vehicles in close proximity must be addressed; does the TPDM release to the initial capture position configuration prior to the transfer operation?</i>
1.5	<p>The TPDM shall recover target satellites having irregular surfaces.</p> <ul style="list-style-type: none">• <i>This also addresses appendages and points out the desirability requirement for flexibility of placement of the docking sensor.</i>
1.6	<p>The TPDM shall be flexible enough to capture target vehicles without prior knowledge of the condition of the satellites, provided they are sufficiently stable and structurally intact.</p> <ul style="list-style-type: none">• <i>It is desirable to provide some flexibility on configuration (partial</i>

Figure 3-2, Sheet 2 of 6

deployment of solar panels; hanging appendage resulting in off center loads).

- 1.7 The TPDM must resist the applied loads due to stabilizing the target vehicle.
- *The issue surrounding this item pertains to just how much capability do we want to build into the composite TPDM/chase vehicle in terms of "capturing" non-stationary target vehicles. They may be spinning, and must be stopped; they may be coning, giving rise to additional side loads.*
- 1.8 The TPDM shall be capable of controlled jettison of the target vehicle.
- *This brings up the issue of thruster loads during the jettison function which may have slight moments (off the centerline thrust axis).*
- 1.9 The capability of the TPDM/chase vehicle shall accommodate a limited coning due to geometrical and principle axis offset.
- *As presently planned, the TPDM does not have this functional capability; it must be allocated to a support structure, i.e. a spin table that provides alignment with the target vehicle capture plane.*
- 1.10 The target vehicle interfaces shall not be recessed and shall be located in an accessible area.

Figure 3-2, Sheet 3 of 6

2.0 Safety

2.1 The TPDM mission shall be accomplished with minimum risk of damage to the TPDM by establishing adequate operations procedures, sensory input, automated emergency response, interface design, system robustness to mitigate the potential for electrostatic discharge and inertia effects, contact and dynamic loads, and fault detection.

• *Leads to further definition of risk issue.*

2.2 The TPDM will be able to capture target vehicles possessing hazardous conditions without overly exposing the chase vehicle to risk or damage. Minimum risk can be facilitated by jettison capability, loads analysis, contamination analysis, operations procedures, and a standoff distance of TBD.

• *Question of "breakaway" design for TPDM in case loads are exceeded.*

2.3 The nominal TPDM mission shall be accomplished with minimum risk of damage to the target vehicle interface.

• *This leads to an analysis of the tolerable contact and dynamics of the target vehicle.*

• *Question of requiring the TPDM to include provisions for special damping to avoid impact contact loads on the target vehicle - how does the impact load capability of the target vehicle drive the TPDM design.*

3.0 Operations

3.1 The TPDM shall accommodate timely and efficient on-orbit EVA and remote telerobotic subsystems release and latch.

• *Although no provision in the design for EVA intervention is available, perhaps this should be included; human factors and operations procedures and requirements from NSTS and SSF must be addressed if this capability is included.*

3.2 The TPDM mission will be accomplished within the chase vehicle's propellant limitations.

Figure 3-2, Sheet 4 of 6

4.0 **Functional**

4.1 The TPDM shall accommodate torques associated with capture, stabilization, rigidization, and transport.

4.2 The TPDM will have a standoff distance of a minimum of TBD inches from the chase vehicle to prevent inadvertent contact from the target vehicle. This distance will consider a safety factor associated with potential hazards due to the dynamics of capture.

• This may not be considered a real issue owing to the controlled cases considered to be within the design basis. But, if inadvertent contact results from extreme rebound velocities, contact between target vehicle and chase vehicle is feasible; but do we consider it a credible event?

4.3 The TPDM will provide a structural, data, power, and thermal control interface with the chase vehicle that does not require additional chase vehicle augmentation.

• The options and functional allocations of the elements must be addressed. They may, in some cases be chase vehicle application dependent.

4.4 The propulsion vehicle shall match the target vehicle spin rate and phase angle with sufficient accuracy to safely accomplish capture with the TPDM.

• The functional allocation of the capability to match spin rates and angular effects must be addressed. Either the function has to be provided by the chase vehicle, the TPDM assembly (adding hardware/software) or by constraining the definition of an acceptable mission.

4.5 The TPDM shall be able to rigidize contact between the target vehicle and chase vehicle sufficiently to allow chase vehicle attitude control and propulsion systems transport of the combined structure.

4.6 The TPDM shall be capable of realigning with the geometric center of the target vehicle trunnions with respect to the chase vehicle major axis after stabilization is performed.

• Target vehicle alignment is important for umbilical interface control. For stationary vehicles, the centering action is feasible concurrent with TPDM docking. If motion matching is first required before attaining the initial capture position, we may want to hold the centering requirement until we are ensured of a stable configuration to work with. This requires further study.

4.7 The contact with the target vehicle shall not impose damage to the TPDM.

4.8 The TPDM/chase vehicle shall be capable of emergency release.

Figure 3-2, Sheet 5 of 6

4.9 Initial contact with the target satellite will facilitate allowing the latching alignment to be adjusted prior to rigidizing the interface.

• *Consistent with NASA/MSFC approach.*

4.10 The TPDM missions will be accomplished within the automated control limits, and chase vehicle and TPDM dead bands.

4.11 The TPDM shall be able to perform all phases of the missions within subsystem thermal limits.

5. **Interfaces**

5.1 The chase vehicle will supply all mission support functions, power and data requirements.

5.2 The TPDM shall be chase vehicle compatible with no impact on the chase vehicle reference configuration.

5.3 The dynamic and inertial loads induced by the TPDM operation shall not impart loads upon the chase vehicle or target vehicle beyond their established limits.

5.4 The TPDM ground control systems requirements will be integrated into the chase vehicle ground station.

5.5 Telemetry Support - The control station will be capable of processing commands, status and housekeeping telemetry data which will be transmitted and received through the chase vehicle C&DH. All TPDM commands will be archived.

5.6 Fault detection & diagnostics support - The control station will support fault detection and diagnostics during TPDM operations. The operator will be alerted of faults, failures, or out-of-limit conditions. Raw data and parameters will be accessible.

5.7 The TPDM stowed diameter shall not exceed the shuttle cargo bay envelope diameter.

5.8 Stowage of the TPDM in the shuttle cargo bay shall require a minimum distance along the centerline of the cargo bay.

• *Noted for purpose of planning in case a support arm & spin table is required to execute off nominal cases.*

Figure 3-2, Sheet 6 of 6

- 5.9 TPDM operations shall be accomplished within the space shuttle workload limitations and per integration and launch procedures and constraints as defined in the NSTS Payload Integration Plan.
- *Operational requirement to be determined.*
- 5.10 The TPDM shall accommodate horizontal or vertical STS payload integration.
- 5.11 The TPDM will require a minimum of stowage and housekeeping resources for on-orbit or vertical SSF stowage.

4 - TPDM Latching Sequence Analysis

4.1 TPDM Assembly Description

The TPDM consists of 3 latches which attach to a structural member on the delivery vehicle and data and electrical interfaces. The latches are located on a 36" radius and are equally spaced 120 degrees apart. The TPDM is fastened to the capture vehicle by bolts. Figure 4-1 shows the TPDM attached to a chase vehicle. Please note the coordinate system shown on the figure is used in this study effort; it is consistent with that from the OMV Program.

4.1.1 Latch Mechanism

As shown in Fig. 4-2, each latch mechanism consists of two 5/8" thick aluminum alloy machined plates that are fastened together with bolts and spacers. The spacers provide a gap of 1-3/4" between each plate. Two aluminum arms (material same as plate material) are mounted between the two plates. The arms are driven by a reversible DC motor. The motor is activated by redundant two-beam electro-optical proximity sensors and the overall TPDM latch actuation logic. Two pairs of light beam sensors contained in each latch machine plate illuminate respective photo-detectors positioned directly opposite across the width of the capture envelope (an alternate geometry would have all sensors on the inboard side).

The LED sensors provide a two step capture actuation sequence. Latch arm electrical arming will be initiated according to an overall control algorithm based on two trunnions passing their respective outer LED sensors. This overall control logic electrically arms all motors and starts selected latch arm movement based on trunnion interrupt signals. Initial latch arm movement occurs when one interrupt signal is received from each of two latch plate LED sets. The signals are generated when the beams are blocked from their respective receivers by the passing trunnions. Once the latch arms are activated, they first capture (envelop) and then may guide (through contact) the trunnion firmly towards the latch seat. The point at which the latch arm may contact the trunnion is dependent on the relative speed of the vehicles and the path of the trunnion within the latch envelope. The movement envelope of a trunnion within a latch arm, assuming a nominal travel path is shown on Fig. 4-3. The travel of each arm from full open position to initial capture position takes approximately about 3 seconds; the initial capture position is defined as the dual latch arm position which just envelopes the trunnion diameter, preventing it from escaping. Fig. 4-4 shows the position of the arms against the trunnion in a position that just prevents escape. Once the two initiating arms reached their initial capture position, movement towards the pre-rigidization position (trunnion located in the seat of the latch) proceeds slowly (about 60 seconds). Each trunnion is then firmly seated by the locking pawl mechanical action engagement and the arm motors are deactivated based on resolver sensor data.

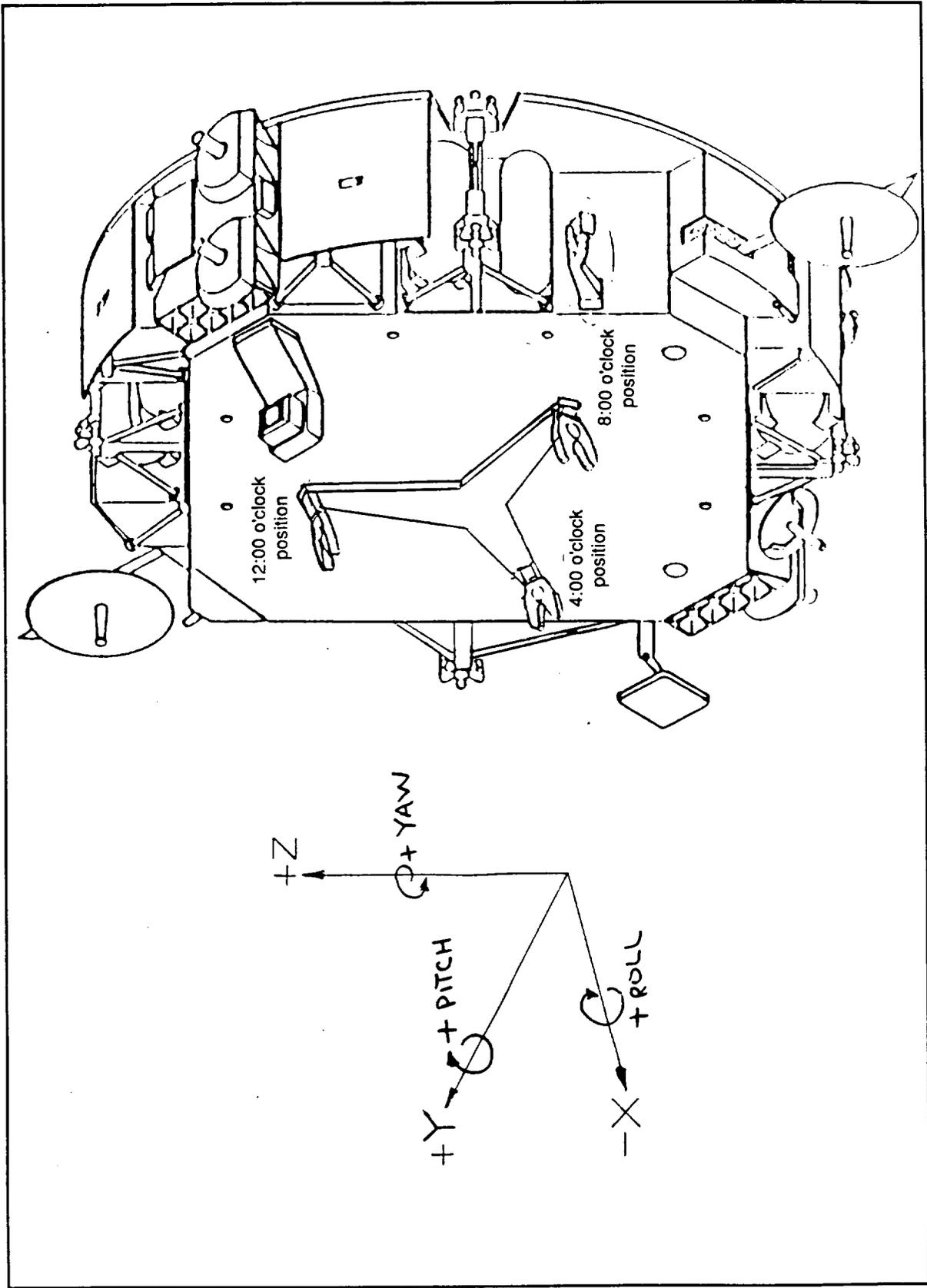


Fig. 4-1 Three point docking mechanism shown attached to an OMV

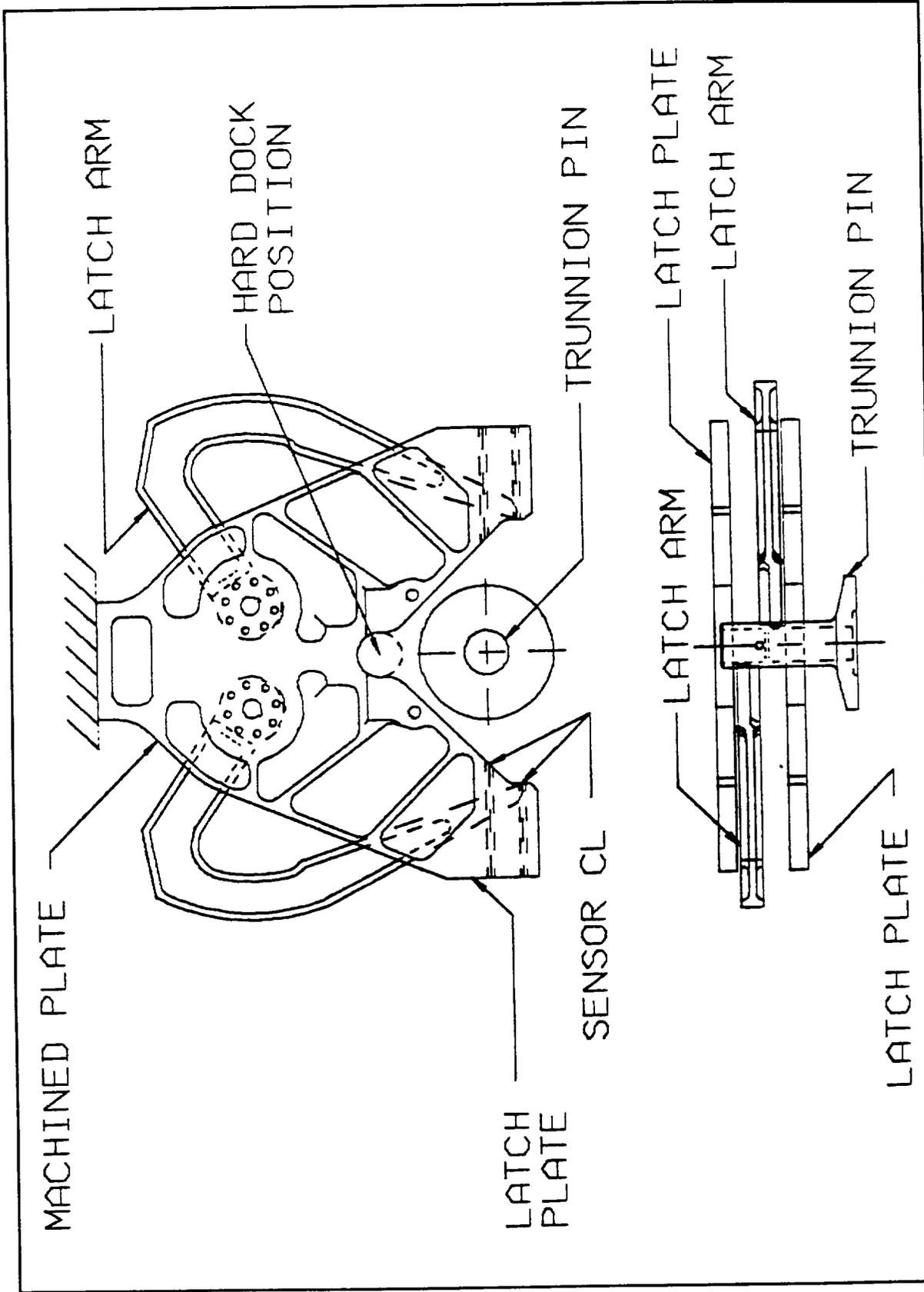
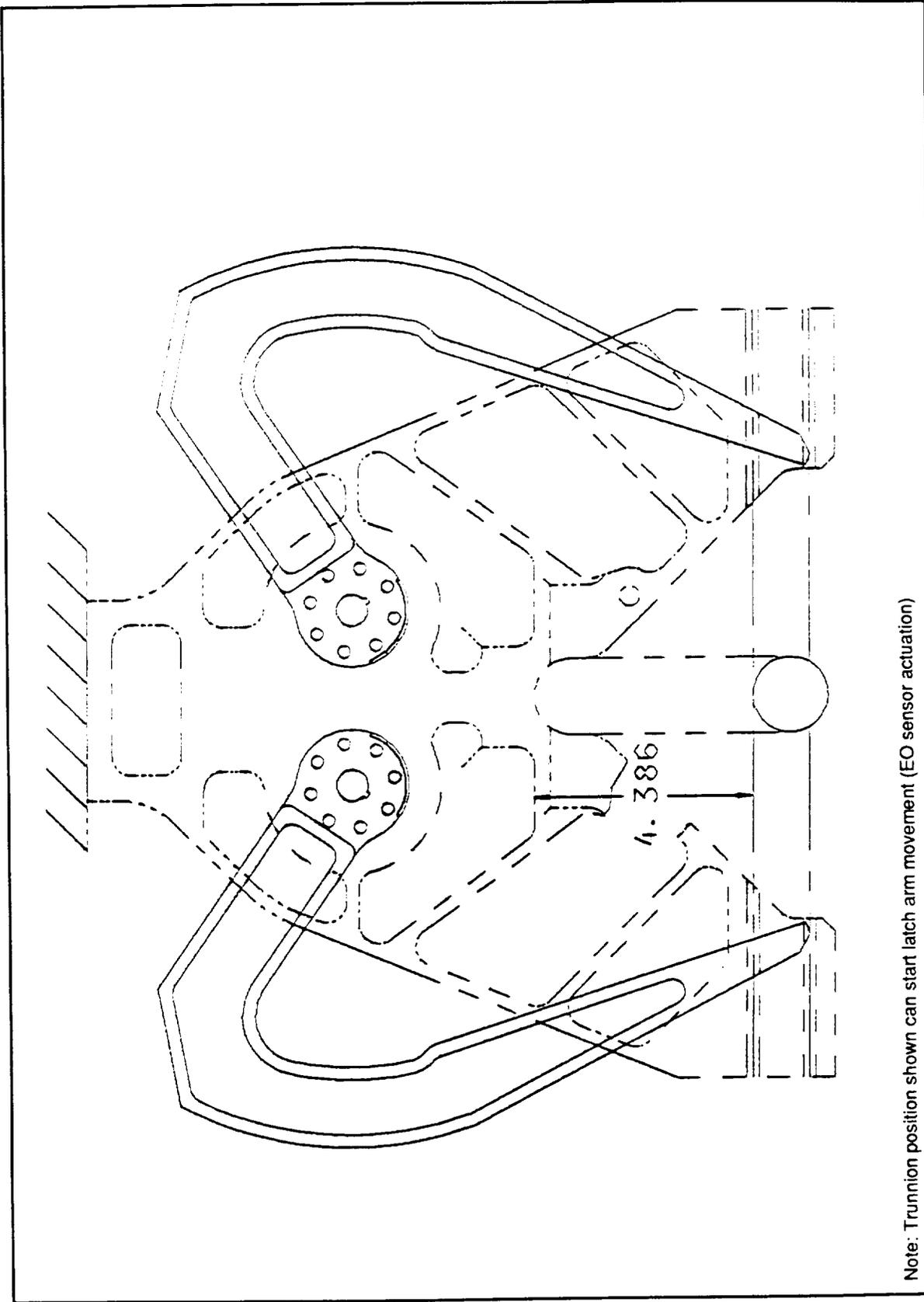


Fig. 4-2 TPDM Latch Assembly - trunnion in capture envelope



Note: Trunnion position shown can start latch arm movement (EO sensor actuation)

Fig. 4-3 Nominal trunnion movement envelope within a latch assembly

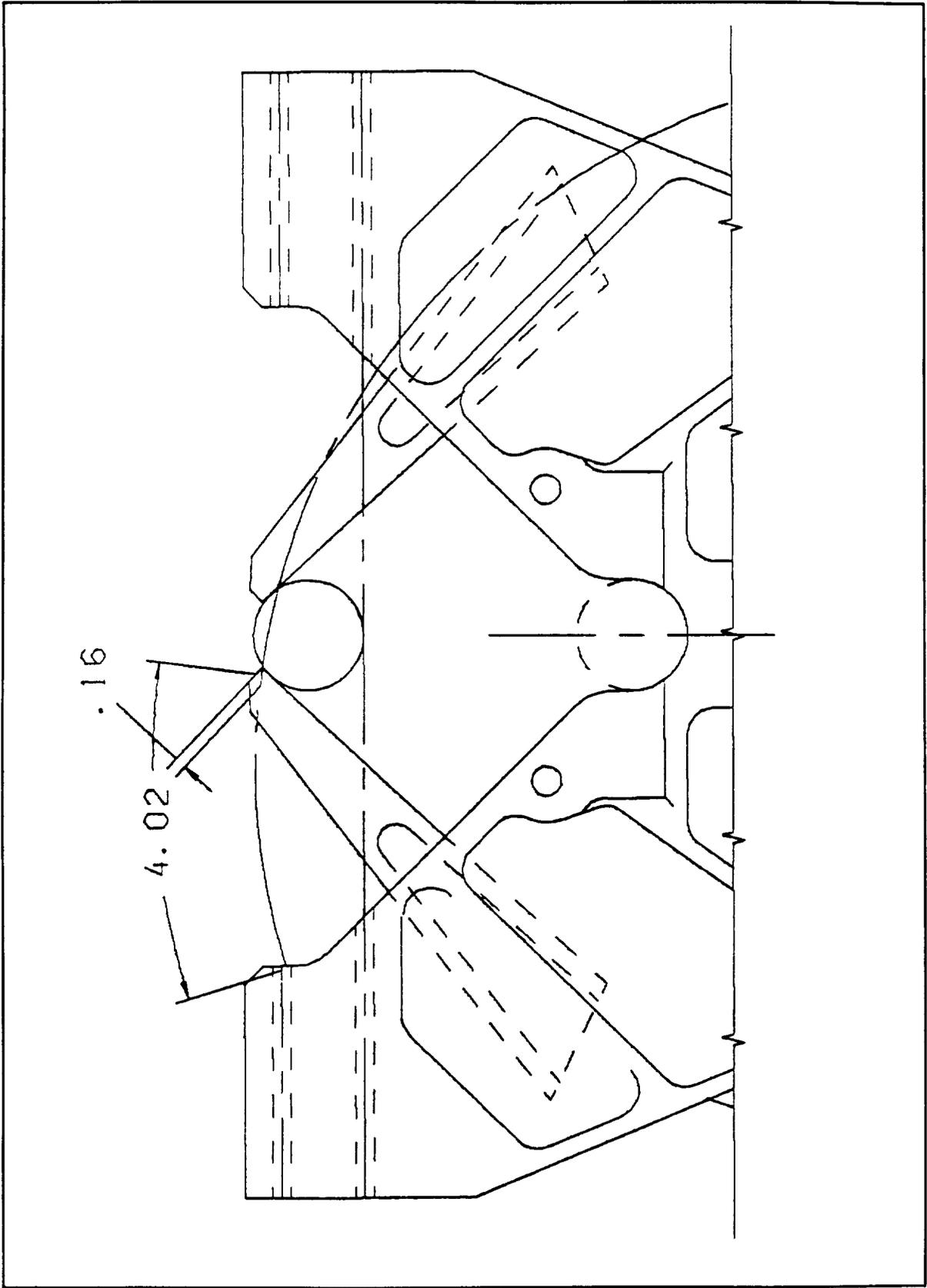


Fig. 4-4 Nominal latch arm/trunnion position at first contact

Presently, the logic for TPDM latch movement requires that:

- 1 - at least two trunnions interrupt their respective inner electro-optical beams; this actuates only the motors for those latches. These latches then move rapidly (in about 3 seconds) to the initial capture position defined by the arm tips being closer than the diameter of the trunnion. The activated latches continue moving slowly to the pre-rigidization position (taking about 60 seconds).
- 2 - the remaining latch only starts moving when its inner beam is broken by the remaining trunnion path; the arms reach the initial capture position rapidly and then continue moving slowly to the pre-rigidization position.
- 3 - all arms move to the pre-rigidization position independently and wait until all three arrive at that position.
- 4 - all latch mechanisms execute their linkage movements to attain hard dock (rigidization) simultaneously.

4.1.2 Automated Rendezvous and Docking System (ARAD)

(This is a typical carrier vehicle system - shown here for information only)

The purpose of this sensor is to guide the chase vehicle to a controlled docked condition with the target vehicle. It assumes navigational control of the chase vehicle when it is approximately 50 meters from the target vehicle; prior to that another radar guidance and tracking system would be used to establish general vicinity proximity and desired attitude relationship with the target vehicle.

The sensor presently being investigated by NASA/MSFC for use in this application is composed of two parts. The first part is the sensor which consists of a video camera ringed with two wavelengths of laser diode. The second part is a standard Remote Manipulator System (RMS) target used on the orbiter that has three circular pieces of reflective tape covered by optical filters which correspond to one of the wavelengths of laser diode. The sensor is on the chase vehicle and the target is on the target vehicle. The ARAD system works by pulsing one wavelength laser diodes and taking a picture. Then the second wavelength laser diodes are pulsed and a second picture is taken. One picture is subtracted from the other and the resultant picture is thresholded. All adjacent pixels above threshold are blobbed together (X and Y centroids calculated). All blob centroids are checked to recognize the target out of noise. Then the three target spot centroids are used to evaluate the roll, yaw, pitch, range, azimuth, and elevation. From that a guidance routine can guide the chase vehicle with the correct orientation.¹²

The location of the sensor on the chase vehicle TPDM has not been finalized. Its location may vary due to the availability of space for the sensor target on the target vehicles. For the purposes of this study, a location was chosen that places the target 30" beyond the plane of the trunnion fitting centerline at a radius beyond the latches. The sensor reference plane is assumed to be located in the Y-Z plane at a distance 30"

outboard from the trunnion fitting centerline when the two vehicles are in a docked configuration. Please refer to Section 4.2 below.

4.1.3 Structure & Vehicle Mounting Surface

(This is a typical carrier vehicle system - shown here for information only)

The structure is a beam casting with a bolt ring used to affix the TPDM onto the chase vehicle surface.

4.1.4 Target Satellite Interfaces

Currently a single TPDM latch design is planned for use to interface with two types of target vehicles. Each target vehicle latch mating configuration is slightly different. The two configurations are follows:

Explorer

The Explorer satellite is fitted with three trunnion pins, spaced 120 degrees on a radius consistent with the TPDM latch assembly location and an autodocking target located in the plane of the hard dock position. Please refer to Section 4.2 for a further discussion of the autodocking target.

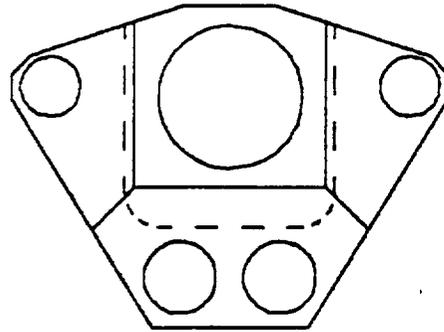
Each trunnion is fabricated from an aluminum alloy plate. The capture portion of the trunnion is a 1-1/2" diameter bar approximately 4" long. The bar has an integrally machined five-sided base, wide enough to accommodate four installation bolts. As shown in Fig. 4-5, the overall length of the trunnion is 4.618". The nominal mating position of the latch and trunnion is 1.3" from the end of the trunnion. In this location, the outboard latch plate extends 0.22" beyond the trunnion end and the centerline of the two-beam electro-optical proximity sensors is 0.11" inboard of the trunnion end (alternately locating all sensors on the inboard side would eliminate this problem).

Fig. 4-6 shows the nominal clearance between the inboard TPDM latch plate and fitting fillet radius to be 1.1 inches. Since the trunnions are mounted on the side of the satellite, no clearance issue exists in the direction of motion beyond the trunnion. In the current design, the resolvers are mounted inboard. Users must determine if this resolver location creates a clearance problem for the specific payload.

Hubble Space Telescope (HST)

The HST includes a trunnion towel bar design. Each of the three towel bars are fabricated from aluminum alloy plate. They are, in a similar fashion to the trunnions, spaced 120 degrees on a radius consistent with the TPDM latch assembly locations. The machined part is 3" wide, 12-1/4" long and 7 1/2" deep. The capture portion of the towel bar has a circular cross section 1.5" in diameter and 6.75" long. The centerline of the bar is 6.34" from the mounting base. The nominal mating position is in the center of the 1.5" diameter bar as shown in Fig. 4-7. This location provides a nominal clearance of 1.86" on each side of the towel bar as shown in Fig. 4-8.

Figure 4-9 shows the latch in the docked position and with the arms in a



PLAN VIEW

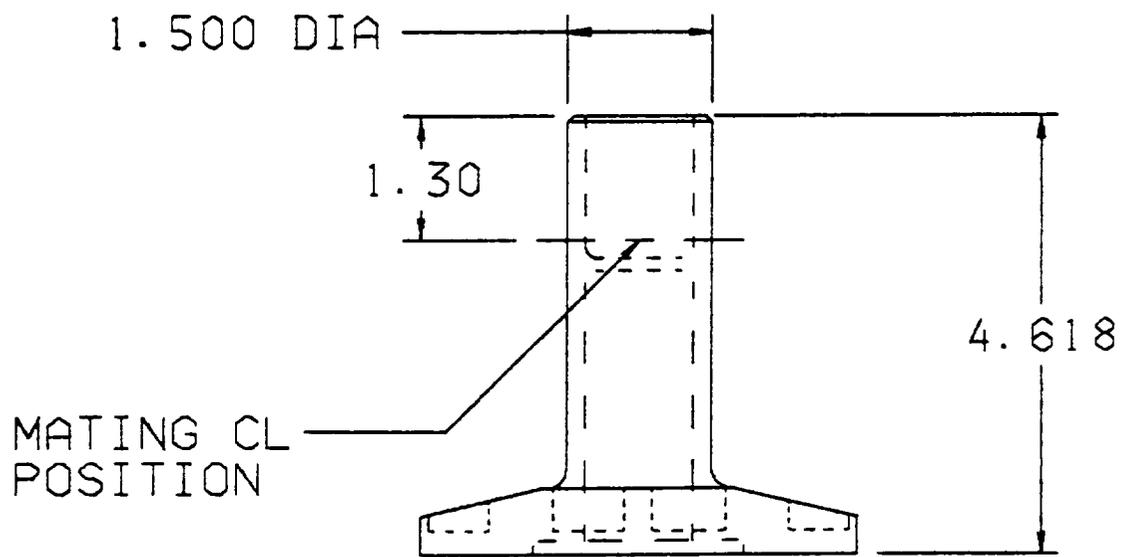


Fig. 4-5 Trunnion pin dimensional description

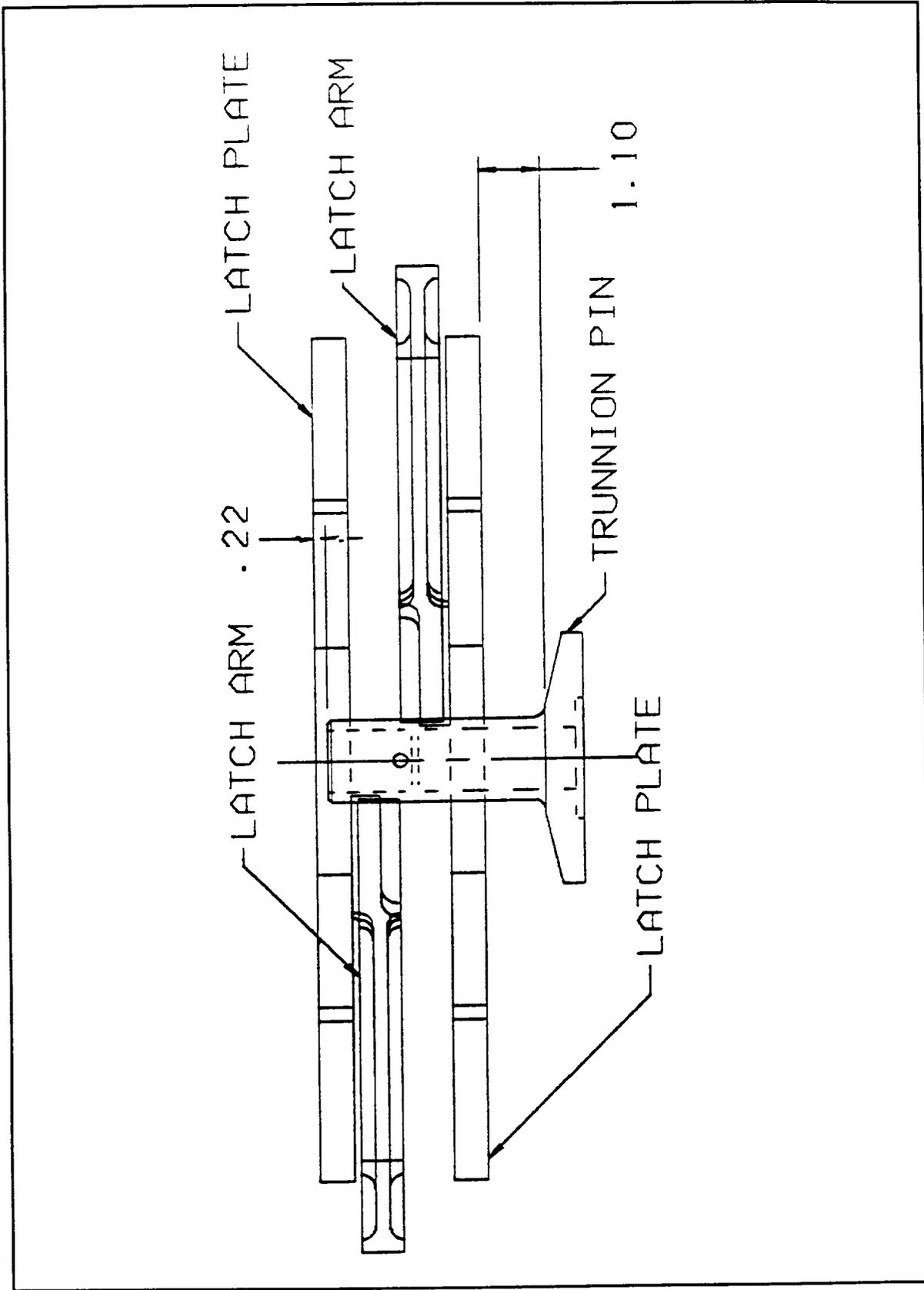


Fig. 4-6 Nominal position of trunnion within TPDM latch (docked)

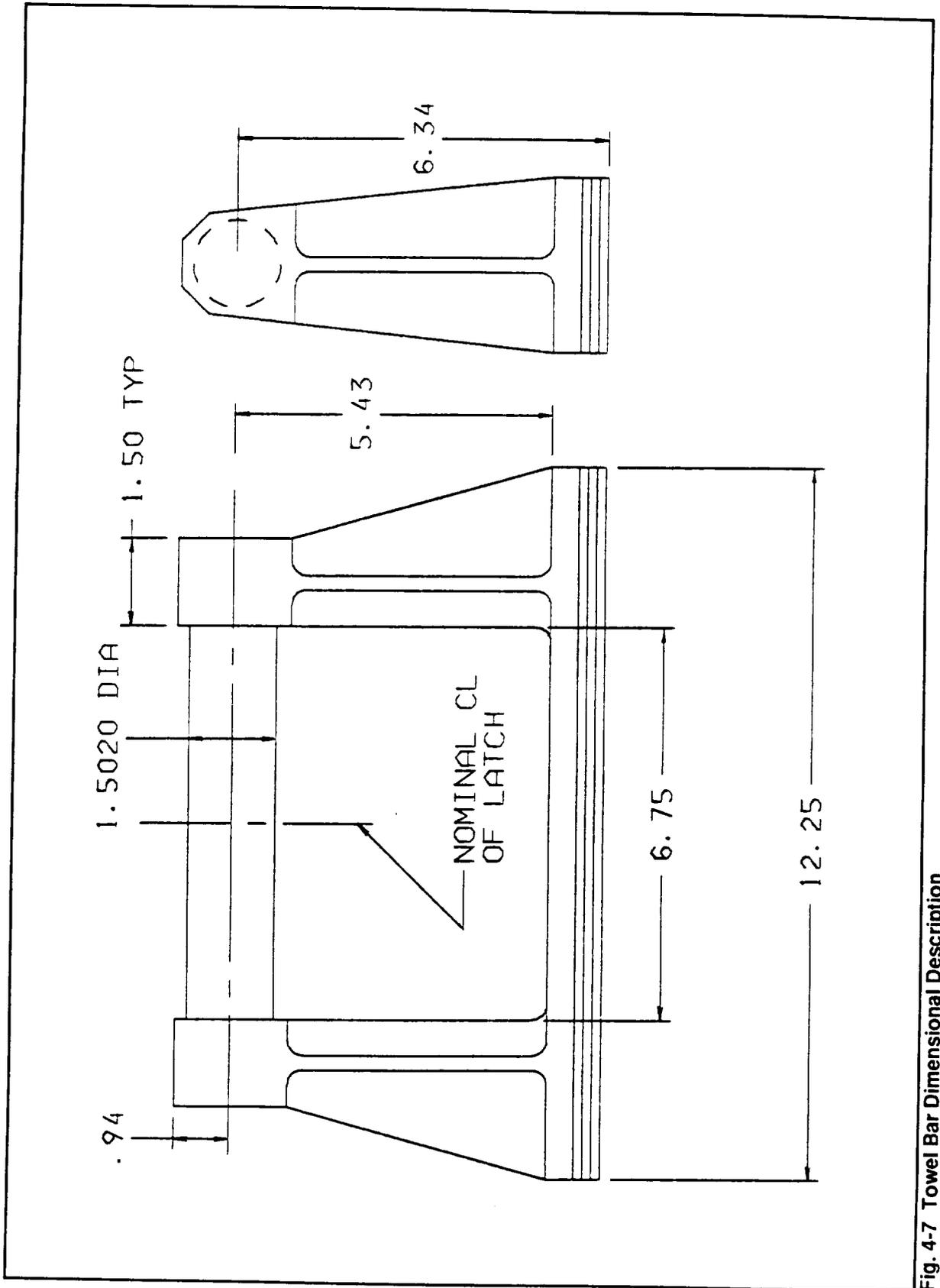


Fig. 4-7 Towel Bar Dimensional Description

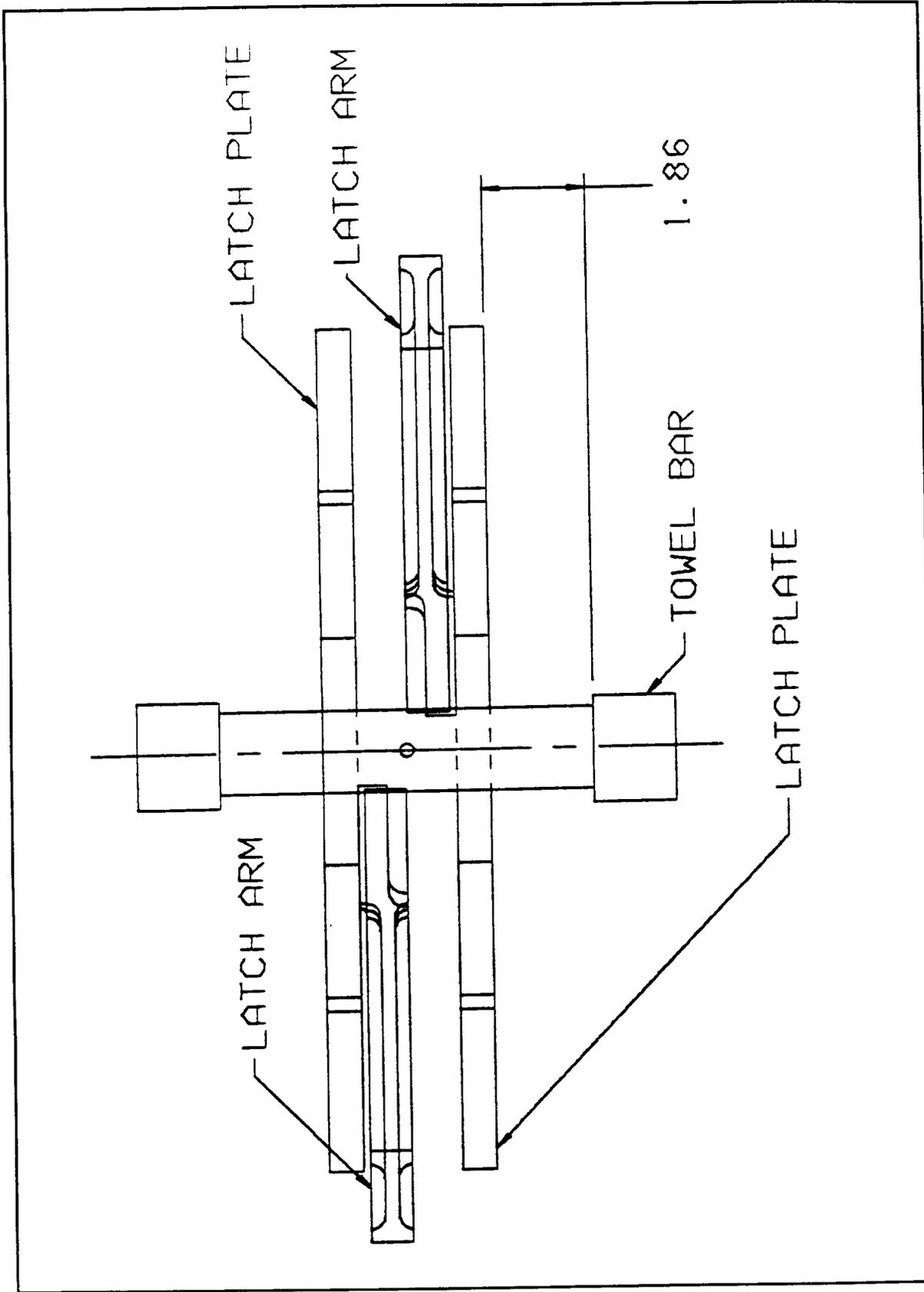


Fig. 4-8 Nominal position of towel bar within TPDM latch (docked)

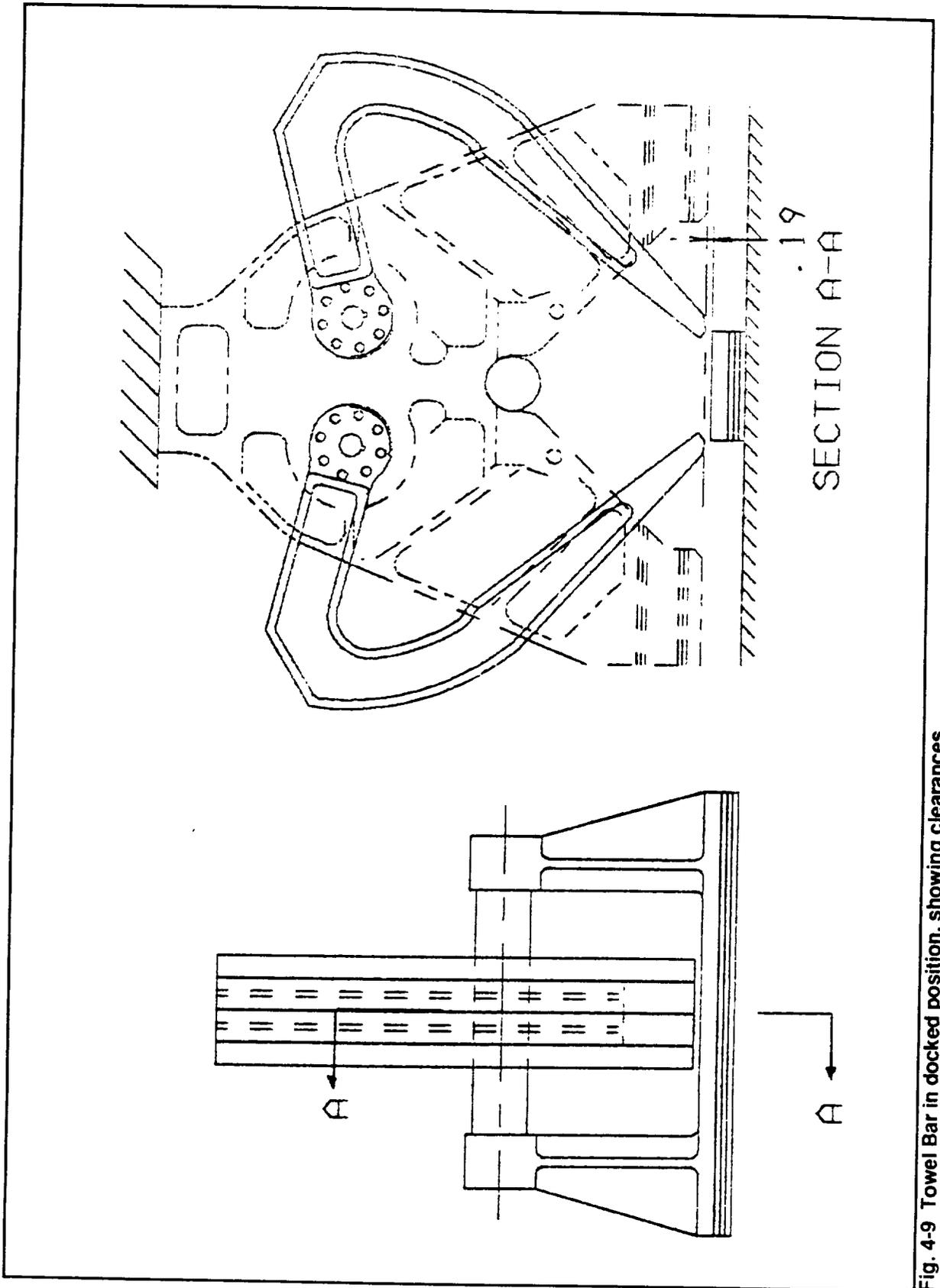


Fig. 4-9 Towel Bar in docked position, showing clearances

position that reflects the minimum clearance between it and the towel bar base. This distance is 0.19"; the latch arm should have passed this position prior to reaching the seated configuration.

Autodocking was not planned for the HST, therefore, there is no suitable autodocking sensor target on the HST.

4.2 Auto Docking Sensor Tolerance Study

The final docking operation is performed using the ARAD system controlling the movement of the chase vehicle to dock with the target vehicle. It is assumed that the target vehicle is relatively stationary. The ARAD sensor was located 37.3" from the center of the three latches. The sensor target was located on the target vehicle in the plane of the hard dock position (using the centerline of the target vehicle trunnion/towel bar as a reference) as shown on Fig. 4-10. In the docked configuration, the ARAD sensor is separated by 30" from the target (see Fig. 4-10).

In this study we analyzed the mating configuration that would result from application of alignment errors between the ARAD system and target vehicle alignment aid (sensor target). In the nominal case where no alignment errors are considered, the two vehicles would approach each other along the X-axis vector parallel to the Y-Z plane. The application of alignment errors places the target vehicle trunnion fittings (mating latch interfaces) at an angle and slightly skew to the nominal latch mechanism capture plane and direction vector.

4.2.1 Application of TPDM Orientation

The coordinate system used in this study is equivalent to that of the OMV Program. As shown in Fig. 4-1, the chase vehicle/TPDM travels along the X-axis in the plane of the Y-Z axes to perform its docking maneuver. The ARAD sensor, located at a radius of 37.3" from the X axis vector, generates signals guiding the chase vehicle's travel along the X-axis vector to perform docking. In this study we have introduced the effects of ARAD sensor alignment error by applying translations and rotations (± 0.2 " in the three transitional axes and ± 0.33 degrees in the three rotational axes) to the nominal position of the trunnion (using its centerline as a reference) in a manner to maximize the distance between new (apparent) location and original location.

The errors were applied one at a time, with each succeeding error direction selected to increase the error magnification. The resultant effect shifts direction vector on the chase vehicle centroid by: 1.49 degrees relative to the original X axis, 1.15 degrees relative to the original Y axis, and 0.48 degrees relative to the original Z axis.

Imposing this total error alters the position and path of each latch relative to its associated target satellite interface. Our selection of the sensor at 180 degrees from the furthest latch provides a maximum change on the capture envelope of that latch.

As shown in Fig. 4-10, in a view looking forward, the TPDM latches are

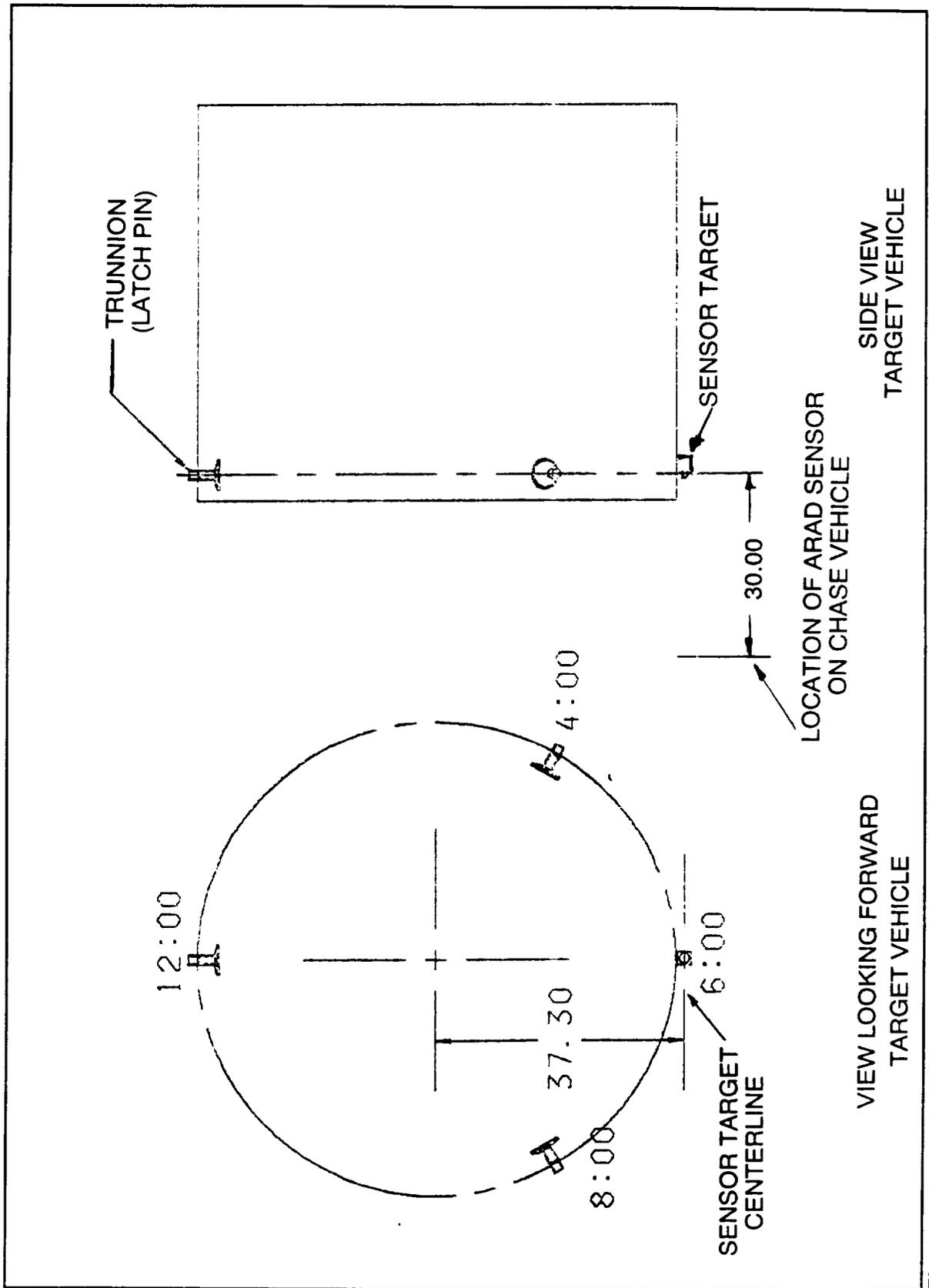


Fig. 4-10 Position of ARAD sensor and target relative to TPDM

positioned in the 4, 8, and 12 o'clock positions. The target sensor was located 37.3" from the center of the three latches in the 6 o'clock position to maximize the effective angulation resulting from incorporating the alignment errors.

4.2.2 Case 1 - Explorer Platform

The following discussion describes the resultant change at each latch location, the worst case being at the 12 o'clock position. For purpose of initial analysis, we assumed that each trunnion is allowed to pass completely into the latch without the arm hindering its progress (the possibility of contact will be addressed later) and without considering the effect of overall TPDM latch closure control logic. The final position that would be reached is described; bounce effects are not considered. After we provide conclusions on the final positions, we provided a discussion of the effects of speed, latch control logic, and latch contact during the process.

We used the nominal 36" radius of the latch arm/trunnion interface as the location at which to impose the alignment errors. Taking this target point as Point (Pt) 0, as shown in Fig. 4-11, and imposing the alignment errors one at a time, the movements imposed were:

- a. Translated 0.2" in the X, Y, & Z direction (Pt 1)
- b. Pitched +0.33 degrees about the Y axis (Pt 2)
- c. Roll +0.33 degrees about the X axis (Pt 3)
- d. Yaw +0.33 degrees about the Z axis (Pt 4)

The new location for Pt 0 is Pt 4. Pt 0 moved 0.62" in the +X direction, 0.80" in the +Y direction and 0.20" in the +Z direction. Assuming the target vehicle remains fixed and all alignment errors were introduced on the chase vehicle, this would skew the side of the chase vehicle on which the ARAD sensor is mounted forward (towards the target vehicle), and the latch furthest from the ARAD sensor away from the target vehicle.

Based on the assumed orientation, the latches closer to the sensor location would arrive first. It was assumed that no bounce effects would occur and the latch retaining motion between the chase vehicle/target vehicle would make the vehicles become "parallel" in the off-nominal position. The latch furthest away from the sensor would reach its final position last.

The results of the translations at each latch location are as follows:

- a. The far side of the outboard latch machine plate at the 12 o'clock position was 0.42" outboard of the trunnion; its electro-optical sensors would not be interrupted by the trunnion and therefore could not participate in latch arm motor activation. Please refer to Fig. 4-12.
- b. The near side of the outboard latch plate at the 4 o'clock position was 0.18" outboard of the trunnion. The electro-optical sensors in this plate would not be interrupted by the trunnion and could not actuate the latch arm motor. The inboard sensor would still actuate the latch arm motor. Please refer to Fig. 4-13.

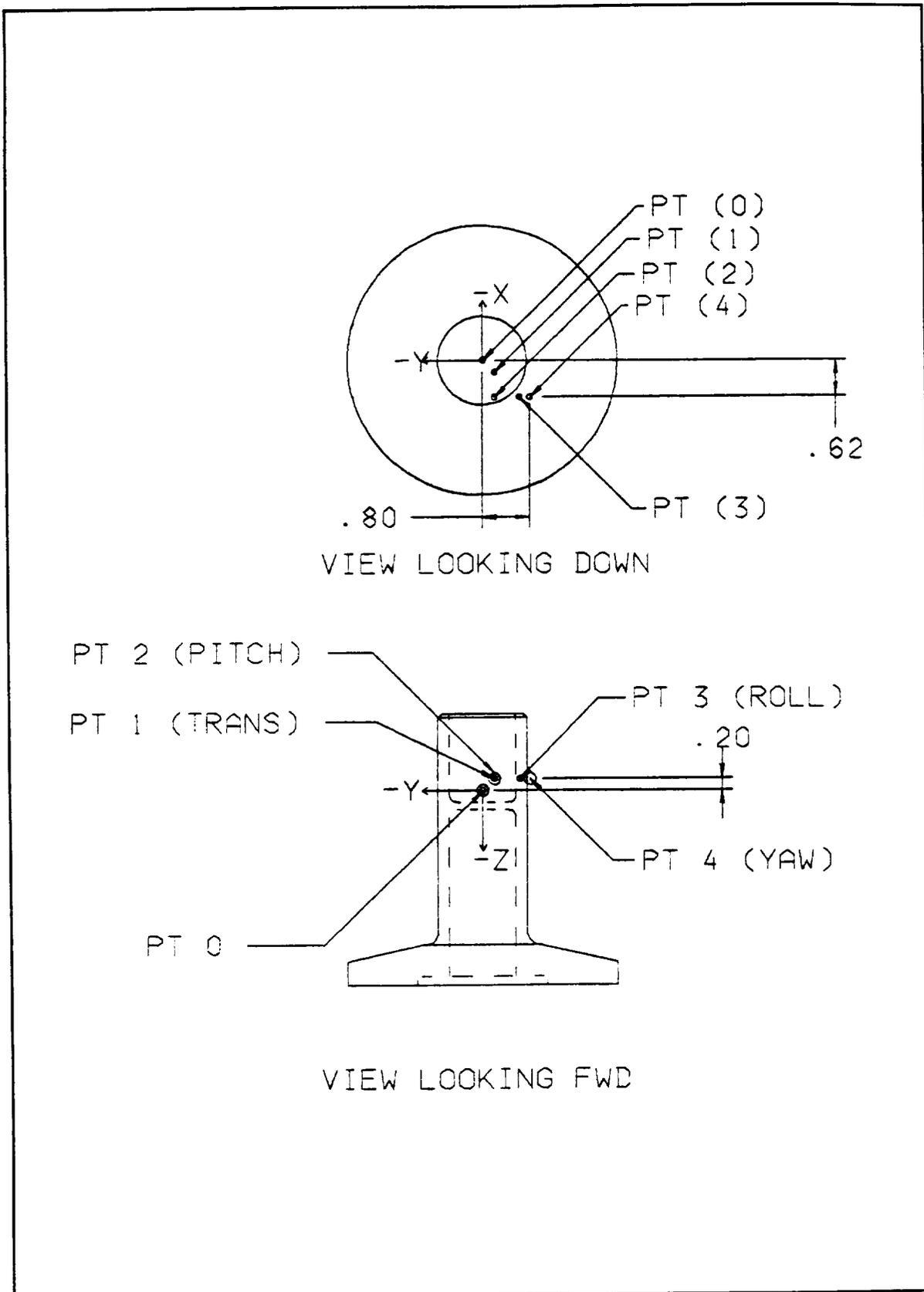


Fig. 4-11 Summary of alignment errors applied to trunnion (12:00 o'clock TPDM position)

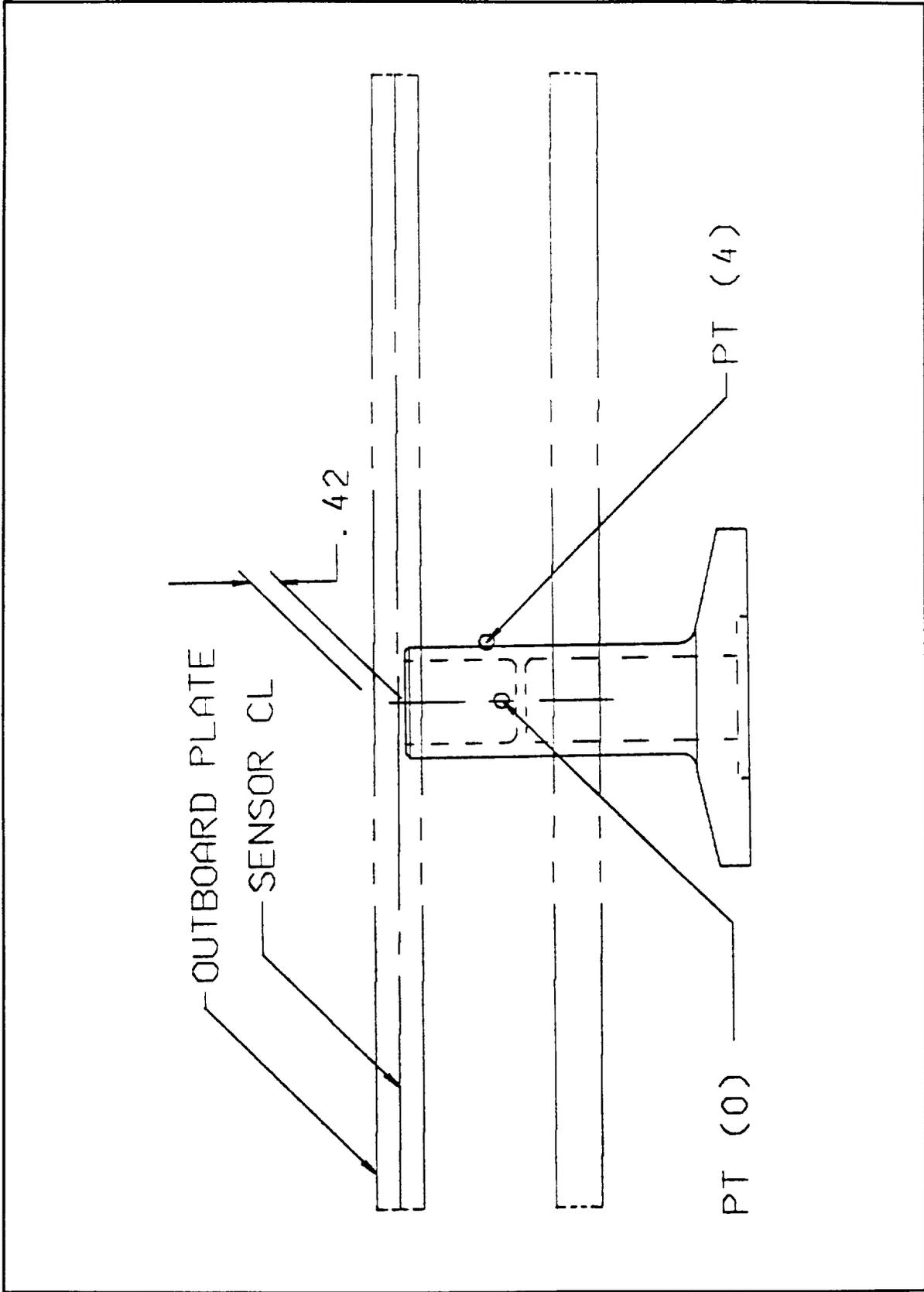


Fig. 4-12 Latch/trunnion position with alignment errors applied - 12:00 o'clock location

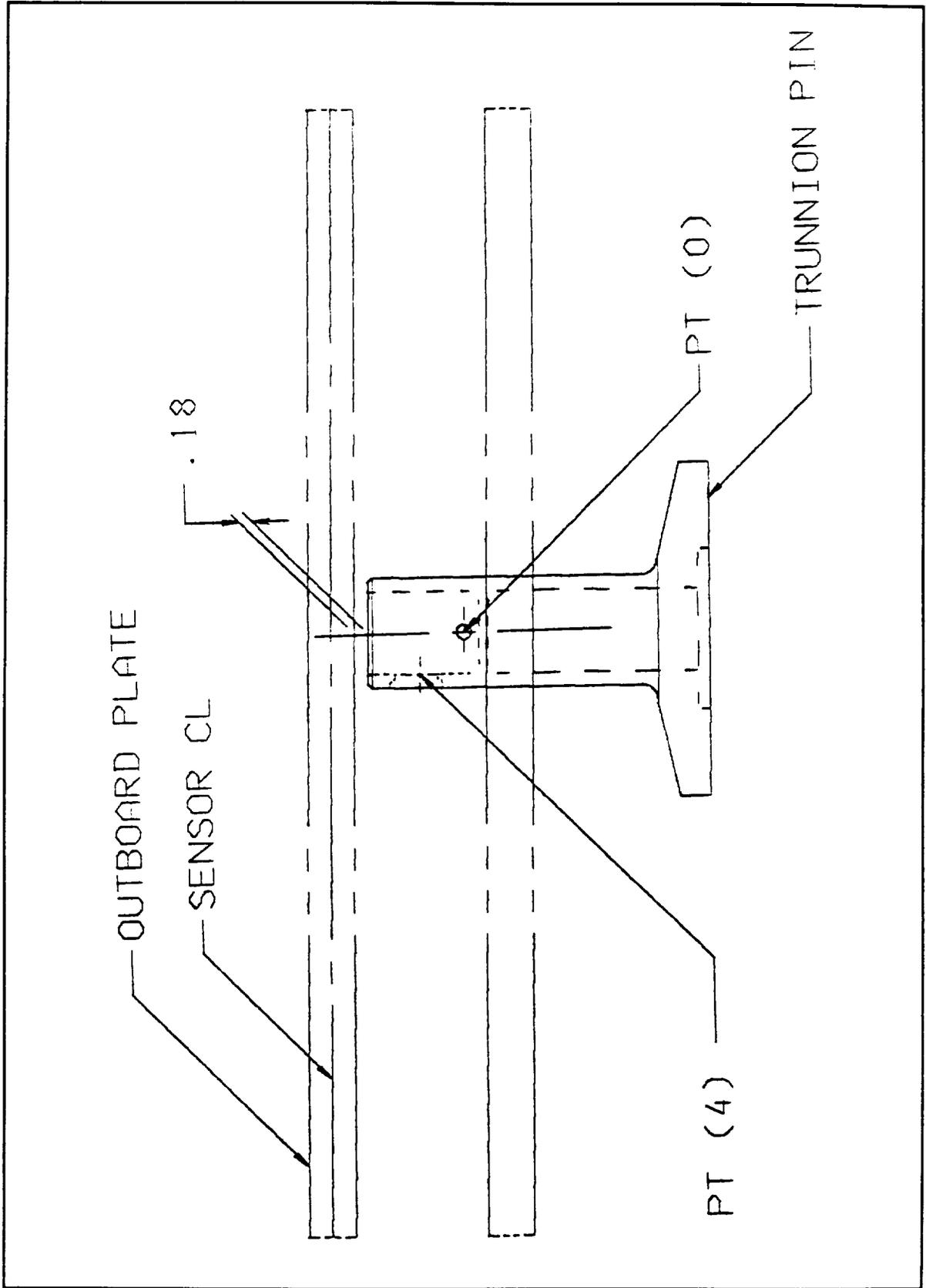


Fig. 4-13 Latch/trunnion position with alignment errors applied - 4:00 o'clock location

- c. Both sides of the latch assembly located at 8 o'clock are positioned such that their electro-optical sensors would activate its latch arm motor. The near side of the inboard latch plate at the 8 o'clock position clears the trunnion fillet radius by 0.10". Please refer to Fig. 4-14.

To preclude the undesirable conditions above, the following could be performed:

- a. Relocate the trunnions 0.90" toward the vehicle center. Maintain the nominal mating position on the 36" radius and increase the pin length by 1.80". While this change is more easily implemented on an HST type vehicle, it could be considered for future target satellites assuming the STS Flight Support System interface is maintained.
- b. A second solution would be to position the latches at a radius of 36.9" and increase the pin length by 1.80".

Figure 4-15 shows all three latch assemblies in their final docked position. From the layout on Fig. 4-15 we see that the capture could still be made based on the geometry. We will revisit this comment in the review of the HST.

The latch actuation control logic initially postulated called for all latches to start their closure movement once the first trunnion passed the inner beam location of any latch. We refer to this as the "first-in" control basis. Using this premise, we considered the potential for any of the other two latches to be outside of the latching envelope at the instant when the latches are actuated. In our "first-in" study case, the first two latch arms essentially start moving in unison because both would pass their inner beams at about the same time. We found that the trunnion at the 12 o'clock position was marginally within the capture envelope assuming no other relative motion (closure) occurs between the two vehicles. See Fig. 4-16. Based on the position of the latch arms without considering the potential for dynamic "pull-in" effects from the other latches or relative motion, the former (12 o'clock) may bind the latch arms or remain outside of the closing arms. It appears that two of the three latch mechanism arms would still capture their respective trunnions but the planned rigidization point might not be reached due to the potential skewed capture position. However, when we applied the current control logic as discussed in Section 4.1.1, the potential for the last latch to bind with or remain outside of the closing arms is eliminated.

The position of the guidance sensor affects the nominal latch/trunnion position mismatch. Generally, the effect is magnified as the distance between the sensor and the latch location increases. Figure 4-17 shows the projected deviation of final docked position relative to the nominal (0,0) location in the Y-Z plane versus sensor distance from the (0,0) Y-Z location. Two data points are indicated; the first (0.8") being the deviation at the 12 o'clock position for the sensor located at a radius of 37.3" and the second (0.58") the deviation for the sensor located at the vehicle centerline location. In the latter case we used a 30" distance between the ARAD

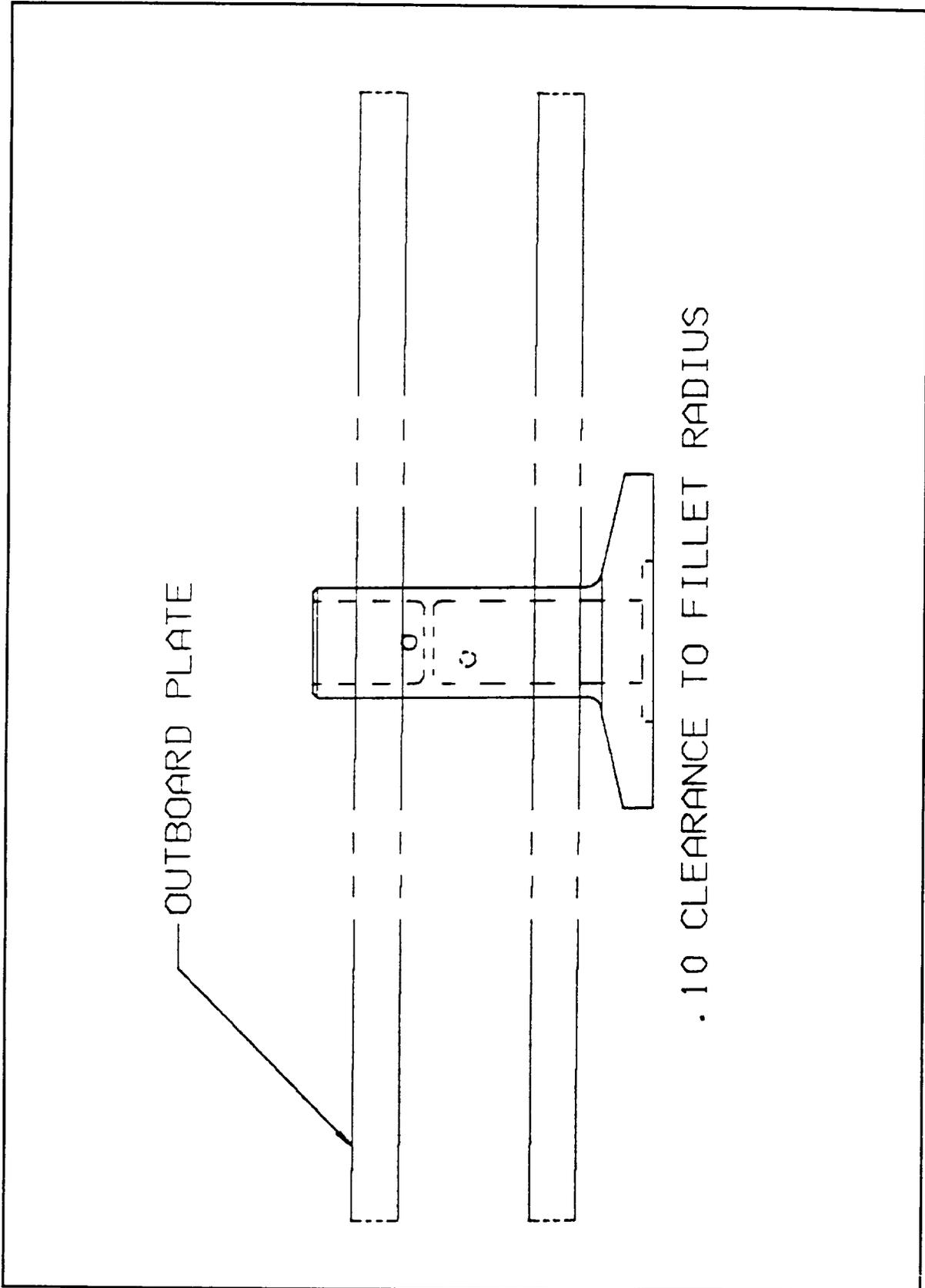


Fig. 4-14 Latch/trunnion position with alignment errors applied - 8:00 o'clock location

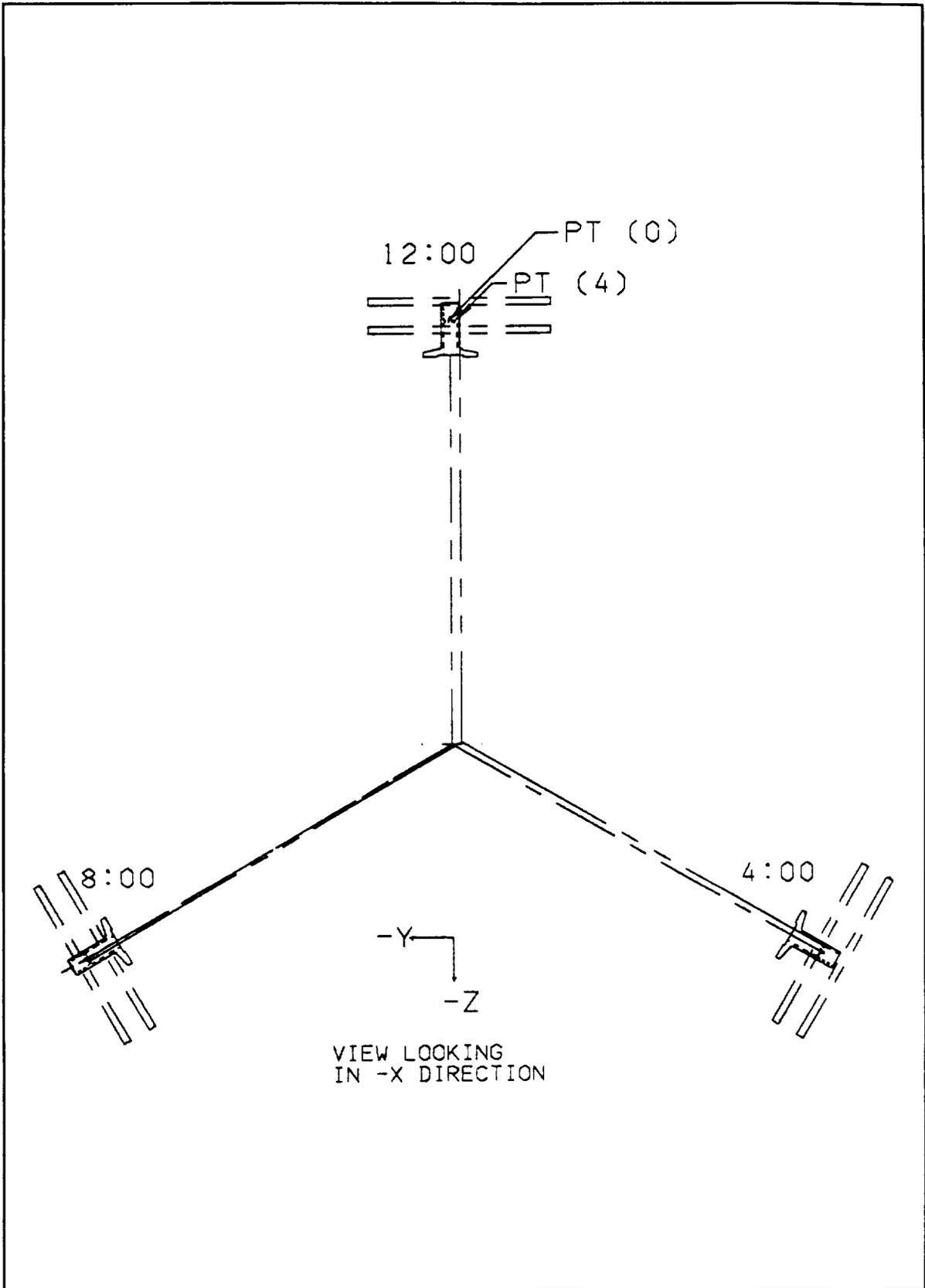


Fig. 4-15 View of TPDM latches showing composite effect of alignment errors applied to trunnions.

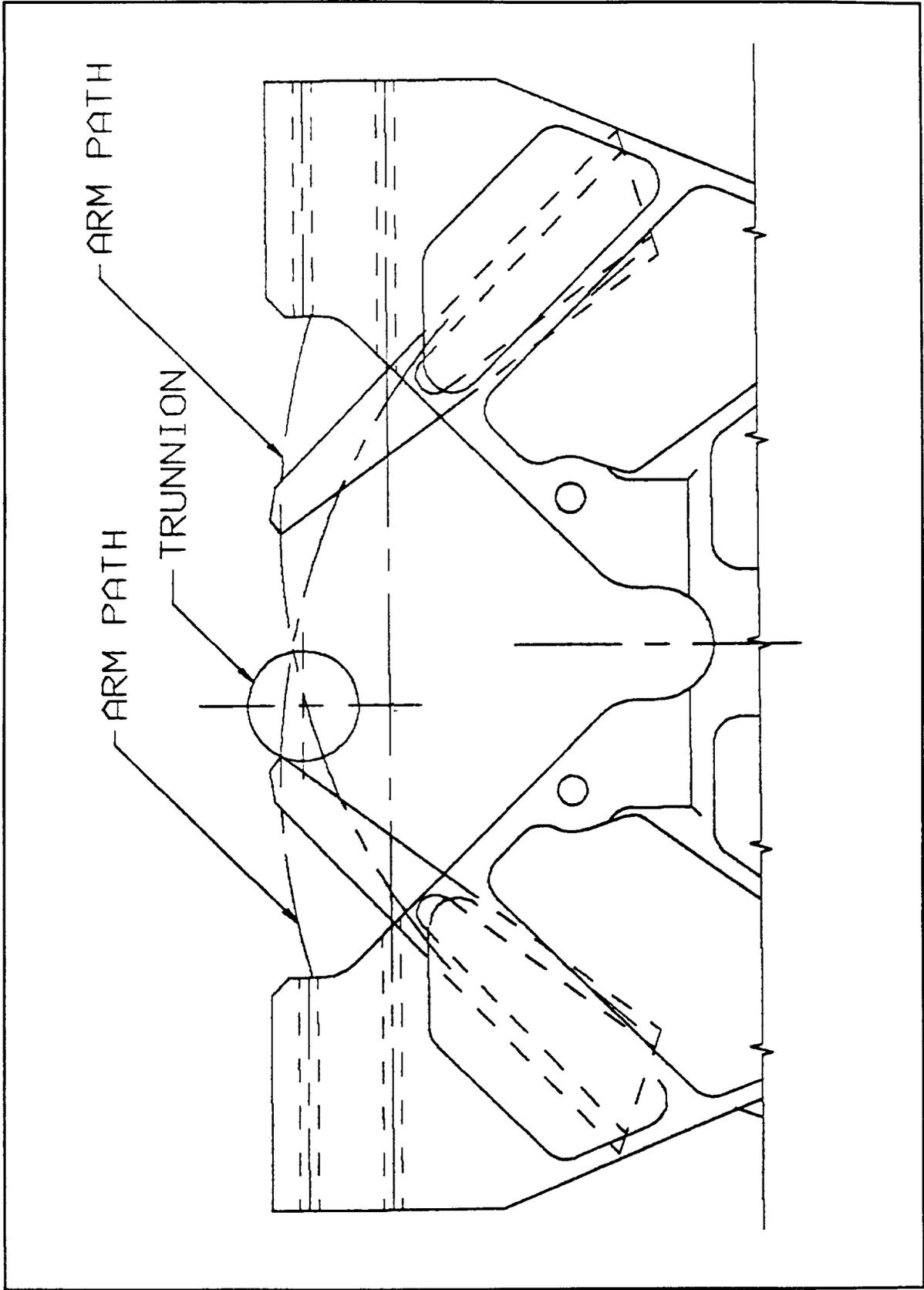


Fig. 4-16 Position of 12:00 o'clock trunnion for case when "first-in" EO sensor activates TPDM latch logic

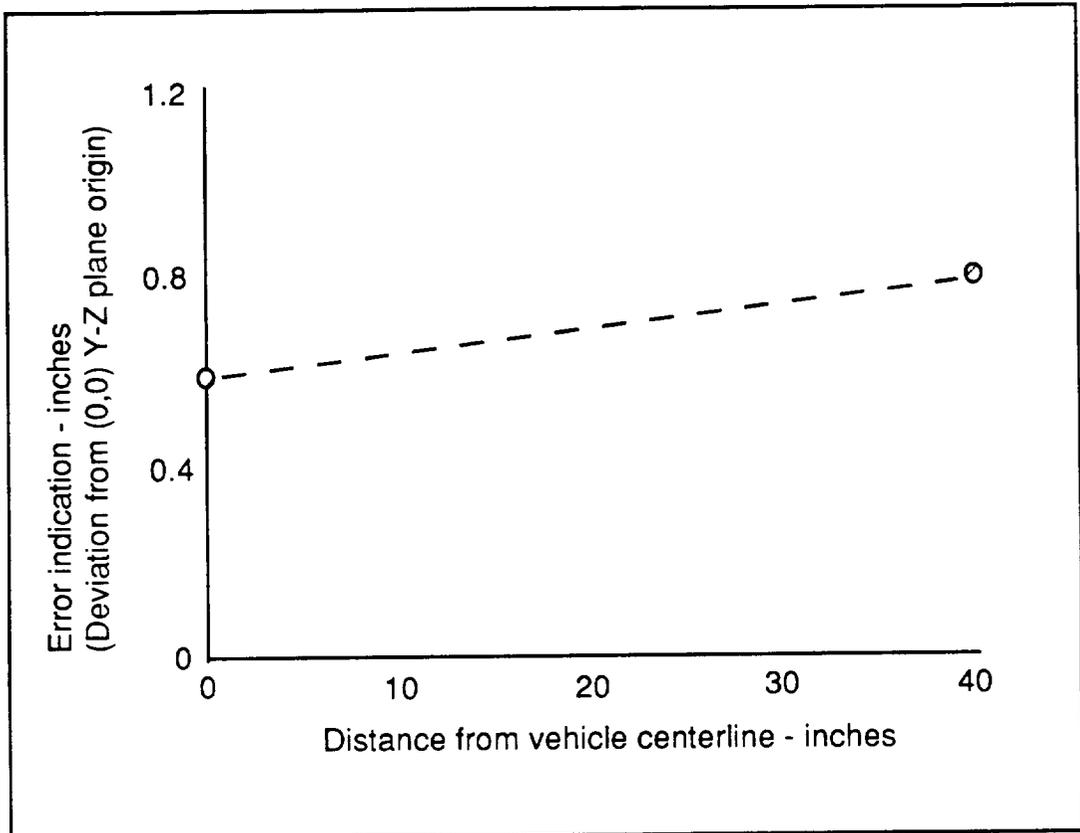


Fig. 4-17 Variation of alignment error verses sensor position

sensor and its target in a hard docked position. While this is not realistic because the target would be within the body of the target vehicle, it still conveys the effect of the parameter which is important for planning umbilical connection alignment. This implies, from a purely geometric error consideration, that the best sensor location is in the center of the TPDM (along the X direction vector).

4.2.3 Case 2 - Hubble Space Telescope

The same methodology was applied to the HST towel bars. For this vehicle configuration there was no instance where any of the electro-optical sensors were positioned to not provide interrupt signals.

The results of the translations at each latch location are as follows:

- a. The centerline of the latch assembly at the 12 o'clock position shifted 0.2" outboard of its nominal location, providing a minimum clearance of 1.47" to the outboard towel bar end plate. All its electro-optical sensors would be interrupted by the towel bar and therefore the latch arm motor would be activated. Please refer to Fig. 4-18.
- b. The centerline of the latch assembly at the 4 o'clock position shifted 0.59" outboard of its nominal location, providing a minimum clearance of 1.27" to the outboard towel bar end plate. All its electro-optical sensors would be interrupted by the towel bar and therefore the latch arm motor would be activated. Please refer to Fig. 4-19.
- c. The centerline of the latch assembly at the 8 o'clock position shifted 0.79" inboard from its nominal location, providing a minimum clearance of 1.07" to the inboard towel bar end plate. All its electro-optical sensors would be interrupted by the towel bar and therefore the latch arm motor would be activated. Please refer to Fig. 4-20.

Figure 4-21 shows all three latch assemblies in their final docked position. The mismatch (between vehicle centerlines) is 0.8", assuming the latches are captured at their new position. This figure is significant for evaluating allowable tolerance for feed-through type servicing fittings (i.e. propellant transfer).

Finally, we again considered the potential for any of the latches to be outside of the latching envelope. Again two latch actuation control logic cases were considered; the "first-in" case as discussed in the prior section (where all latches move at the instant when the first latch is actuated) and the current control logic case. As discussed for the Explorer case above, we found that the improved logic of the current latch control sequence eliminated the concern for any latch being outside of the capture envelope once the latch arms began their movements. Please refer to the discussion in the above section for details. This analysis also does not consider the effects of extremely rapid bounce-back between vehicles.

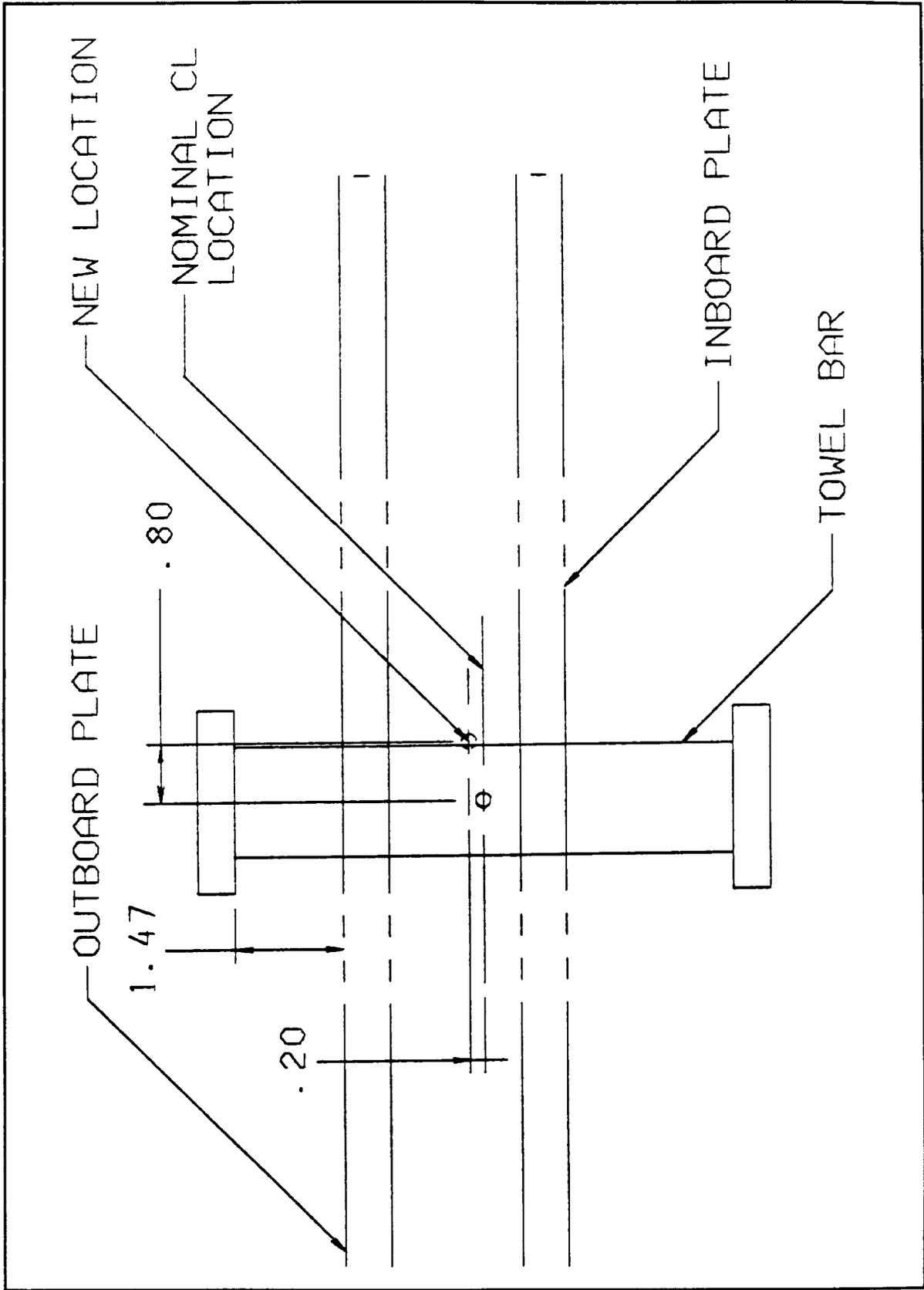


Fig. 4-18 Latch/towel bar position with alignment errors applied - 12:00 o'clock location

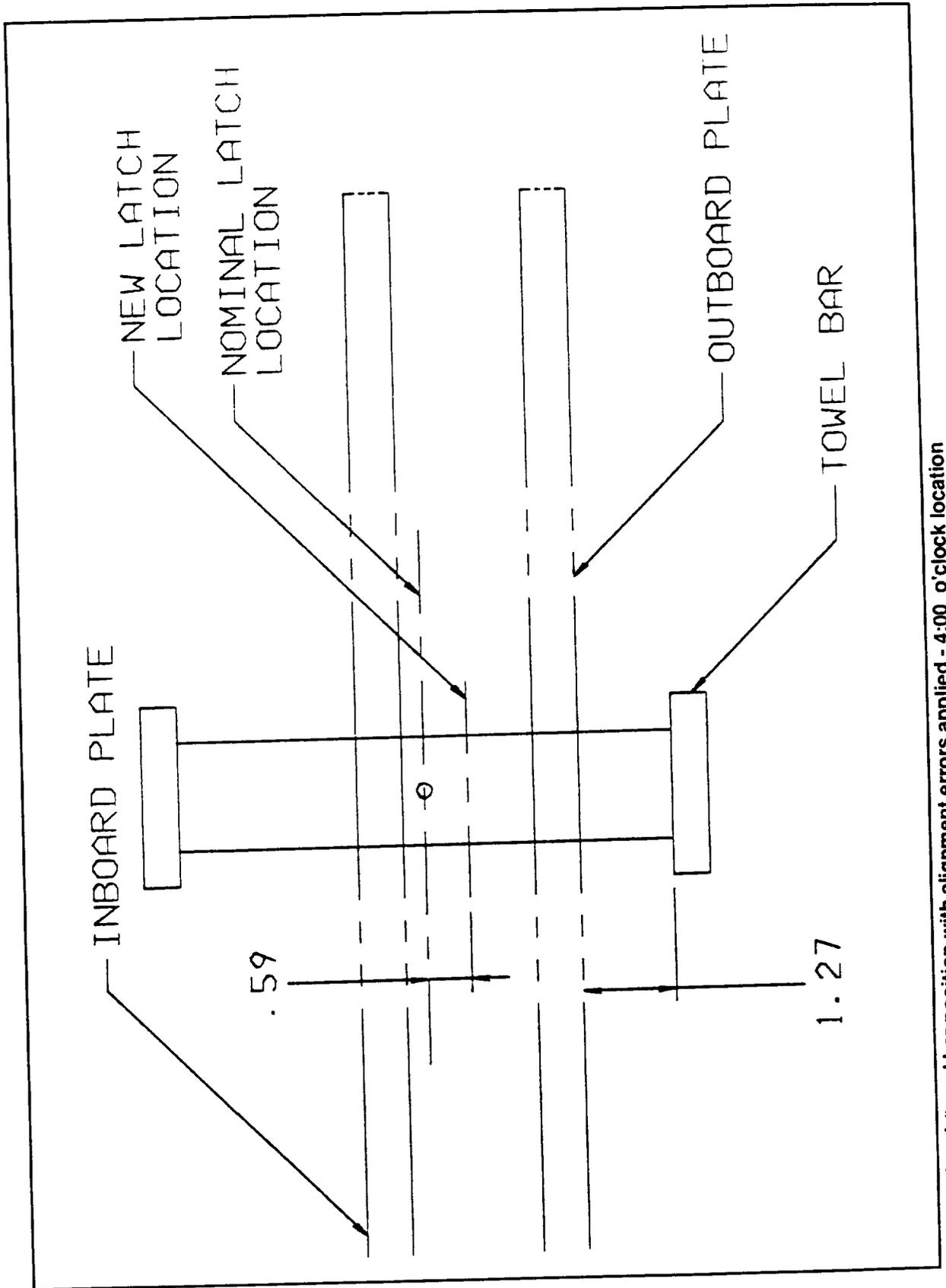


Fig. 4-19 Latch/towel bar position with alignment errors applied - 4:00 o'clock location

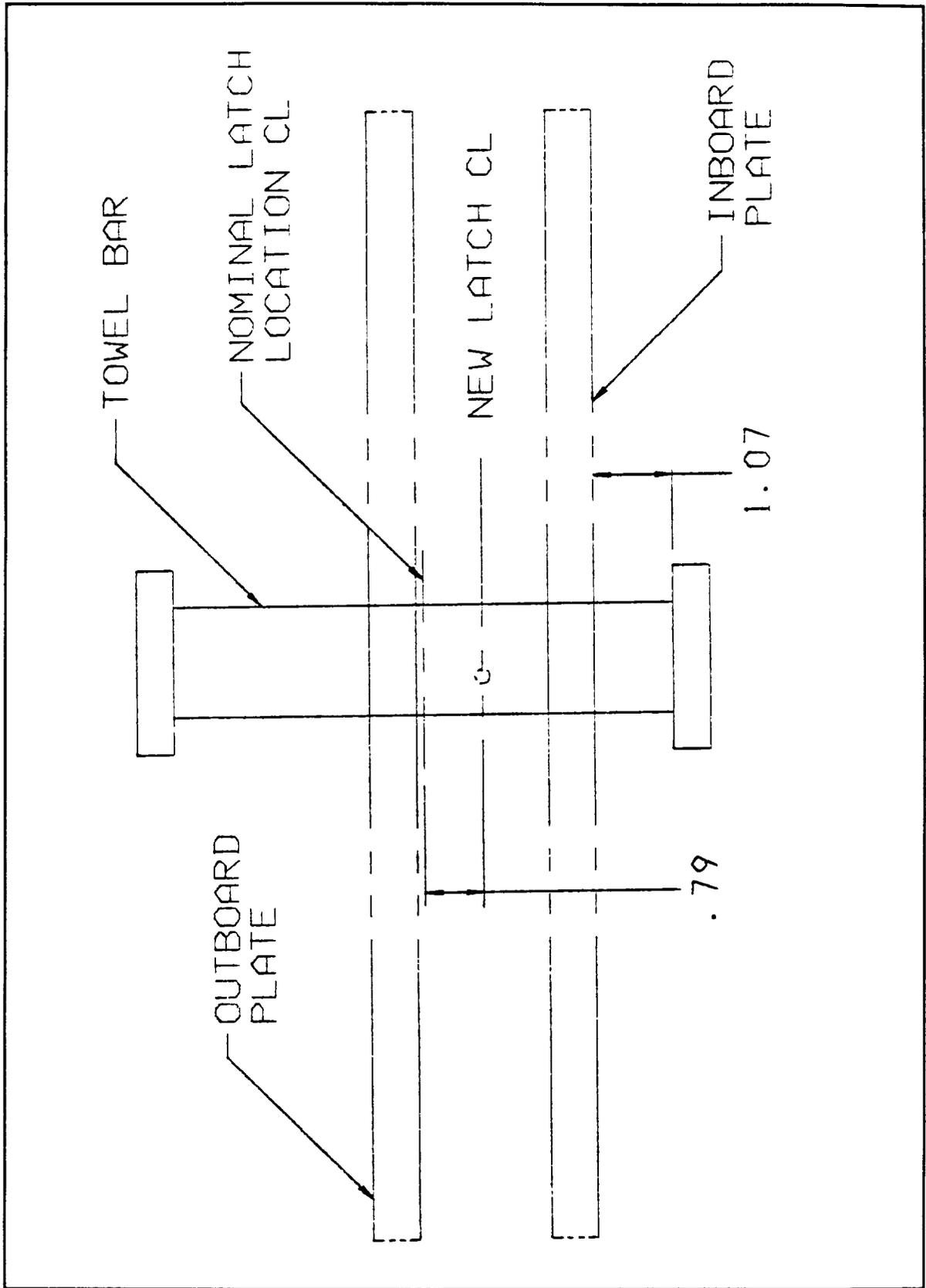


Fig. 4-20 Latch/towel bar position with alignment errors applied - 8:00 o'clock location

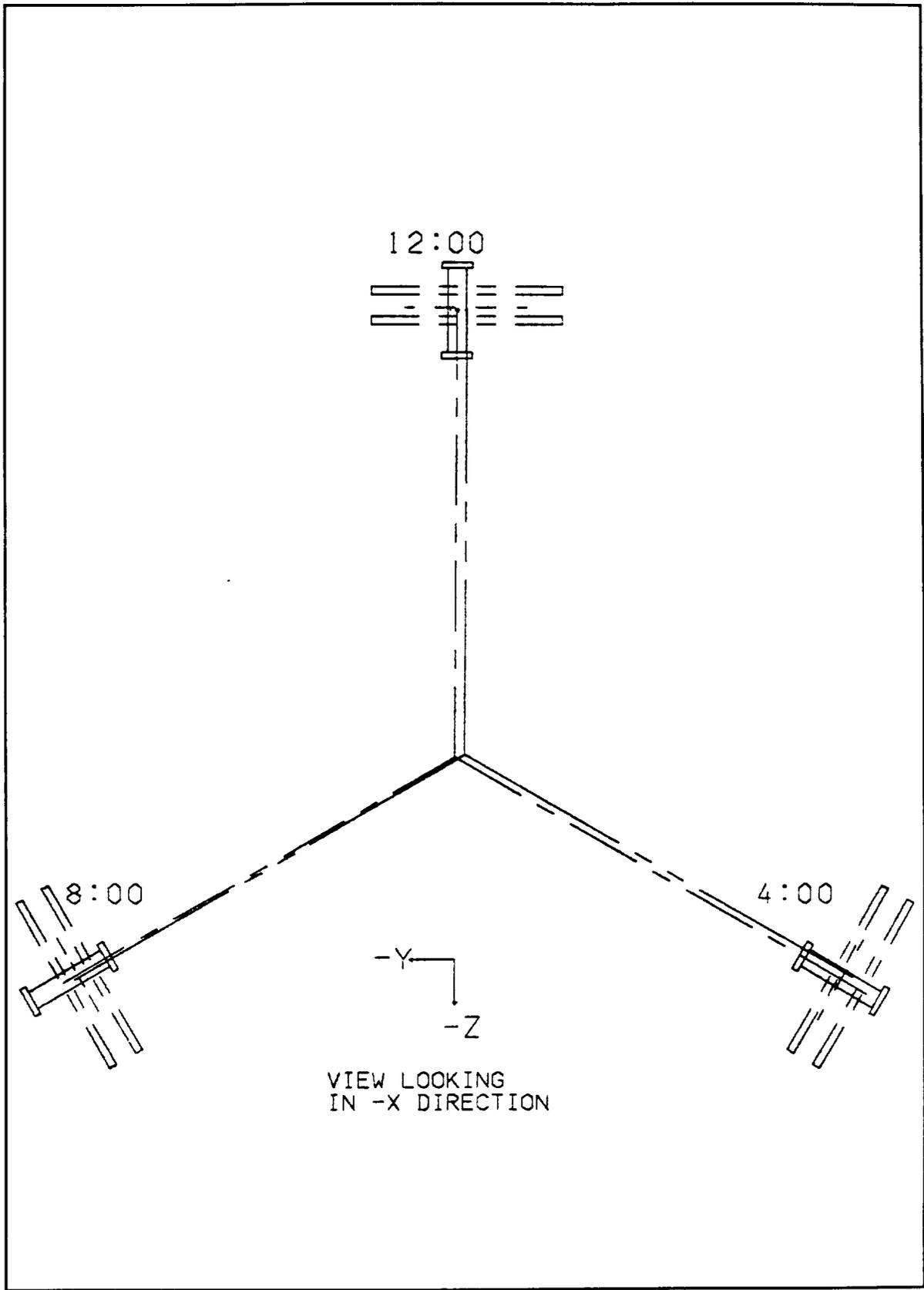


Fig. 4-21 View of TPDM latches - composite effect of alignment errors applied to towel bars

4.3

Alternate Capture Sensor/Capture Mechanism Concepts

The following paragraphs describe suggested changes to the interim TPDM design and documents comments which lead to the current latch actuation logic.

Assuming two latch arms are activated (with the third not in place yet for activation), each of the two latches travel an arc of approximately 4 inches to reach the initial capture position; this takes approximately 3 seconds (design parameter not firm). For a stipulated maximum final docking velocity of 0.1 cm/sec (.0394 in/sec) the latch arms should not contact the trunnions unless rebounding action takes place.

The remaining latch will move only when its inner beam is broken. For the worst case condition (Explorer scenario), the first latch to break the inner beam is 2.95" away from its contact point on the latch structure. Since it takes approximately 60 seconds for the latch to reach its pre-rigidization position and with the maximum relative postulated travel rate between the two vehicles being 0.1 cm/sec, the first trunnion is expected to travel $.0394 \times 60 = 2.364$ " further into the capture envelope during this process. This implies that it would finally contact 15 seconds

$$[(2.95" - 2.364")/.0394 \text{ inches per sec.}]$$

after the latch reached its initial capture position. The worst case trunnion is 3.13" away from its projected contact point when the first latch arm starts to move. This implies that it should break its inner beam 11 seconds after the first arm starts moving. The latch arms for the worst case trunnion will reach their initial capture position 4 seconds prior to first latch contact. The worst case trunnion is projected to make contact approximately 5 seconds after first latch contact. Based on the above parameters, the initial two trunnions could "bounce" off their respective latch plates and rebound towards the latch arms only after they would have reached their initial capture positions. The same is true for the remaining trunnion. If the initial capture position is approximately equal to the trunnion diameter, the rebound contact point could be close to the tip (see Fig. 4-4), resulting in a high moment arm and contact impact load. It is recommended that a review be made to establish the soft capture position is at least full tip to tip overlap.

Consideration was also given to moving the inner beams more inboard, towards the base of the structure. Based on the above analysis, this is not suggested. It could lead to earlier rebounding with high closing speeds, before the latch arms fully contain their respective trunnions. The concern for "bouncing" off the latch plates suggests additional review for including mechanical dampers between the TPDM structure and chase vehicle. This may soften the bounce, but a detailed dynamics model is required to adequately affirm this conclusion.

The potential for X-axis misalignment still exists, including cases where the LEDs on the one side of the latch arm assemblies would be beyond the trunnion and could not provide actuation signals. This condition (see Fig.

4-15 and Fig. 4-21) can be diminished by incorporating alignment guides on the outboard side of each latch mechanism which provide a centering action force while the latches draw the target satellite trunnions in towards its final position; this is important for umbilical connection applications. This change also diminishes the constraints on ARAD sensor/target errors and vehicle thruster control accuracy. The alignment guide slide surface can also be curved to help in centering the trunnion relative to the latch mechanism. Further changes to facilitate the centering action are to place spherical bearings on the latch arm surfaces that contact the trunnion surface and add grease to the surfaces to lower friction; these would facilitate the sliding action towards the center position. Should any of the bearings seize, we would revert to the present design (sliding between two surfaces).

Assuming a worst case contact geometry, the minimum clearance between the HST towel bar assembly and the latch mechanism arm is 0.19". A further review towards increasing the elevation of the towel bar off the vehicle base is suggested on future vehicles.

5 - Flight Issues

To minimize risk in proceeding into the flight hardware phase with a design that includes an automated control capability, specific issues require resolution. This section identifies these issues and discusses their relevance. The next section (Section 6) proposes test simulation methods that could be used to resolve them.

As a vehicle for identifying issues, we prepared a matrix chart that lists the elements of a mission scenario (from Section 2 of this report) and identifies the some of the major issues. To resolve an issue, it must be demonstrated that the mission task is feasible, based on ground simulation or analysis results. The issue/mission element matrix is presented in Figure 5-1. Three major areas stand out:

- development of a docking sensor system which can function in real time, based on illuminated sensor data cross-linked into an onboard propulsion system,
- docking dynamic effects, the case where the two vehicles are close to the same relative mass, and
- providing a higher level of control integral to the TPDM system to support automated docking and initiating abort when data requires; this issue also includes the transmission of limited data down to the ground control station for operator information/abort override action.

To facilitate discussion of issues, Figure 5-2 correlates them to subsystems comprising the chase vehicle/TPDM system. This presentation approach drives out requirements.

In the following paragraphs we discuss each of the issues identified.

5.1 Health Monitoring Information/abort Criteria

Lessons learned from TPDM simulation results performed in Grumman's Large Amplitude Space Simulator indicate high operator work load for teleoperated capture operations. From a human factors viewpoint, the effects peaked when capture of spinning satellites with assumed data transmission time delay was attempted. The automated docking operation approach, limiting the operator to an override abort function based on filtered data appears realistic.

The health monitoring information issue relates to the selection of real-time data from which the system should take abort measures. To some degree, an abort decision could be made from the ground in a timely manner, but based on postulated contact dynamics scenarios (and experience with Intelsat capture) it is proposed that higher level control logic be "built in" to

Issue	Mission Elements						
	2.2.1 Propulsion Vehicle/TPDM deployment	2.2.2 Rendezvous	2.2.3 Proximity Maneuvers (up to initial capture)	2.2.4 Stabilization (initial capture to rigidization)	2.2.5 Rendezvous with On-orbit Support System	2.2.6 Handoff to Support System	2.2.7 Chase Vehicle/ TPDM Storage
Health monitoring information/abort criteria	✓	✓	✓	✓	✓	✓	✓
Recognition of target satellite using ARAD target			✓	✓			
Target satellite movement due to chase vehicle jet plume effects			✓	✓	✓	✓	
Chase vehicle thrust vector stability			✓	✓	✓	✓	
Chase vehicle orientation update based on ARAD sensor data			✓	✓	✓	✓	
TPDM latch closure criteria & speed			✓	✓		✓	
Two body dynamics				✓			
Target satellite centering criteria					✓		
Handoff procedures (three body dynamics)						✓	

Fig. 5-1 Identification of TPDM Issues and Effected Mission Elements

Issue	Environment		Chase Vehicle		Comm. Link comm. sat., ground comm. transfer link	Three Point Docking Mechanism				
	Space conditions		Propulsion system	Onboard processor		Structure	latch assembly	ARAD	target vehicle ARAD targets	Auxiliary systems (fluid transfer umbilicals, electrical connection)
Health monitoring information/abort criteria	X			X	X		X			X
Recognition of target satellite using ARAD target	X							X	X	
Target satellite movement due to chase vehicle jet plume effects	X		X					X		
Chase vehicle thrust vector stability	X		X	X				X		
Chase vehicle orientation update based on ARAD sensor data	X		X	X				X		
TPDM latch closure criteria & speed	X					X			X	
Two body dynamics	X		X			X				
Target satellite centering criteria	X					X				X
Handoff procedures (three body dynamics)	X		X		X	X	X			

Fig. 5-2 TPDM Issues and Postulated Functional Allocation

the onboard system. The response time requirement appears too short relative to the anticipated data transmission time delays.

Candidate data to support the automated abort function will include latch force measurements from sensors located at the latches and target motion thresholds, as measured by the ARAD system. The refinement of the data parameters will be derived from future ground development testing.

"Fuzzy logic control" is a rule based control approach which has potential application to this problem. Several studies have been performed applying this approach to Shuttle orbital rendezvous problems. The results have shown very good performance in comparison to a human pilot.

5.2 Recognition of Target Vehicle ARAD Targets

Current laboratory data infers that the system will acquire the target at 50 meters. This ability must be confirmed with simulated testing under space environmental conditions. While sun reflection is not expected to disrupt signals, the effect of chase vehicle jitter due to steady state harmonics, potential station keeping maneuvering jet firings, and potential target satellite movement must be analyzed. Also at issue is the effect of the target being skew to the sensor.

5.3 Target Vehicle Movement Due to Chase Vehicle Jet Plume Effects

When the chase vehicle maneuvers close to the target vehicle, the chase vehicle thrusters may generate disturbance torques on the target vehicle. This case will be especially evident if the target satellite has deployed solar panels, extending from its body. There are approach orientations that minimize the need for forward thruster firings; these should be evaluated along with chase vehicle plume deflectors which lower the efficiency of X-vector movement, but redirect the plume to beyond the effective geometry of the target vehicle.

5.4 Chase Vehicle Thrust Vector Stability

Chase vehicle disturbance inputs to the ARAD system (i.e. thrusting, attitude control system) must fall within the disturbance rejection capability of the ARAD system.

5.5 Chase Vehicle Orientation Update Based on ARAD Sensor Data

The OMV program evaluated various automated docking technologies. From information available on the ARAD application, the orientation error between two ARAD measurement cycles produces updated chase vehicle propulsion thruster control system signals (deviation from planned

direction, speed and acceleration). The chase vehicle control system should be capable of accepting command updates at a minimum rate equal to the ARAD update rate.

5.6 TPDM Latch Closure Criteria & Speed

Docking can be theoretically planned (as laid out in Section 4 of this report) for ideal and off-nominal cases; however, its ultimate verification is dependent on a completing a multitude of cases affected by contact dynamics sensor response time and control algorithm feedback dynamics. Based on postulated criteria, rules for successful engagement must be developed; these will be used to form the basis for acceptable automated procedures.

5.7 Two Body Dynamics

The aim of initial capture is to attain a docking (non escapable) condition with minimum disturbance to the target vehicle. The analysis in Section 4 suggests that contact bouncing between the chase and target vehicles probably will occur (to some degree). The objective is to establish an initial capture position prior to any contact.

Beyond the initial capture issue, the thrust vector control authority for the chase vehicle must also accommodate the added weight and altered center of mass condition of the newly joined target vehicle. While this is more of a design problem, it is mentioned for completeness.

5.8 Target Vehicle Centering Criteria

The requirement to perform umbilical transfer fluids or power connection after capture, places additional restraints on the capture geometry. A centerline-to-centerline tolerance of approximately $\pm 1/8$ inch is generally desirable for umbilical insertion. From the initial review performed, it appears that a positive design solution which supports centering is needed. The umbilical transfer function, albeit performed with a nominal alignment condition, would be improved if some relative movement between vehicles were possible to relieve stresses during probe insertion.

5.9 Target Vehicle Handoff

The issue in this case could involve the dynamics of three bodies in space. Typical scenarios could take the form of:

- a delivery of the target vehicle to the space station (repair/maintenance/logistics center),
- transfer directly to shuttle RMS (believed not to be within present

NSTS safety criteria),

- a jettison of the target vehicle into the atmosphere, or
- a parking of the target vehicle in a selected orbit/location

The major issue is the potential effect of thruster plume on the desired stable condition of the target vehicle after release from the chase vehicle.

6 - TPDM Issue Resolution

This section examines the flight issues in the prior section and proposes a development program to resolve them. In the discussion of the various approaches comprising the development program, acknowledgment and infusion of completed and ongoing development work is included; omission of any relevant work should not be taken negatively since a complete literature search was not performed.

The general aim is to resolve all issues using a ground test/analysis program to a point where only a flight demonstration can provide the remaining verification (i.e., true two-body dynamic interactions and performance of in-situ automated docking). Thereafter, planning for an operational flight capability can proceed with a minimum of uncertainty.

Figure 6-1 and 6-2 presents flight issues identified in Section 5 correlated to proposed approaches for resolution. More detailed issue descriptions are also shown; these can be derived from the more general items identified originally. We have used a coding on the chart that indicates the suggested primary approach (P) that would resolve the issue; other approaches (S) which can provide effective contributions; and approaches that provide confirmatory data (C), thereby further reducing risk.

As identified by Fig. 6-1 and 6-2, various computer software analysis/simulation tools can contribute; an integrated approach that establishes data/results correlation with testing will minimize the final risk.

As shown by Fig. 6-1, most of the issues pertinent to the TPDM system should be resolved once the ground demonstration is completed. Only those areas which pertain to space contact dynamics must receive confirmatory level resolution through a flight demonstration. The ground simulation test program should provide a strong basis for projection of flight results. Figure 6-2 presents the issues pertinent to the vehicle systems associated with the TPDM. These generally include the ARAD sensor, chase vehicle and data transmission to the ground station. This area is more dependent on the results of a flight demonstration to establish a basis issue resolution.

6.1 Design & Analysis

NASA/MSFC has undertaken the modification and upgrade of the TPDM to address issues that improve the probability of successful capture. These changes include a wider and deeper latch mechanism capture envelope and other changes to the structure, mechanism subsystems and capture control algorithms (including a more autonomous operation).

Design work has proceeded to a point where a new latch mechanism design has been completed. Integration with flight type structure has not been addressed beyond the concept level. Most of the TPDM related issues will

Issue	Resolution Approach			
	Design & Analysis	Computer simulation	Ground test simulation	Flight demonstration
Health monitoring information/abort	P	S	C	
Adequacy of data/status/display information transmitted to ground for operator action	P	S	C	
Timeliness of telemetry data for operator abort decisions	P	S	C	
Level of control system integration required	P	S	S	
Philosophy of man-machine interface	P	S	C	
TPDM electrical and mechanical interfaces	P		C	
Light beam sensor technology	P		C	
Latch movement actuation control system	P	S	C	
Operational latch loads and dynamics	P	S	S	C
Latch rigidization controls methodology	P	S	C	
Latch motor load transient requirements	P	S	S	C
TPDM latch open/closure criteria & speed of operation	P	S	C	
Two body dynamics	P	S	S	C
Target vehicle centering criteria	P		C	
P - primary method S - support method C - confirmatory method				

Fig. 6-1 Identification of TPDM Issues and Potential Resolution Approaches

Issue	Resolution Approach			
	Design & Analysis	Computer simulation	Ground test simulation	Flight demonstration
Recognition of target satellite using ARAD target	P		S	C
Effect of skew relationship between sensor and target	S	S	P	
Target satellite movement due to chase vehicle jet plume effects	P	S	C	C
Chase vehicle thrust vector stability & effect on ARAD	P	S	C	C
Chase vehicle orientation update based on ARAD sensor data	P	S	S	C
Protection of chase vehicle and abort philosophy	P	S	S/C	
Capture approach	P	S	S/C	
Capture object transport technique	P	S		C
Level of automation	P	S	C	
Handoff procedures (three body dynamics)	P	S	S	C
Transmission delays on TPDM status	P	S	C	
P - primary method S - support method C - confirmatory method				

Fig. 6-2 Identification of TPDM Support System Issues and Potential Resolution Approaches

be resolved using design and analysis approaches. Similar equipment (materials, controls elements, mechanisms) have been flight qualified before; only the application arrangement and control methodology must be verified. No enabling technology problems must be solved.

It is suggested that a systems approach be taken now to ensure that all requirements are identified and complied with, and integration parameters are identified early in the process. While these items may not directly relate to resolving technical issues, they support the identification and performance specification of the subsystems comprising the TPDM system.

The TPDM source material (earlier generation design information) carries valuable data which may direct resolution approaches. Earlier selection of constraint criteria for items such as chase vehicle jitter requirements, processor cycle time, and desirable propulsion thruster level may facilitate and aid in-process engineering activities. The health monitoring system is a higher level control application which must be developed to support mission operations and component diagnostics requirements, including fault tree decision analysis. There does not appear to be any enabling technology issue in this area. Once developed, adequate time and opportunity is available for confirmation of design and requirement verification.

Beside the initial system design task, the resolution of issues surrounding ARAD system use for this application awaits stand-alone feasibility testing, with the host chase vehicle propulsion system integration being a subsequent further step. The vehicle thrust vector stability with current use of auxiliary front-end kit systems was an ongoing issue on the OMV program; this application must be tested to ensure design compatibility or identification of additional requirements.

Work has been performed on capture algorithms selection and collecting data on resulting loads and dynamic effects on the mechanisms and attached structure. The bulk of this effort comes from the OMV program efforts.

The requirements for target vehicle centering must be firmed up. Presently the TPDM design does not promote centering of the target vehicle beyond that of the initial ARAD system alignment control. It appears that TPDM auxiliary kits (fluid transfer, electrical umbilicals) may require a tight centering tolerance. Even if the ARAD system provides exacting tolerances, movement during rigidization may bring about misalignments. It is suggested that a supportive design solution be considered. Please refer also to section 4.3.

6.2 Computer Simulation

As indicated on Fig. 6-1 and Fig. 6-2, computer modeling is seen as a support approach. Its value for the TPDM program is in two areas: dynamic modeling and controls simulation.

6.2.1 Dynamic Modeling

Based on Grumman funded work, it became apparent that robotic simulation software could effectively support functional mission task analysis and concurrent design by exposing problems of in-process design configurations. It enables functional modeling of design solutions and run-throughs (simulations) of tasks prior to committing to hardware, mockups, models, or even expensive testing. With the availability of software that performs dynamic modeling, it is suggested that this avenue be considered with the understanding that it cannot replace simulation testing, only augment and facilitate its success.

As a typical example, ADAMS is a CAE program that solves for joint position, displacement, velocity, acceleration, total and potential energy, and model internal reaction forces. It performs assembly static, kinematic, inverse dynamic and dynamic analysis. Animation of flexible bodies is available. Models can include both rigid and flexible bodies and make use of libraries of components, joints, and forces. Results are used to evaluate mechanical system performance, range of motion, collisions, peak loads, and to calculate finite element analysis load inputs. Automatically calculated outputs include all displacements, velocities, accelerations, and reaction forces.

Use of a software program such as the former is expected to drive out design issues and provide added credibility prior to running "full-up" facility tests. Beside the modeling of hardware, test plan procedures can be verified by "running" mission scenarios using the software graphic presentation formats. Data results can be forecasted, to act as guideline test parameters. A further integration of the dynamics program and a control simulation is possible; this requires additional study.

The areas in Fig. 6-1 and Fig. 6-2 can all be investigated with the indicated simulation techniques.

6.2.2 Controls Simulation

Simulation of the integrated control system (chase vehicle control, ARAD) can be performed non-real time and real time. A number of control analysis tools are available to perform off-line non-real time analyses (such as ACSL, MATLAB). Mathematical models of the target and chase vehicle dynamics can be developed and integrated with models of the ARAD system.

Real time control simulation can be performed in a ground test simulation facility where the contact dynamics issue can be adequately addressed.

6.3 Ground Test Simulation

The facility requirements for TPDM development are available at NASA/MSFC. Grumman also has a simulation facility which could support the effort. The issues to be addressed focus on the integrated use of

the ARAD sensor to perform the docking operation, and contact dynamics between the chase and target vehicles.

In view of the importance of the latch mechanism function relative to the capture issue, it is suggested that a priority be given towards development of flight-like mechanisms for use in the near term test efforts. The aim is to reduce, by ground testing, all risk and uncertainty, prior to commitment to flight demonstrations. This therefore enables early confirmation/validation of dynamic models and allows computer simulation of mission cases to verify intended control techniques and probable vehicle interactions using these models.

Two NASA/MSFC facilities are required to support the TPDM development process:

- The Flight Robotic Laboratory
- The 6-DOF Contacts Dynamics Facility

6.3.1 Flight Robotic Laboratory

As a precursor to mission simulations within this laboratory, it is envisioned that the assembled TPDM will be placed on a stand which has 6 DOF positioning capability, and linear rate control in one direction (the principle X axis vector). It would be used to establish confirmation that the latch actuation scheme functions as designed, both in nominal engagement configuration and "worst case" skewed position. This test examines latch movements during target vehicle engagement to attain the initial capture position.

The following represent relevant mission scenario test work that has been performed (list not complete):

- OMV mission operations using mockup TPDM (teleoperated) (References 1, 2 of Appendix A)
- Grumman simulation of OMV attached TPDM mockup (teleoperated)
- Rendezvous technology - Grumman
- Rendezvous technology - MSFC

Mission operations with diminished man-in-the-loop participation have not been performed (simulated) to any operational extent. Some expert system logic is desirable to support near-autonomous TPDM operations. The issue of the docking sensor system commanding the propulsion vehicle navigation and guidance system direction and range to attain docking needs to be demonstrated along with the integration of the additional inputs from the latch control and status signals in the overall operations logic.

The formulation and selection of status monitoring signals required by local/ground control stations for "limited" abort authority must be established; transmission frequency must be established to support the desired basis for operations. The in-situ system should have the necessary

decision logic to implement all planned off-nominal cases. The desired control authority of the remote operator must be examined in light of test experiences. Can information be transmitted, in a timely fashion, which enables the operator to take positive action - or should the entire decision making authority be delegated to an expert system?

The simulation work to be performed in the laboratory has a controls and sensor integration focus. It represents an opportunity to verify the usefulness to an operator of transmitted 'remote' test data to the simulated ground station and to test out the logic of the automated docking system and health monitoring/abort criteria. It is an opportunity to demonstrate the ARAD system functioning on an integrated basis with the chase vehicle control system.

Another issue that must be addressed is potential plume disturbance effects. This effect is strongly dependent on the configuration of the target satellite, especially the frontal area extending beyond the main body of the satellite. The chase vehicle thruster firings in the direction of the target satellite are required to slow the chase vehicle down, but at the same time the propulsion system plume "pushes" on the surfaces of the target satellite, causing spin, tumble or other undetermined motion. As suggested earlier, plume deflectors will diminish the effect, but will increase fuel requirements due to the restricted angular thrust vector component. Chase vehicle thruster effects can be included in the simulation by plume force computer modeling.

6.3.2 MSFC 6-DOF Motion Simulator Facility

Previous relevant TPDM development test work, as documented in some of the references to this report, is as follows:

- OMV Contact Dynamics Test - Overview and Status Update, March 30, 1990, TRW presentation
- 6 - DOF TPDM Contact Dynamics Testing, September 1990, NAS8-36800, TRW document
- Three Point Docking Mechanism Contact Dynamics Test, November 7, 1990, TRW presentation
- Equipment Specification Three Point Docking Mechanism (TPDM), EQ2-830 Rev A dated April 23 1989, TRW document
- Contact Dynamics Simulations, Report #2, document OMV.89.300-103 dated April 11, 1989, TRW document

The focus continues to be the area of two body dynamics and what happens when two bodies of specific (large) masses contact. In the best case we would want them to remain together, the contact energy being acceptably absorbed in the adjoining structure. This however is not the case and "bounce back" conditions can occur, placing the intended latching function in jeopardy. The flexibility parameters of the two bodies, specifically the

adjoining structures must be known so that acceptable approach/contact velocities can be established. If testing and associated dynamics modeling determine that stiffness remains a problem, special preloaded dampers interfacing the TPDM to the chase vehicle may be an acceptable resolution to the issue. These may be preset to accommodate specific vehicle missions; this approach mitigates risk and favors a more flexible design basis.

To summarize, the detail contact issues that are to be addressed in this facility testing include:

- first contact,
- bounce effects,
- latch arm loads from bounce effects,
- plume effects,
- differential mass effects between vehicles,
- target vehicle centering design verification testing, and the
- effect of structural flexibility of/between target vehicle and chase vehicle.

6.4 Suggested TPDM Development Program Logic

Figure 6-3 presents a suggested development path logic for the TPDM showing use of the various facilities.

The Design & Analysis effort, presently underway, is identifying the TPDM critical design parameters to be used as a basis for development tests and generation of relevant results. Requirements compilations and performance specification for all supporting and interfacing systems should be completed in this phase. The requirement for a flight demonstration to resolve some of the issues mandates conducting a thorough review to establish the envelope mission case(s). This ensures that ground demonstrations investigate these sufficiently to maximize the benefit of the flight element.

It is suggested that computer modeling of the dynamics problem be started at this time frame to drive out the design specific flexibility issues and set up projected test correlation parameters for the tests. The simulation software will also support development of test plan scenarios and establish confidence in formulation of planned procedures. The leap frog approach between test and design computer simulation should continue to productively evolve the final design.

The fabrication of test hardware, evolving out of design analysis, should accommodate as many of the flight dynamic hardware qualities as possible since these are the factors we are looking to simulate in the ground test program and subsequent flight demonstration. The first test to be performed is a form-fit test that examines the correlation of the geometry and latch movement initiation algorithm. Test objectives are to include areas such information on tolerances and the possibility of off-nominal capture binding conditions; the computer dynamics software can be modeled to accommodate some of the former goals.

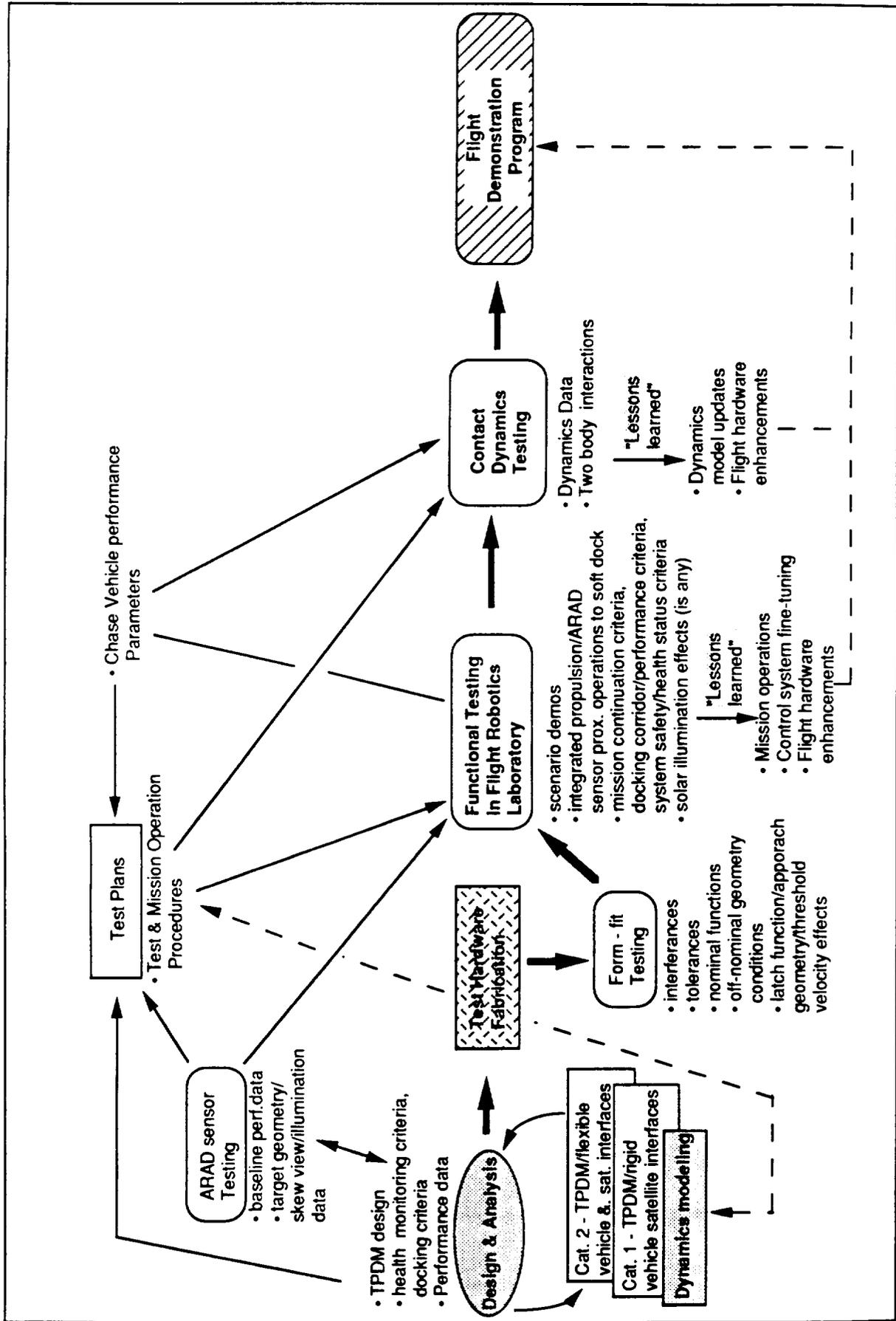


Fig. 6-3 TPDM Development Path - Resolution of Flight Issues

The functional testing in the Flight Robotics laboratory represents the first opportunity to test the integrated propulsion control-ARAD sensor-docking/abort systems with limited (as planned) operator supervision. Testing would include a full mission simulation from at least the point of attempted initial target recognition by the ARAD sensor to attaining initial capture position. Breakaway targets may be used in the test to mitigate the possibility of damage to the facility 6-DOF arm if off-nominal contact loads occur. "Lessons learned" will be included in the design implementation.

The contact dynamics testing will address the areas starting from just before latch movement to rigidization. "Lessons learned" should be incorporated in the design implementation.

Based on successful completion of the ground test development program and the careful incorporation of "lessons learned" upgrades in the test hardware, we should have a lower risk basis for proceeding with a flight experiment to resolve the remaining issues. Data should be available from the ground program to provide a detail projection of flight demonstration test results.

Appendix A

Documents Transmitted for Use and Review

1. *OMV Contact Dynamics Test - Overview and Status Update*, March 30, 1990, TRW presentation
2. *Multi-mission Modular Spacecraft Flight Support System User's Guide (through change notice 2)*, 408-2112-0004, March 1980, NASA/GSFC document
3. *Preliminary Design Review for the Three Point Docking Mechanism Latch Assembly (TPDML)*, dated May 22-24, 1990, Spar Aerospace Limited document
4. *6 - DOF TPDM Contact Dynamics Testing*, September 1990, NAS8-36800, TRW document
5. *Three Point Docking Mechanism Contact Dynamics Test*, November 7, 1990, TRW presentation
6. *Equipment Specification Three Point Docking Mechanism (TPDM)*, EQ2-830 Rev A dated April 23 1989, TRW document
7. *Contact Dynamics Simulations, Report #2*, document OMV.89.300-103 dated April 11, 1989, TRW document
8. *User's Guide for the Orbital Maneuvering Vehicle*, October, 1987, NASA/MSFC document
9. *User's Guide for the Orbital Maneuvering Vehicle*, March, 1989, NASA/MSFC document
10. *User's Guide for the Orbital Maneuvering Vehicle*, July, 1989, NASA/MSFC document
11. *OMV/Payloads Interface Requirements Document I Space Telescope*, OMV/ST IRD, January 9, 1985, GSFC document
12. Book, Michael L., Bryan Thomas C., et. al. "Autoguidance Video Sensor for Docking", (technical paper)
13. *Use of Explorer Platform to Demonstrate Automatic Closure and Docking*, dated October 11, 1991, Fairchild presentation
14. TPDM Survey Sheets; requested via memorandum dated June 3, 1991, Thomas C. Bryan to Distribution

15. *Equipment Specification Mechanism Control Electronics (MSE)*, EQ4-4100 Rev A dated April 24 1989, TRW document
16. *Design Criteria for Controlling Stress Corrosion Cracking*, MSFC-Spec-522B, July 1, 1987,
17. *Protective Finishes for Space Structures and Associated Flight Equipment General Specification for*, MSFC-SPEC-250A, October 1, 1977
18. *General Specification Vacuum Stability Requirements of polymeric Material for Spacecraft Application*, JSC specification SP-R-0022A, September 9, 1974
19. *Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for materials in Environments That Support Combustion*, NHB 8060.1C, April, 1991
20. *Man System Requirements for Weightless Environments*, MSFC-STD-512A, December 1, 1976