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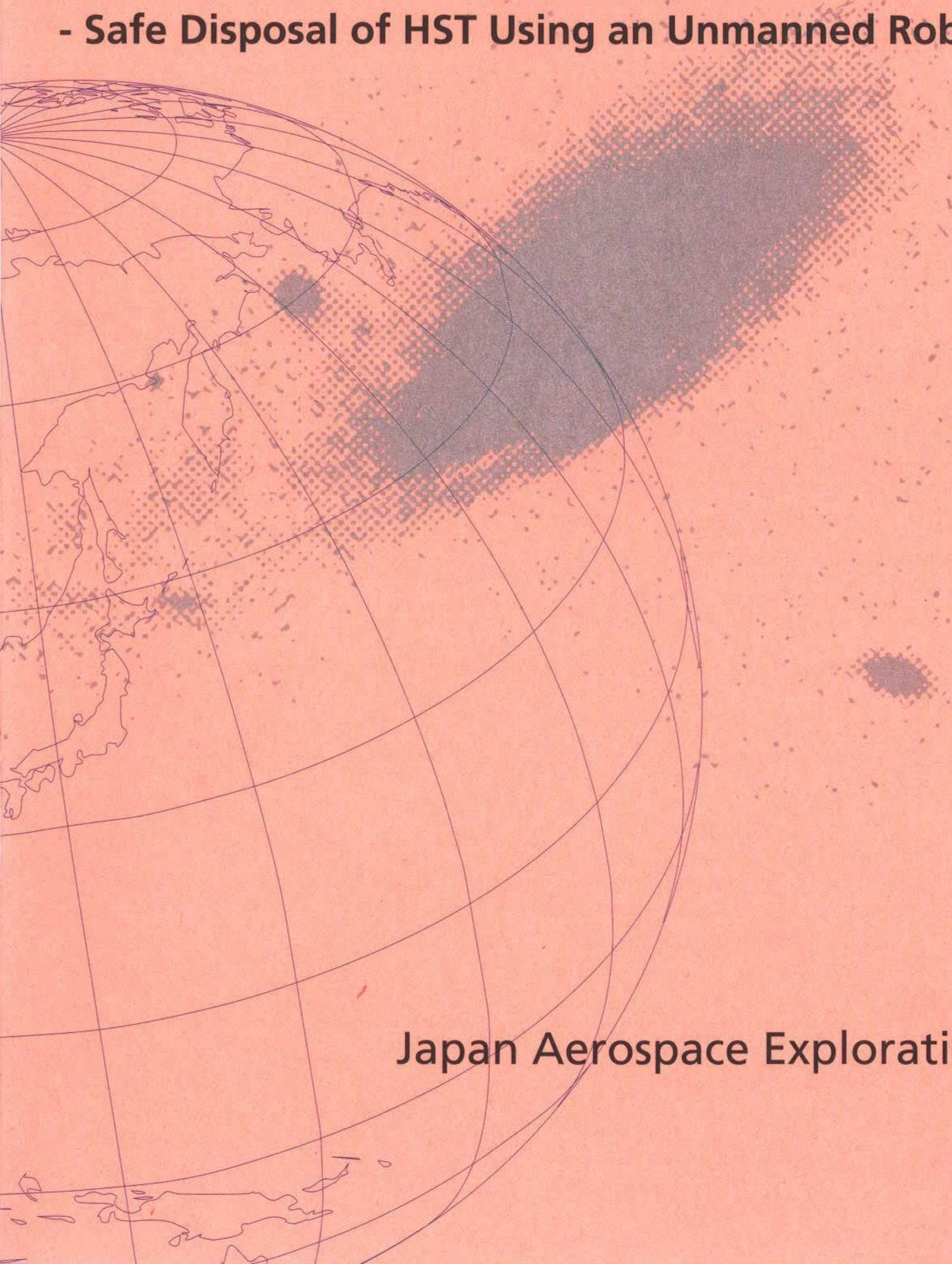
JAXA Research and Development Memorandum

# Feasibility Study of Robotic Servicing for the Hubble Space Telescope

## - Safe Disposal of HST Using an Unmanned Robot Vehicle -



July 2004

Japan Aerospace Exploration Agency

JAXA-RM-04-001E

JAXA Research and Development Memorandum
宇宙航空研究開発機構研究開発資料

# Feasibility study of Robotic Servicing for the Hubble Space Telescope

## - Safe disposal of HST using an unmanned robot vehicle -

# ハッブル宇宙望遠鏡に対する保守・投棄サービスの実現性研究

## - 無人宇宙機によるハッブル宇宙望遠鏡の安全な投棄 -

Hubble Space Telescope Robotic Service Mission Study Team
Institute of Space Technology and Aeronautics

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July 2004
2004 年7月

Japan Aerospace Exploration Agency
宇宙航空研究開発機構

Abstract

The Hubble Space Telescope (HST) was launched in 1990 and has produced various scientific results since then. HST is receiving periodical maintenance by Space Shuttles crew members every few years.

However the accident involving the Space Shuttle Columbia that occurred on February 1, 2003 resulted in the cancellation of the planned shuttle visit to HST. Since HST dose not have a capability of safe disposal while its body is massive, part of spacecraft my come down in some populated area in the near future.

Therefore, some kind of robotic mission is needed to extend HST's life and/or to remove HST from orbit.

This report summarizes the study result that an unmanned robot vehicle named HDV (HST De-orbit Vehicle) that will be developed using currently being developed H-II Transfer Vehicle (HTV) and JEM remote manipulator system can conduct the requested mission as follows.

- launch by an expendable launcher
- automated rendezvous to HST
- capture HST using HDV's robot arm
- docking to HST
- controlled atmospheric re-entry (safe disposal of HST)

Study of HDV was conducted by the HST robotic service mission study team, being organized by members from Japan Aerospace Exploration Agency, Mitsubishi Heavy Industries, Ltd, Mitsubishi Electric Corporation, NEC Toshiba Space Systems, Ltd, and Kawasaki Heavy Industries, Ltd. The members of this study team are listed in Appendix-2.

keywords

Hubble Space Telescope
HST
Rendezvous
Space Robot
De-orbit

**和文抄録**

ハッブル宇宙望遠鏡(HST)は1990年に打ち上げられ、多くの有益な成果をあげている。HSTはその打上げ後、スペースシャトルによる軌道上での定期的な保守を受けているが、2003年2月に起きたスペースシャトルコロンビア号の事故に関連して、予定されていたHSTへの最後の保守ミッションは中止となった。
HSTは12トンと巨大な衛星であるが、それ自身による安全な軌道離脱能力は有していない。HSTに搭載されている電子機器、特にバッテリやジャイロの劣化が進行しており、このままでは後、数年程度の運用しか出来ない。
このような状態にあってNASAはHSTの延命、及び／または安全な軌道離脱の提案要請(RFP)を出した。

本報告書は日本がこれまでの技術蓄積をもとに、求められているミッションを実施できる宇宙機(HDV)を現在JAXAが開発中の宇宙ステーション補給機(HTV)をベースとして速やかに開発できることを検討した結果をまとめたものである。

HDVはHTVの推進モジュール、電気モジュール、宇宙ステーション用マニピュレータ(JEMRMS)、ETS-VII用ドッキング機構等の設計を活かして開発される。HDVの直径は4.4m、全備質量は約7.1トンである。

HDVは使い捨てロケットで打上げられ、HSTへの自動的なランデブ、ロボットアームによる捕獲、HSTとHDVのドッキング、HSTとHDVを結合した状態での両宇宙機の安全な軌道離脱が可能である。

本検討はHSTサービスミッション検討チーム（JAXA、三菱重工業、三菱電機、NEC東芝スペースシステム、川崎重工業の各社のエンジニア、研究者で構成）により行われた。検討チームの構成メンバはAppendix-2に掲載されている。

**和文キーワード**
ハッブル宇宙望遠鏡、スペースシャトル、宇宙ステーション補給機、HDV、ランデブ、軌道離脱

JAXA Research and Development Memorandum (JAXA-RM-04-001E)

# Feasibility of Robotic Servicing for the Hubble Space Telescope
## - Safe disposal of HST by an unmanned robot vehicle -

## Index

## 1. Scope of this document

NASA issued a Request for Proposal (RFP) on June 1, 2004, requesting proposals for either of the following systems. (A copy of the RFP is attached in Appendix 1 of this document.)

- Hubble Space Telescope (HST) Robotic Vehicle De-orbit Module (HRVDM): This is a component of a larger vehicle whose combined purpose is to provide robotic servicing and life extension of the HST, and ultimately end-of-life controlled re-entry or other safe disposal of HST.
- Hubble Disposal Vehicle (HDV): This is a stand-alone vehicle whose only purpose is to provide end-of-life controlled re-entry or other safe disposal of the HST.

It is interesting to note that the systems required in NASA's RFP can be easily created by assembling various systems that have been developed or are under development by JAXA and Japanese companies.

The Japan Aerospace Exploration Agency (JAXA) and Japanese companies working with JAXA have considerable experience in the area of unmanned on-orbit servicing. Having successfully completed the pioneering project Engineering Test Satellite VII (ETS-VII), they are now developing the H-II Transfer Vehicle (HTV) and the Remote Manipulator System for the Japanese Experimental Module of ISS (JEMRMS). Through the development and operations of these systems and other experimental missions, we have acquired a solid technical basis for automatic rendezvous and docking, intelligent tele-manipulation of a dexterous space manipulator, and controlled re-entry.

Members of JAXA and Japanese companies initiated a feasibility study of the system described in the RFP. The system designed in our study is basically an HDV system based on our HTV. The system could also become an HRVDM through the addition of some optional equipment and functionality. Our conclusion is that the system is feasible.

## 2. Outline of the study results

### 2.1 Overview

### (1) Background

The Hubble Space Telescope (HST) was launched in 1990 and has produced various scientific results since then. HST is receiving periodic maintenance by Space Shuttles crew members every few years to replace degraded equipment. However, the accident involving the Space Shuttle Columbia that occurred on February 1, 2003, resulted in the cancellation of the planned shuttle visit to HST, referred to as Service Mission 4 (SM4).

Since some key equipment on HST is aging and degrading, HST will not be able to continue safe operation for more than a few years. Moreover, since HST is a massive spacecraft and does not have a capability for safe de-orbiting, part of the spacecraft may come down in some populated area in the near future. Therefore, some kind of robotic mission is needed to extend HST's life and/or to remove HST from orbit. These circumstances prompted NASA to issue the above-mentioned RFP.

### (2) Feasibility study

In response to the RFP, engineers and researchers from JAXA and from Japanese companies worked together to conduct a joint feasibility study of robotic servicing of the Hubble Space Telescope. (The members of this study team are listed in Appendix 2 of this document.) After the study, we concluded that capturing and de-orbiting HST by an unmanned robot vehicle is possible using existing technology that JAXA and Japanese companies have developed during past and on-going missions such as Engineering Test Satellite VII (ETS-VII), Japanese Experiment Module Remote Manipulator System of the International Space Station (JEMRMS), and the H-II Transfer Vehicle (HTV).

We also concluded that robotic servicing to extend the life of HST would be feasible but also highly risky, since extensive preparations are needed to conduct such a mission in a very limited time.

In this report, we propose a system that performs the safe disposal of HST as the baseline system and a system that extends the life of HST as an option.

## 2.2 Spacecraft

### (1) HST de-orbit vehicle

The HST de-orbit vehicle (HDV) is a 4.4m-diameter spacecraft with a mass of 7.1 tons, including 2.4 tons of fuel. It consists of a propulsion module, an avionics module, a mission module that includes a remote manipulator system, a docking mechanism, a data relay antenna, and photovoltaic solar cell paddles. Figures 2.2-1 through 2.2-3 depict an artist's images of the HDV.

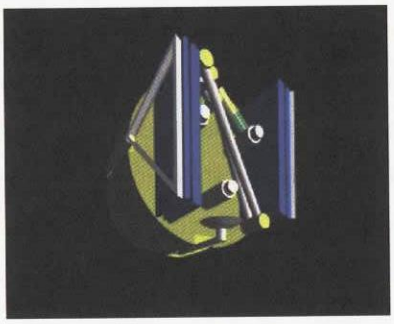


Fig.2.2-1 HDV at launch phase

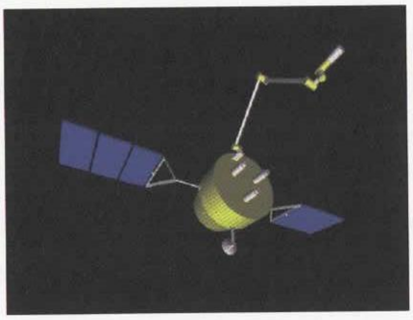


Fig.2.2-2 Orbiting HDV

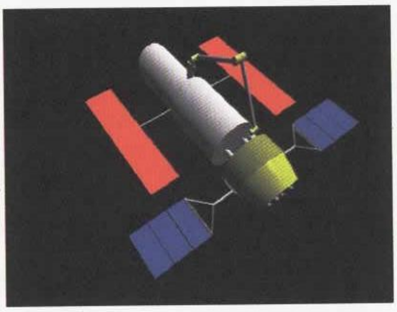


Fig.2.2-3 Docking with HST

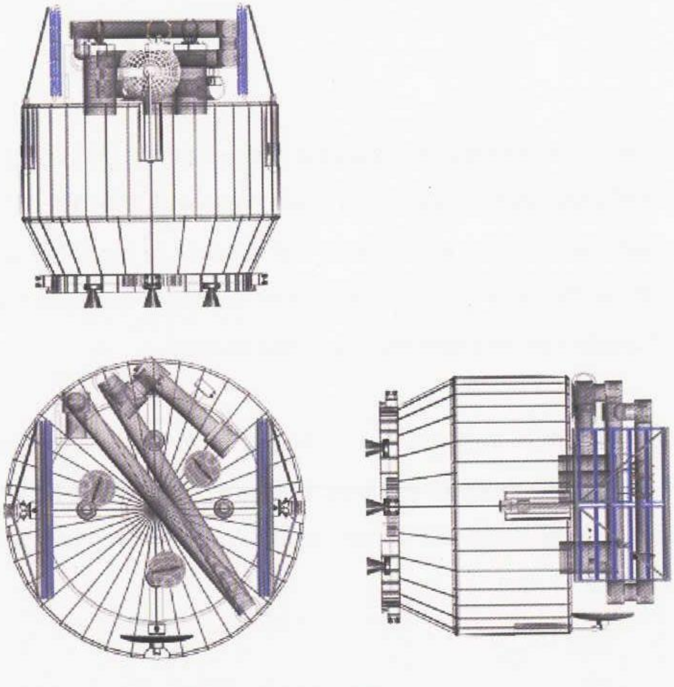


Fig.2.2-4 HDV launch configuration

Major specifications of the HDV are as follows.

| | |
|---|---|
| Mass (dry) | 4.7 tons |
| Mass (total) | 7.1 tons |
| Diameter (at launch) | 4.4 m |
| Required Electrical Power | 2 kW |
| Communication | via TDRSS and direct |
| Mission life | 3 months -- up to 1 year (TBD) |

The HDV will be launched by an expendable vehicle such as JAXA's H-IIA rocket. The HDV will perform an autonomous rendezvous with HST and will capture HST at its grapple fixture using the HDV's remote manipulator system. The manipulator will then place HST in a docking position such that HST's aft bulkhead will face the HDV's docking mechanism. Finally, HDV's docking mechanism will grasp the berthing pins of HST. The HDV will then conduct an atmospheric controlled re-entry with HST attached, ending in the southern Pacific Ocean, the Indian Ocean, or the southern Atlantic Ocean.

This HDV will be built based on the existing design and technology of the HTV, the JEMRMS, and ETS-VII. The HDV's spacecraft frame, propulsion module and avionics module are taken from the HTV, with minor modifications.

(2) HTV

The HTV will normally carry cargo to the International Space Station (ISS). The HTV will be launched by JAXA's H-IIA rocket and will conduct an autonomous rendezvous with ISS. The HTV will then be captured by the space station remote manipulator system (SSRMS) and attached to the ISS's node. After the cargo on the HTV is transferred to the JEM, the HTV will be loaded with unneeded items and will then be separated from ISS. Finally, the HTV will conduct an atmospheric controlled re-entry.

The mass of a fully loaded HTV is 16 tons and that of the HTV core module (propulsion module and avionics module), which does not include the payload sections, is 4 tons. The HTV's core module thus has sufficient capability to conduct the rendezvous with HST as well as the controlled re-entry with HST. Figures 2.2-5 and 2.2-6 illustrate the HTV.

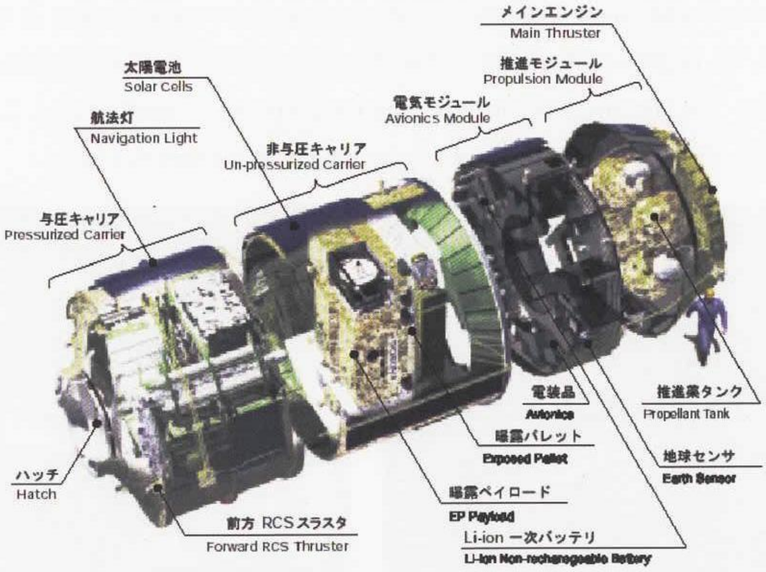


Fig. 2.2-5 H-II Transfer Vehicle

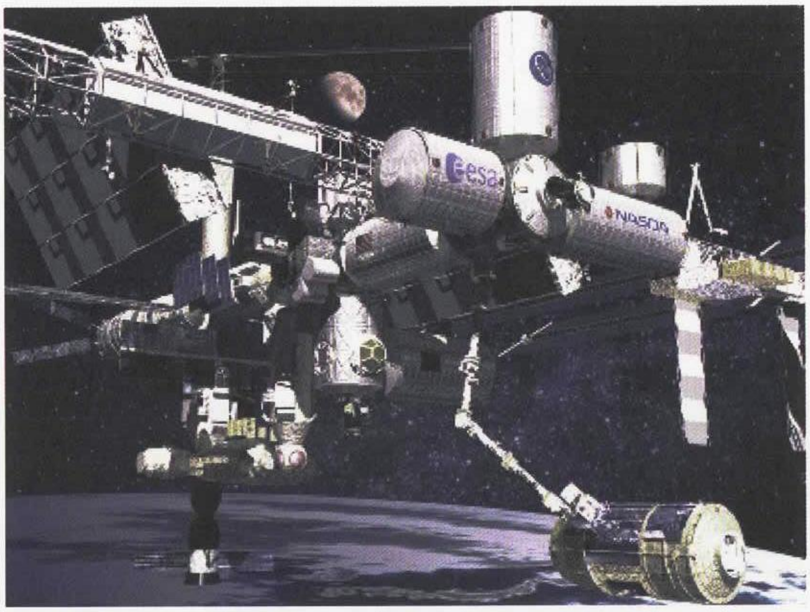
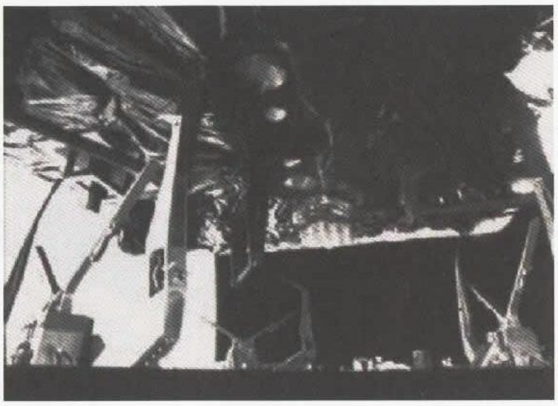


Fig. 2.2-6. HTV being captured by the space station manipulator

(3) ETS-VII

Autonomous rendezvous docking between two unmanned satellites was demonstrated in 1998 and 1999 by NASDA's ETS-VII satellite. ETS-VII consists of a chaser satellite and a target satellite. Both satellites were launched together in 1997 using the H-II rocket. The target satellite was released from the chaser satellite during the rendezvous docking experiments. At the end of each experiment, the target satellite was captured and docked to the chaser satellite using the docking mechanism. Figure 2.2-7 shows an artist's image of the orbiting ETS-VII chaser and target satellites. Figure 2.2-8 shows a picture taken at the docking of ETS-VII satellites. The ETS-VII target satellite (Fig. 2.2-8) has three sets of docking handles that are similar to the berthing pins of HST. The docking mechanism of the ETS-VII chaser satellite (Fig. 2.2-8) grasps the docking handles automatically. The shock generated by this docking was less than 0.1 G.



(Left) Fig. 2.2-7 Artist's image of ETS-VII satellites (Chaser left, target right)

(Right) Fig. 2.2-8 Docking of the ETS-VII chaser (lower) and target (upper) satellites

### (4) JEMRMS

HST will be captured using the HDV's RMS, which is equivalent to the JEMRMS. The JEMRMS manipulator is 10 meters long and has an end-effector similar to that of the space shuttle remote manipulator system (SRMS). The HDV's manipulator will grasp an HST grapple fixture (GPF) used for capturing HST with SRMS. Since the diameter of the HDV and that of the JEM Pressurized module to which the JEMRMS is to be attached are the same (4.4 meters), the JEMRMS can be attached to the HDV without major modifications.

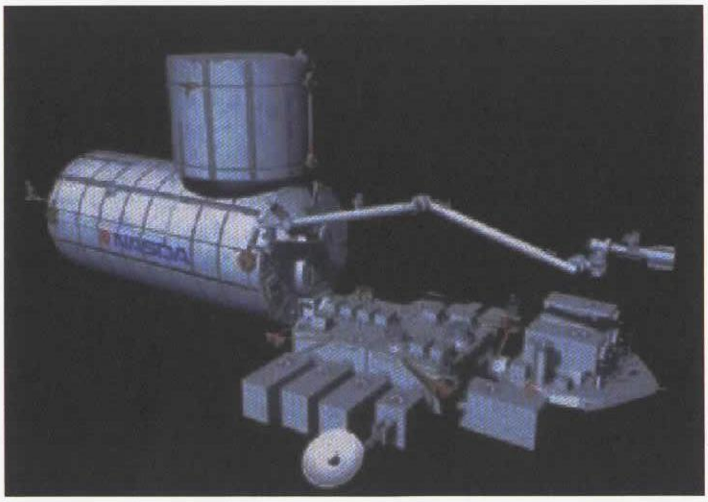


Fig. 2.2-9 Artist's image of JEM and JEMRMS

Fig. 2.2-10 JEMRMS flight model

### (5) Autonomous satellite capture

Autonomous satellite capture by a satellite-mounted manipulator was demonstrated by NASDA's ETS-VII satellite in 1999. The ETS-VII chaser satellite has a 2m long manipulator that operates in the remote-controlled mode or the autonomous control mode.

During the autonomous satellite capture experiment, the docking mechanism was partially released to allow both satellites to move freely. The manipulator was placed into a vision-based autonomous control mode and was guided to the appropriate position to capture the target satellite. Finally, the manipulator successfully grasped a handle on the target satellite. Figure 2.2-11 shows the autonomous satellite capturing experiment performed on the ETS-VII satellite.

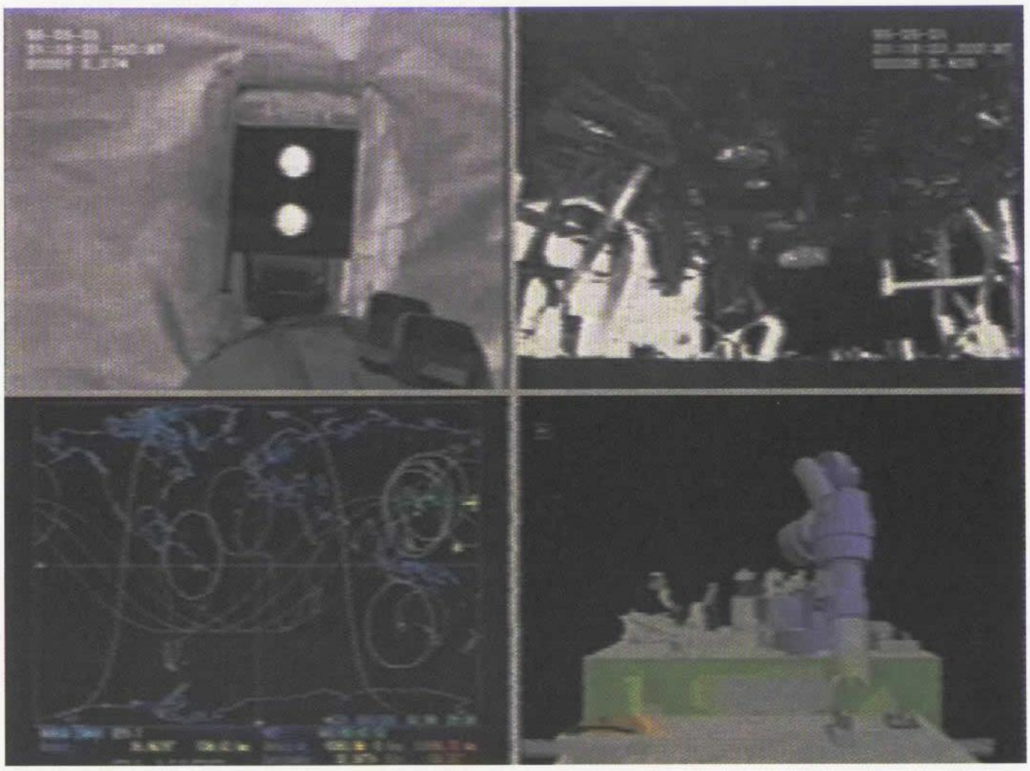


Fig. 2.2-11 Autonomous satellite capture experiment conducted by ETS-VII

## 2.3 Mission scenario

The HDV's mission will be conducted as follows. (Details of the individual tasks are analyzed in Section 4.)

### (1) Launch of the HDV

The HDV will be launched by an H-IIA, or other available expendable launch vehicle, into LEO (altitude TBD; inclination 28deg). If an H-IIA is used, the H-IIA will have sufficient capability to place HDV into an orbit close to HST.

After the HDV separates from the rocket, its solar panels and a data relay antenna mast will be deployed. Communications with the HDV will be realized via NASA's Data Relay Satellite (TDRS).

### (2) Rendezvous with HST

After the HDV separates from the rocket, the HDV will perform a phasing maneuver to adjust the phase between the HDV and HST.

After the phasing maneuvers, the HDV will be injected into an approach initiation (AI) point that is at the same altitude with HST and TBD km behind HST.

### (3) Fly-around inspection (optional)

After the HDV arrives at the AI point, the HDV will conduct a fly-around inspection. In this fly-around maneuver, the HDV goes forward, passing TBD meters beneath HST, and arrives at a point TBD meters ahead of HST. The HDV then goes back, passing TBD meters above HST, and returns to the AI point.

During these maneuvers, a visual inspection of HST and a final check of the rendezvous sensors on the HDV will be conducted.

### (4) Final approach to HST

After the fly-around inspection, the HDV will move to the V-bar injection point (VI), which is 3 km (TBD) ahead of HST and at the same altitude as HST, using GPS-based navigation data and the predicted HST positional data. At the VI point, the Far-range Rendezvous Sensor (FRS) on the HDV will acquire HST in its Field of View (FOV). The HDV then approaches the HST from a position ahead of the HST.

During the V-bar approach, the HDV's attitude is maintained such that the HDV points towards the HST. This final approach maneuver will be conducted at local noon or under other circumstances that allow the solar paddles of HST to be placed in a position parallel with the main body of HST.

When the HDV approaches to within TBD meters, the HDV's manipulator will be deployed and placed into the capturing pose.

When the HDV approaches to within TBD meters, attitude control of HST and the HDV will be inhibited to avoid unpredictable attitude motion.

## (5) Capturing HST

When the HDV approaches to within 7 meters (TBD) of HST, the HDV's Remote Manipulator Subsystem (RMS) will be guided toward the grapple fixture of HST. After the end-effector of the manipulator approaches to within 0.5 meters (TBD) from the GPF of HST, the end-effector will grasp the GPF of HST.

## (6) Capturing the uncontrolled HST

If HST is no longer functioning properly and thus is unable to maintain its attitude at the time of the proposed mission, it will be tumbling. In this case, the HDV will approach to a distance of 10 meters (TBD) from HST and wait until the motion and attitude of HST allow it to be captured by the HDV's manipulator. If HST's GPF faces towards the HDV, the HDV will continue its approach until it is within TBD meters and able to grasp HST's GPF using the HDV's manipulator. Attitude control of the HDV will be suspended when HST is captured by the manipulator. After HST has been captured by the manipulator, any relative motion of the two satellites will be gradually absorbed by the manipulator. Attitude control of HDV will be resumed after all relative motion of the two satellites has been absorbed.

## (7) Docking HST with the HDV

After the HDV's manipulator has grasped HST's GPF, the manipulator moves HST into a position in which the HDV's docking mechanism can grasp HST's berthing pins. The HDV's docking mechanism will then grasp HST's berthing pins. Once the docking mechanisms close their latching levers, a firm connection between the HDV and HST will be realized.

After docking of the HDV and HST is accomplished, attitude control of the HDV will be resumed and the HDV will achieve TBD attitude.

### (8) Life extension of HST

After docking of the HDV and HST is accomplished, attitude and orbit controls for the unified spacecraft will be maintained by the HDV. In this control mode, power is supplied to HST by HST's own electrical power system. Supplying power through HST's umbilical connector is possible. The period over which HST can continue to operate depends on the lifespan and reliability of the HDV. Since the nominal mission life of the HTV, the base spacecraft for the HDV, is 3 months, the duration of the HDV's mission, including continuation of the operation of HST, should be 3 months or less. Extension of the mission life of the HDV is optional.

Extension of HST's mission operation for more than one year will require a separate system, discussed in Section 7 as an option.

### (9) De-orbiting HST

The united HDV and HST will reduce their altitude to 150 km using the HDV's propulsion system. The vehicle will then wait for the final de-orbit timing.

De-orbiting is realized by a controlled re-entry to the Earth. The re-entry point will be the southern Pacific Ocean, the southern Atlantic Ocean, or the Indian Ocean.

# 3. Technologies to be applied

## 3.1 Rendezvous docking

JAXA (NASDA) successfully conducted automated rendezvous docking experiments using NASDA's ETS-VII chaser and target satellites. The chaser satellite weighs about 2.5ton and the target satellite weighs 0.4ton. The two satellites were launched together in a connected configuration by NASDA's H-II rockets. Orbit of ETS-VII is 550km altitude and inclination is 35deg. The two satellites was separated during the rendezvous docking experiments and re-united within each rendezvous docking experiment session.

Fig.3.1-1 NASDA's Engineering Test Satellite VII (Left: Target satellite, Right: Chaser satellite)

### (1) Rendezvous docking experiments

Following three rendezvous docking experiments were successfully conducted during the ETS-VII's two years mission life.

#### a) Undocking / docking experiment

In this experiment, the target satellite was released from the chaser satellite up to 2m distance and re-united each other using the docking mechanism. While two satellites were flying separately, relative position and attitude of both satellites were measured by the proximity sensor mounted on the chaser satellite. The proximity sensor is a CCD camera based sensor that detects marker reflectors on the target satellite. The marker reflector was illuminated by LED on the chaser satellite.

b) Relative navigation experiment

In this experiment, the relative navigation using the laser radar up to 500m distance and the relative navigation using GPS up to 12km distance were demonstrated. Rendezvous trajectory was V-bar approach in this experiment.

c) R-bar approach experiment

In order to simulate HTV's rendezvous to the international space station, the R-bar approach experiment was satisfactory conducted. Since docking mechanism and the rendezvous laser radar are mounted to conduct the V-bar approach, the chaser satellite approached an imaginary target which simulates ISS from beneath of it using GPS data and simulated laser radar data.

### (2) Relative navigation and control

ETS-VII demonstrates relative navigation control in following three modes.

- Relative position and attitude control against target satellite using proximity sensor within a few meters relative distance.
- Relative navigation and LOS control of chaser satellite against the target satellite using rendezvous laser sensor within some 500 m distance.
- Relative navigation using two satellites using both satellites' GPS data within 12 km.

### (3) Low impact docking

Docking of both satellites were realized by the docking mechanism on the chaser satellite and the docking handles on the target satellite. During the docking operation, the chaser satellite slowly approached toward the target satellite. When the docking handles of the target satellite comes in the envelope of the docking mechanism, latching lever of the docking mechanism was closed to capture the docking handle of the target satellite. Relative distance and relative attitude between the two satellites were measured by the proximity sensor that is based on CCD camera that detects reflector markers on the target satellite. Docking mechanisms of chaser and target satellites are shown in Fig.3.1-2 and Fig.3.1-3. ETS-VII's docking was so-called "low impact docking. Sock at the docking of two satellites was less than 0.1G.

Fig.3.1-2 Docking Mechanism of ETS-VII

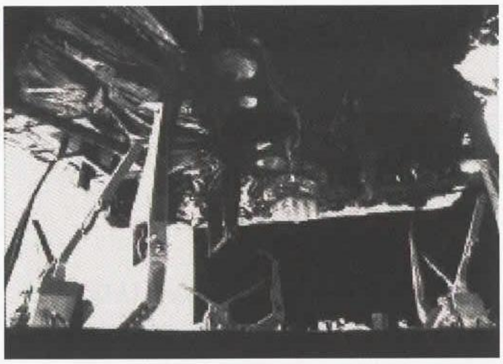


Fig.3.1-3 Docking of ETS-VII
chaser (lower) and target satellite (upper)

### (4) V-bar approach and R-bar approach

ETS-VII also demonstrated two types of rendezvous maneuvers, the V-bar approach and the R-bar approach. In the V-bar approach, the chaser satellite approached the target from forward of the target satellite at the same altitude. In the R-bar approach, the chaser satellite approached the simulated (imaginary) target satellite from beneath of it.

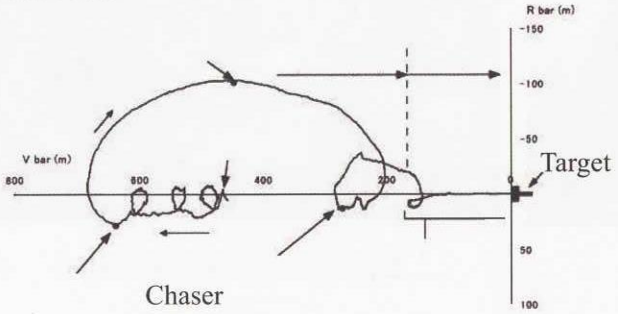


Fig.3.1-4 V-bar approach of ETS-VII chaser to the target satellite

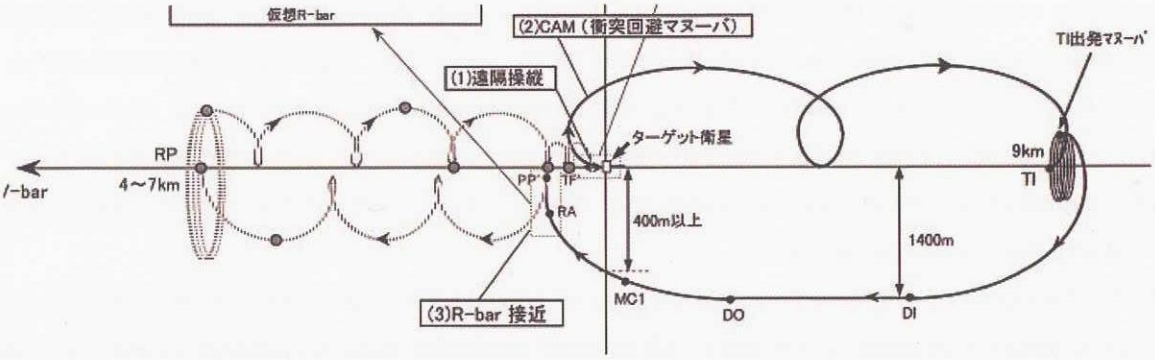


Fig.3.1-5 R-bar approach of ETS-VII chaser to an imaginary target that simulates ISS

## 3.2. Space robot

JAXA (former NASDA) conducted following two robot missions and preparing launch of manipulator system (JEMRMS) for ISS.

### 3.2.1 Manipulator Flight Demonstration mission (MFD)

In 1997 NASDA conducted MFD (Manipulator Flight Demonstration) mission using the Space Shuttle. In this mission, equivalent model with JEMRMS small fine manipulator (1.5m long manipulator of 6 degrees of freedom) were mounted on the space shuttle cargo bay and operated by onboard astronaut. Objective of this mission was to verify design of space manipulators to be used on ISS/JEM. This mission was successfully conducted.

Fig.3.2-1 MFD mission

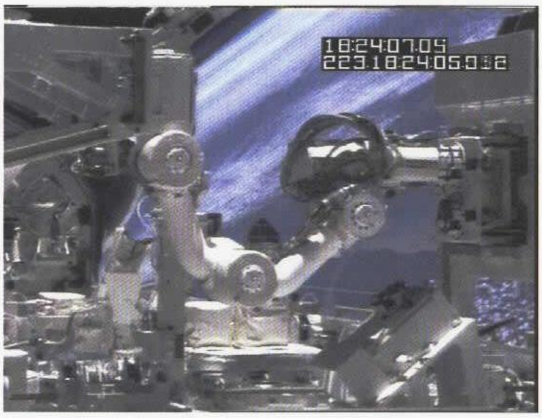


Fig.3.2-2 Manipulator of MFD

### 3.2.2 ETS-VII (Engineering Test Satellite VII)

Another robot mission was ETS-VII. Missions of ETS-VII were to demonstrate the automated rendezvous docking technologies and space remote-robotic system. In the space robot experiments, a manipulator on the ETS-VII chaser satellite whose length is 2m long was remote-operated from the on-ground control station at NASDA Tsukuba space center. In this robot experiments, various technologies were demonstrated such as;

(a) Coordinated satellite attitude and manipulator control not to disturb satellite attitude stability when a manipulator works on the satellite.

(b) Remote-operation of onboard manipulator from on-ground control station by various ways.

(c) Demonstration of some robotic tasks such as visual inspection using manipulator's hand eye camera, ORU (Orbital Replacement Unit) handling (de-mating / mating), simulated fuel supply, autonomous satellite capture by a manipulator, and others)

Fig.3.2-3 shows ORU handling experiment using remote-operated manipulator. Fig.3.2-4 shows target satellite handling experiment.

Fig.3.2-3 ORU handling by the manipulator

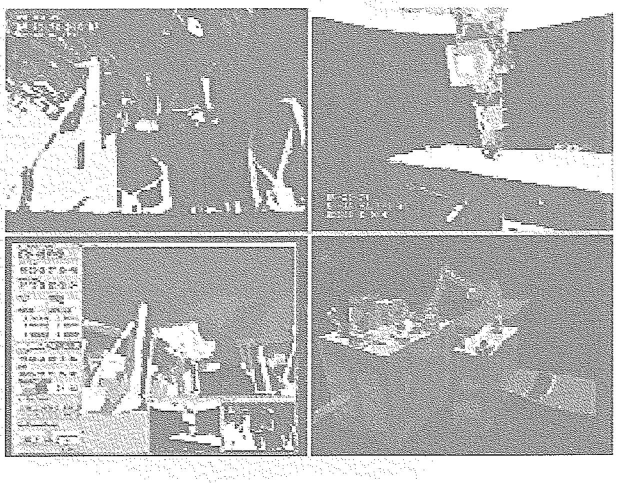


Fig.3.2-4 Target satellite handling experiment

### 3.2.3. JEMRMS (Japanese Experiment Module Remote Manipulator System)

NASDA developed Japanese Experiment Module (JEM) for ISS. JEM is now waiting launch at NASA Kennedy Space Center. JEM Remote Manipulator System (JEMRMS) is attached to JEM and will be used to handle equipments on JEM such as the logistic module and ORU. JEMRMS consist with large Main manipulator (6 degrees of freedom and 9.9m long) and the small fine manipulator (6 degrees of freedom and 1.9m long). The Main is used to handle large logistic module and large experimental equipment. The small fine will be used to handle small ORUs.

Major specification of JEMRMS is as follows.

| | | |
|---|---|---|
| Degrees of freedom | 6 | 6 |
| Length | 9.9m | 1.9m |
| Mass | 780kg | 200kg |
| Max P/L | 7ton | 300kg |

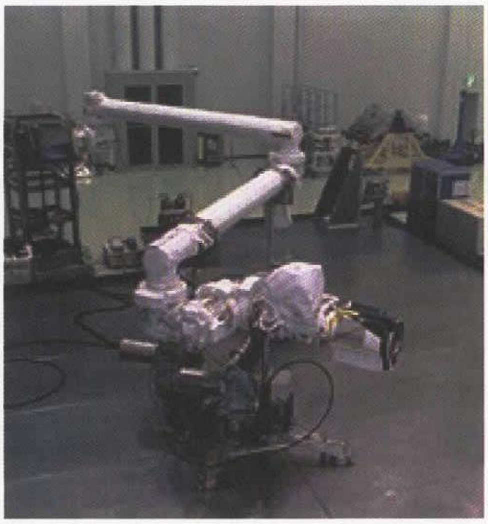


Fig.3.2-5 JEMRMS flight model

Fig.3.2-6 JEMRMS attached to JEM Pressurized module

## 3.3 H-II Transfer Vehicle (HTV)

H-II Transfer Vehicle (HTV), currently under development, is designed specifically to transport various cargos to the International Space Station (ISS) using the H-IIA launch vehicle. The orbital transfer vehicle approaches the ISS and stays at a predetermined stationary position. HTV is then captured by the Space Station Remote Manipulator System (SSRMS) and berthed to the designated port. Accordingly, the HTV must satisfy the same reliability and safety as manned spacecraft in order to prevent any possible to the ISS.

After being placed in orbit backward the ISS, HTV approaches the ISS using the relative GPS and Rendezvous Laser Rader. The vehicle halts at a predetermined region called Berthing Box, and the SSRMS captures and berths it to the ISS.

HTV uses the rendezvous algorithm which was developed through the Engineering Test Satellite-7 (ETS-VII) project. The ETS-VII performed an approach and rendezvous flight demonstration simulating the HTV final approach trajectory to the ISS. The result proved the algorithm capable to the actual flight of HTV.

Major specifications of HTV are as follows.

| | |
|---|---|
| Diameter: | 4.4 meter |
| Length: | 9.2 meter |
| Weight: | 15 metric tons (at launch) |
| Payload: | 6 metric tons (excl. mass of payload carriers) |
| Rendezvous orbit: | altitude 350km – 460km, Incl. 51.6deg |

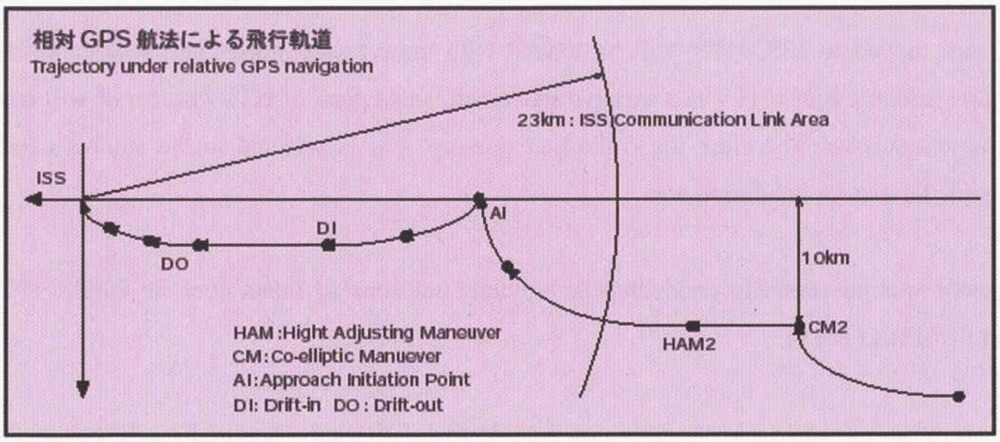


Fig.3.3-1 HTV's rendezvous trajectory to ISS

HTV consists of the propulsion module, the avionics module and the payload carriers.

Propulsion module is installed at the rear of HTV and composed of main engines, thrusters and the like. Four propellant supply tanks feed to main engines and RCS thrusters by using helium gas supplied from pressure vessels. Avionics module has two separate decks. Lithium batteries are installed on forward deck and electronic equipments for GNC, C&DH are installed on aft deck. On the surface of HTV Avionics module, antennas and sensors are mounted.

HTV logistics carrier has 2 sections: pressurized section that can carry up to eight ISS standard payload racks; and un-pressurized section that can carry up to three EF Payloads on Exposed Pallet. With up to two operational flights a year, HTV is planned to deliver not only experiment equipment but also many kinds of logistics, such as clothes, foods, water and batteries for the ISS.

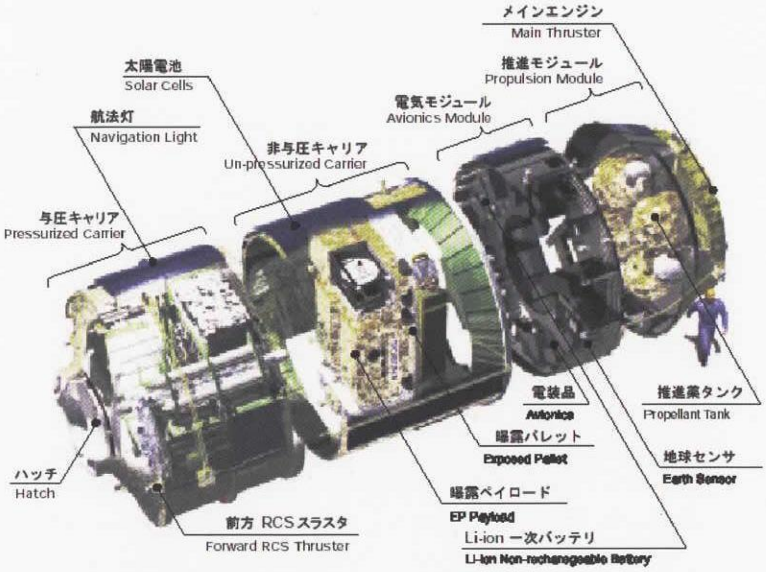


Fig.3.3-2 H-II Transfer Vehicle (HTV)

After the payloads are moved to ISS, HTV will be loaded with unnecessary goods and will conduct the controlled atmospheric re-entry. Since HTV is a massive spacecraft, some parts of HTV spacecraft will remain until splash down to sea surface. Therefore the controlled re-entry area is selected in the southern Pacific Ocean to avoid possible hazard for habitation area.

The controlled re-entry was successfully conducted in previous missions in Japan such as OREX (1994), HYFLEX (1996) and USERS (2003).

HDV will use the propulsion module and the avionics module of HTV. Major required modifications from HTV to HDV are as follows.

- Removal of the logistic carriers
- Removal of Lithium batteries
- Adding deployable solar panels and rechargeable batteries.
- Adding high gain data relay antenna and transponders
- Adding a manipulator and its control electronics
- Adding docking mechanism and its control electronics

# 4. Mission Analysis

## 4.1 Rendezvous with HST

### 4.1.1 Launch Phase

The HDV is launched by the H-IIA or other expendable launch vehicle and is injected into a circular orbit of 500km (TBD) altitude and same inclination with HST (i=28.45deg).

HDV's separation from the launch vehicle needs to satisfy a couple of conditions. First of all, the HTV attitude immediately after separation must be such that the X-axis in the HTV body axis coordinate is constrained in the direction of the velocity vector and the Z-axis axis is aligned with the nadir direction. The error about each axis must be less than 10 degrees. Also, the attitude rate about each axis of roll, pitch, and yaw after separation must not exceed 1 deg/sec.

### 4.1.2 Nominal Trajectory for Rendezvous

The nominal trajectory for rendezvous is defined as a period after launch vehicle separation to 20 km (TBD) aft point of HST co-orbit (AI : Approach Initiation point ) in this report. Design concepts for the nominal trajectory are as follows;

- Phase Adjustment Capability:

  The nominal trajectory has the phase adjustment capability of more than 380 degrees.

- Time Adjustment:

  The nominal trajectory has the time adjustment capability of 24 hours. With the support of Ground Operation Control System, it is done before launch by adjusting the number of orbital revolutions in the phase adjustment phase.

- Safety:

  The nominal and abort trajectories in the rendezvous phase including 3-sigma dispersions (sensor, thruster, and mass property errors) shall stay outside of a certain area defined by safty rules of the mission to be defined..

- Backup Maneuvers:

  The HDV has the capability to plan a set of backup maneuvers after an accidental delay of the pre-determined maneuver.

The nominal trajectory is shown in Fig.4.1.2-1. Maneuver points and altitude in the nominal trajectory will be optimized in the future work.

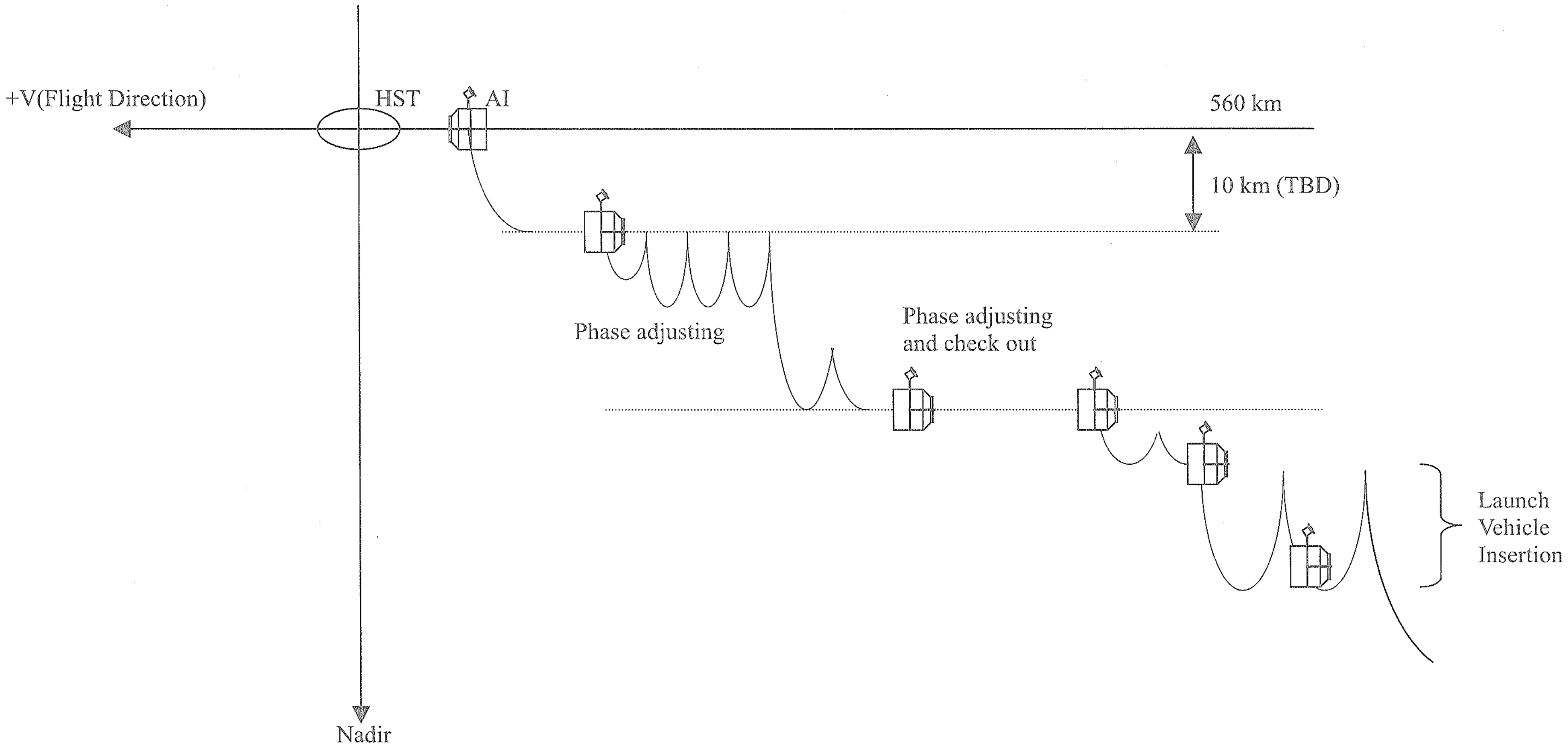


Fig.4.1.2-1 HDV rendezvous trajectory

### 4.1.3 Trajectory for Proximity Approach

Two types of proximity approach are considered to realize capture and direct docking.

#### (1) +V-bar Approach

HDV automatically executes several maneuver burns and flies from the AI point to the V-bar injection point (VI), where the target acquisition is performed using the Far-range Rendezvous Sensor (FRS). The navigation is based on the GPS absolute navigation using HDV/GPSR data and predicted HST position. The guidance is based on the CW (Clohessy-Wiltshire) algorithm, using the GPS navigation data.

Trajectory design should be conducted under some constraints of relative approach,

- TDRS communication coverage
- FRS navigation performance（FOV, Range and Range Rate, LOS angle, accuracy,）
- GPS navigation accuracy using HDV SIGI
- HST predicted position accuracy
- AI hold accuracy
- Atmospheric drag effect

Fig.4.1.3-1 shows HDV +V-bar insertion and approach in typical case. HDV departs from AI and stops at +V-bar. After acquisition of HST in the FRS FOV, HDV approaches on the V-bar with pre-programmed relative velocity in accordance with relative range from HST. FRS target acquisition (Catching HST) is an important event in the rendezvous. An active scanning strategy using attitude control and orbit dynamics is an option for sure acquisiton as shown in Fig.4.1.3-2.

In the proximity approach on the +V-bar, main navigation sensor is changed from FRS to Near-range Rendezvous Sensor (NRS). These sensors should be designed to be compatible in two case of HST attitude shown in Fig.4.1.3-3 and Fig.4.1.3-4.

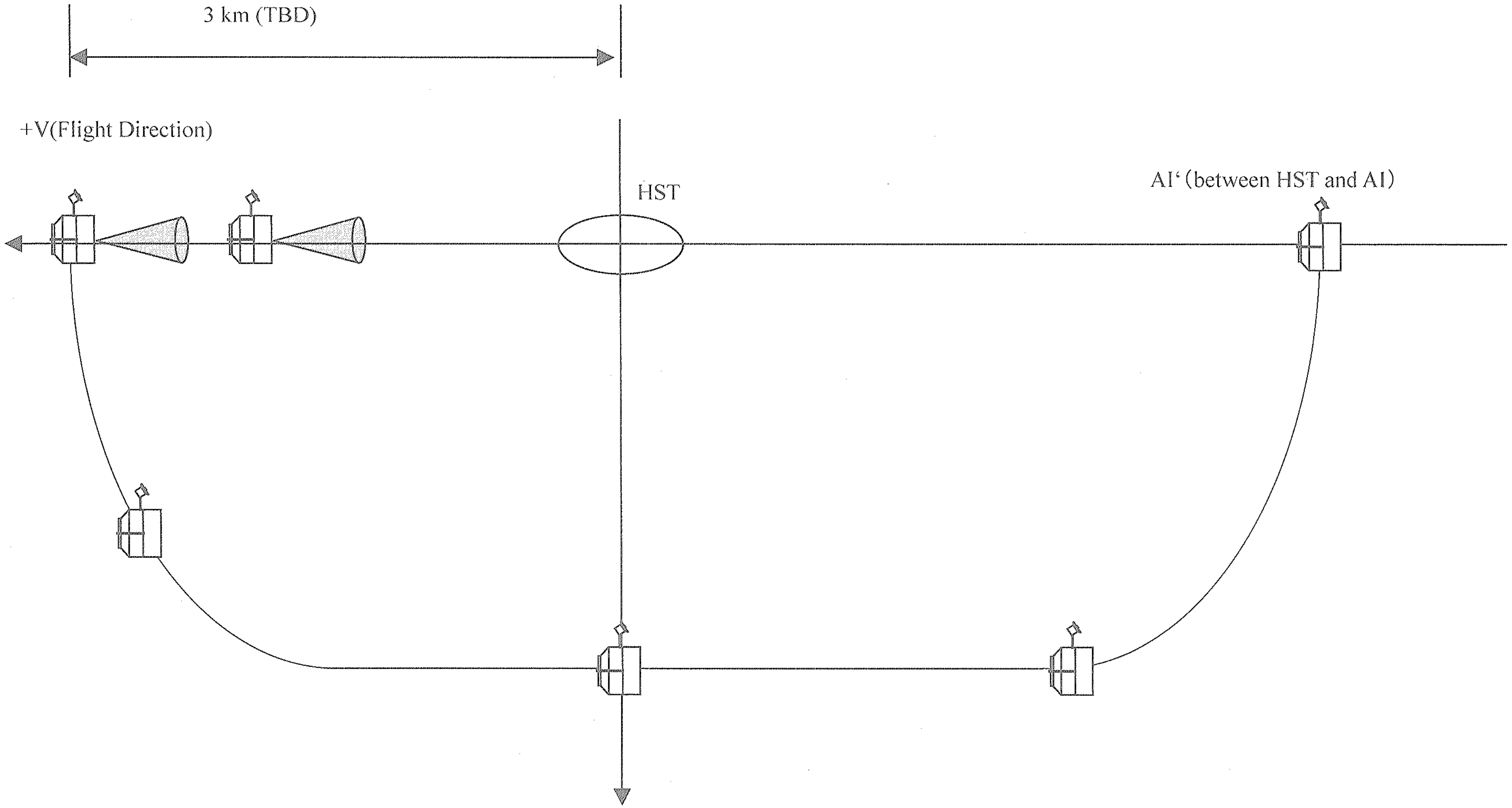


Figure 4.1.3-1 HDV +V-bar insertion and approach (typical case)

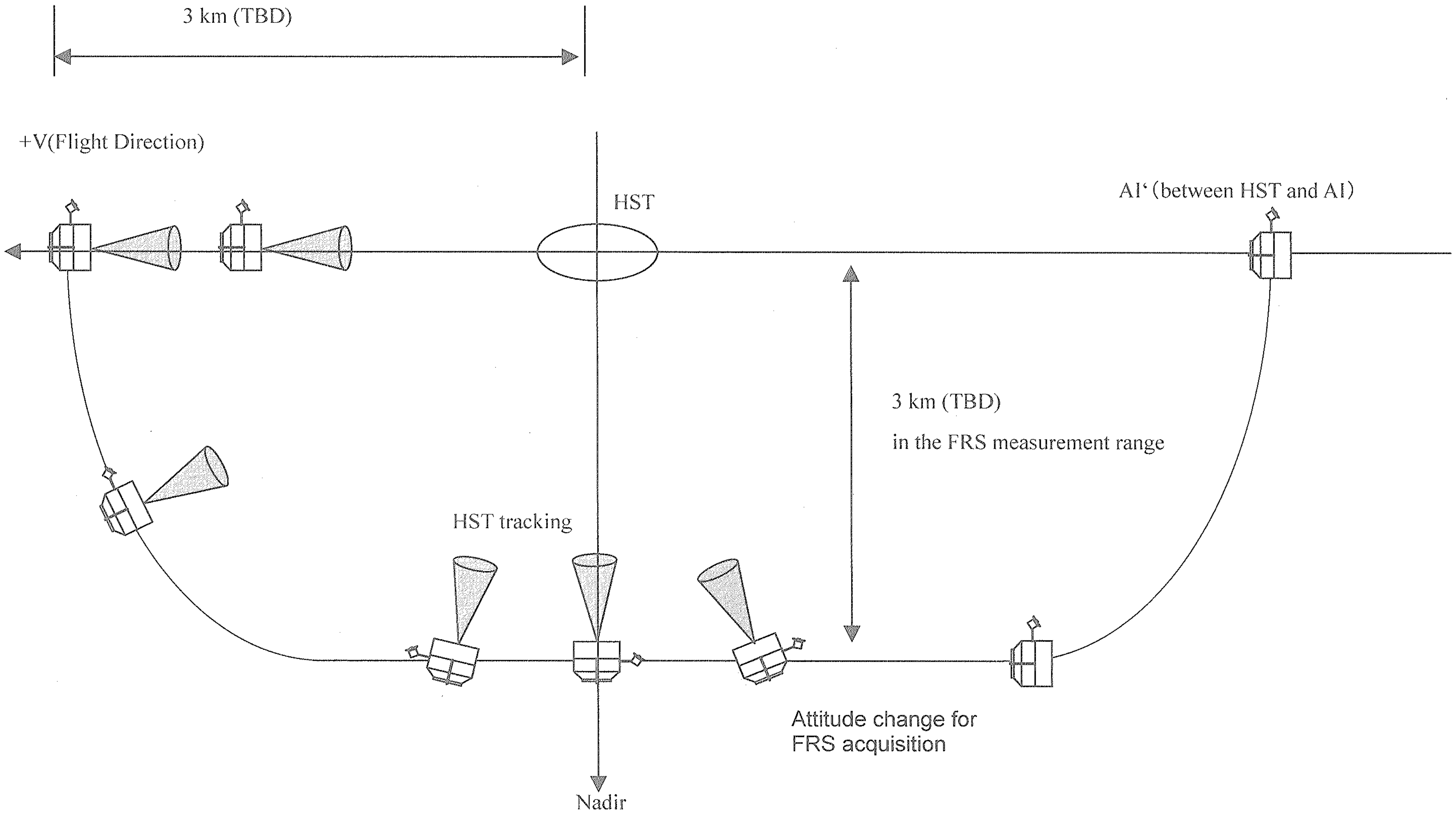


Fig.4.1.3-2 HDV +V-bar insertion and approach with active scan

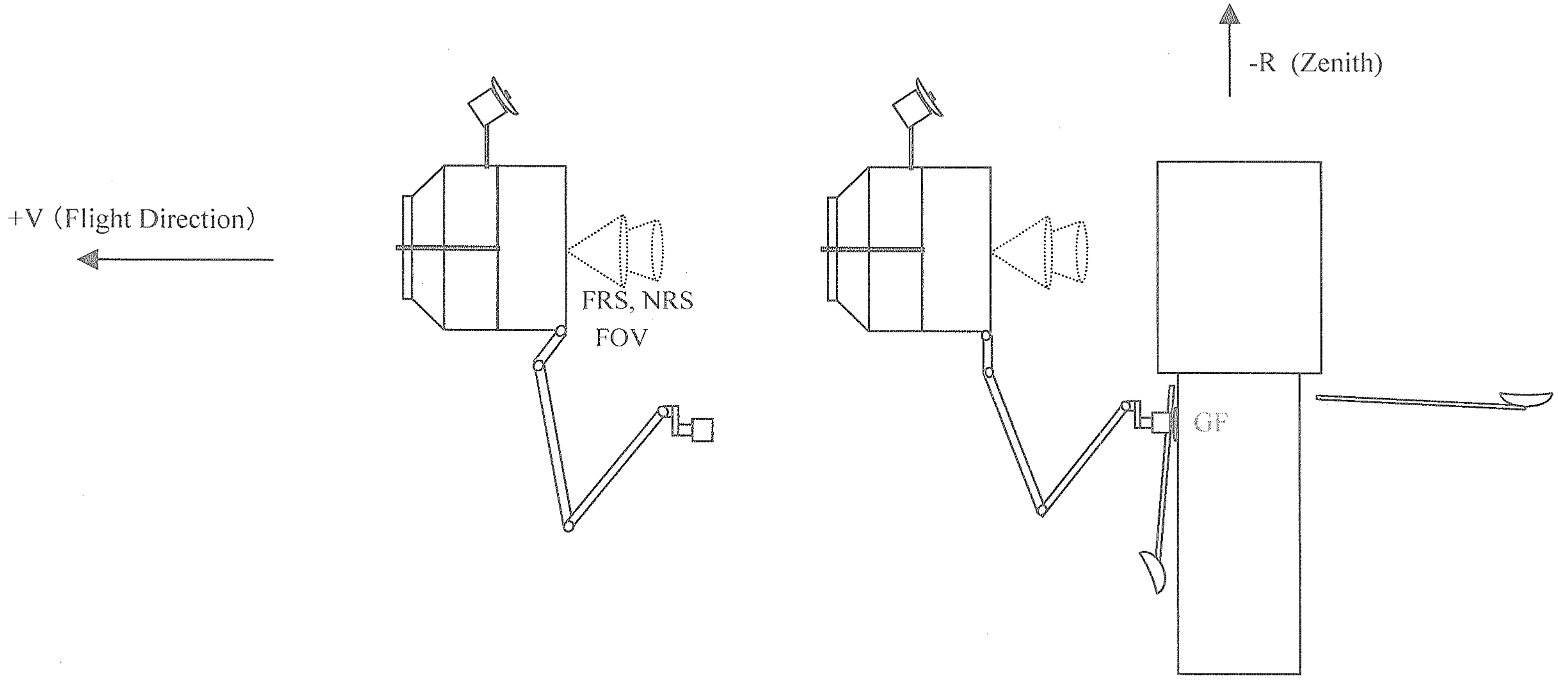


Figure 4.1.3-3 V-bar Approach and GF capture

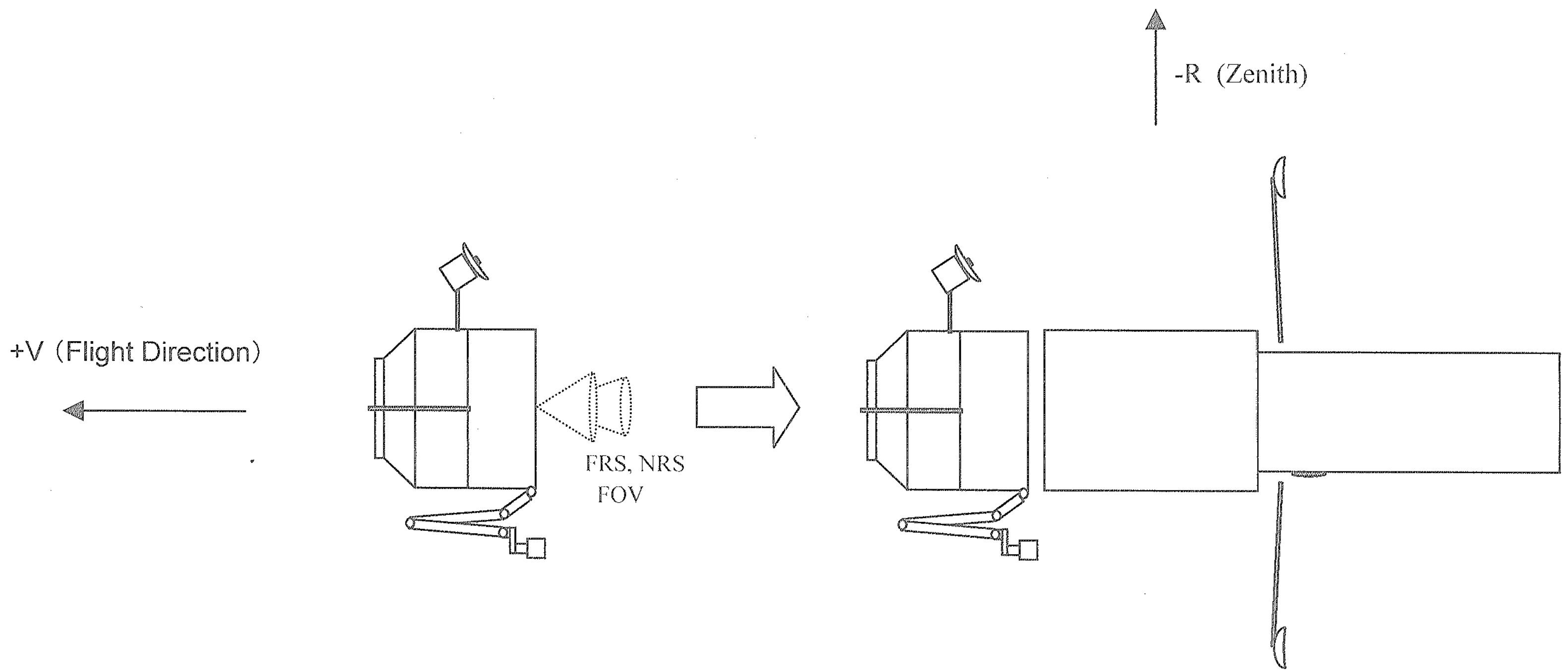


Figure 4.1.3-4 V-bar Approach and Direct Docking

### (2) R-bar Approach

HDV automatically executes several maneuver burns and flies from the AI point to the R-bar injection point (RI), where the target acquisition is performed using the Far-range Rendezvous Sensor (FRS). The navigation is based on the GPS absolute navigation using HDV/GPSR data and predicted HST position. The guidance is based on the CW (Clohessy-Wiltshire) algorithm, using the GPS navigation data.

Trajectory design should be conducted under some constraints of relative approach,

- TDRS communication coverage
- FRS navigation performance（FOV, Range and Range Rate, LOS angle, accuracy,）
- GPS navigation accuracy using HDV SIGI
- HST predicted position accuracy
- AI hold accuracy
- Atmospheric drag effect

Fig.4.1.3-5 shows HDV +R-bar insertion and approach. HDV departs from AI and performs FRS target acquisition (HST in the FRS FOV). After R-bar insertion, HDV approaches on the R-bar with pre-programmed relative velocity in accordance with relative range from HST. In this approach, HDV pitch attitude control is needed to get HST image in the rendezvous sensor FOV.

In the proximity approach on the R-bar, main navigation sensor is changed from FRS to NRS. These sensors should be designed to be compatible in two case of HST attitude shown in Fig.4.1.3-6 and Fig.4.1.3-7.

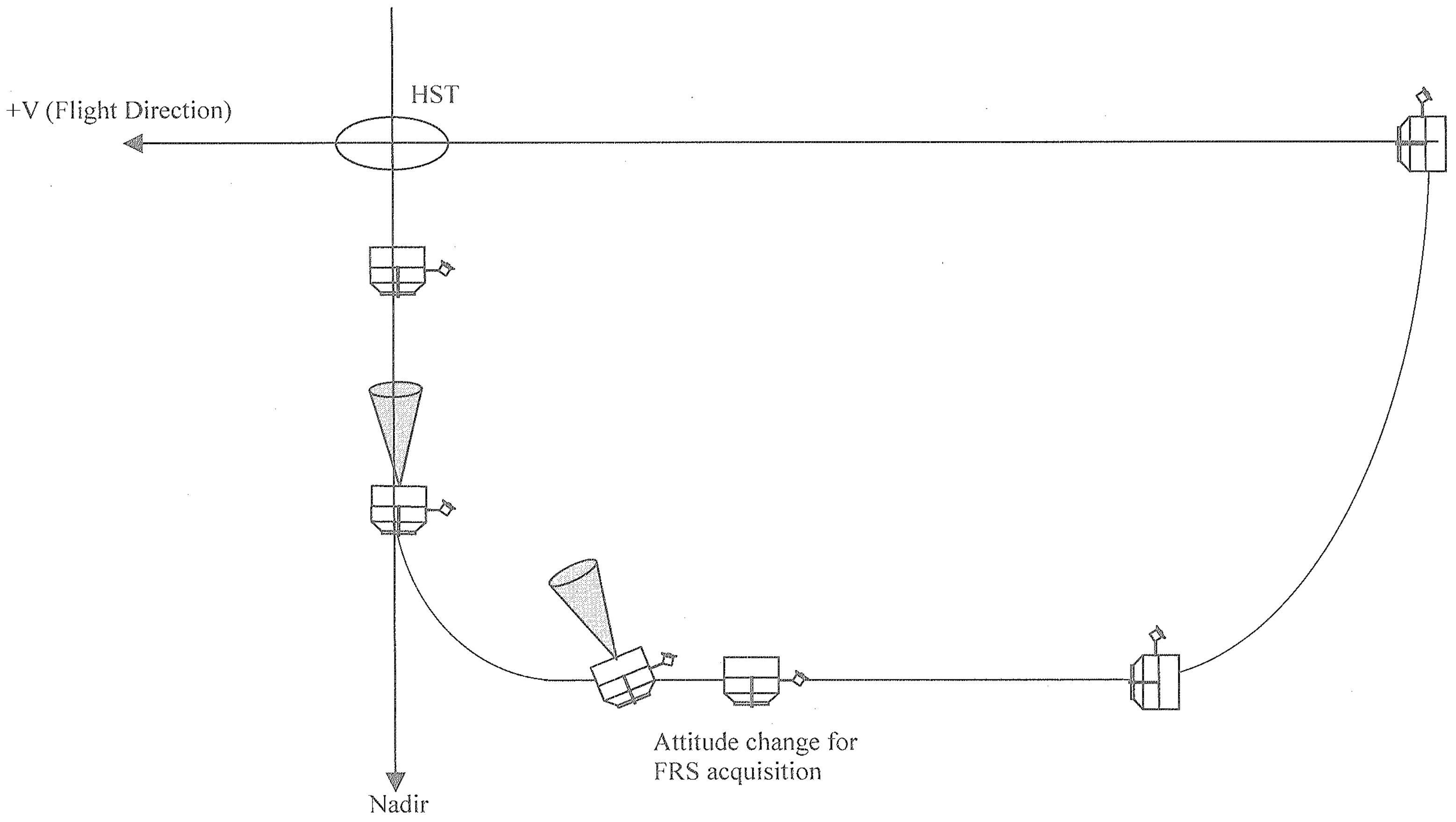


Figure 4.1.3-5 HDV R-bar insertion and approach

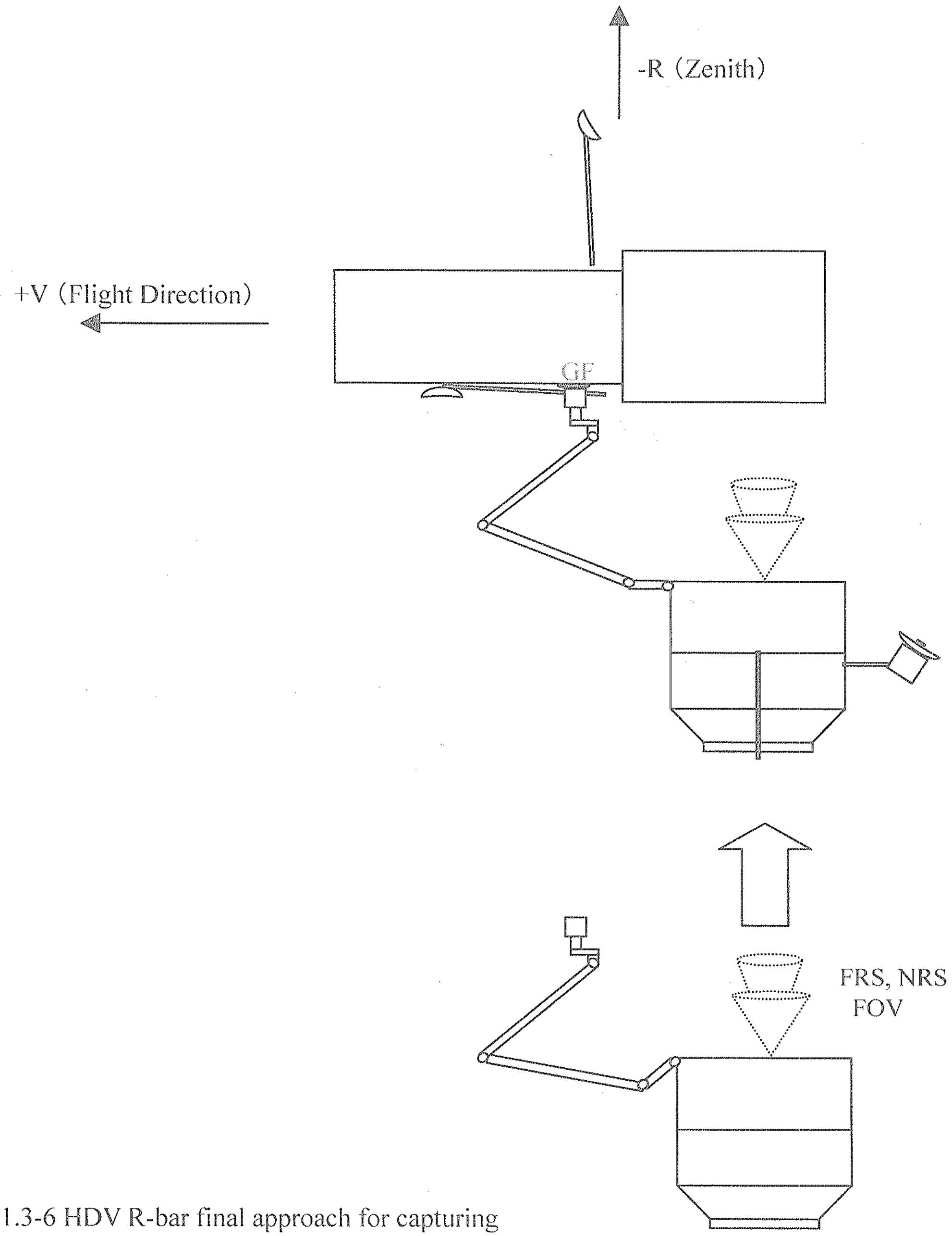


Figure 4.1.3-6 HDV R-bar final approach for capturing

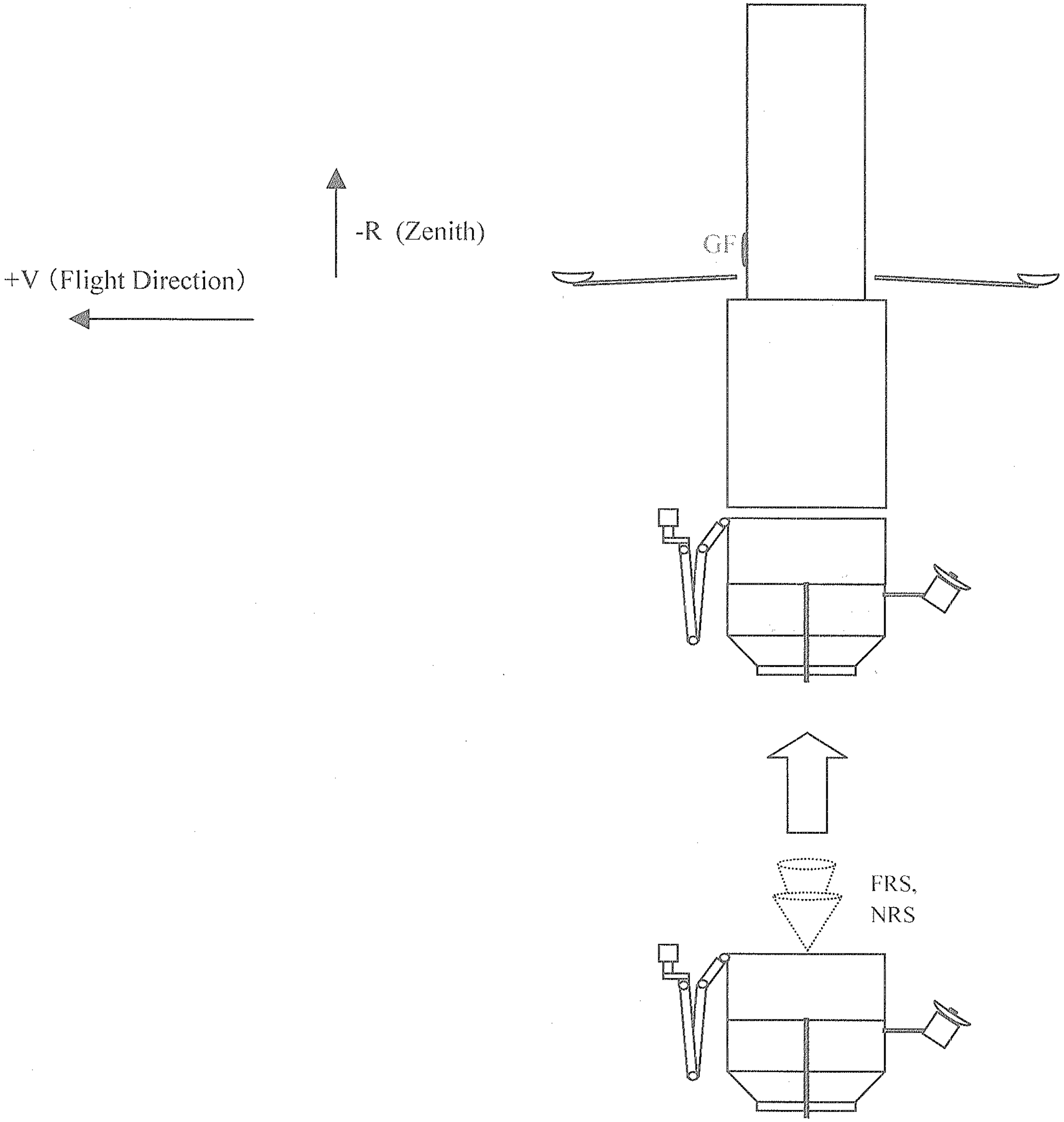


Figure 4.1.3-7 R-bar Approach for Direct Docking

## 4.2 Capturing HST

### 4.2.1 Final approach

The sequence of the final approach for HST capture is performed based on the technique of ETS-VII. Fig.4.2.1-1 shows the mode transition of the final approach. Before the final approach, HDV's manipulator shall be deployed to initial posture for the capture. The contents of each mode are described as follows.

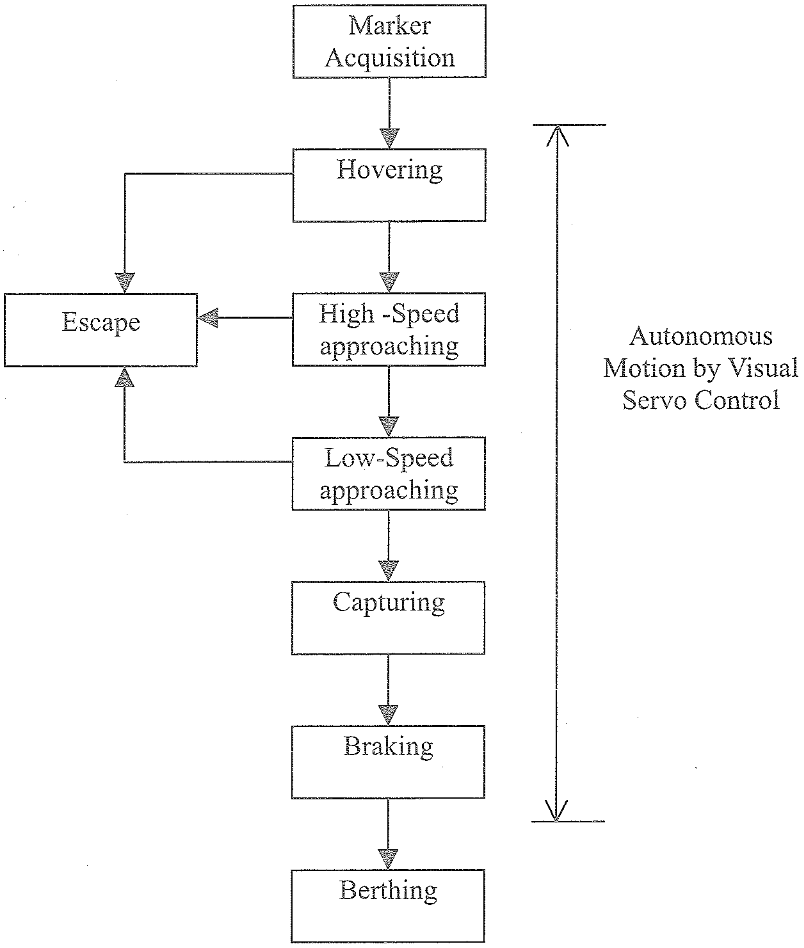


Fig.4.2.1-1 The mode transition of the final approach

### (1) Marker Acquisition

When HDV arrives within HST capture range, the manipulator starts measuring the range, range rate, and orientation of the HST GPF using the GPF target marker image of its wrist camera. In case that the target marker image cannot be seen by the wrist camera, the manipulator shall be tele-operated from the ground station utilizing necessary information and shall be guided to the target marker image into the camera's field of view. Then, if necessary, the position of the marker in the image data taken by video data processor is instructed from the ground for initial marker acquisition. When normal tracking is confirmed, the mode transits to the next mode by the trigger from the ground.

The sequence from the next hovering mode to the braking mode is automatically executed by the visual servo control.

### (2) Hovering

Visual servo control is used to hold the marker in the center of the camera's field of view, while keeping a certain distance between the camera and the marker. When the manipulator reaches within the predetermined position above the marker, the automatic sequencer switches to the high-speed approach mode.

### (3) High-Speed Approaching

The approaching mode begins from a high-speed approach. The manipulator tip position and orientation are controlled to reach an intermediate point just above the grapple fixture. The approaching rate is maximum rate (60[mm/s]) with respect to the manipulator base coordinate system in this mode.

### (4) Low-Speed Approaching

Once the manipulator reaches the intermediate point, the low-speed approach mode is started. The maximum manipulator-tip rate relative to the marker is limited to 10 [mm/s] in this mode for fine tracking.

### (5) Capturing

The capturing mode is started automatically by closing the snare wire of the end effector after confirming that the manipulator reached the aiming point relative to the marker. When the end-effector completes the GPF capture, the automatic sequencer switches to the braking mode.

### (6) Braking

After the end-effector captures GPF, the controller puts the brake on the joints of the manipulator. The manipulator stops its motion relative to the manipulator base with a smooth braking pattern.

The automatic sequence ends with the braking mode.

### (7) Escape

If the predetermined conditions are not satisfied in the automatic mode transition, the manipulator automatically exits to the predefined position where the manipulator will not contact the HST. The manipulator exits under any of the following conditions:

-Loss of the visual marker
-Departure of target from the range
-Trouble of the manipulator and/or the HDV

Once the process enters into the capture mode, the manipulator will not exit even if the contingency above occurs. The transition of escape can be executed from the ground.

### (8) Berthing

The manipulator moves HST to the berthing point by preprogrammed joint servo control.

### 4.2.2 Clearance and capturing envelopes

#### (1) HST Capture Range

The configuration of HST capture is shown in Fig.4.2.2-1. The precondition of HST capture range analysis is as follows.

- HDV approaches to HST from the -V3 side.
- The size of HDV manipulator is same as JEMRMS main manipulator.

The hatched area in the figure shows the end-effector's reachable envelope which is analyzed under the condition that the X-axis of the end-effector coordinate system and the X-axis of the manipulator coordinate system is same direction.

As the result of above analysis, the maximum reachable length is 9.6m from the manipulator base. In case that orientation error of 30 degree around Y-axis and Z-axis is taken account into above analysis, the maximum reachable length becomes 8.7m.

In case that the HST Capture range is 7.7m, manipulator-tip reach envelope is enough to capture the HST as shown in Fig.4.2.2-2.

#### (2) HST Berthing Clearance

The configuration of HST berthing is shown in Fig.4.2.2-3. As shown in the figure, the clearance between manipulator base and aft bulkhead is about 1.5 m (max.). That is enough for the envelopes of docking mechanism and the clearance of manipulator berthing motion.

Fig.4.2.2-4 shows the analysis result of the clearance between the HST and the manipulator which is berthing the HST to the docking mechanism. As shown in the figure, there are no interferences between manipulator and HST, and the berthing can be performed in the manipulator reach envelope.

#### (3) Launch Configuration

Fig.4.2.2-5 shows manipulator launch configuration and the HST docking mechanism envelopes. As shown in the figure, there are no interferences between manipulator and docking mechanism envelope. And it was also confirmed by the analysis that there are no interferences between the manipulator and the docking mechanism envelopes when the manipulator is deployed. Fig.4.2.2-6 shows deployment of the manipulator and clearance between the manipulator and the docking mechanism.

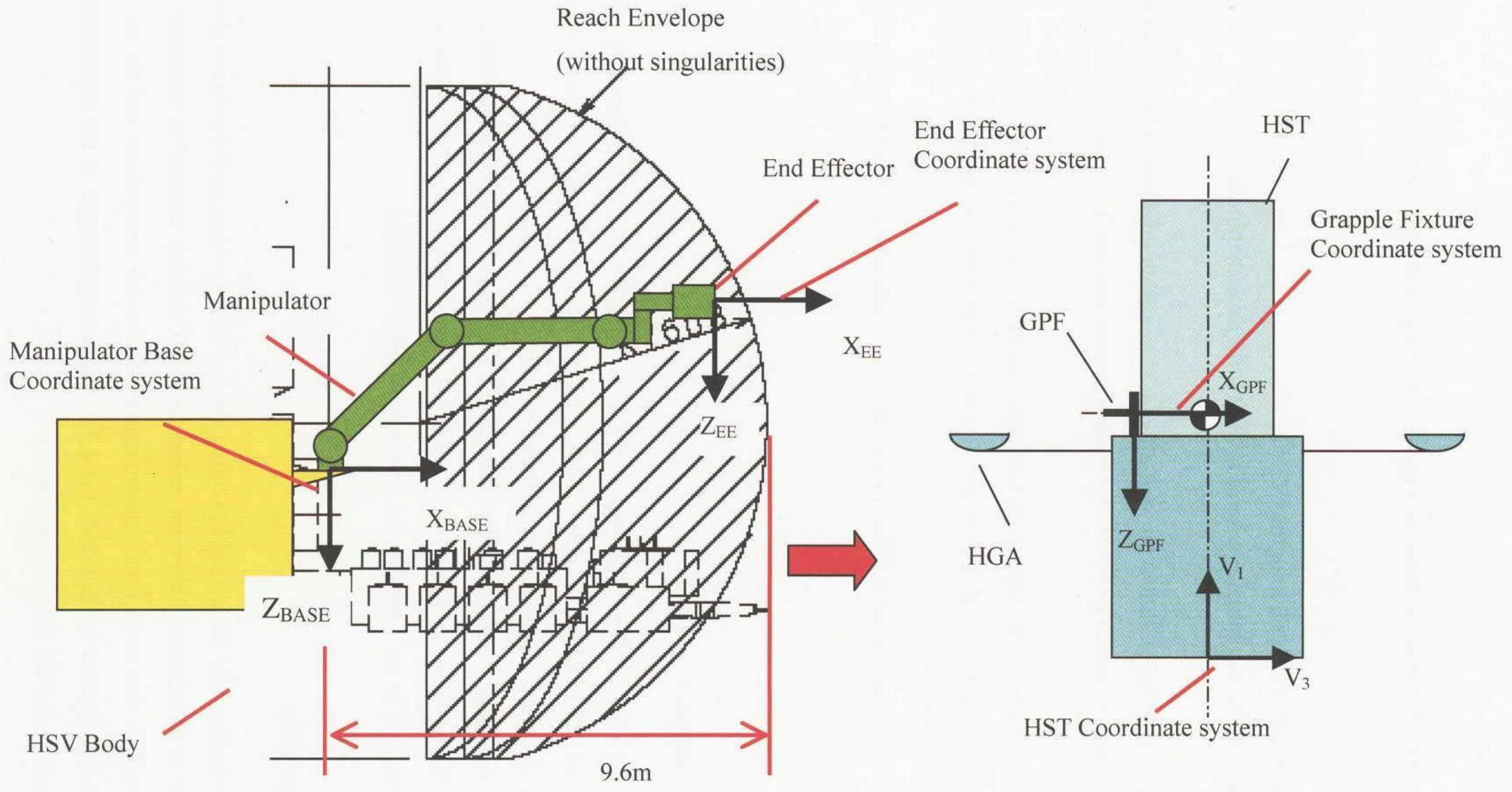


Fig.4.2.2-1 HST Capture configuration

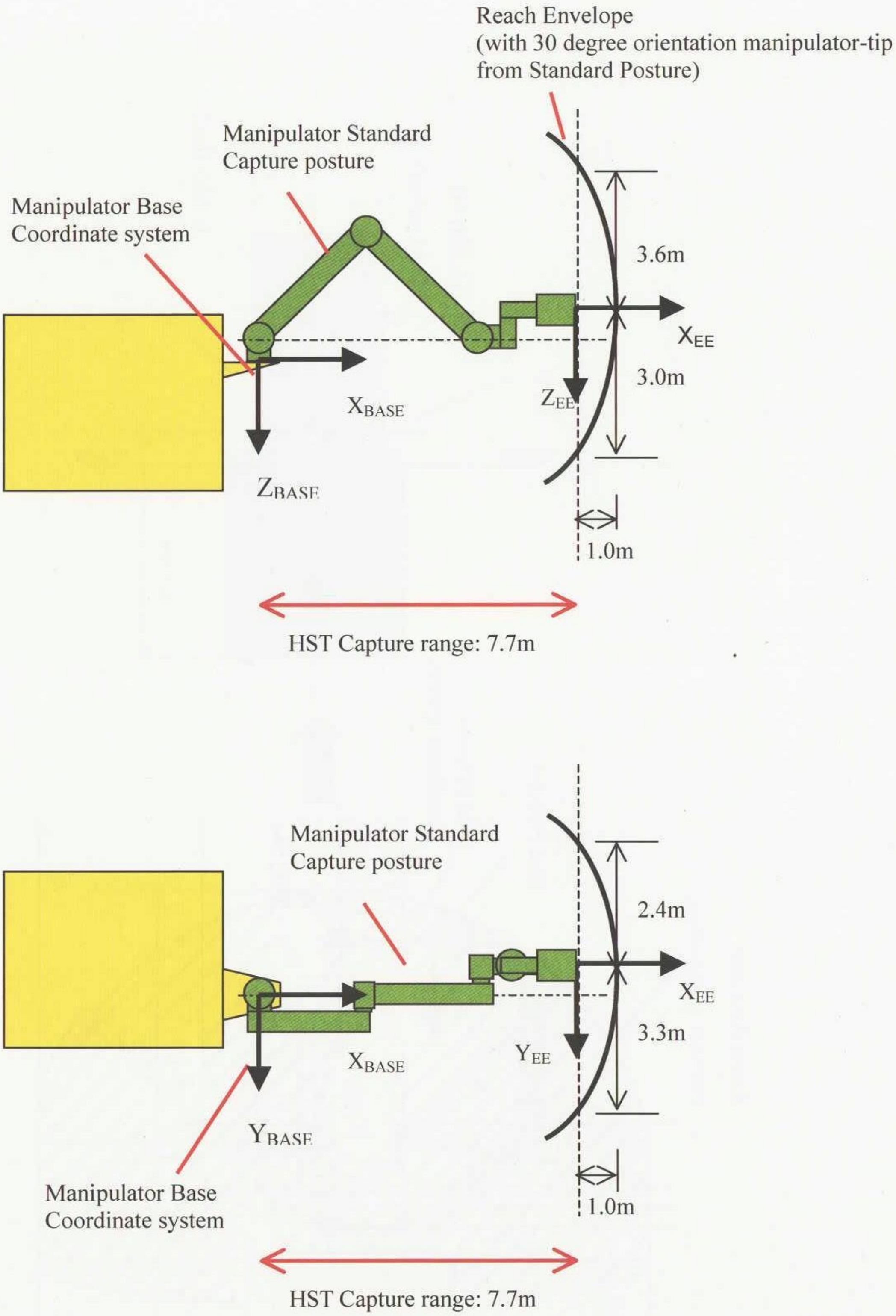


Fig.4.2.2-2 HST Capture Range

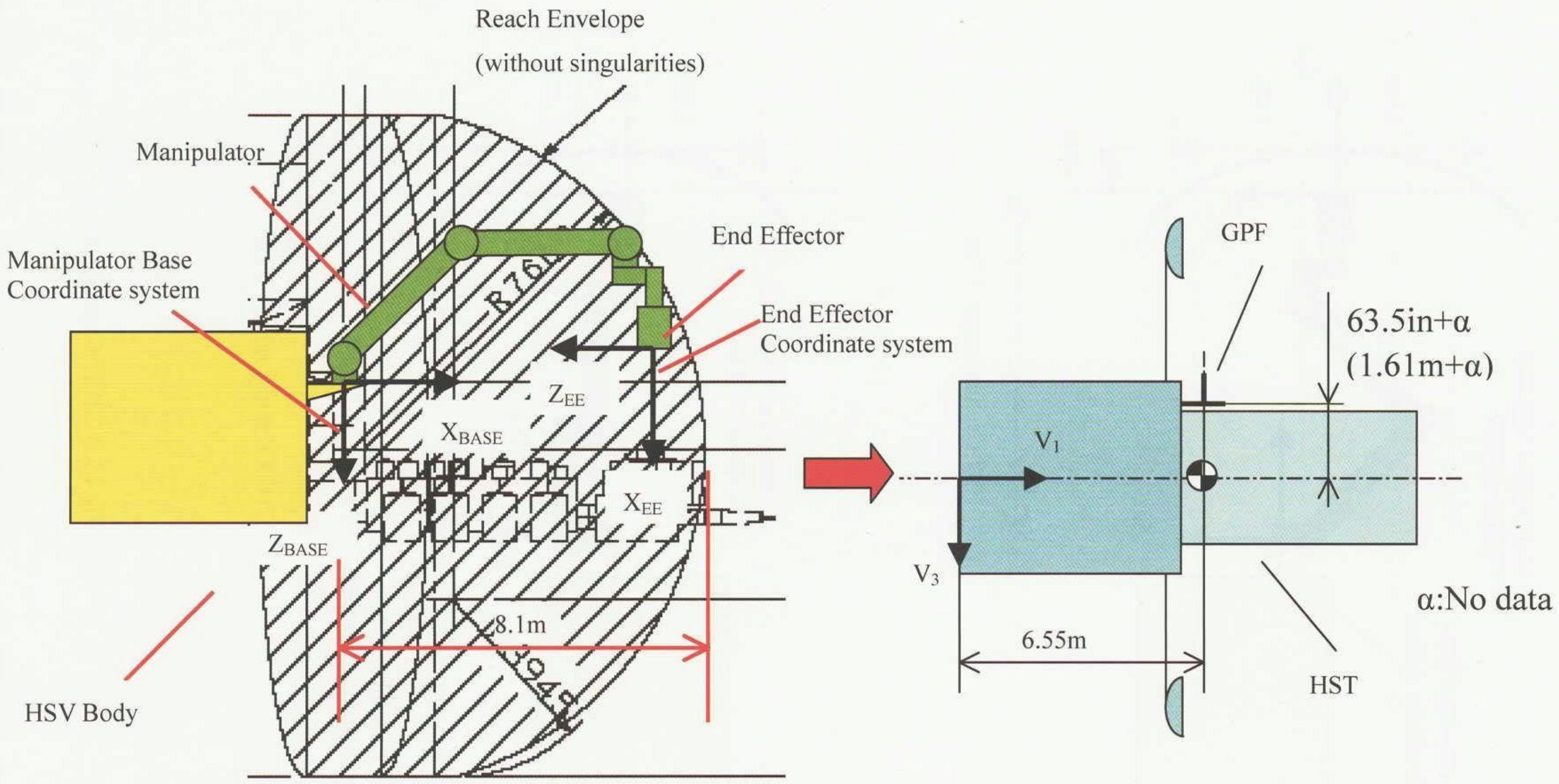
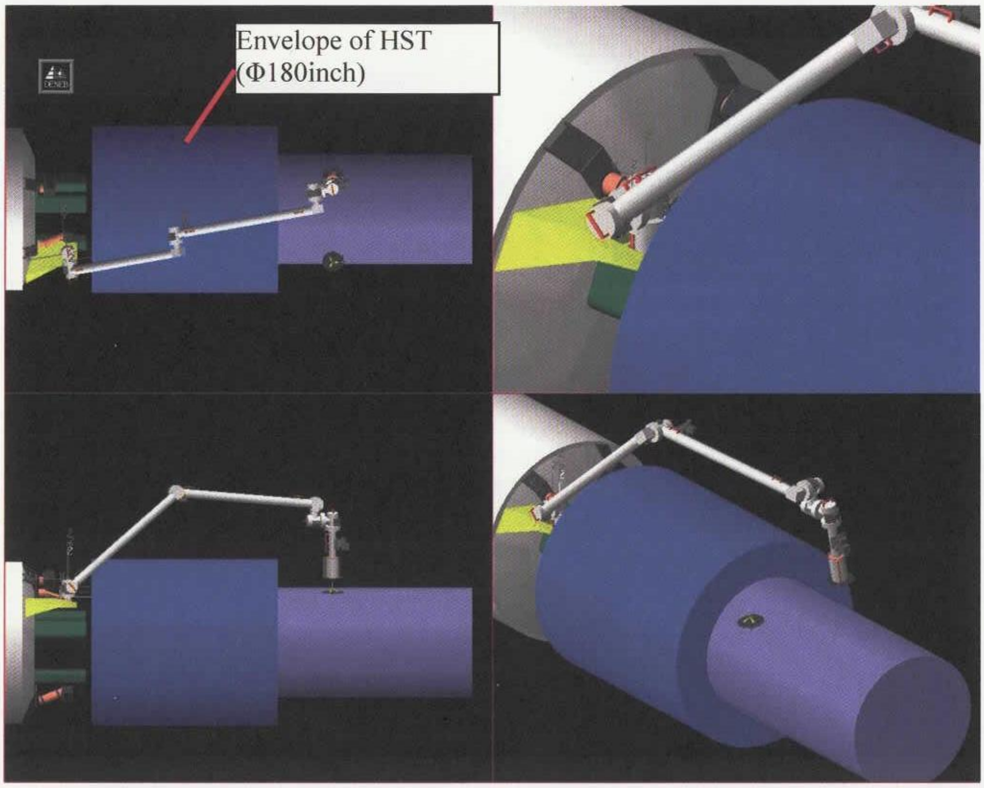
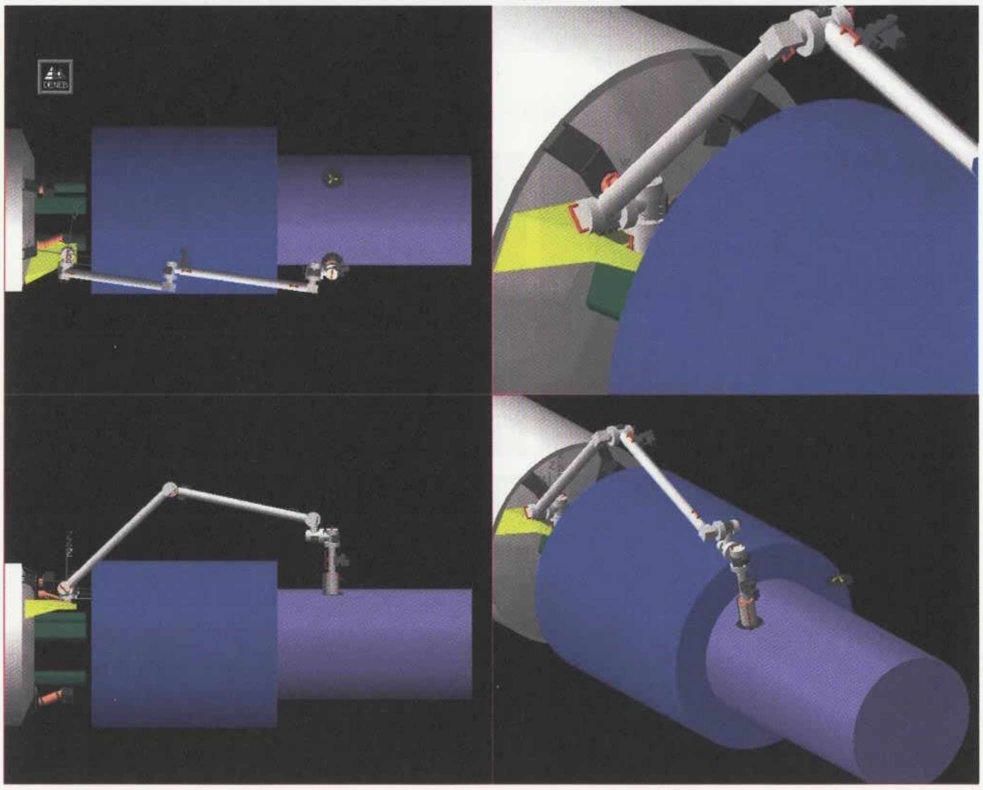


Fig.4.2.2-3 HST Berthing configuration



(a) Case of Capturing theGPF1



(b) Case of Capturing theGPF2

Figure 4.2.2-4 the Clearance Analysis Result at the HST Berthing

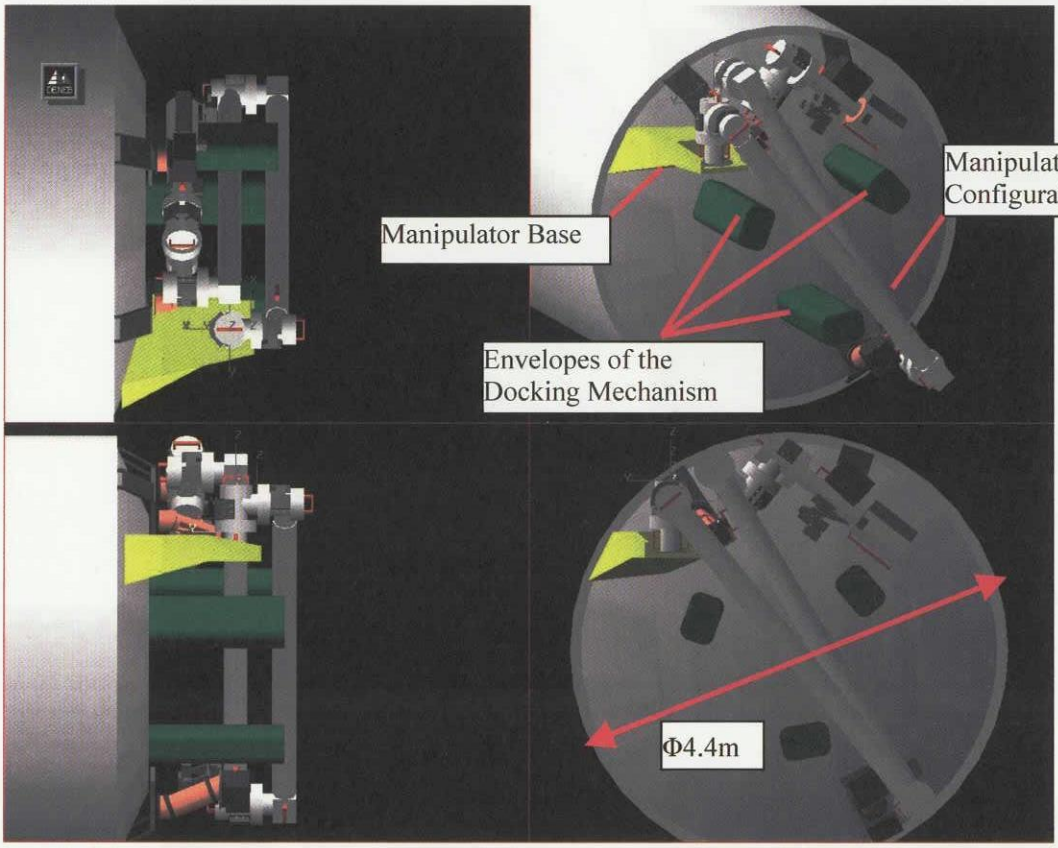


Figure 4.2.2-5 Manipulator Launch Configuration and Docking Mechanism envelopes

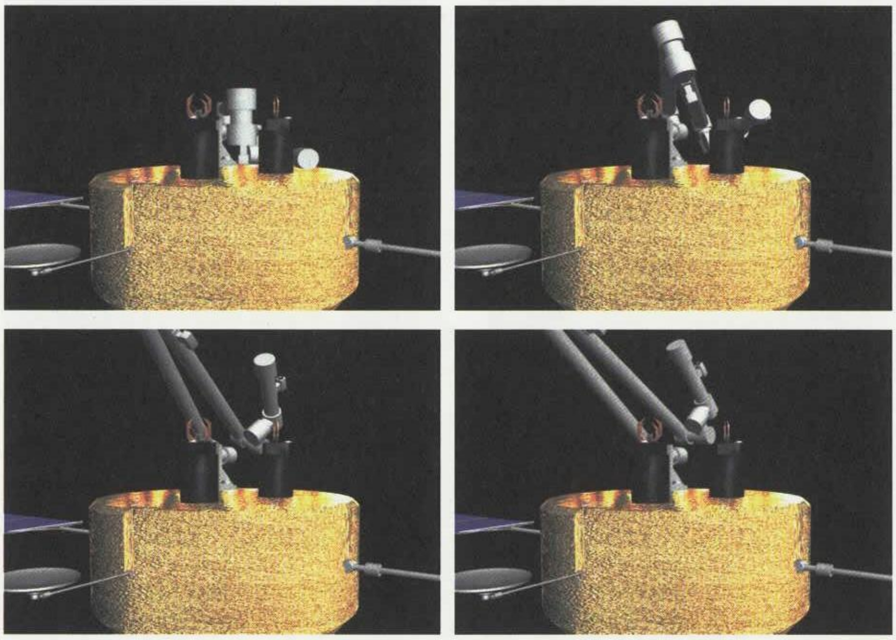


Fig.4.2.2-6 Deployment of manipulator and clearance from Docking Mech.

### 4.2.3 Required modification from JEMRMS

(1) Manipulator length

According to HST capturing configuration, if required, manipulator length will be longer than the main manipulator length of JEMRMS to have larger capturing envelope for HST. As described in 4.2.2, for current capturing configuration, the manipulator length is same as the length of the main manipulator of JEMRMS.

(2) Control system

Autonomous HST capturing capability by visual feedback of the wrist camera, based upon the on-orbit successful experiment of ETS-VII, will be added to the control system of JEMRMS. Estimation algorithm for position and orientation of HST with the grapple target will be prepared based upon the ranging algorithm of JEMRMS.

(3) Avionics

Avionics of JEMRMS, used in pressurized environment, will be modified for usages in exposed environment. The crew interface such as GUI and switches of JEMRMS will be changed to autonomous control or ground commanding.

## 4.3 Capturing uncontrolled HST using RMS

In the case where HST has lost the functional capability to maintain its attitude, it is assumed that it could be performing attitude motion with worst estimated attitude rate for each axis of 0.22 deg/sec (TBR). The +V-bar approach from –V3 axis of HST should be adopted other than R-bar approach in such a situation for rendezvous by HDV.

After the ordinary rendezvous using FRS to the relative distance of approximately 100m, HDV keeps the constant distance measuring it using image data of the HST taken by onboard cameras. During this "station keeping" phase, HDV tries to estimate attitude motion of HST using sequentially captured image data.

Strategies for capturing the Grapple Fixture on HST by RMS are different depending on the attitude rate of HST.

If it is low enough for RMS to follow GPF, the procedure is almost the same as that of the previous section "4.2 capturing (attitude controlled) HST" and such autonomous satellite capturing by a satellite mounted manipulator was demonstrated by NASDA's ETS-VII satellite in 1999.

If it is too high to follow GPF for RMS, attitude and position control maneuver (6-DOF maneuver) of HDV will be necessary in combination with RMS motion control. Details of it are given in 7.1.

### 4.3.1 Station keeping and motion measurement using image data

Since no information relating the attitude motion is given from HST on orbit, it is necessary to collect such sort of information using NRS (Near-range Rendezvous Sensor) in the range of less than 100m. Illumination by the Sunlight and the Earth albedo plays important role for this purpose. The portion of HST where can be viewed from HDV varies according to the relative distance such as

A) the full view image of HST (50m~100m)
B) the part view image of HST (10m~50m)
C) image of the target marker at Grapple Fixture (0m~10m)

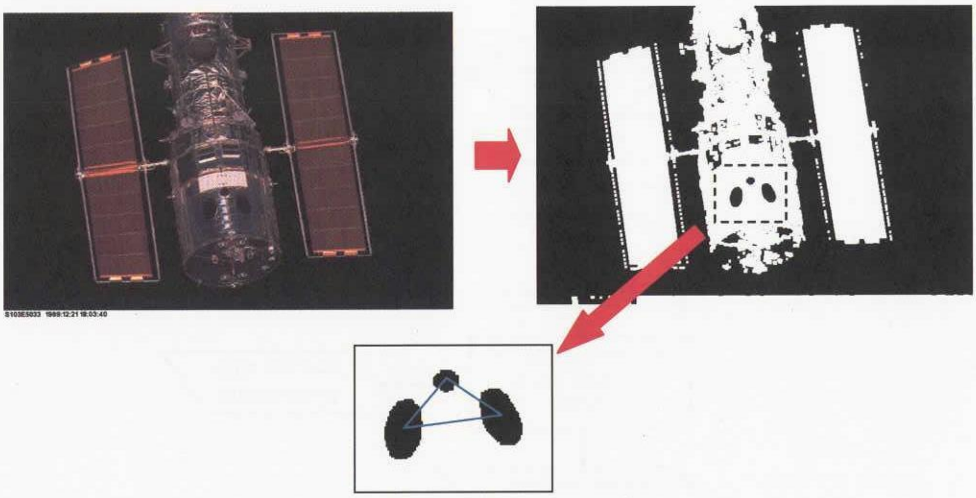


Fig.4.3-1 Star Tracker's ducts as Visual Marker

In the case of B, Star Tracker's ducts shown in Fig.4.3-1 could be used as Visual Maker. These ducts look white and black marks, so it is easy to identify them as feature part in the image and relative position and attitude are expected to be estimated using the size and shape of the triangle formed by median points of each black mark. There could be suggested several motion estimation algorithms using sequentially captured stereo color images for case A.

1. (1) calculate 3D optical flow vector of common feature points in both images and estimate attitude rate from them (relative attitude rate estimation)
2. (2) extract silhouette of HST for both stereo images, apply stereo vision for these silhouettes to give 3D position of dots on the silhouette and estimate attitude rate by differentiating of position of each dot (relative attitude rate estimation)
3. (3) extract particular parts of the image using color information such as orange rails on the surface of HST, perform stereo vision to give 3D position of dots comprising each particular cluster and apply 3D model matching between measured dots and dots given from CAD model data of HST to estimate relative position and attitude (relative position and attitude estimation)

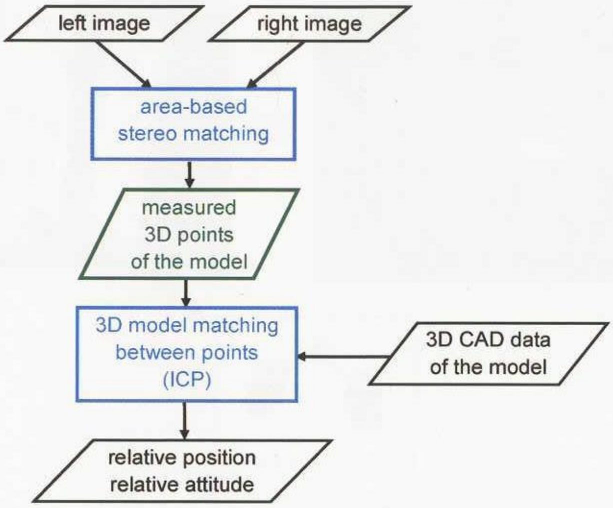


Fig.4.3-2 Stereo Vision and 3D Model Matching applying ICP algorithm

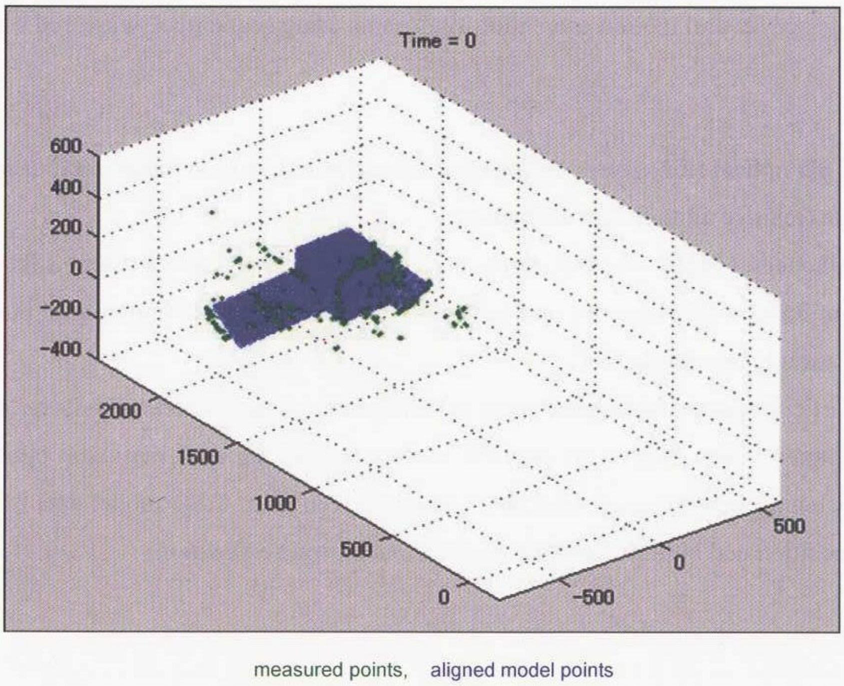


Fig.4.3-3 An Example of The Result by ICP Algorithm

For the algorithm (2), ICP (Iterative Closed Point) algorithm can be applied for the 3D model matching between groups of point data (Fig.4.3-2, 4.3-3)

If the estimation algorithm is computationally intensive and unable to be performed by onboard computer, estimation process will be done off-line using on ground computer and result of it could be uplinked.

**Reference**

F. Terui, H. Kamimura and S. Nishida, "Quick Motion Estimation of a Large Space Debris Object", Proceedings of 24th International Symposium on Space Technology and Science, Miyazaki, JAPAN, 2004.

Paul J. Besl and Neil D. McKay, "A Method for Registration of 3-D Shapes", IEEE Transactions of Pattern Analysis and Machine Intelligence, Vol.14, No.2, 1992

## 4.4 Berthing HST

After the robot arm grasps HST, HST will be mated (berthed / docked) with HDV using the docking mechanism and HST's berthing pins. Analysis of robot arm's capability for berthing / docking HST is shown in section 4.2.

### 4.4.1 Docking mechanism

Docking mechanism is described in section 5.1.6.

### 4.4.2 Docking sensor

Rendezvous sensor (Near-range Rendezvous Sensor : NRS) is used in Docking phase. NRS is described in section 5.1.7. Because the distance between GPF and berthing pins is long, HDV's manipulator position control error makes large relative position error between the berthing pins and docking mechanisms. Then HDV's manipulator must be controlled based on measured relative position/attitude by NRS.

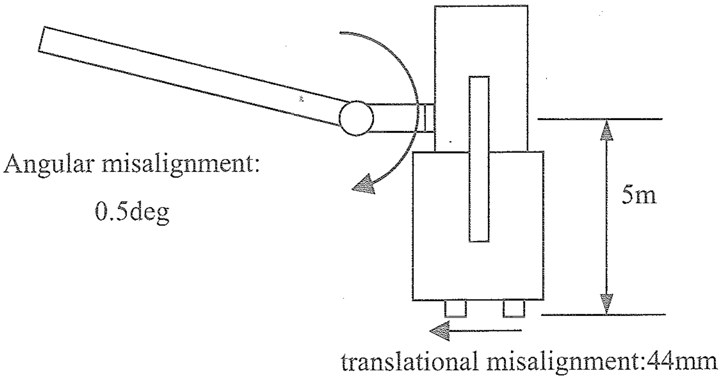


Fig.4.4.2-1 Translational misalignment at HDV docking mechanism

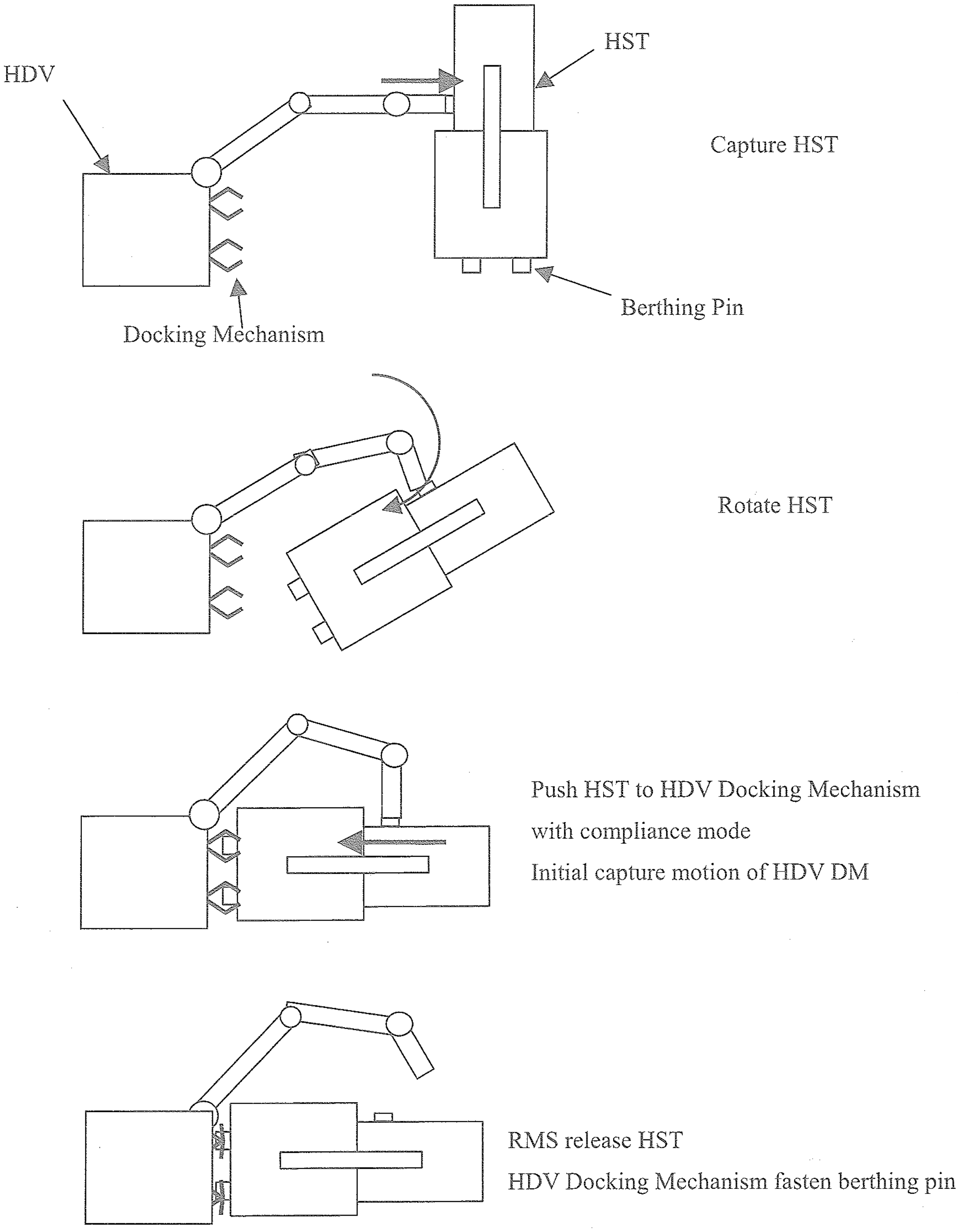
### 4.4.3 Docking scenario

After grasping HST's GPF by HDV's manipulator, the manipulator moves HST in the position where HDV's docking mechanism can grasp HST's berthing pins based on measurement of the relative position/attitude by NRS, and consecutively the manipulator pushes HST berthing pins to docking mechanisms.

Then HDV's docking mechanism will grasp HST's berthing pins. Once the docking mechanisms capture the berthing pins, the manipulator releases HST's GPF. After the docking mechanisms close their latching levers, the firm connection of HDV and HST is realized.

After docking of HDV and HST is made, attitude control of HDV is resumed and HDV gains TBD attitude.

Docking sequence after RMS capturing is shown in Fig.4.4.3-1.



Capture HST

Rotate HST

Push HST to HDV Docking Mechanism
with compliance mode
Initial capture motion of HDV DM

RMS release HST
HDV Docking Mechanism fasten berthing pin

Fig.4.4.3-1 HST docking sequence after RMS capturing

## 4.5 Direct Docking with HST

After rendezvous phase, HDV stops at VP (within 10 meters), and NRS image processing target is changed into the berthing target on HST aft shroud bulkhead from HST body. When HDV arrives within TBD meters, attitude control of HST and HDV is inhibited to avoid unpredictable attitude motion. At the same time, the docking mechanism start to close their latching levers, then grasp berthing pins, and finally firm connection of HDV and HST is realized.

Allowable maximum single misalignment (docking mechanism)

X(V1) ≦ ±30(TBD)[mm]
Y,Z rss(V2,V3) ≦ ±45(TBD)[mm]
Φ ≦ ±2.8(TBD)[deg]
θ,ψrss ≦ ±2.5(TBD)[deg]

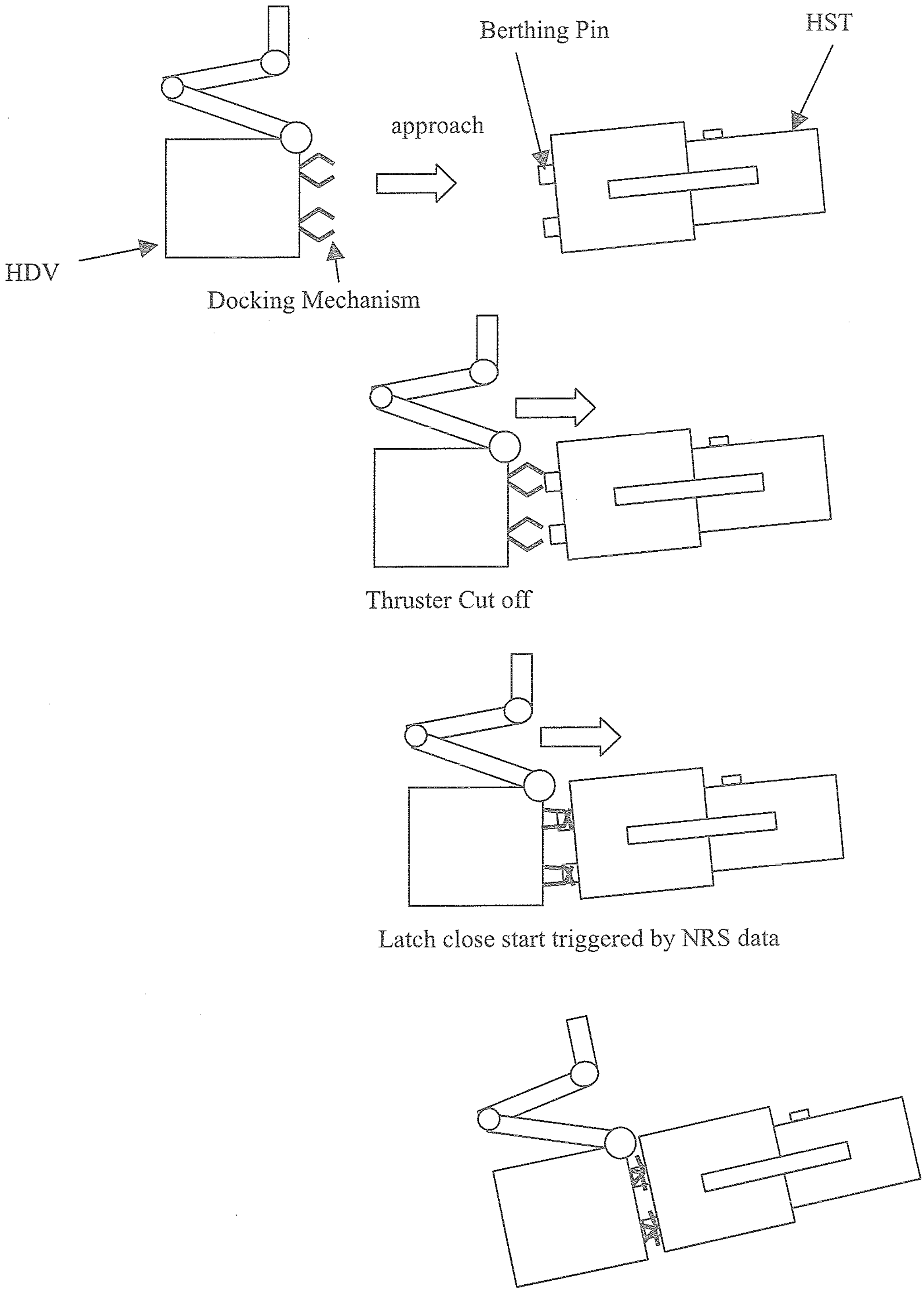
Here is allowable NRS error at docking point (ETS-VII PXS spec).

X(V1) ≦ ±15(TBD)[mm]
Y,Z rss(V2,V3) ≦ ±6(TBD)[mm]
Φ ≦ ±1.3(TBD)[deg]
θ,ψrss ≦ ±1.3(TBD)[deg]

Docking phase guidance accuracy must be better than allowable misalignment of the docking mechanism, but it depends on the time from HDV thruster's cut-off to initiation of the capture.

After docking of HDV and HST is made, attitude control of HDV is resumed and HDV gains TBD attitude.

Direct Docking sequence is shown Fig.4.5-1.



Thruster Cut off

Latch close start triggered by NRS data

Docking complete and attitude control start

Fig.4.5-1 HST Direct Docking Sequence

## 4.6 Extending Life of HST

Designed mission life of HTV, a base spacecraft of HDV, is three months. Therefore the baseline mission life of HDV will be 3 months. The life of HDV can extend up to one year by loading additional fuel. HDV's fuel tanks have enough volume for additional fuel.

However, attitude control accuracy of HDV is not good as HST, HST must control its attitude in a configuration that HDV is attached to HST. HST's capability for the attitude control in this configuration is needed to be investigated.

Study results of the extending life of HST by replacing batteries and gyro or their lines are shown in section 7.

## 4.7 Controlled Re-entry

Controlled re-entry mission scenario is shown in Fig.4.7-1. HST/HDV performs controlled re-entry through 4 maneuvers after adjusting de-orbit timing for splashdown. Because maximum maneuver time has restrictions, 4 maneuvers are needed for re-entry. HST/HSV is descended to 150km (perigee height) by 3 maneuvers and is performed re-entry by the final maneuver into the target area planned in advance. Before and during the final maneuver, the health status of HDV is checked as a part of re-entry flight safety operation. After re-entry, HST/HDV will be broken into the several pieces and melted. The wreckages splash down into planned area in ocean (near latitude –28deg).

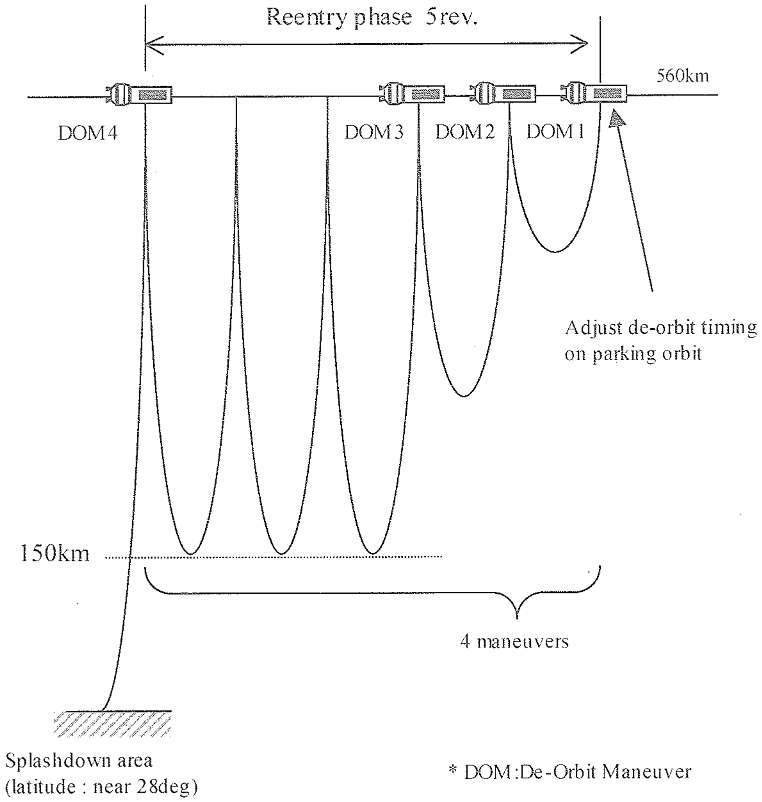


Fig.4.7-1 Re-entry mission scenarios

## 4.8 Mass

Mass of HTV based HDV is shown in Table 4.8-1. Propulsion module and avionics module are estimated based on the mass of HTV. The changes from HTV are shown in Table 5.1.1-1.

Table 4.8-1 Estimated mass of HTV based HDV

| ITEM | MASS (kg) | NOTE |
|---|---|---|
| Propulsion Module | 1,370 | HTV based |
| Avionics Module | 1,650 | HTV based |
| Mission Module | 1,620 | Including Manipulator, Docking mechanism, Rendezvous Sensor、Communication System and so on. |
| Propellant/Pressurized Gas | 2,450 | Maximum |
| Other | 10 | Fastener between module |
| Total (DRY) | 4,650 | |
| Total (WET) | 7,100 | At lift off |

## 4.9 Electric Power

Table 4.9-1 shows HDV electric power budget based on component heritage and some estimation.

Table 4.9-1 Power budget（Orbital average power for proximity operation）

| Subsystem | Power Consumption (W) | Remarks |
|---|---|---|
| GNC | 340 | *1. Redundant sensors are operating. |
| DTCS | 20 | |
| IOCS | 150 | |
| DH | 127 | |
| EPS | 85 | |
| SPS | 11 | Paddle driving power |
| THR | 660 | Budget for heater power based on HTV |
| INT | 105 | Heater controller, Harness loss |
| Vision System | 100 | Estimated value including 4 cameras and 2 illumination lights |
| RMS | 400 | JEM RMS base |
| DM | 30 | Budget for stand-by power |
| Total | 2028 | |

*1 ; Based on heritage except for FRS and NRS.

● Power budget for FRS and NRS are 50 W * 2 and 30 W * 2.

Target of power distribution capability is settled as 2 kW in accordance with this power budget.

Capability of electrical power system is evaluated as follows considering 52 deg of Sun angle to orbital plane;

- Two solar array paddle configuration
- Each solar array paddle is driven by a paddle drive mechanism in one axis.
- A paddle consists of 3 solar allay panels that JAXA developed GaAs triple junction cells are attached on. Size of a solar allay panel is 2.61 m * 1.5 m.
- 100 Ahr Li-Ion Secondary battery.

## 4.10 Fuel

Estimated mass of propellant (MON3, MMH) is shown in Table 4.10-1. In case of 3-month mission and 1-year mission, required propellant for both missions are within maximum loading fuel in the tanks.

Table 4.10-1 Estimated Mass of Propellant

| No. | Phase | Thruster | Delta-V (m/s) | Propellant (kg) | NOTE |
|---|---|---|---|---|---|
| 1 | Rendezvous | Main | 65 | 148 | Rocket insertion orbit : 500x500km |
| | | RCS | 32 | 90 | |
| 2 | Proximity operation | RCS | 192 | 507 | 4 times attempt |
| 3-1 | Parking after docking (3-month) | RCS | 11 | 97 | Control dead band 10deg<br>Not considered adjusting altitude |
| 3-2 | Parking after docking (1-year) | RCS | 44 | 385 | |
| 4 | De-orbit | Main | 154 | 893 | Re-entry flight path angle -1.8deg at 120km(altitude) |
| | | RCS | 26 | 190 | |
| 5 | Null propellant | | | 111 | Same as HTV |
| 6 | Margin | | | (3%) | For subtotal |
| Total (3 month) | | | | 2097 | < 2436 (Maximum loading) |
| Total (1 year) | | | | 2394 | < 2436 (Maximum loading) |

## 4.11 Communication

HDV has Inter Orbit Communication Subsystem (IOCS) and Direct TTC Communication Subsystem. IOCS provides S band forward/return and Ka band return link between HDV and TDRS. In this section, IOCS communication capacity is described.

TDRSS forward and return service characteristics are shown in Table 4.11-1 and Table 4.11-2.

Table 4.11-1 TDRSS Forward Service

| | SSA | KuSA | KaSA |
|---|---|---|---|
| Customer service links/satellite | 2 | 2 | 2 |
| Space-to-Space Freq. Bands | 2025.8-2117.9 MHz | 13.775 GHz | 22.55-23.55 GHz |
| Max Data Rate | 7 Mbps | 25 Mbps | 25 Mbps |

* Ref., 450-SNUG, Space Network Users' Guide, Revision 8.

Table 4.11-2 TDRSS Return Service

| | SSA | KuSA | KaSA |
|---|---|---|---|
| Customer service links/satellite | 2 | 2 | 2 |
| Space-to-Space Freq. Bands | 2200-2300 MHz | 15.0034 GHz | 25.25-27.5 GHz |
| Max Data Rate | 6 Mbps (rate 1/2 coded) | 300 Mbps (uncoded) | 300 Mbps (uncoded) |

* Ref., 450-SNUG, Space Network Users' Guide, Revision 8.

Budget of HDV remote-operation command in the forward link;

- Vehicle velocity control
  8 bit * 3 axis /0.5 sec = 0.05 kbps
  (Note; vehicle attitude control is performed automatically)
- Manipulator translation velocity control
  8 bit * 3 axis /0.5 sec = 0.05 kbps
- Manipulator angular rate control
  8 bit * 3 axis /0.5 sec = 0.05 kbps
- Time equivalence for remote-operation commands; One virtual channel is assigned.

HDV forward link requirements are complied with TDRS I/F as shown in Table 4.11-3.

Table 4.11-3 Compliance of HDV forward link requirement to IOCS and TDRS I/F

| Item | Data Rate | Required Total | IOCS performance | TDRS I/F |
|---|---|---|---|---|
| Vehicle position control | 0.05 kbps | 0.4 kbps | 0.5 kbps | 7 Mbps |
| Manipulator translation velocity control | 0.05 kbps | | | |
| Manipulator angular rate control | 0.05 kbps | | | |
| HK command | 0.25 kbps | | | |

Budget of HDV video data on the return link;

Budget of HDV video signals in the return link;

- Video Cameras (one is attached on manipulator, the other one is attached on main body);

512 bit * 512 bit * 12 bit * 4 cameras / 0.5 sec = 25 Mbps (Maximum rate)

(Some image compression technique may be used.)

- FRS monitor

256 bit * 256 bit * 8 bit * 2 cameras / 0.5 sec = 2 Mbps

- FRS monitor

256 bit * 256 bit * 8 bit * 2 cameras / 0.5 sec = 2 Mbps

HDV return link requirements are complied with TDRS I/F as shown in Table 4.11-4.

Table 4.11-4 Compliance of HDV return link requirement to IOCS and TDRS I/F

| Item | Data Rate | Required Total | IOCS performance | TDRS I/F |
|---|---|---|---|---|
| Video Cameras data | 25 Mbps | 29.01 Mbps | 66 Mbps | 300 Mbps |
| FRS monitor data | 2 Mbps | | | |
| NRS monitor data | 2 Mbps | | | |
| HK data | 8 kbps | | | |

## 4.12 Timeline of Rendezvous and Docking Phase

It is very important to design a timeline of critical phases of the mission from final rendezvous to docking described from section 4.1 to 4.5 considering lighting-condition on orbit and communication link.

### (1) Communication link

It is highly desired to have continuous communication link from final approaching to completion of berthing to monitor the sequence of the procedure and to cope with contingencies. Since it seems to be difficult to complete the whole critical procedure within a single TDRS communication path, appropriate TDRSS hand over timing should be designed in the timeline.

### (2) Lighting condition

Since the Near-range Rendezvous Sensor (NRS) works under ambient lighting, the final approach should be started in orbital daytime. In addition to this, direct insertion of sunlight into NRS should be avoided.

### (3) Approaching speed

Approaching speed limits should be decided such that collision is avoided by means of disabling of thrusters or taking active collision avoidance maneuver.

### (4) Berthing Process

The maximum tip velocity of the manipulator with loaded configuration gives us an approximate time needed to move the HST from capturing position to the berthing. The time required to move the HST and complete the berthing is approximately 15 minutes.

An example of final approaching procedure in +V bar approaching case is presented with the approaching speeds in figure 4.12-1. An example of a timeline in the critical phase is depicted with conditions of lighting and communication in figure 4.12-2.

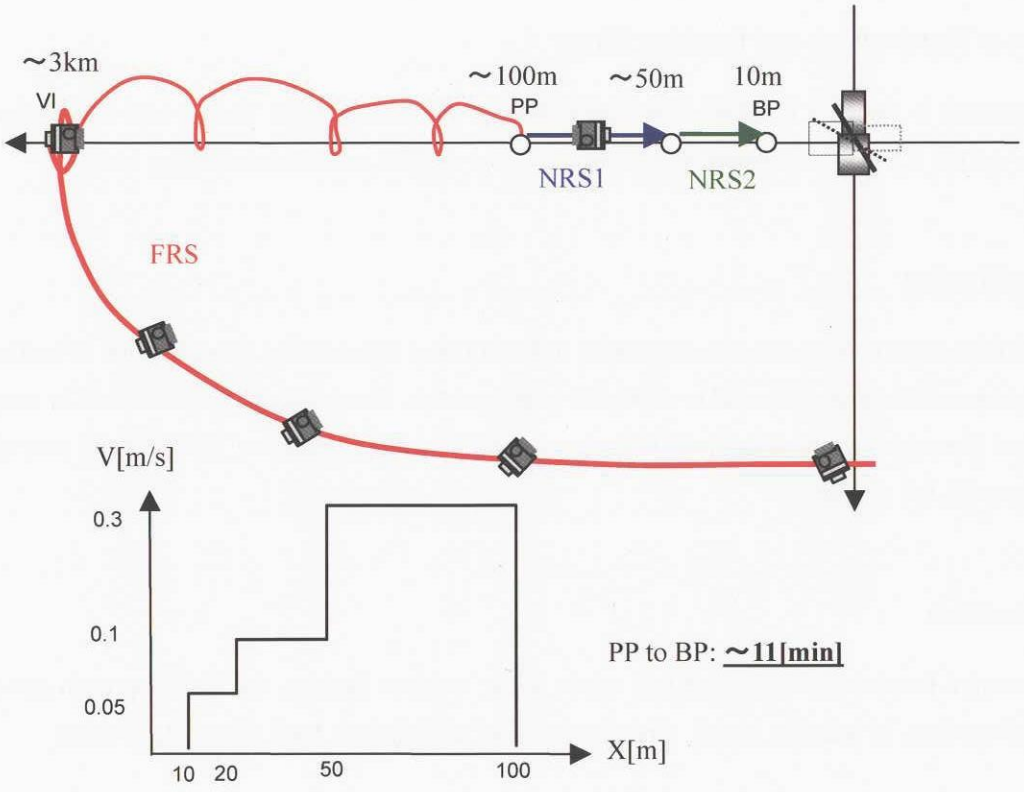


Fig 4.12-1 Final Approach Procedure (+V bar approach case)

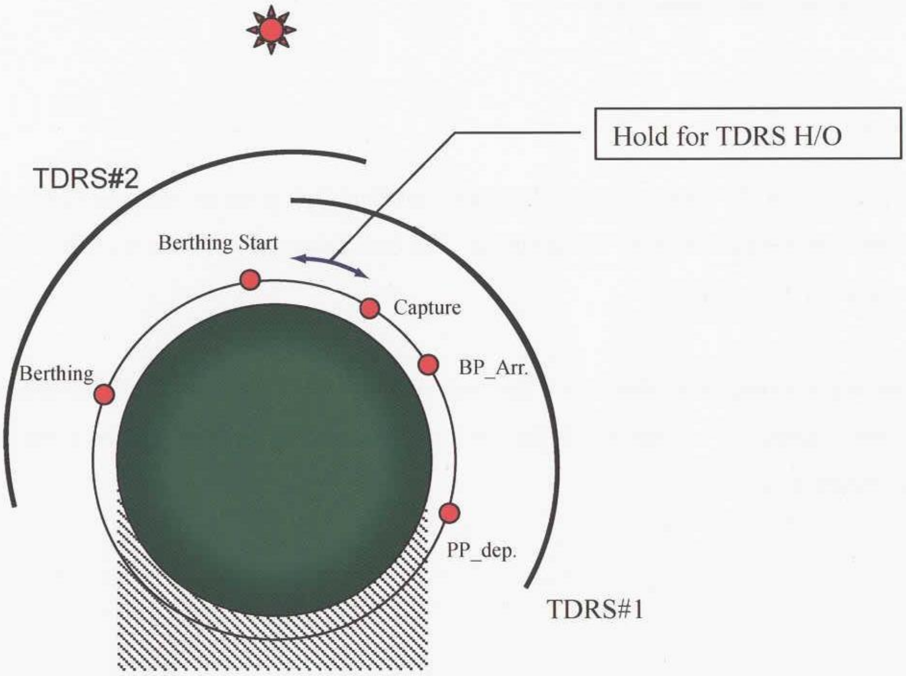


Fig 4.12-2 Timeline with Lighting and TDRSS visibility

# 5. System Description

## 5.1 Spacecraft system

### 5.1.1 Spacecraft Configuration

HTV based HDV consists of following modules:

- Propulsion Module (HTV based)
- Avionics Module (HTV based)
- Mission Module

HTV based HDV configuration is shown in Fig.5.1.1-1, system block diagram is shown in Fig.5.1.1-2. Changes of components from HTV are summarized in Table 5.1.1-1.

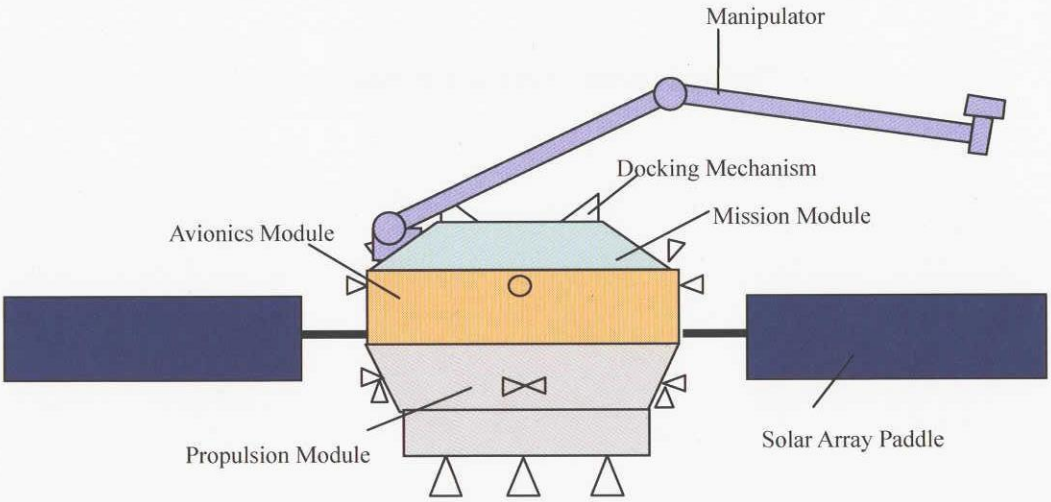


Fig.5.1.1-1 HTV based HDV

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Fig.5.1.1-2  HTV based HDV system block diagram

Table 5.1.1-1 Changes of Components from HTV

| | Removed component from HTV | Added component to HTV | NOTE |
|---|---|---|---|
| Propulsion Module | - | - | Same as HTV |
| Avionics Module | ◎ Solar Array (Body mounted)<br>◎ Primary Battery (P-BAT)<br>◎ Power Distribution Control Unit (PDCU)<br>◎ ISS DC/DC<br>◎ Proximity Link System (PLS)<br>◎ Auto CAM Unit (ACU)<br>◎ Valve Drive Unit 2 (VDE2)<br>◎ Rendezvous Sensor (RVS)<br>◎ Inter-Orbit Link System (IOS)<br>◎ Heater Control Electronics2 (HCE2)<br>◎ Main Bus Unit 2 (MBU2)<br>◎ SIGI-C | ◎ Solar Array Paddle System (SAS)<br>◎ Solar Array Paddle (SAP)<br>◎ Solar Array Drive Mechanism (PDM)<br>◎ Solar Array Drive Electronics (PDE)<br>◎ Direct TTC Communication Subsystem (DTCS) | |
| Pressurized Logistics Carrier | ALL | - | Not used |
| Unpressurized Logistics Carrier | ALL | - | Not used |
| Mission Module | - | ◎ Remote Manipulator System (RMS)<br>◎ Arm Driver Electronics (ADE)<br>◎ Mission Data Processor (MDP)<br>◎ Docking Mechanism (DM)<br>◎ Docking Mechanism Driver Electronics (DMDE)<br>◎ Vision System (VIS)<br>◎ Cameras (CAM)<br>◎ Illuminator (ILL)<br>◎ Video Signal Processor (VSP)<br>◎ Inter Orbit Communication Subsystem (IOCS)<br>◎ Far-range Rendezvous Sensor (FRS)<br>◎ Near-range Rendezvous Sensor (NRS) | |

## 5.1.2 Propulsion Module

### (1) Configuration

HTV based HDV Propulsion Subsystem configuration is shown in Fig.5.1.2-1 and schematic is shown in Fig.5.1.2-2

### (2) Thrusters

Two types of thrusters are used in HTV based HDV Propulsion Subsystem.
One is 500N main thruster that is used for large orbit maneuver and collision avoidance maneuver (CAM). The other is 120N RCS thruster that is used for attitude control, small orbit maneuver and CAM.

HDV has 2 strings of thruster set. And each string set consists of 2 main thrusters and 14 RCS thrusters (6 forward-RCS thrusters and 8 after-RCS thrusters).

Both thrusters are bi-propellant type and flight proven in other manned space vehicles.

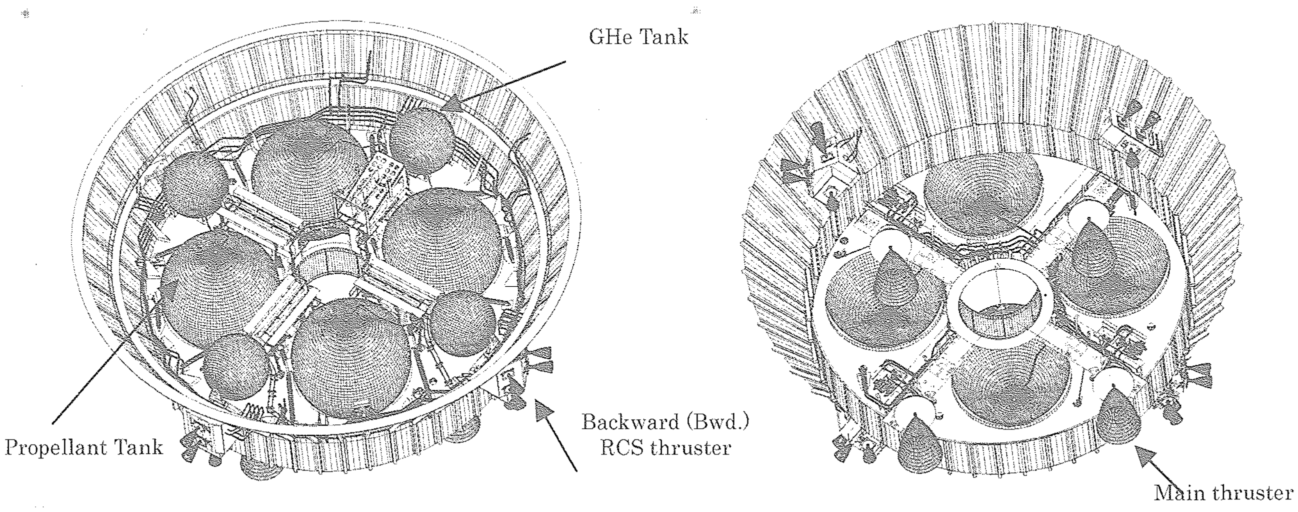

Fig.5.1.2-1 HTV based HDV Propulsion Subsystem Configuration

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Fig.5.1.2-2 HTV based HDV propulsion system schematic diagram

### 5.1.3 Avionics Module

The Avionics System of HDV consists of some subsystems as follows:

- Guidance Navigation and Control Subsystem (GNC)
- Direct TTC Communication Subsystem (DTCS)
- Inter Orbit Communication Subsystem (IOCS)
- Data Handling (DH)
- Electric Power Subsystem (EPS)
- Communication Subsystem (COM)
- Harness and integration Subsystem (INT)
- Solar Array Paddle Subsystem (SAS)

Major electric components and elements installed on the Avionics Module are identified in table 5.1.3-1.The avionics system on the avionics module has some specific features for the unmanned mission,

- One power bus configuration (HTV has two power bus configuration and abort capability after one bus failure)
- Two sensors (HTV has the additional third SIGI(gyro))
- Two strings of thruster valve control (VDE-1A and 1B) to perform orbit control, attitude/position control, and abort. (HTV has the third string for abort with VDE-2)
- Two strings to perform heater control (HTV has three strings)

GNC subsystem overview is described in section 5.2.1.

Table 5.1.3-1 Major Avionics Components and Elements

| S/S | Component | Abbreviation | Quantity | Operation for Redundancy | Installed area | | Based System | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Avionics Module | Mission Module | HTV Avionics Module | Other Program |
| GNC | Guidance and Control Computer | GCC | 1 | Three CPUs are operating.<br>Redundant IOC is stand-by. | X | | X | |
| | Space Integrated GPS/INS | SIGI | 2 set | Operating | X | | X | |
| | Earth Sensor Assembly | ESA | 2 set | Operating | X | | X | |
| | Far Rendezvous Sensor | FRS | 2 set | Operating | | X | | X |
| | Near Rendezvous Sensor | NRS | 2 set | Operating | | X | | X |
| | Valve Drive Electronics-1 | VDE-1 | 2 | Redundant VDE-1 is stand-by | X | | X | |
| DTCS | DTCS Transponder Transmitter | D-TRX(TX) | 2 | Stand-by. Attached on the propulsion module. | X | | | X |
| | DTCS Transponder Receiver | D-TRX(RX) | 2 | Operating | X | | | X |
| | DTCS Antenna | D-ANT-Z<br>D-ANT-N | 1 each | One for zenith direction, the other one for nadir direction. | X | | | X |
| | DTCS passive element | HIB, SW, DIP | 1 set | — | X | | | X |
| IOCS | K–Band Transponder Transmitter | IK-TRX(TX) | 2 | Redundant transmitter is stand-by. | | X | | X |
| | K–Band Transponder Receiver | IK-TRX (RX) | 2 | Operating | | X | | X |
| | S–Band Transponder Transmitter | IS-TRX(TX) | 2 | Redundant transmitter is stand-by. | | X | | X |
| | S–Band Transponder Receiver | IS-TRX (RX) | 2 | Operating | | X | | X |
| | Antenna | IOCS-ANT | 1 | | | X | | X |
| | Antenna Pointing Mechanism | APM | 1 | | | X | | X |
| | Antenna Pointing Electronics | APE | 1 | | | X | | X |
| | Passive RF element | — | 1 set | | | X | | X |
| DH | CCSDS Data Processor | CDP | 2 | Tte redundant CDP is operating in the stand-by mode. | X | | X | |
| | Bus Interface and Multi function Unit | BMIU | 3 | Redundant BMIU is stand-by. | X | | X | |

Table 5.1.3-1 Major Avionics Components and Elements (Cont.)

| S/S | Component | Abbreviation | Quantity | Operation for Redundancy | Installed area |  | Based System |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Avionics Module | Mission Module | HTV Avionics Module | Other Program |
| EPS | Main Bus Unit | MBU | 1 |  | X |  | X |  |
|  | Power Control Unit | PCU | 1 | Redundant control circuit is operating. | X |  | X |  |
|  | Secondary Battery | S-BAT | 1 string | Bypass switches in parallel | X |  | X |  |
| INT | Wire Harness | — | 1 set |  | X |  | X |  |
|  | Heater Control Electronics1 | HCE1 | 1 | Operating | X |  | X |  |
|  | Ordnance Control Circuit | — | 1 | Operating | X |  |  | X |
| SPS | Solar Array Paddle | SAP | 2 | Operating | X |  |  | X |
|  | Solar Array Paddle Drive Mechanism | PDM | 2 | Operating | X |  |  | X |
|  | Solar Array Paddle Drive Electronics | PDE | 2 | Operating | X |  |  | X |
| VIS | Viewing Camera | VC | 4 | Operating |  | X |  | X |
|  | Illumination Light | ILL | 2 | Operating |  | X |  | X |
|  | Video signal processor | VSP | 1 |  |  | X |  | X |
| ARMS | Manipulator | — | 1 |  |  | X |  | X |
|  | Arm Drive Electronics | ADE | 1 |  |  | X |  | X |
| DMS | Docking Mechanism | DM | 1 set |  |  |  |  |  |
|  | Docking Mechanism Drive Electronics | DMDE | 1 set |  |  | X |  |  |
|  | Mission Data Processor | MP | 2 | Operating |  | X |  | X |

The HDV has Failure Detection Isolation and Recovery (FDIR) function based on the HTV that is reviewed in the Independent Verification and Validation activity by the Charles Stark Draper Laboratory, Inc. Basic concept of Failure Detection Isolation and Recovery (FDIR) of HDV is "One fail operative for mission". This is a relaxed system concept from "One fail operative for mission, 2 fail safe (abort)" on the HTV that has the third string for abort control.

The typical FDIR functions of avionics system are as follows;

- Detection for GNC sensor failure by multiple sensor data and crossover information using other method
- Voting for outputs of three operating CPU
- Cross health check between CPU and IOC
- String exchange in case of propulsion subsystem failure
- Periodical heater ON/OFF check out by using heater current sensor data

And FDIR related functions are
- DTCS Antenna change after attitude contingency,
- Transition to power save mode after power source failure.

### 5.1.4 Mission Module

In order to minimize design changes from HTV, additional equipment such as the remote manipulator system, docking mechanism, additional rendezvous sensors are mounted in an additional section named Mission module. Details of these equipments are described in following sections.

### 5.1.5 Remote Manipulator System (RMS)

#### (1) Overview of RMS

RMS consists of following assemblies and components

- RMS Avionics
- Manipulator
- Hold and Release Equipiment
- System Outfitting

RMS composition is shown in Fig.5.1.5-1, configuration is shown in Fig.5.1.5-2. Schematic diagram of the RMS's Data manegement system is shown in Fig.5.1.5-3.

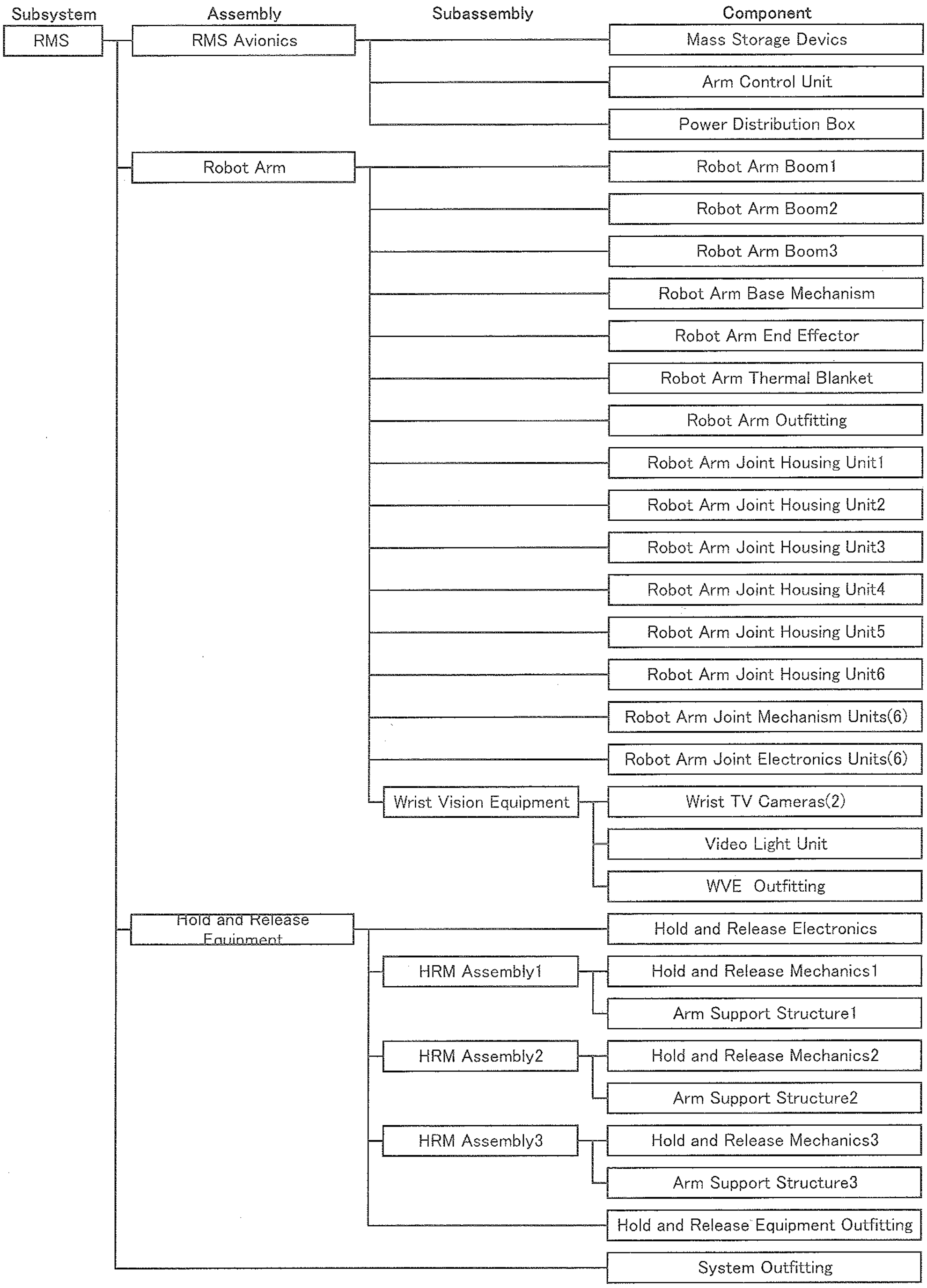


Fig.5.1.5-1 RMS compotision

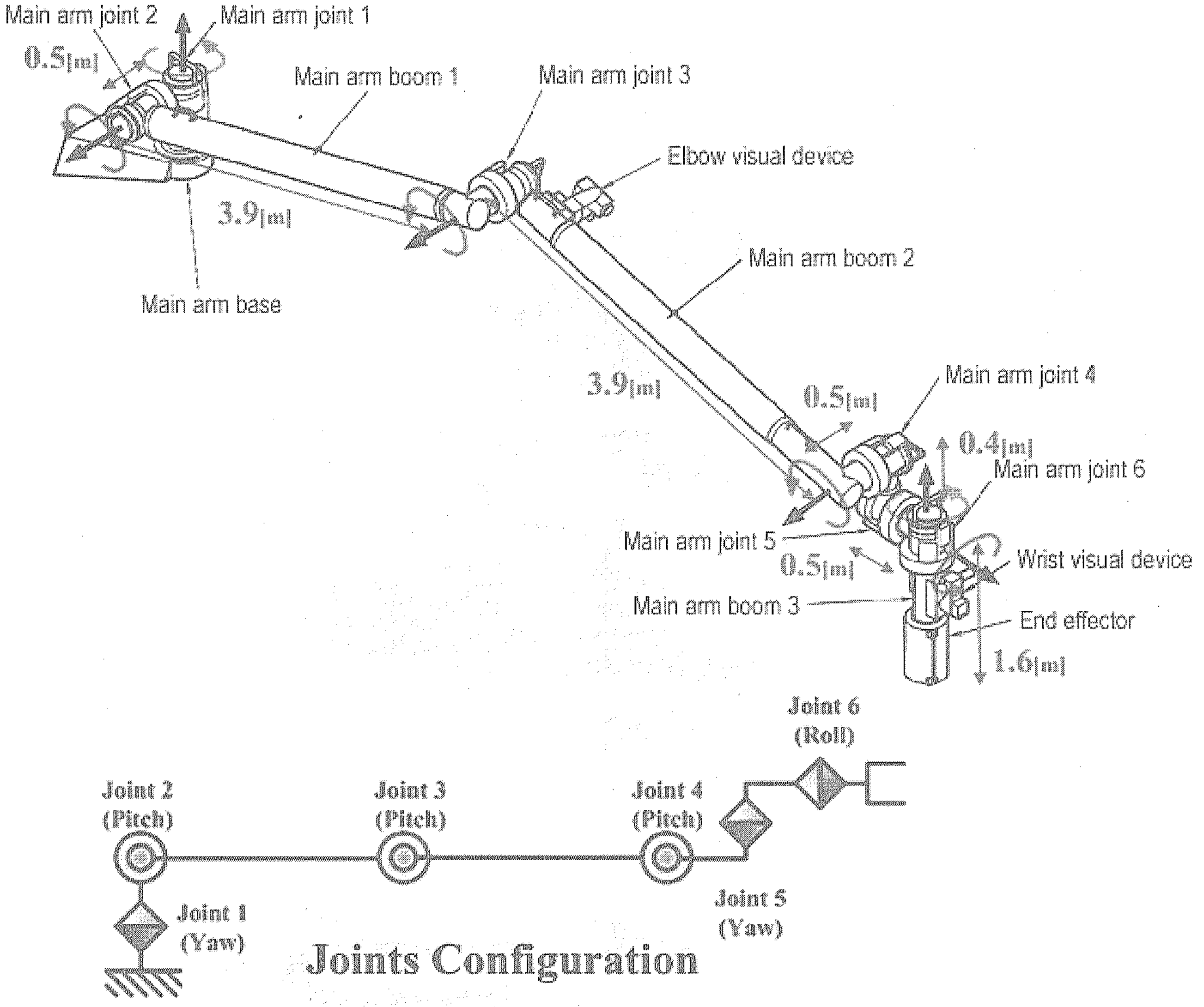


Fig.5.1.5-2 RMS configuration (1/2)

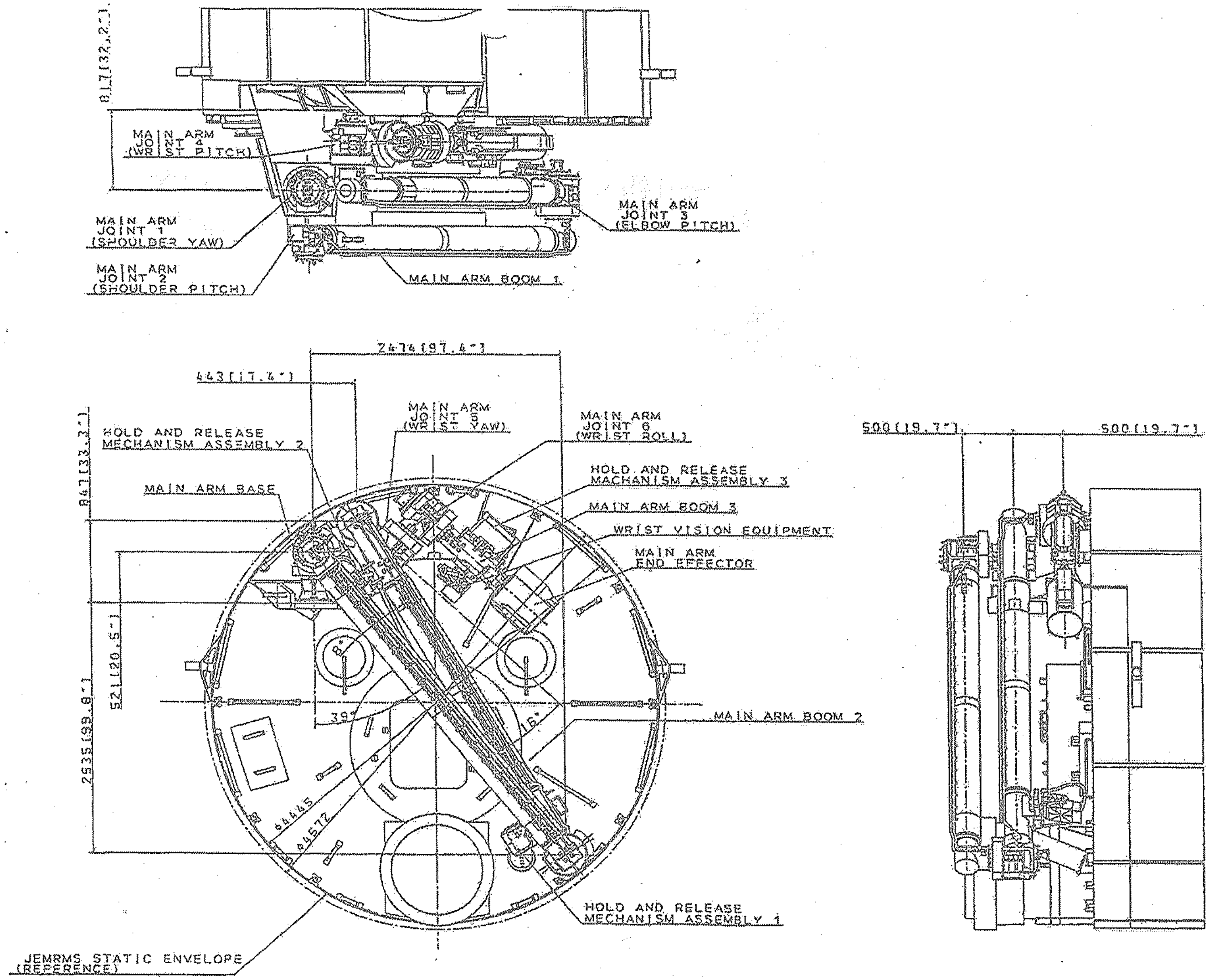
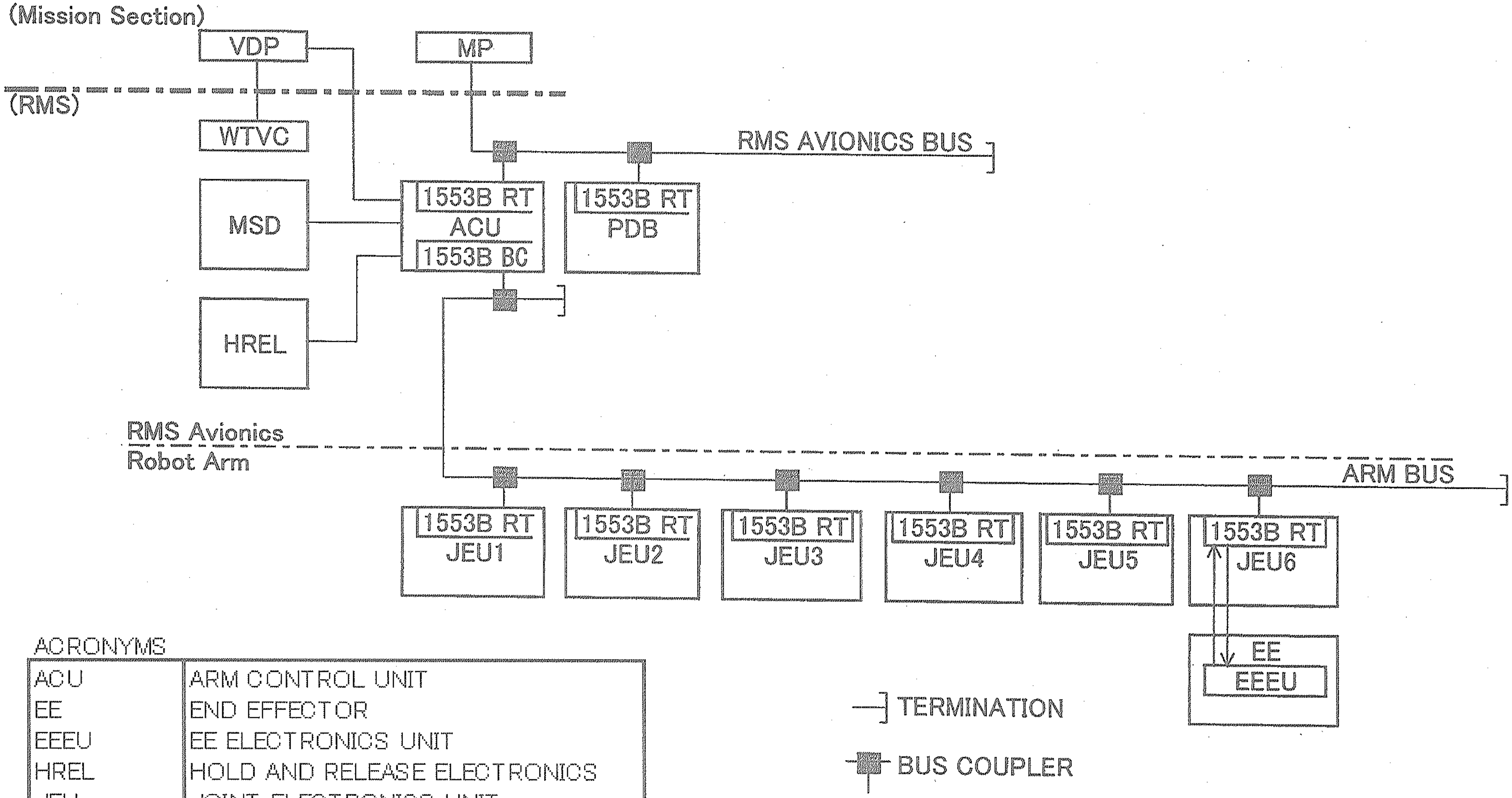


Figure 5.1.5-2 RMS launch configuration (2/2)



ACRONYMS

| | |
|---|---|
| ACU | ARM CONTROL UNIT |
| EE | END EFFECTOR |
| EEEU | EE ELECTRONICS UNIT |
| HREL | HOLD AND RELEASE ELECTRONICS |
| JEU | JOINT ELECTRONICS UNIT |
| MP | MAIN PROCESSOR |
| WTVC | WRIST TV CAMERA |
| MSD | MASS STORAGE DEVICE |
| JDP | VIDEO DATA PROCESSOR |

Fig.5.1.5-3 DMS Schematic diagram

(2) Weight and Power consumption

RMS weight is shown in Table 5.1.5-1, Power consumption is shown in Table 5.1.5-2.

Table 5.1.5-1 RMS weight

| Item | Weight (kg) |
|---|---|
| RMS Avionics | 300 |
| Manipulator | 750 |
| Hold and Release Equipment | 195 |
| System Outfitting | 40 |
| RMS Total | 1285 |

Table 5.1.5-2 RMS Power consumption

| Mode | Power consumption (W) |
|---|---|
| Stand-by | 400 |
| Operation | 840 |
| heater | 200 |

### 5.1.6 Docking Mechanism

HST has three berthing pins on Aft shroud bulkhead, then the docking mechanism shall consist of three latching mechanism just like ETS-VII Docking Mechanism (DM). Therefore, it is most efficient and cost-effective to modify EST-VII DM according to HDV's docking condition.

#### 5.1.6.1 ETS-VII Docking Mechanism (DM)

ETS-VII docking mechanism is shown in Fig.5.1.6.1-1. Its main performance is as follows.

(1) Large relative allowable misalignment
Capturing area: 130mm×150mm

(2) Contact shock absorption ability
Acceleration(X axis):0.04G

(3) High stiffness after docking
Axial : $7.0\times10^5$[N/m]
Lateral : $7.0\times10^5$[N/m]
Roll : $7.0\times10^5$[Nm/rad]
Pitch,Yaw : $7.0\times10^5$[Nm/rad]

(4) Low electric power
129[W](max)

(5) Launch Lock
DM has a launch lock mechanism to protect itself from vibration at launch phase.

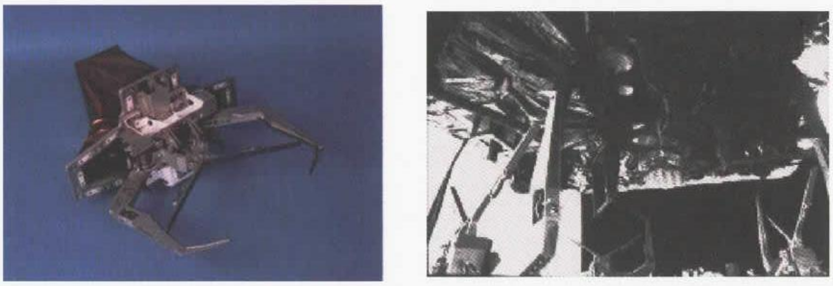
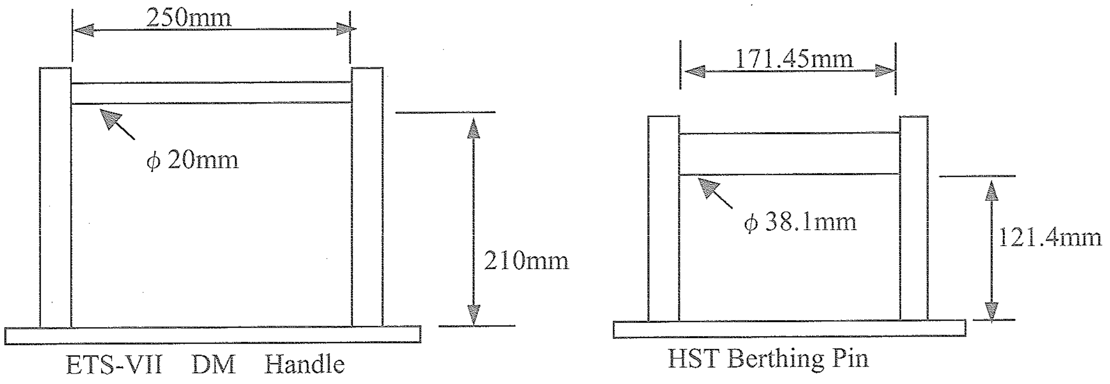


Fig.5.1.6.1-1 ETS-VII Docking Mechanism

### 5.1.6.2 ETS-VII DM Modification

ETS-VII DM must be modified according to HDV's docking condition.

(1) Berthing pin configuration and latching lever length



ETS-VII DM Handle

HST Berthing Pin

Fig.5.1.6.2-1 Comparison between ETS-VII DM handle and HST berthing pin

HST berthing pin length and height is about two-thirds of ETS-VII DM handle. Then latching lever length must be about two-thirds of ETS-VII DM claw length. Short latching lever makes allowable misalignment small and stiffness after docking high. And HST berthing pin diameter is about as twice as ETS-VII DM handle. Then latching lever closing motion pattern must be changed according to the large size pin.

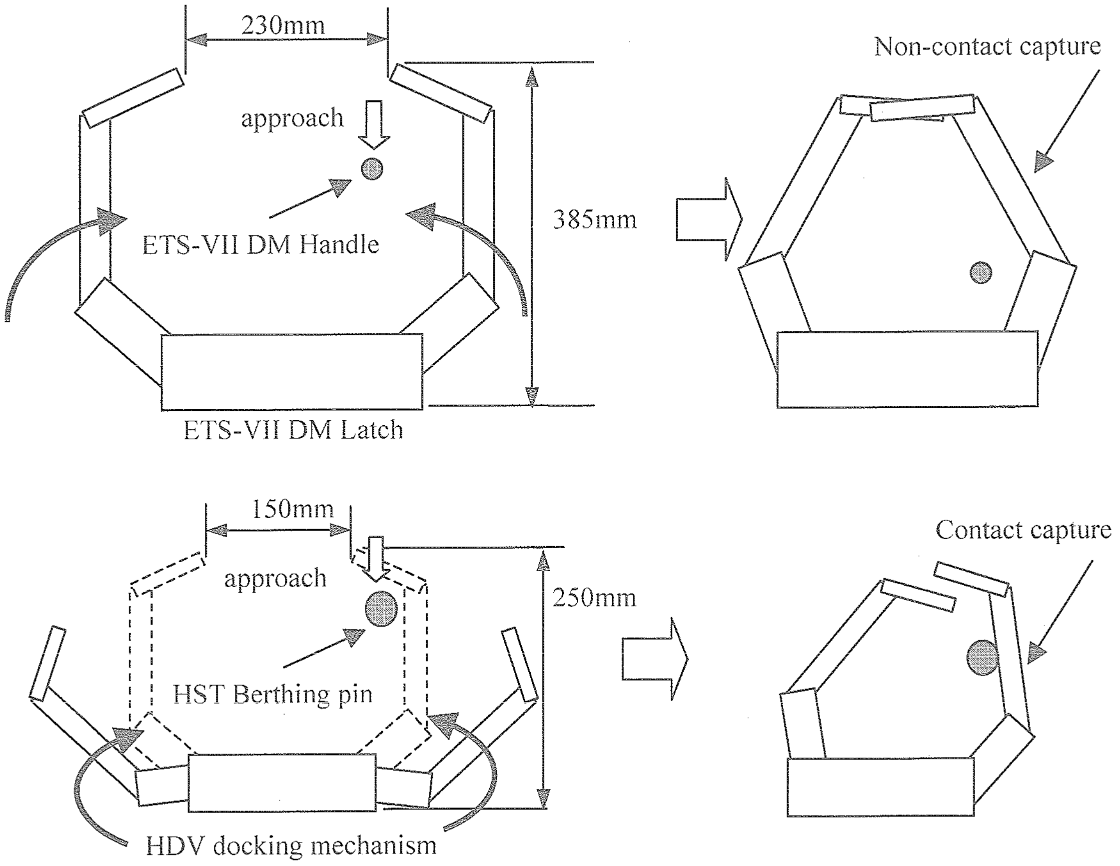


Fig.5.1.6.2-2 Comparison between ETS-VII DM latch and HDV docking mechanism

ETS-VII DM capturing method is non-contact capture, it means that contact doesn't occur before capturing. Then it had to have long claws and large capturing area. However, HDV docking mechanism laching lever must be shorter than ETS-VII DM because of small berthing pin length and height. Then, if HDV docking mechanism is actuated as a same pattern as ETS-VII DM, its capturing ability becomes lower than ETS-VII DM.Consequently, HDV docking mechanism has to be modified to be actuated with tolarating contact befor capturing.

(2) Shock absorption ability

ETS-VII chaser satellite weight is about 2,200[Kg](EOM), and target satellite weight is about 400[Kg]. On the other hand, HST weight is about 12,000[Kg] and HDV weight is 6,500[Kg], then kinetic energy to be absorbed is larger than ETS-VII when approach speed is the same. The shock absorption mechanism is modified according to large energy.

(3) Stiffness after docking

Required HDV stiffness after docking depends on the loads affected on orbit. The largest load is the de-orbit thrust load (890[N]). But this load affects HDV docking mechanism as an axial compression load, then it doesn't affect HDV docking mechanism critically. Critical loads for HDV docking mechanism is assumed as a pitch/yaw moments with the same stiffness as ETS-VII, because axial distance from HDV to HST center of mass is long.

(4) Actuator

A Stepping motor was used for ETS-VII DM. However, brushless DC motor is better for HDV docking mechanism. DMDE(Docking Mechanism Drive Electronics) must be changed to drive brushless DC motor, but micro switch interface must not to be modified.

(5) Docking mechanism mounted configuration

Firstly, docking mechanism consist of three latches, and they must be mounted at every 120[deg] apart from each other.

Secondly, in order to avid an interference between HDV Remote Manipulator Subsystem (RMS) mount and HST aft bulkhead during docking phase, docking mechanism must be mounted at protruding position apart from

HDV surface.

Thirdly, HDV RMS shall not contact docking mechanism and its mount during deploying motion before HST capture.

Fig.5.1.6.2-3 shows the docking mechanism mounted configuration on HDV. In this figure, RMS end effecter contacts a docking mechanism mount, then end effecter must be positioned near the edge of HDV. If #4 joint is rotated 5[deg], end effecter RMS configuration becomes a figure in section 4.2.2, then interference between end effecter and docking mechanism doesn't occur.

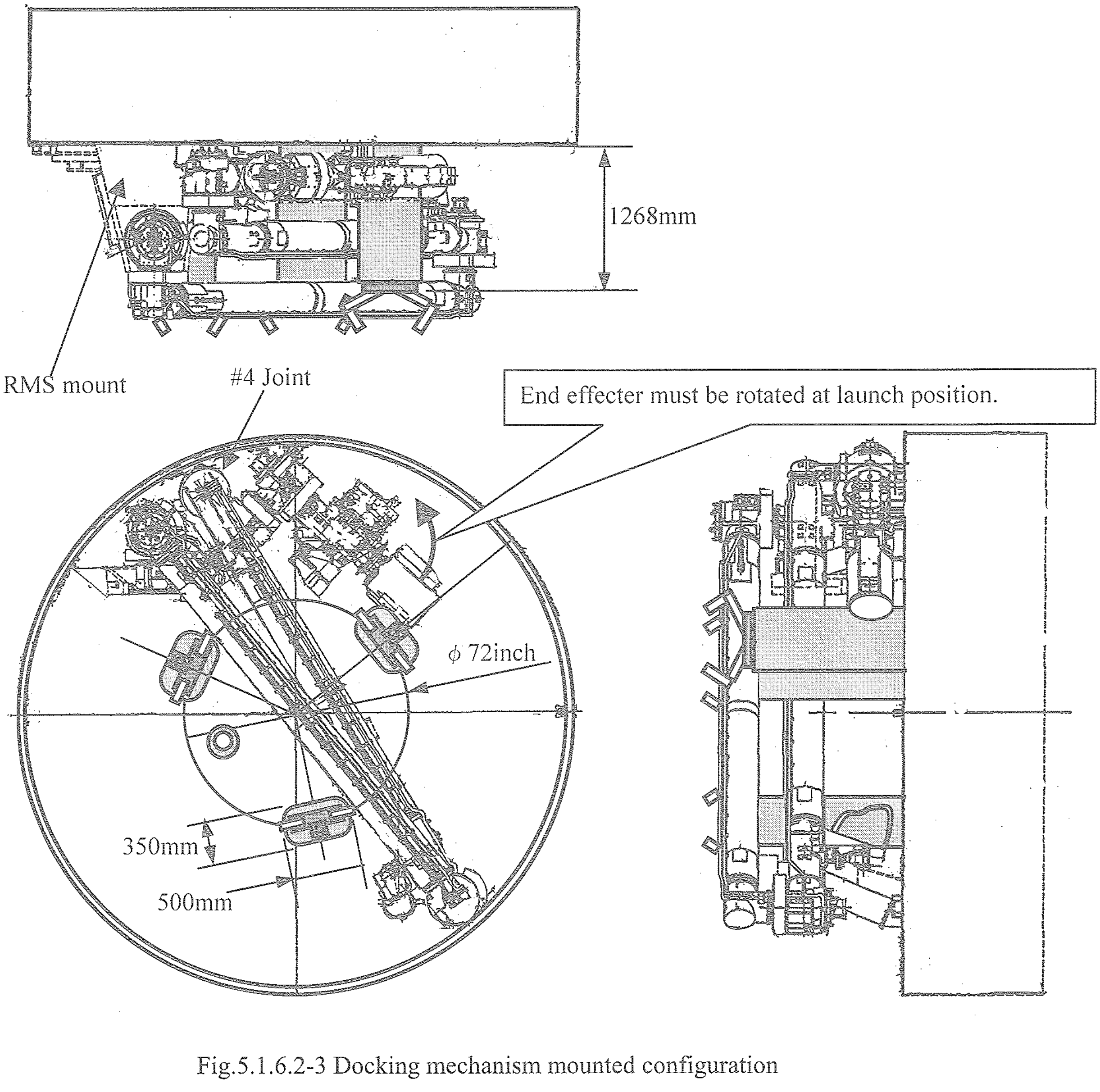


Fig.5.1.6.2-3 Docking mechanism mounted configuration

Based on RMS deployment analysis(section 4.2.2), RMS don't contact docking mechanism during deploying motion.

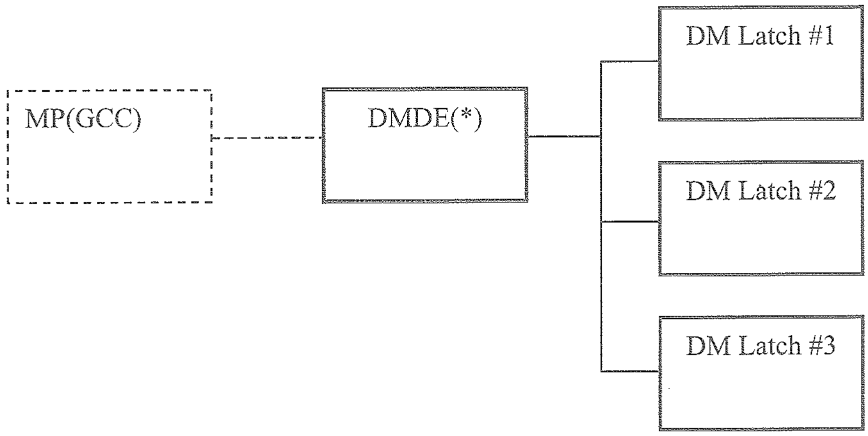
As the docking mechanism is mounted at higher position than that of RMS, then HST bulkhead doesn't contact HDV.

In RMS contingency case, we must conduct direct docking with RMS folded. Following studies(2 types of options) must be done.

1) Extend docking mechanism mount in the direction of HST from launch position
2) Lengthen RMS booms

### (6) System Block

HDV docking mechanism system block diagram is shown in Fig.5.1.6.2-4.



(*)DMDE :Docking Mechanism Drive Electronics

Fig.5.1.6.2-4 Docking mechanism system block diagram

### (7) Weight, size and power

Docking mechanism specification is shown in Table 5.1.6.2-1.

Table 5.1.6.2-1 Docking Mechanism Size / Weight / Power consumption

| Item | Number | Size(mm) | Weight(kg) | Power consumption (W) |
|---|---|---|---|---|
| Docking mechanism latch | 3 | 500×350×1300 (including mount) (TBD) | 25×3 (TBD) | 360 (TBD) |
| DMDE | 1 | 350×350×300 (TBD) | 25 (TBD) | |
| total | | | 100 | 360 |

5.1.6.3 Development test

Docking test must be conducted using JAXA Rendezvous and Docking Operation Test System (RDOTS). Fig.5.1.6.3-1 shows RDOTS. Fig.5.1.6.3-2 shows detail of HDV docking mechanism side, and Fig.5.1.6.3-3 shows detail of HST aft shroud bulkhead side.

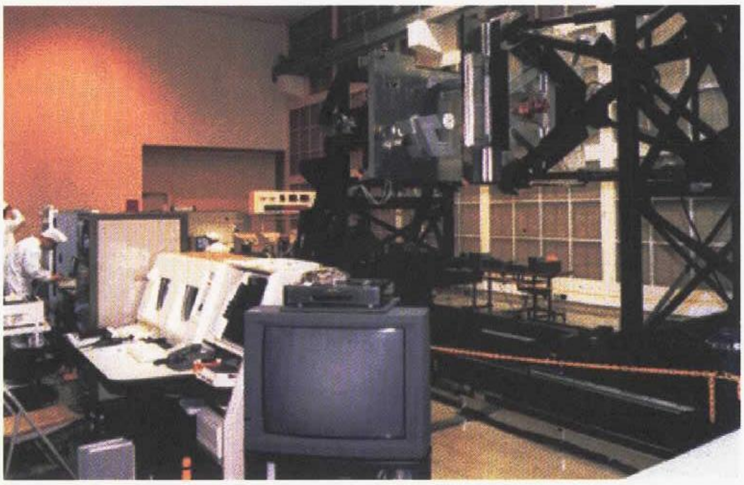


Fig.5.1.6.3-1 RDOTS configuration

Fig.5.1.6.3-2 HDV side detail

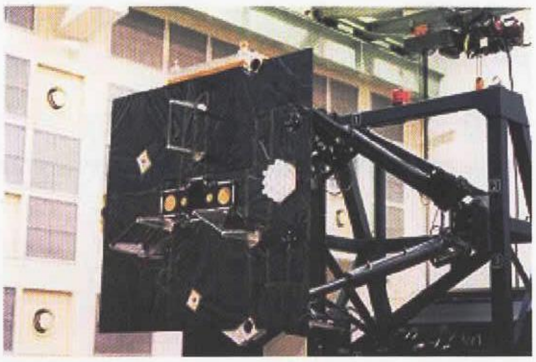


Fig.5.1.6.3-3 HST side detail

RDOTS can simulate mass property of two spacecrafts, guidance program, and contact dynamics. And NRS can be mounted on HDV side. Then we can simulate guidance and contact dynamics of HDV and HST at direct docking phase.

### 5.1.7 Rendezvous sensors

Three types of sensors, GPS receivers, Far-range Rendezvous Sensors (FRS) and Near-range Rendezvous sensors (NRS) are used for rendezvous operation of HDV depending on the distance between HST and HDV, while two types of sensors, GPSR and Rendezvous Sensors (RVS) are used in HTV.
The FRS can easily be realized by modifying HTV's RVS or Rendezvous Laser Sensor that JAXA is currently developing. The NRS is developed based on ETS-VII's video sensor. Following section shows FRS based on Rendezvous Laser Sensor that JAXA is developing.

#### 5.1.7.1 FRS (Far-range Rendezvous Sensor)

#### 5.1.7.1.1 Sensor System Overview

FRS is a relative navigation sensor which is used to detect and track HST when HDV is too far from HST to use NRS.

After the launch, HDV maneuvers to HST by absolute navigation using on-board GPS receivers. Then detection of HST is performed by FRS. FRS has wide FOV and long measurement range. HDV approaches to HST while tracking it in the center of FRS scan area. When HDV reaches close enough, the main rendezvous sensor is switched to NRS.

JAXA has developed a rendezvous laser sensor for ETS-VII (Fig.5.1.7.1.1-1), and succeeded to perform autonomous rendezvous-docking experiments.

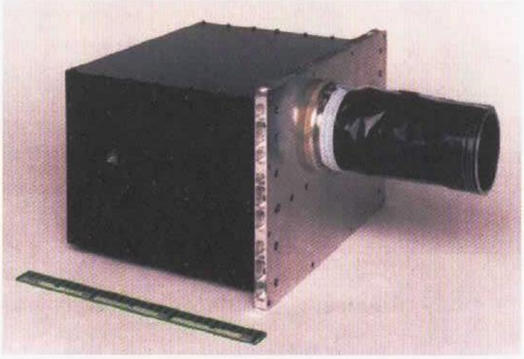


Fig.5.1.7.1.1-1 ETS-VII Rendezvous Laser Rader

Based on this heritage, JAXA studies about a new rendezvous sensor with wide FOV. It is designed for the target with laser reflectors. However, it has a potential that it can be used to the target without laser reflectors by slight modification.

Fig. 5.1.7.1.1-2 shows the illustration of the rendezvous sensor which is under development. It has a near infrared pulsed-laser transmitter, and a two-axis (Azimuth and Elevation) mirror scanning mechanism. The laser scans rectangle area, and APD (Avalanche Photo Diode) detects its return light from the target. Then we can know range and LOS (Line Of Sight) angle of the target from the FRS.

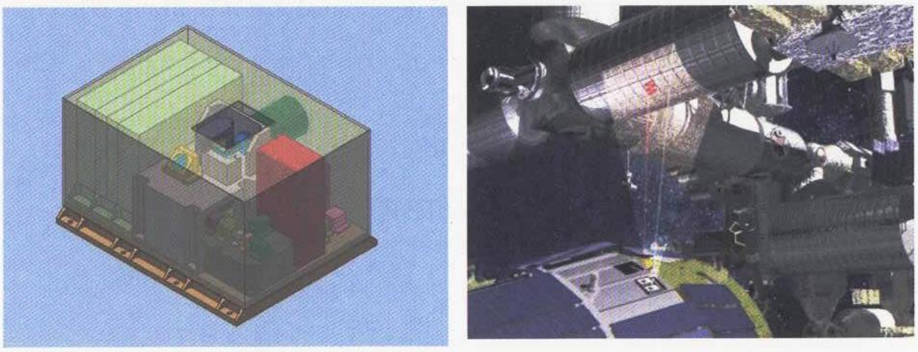


Fig.5.1.7.1.1-2 Rendezvous Laser Sensor being developed in JAXA

## 5.1.7.1.2 FRS operation overview

### 5.1.7.1.2.1 Prior Conditions of this investigation

#### (1) HST orbit determination accuracy

HST is tracked using TDRSS. Orbit determination accuracy is estimated as follows:

In-Track : ± 0.15[km] (TBR)
Cross-Track : ± 0.15[km] (TBR)
Radial : ± 0.15[km] (TBR)

#### (2) HDV maneuver accuracy

Position error of HDV when it maneuvers to the substantial point on V-BAR of HST by CW (Clohessy-Wiltshire) guidance method is estimated. Navigation error of GPSR is assumed to be 100[m] in the worst case. And $\Delta V$ error is 0.1[m/s] also in the worst case. When HDV performs mid-course maneuver at the one-twelfth point of the whole one orbit, the position error of the maneuver is estimated as follows:

In-Track : ± 1.00[km] (TBR)
Cross-Track : ± 0.40[km] (TBR)
Radial : ± 0.40[km] (TBR)

(3) VI point

HDV maneuvers to the substantial point on V-BAR of HST. The point is called "VI point". Position of the VI point should be determined considering about orbit determination accuracy of HST, HDV maneuver accuracy, and FRS measurement range. In this study, the point is determined that it is 4[km](TBR) from HST.

5.1.7.1.2.2 FRS operation scenario

Fig.5.1.7.1.2.2-1 shows the operation scenario of FRS.

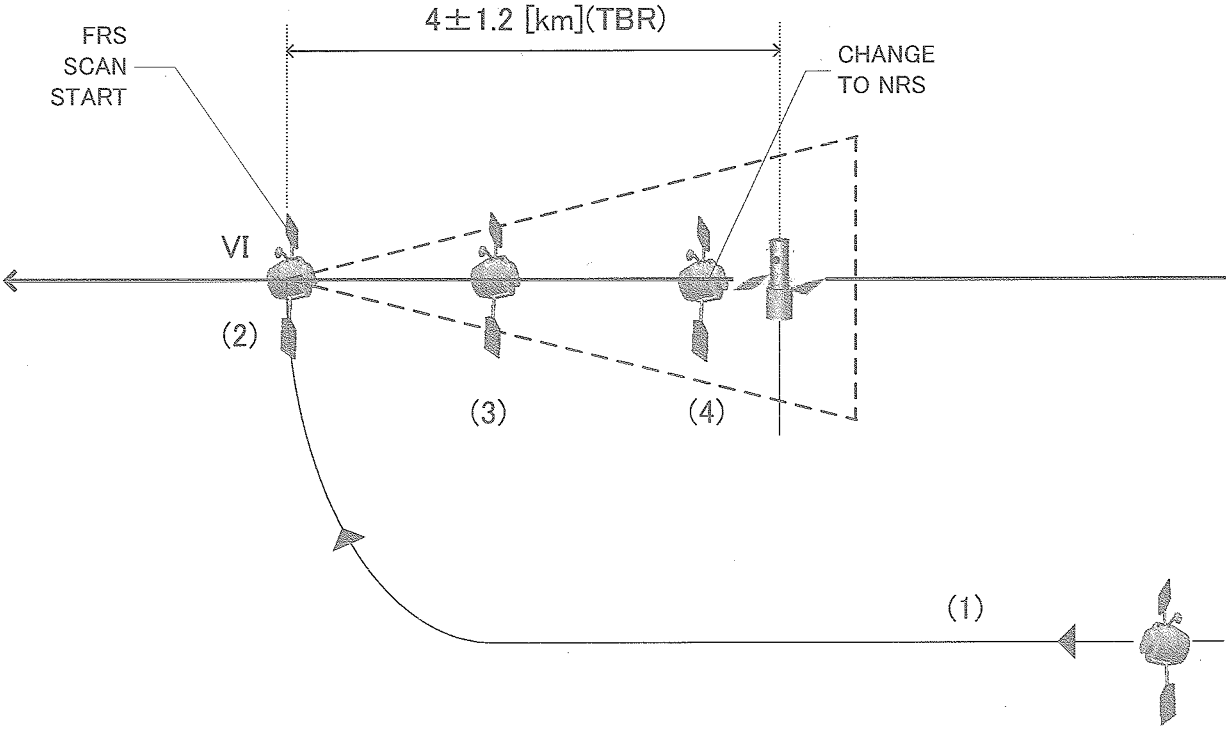


Fig. 5.1.7.1.2.2-1 FRS Operation Scenario

(1) HDV is on the phasing orbit. Then it maneuvers to the VI point on V-BAR of HST.

(2)HST detection phase

At VI point, FRS scanning starts. In this phase, FRS scans the widest area, and scanning pattern is set very tight not to miss HST. So it takes long time (about two minutes) to detect HST, but in this phase it is not critical.

(3)HST tracking and approach phase

After successful detection of HST, FRS changes its mode to "tracking mode". FSR narrow the scan area to the peripheral region of HST, and realizes high-frame rate.

HDV approaches to HST while controlling its attitude so that LOS of FRS is directed to HST. The nearer HDV approaches to HST, the apparent diameter of HST in the FOV of FRS is getting larger. To keep sufficient frame-rate, FRS has to change its scanning area and scanning pattern as the change of the distance between HDV and HST.

### (4)Change main rendezvous sensor to NRS

When HDV reaches to the substantial point on V-BAR (distance:100[m] (TBR)), the main rendezvous sensor is switched to NRS.

## 5.1.7.1.3 Study on FRS detection phase

### 5.1.7.1.3.1 Measurement Range Design

Considering about orbit determination accuracy of HST and HDV maneuver accuracy, the maximum distance between HDV and HST is as follows: $\sqrt{(4.00+1.00+0.15)^2+(0.15+0.40)^2+(0.15+0.40)^2} = 5.20[\text{km}]$。

### 5.1.7.1.3.2 Scanning Area Design

When FRS starts scanning to detect HST, it must be within the FOV of FRS. Considering about orbit determination accuracy of HST and HDV maneuver accuracy, the worst case is shown in Fig. 5.1.7.1.3.2-1.

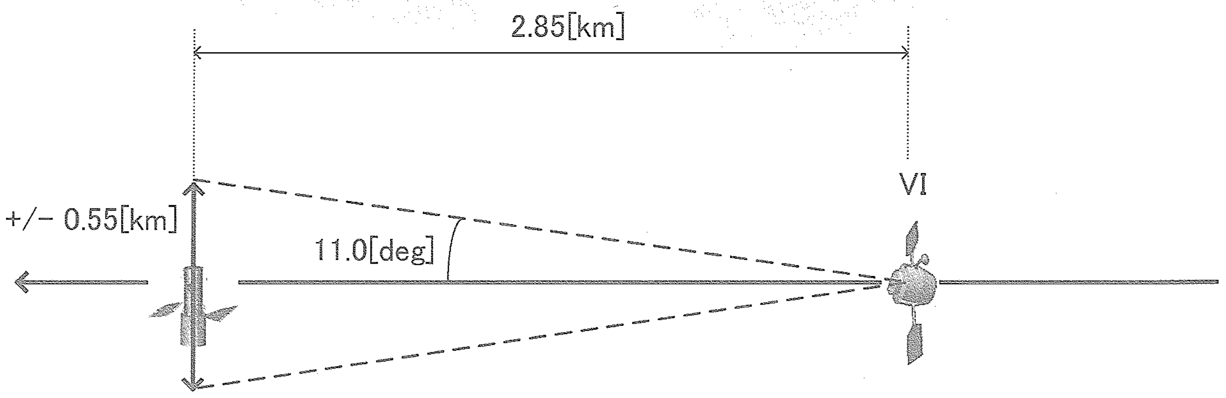


Fig.5.1.7.1.3.2-1 FRS Scanning Area Worst Case

To manage this worst case, the scanning area should be more than 11.0[deg].

### 5.1.7.1.3.3 Scanning Pattern and Laser Link Budget

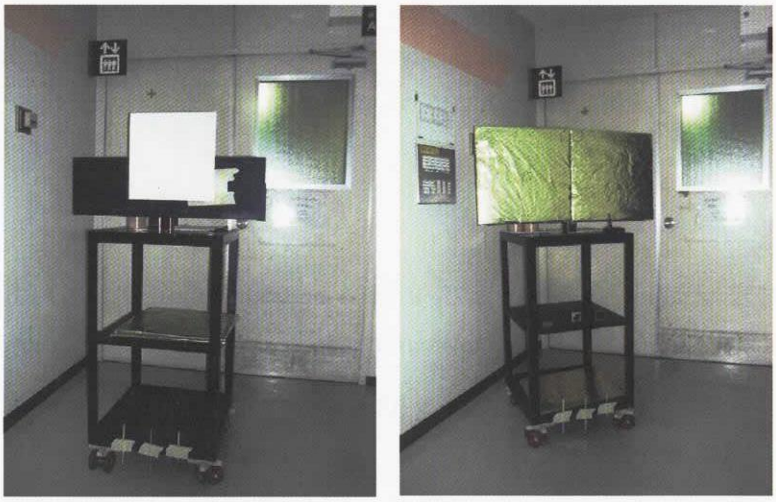
#### (1) Measurement range and scanning area specification

With respect to the study of previous sections, the specification of the FRS is determined as follows:

| | |
|---|---|
| FRS Measurement Range: | 5.2[km] |
| FRS Scanning Area: | 24 * 24 [deg] rectangle area（± 12[deg]） |

#### (2) Evaluation of Laser Return from HST

JAXA performed a basic experiment to evaluate the laser return from the panel covered with MLI (Multi Layer Insulator). The external coating of HST is not a typical MLI, but its characteristic of reflectivity may be similar to it. Fig.5.1.7.1.3.3-1 shows the target panel with MLI (right figure) and the reference target panel which has nearly perfect diffusion characteristics (left figure).



Reference Target Panel
Perfect Diffusion Surface

MLI Target Panel

Fig. 5.1.7.1.3.3-1Target Panel for Laser Return Evaluation Experiment

Laser return power from the panel was measured while changing the angle of incidence from 0[deg] to 50[deg]. MLI has a similar characteristic to mirrors. When the angle of incidence is 0[deg], the laser return is almost one hundred times as strong as that of the reference panel. On the contrary, when the angle of incidence is 30[deg], it returns only 4[%] laser return relative to the reference one.

In the following study, we consider only the area of which the angle of incidence is less than 30[deg]. Because the reflectivity of the panel with more than 30[deg] is small and negligible.
From the area with less than 30[deg] angle of incidence, we can get at least 4[%] laser return. For simplicity, in

the following study we estimate that all area with less than 30[deg] angle of incidence returns the same laser power: 4[%] relative to perfect diffusion.

This is very severe assumption. Because the reflectivity of the area where the angle of incidence is less than 30[deg] is expected to be 4~10000 [%] relative to the reference perfect diffusion panel. Then the following analysis is based on the extreme worst case.

### (3) Estimation of HST Effective Laser Return Area

The target is the cylinder shaped structure of HST. Its height is about 13[m] and its diameter is about 4.25[m]. The effective laser return area, which means that the angle of incidence is less than 30[deg], is shown in Fig. 5.1.7.1.3.3-2 (center)

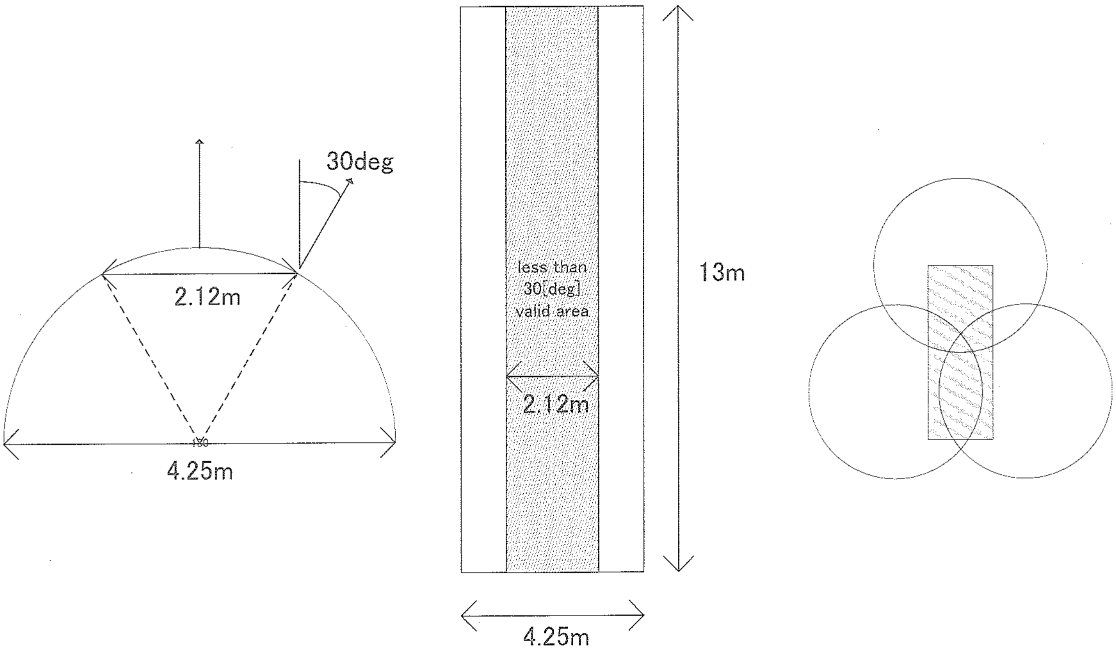


Fig. 5.1.7.1.3.3-2 Effective Laser Return Area of HST cylinder shaped structure

HST may be divided in two or three laser spots. As shown in Fig. 5.1.7.1.3.3-2 (right), the effective laser return area is at least a half of the whole area: 2.12[m]*13.0[m]/2 = 13.8[$m^2$] in the worst case.

### (4) Scanning Pattern Design

Scanning area is 24[deg]*24[deg]. Necessary time to scan this one frame area: *Ts* can be calculated by a following numerical formula.

$$T_s = \frac{\theta_{AZ} \cdot \theta_{EL}}{\alpha \cdot \beta} \cdot \frac{1}{\eta_{AZ} \cdot \eta_{EL}} \cdot \frac{1}{f_P}$$

| | | | | | |
|---|---|---|---|---|---|
| $\theta_{AZ}$ | : | Azimuth Scan Range | 0.419 | rad | (24deg) |
| $\theta_{EL}$ | : | Elevation Scan Range | 0.419 | rad | (24deg) |
| $\alpha$ | : | Azimuth Step Angle | | | |
| $\beta$ | : | Elevation Step Angle | | | |
| $\eta_{AZ}$ | : | Azimuth Scanning Efficiency | 0.8 | | |
| $\eta_{EL}$ | : | Elevation Scanning Efficiency | 0.8 | | |
| $f_P$ | : | Laser Pulse Frequency | | | |

Specification of laser is determined as follows:

| | |
|---|---|
| Laser Pulse Power: | 1[MW] |
| Pulse Width | 10[ns] |
| Laser Pulse Frequency | 100[pps] |

Bearing this specification in mind, and determining *Ts* to be 110[sec], $\alpha$ and $\beta$ is calculated: $\alpha$、$\beta$ = 0.0050[rad]

Then, step angle is to be 0.005[rad], laser spot diameter is to be 0.005*4/3 = 0.0067. Scanning pattern is shown in Fig. 5.1.7.1.3.3-3.

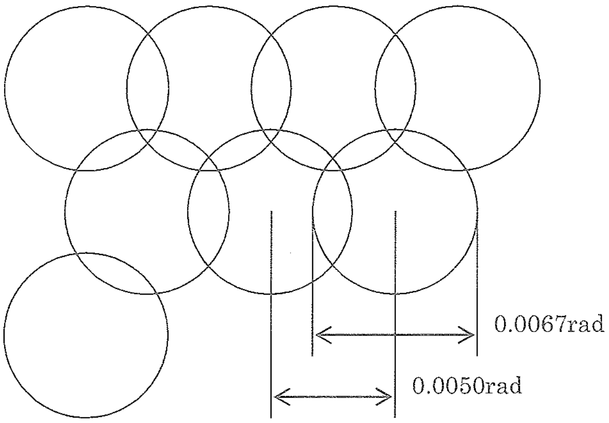


Fig. 5.1.7.1.3.3-3 Scanning Pattern of FRS (detection phase)

(5) Laser Link Budget

With respect to the study of previous sections, the laser link budget is calculated. The assumptions are listed in

Table5.1.7.1.3.3-1, and the calculation result is shown in Fig. 5.1.7.1.3.3-4. An avalanche photo diode is assumed as a detector device.

Table5.1.7.1.3.3-1 Assumptions of Link Budget Calculation

| | |
|---|---|
| Laser Pulse Power | 1000000 W |
| Reflectivity Factor | 4 % |
| Lens Diameter of Detector | 0.06 m |
| Pulse Laser Frequency | 100 Hz |
| Beam Spread Angle | 0.00667 rad |
| Azimuth scanning angle range | 24 deg |
| Elevatin scanning angle range | 24 deg |
| Step Angle | 0.005 rad |
| Scanning Time | 110 sec |

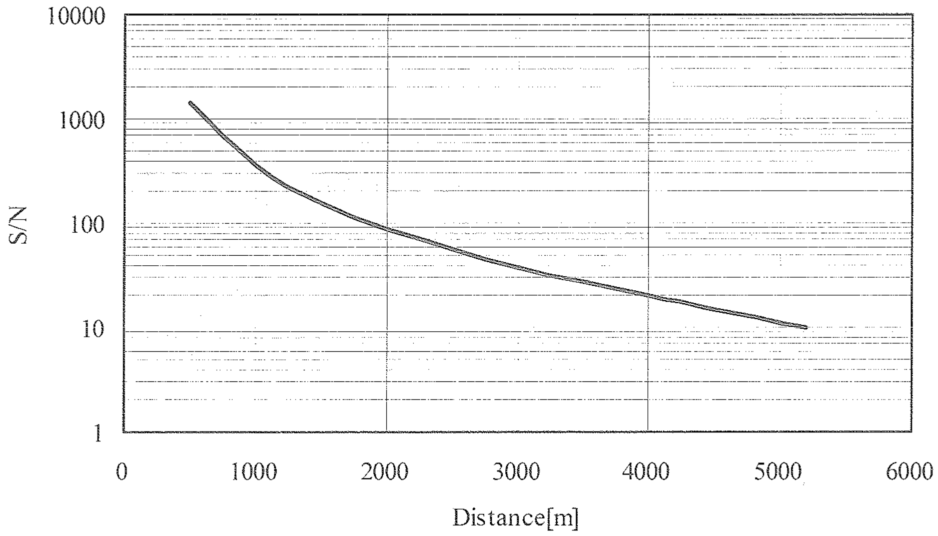


Fig. 5.1.7.1.3.3-4 Distance and S/N

From Fig. 5.1.7.1.3.3-4, it is clear that we can guarantee sufficient S/N:10 even if the distance between HDV and HST is the maximum range: 5.2[km].

#### 5.1.7.1.4 Study on FRS Tracking Phase Design

##### 5.1.7.1.4.1 Measurement Range Design

After FRS detects HST, scanning area is narrowed to the peripheral region of HST, and much high frame-rate can be achieved. HDV approaches to HST controlling its attitude so that the LOS of FRS is at the center of the FOV of FRS.

On this study, measurement range of FRS is between 100[m] and 5.2[km]. Hence, when HDV reaches to the point with 100[m] distance from HST, its main rendezvous sensor is switched to NRS.

##### 5.1.7.1.4.2 Scanning Area and Scanning Pattern Design

It is difficult to track HST using the same scanning area and scanning pattern.

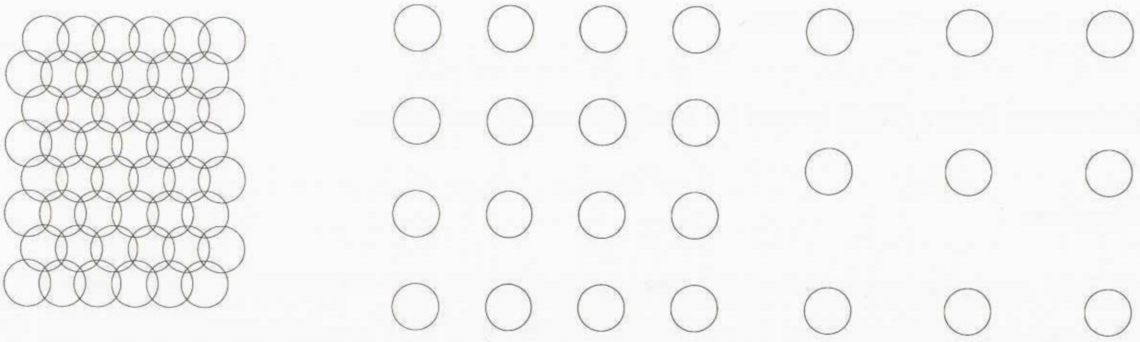
As the scanning area is getting smaller, the more high-speed frame rate can be achieved. Otherwise, as HDV approaches closer, an apparent diameter of HST is getting bigger, and scanning area must be also larger.

Also, when the distance between HDV and HST is long, it's necessary to scan the scanning area tightly not to lost HST. Otherwise, at near region from HST, an apparent diameter is so big that interlaced scanning can be adopted.

Considering these factors, to keep practical frame-rate through long measurement range, the size of scanning area and densitu of scanning pattern should be chosen properly as the distance from HDV to HST.

On this study, scanning pattern is designed according to the following criteria.
1) At far range, when the number of expected laser return is less than one, select tight scanning pattern (not interlaced).
2) The apparent size of HST should be less than 10[%] of the whole scanning area.
3) At near range, less than 300[m], the number of expected laser return should be more than two.

Fig.5.1.7.1.4.2-1 shows the result of the scanning pattern design. Fig.5.1.7.1.4.2-2 shows scanning pattern change design with respect to the distance.



Scan pattern 1
Step Angle = 0.0040[rad]

Scan pattern 2
Step Angle = 0.0107[rad]

Scan pattern 3
Step Angle = 0.0213[rad]

Fig. 5.1.7.1.4.2-1 Scanning Pattern

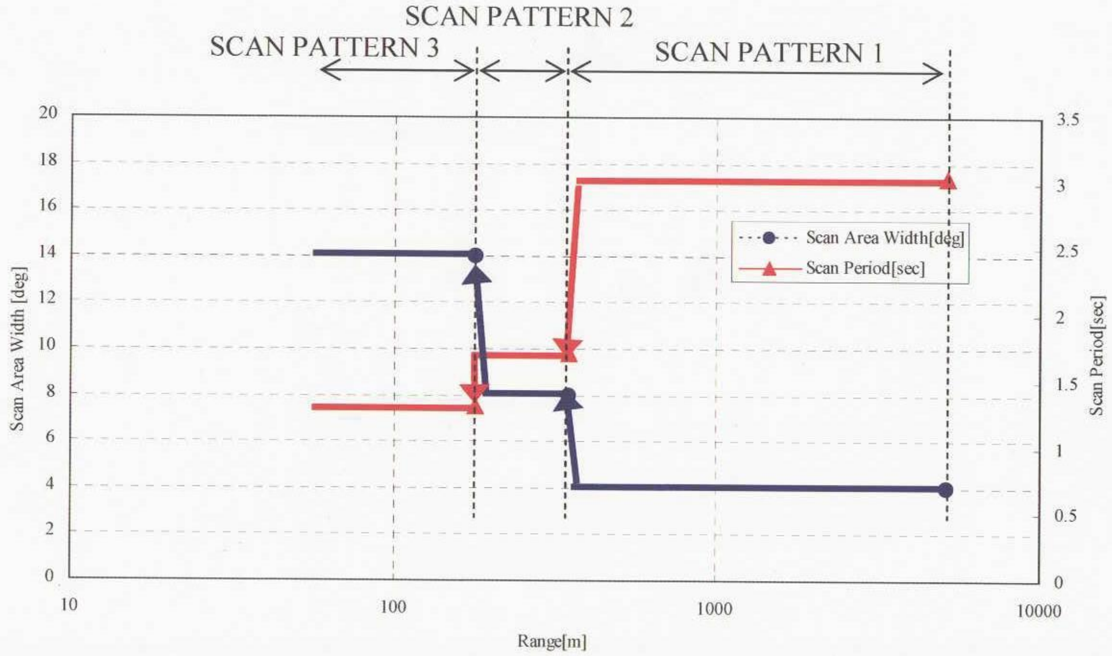


Fig.5.1.7.1.4.2-2 Scanning Pattern Change Design

According to the results of this study, we know that it is possible to keep practical frame-rate (about 1 - 3 [sec]) throughout all distance necessary for FRS, which from 5.2[km] to 100[m].

### 5.1.7.2 Near Rendezvous Sensor (NRS)

Near Rendezvous Sensor (NRS) is used for final approach of rendezvous.

#### (1) NRS system

Fig.5.1.7.2-1 shows the layout of the NRS. Cameras for recognition of Aft Bulkhead's form is attached and arranged to each Docking Mechanism. The camera for recognition of HST's berthing target is arranged so that it may come to the position of the front of the berthing target at the time of docking.

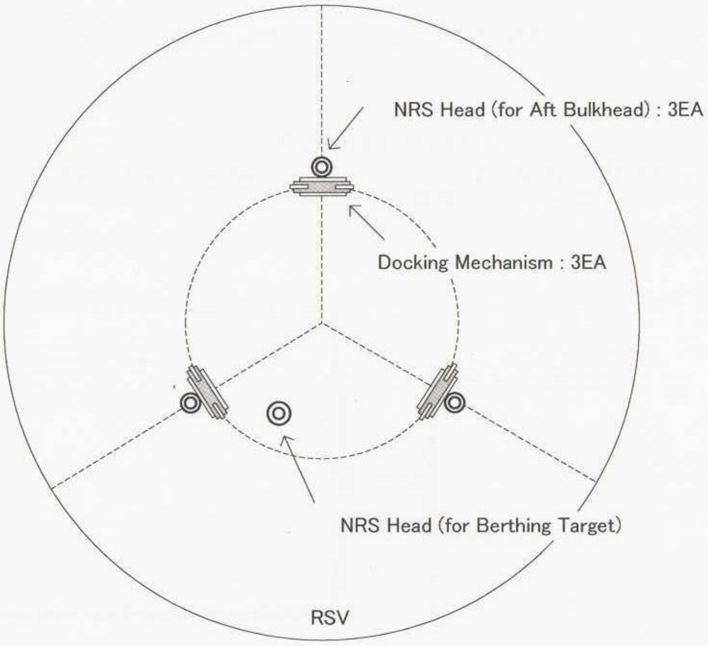


Fig.5.1.7.2-1 NRS Layout

NRS will be built based on heritage of ETS-VII's Proximity Sensor（PXS） which was used by ETS-VII's docking operations . Fig.5.1.7.2-2 shows ETS-VII's PXS.

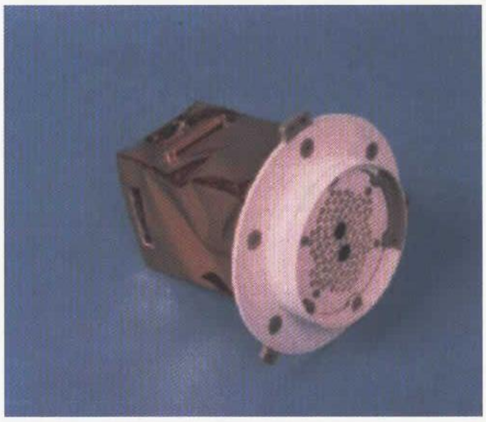


Fig.5.1.7.2-2 Proximity Sensor of ETS-VII

Fig.5.1.7.2-3 shows system block diagram. The image of each camera is processed by each CPU. HST's 3D-positions and attitudes are calculated by main MPU based on results of each camera's CPS.

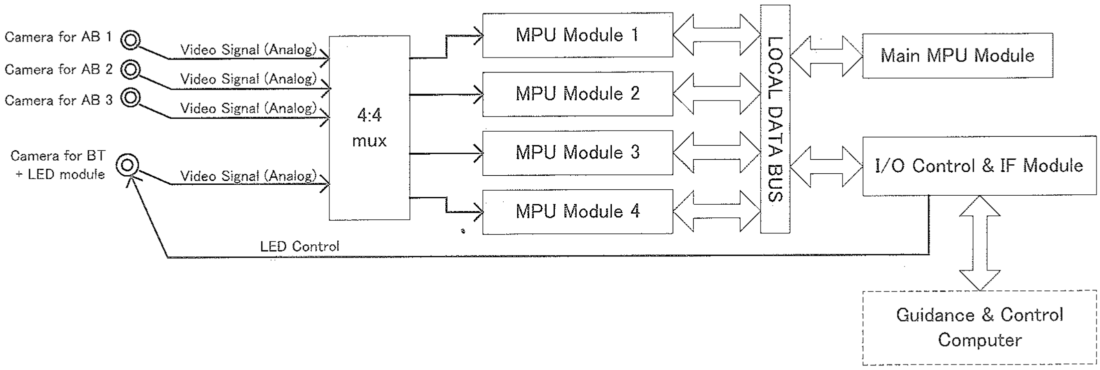


Fig.5.1.7.2-3 System Block Diagram

(2) Weight, Size and Power consumption

Specifications of composition apparatus is shown in Table 5.1.7.2-1, 5.1.7.2-2 and 5.1.7.2-3.

Table 5.1.7.2-1 Size / Weight / Power consumption

| Item | Number | Size(mm) | Weight(kg) | Power consumption (W) |
|---|---|---|---|---|
| Camera unit | 4 | φ100×150 | 1×4 | 2×4 |
| LED-module | 1 | φ150×40 | 1 | 10 |
| Processing unit | 1 | 250×320×300 | 25 | 100 |
| Harness | | | 5 | - |
| | | | 35 | 118 |

Table 5.1.7.2-2 Camera Specification

| Item | CCD Resolution (W×H) | FOV (AZ×EL, deg) | Lens Focal Length(mm) |
|---|---|---|---|
| Camera for AB | 640×480 | 29.8×22.6 | 12 |
| Camera for BT | 1600×1200 | 29.8×22.6 | 12 |

Table 5.1.7.2-3 LED-module Specification

| Item | |
|---|---|
| Number | 250 |
| Luminous Intensity (cd) | 100(TBD) |
| Angle (deg) | 30 (TBD) |
| Power consumption (W) | 10 |

(3)The approach scenario with NRS (for - V1 approach case)

The proposed method for measurement of HST's 3D (three dimensional) positions and attitudes is shown in Fig.5.1.7.2-4

NRS measured 3D-positions and attitudes from Aft-Bulkhead outline in the view of CCD cameras

NRS detects the berthing target in the view of the CCD camera of NRS head (for berthing target)

NRS measures 3D positions and attitudes from berthing target's marker in the view of CCD camera.

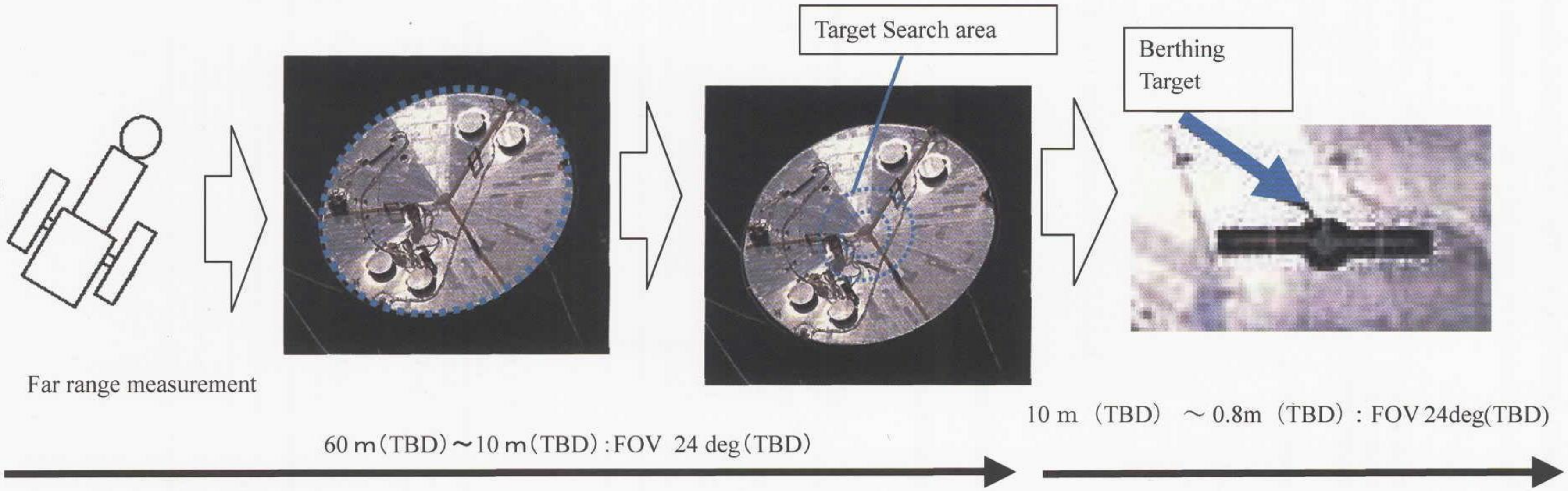


Fig.5.1.7.2-4 Approach scenario

### (4) Semiautomatic system

It is difficult to automate all the sequences of NRS, then semiautomatic system is desirable, that is complemented by operation from the ground. Table 5.1.7.2-4 shows full automation system problem, operator's work and semiautomatic system advantages.

Table 5.1.7.2-4 The merit of a semiautomatic system

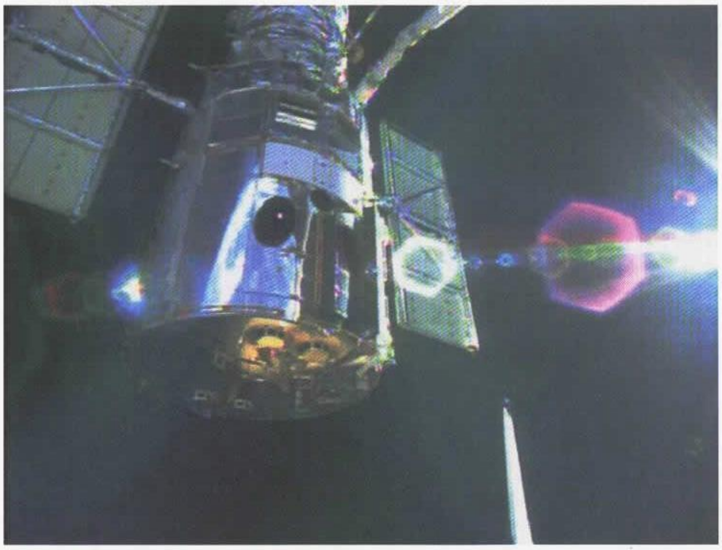
| No | Function | Problem of full automation | Manual operation | The advantage of the Semiautomatic system |
|---|---|---|---|---|
| 1 | **Adjustment of exposure** | What to see cannot necessarily be seen with proper brightness. | Adjustment of exposure | Reduction of image-processing time |
| 2 | **Detection of HST's outline** | Image-processing time increases for the stable recognition and the large range recognition. | Directions of the near size and positions of an outline on the image. | Reduction of image-processing time.<br>Stable recognition of Aft Bulkhead. |
| 3 | **Detection of the berthing target** | Image-processing time increases for the stable recognition | Directions of the position of the target in the image | Reduction of image-processing time<br>Stable recognition of the berthing target. |
| 4 | **Detection of the marker on the target** | Image-processing time increases for the stable recognition | Directions of the position of the marker on a target | Stable recognition of the mark on the berthing target. |
| 5 | **Detection of incorrect recognition and measurement** | In order to reduce the probability of a detection mistake of incorrect recognition and measurement, processing load increases. | Directions of urgent abort operation | Reduction of image-processing time.<br>Safety increases. |

(5) Optical environment

The optical precondition for measuring HST's 3D-positions and attitudes is shown Table 5.1.7.2-5.

Table 5.1.7.2-5 Optical environment

| **Range** | **Measurement target** | **Prerequisite** | **Problem** |
|---|---|---|---|
| **All (～0.8m)** | 1 target | The sun must not go into the view of the CCD cameras in the NRS systems (Fig.5.1.7.2-5) | The approach scenario that the sun does not go into a view needs to be inquired. |
| **～50m (TBD)** | HST's outline | - | - |
| **50m～ 10m (TBD)** | Aft Bulkhead outline | The whole bulkhead side must be under sunlight or albedo light.<br>Sunlight must not reflect in Aft Bulkhead within a view of the CCD cameras. | Study of the angle and intensity of the incidence light to Aft Bulkhead is required. |
| **10m～ 0.8m (TBD)** | Berthing target | The image of the Berthing target is acquired using NRS's light in the shadow of the earth. | The lighting system needs to be improved, in order to obtain the contrast.of the marker on a target from the 10m(TBD) away position. |



No good

Fig.5.1.7.2-5 The sun exists within the view area of the camera

(6) Measurement accuracy of the NRS

Table 5.1.7.2-6 and Table 5.1.7.2-7 show the specifications of the PXS used in ETS-VII.The specifications are verified in a ground examination and the examination on orbit. In order to use PXS as the NRS head (for Berthing Target), examination of two items shown below is required.

1. Influence on the measurement accuracy by using a berthing target instead of the reflector of exclusive use.
2. Improvement of the measurement accuracy in distance 3m or more

Table 5.1.7.2-8 shows the target value of measurement accuracy of 3D-positions and attitudes of Aft Bulkhead of 10m beyond.

The target values are calculated based on the result of a measurement experiment of a similar structure using Rendezvous and Docking Operations Test System (RDOTS) in Tsukuba Space Center of JAXA..

Table 5.1.7.2-6 Measurement accuracy of PXS (ETS – VII: Specification value)

| **Range (C/PXSH-T/PXSM)** | | **R(m)** | **0.35～2** | **2～3** | **3～10** |
|---|---|---|---|---|---|
| **Random error** | **three dimensional positions** | X(m) | Max(0.005,0.005R) | | 0.015+0.02(R-3) |
| | | Y(m) | Max(0.001,0.001R) | | 0.006+0.01(R-3) |
| | | Z(m) | Max(0.001,0.001R) | | 0.006+0.01(R-3) |
| | **Three dimensional attitudes** | Φ(deg) | 0.2 | 0.4 | |
| | | θ(deg) | 0.2 | 0.4 | |
| | | ψ(deg) | 0.2 | 0.4 | |

＊・・・X-axis（Approach direction）

Table 5.1.7.2-7 Measurement accuracy of PXS (ETS – VII: Specification value)

| **Range (C/PXSH-T/PXSM)** | | **R(m)** | **0.35～2** | **2～3** | **3～10** |
|---|---|---|---|---|---|
| **Bias error** | **Three dimensional positions** | X(m) | Max(0.005,0.005R) | | 0.015+0.02(R-3) |
| | | Y(m) | Max(0.001,0.001R) | | 0.006+0.01(R-3) |
| | | Z(m) | Max(0.001,0.001R) | | 0.006+0.01(R-3) |
| | **Three dimensional attitudes** | Φ(deg) | 0.2 | 0.4 | |
| | | θ(deg) | 0.2 | 0.4 | |
| | | ψ(deg) | 0.2 | 0.4 | |

＊・・・X-axis（Approach direction）

Table 5.1.7.2-8 The target value of measurement accuracy of 10m(TBD) beyond

| **Range** (between Aft Bulkhead and NRS) | | **R(m)** | **10m ～ 20m (TBD)** | **20m～60m (TBD)** |
|---|---|---|---|---|
| **Error** ( **Bias and random both are included**) | **Three dimensional positions** | X(m) | 0.005R(TBD) | 0.01R(TBD) |
| | | Y(m) | 0.004R(TBD) | 0.004R(TBD) |
| | | Z(m) | 0.004R(TBD) | 0.004R(TBD) |
| | **Attitudes** | Φ(deg) | — | — |
| | | θ(deg) | 0.7(TBD) | — |
| | | ψ(deg) | 0.7(TBD) | — |

＊・・・X-axis（Approach direction）

(7) Experiment

The measurement test image using RDOTS(Rendezvous and Docking Operation Test System : JAXA) is shown in Fig.5.1.7.2-6.

Model scale must be changed for several measurement ranges.

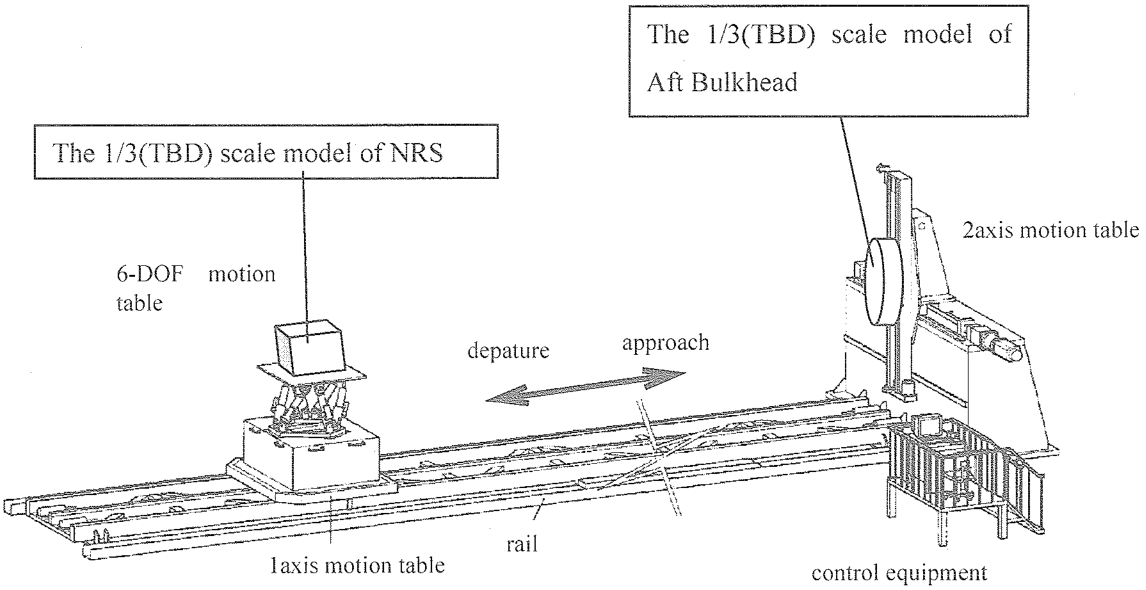


Fig.5.1.7.2-6 Measurement test image using RDOTS

### 5.1.7.3 NRS (for –V3 axis approach)

A Near-range Rendezvous Sensor (NRS) to realize –V3 axis of HST is described in this section. As depicted in Fig.4.1.3-3 and 4.1.3-6, -V3 axis approach has a merit to realize a safe capture of HST by maximizing the benefit of wide range of manipulator's dynamic envelope comparing –V1 axis approach.

The camera sensor described in 5.1.7.2 is used for –V3 approach. In a distance approximately 100m to 50m, binocular stereo vision is used by making correspondence between the images of camera-AB1 to AB3.

In a final approaching phase from 50m to berthing point, some templates from which features for measurements of relative position and orientation can be easily extracted. One candidate for the templates is ducts of star sensors on –V3 side of HST. Since ducts of the star sensors are painted by matted black, they can be easily recognized in contrast with other HST's shining surface. As the physical dimension of the ducts is known, measurements of relative distance and orientation for approaching and holding at the berthing point are feasible. An example of NRS's image processing is shown in Fig.5.1.7.3-1 and -2. Active lighting at the berthing point is effective to improve the sensor's S/N ratio and accuracy.

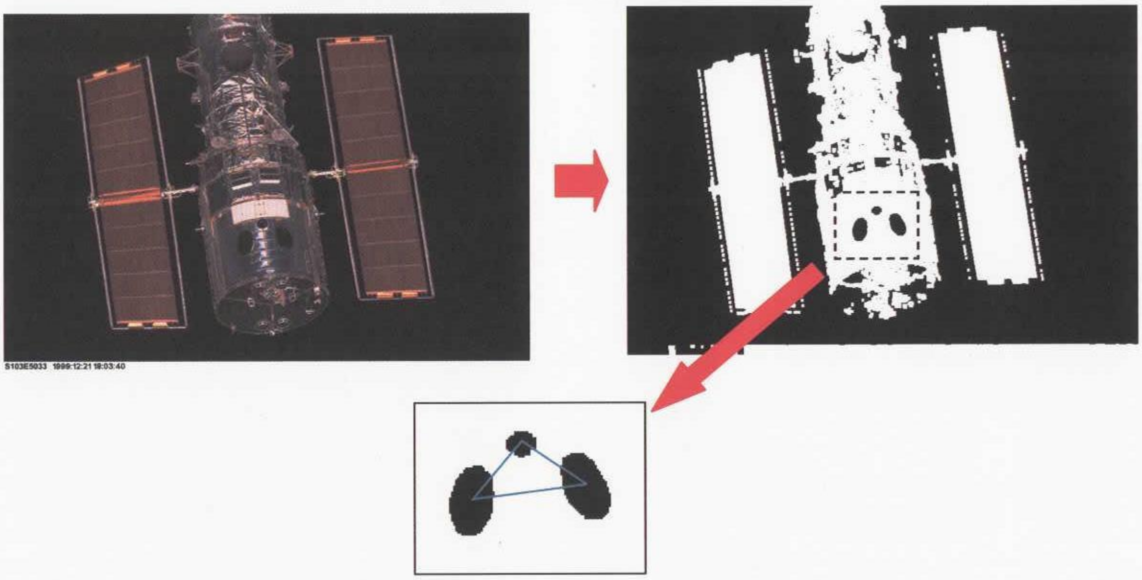


Fig.5.1.7.3-1 Using Ducts of Star Sensor for NRS Image Templates

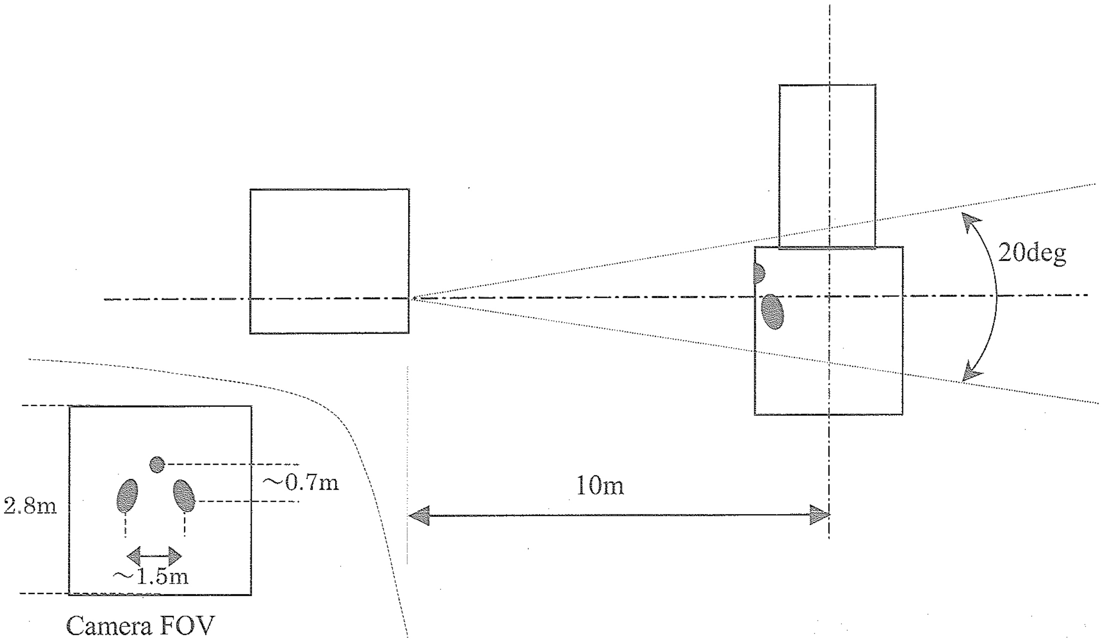


Fig.5.1.7.3-2 Example of NRS's Field of View

### 5.1.8 Other sensor

#### (1) Camera on HDV manipulator

The HDV manipulator is equipped with a camera at the wrist. The wrist camera is attached so as to agree with the center of the T-bar target of the grapple fixture when the end effecter is aligned with the center of the grapple fixture. At the last stage of the HST capturing operation the grapple fixture can no longer be seen from the camera since the end effecter blocks the camera's view. Instead, the manipulator will be controlled with the visual feedback loop using the extracted image of the T-bar target which is attached to the grapple fixture.

#### (2) Specification of camera on HDV manipulator

Type of image sensor: color CCD / CMOS image sensor
Field of view: 44 deg(W) x 33 deg(H)
Number of effective pixels: 640(W) x 480(H), or beyond
Frame rate: larger than 4 Hz
Focus length: 14 mm
Volume/Weight: less than half the camera for JEMRMS
Lighting system for the wrist camera: a flash light or LED

## 5.1.9 On-ground System

### 5.1.9.1 Total operational system based on HTV operational system

Basically, the ground operation system to be used for HTV can be used for HDV operation (figure 5.1.9.1-1). Small additional interface may be added between NASA/GSFC, NASA/JSC and JAXA/TKSC to perform coordinated operations between HST and HDV.

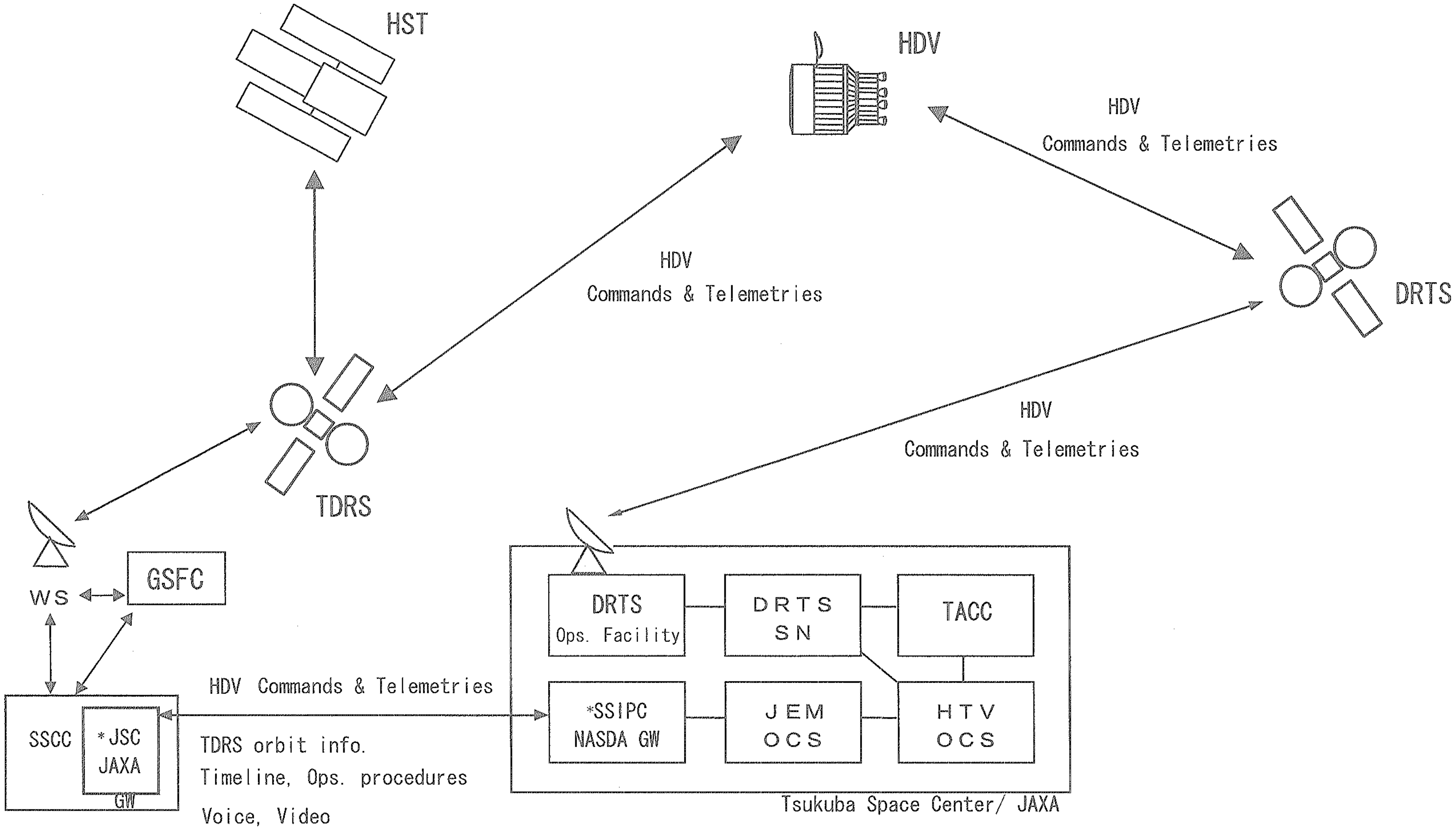
### 5.1.9.2 Ground teleoperation system for rendezvous and manipulator

A part of rendezvous and manipulator operation may be conducted by teleoperation from ground. The same teleoperation system which was used for ETS-VII teleoperation via TDRSS will be integrated into the above HTV based operation system for those operations. More than two years safe operations of ETS-VII imply high reliability of the system. The teleoperation system is shown in Fig.5.1.9.2-1.

Fig.5.1.9.2-1 ETS-VII's teleoperation system

### 5.1.9.3 Ground support equipment for image processing

In a case that HST capturing operation is conducted in remote operation, images captured on orbit are sent down to the ground and are processed with on-ground system. The on-ground system consists of an image processing computer system, a controller, and a simulator. The image processing computer system mainly takes charge of the target detection, the stereo image processing, ICP (Iterative Closest Point Method), and HST motion estimation. The simulator receives simulation parameters from the controller and keeps visually showing the result of simulation in pseudo real time. In the controller the results of the image processing and the simulation are analyzed and the up-linked commands are determined with the help of operator's judgment. The block diagram of the system is illustrated in Fig.5.1.9.3-1.



*:JEM

Fig.5.1.9.1-1 Ground operational network for HST and HDV coordinated operation based on HTV operational system

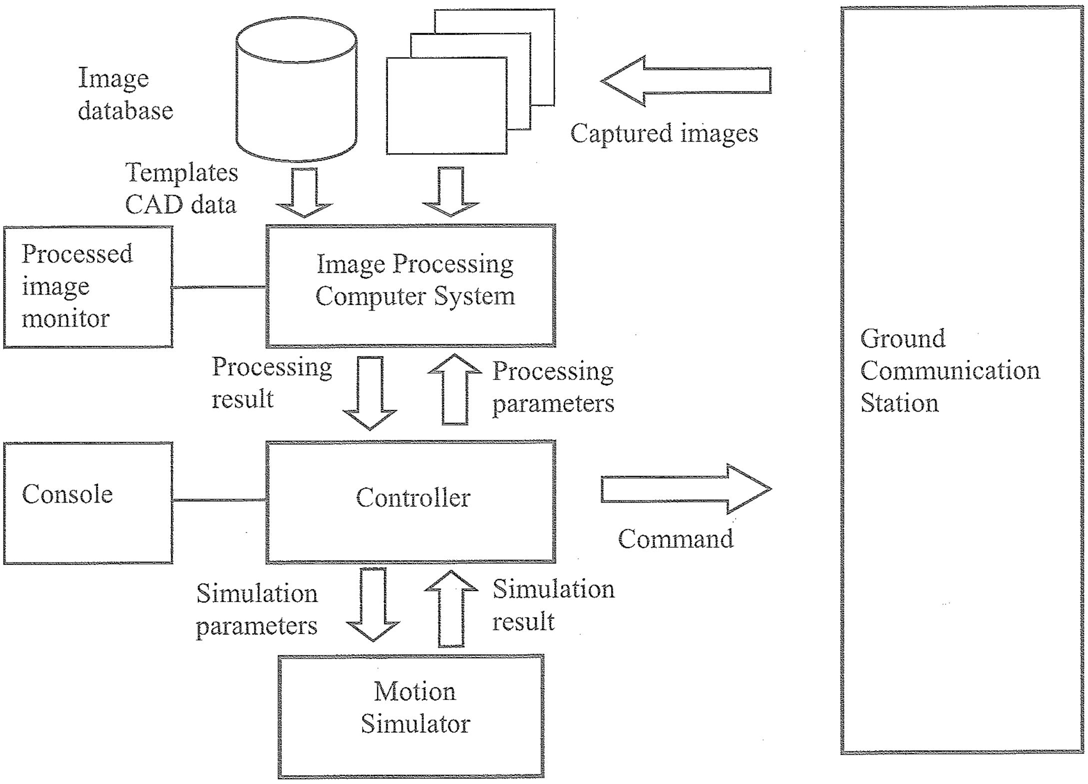


Fig.5.1.9.3-1 Block diagram of ground support equipment for image processing

## 5.2 Dynamics and control systems

### 5.2.1 Guidance, Navigation & Control (GN&C) subsystem

### 5.2.1.1 Configuration of GNC

Guidance, Navigation and Control (GN&C) subsystem is designed to control the trajectory and attitude through all flight phase. It consists of Guidance and Control Computer (GCC), Earth Sensor Assemblies (ESA), Space Integrated GPS/INS (SIGI), Far-range Rendezvous Sensor (FRS), Near-range Rendezvous Sensor (NRS), and Valve Drive Electronics-1 (VDE-1). Fig.5.2.1.1-1shows the block diagram of GN&C subsystem.

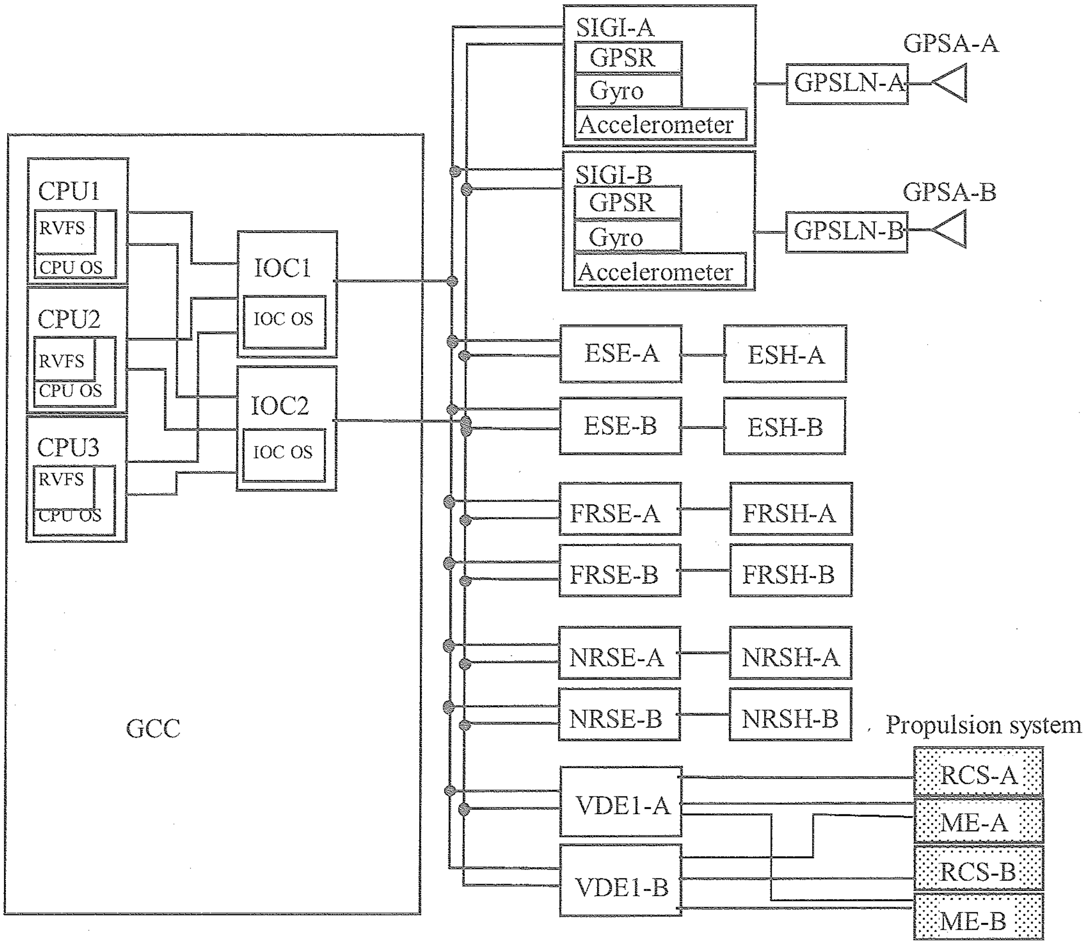


Fig.5.2.1.1-1 Block diagram of GN&C subsystem

Table 5.2.1.1-1 shows the component list of GNC subsystem. Table 5.2.1.1-2 shows the major functions of GNC components.

Table 5.2.1.1-1 Component List of GNC Subsystem

| Component | Abbreviation | Quantity | Remarks |
|---|---|---|---|
| Guidance and Control Computer | GCC | 1 | GCC consists of 3 CPUs and 2 IOCs.<br>HTV GNC has abort control unit (ACU) in addition for safety. |
| Rendezvous Flight Software | RVFS | 1 set | |
| Space Integrated GPS/INS | SIGI | 2 set | A SIGI includes a GPS receiver, a set of 3-axis gyro and accelerometer.<br>A set of SIGI includes a SIGI, a GPS Antenna (GPSA) and a GPS Low noise amp (GPSL).<br>HTV GNC has the third SIGI(Gyro) in addition for safety. |
| Earth Sensor Assembly | ESA | 2 set | A set of ESA includes an ESA Electronics (ESA-E) and an ESA optical head (ESA-H). |
| Far-range Rendezvous Sensor | FRS | 2 set | A set of FRS includes FRS Electronics (FRS-E) and a FRS optical head (FRS-H). |
| Near-range Rendezvous Sensor | NRS | 2 set | A set of NRS includes a NRS Electronics (NRS -E) and a NRS optical head (NRS -H). |
| Valve Drive Electronics-1 | VDE-1 | 2 | HTV GNC has the third VDE in addition for safety. |

Table 5.2.1.1-2 Major Functions of GNC Components

| Component | | Major Functions |
|---|---|---|
| GCC (Guidance Control Computer) | | Sensor Interface, actuator interface, GNC component power ON/OFF, guidance, navigation, control, CMD/TLM processing, FDIR functions |
| Rendezvous Flight Software (RVFS) | | Data processing for guidance, navigation, control and FDIR. RVFS is installed on the GCC CPU |
| SIGI ( Space Integrated GPS / INS ) | Gyro | Roll/Pitch/Yaw angular rate detection |
| | Accelerometer | Three axes acceleration detection |
| | GPSR (GPS Receiver) | GPS data receive, absolute navigation |
| ESA (Earth Sensor Assembly) | | Roll/Pitch attitude detection |
| FRS (Far-range Rendezvous Sensor) | | Target line of sight angle and relative position detection and their derivatives in the far area. |
| NRS (Near-range Rendezvous Sensor) | | Relative attitude and position detection, relative attitude rate and velocity detection in the near area. |
| VDE (Valve Drive Electronics) | | Valve drive to operate propulsion subsystem |

### 5.2.1.2 Abort Functions

HDV has two types of abort methods. One is Passive Abort (PA), the other is Collision Avoidance Maneuver (CAM). PA is performed by disabling translation control and HDV is controlled by orbit dynamics. CAM is performed by generating delta-V. In CAM there are three types (small delta-V CAM, medium delta-V CAM and large delta-V CAM). The small delta-V CAM is executed to check out CAM function. Other CAM type depends on the position where CAM is executed.

HDV has two controllers (CPU, and IOC) for abort. And all controllers have the capability to execute PA and CAM. When CPUs or IOC execute abort, HDV can maintain attitude control.

### 5.2.1.3 Option for attitude determination

HDV has ESA and Gyro (SIGI) to determine absolute 3-axis attitude. Optional sensor configuration for the attitude determination is Star Tracker (STT) and Gyro (SIGI). JAXA/MELCO has flight heritage of this configuration by using

- Onboard star matching for all star catalog,
- Autonomous 3-axis attitude determination from STT output data,
- Gyro data calibration.

JAXA would select alternative one or both (ESA/STT/Gyro) in accordance with attitude requirements from mission operation in the proximity area.

### 5.2.1.4 Dynamic Closed Test

Verification strategy for GNC functions and performance is a very important part of this kind of mission. JAXA has confirmed effective verification in the Dynamic Closed Test (DCLT) that actual GCC controls relative motion using by actual sensors in the real 3D space on the Rendezvous and Docking Operation Test System (RDOTS). Fig.5.2.1.4-1 shows DCLT concept in the RDOTS middle range test facility.

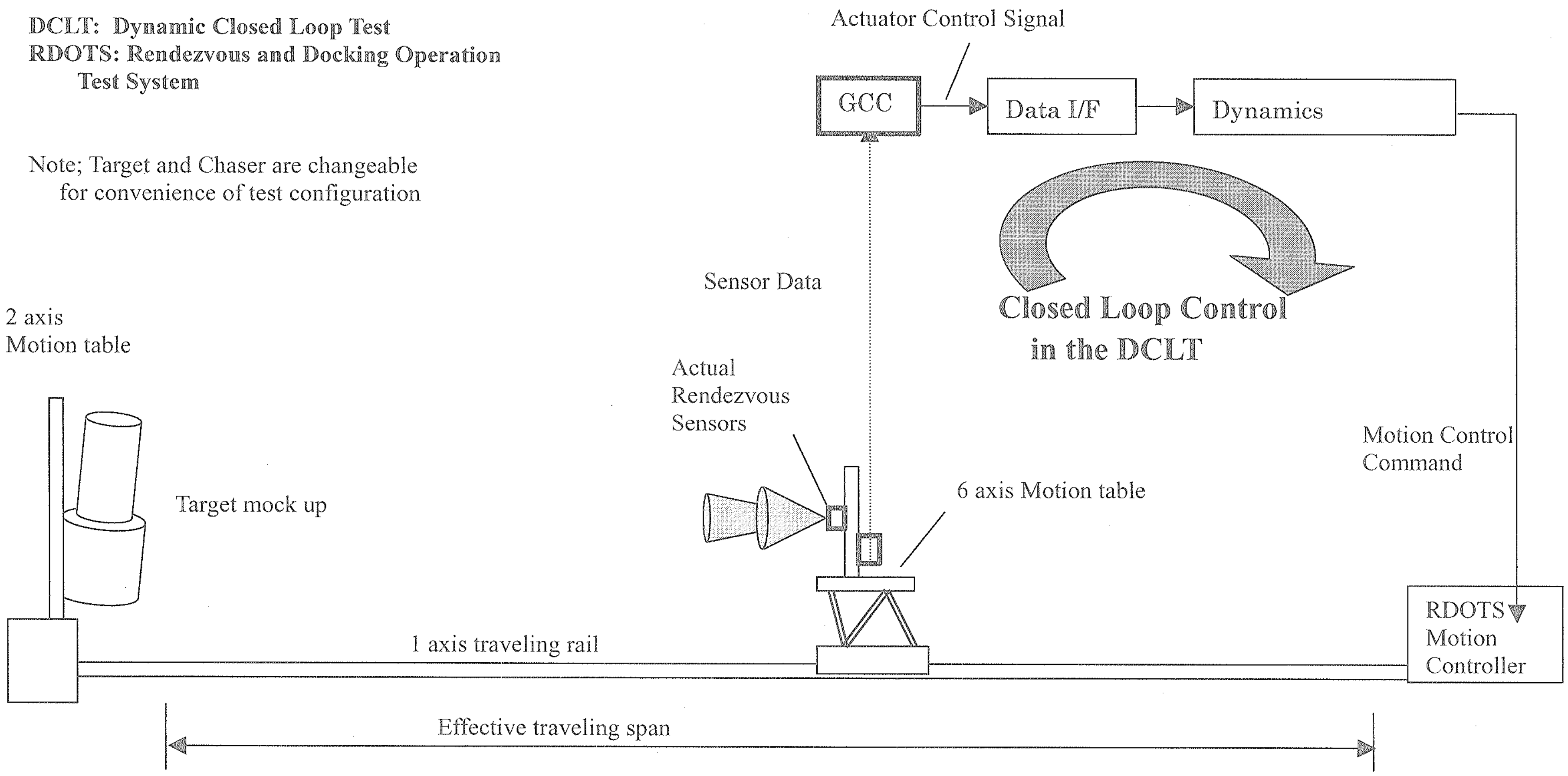


Fig.5.2.1.4-1 DCLT concept in the RDOTS middle range test facility

### 5.2.2 Manipulator control

The Manipulator control system consists of the following.

#### (1) Visual Servo Control

The functional block diagram of visual servo control is shown in Fig.5.2.2-1.

Visual servo control is used for capture of moving HST. Arm Drive Electronics (ADE) measures the range, range rate, and orientation of the HST GPF using the GPF target marker image of wrist cameras on real time. Then ADE generates the manipulator tip commands to the position the tip within the GPF capture envelope. The commands are transformed to motor angle commands of manipulator joints. And the motors of manipulator joint are driven by motor angle feedback control.

The process cycle of the measurement is 250 ms in ETS-VII.

#### (2) Manipulator-tip Auto Control

The functional block diagram of Manipulator-tip Auto control is shown in Fig.5.2.2-2.

Manipulator-tip Auto Control is used for control of manipulator tip trajectory, such as insertion the HST trunnion into the capture envelope of the docking mechanism. The motion profiles of manipulator tip are programmed before manipulator motion by ADE. The parameters of the motion profile are inputted from the ground. ADE calculates the trajectory of the manipulator tip position and orientation according to the program on real time. The trajectory is transformed to motor angle commands of manipulator joints. And the motors of manipulator joints are driven by motor angle feedback control.

#### (3) Joint Auto Control

The functional block diagram of Joint Auto control is shown in Fig.5.2.2-3.

Joint Auto Control is used for big transformation of the manipulator posture, such as the deployment motion. The motion profiles of joint angles are programmed before manipulator motion by ADE. The parameters of the motion profile are inputted from the ground. ADE calculates the commands of the joint angles according to the program on real time. The motors of manipulator joints are driven by motor angle feedback control.

#### (4) Remote Control

The functional block diagram of Remote control is shown in Fig.5.2.2-4.

Remote Control is used for the support of the visual servo control, such as initial marker acquisition, or for backup of the visual servo control, such as capturing the HST moving with slow rate. The commands of manipulator-tip position and orientation are transmitted from the ground system monitoring the manipulator motion on real time. The commands are transformed to motor angle commands of manipulator joints. And the motors of manipulator joints are driven by motor angle feedback control.

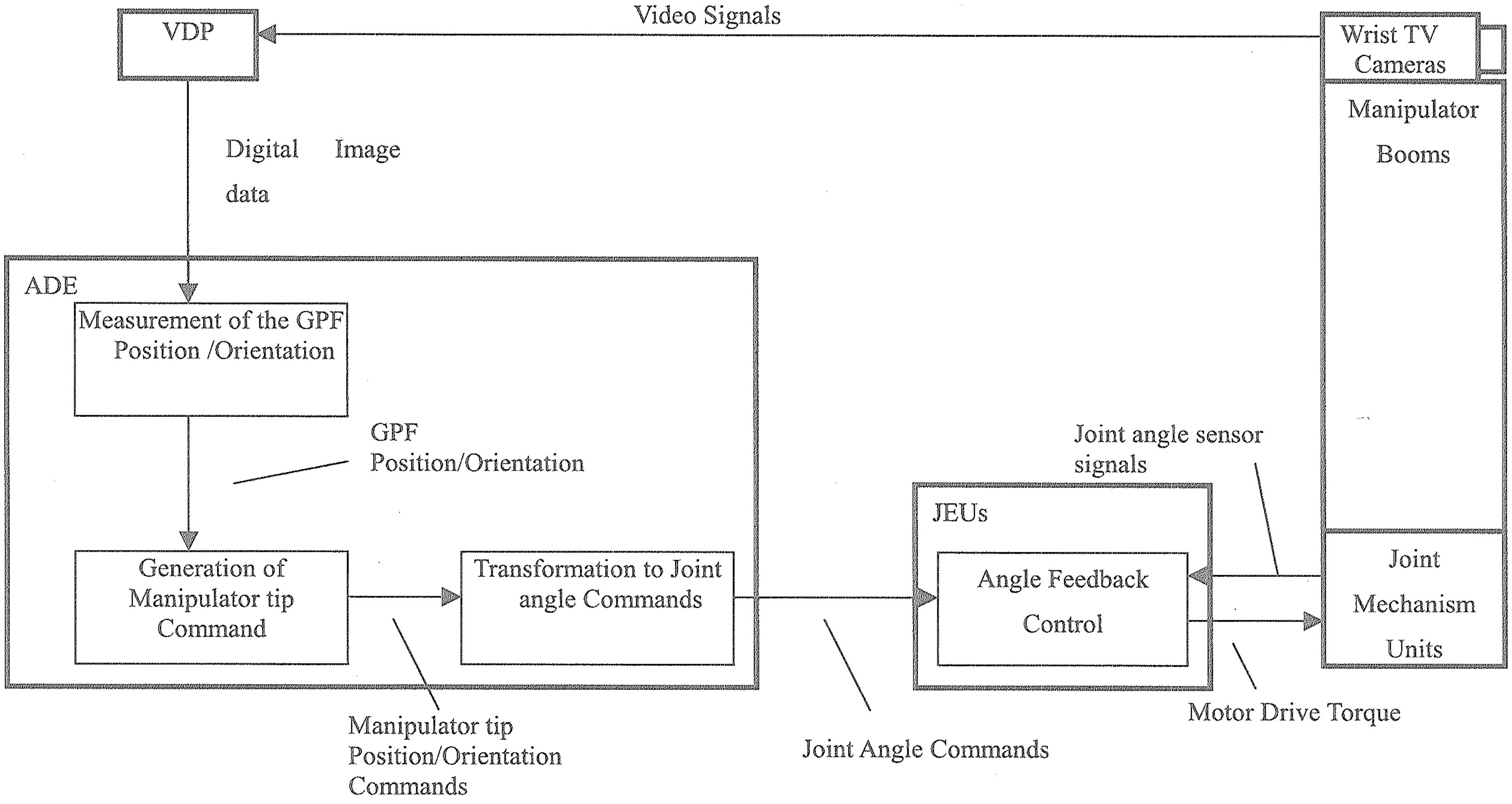


Fig.5.2.2-1 The functional block diagram of Visual servo control

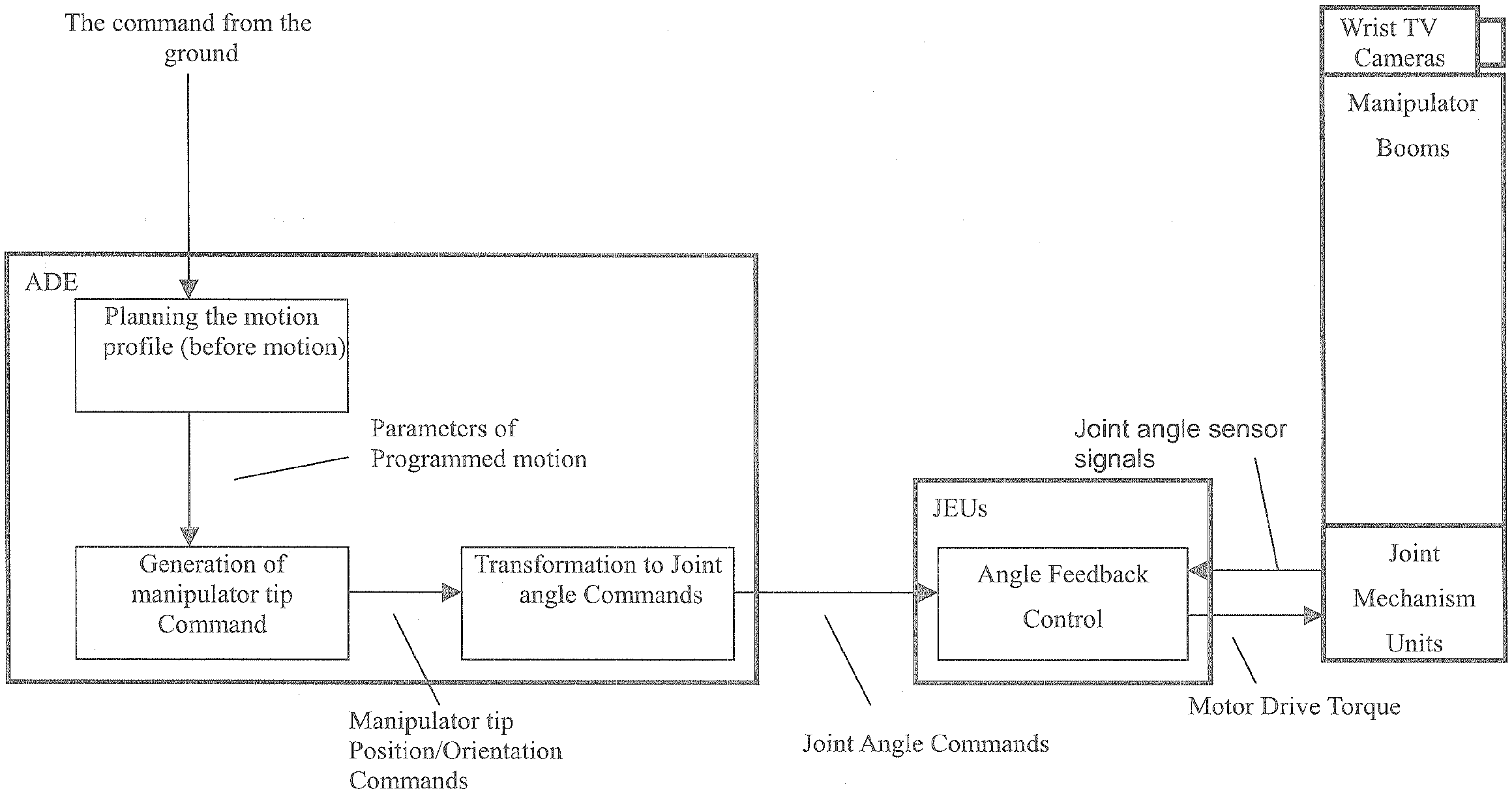


Fig.5.2.2-2 The functional block diagram of Manipulator tip Auto control

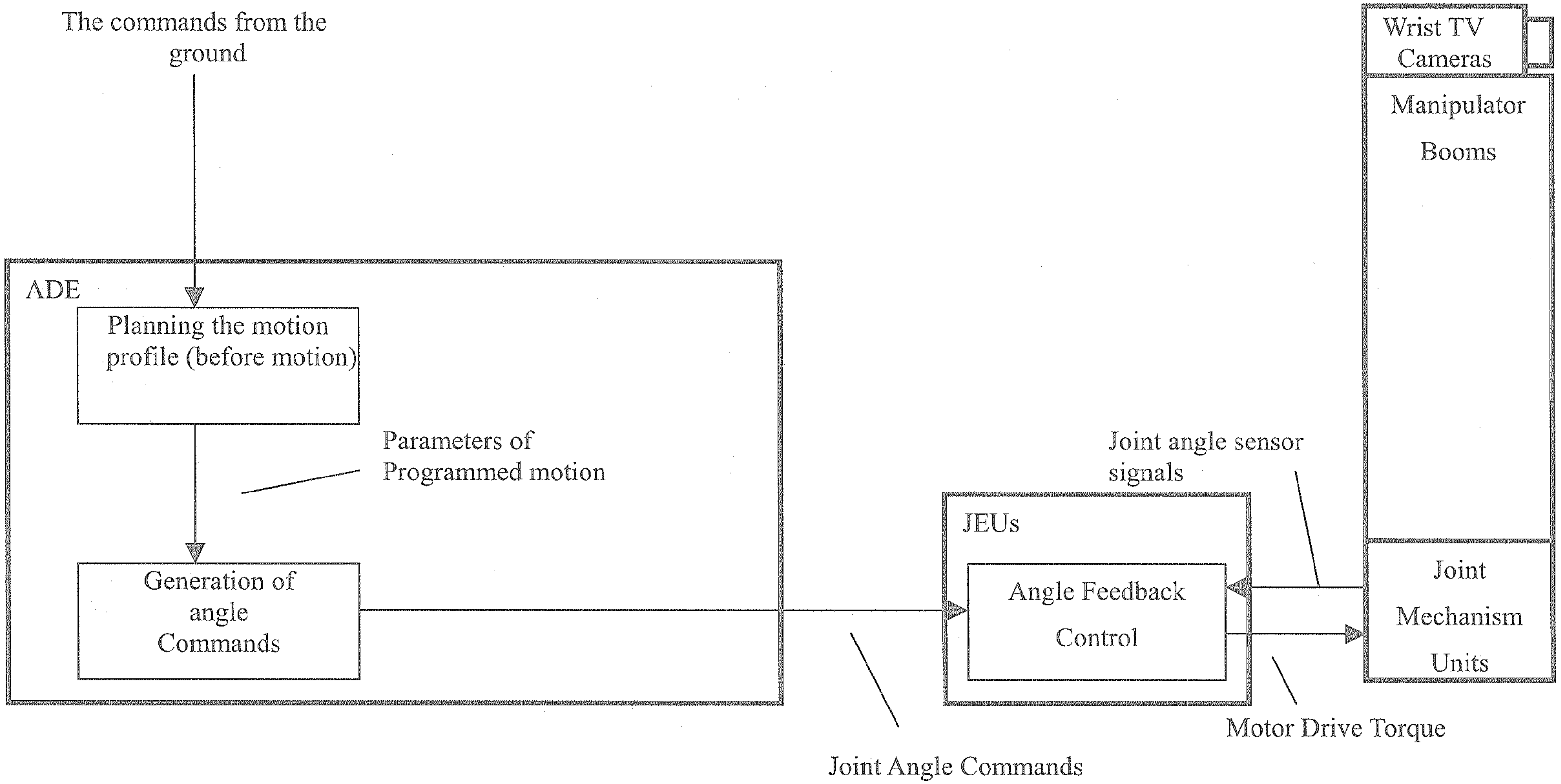


Fig.5.2.2-3 The functional block diagram of Joint Auto control

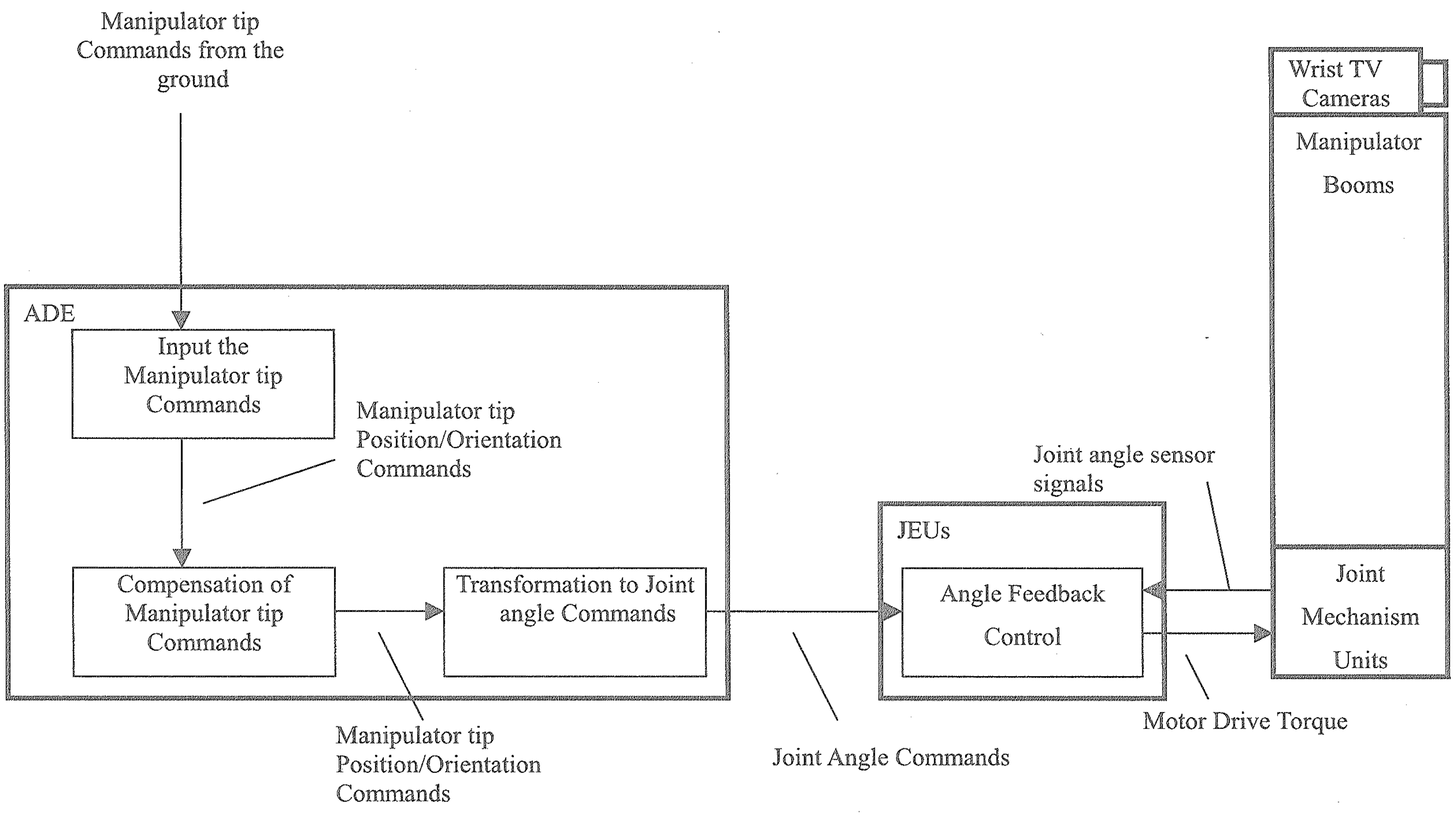


Fig. 5.2.2-4 The functional block diagram of Remote control

### 5.2.3 Capturing Dynamics and Control

There seems to be no major difficulty to capture the HST by the manipulator in a case that HST's attitude control system is fine. The attitude control of both vehicles will be disabled during the final phase of capturing. Relative motion in terms of position and attitude will remain very small in a time frame of one minute or so.

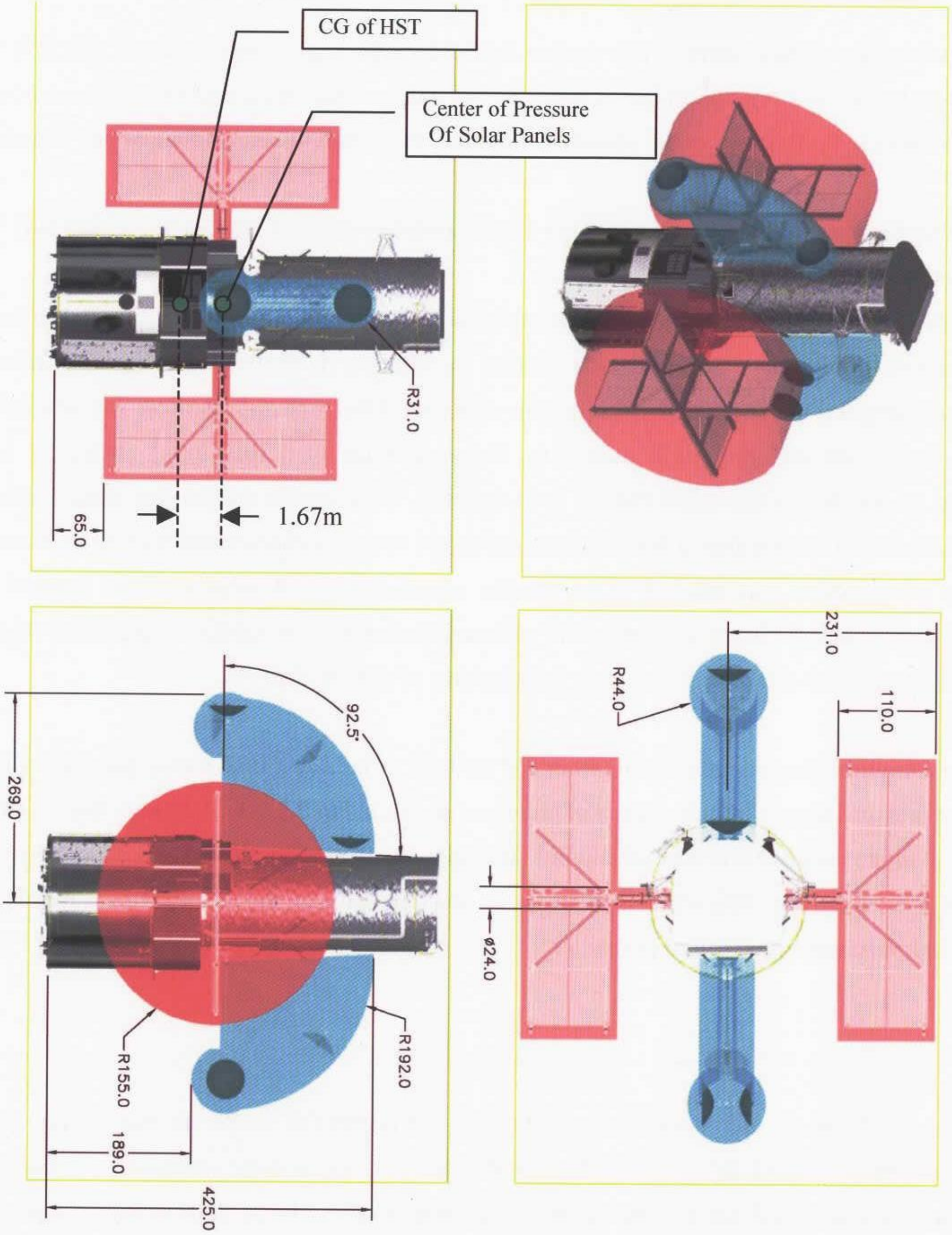
On the other hand, it is very difficult to predict natural attitude motion of HST in a case that HST's attitude control function is lost.

For example, a strange natural attitude motion in orbit was observed in a Japanese satellite when it lost attitude control. The satellite began natural attitude motion by rotating its pitch axis at the orbit rate without any residual angular moments in its reaction wheels. After chaotic motion for several weeks, angular velocity around the pitch axis (i.e., the minimum principle axis) strangely increased linearly up to ten times the orbit rate in two months. This strange motion was caused mainly by an unbalance of radiation torques arising from the large difference of optical characteristics of the front and the back of the solar panel, which was attached to the satellite asymmetrically. Analysis of the natural motion, conducted considering shape and physical characteristics of the satellite, clarified this strange motion trend and also enabled short-term forecasting of the motion [1].

It seems that optical characteristics of the front and the back of the latest HST's solar panel are different and the center of pressure is apart from the center of gravity as shown in Fig.5.2.3-1. Therefore, there is a possibility that HST will rotate in its V2 axis in relatively fast rate (up to one degree per second or so) in a long run. Direct capturing will be extremely difficult in such a case as described in 4.3. Precise analysis is mandatory using precise optical parameters and inertial properties.

**Reference**

[1] N. Inaba, S. Taniwaki and Y. Ohkami: ANALYSIS AND PREDICTION OF NATURAL ATTITUDE MOTION OF SPACECRAFT IN LOW-EARTH ORBIT, AAS Advances in the astronautical sciences vol. 117, 10th International Space Conference of Pacific-Basin Societies on Dec. 10- 12, 2003 at Tokyo, Japan.



**From NNG0461779R(HRVDM) Attachment B**

Fig.5.2.3-1 Center of Gravity and Center of Radiation Pressure

### 5.2.4 De-orbit

#### (1) Acceleration

In the re-entry phase, HDV performs de-orbit maneuvers using two main thrusters. Maximum and minimum acceleration are estimated as follows and satisfies the requirement, smaller than 0.98[m/s$^2$] (0.1G).

- MAX: 0.063 [m/s$^2$] < 0.98[m/s$^2$] (0.1G)
  - Minimum mass: 16,779.3[kg] (HST: 12,129.3[kg], HDV: 4,650[kg])
  - Maximum thrust: 530[N] x2 (Main thruster)
- MIN: 0.046 [m/s$^2$]
  - Maximum mass: 19,229.3[kg] (HST: 12,129.3[kg], HDV: 7,100[kg])
  - Minimum thrust: 445[N] x2 (Main thruster)

Delta-V for de-orbit is 153m/s in case of re-entry flight path angle –1.5deg at 120km altitude. Therefore, the total maneuver time for de-orbit is 3300sec in the minimum acceleration case. As the maximum maneuver time is limited to 1000 sec, de-orbit needs 4 maneuvers.

#### (2) Control torque

In case of maneuver using main thruster for de-orbit, the controllability is estimated as following.

The result of estimated about control torque and disturbance torque is shown in Table 5.2.4-1 Estimated HST/HDV center of mass is shown in Fig.5.2.4-1. Mass center offset of V2/V3 axis was assumed to be 0.3[m].

Since the ratio of disturbance torque and after-RCS control torque is 0.75 and the ratio of disturbance torque and total control torque is 0.38, it would be controllable.

Table 5.2.4-1 Estimated Control torque / Disturbance Torque

| Item | Value | NOTE |
|---|---|---|
| After-RCS control torque | 537 [Nm] | Nominal thrust (RCS) 122[N] (See Fig.5.2.4-1) |
| Forward-RCS control torque | 329 [Nm] | Nominal thrust (RCS) 122[N] (See Fig.5.2.4-1) |
| Total control torque | 866 [Nm] | |
| Main thruster alignment error torque | 77 [Nm] | Nominal thrust(Main) 475[N]x2, alignment error 1.5deg (See Fig.5.2.4-1) |
| CG offset torque | 285 [Nm] | Nominal thrust(Main) 475[N]x2, V2/V3 axis CG offset 0.3[m] (assumption) |
| Thrust unbalance torque | 92 [Nm] | Nominal thrust(Main) 475[N], Thrust error +/-5%<br>Arm length between main thrusters 3.84m |
| Total disturbance torque | 332 [Nm] | RSS for main thruster alignment error torque and thruster unbalance torque |
| (Total disturbance torque) / (After-RCS control torque aft-RCS) | 0.75 | |
| (Total disturbance torque) / (Total Control torque) | 0.38 | |

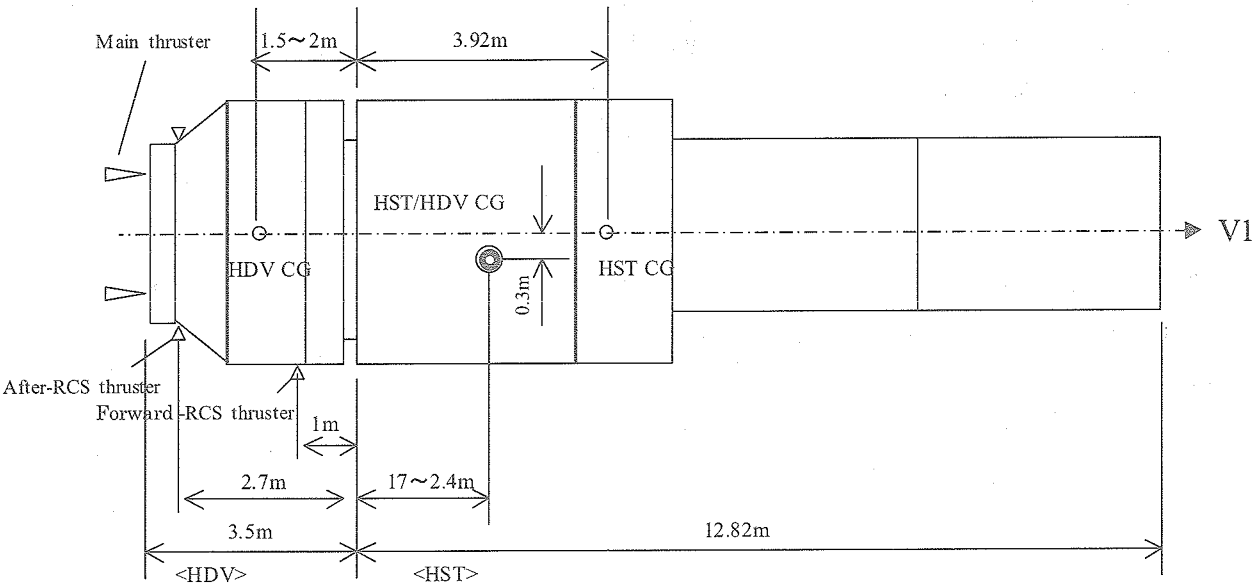


Fig.5.2.4-1 HST/HDV center of mass (assumption)

## 5.3 Mission Operation

### 5.3.1 Launch phase

The HDV will be launched by the H-IIA or other expendable launch vehicle and injected into an orbit (500x500km, $i = 28.45$deg). The launch window opens when the ground track of HST orbit ($i = 28.45$deg) path through the launch point.

Separation of HDV from the launch vehicle needs to satisfy a couple of conditions. First of all, the HTV attitude immediately after separation must be such that the X-axis in the HTV body axis coordinate is constrained in the direction of the velocity vector and the Z-axis is aligned with the nadir direction. The error about each axis must be less than 10 degrees. Also, the attitude rate about each axis of roll, pitch, and yaw after separation must not exceed 1 deg/sec.

After separation from the launch vehicle, HDV will deploy the folded solar paddles and TDRS communication antenna. The manipulator is also deployed and initial check of major HDV's functions will be conducted.

### 5.3.2 Rendezvous, Final approach

#### 5.3.2.1 Rendezvous Phase

At rendezvous phase, rendezvous maneuvers raise the HDV altitude, adjust the phase gap between the HDV and the HST. The HDV automatically executes maneuvers based on the predetermined flight plan. To generate maneuvering commands, the HDV uses the HDV GPS navigation data and HST navigation data (non real time). The HDV Operation Control System receives HST latest navigation data and sends it to the HDV. Fig.5.3.2.1-1 shows major sequence of events by ground commanding and automatic control.

#### 5.3.2.2 Proximity Operation Phase

The proximity operation starts from AI departure maneuver that is executed by ground command. After the AI maneuver the HDV automatically approach to the VI point which is 3 km (TBD) forward from HST with absolute GPS navigation. On the VI point, the HDV finds the HST in Far-range Rendezvous Sensor (FRS) FOV. HDV starts relative navigation using the FRS, and approaches to the HST on the V-bar in accordance with pre-programmed velocity profile. HDV stops at 10 m (TBD) to HST, changing main navigation sensor to NRS. HDV re-stars to capturing box to perform capture HST or soft docking. Fig.5.3.2.2-2 shows major sequence of events by ground commanding and automatic control in this phase.

#### 5.3.2.3 Task Allocation in the Operation

Table 5.3.2.3-1 shows task allocation for HDV autonomy and ground control in the final approach capture and docking.

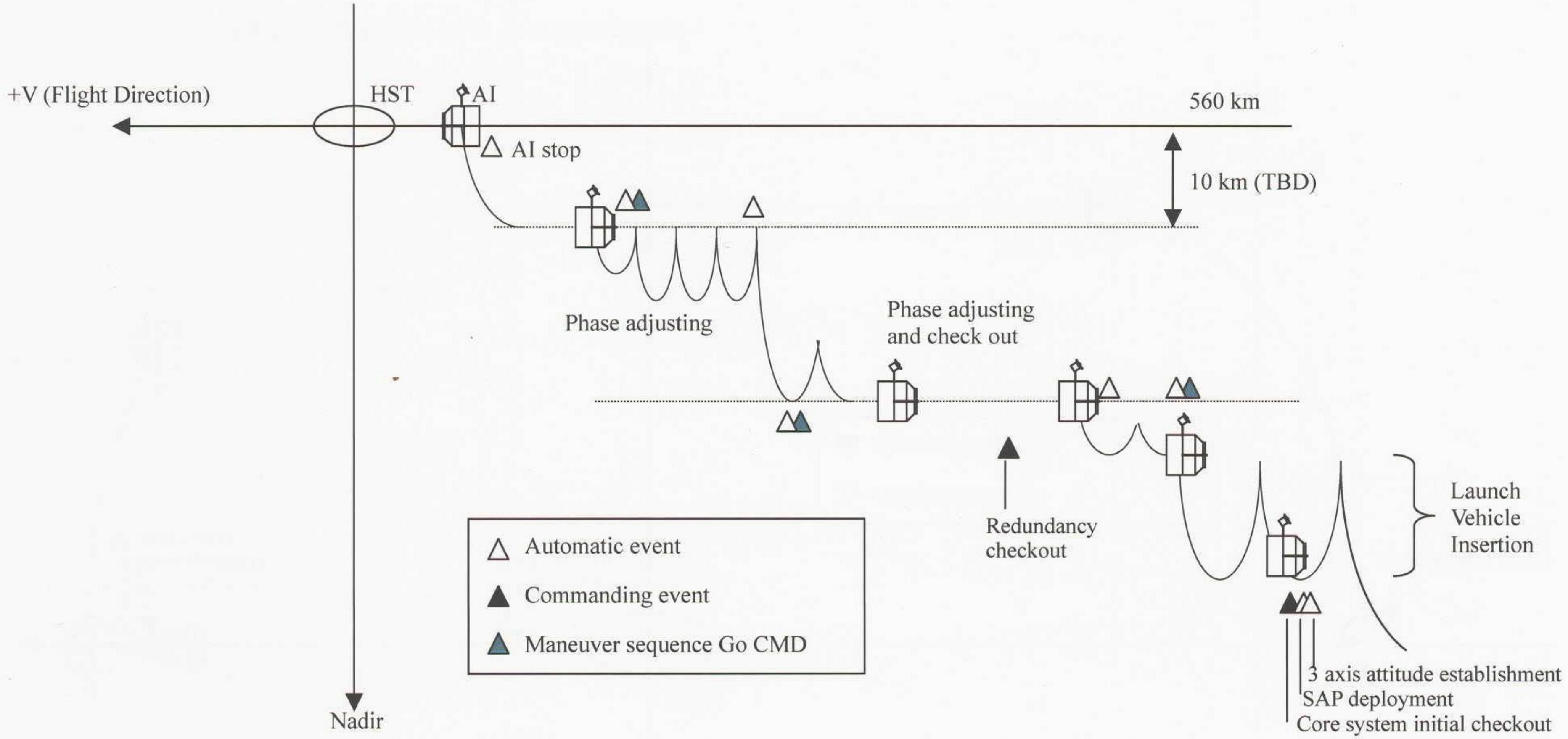


Fig.5.3.2.1-1 Major SOE in the rendezvous

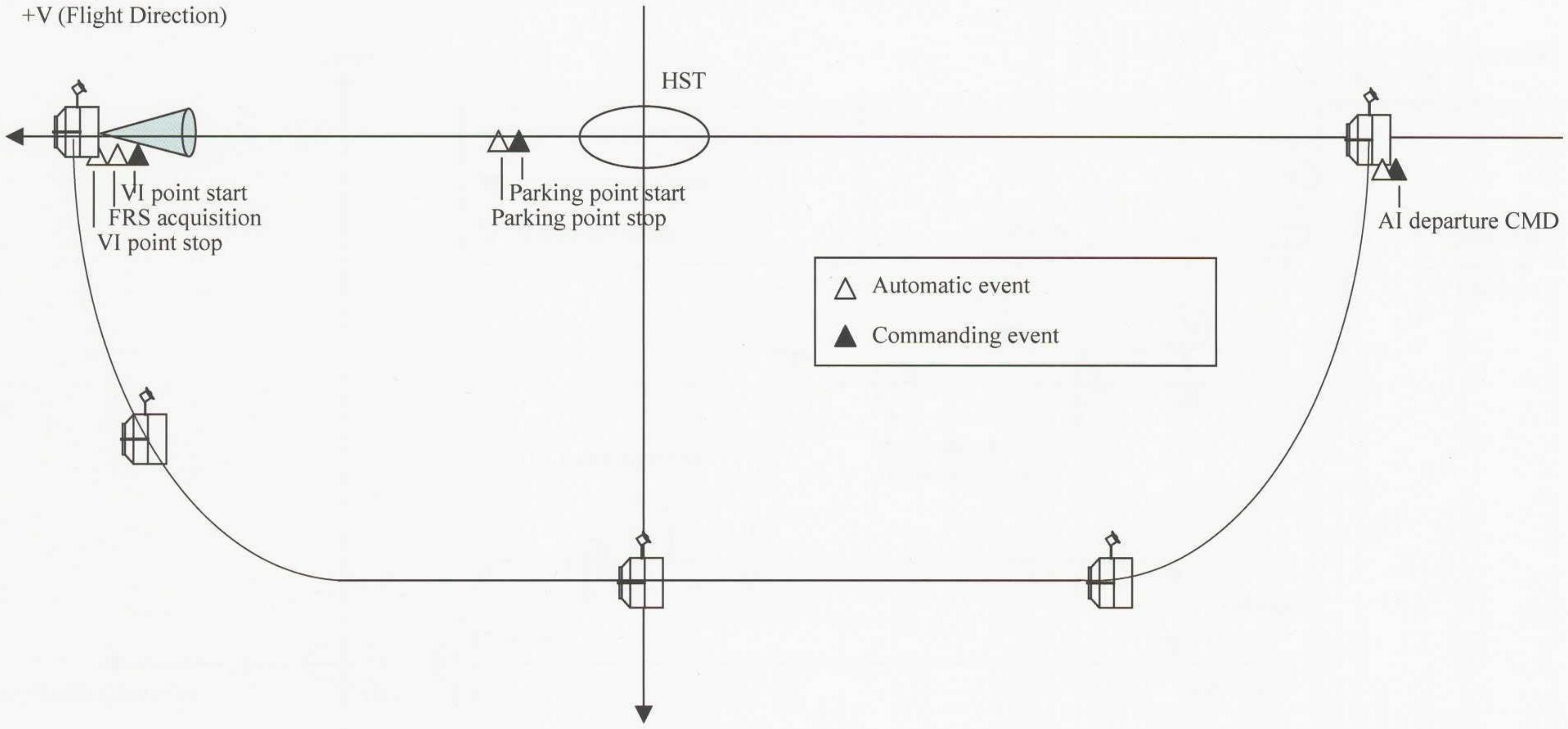


Fig.5.3.2.2-2 Major SOE in the proximity phase

Table 5.3.2.3-1 Task Allocation for HDV Autonomy and Ground Control in the Final Approach, Capture and Docking.

| | Approach | Capturing Phase | Docking Phase |
|---|---|---|---|
| V-bar Approach & capture | Automated Function<br>- Relative Navigation (FRS, NRS)<br>- Position Control according to fixed profile<br>- Attitude Control<br>- FDIR<br><br>Ground Operation<br>- Monitoring<br>- Override command for abort | Automated Function<br>- Relative Navigation (NRS)<br>- Position Control in a certain area<br>- Attitude Control<br>- FDIR<br>- RMS vision based guidance<br>Ground Operation<br>- Manipulator operation (option)<br>- Monitoring<br>- Override command for abort | N/A |
| V-bar Approach & Direct Docking | Same as above | N/A | Automated Function<br>- Relative Navigation (NRS)<br>- Disabled Control during docking motion (if required)<br>- FDIR<br><br>Ground Operation<br>- Monitoring<br>- Override tele-operation for axis settling |
| R-bar Approach & capture | Same as above | Automated Function<br>- Relative Navigation (NRS)<br>- Position Control in a certain area<br>- Attitude Control<br>- FDIR<br>- RMS vision based guidance<br>Ground Operation<br>- Manipulator operation (option)<br>- Monitoring<br>- Override command for abort | N/A |
| R-bar Approach & Direct Docking | Same as above | N/A | Automated Function<br>- Relative Navigation (NRS)<br>- Disabled Control during docking motion (if required)<br>- FDIR<br><br>Ground Operation<br>- Monitoring<br>- Override tele-operation for axis settling |

### 5.3.3 Capturing

Fig.5.3.3-1 shows the mode transition of the final approach for HST capture. Before the final approach, HDV's manipulator shall be deployed to initial capture posture. The contents of each mode are as follows.

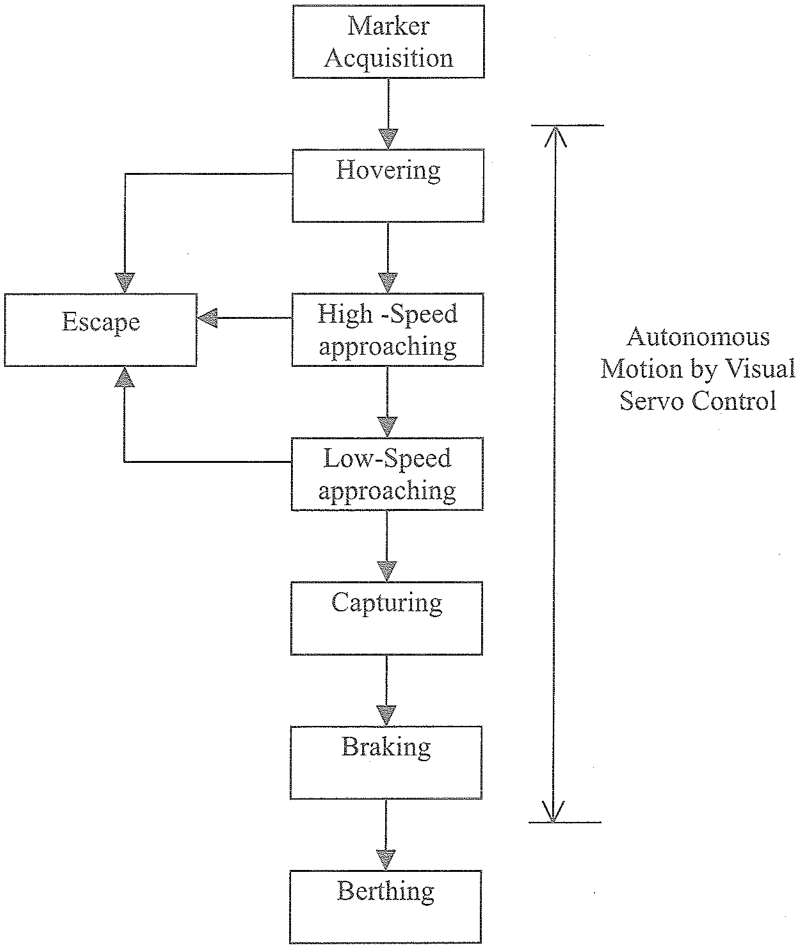


Fig.5.3.3-1 The mode transition of the final approach for HST capture

### (1) Marker Acquisition

When HDV arrives within HST capture range, the Arm Drive Electronics (ADE) starts to measure the range, range rate, and orientation of the HST GPF using the GPF target marker image of wrist camera. When the target marker image cannot be seen with the wrist camera, the manipulator shall be operated from the ground until target marker image into the camera's field of view. Then, if necessary, the position of the marker in the image data taken by video data processor is instructed from the ground for initial marker acquisition. When normal tracking is confirmed, the mode transits to the next mode by the trigger from the ground.

The sequence from next hovering mode to braking mode is executed automatically by visual servo control.

### (2) Hovering

Visual servo control is used to hold the marker in the center of the camera's field of view, while keeping the distance between the camera and the marker. When the manipulator reaches a position right above the marker, the automatic sequencer enters the control mode to the next mode.

### (3) High Speed Approach

The approaching phase starts in a high-speed approach mode. The manipulator tip position and orientation are controlled to reach an intermediate point right above the grapple fixture. The maximum manipulator-tip rate is maximum rate (60[mm/s]) with respect to manipulator base coordinate system in this mode.

### (4) Low-Speed Approach

Once the manipulator reaches the intermediate point, the low-speed approach phase starts. The maximum manipulator-tip rate relative to the marker is limited to 10 [mm/s] in this mode for fine tracking.

### (5) Capture

Capturing sequence starts automatically by closing the snare wire of the end effector after confirming that the manipulator reached the aiming point relative to the marker. When the end-effector completes the GPF capture, the automatic sequencer enters the control mode to the next mode.

### (6) Braking

The automatic sequence ends with the braking mode. The manipulator stops its motion relative to the manipulator base with a smooth braking pattern.

## (7) Escape

If the predetermined conditions are not satisfied in the automatic mode transition, the manipulator automatically exits to the predefined position where the manipulator will not contact the HST. The manipulator exits under any of the following conditions:

-Loss of visual marker,  
-Departure of target from the range, or  
-Trouble of the manipulator and/or the HDV

Once the process enters into the capture mode, the manipulator will not exit even if the contingency above occurs. The transition of escape can be executed from the ground.

## (8) Berthing

The manipulator moves HST to the berthing point by preprogrammed joint servo control.

### 5.3.4 Direct Docking

HDV has a capability for direct docking with HST in case berthing by its manipulator can not be conducted by some reason. In this case, HDV approach HST's Aft Bulkhead and capture HST's berthing pins using HDV's docking mechanism. In this case, two types of final approach, +V-bar and R-bar can be used. These flight maneuvers for final approach were already demonstrated by ETS-VII.

◉+V-bar approach

Using the V-bar approach procedure depicted in Fig. 4.1.3-1, HDV performs the +V-bar approach towards HST. The imaging sensor measure relative distance and relative attitude ( 6DOF) between HST and HDV. When HDV comes within TBD centimeters from HST, HDV's Docking Mechanism hook HST's three Berthing Pin.

◉R-bar approach

Using the R-bar approach procedure depicted in Fig. 4.1.3-5, HDV performs the R-bar approach towards HST. NRS measure relative distance and relative attitude ( 6DOF) between HST and HDV. When HDV comes within TBD centimeters from HST, HDV's Docking Mechanism hook HST's three Berthing Pin.

(1) Mission Operations Requirement

◉+V-bar approach

- It is performed during the sun doesn't exist in the image sensor's visual field.
- HST faced Aft Bulkhead toward the flight direction.
- HDV is controlled same attitude as HST.

◉R-bar approach

- HST faced Aft Bulkhead toward the earth ( LVLH Attitude ).
- Lighting condition is steady-state by albedo of the earth.
- HDV is controlled same LVLH Attitude as HST.
- The approach from 10 meters is conducted in a phase of the eclipse to keep lighting condition constant under illuminating by HDV's lighting.

Common requirements for +V-bar & R-bar approach.

- Both automatically approach and tele-operating approach are feasible.
- Downlink of the image sensing data is available for tele-operating approach.
- Automatic safety function is necessary to stop the approach when irregular action happens.
- It has a mode of emergency abeyance.
- Communications with HDV will be realized via NASA's Data Relay Satellite (TDRS).

- HDV's manipulator is folded or ducked for not to obstruct direct docking.

(2) Overview of Direct Docking Mission

●+V-bar approach

The approach trajectory is designed based on the following concepts.

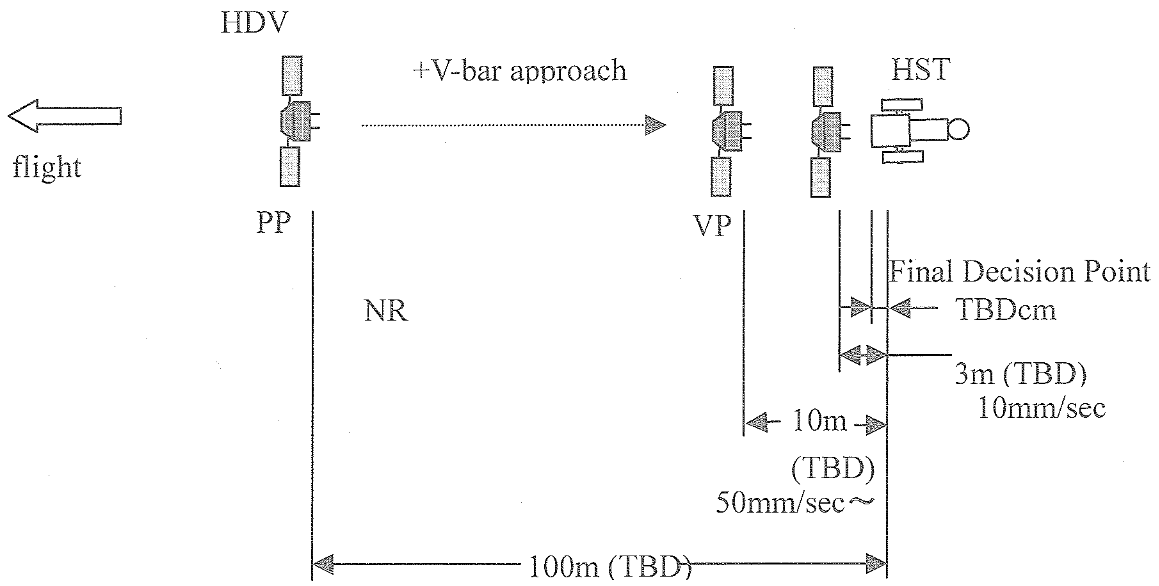


Fig.5.3.4-1 DIRECT DOCKING +V-bar APPROACH

◉R-bar approach

The approach trajectory is designed based on the following concepts.

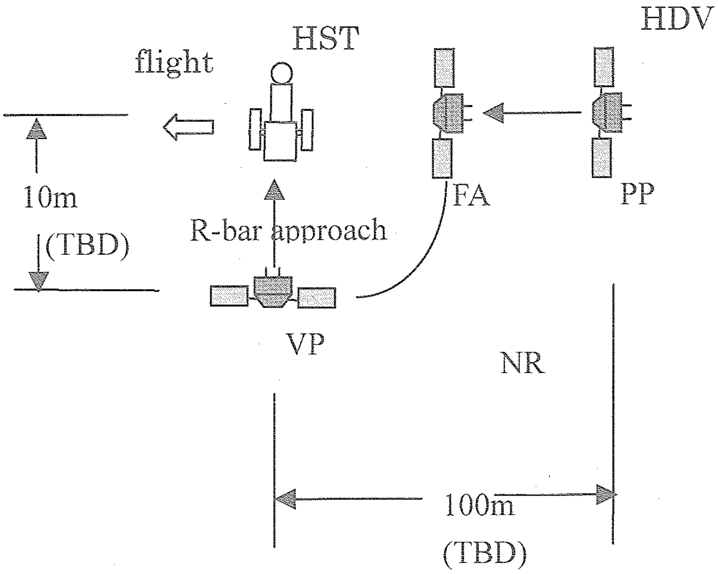


Fig. 5.3.4-2 DIRECT DOCKING R-bar APPROACH

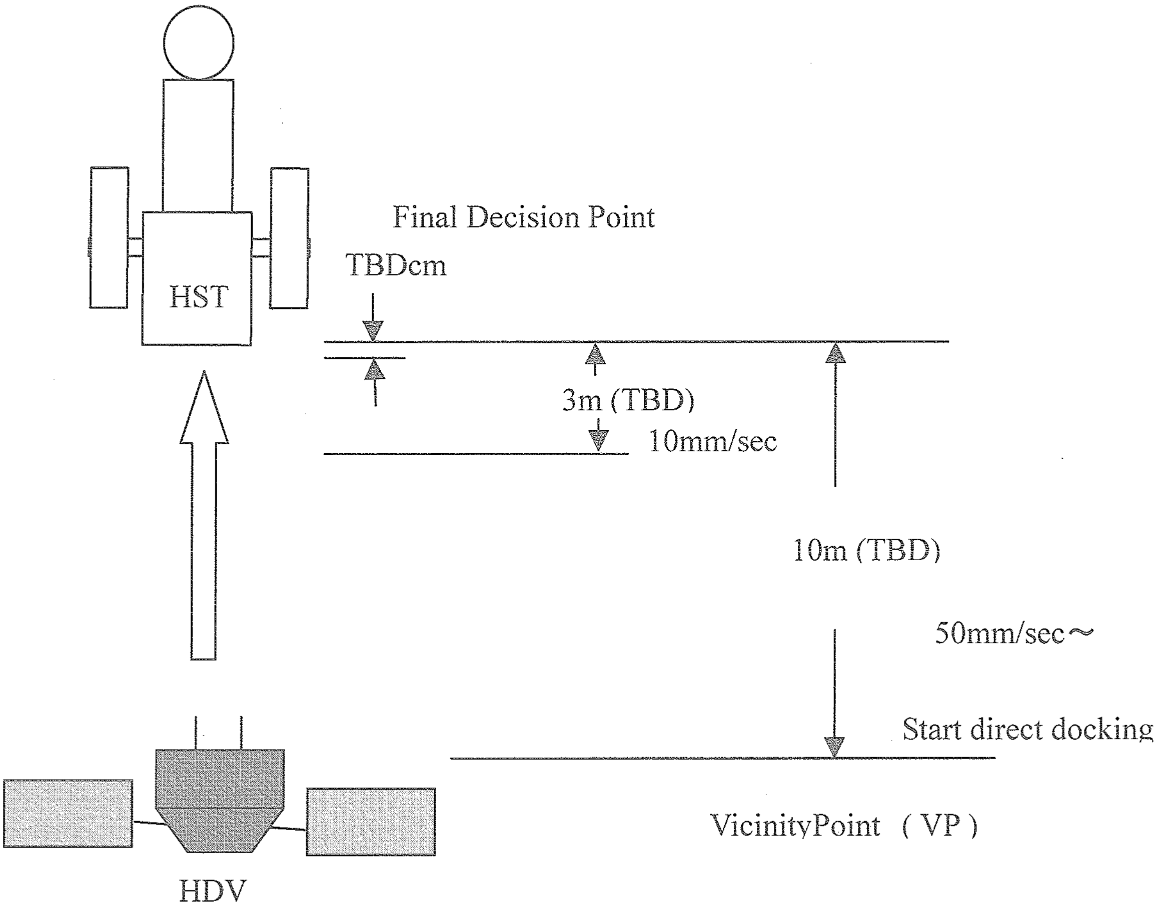


Fig.5.3.4-3 Direct Docking Approach from VP to Docking

### (3) Mission Scenario

### (a) +V-bar approach

From PP (Parking Point) to VP (Vicinity Point)

~100 meters(TBD) from HST. : PP

Approach from PP to VP.

- Approach by Continuous Control.
- NRS(Near-range Rendezvous Sensor) measure the shape of over HST.
- High-precision Navigation by NRS data.
- Approach to HST Aft Bulkhead.
- Lighting for NRS.

From VP to DOCKING point

10 meters(TBD) front toward HST Aft Bulkhead. : VP

Approach from VP to 3m(TBD) distance.

- Stop at VP.
- Measure the Relative Position/Attitude. to HST continuously.
  Object: The Contour circle line of HST Aft Bulkhead
  The Berthing Target on HST Aft Bulkhead.
  The Berthing Pin on HST Aft Bulkhead.
- Approach to HST at 50mm/sec(TBD)～ .
- Relative 6 DOF Control.

From 3m(TBD) distance to Final Decision Point (TBDcm).

- Approach to HST at 10mm/sec(TBD).
- Measure the Relative Position/Attitude. to HST continuously.
  Object: The Berthing Target on HST Aft Bulkhead.
  The Berthing Pin on HST Aft Bulkhead.
- Adjust the position of Docking Mechanism.

At the Final Decision Point (TBDcm).

- Final check of the condition and decide GO/NOGO.
- Thruster(AOCS) cut off
- Docking Mechanism hook the Berthing Pin.
- Latch the Docking Mechanism.
- Thruster(AOCS) on

If NOGO,

- Abort.

(b) R-bar approach

From VP to DOCKING point

10 meters(TBD) front toward HST Aft Bulkhead. : VP (Vicinity Point)

Approach from VP to 3m(TBD) distance.

- Stop at VP.
- Measure the Relative Position/Attitude. to HST continuously.

  Object: The Contour circle line of HST Aft Bulkhead
  The Berthing Target on HST Aft Bulkhead.
  The Berthing Pin on HST Aft Bulkhead.
- Approach to HST at 50mm/sec(TBD)～.
- Relative 6 DOF Control.

From 3m(TBD) to Final Decision Point (TBDcm).

- Approach to HST at 10mm/sec(TBD).
- Measure the Relative Position/Attitude. to HST continuously.

  Object: The Berthing Target on HST Aft Bulkhead.
  The Berthing Pin on HST Aft Bulkhead.
- Adjust the position of Docking Mechanism.

At the Final Decision Point (TBDcm).

- Final check of the condition and decide GO/NOGO.
- Thruster(AOCS) cut off
- Docking Mechanism hook the Berthing Pin.
- Latch the Docking Mechanism.
- Thruster(AOCS) on.

If NOGO,

- Abort.

(c) Abort

It is necessary to decide GO/NOGO before the Docking (placed in the hooking pose), and abort and revenge will be conducted if condition is not complete for docking.

### 5.3.5 Extending Life of HST

Designed mission life of HTV, a base spacecraft of HDV, is three months. Therefore the baseline mission life of HDV will be 3 months. Life of HDV can extend up to one year by loading additional fuel and replacing high reliability equipments. HDV's fuel tanks have enough volume for additional fuel. However attitude control accuracy of HDV will not be enough for HST's mission operation, and HST's capability of attitude control when HDV is attached to HST is not known.

Therefore it is not advisable to extend mission life of HST in a condition that HDV is docked to HST. It is advised to conduct the de-orbit maneuvers soon after HDV is docked to HST.

Feasibility and strategy for extending Life for up to 1 year or more are described in the chapter 7 as an optional system.

### 5.3.6 De-orbit

De-orbit is performed by 4 maneuvers. TDRS communication is needed for HDV health check before and during the last maneuver. After de-orbit, HST/HDV will be broken due to aerodynamic heating and load. After the atmospheric re-entry, wreckage of some portion of HST/HDV will splashdown on ocean.

TDRS communication zone (TSRS-ZOE, TDRS-WEST, TDRS-EAST) and candidate of splashdown area are shown in Fig.5.3.6-1. TDRS communication zone show the visibility from HDV on LVLH to TDRS. Candidate of splashdown area is on the Pacific Ocean, the Atlantic Ocean, and the Indian Ocean near latitude –28deg. The ground track moves west by 25 degrees in every revolution. And HST/HDV goes the earth 15 times around in one day. De-orbit window opens in orbits whose ground track path through the planned splashdown area. The splashdown area of the Pacific Ocean is wider than other area, so the area of the Pacific Ocean will be planned for splashdown area. And HDV health status will be checked as a part of flight safety operations via TDRS-ZOE link.

Result of Monte-Carlo simulation of the wreckage splashdown area is shown in Fig.5.3.6-2. The ballistic coefficient range of the wreckages for estimation is as follow:

- 10-500kg/m$^2$.
- 10-1000kg/m$^2$

In case of 10-500kg/m$^2$, the downrange of splashdown area is estimated as 2,300km. And in case of 10-1000kg/m$^2$, the downrange of splashdown area is estimated as 2,600km. There is no much difference in two cases. Re-entry flight path angle at 120km altitude is chosen –1.5deg.

De-orbit flight plan considering TDRS communication and splashdown area are shown in Fig.5.3.6-3. HDV health status will be checked as a part of flight safety operations 5 minutes before the last maneuver at least via TDRS link.

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Fig.5.3.6-1 TDRS Communication Zone / Candidate of Splashdown Area

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Fig.5.3.6-2  Splashdown Area (Monte-Carlo simulation: 6000cases)

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Fig.5.3.6-3  Re-Entry Trajectory – Case of Splashdown in Pacific Ocean

## 5.4 Reliability

HTV based HDV's reliability is shown in Table 5.4-1. Propulsion module, Avionics module and Remote Manipulator Subsystem (RMS) reliability are estimated based on HTV and JEMRMS.

In the 3 months case, the reliability is likely within 0.97 but not in the 1-year case.

While JEMRMS is designed for 10 years mission life on the International Space Station, HTV is designed for shorter mission life (up to 3 months). Therefore it is recommended to execute HDTV's operation within 3 months. Extension of mission life of HDV will require replacing currently designed equipment / parts with higher reliability ones. Extension of HST's mission operation for more than one year will require additional system that is shown in section 7 as an optional system.

Table 5.4-1 Estimated reliability of HTV based HDV

| Item | Reliability (3 month) | Reliability (1 year) |
|---|---|---|
| Propulsion Module (PM) | 0.994 | 0.977 |
| Avionics Module (AM) | 0.995 | 0.984 |
| Remote Manipulator Subsystem | - | 0.945 |
| Total | - | 0.945 |

## 6. Development Plan and Schedule

### 6.1 Basic policy

The HDV mission must be conducted before HST reaches the end of its healthy operation. In order to minimize the cost and time necessary to prepare the spacecraft for this mission, the HDV will be based on the H-II transfer Vehicle (HTV) that JAXA is currently developing.

The HTV's development schedule has been revised several times to reflect the delayed launch schedule of ISS's elements. JAXA is currently developing the engineering models for the HTV's major equipment. In order to save time and money, HDV development should make the best use of the HTV efforts. In order to reduce the chance of errors associated with transferring the design from the HTV to the HDV, modifications of the design from the HTV will be minimized.

### 6.2 Development Schedule

A proposed development plan and schedule for the HDV are shown in Fig. 6-1. If JAXA's H-IIA rocket can be used as the launcher for the HDV, a few months that would normally be required for transportation and other work will be saved.

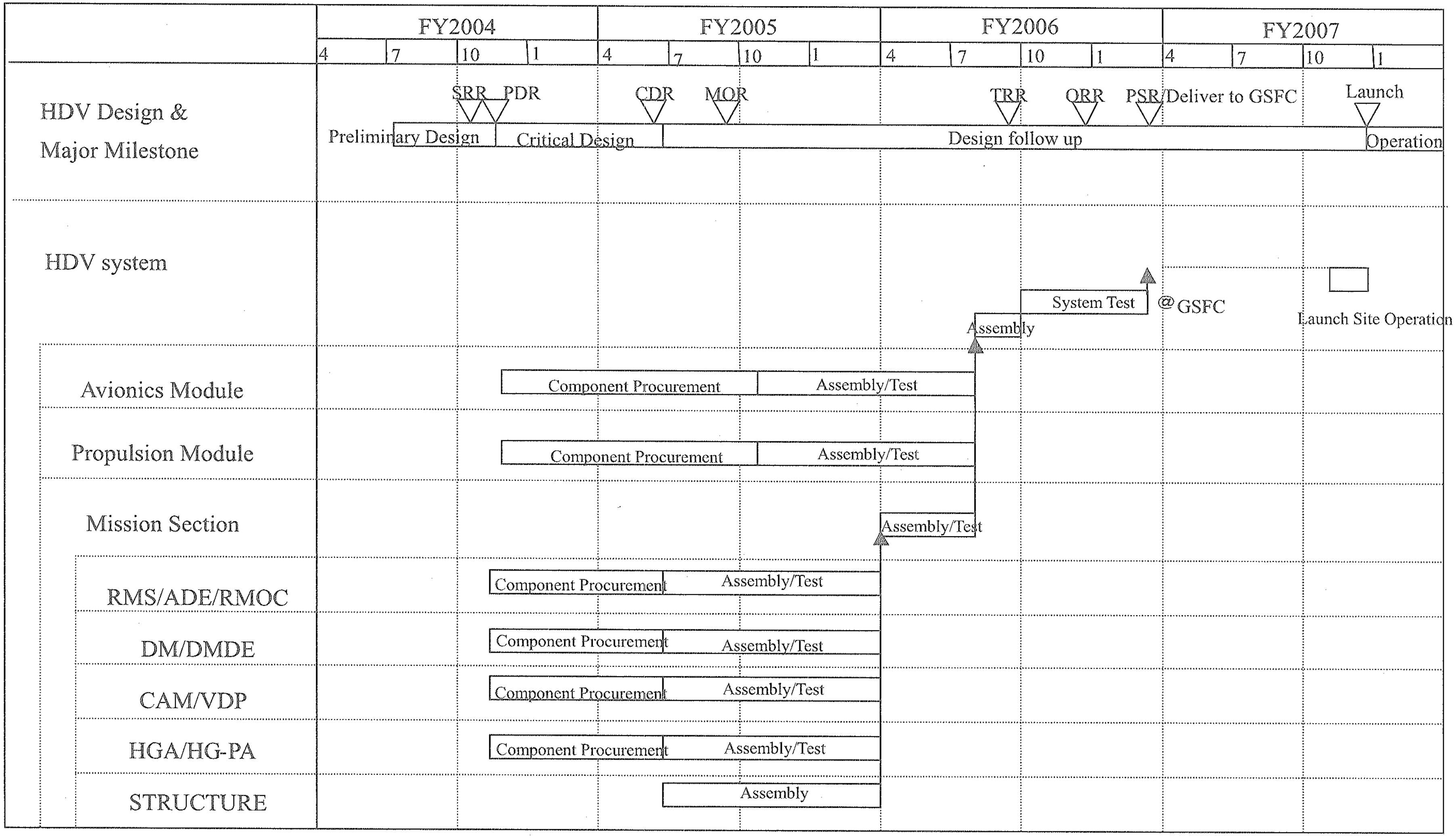


Fig.6-1 HDV Development Schedule (TBD)

## 6.3 Cost of the HDV and its operation

The cost of the HDV and its operation depends on how the HTV and HDV development projects are to be coordinated. Due to the re-scheduling of the HTV launch schedule, which in turn was caused by the re-scheduling of the launch for ISS's elements, the HDV will be launched before the launch of the first HTV. As a result, if the HDV requires engineering models for key subsystems and components, these must be specially prepared for the HDV. How to share the cost of development work for HTV and HDV will be discussed. The HTV's on-ground operation system will also be utilized by the HDV through the addition of certain functions, such as remote operation of the manipulator.

If the experience of HTV development work and the HTV's on-ground operation system are properly utilized, then the total mission cost for the HDV will be considerably lower than the cost of sending the space shuttle to HST to conduct a similar mission.

## 6.4 Risk management

The HDV will be developed based on the design of the HTV and JEMRMS, as well as on our experience with ETS-VII. However, since the HDV will be launched earlier than the HTV and JEMRMS, we must be prepared for unforeseen malfunctions. The ETS-VII satellite was built in a very short time because ETS-VII was to be launched together with the Tropical Rainfall Measurement Mission (TRMM) satellite, whose launch schedule was fixed. ETS-VII was quite a new satellite, with no history of successfully conducting autonomous rendezvous docking and Remote Manipulator operations in space. Therefore, we were prepared to cope with unforeseen malfunctions in orbit. The most critical event involved the malfunction of the gas jet thrusters, which are indispensable to the docking operation. This malfunction occurred just as the chaser satellite was conducting the rendezvous docking operation. The malfunction was overcome by modifying the onboard control software so as to use the remaining thrusters instead of the faulty ones. Remote rendezvous operation directed from the on-ground control station was also tested to prepare for any failures of the autonomous rendezvous docking. The operations involved in HDV's rendezvous with and capturing of HST are basically autonomous. We should establish a similar procedure for the HDV to test ground-based remote piloting of the HDV and its manipulator.

# 7. Optional system's description

## 7.1 Basic Strategy

The composition of HST is not suitable for the service work by the robot in the attachment method of a component, the connection method of an electric connector, etc. For this reason, at present, it is in a difficult situation that equipment exchange, connector combination, etc. operated by the robot arm, can be worked and guaranteed certainly. Although considering and the best efforts which were turned to completion of service by robot work in the period to a launch of HST service missions were paid, the option supposing the case where it does not result in the situation that implementation of service work can be guaranteed in a predetermined period was also studied.

Two kinds of mission forms as follows were studied.

- option A: The life extension module, which performs the power supply via an umbilical connector and attitude control, is attached to HST for the life extension of HST.
- option B: By the dual-arm dexterous robot, the full repair work, such as "diode box connection of a new battery" and "exchange work of WFC", is done.

The composition of option B includes the composition of option A. Then, option A is chosen, when development towards option B is furthered and the prospect of repair by the robot does not stand enough.

### 7.1.1 Option A

#### (1) Composition

A spacecraft is taken as the following 2 module composition.

a. HDV
b. Life Extension Module (LEM )

In the state that it connected with LEM, HDV performs inter orbital flight and reaches to HST. Then, LEM is connected with HST by capture and berthing. After a prolongation-of-life function works is confirmed, the reentry to the earth atmosphere of the HDV is carried out and it is burned out.

#### (2) Missions sequence

The flow of the missions of option A is shown in Fig.7.1.1-1. The sequence of a rendezvous, capture, and berthing is the same as nominal HDV. The concept of HST capture is shown in Fig.7.1.1-2.

After carrying out the berthing (Fig.7.1.1-3) of the HST with the capture arm, solar arrays are unfolded promptly and electric power is obtained. Next, it is confirmed that the function of the electric power supply from LEM to HST and the attitude control function by LEM work normally. Then, HDV is separated and carries out a reentry to the earth atmosphere.

Astronomical observation is continued while the gyroscope of HST is working normally.

After being in the state that it does not work normally by failure of the gyroscope of HST etc., LEM substitutes for attitude control, and the attitude control of an earth-oriented or a sun-oriented is performed so that it may not lapse into a tumbling state (Fig.7.1.1-4).

However, in this state, the highly precise inertial reference attitude control for astronomical observation is difficult.

Mounting star tracker (STT) and dealing with highly precise inertial reference attitude control as an option, also deserves considering, attitude control accuracy and stability are secured by the system that connected to HST.

Moreover, it has LEM, when serving HST repair etc. for later by another spacecrafts, such as a space shuttle, and it is equipped with cooperative equipments, such as CCR, a capture handle, a color marker, and GPS receiver, for rendezvous and capture.

### 7.1.2 Option B

#### (1) Composition

A spacecraft is RSM which mounted a dual-arm robot arm and the equipment for exchange in LEM although set as 2 module composition like option A.

a. HDV

b. Robotic Service Module (RSM)

The inter orbital flight is performed in the state that it connected with RSM and it reaches to HST, it connects with HST and the work by the robot is completed. After it is confirmed that HST works, it separates, and the reentry to the earth atmosphere of the HDV is carried out, and it is burned out.

When HST does not work normally after doing service work, it is possible to carry out the de-orbit of the HST by HDV.

#### (2) Missions sequence

The flow of missions is shown in Fig.7.1.2-1. The sequence of a rendezvous, capture, and a berthing is the same as nominal HDV. After carrying out the berthing of the HST with a capture arm, a solar cell paddle is unfolded promptly and electric power is obtained.

The fundamental flow of HST repair work using a Dexterous arm is shown in Fig.7.1.2-2.

After grasping of the GPF, attached to the base of Dexterous arm, by the capture arm is carried out, a Dexterous arm is taken out from a RSM body. (Fig.7.1.2-3) Then, the equipment on HST exchanged is removed and it is fixed to the temporary holder on RSM by the Dexterous arm. In addition, the new equipment for HST is taken out by the Dexterous arm, and attachment to HST is performed. Many robot tools are required for repair work of HST. The holder of robotic tools is set on the RSM or the central box of Dexterous arm.

After the equipment exchange of WFC by Dexterous arm is completed, it is confirmed that the electric power supply from RSM to HST works normally, and HDV carries out a reentry to the earth atmosphere.

It has the following functions in order to conduct the repair work of HST, in addition to the function of option A.

- Dexterous arm (dual arm)
- Dexterous robot holding / release mechanism
- Removal equipment temporary holder
- Tool holder
- Robotic tools

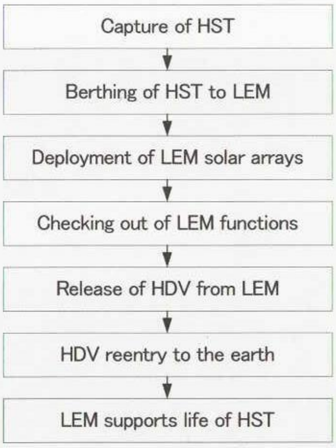


Fig.7.1.1-1 Mission flow of option A

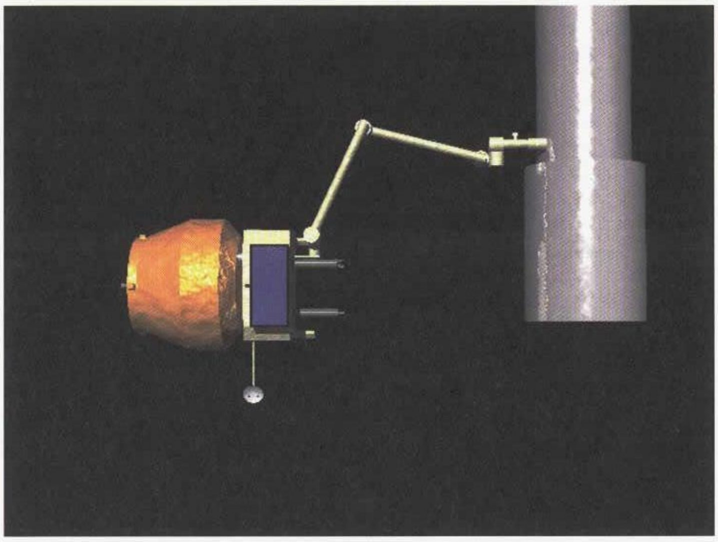


Fig.7.1.1-2 Artist concept of HST capture

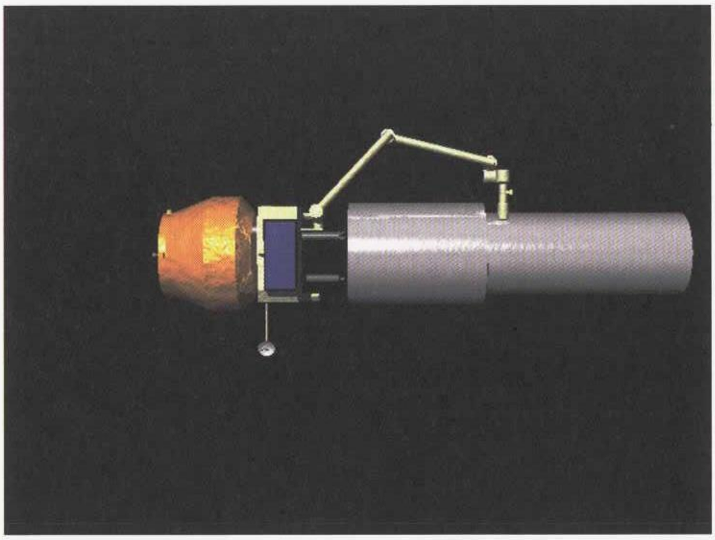


Fig.7.1.1-3 Artist concept of HST berthing

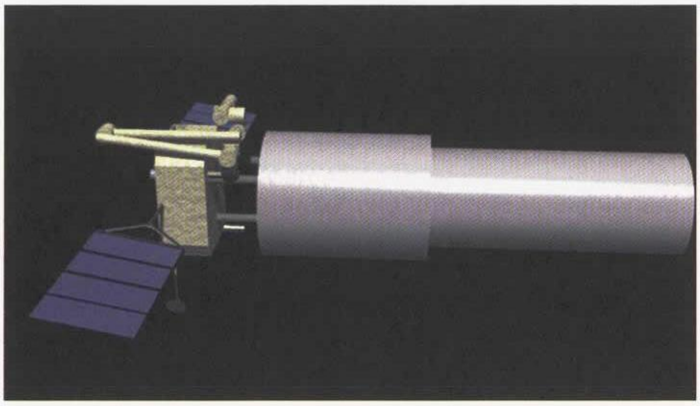
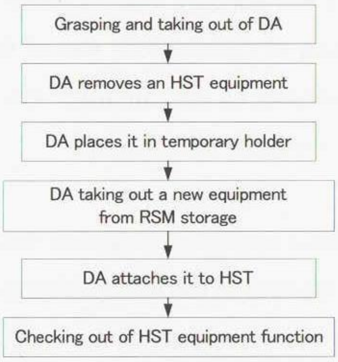


Fig.7.1.1-4 LEM supporting HST life

Fig.7.1.2-1 Mission flow of option B



Note: DA is Dexterous Arm

Fig.7.1.2-2 Fundamental work flow of HST repair work using Dexterous arm

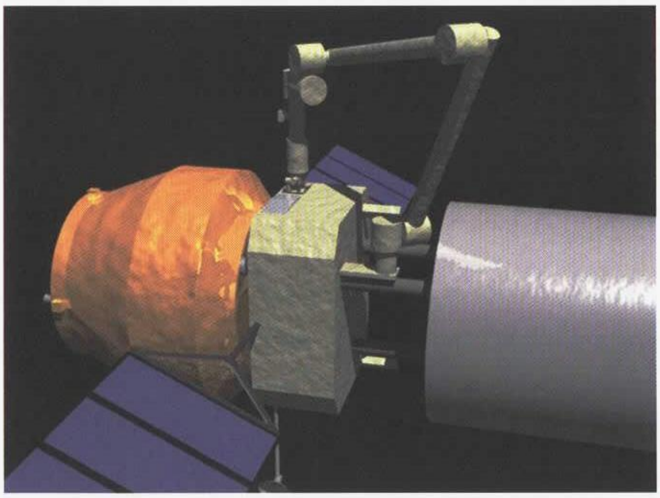


Fig.7.1.2-3 Artist concept of taking out of the Dexterous arm from RSM

## 7.2 Proximity flight and capturing un-controlled HST using RMS

If attitude rate of HST is too high (e.g. more than 0.22 deg/sec) to follow GPF, attitude and position control maneuver (6-degrees of freedom maneuver) of HDV will be necessary in combination with RMS motion control.

Such maneuver will be performed in the phase of "flying around" and "final approach" where HDV performs proximity flight and gets closer to the HST within the range of RMS.

In these phases, HDV has to control its position and attitude simultaneously. If HST is doing attitude motion like nutation, 6-DOF control becomes more difficult. The information required as feedback signal for such sort of controller is relative- position, velocity, attitude, and angular velocity. These information are expected to be measured or estimated from motion estimation, as described in 4.3.1.

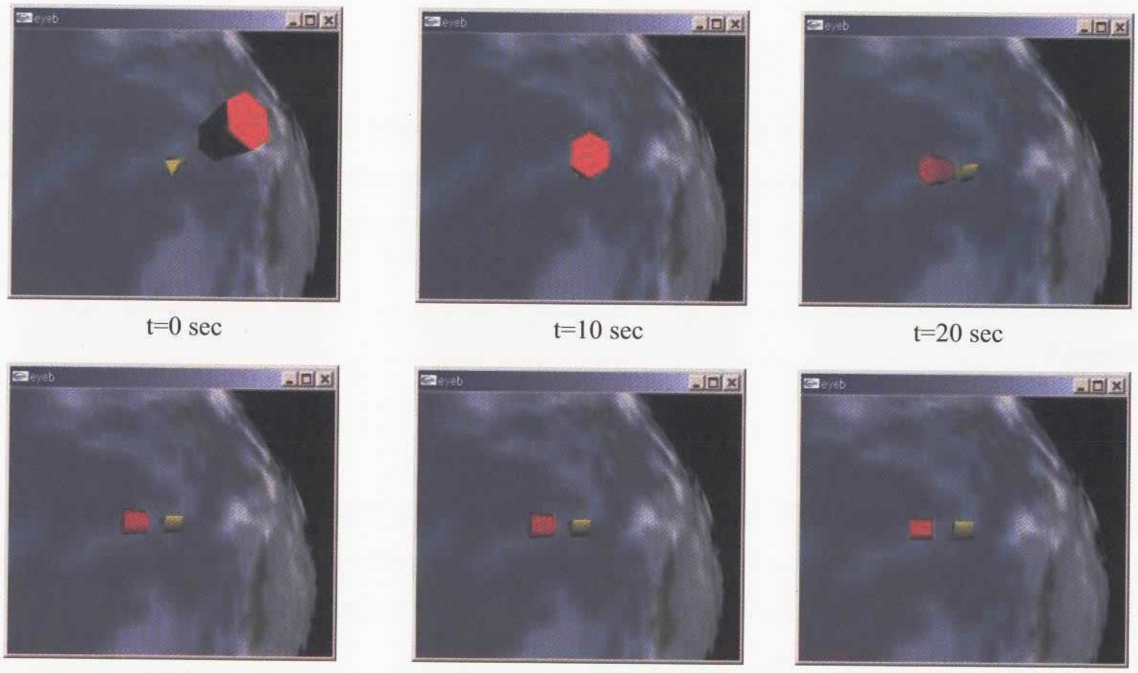
Since the equation of motion of a rigid body that performs attitude and translational motion is a nonlinear equation (Euler's equation of motion), it is not easy to apply linear control theory for the controller design. One of the solution for this is an application of sliding mode control that can handle a nonlinear system. Fig.7.2-1 shows one of the examples of the maneuver by this controller. (Detail of the algorithm is given in the paper of reference) The characteristics of this controller is as follows

- it has astonishing robustness against dynamical parameter uncertainty (these uncertainty satisfies so called "matching condition") such as mass, moment of inertia, etc. This means the controller does not go unstable even after the capturing, for example, HST+HDV configuration
- position control without overshoot can be achieved and it can avoid collision to the HST in the final approach phase

Numerical simulation is underway to confirm the performance of the controller with the combination of motion measurement using image data, and the hardware-in-the-loop DCLT of the maneuver using simulated image data is also to be necessary.

**Reference**

F. Terui : Position and Attitude Control of a Spacecraft by Sliding Mode Control ;
Proceedings of the American Control Conference, pp.217-221 (1998)



t=0 sec

t=10 sec

t=20 sec

t=30 sec

t=40 sec

t=50 sec

Fig.7.2-1 : An example of the 6-DOF proximity flight

## 7.3 Extending life of HST

Although research of the onboard servicing by the space robot is advanced eagerly, there is no basis which can be referred to as surely being able to perform repair service of HST by the robot. Thus, in this proposal document, it is proposed the simple option (option A) for planning only the life extension of HST.

### 7.3.1 Option A

#### 7.3.1.1 Configuration

This service vehicle consists of HDV and LEM. HDV has orbital transformation and a de-orbit function, and LEM has the function to perform on-orbit maintenance of HST. The configuration of the servicing vehicle is shown in Fig.7.3.1-1. It will be launched in the configuration that LEM is connected with HDV, and LEM can be separated from HDV by holding / release mechanism on-orbit.

Since LEM is located in front of a service vehicle during rendezvous and capture phase to HST, the sensor for rendezvous, a berthing mechanism are mounted on LEM.

Moreover, in order to perform an electric power supply to HST, it has a solar cell paddle.

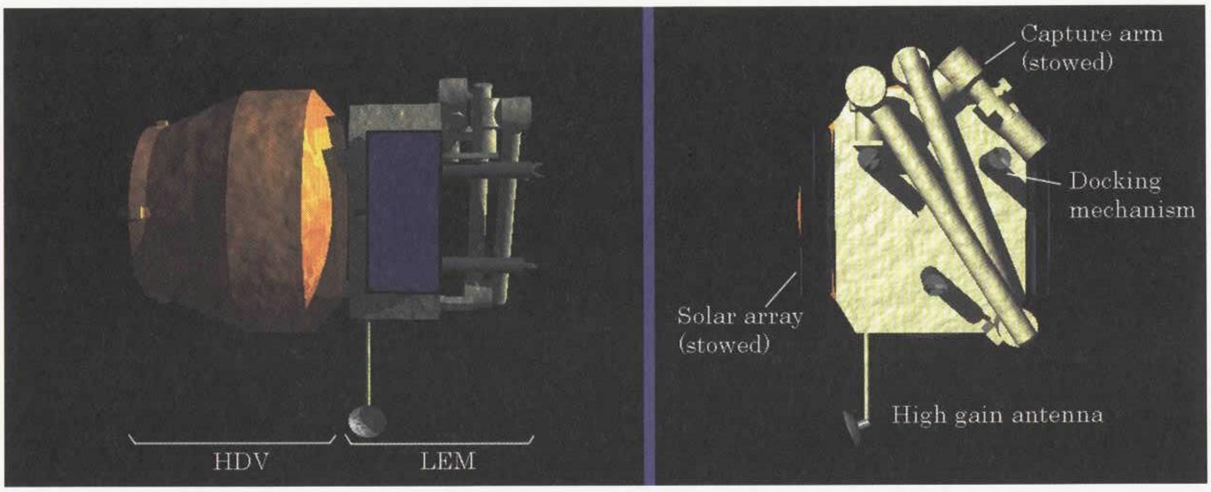


Fig.7.3.1-1 Configuration of the servicing vehicle （HDV&LEM）

#### 7.3.1.2 Power system

As a countermeasure of secular degradation of the battery of HST, an electric power supply is performed via an umbilical connector from LEM. Since the diode is contained in the power supply line, electric power flows only to one side, which means that the electric power generated in the solar cell array of HST cannot be charged in the battery of LEM. For this reason, in order to carry out an electric power supply to HST, a solar cell paddle is required for LEM.

In the daytime of HST, the electric power generated in the solar cell paddle of HST is applied for HST, and the battery in LEM is simultaneously charged by the solar cell paddle of LEM. In the night, the electric power charged to the battery of LEM is applied for the electric power supply to HST. Therefore, the solar array of LEM is located in the same direction as that of HST. In addition, an electric power supply is performed also to HDV from LEM, in the state that HDV is connected.

### 7.3.1.3 Structure

The solar cell paddle of LEM is located in the position greatly offset from the center of gravity of HST. Therefore, the solar cell paddle of LEM must be a rigid panel from a viewpoint of attitude control.

If receipt of such a rigid solar array panel is considered, the shape of the LEM will serve as square box structure fundamentally. Holding/release mechanism for connection to HDV is located on the hard point by the side of the base of square box structure, and a berthing mechanism is located on the hard point by the side of a tip.

### 7.3.1.4 Attitude control

LEM performs attitude control by the actuator in the state that it connected with HST. An attitude sensor and rate gyroscopes, such as an earth sensor and a solar sensor, are applied. Although it needs a star sensor similar as the sensor used in the observation missions of HST, a star sensor is not mounted considering of survival missions here.

Four sets of reaction wheels are used for an attitude control actuator.

Magnetic torquer is mounted for the unloading of the accumulation momentum by disturbance torque.

The composition of the attitude control system of LEM is shown in Fig.7.3.1-2.

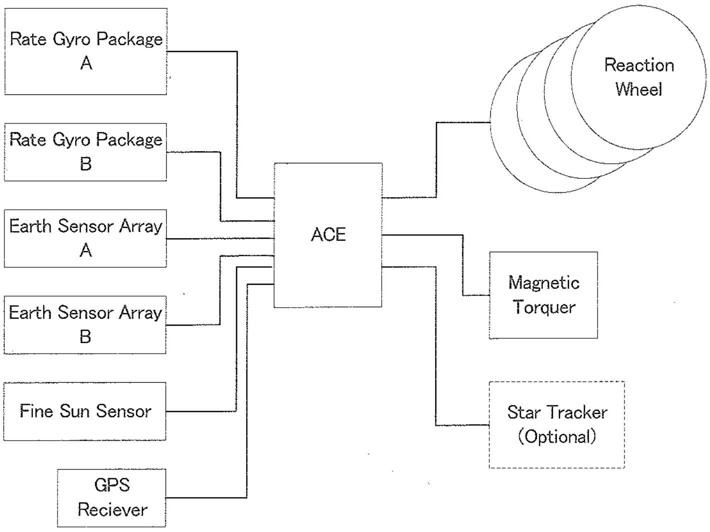


Fig.7.3.1-2 Composition of the attitude control system of the LEM

#### 7.3.1.5 Communication

A communication system is constituted independently of HST like the basic composition of HDV described in the section 5.1.3. A high gain communication system is mounted in LEM for transmission of a camera image. A fundamental telemetory / command communication system is also mounted in the both of HDV and LEM, respectively

#### 7.3.1.6 GN & C

In order to perform guidance and navigation of the orbital transformation and rendezvous to HST, the GN&C equipments shown in Table 5.1.3-1 are mounted in LEM.

### 7.3.2 Option B

#### 7.3.2.1 Configuration

This vehicle consists of RSM(s) that has the function to offer repair servicing of equipment exchange of HST, and HDV that has orbital transformation and a de-orbit function.

Configuration of the vehicle is shown in Fig.7.3.2-1.

It is launched in the state that it was connected on HDV, and RSM can be separated from HDV by the holding / release mechanism by the on-orbit.

RSM has robot equipments, such as an arm for capture, and a dexterous work arm.
Furthermore, since it is located on the front side of a vehicle during a rendezvous and capture of HST phase, a navigation sensor, guidance sensor, a berthing mechanism are mounted on RSM.

When the repair work by the robot is not successful enough, RSM separates HDV and operates the on-orbit life extension of HST, for example, performing an electric power supply and attitude control in case that it is needed as option A of LEM.

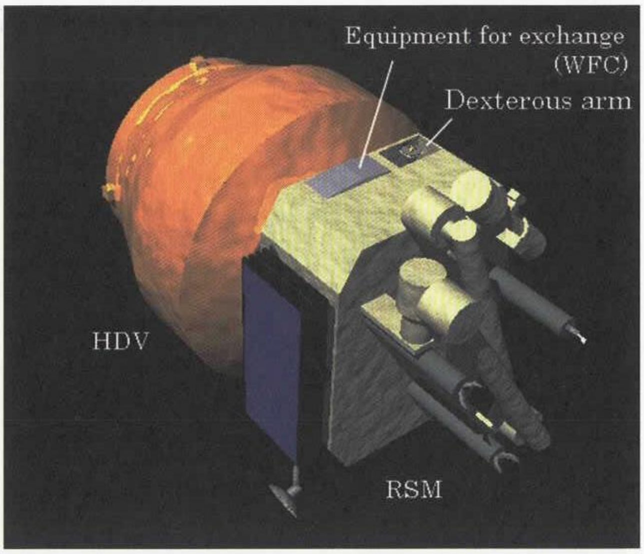


Fig.7.3.2-1 Configuration of HDV & RSM

### 7.3.2.2 Dexterous robot

A dexterous robot is taken as the dual-arm configuration which constituted from two arms designed base on ETS-VII robot arm. The external view of the dexterous arm is shown in Fig.7.3.2-2. This dexterous arm does service work in the state that it was connected at the tip of a capture arm. For this reason, it has a GPF on the base of the dexterous arm.

This configuration can be considered as the parents / child arm of JEMRMS. DOF allocation of an arm is shown in Fig.7.3.2-3.

Offset of joints of each arm are as symmetrical composition.

A dexterous robot's system block diagram is shown in Fig.7.3.2-4.

The main changed parts from an ETS-VII arm are the followings.

a. To reduce the cables of arms

b. To change the end-effecter into micro-fixture correspondence.

c. To change a hand-eye camera into a small color camera.

These changed parts have established technology by trial productions and testing, and these application are not difficult. An prototype end-effecter corresponding to micro-fixture is shown in Fig.7.3.2-5

A dexterous robot's principal performances are shown in Table 7.3.2-1.

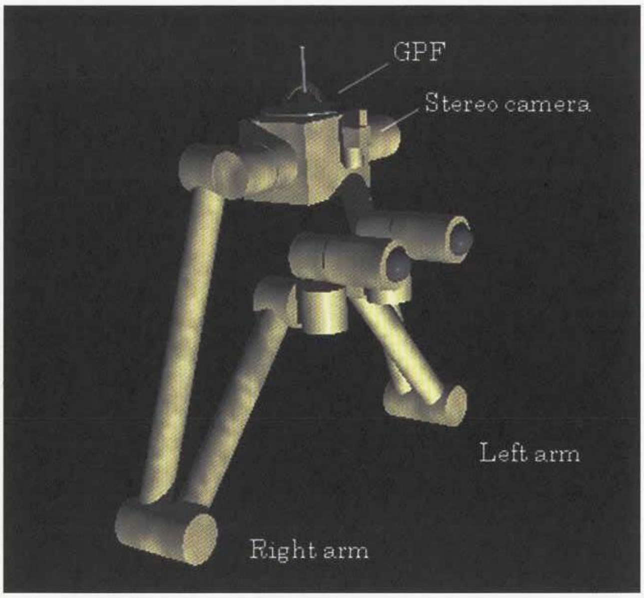


Fig.7.3.2-2 Composition of the dexterous robot

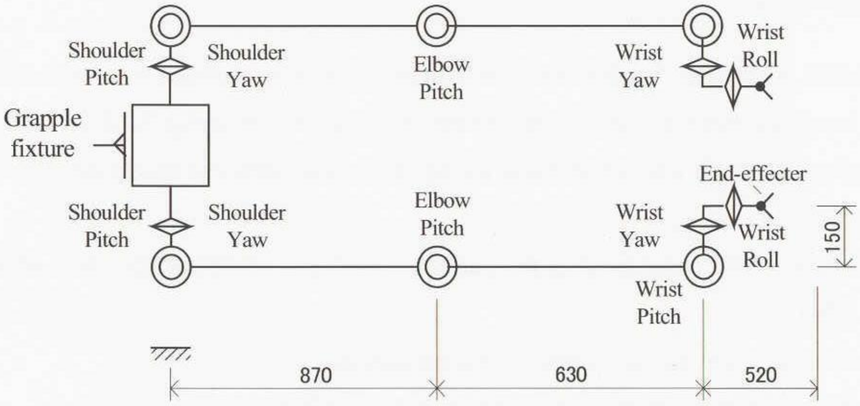


Fig.7.3.2-3 Layout of degrees of freedom of the dexterous arm

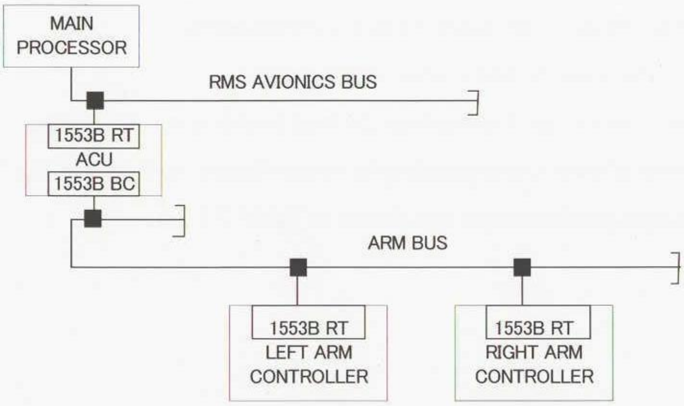


Fig.7.2.2-4 Block diagram of the dexterous arm system

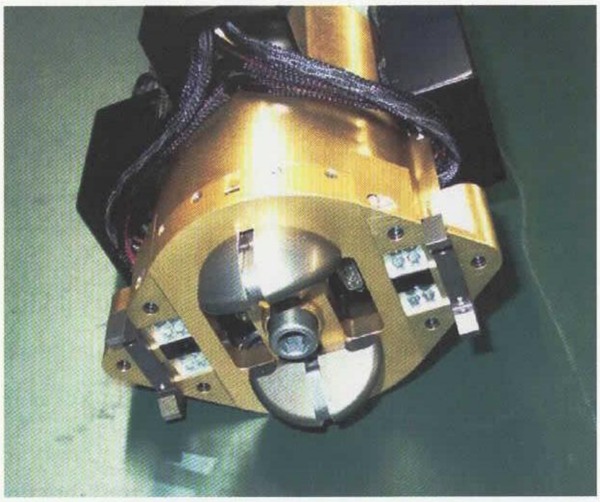


Fig.7.3.2-5 A prototype end-effecter for grappling micro-fixture

Table 7.3.2-1 Principal performances of the dexterous robot

| Items | Performance | Remarks |
|---|---|---|
| Maximum tip force | 40N, 10Nm | |
| Maximum tip rate | 50mm/s, 5deg/s | |
| Positioning accuracy | 1.3mm | Repeatable |
| Mass | 240kg | Dual arm |

In the work of equipment exchange etc., the robot arm will be in a closed link state frequently.

In order not to damage object equipment and the arm itself, in such a situation, a force/torque control function is very important. Active compliance robot motion using force/torque control is useful for guiding the robot arm tool to target work. And groping function using force/torque control is also useful to access to target work. Various on-orbit experiments and evaluations of force/torque control function were conducted in MFD or ETS-VII, and effectiveness and the validity of the force/torque control system was verified.

The dexterous tasks proved in robotic experiments of ETS-VII are listed in Table 7.3.2-2.

Table 7.3.2-2 The dexterous tasks proved on ETS-VII robot flight experiments

| OOS tasks | Remarks |
|---|---|
| Autonomous satellite capture | Corporative target capture by visual feed-back control |
| Berthing of target satellite | Compliant motion |
| Docked inspection of target | Stereo image processing |
| Replacement / maintenance | ORU, pushing button, pulling ball, peg-in-hole, toggle switch operation, curved surface tracking, linear-slider operation |
| Deploy / stow | Deployable truss |
| Fuel transfer | transferring of water after tank module detachment/attachment |
| Non-coordinated tasks | Manual tele-operation from the ground |

The robot experiment of ETS-VII is the one and only mission which could demonstrate and evaluate many kinds of force controlled dexterous robot tasks in space.(Fig.7.3.2-6, Fig.7.3.2-7 )

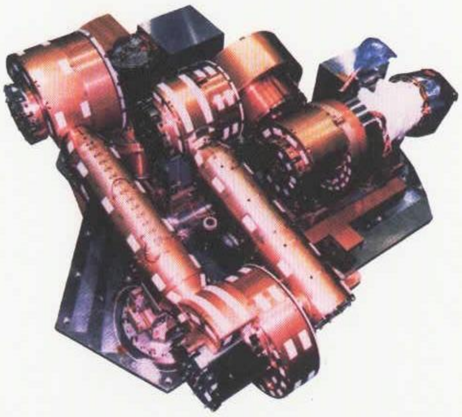


Fig.7.3.2-6 ETS-VII robot arm ( PFM stowed )

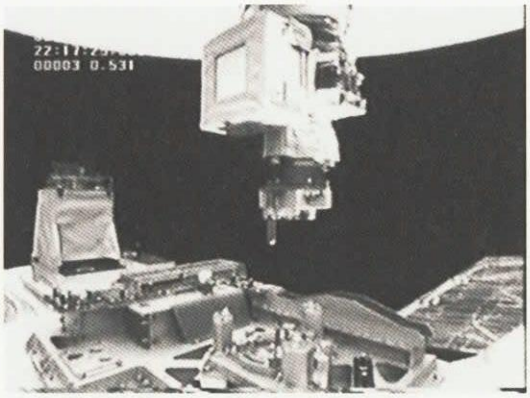


Fig.7.3.2-7 ETS-VII robot flight experiment
(Curved surface tracking experiment with a peg tool)

In addition, cooperation and optimization of control / operation procedure and tools are indispensable for equipment exchange or attachment-/-detachment work of electric connectors.

Experimental investigation of autonomous dual arm operation which substitutes for EVA tasks of JEM equipment exchange have been conducted using the ground test bed of the ETS-VII arm. (Fig.7.3.2-8)

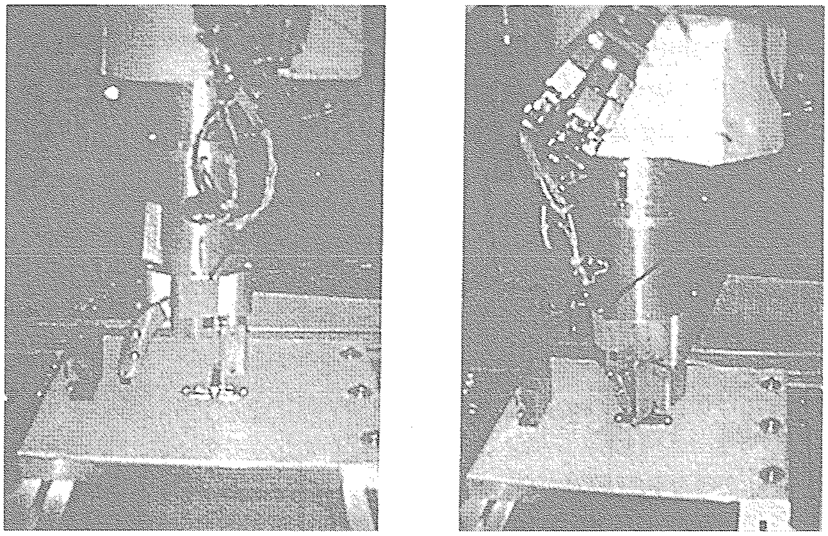


Fig.7.3.2-8 Autonomous EVR experiment using ETS-VII ground test bed

### 7.3.2.3 Replaceable equipments

It is combined on RSM and the equipment exchanged by a dexterous robot's work, such as WFC-II and Costa, is launched, by the on-orbit, is used as a dexterous robot choice outside, is used as him, and is attached in a predetermined part.

First, the equipment for exchange on HST is removed.

Temporary fixation of the removed equipment is carried out in the place for the temporary fixation on RSM.

### 7.3.2.4 Power system

During the repair work period by the dexterous robot, the solar cell paddle and a battery of RSM perform the electric power supply to HDV or a robot arm.

As a countermeasure of secular degradation of the battery of HST, an electric power supply is performed via an umbilical connector.

If installation of the bypass wiring from the diode box by the dexterous robot is completed, it will become possible to charge the electric power generated by solar array of HST in the battery of RSM via this bypass line.

However, in the state that this wiring is not installed, the electric power, which the solar array of HST generates , cannot be charged to the battery of LEM because of the diode that contained in the power supply line of the HST umbilical connector.

Since it corresponds to such a situation, a pair of solar array is equipped with RSM to supply electric power to HST.

### 7.3.2.5 Structure

Although the structure of RSM is square box shape similar as that of LEM, the onboard space of a dual-arm robot and the equipment for exchange task of HST is secured, and it has the holding mechanism of these equipment.

### 7.3.2.6 Attitude control

The attitude control after HST capture is carried out by RSM and HDV.
If a high gain antenna is removed, high attitude accuracy is not required.
A high gain antenna maintains high inclination accuracy by cooperation control with attitude control.

### 7.3.2.7 Communication

The communication function of RSM is the same as that of HDV, and it has an image transfer function by the high gain antenna.

### 7.3.2.8 GN & C

Since RSM works as a head module of navigation while flying by connecting with HDV, it has the same navigation and guidance function as the aviation subsystem of HDV.

## Appendix-1 NASA's RFP

National Aeronautics and
Space Administration

**Goddard Space Flight Center**
Greenbelt, MD 20771

Reply to Attn of: 210.S June 1, 2004

TO: POTENTIAL OFFERORS

SUBJECT: NNG9461779R for the Hubble Space Telescope (HST) Robotic Vehicle Deorbit Module (HRVDM)/Hubble Disposal Vehicle (HDV) Solicitation.

You are invited to submit proposals to NASA/GSFC for the above solicitation, which will result in award of either of the following efforts in accordance with the provision contained in Section L.2 of this solicitation:

- HST Robotic Vehicle Deorbit Module (HRVDM): This is a component of a larger vehicle whose combined purpose is to provide robotic servicing and life extension of the HST, and ultimately end-of-life controlled re-entry or other safe disposal of HST.

- Hubble Disposal Vehicle (HDV): This is a stand-alone vehicle whose purpose is to only provide end-of-life controlled re-entry or other safe disposal of the HST.

For either the HRVDM or HDV efforts, offerors are free to propose any method of HST disposal that complies with NASA Program Directive (NPD) 8710.3B.

The above efforts will be unrestricted (full and open) competition. The North American Industry

Classification System (NAICS) code for this acquisition is 336414 and the Small Business size standard is 1,000.

Due to schedule constraints created by the condition of the Hubble Space Telescope, it is necessary for the agency to release this Request for Proposal (RFP) prior to the final decision by the agency on which of the above mission efforts will be awarded a final contract. Offerors are invited to submit proposals for either vehicle, however offerors who propose a vehicle for the servicing and deorbit mission shall also propose a vehicle for the disposal-only mission. **Offerors submitting only a proposal for the servicing and deorbit mission will be determined to be non-responsive to this request for proposals and their proposal will not be evaluated.**

Source selection procedures will be utilized to select a proposal for each vehicle effort. The agency will then select one of these two proposals for contract award, based upon the agency's ultimate programmatic mission profile determination. However, the agency reserves the right to not make any award from this solicitation. The award of a contract resulting from this solicitation is contingent upon the availability of appropriated funds from which payment for contract purposes can be made.

Please read the enclosed documents carefully, particularly the instructions and evaluation criteria contained in Sections L and M. In addition to the consolidated sections K, L, and M that apply to both efforts, offerors should take note that there are additional attachments (see Section L.18) that provide proposal instructions and evaluation criteria that are specific to each effort. Failure to comply with these instructions could result in your proposal being considered unacceptable.

Your offer must have an acceptance period of not less than 180 days.

Offerors are requested to pay particular attention to all fill-ins required in the model contract to ensure that the copies submitted with the proposal(s) provide the Government the ability to award based on initial proposals.

A preproposal conference will be held as indicated below

Date: June 10, 2004
Time: 10: 00 am – 12:00 PM (HRVDM); 1:00 pm – 3:00 pm (HDV)
Location: GSFC Conference Room/Bldg. 8, Auditorium

Government personnel will discuss the requirements and answer questions regarding the solicitation. If you have questions, it is helpful if you submit them in writing to the Government representative at least two (2) calendar days prior to the conference. Additionally, attendance is limited as described in section L.7. Written comments and questions to be addressed at the pre-proposal conference shall be sent to:

Carlos R. McKenzie
NASA/GSFC
Mail Code 464
Greenbelt, MD 20771
Phone: (301)286-0599
Fax: (301)286-0214
E-mail: Carlos.R.McKenzie@nasa.gov

**As stated in Section L.12 of this solicitation, the Mission Suitability and Cost Proposal Volumes must be received at the designated receiving office by July 16, 2004, at 2:00 PM EST. However, the Business Volume of the proposal must be received by July 2, 2004, at 2:00 PM EST.** Offerors are advised that the HRVDM/HDV acquisition schedule has several external factors that limit schedule extensions or delays. The proposal due date will not be extended based on routine issues or requests.

**As of this date, the procurement is in an official "Black-out." The undersigned is the sole point of contact concerning this solicitation.** The contracting officer may contacted by electronic mail at Carlos.R.McKenzie@nasa.gov or by telephone at (301) 286-0599 with any inquiries. For identification purposes, all communications regarding this solicitation should include the above-referenced solicitation number.

Your interest in NASA requirements is appreciated.

/s/
Carlos R. McKenzie, Jr.
Contracting Officer

Enclosures

## Appendix-2

Members of the HDV study team

Japan Aerospace Exploration Agency (JAXA)

- Mitsushige Oda (Leader)
- Shin-ichiro Nishida
- Heihachiro Kamimura
- Fuyuto Terui
- Noriyasu Inaba (Sub Leader)
- Hiroshi Ueno
- Toru Yamamoto
- Tatsuya Endo
- Shinji Mitani
- Hirotaka Sawada

Mitsubishi Heavy Industries, Ltd (MHI)

- Naohiko Abe
- Kazumi Masuda
- Katsushi Shibata

Mitsubishi Electric Corporation (Melco)

- Kuniharu Yasuda
- Jun Tsukui

NEC Toshiba Space Systems, Ltd (NTSpace)

- Masato Hayashi
- Tsuguhiko Okamoto
- Tatsuya Yoshida
- Fumihiro Kuwao

Kawasaki Heavy Industries, Ltd (KHI)

- Nobuyuki Kubota
- Nobuyoshi Muroi
- Masayuki Enomoto
- Atsushi Yokoo

## Appendix-3 Compliance Matrix

The compliance matrix that is requested by NASA's RFP is prepared in following pages.

# APPENDIX 3

## Compliance Matrix (1/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 3 | REQUIREMENTS | | | |
| 3.1 | SYSTEM DESCRIPTION | The function of the HDV is to safely dispose of the HST at the end of its science mission. HST end of mission disposal shall be provided by a controlled re-entry to Earth or a boost to a 2500 km parking orbit that meets the conditions of NASA NPD 8710.3. | COMPLY | HST end of mission disposal shall be provided by a controlled re-entry to Earth, but not a boost to a 2500km parking orbit. |
| 3.1.1 | Launch Vehicle (LV) | The HDV shall be launched on an ELV that is provided through the NASA Launch Services (NLS) contract.<br>The HDV separation system shall be provided by the LV. The relative separation velocity and tip-off constraint requirements are contained in the HDV to LV Interface Requirements Document (IRD), to be provided after LV selection. | COMPLY | New development |
| 3.1.2 | Coordinate Systems | The HST coordinate system, shown in Figure 3-1, is a right-handed, orthogonal coordinate system with the +V1 (optical) axis on the HST centerline extending along the long axis of the HST out the aperture door. The origin is 100 inches behind the Surface of the AB. The +V3 axis (Sun direction) extends perpendicular to the SA mast and parallel to the HST keel fitting. The +V2 axis extends parallel to the SA mast to complete the right-handed coordinate system. | - | Definition |
| 3.1.2.1 | HDV Coordinate System | The HDV coordinate system shall be a right-hand, mutually orthogonal coordinate system (D1,D2,D3) with the origin offset 100 inches in the -V1 direction from the aft bulkhead | - | Definition |
| 3.1.3 | Tolerances | Unless otherwise noted, all dimensions are in inches and tolerances are as follows:<br>Linear Dimensions<br>· .XXX = ± 0.010<br>· .XX = ± 0.03<br>· .X = ± 0.1 Angles = ± 0.5 deg<br>All dimensions of the above figures are applied at 68°F. | - | Definition |
| 3.2 | PERFORMANCE (Note: Level II Requirements Section) | | - | Title |
| 3.2.1 | Autonomous Pursuit and Capture | The HDV shall be capable of pursuit, proximity operations, and capture with the HST in an un-powered state at a maximum altitude 560 km and an orbital inclination of 28.45 degrees. | COMPLY | |
| 3.2.1.1 | Uncontrolled HST Body Rate | The HDV shall meet Section 3.2.1 with HST body rates of up to 0.22 degrees per second per axis. (TBR) | NOT COMPLY | Realistic condition should be coordinated. |

## Compliance Matrix (2/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 3.2.1.1.1 | Controlled HST Body Rate | The controlled HST body rates shall be less than or equal to V1=0.057 deg/sec, V2 < 0.046 deg/sec, V3 < 0.132 deg/sec except at orbit dawn when maximum body rates are estimated to be V1 < 0.138 deg/sec, V2 < 0.103 deg/sec, and V3 < 0.132 deg/sec. | COMPLY<br>MAY BE | Definition and realistic condition should be coordinated. |
| 3.2.1.2 | Capture and Docking Attempts | The HDV shall be capable of a minimum of four capture/docking attempts. | COMPLY | |
| 3.2.1.2.1 | Capture Method | The HDV shall support at least two independent means of HST capture. All methods of capture shall be single fault tolerant. | NOT COMPLY | One method of capture is single fault tolerant. The other is not. |
| 3.2.1.3 | Video Observation | The HDV shall provide real time video transmission of proximity operations, and capture with HST. Resolution and frame rate shall support ground supervision of critical operations. | COMPLY | |
| 3.2.1.4 | Range Rate Redundancy | The HDV shall redundantly acquire range, range rate, and orientation data (relative to the HST) using two different types of sensors systems during the proximity operations and capture mission phases. | COMPLY | HTV based HDV have FRS and NRS |
| 3.2.1.5 | Ground Abort Contingency | The HDV shall provide contingency ground abort capability for all autonomous operations. | COMPLY | |

# Compliance Matrix (3/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 3.2.1.6 | Lifetime | The HDV shall provide pursuit, proximity operations, and capture capability for a minimum of one year after launch and successful orbit insertion. | NOT COMPLY | It is written in 5.4 Reliability |
| 3.2.2 | HST Disposal | | - | Title |
| 3.2.2.1 | HST Dispose Vehicle (HDV) Autonomy | The ability of the HDV to dispose of the HST shall be independent of the health or configuration of the HST. | COMPLY | |
| 3.2.2.2 | Disposal Lifetime | The HDV shall be capable of disposal operations at anytime after capture up to a maximum of five years. | NOT COMPLY | It is written in 5.4 Reliability (and 7. Option system) |
| 3.3 | HST to HDV Interfaces | | - | Title |
| 3.3.1 | HST Mechanical | | - | Title |
| 3.3.1.1 | HDV Coordinate System | The HDV coordinate system shall be as defined in Section 3.1.2. | - | Definition |
| 3.3.1.2 | Capture and Docking | Capture, may, but is not required, to be accomplished using the following HST fixtures. However, for any other capture interface, contractors must show analysis and ample structural safety margins. | - | Definition |
| 3.3.1.2.1 | Grapple Fixture Capture | The HDV may capture using one of the two HST grapple fixtures, located at HST station 358 (V1, 258 inches forward of the Aft Bulkhead) and +46 inches (V2) (Reference Lockheed drawings 4177659, 4171580, 4171583 and 4177051). | - | Definition |
| 3.3.1.2.2 | Berthing Pin Capture | The HDV may dock to and may capture the HST at the HST AB FSS Berthing Pins, see Figure 3-2. The HST has three equidistant FSS Berthing Pins located on the HST AB at HST station 93.970 inches (V1) and at a radius in the V2 – V3 plane of 36.000 inches) (Reference Lockheed drawings 4177659, 4175792 and 4171550). One of the three equidistant FSS Berthing Pins is aligned with the +V3 axis. An interface verification tool (GFE) is available for FSS Berthing Pin interface verification, 96337201000 (FSS Interface Gauge Assy.).<br>The AB has a berthing target that is shown in Figure 3-2, reference Lockheed drawing 4175650. | - | Definition |
| 3.3.1.2.3 | Trunnion/Keel Fitting Capture Mode | The HDV may capture using either one of the station 240 two trunnion fittings located on the +/-V2 sides of HST, or the station 240 keel fitting on +V3. | - | Definition |
| 3.3.1.3 | Clearances | | - | Title |

# Compliance Matrix (4/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 3.3.1.3.1 | Grapple Clearances | The HST static envelope is defined in Section 3.3.1.5.1. The SA3 and High Gain Antenna (HGA) sweep volumes are shown in Figure 3-3. This figure protects for dynamics of an additional 6 inches. | COMPLY | |
| 3.3.1.3.1.1 | Grapple Fixture Capture Tolerances | To grapple a Grapple Fixture requires the following alignment and positioning requirements, as shown in Figure 3-4:<br>+ 15 deg about two axes (pitch and yaw)<br>+ 10 deg in roll<br>4 inch band in axial direction<br>4 inch band in radial directions | COMPLY | |
| 3.3.1.3.2 | Docked Clearances | The HDV shall maintain at least a (TBD) static clearance between the HST and HDV (except at structural load paths). The HST AB static envelope is defined in Lockheed drawing 4171550 and GSFC drawing GE 2044728. | COMPLY | |
| 3.3.1.4 | Mass Properties | | - | Title |
| 3.3.1.4.1 | HST Mass Properties | The mass of the HST is 26745 lbs. (12129.3 kg)<br>The center of gravity is:<br>V1=254.3 inches (6.46m)<br>V2=1.0 inches (0.03m)<br>V3=-7.5 inches (-0.19m)<br>The HST Mass Properties Report is provided in ST/SE-04. | - | Definition |
| 3.3.1.5 | Envelopes | | - | Title |
| 3.3.1.5.1 | HST Envelopes | The HST Envelope is defined in Lockheed drawing 4171550 (HST Assembly Complete), 4177659 (Inboard/Outboard Profile) and GSFC drawing GE 1525373 (Exception: ASCS Radiator and conduit was not installed). | - | Definition |
| 3.3.1.5.2 | HST Central Body Cross-Sectional Area | The maximum cross-sectional area of the HST central body is 87,200 sq. inches. The minimum cross sectional area of the HST central body is 24,600 sq. inches. | - | Definition |
| 3.3.1.5.3 | HST SA3 Cross-Sectional Area | The maximum cross-sectional area of each solar array is 27,600 sq. inches. | - | Definition |
| 3.3.2 | Structural Interfaces | | - | Title |
| 3.3.2.1 | Launch and Ascent Loads | HDV Launch and Ascent loads are defined in the HDV to Launch Vehicle Interface Control Document. | MAY BE COMPLIED | Need to check ICD |
| 3.3.2.1.1 | Acoustic Loads | This section is not applicable to HST to HDV interfaces. | - | Not applicable |

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 3.3.2.1.2 | ELV Pyrotechnic Shock | All HDV structure and components shall survive shock loading due to ELV separations at the separation plane, as defined below (TBR):<br>a) 100 Hz 50g<br>b) 100 <Freq<1600HZ +10 dB/octave<br>c) 1600< Freq<10000Hz 5000g<br>Note: 1g = standard acceleration due to gravity 9.81 m/s<br>Verification will be in the form of a spacecraft level shock test. | NOT COMPLY | c) 1600< Freq<10000Hz 4000g |
| 3.3.2.2 | In-Orbit Loads | | - | Title |
| 3.3.2.2.1 | Plume Loading | | - | Title |
| 3.3.2.2.1.1 | HST Body Plume loading | Plume Loads by HDV on HST, with a maximum surface area as identified in Section 3.3.1.5.2, shall be a maximum of 9.35 in-lbf about its CG as defined in Section 3.3.1.15.1. | | Need to estimate |
| 3.3.2.2.1.2 | SA3 Plume loading | Plume Loads by HDV on HST, with a maximum surface area as identified in Section 3.3.1.5.3, shall be a maximum of 4.5 in-lbf about V2 Axis. | | Need to estimate |
| 3.3.2.2.2 | Grapple Fixture Limit Loads | The allowable forces at the grapple fixture shall be less than that defined in Table 3-1 and Figure 3-5. | - | Need to estimate |
| 3.3.2.2.3 | FSS Berthing Pins Limit Loads | Any combination of applied forces at the FSS berthing pins shall result in positive margins of safety using the Load Transformation (LT) equations in Table 3-2 and the appropriate factors of safety. | COMPLY | |
| 3.3.2.2.3.1 | Backup Capture Interface Loads | The maximum loads imparted to the trunnions/keel fitting are as follows:<br>Allowables (lbs)<br>Aft Trunnion<br>z (V3) 81106<br>x (V1) 106340<br>Keel Fitting: y (V2) 85625<br>The table defines capabilities to be used in calculating margins for the trunnions. Factors of Safety shall be untested as specified in Section 4.1.1.5.1. | - | |
| 3.3.2.2.4 | Use of Handrails or Portable Foot Restraint (PFR) Sockets | If handrails or PFR sockets are used loads shall be limited to 50 lb axial, and 10 lb radial, represented as one cycle of a sine wave of 1.333 Hz. | - | |
| 3.3.2.2.5 | HST Appendage Allowable Accelerations | The allowable accelerations at the HST cg shall be less than or equal to 0.1 g. | COMPLY | The acceleration of de-orbit maneuver is less than 0.1g. |
| 3.3.3 | Environmental Interfaces | | - | Title |
| 3.3.3.1 | Thermal Interfaces | | - | Title |

# Compliance Matrix (6/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 3.3.3.1.1 | HDV to HST Berthing Pin Temperatures | The HDV shall be able to latch to the HST bulkhead when the bulkhead temperature is between –80° C and +5°C. | MAY BE COMPLIED | |
| 3.3.3.2 | Magnetic Field Environments | | - | Title |
| 3.3.3.2.1 | Geomagnetic Fields. | The maximum time varying component of the earth's magnetic field is 0.33 gauss. The constant component of the earth magnetic field is 0.21 gauss and is inclined by 65 degrees to the time varying component. | MAY BE COMPLIED | |
| 3.3.3.2.2 | HST Magnetic Fields. | The maximum magnetic field caused by the HST at any attitude does not exceed the following levels:<br>a. A level of 0.3 gauss time varying field within the HST volume at station plane 100.<br>b. A level of 0.10 gauss constant magnetic field within the HST volume at station plane 100. | MAY BE COMPLIED | |
| 3.3.3.3 | Reserved | | - | - |
| 3.3.3.4 | Ionizing Particle Radiation | The omni-directional ionizing particle environment is specified in Table 3-3. | MAY BE COMPLIED | |
| 3.3.3.5 | Meteoroid | Meteoroid protection supplied by the HDV when subjected to the meteoroid flux model as defined in NASA TM 100-471 shall provide a probability of no failure of at least 0.99. | | Need to estimate |
| 3.3.3.6 | Orbital Debris | Orbital debris protection supplied by the HDV shall use the orbital debris flux model as defined in NASA TM-100-471 (TBR). | | Need to estimate |
| 3.3.3.7 | Ground Environments (Humidity, etc.) | During all ground and prelaunch (except transportation and storage), the HDV environment shall be maintained at 18.3 deg C(65 deg F) to 26.7 deg C (80 deg F). The HDV temperature environment shall change less than 2.7 deg C (5 deg F) per hour. Relative humidity shall be 30 to 70 percent.<br>During transportation and storage, the environment shall be controlled to the following requirements:<br>a. Temperature: 10 deg C (50 deg F) min., 32.2 deg C (90 deg F) max.<br>b. Temperature change: 11.1 deg C (20 deg F) per hour max.<br>c. Relative humidity: 0 to 70% max.<br>d. Pressure: .34 to 1.07 ATM max. | MAY BE COMPLIED | |
| 3.3.4 | Electrical Power System | N/A | - | - |
| 3.3.5 | Guidance Navigation and Control | | - | Title |

# Compliance Matrix (7/26)

| **HDV Requirements (NNG0461779R Attachment B)** | | | **Compliance** | **Note** |
|---|---|---|---|---|
| 3.3.5.1 | HDV Pursuit, Proximity Operations and Docking | HST uncontrolled body rates will yield no additional data to support this HDV mode.<br>During HST controlled body rate capture, HST ephemeris and rate data will be at least as well as defined in 3.2.1.1.1.<br>There shall be a minimum of a 25 Km separation below the HST altitude at orbit insertion to protect the HST from any damage.<br>There shall be Authority to Proceed (ATP) ground commands required prior to initiation of all phases of the mission.<br>During the capture phase, the HDV shall provide an autonomous abort capability for anomalous operation conditions.<br>The HDV shall provide a contingency ground abort capability for all autonomous operations. | COMPLY<br>(Controlled HST)<br>NOT COMPLY<br>(Uncontrolled HST) | |
| 3.3.5.2 | Propulsion | The HDV shall maintain a minimum of 50m (TBR) safety zone from HST during HST inspection and rate determination. | MAY BE COMPLIED | |
| 3.4 | Launch Vehicle to HDV Interfaces | | - | - |
| **4.0** | **HDV REQUIREMENTS** | The only function of the HST Disposal Vehicle (HDV) is to successfully dispose of HST at end of mission per NASA Policy Directive (NPD) 8710.3, either by performing a controlled reentry or a boost to a 2500 km long-term storage orbit. This function shall be accomplished independent of the state of HST. In order to execute this, the HDV will perform different functions during the various mission phases. These phases are defined to be 1) Launch through Orbit Insertion, 2) Orbit Insertion through Capture (pursuit, proximity operations, capture, and docking of the HDV with the HST), and 3) HST disposal. | COMPLY | |
| 4.1 | Design and Functional Requirements | | - | Title |
| 4.1.1 | MECHANICAL AND STRUCTURAL DESIGN | | - | Title |
| 4.1.1.2 | Stiffness | The first lateral mode of the HDV structure shall be greater than or equal to 10Hz(TBR). | MAY BE COMPLIED | |

# Compliance Matrix (8/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.1.2.1 | LV Interface | The interface to the launch vehicle is through the Payload Attach Fitting (PAF). | COMPLY | New development |
| 4.1.1.3 | Relative Deflections | The HDV shall accommodate the relative deflections imposed at FSS Berthing Pins, which arise from HST thermal and mechanical distortions. For purposes of designing the HDV hardware, the maximum relative deflections of the HST FSS Berthing Pins in the V1 direction is +/- 0.38 inches and V2 or V3 directions are +/- 0.25 inches and shall be considered design condition enforced boundary motions. | MAY BE COMPLIED | |
| 4.1.1.4 | Loads | | - | Title |
| 4.1.1.4.1 | Flight Design Loads | All HDV structural components and enclosures shall be designed to the quasi-static loads shown in Table 4-1 until such time when dynamic coupled loads can be provided. These load factors are weight dependent and act through a component's center of gravity. These load factors are to be applied singularly in each component's orthogonal axis and are intended to envelope mechanically transmitted and acoustically induced random vibration as well as low frequency transients. | | Need Estimation |
| 4.1.1.4.2 | Component Equipment Loads | Design load factors for component equipment, such as electronic boxes, motors, compressors, and similar components, shall comply with the design load requirements defined in Section 4.1.1.4.1 of this document. | | Need Estimation |
| 4.1.1.4.3 | Component Random Vibration | HDV components shall be tested to levels consistent with ELV qualification levels defined in GEVS-SE. The levels for components weighing less than 50 lbs are shown in Table 2.4-4 Generalized Random Vibration Test levels (STS or ELV) 22.7-Kg (50 lb or less). For components weighing over 50 lbs., the test levels shall be adjusted per the guidelines in Table 2.4-4 of GEVS-SE. These levels may be substituted for random vibration spectrums derived from levels measured at the component mounting locations during previous subsystem or payload testing if this data is not available. After each axis of testing, the component shall be examined for mechanical integrity and functionally tested unless approved by the HST project in advance. Pre and post random vibration sine sweeps shall show no change greater than 10% in frequency and 15% in damping at major modes. | | Need to check GEVS-SE |
| 4.1.1.4.4 | Acoustic Loads | The HDV assembly hardware shall be subjected to an acoustic test in a reverberant sound pressure field to verify its ability to survive the ELV liftoff acoustic environment and to provide a final workmanship acoustic test.<br>Test levels for this test shall conform to the ELV users guide (TBD). | | Need to check the ELV users guide. |
| 4.1.1.4.5 | Pressure Differential | Non-pressurized components of the HDV shall be vented to ensure that structural capabilities are not exceeded during launch. Maximum depressurization rates are 0.3 pounds per square inch (psi)/second and 0.76 psi/second.<br>Maximum pressurization rate is defined in the ELV users guide. Figure 4-1 provides the component differential pressure versus area to volume ratio. Figure 4-2 provides the ELV depressurization plot. | MAY BE COMPLIED | |
| 4.1.1.4.6 | On-Orbit Interface Loads | | - | Title |

# Compliance Matrix (9/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.1.4.6.1 | Grapple Fixture Limit Loads | The allowable forces at the grapple fixtures shall be as specified in Section 3.3.2.2.2. | | Need to estimate |
| 4.1.1.4.6.2 | Berthing Pin Limit Loads | The allowable forces at the berthing pins shall be as specified in Section 3.3.2.2.3. | COMPLY | |
| 4.1.1.4.6.3 | Trunnion/Keel Limit Loads | The allowable forces at the trunnions/keel shall be as specified in Section 3.3.2.2.3.1. | - | |
| 4.1.1.4.7 | Ground Transportation Loads | Whether stowed on its GSE or packaged in its shipping container(s) the HDV shall be subjected to loads no higher than those given in Sections 4.1.1.4.1 and 4.1.1.4.2 of this document during all ground handling and transport. | | Need to estimate |
| 4.1.1.4.8 | Ground Handling | The HDV shall be capable of being handled +D3 vertical and –D1 (TBR) vertical for installation into or removal from its interfaces using standard Ground Support Equipment (GSE) lifting devices. The HDV shall be –D1 (TBR) vertical for system level thermal-vacuum testing.<br>All handling fixtures used at KSC shall be certified per EWR 127-1 and supplied with the flight hardware. Ground Handling Equipment and processes used at GSFC shall be in accordance with the Mechanical Systems Center Safety Manual, 540-PG-8715.1.1.<br>Lift equipment shall conform to NASA Standard for Lift Devices and Equipment, doc. no. NASA-STD-8719.9. | | Need to estimate |
| 4.1.1.5 | Design Factors | | - | Title |
| 4.1.1.5.1 | Factors of Safety - Non-pressurized Components | The HDV structural elements shall be designed using factors of safety that comply with GEVS-SE. For tested components, an ultimate factor of safety equal to 1.4 and a yield factor of safety equal to 1.25 shall be used. For untested components, an ultimate factor of safety equal to 2.6 and a yield factor of safety equal to 2.0 shall be used. | NOT COMPLY | an ultimate factor of safety equal to 1.25<br>a yield factor of safety equal to 1 |
| 4.1.1.5.2 | Factor of Safety - Pressurized Components | Heat pipe components, which use ammonia as a working fluid, shall be analyzed using minimum factors of safety of 1.5 on yield and 2.5 on ultimate for the maximum design pressure. All pressurized components shall comply with MIL-STD-1522 (TBR). | MAY BE COMPLIED | |
| 4.1.1.6 | Strength | HDV shall be designed and analyzed using the "A" Values of MIL-HDBK-5. The system shall also be designed to withstand, simultaneously, the limit loads and other accompanying environmental effects for each design condition, without experiencing plastic deformation, which would limit the performance of any on-orbit functions or be in excess of that defined as yield by either of the above sources. | MAY BE COMPLIED | |

APPENDIX 3

# Compliance Matrix (10/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.1.7 | Fracture Control | A Fracture Control program in accordance with NASA-STD-5003 shall be developed in order to ensure mission success. Items which require fracture control analysis include:<br>a. Pressure vessels, dewars, lines, and fittings (per NHB-8071.1),<br>b. Castings<br>(unless hot isostatically pressed and the flight article is proof tested to 1.25 times limit load),<br>c. Weldments,<br>d. Parts made of materials on Tables II or III of MSFC-SPEC-522B if under sustained tensile stress.<br>(Note: All structural applications of these materials require that a Materials Usage Agreement (MUA) must be negotiated with the project office: refer<br>e. Parts made of materials susceptible to cracking during quenching,<br>f. Non-redundant, mission-critical preloaded springs loaded to greater than 25 percent of ultimate strength.<br>All glass elements, that are stressed above 10% of their ultimate tensile strength, shall also be shown by fracture analysis to satisfy "Safe-life" or "Fail-safe" conditions or be subjected to a proof loads test at 1.0 times limit level.<br>This analysis shall be performed on the HDV that demonstrates the hardware will survive one mission lifetime (with a scatter factor of four) with a nominal launch. | MAY BE COMPLIED | |
| 4.1.1.8 | Fasteners | Fasteners shall meet the requirements of GSFC S-313-100. | | Need to check for GSFC S-313-100 requirements |
| 4.1.1.9 | Weight | A detailed mass properties tracking and reporting system shall be implemented and kept current during the design and fabrication phases in accordance with SMR-5091 (TBD). | | Need to check for SMR-5091requirements |
| 4.1.1.10 | Mechanisms | All HDV mechanisms shall meet the design requirements of EM: FS&S 1483. | | Need to check for EMF S&S 1483 requirements |
| 4.1.1.11 | Coordinate System | The coordinate system axes used for the HDV shall be per section 3.1.2.1. | - | Definition |
| 4.1.2 | ELECTRICAL DESIGN | | - | Title |
| 4.1.2.1 | Networks | The wiring installation will consist primarily of cable harnesses. The wire used in cable harnesses shall conform to MIL-C-17, MIL-W-22759, or MIL-W-81381. Connectors shall comply with MIL-C-38999 or MIL-C-39012. Electrical connectors using crimped connections shall be in accordance with NHB 5300.4 (3H). Brazing shall be in accordance with Specification MIL-B-7883, and soldering shall be in accordance with NHB 5300.4 (3A-1). Printed circuits shall comply with NHB 5300.4 (3I) or other GSFC approved contractor specifications. Conformal coating shall be in accordance with NHB 5300.4 (3J). When redundant paths are provided in the cabling, they shall be routed through separate connectors to the extent practical. The insulation resistance between each conductor and shields, and between each conductor and connector shell, shall be at least 1 megaohm at an applied potential of 500 Volts Direct Current (Vdc). | MAY BE COMPLIED | Need to check requirements |

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| | | Electrical wiring harness assemblies shall be in accordance with NHB 5300.4 (3G). Protective circuitry and wire sizing shall be in accordance with GSFC-PPL-21 to ensure the safe and reliable operation of the electrical system and prevent fault propagation and damage. Analog circuits, such as those used on thermistors, which require remote signal conditioning, shall be routed on a twisted shielded pair and shall not use structure as a return. Twisted wire pairs shall conform to MIL-C-27500. | | |
| 4.1.2.2 | Grounding | The HDV primary DC power returns shall be isolated from structure by a minimum resistance of one mega ohm. Component case grounds shall comply with MIL-B-5087, class R bonding. | MAY BE COMPLIED | |
| 4.1.2.3 | Electrical, Electronic and Electromechanical (EEE) Parts | The EEE parts shall be selected in accordance with the requirements of GSFC-PPL-21 and MIL-STD-975. The requirements of these documents provide for the maximum use of the National Aeronautics and Space Administration (NASA) Standard Parts Program. These parts are grade 2, but either grade 1 or grade 2 parts may be used. Standard parts shall be procured in accordance with the requirements of GSFC-PPL-21 (Ref. MIL-H-38534). | MAY BE COMPLIED | |
| 4.1.2.4 | Corona Suppression | Electrical and electronic subsystems shall be designed so that their performance will not be impaired by coronal discharge. They also shall not be a source of interference that could adversely affect the operation of other equipment. Where adverse coronal effects are avoided by pressurizing or evacuating a component, the seals shall be capable of maintaining the required internal pressure throughout the life of the hardware. Where adverse coronal effects are avoided by restricting operation to space vacuum conditions, the equipment shall be capable of reaching the required vacuum level of 10-5 torr within 10 hours. | MAY BE COMPLIED | |
| 4.1.2.5 | Electromagnetic Compatibility (EMC) | The HDV shall comply with the requirements of the GEVS-SE. The requirements specified in Table 4-5 shall apply. Test method shall be in accordance with MIL-STD-462. | MAY BE COMPLIED | |
| 4.1.2.5.1 | Radiated Susceptibility (E-Field, RS-03) (Peak field Strengths) | The HDV shall not experience performance degradation when subjected to the following radiated fields:<br>14 KHz to 35 MHz 2 volt/meter CW (continuous wave)<br>35 MHz to 2 GHz 2 volt/meter AM (modulation peak amplitude)<br>2GHz to 12 GHz 5 volts/meter AM (modulation peak amplitude)<br>12 GHz to 18 GHz 10 volts/meter (modulation peak amplitude)<br>Modulation 30 to 100 percent at 1.0 KHz (square wave) | MAY BE COMPLIED | |
| 4.1.2.5.2 | Survival | During ground operations testing, the HDV shall provide uninterruptible backup power. | MAY BE COMPLIED | |
| 4.1.2.5.3 | Magnetic Induction Field Susceptibility (RS02) | The HDV shall not experience performance degradation when subjected to the requirements of RS02 as described in MIL-STD-461A/3. This test shall be applied to all standard wire cable bundles interfacing with the HDV. Sixty volts peak shall be used for this test. | MAY BE COMPLIED | |

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.2.6 | Circuit Protection and Fault Isolation | The HDV design shall incorporate fault protection to isolate electrical shorts occurring within the HDV equipment per EEE-INST-002. Circuit protection shall be sized to ensure that faults are isolated downstream of the power bus(es). | MAY BE COMPLIED | |
| 4.1.2.7 | Workmanship | Workmanship standards shall be in accordance with the requirements listed below, or GSFC approved contractor documentation.<br>· Conformal Coating and Staking: NASA-STD-8739.1<br>· Soldering – Flight Surface Mount Technology: NASA-STD-8739.2<br>· Soldering – Flight, Manual (Hand): NASA-STD-8739.3<br>· Crimping, Wiring and Harnessing: NASA-STD-8739.4<br>· Printed Wiring Board (PWB) Design: Space flight PWB designs shall be per the specifications listed below and shall not include features that prevent the finished boards from complying with Class 3 Requirements of the appropriate manufacturing standards as listed below.<br>o IPC-2221, Generic Standard on Printed Board Design<br>o IPC-2222, Sectional Design Standard for Rigid Organic Printed Boards<br>o IPC-2223, Sectional Design Standard for Flexible Printed Boards<br>· Printed Wiring Board Manufacture (flight): PWB shall be manufactured in accordance with Class 3 requirements of the PWB manufacturing standards referenced below.<br>The contractor shall provide PWB coupons to the GSFC Materials Engineering Branch (MEB) for a GSFC/MEB approved laboratory for evaluation. Approval shall be obtained prior to population of flight PWBs. Coupons and test reports are not required for delivery to GSFC/MEB if the contractor has the coupons evaluated by a laboratory that ahs been approved by the GSFC/MEB, however they shall be retained and included as part of the Project's documentation/data deliverables package.<br>NOTE: When approved by the GSFC Project Office, the contractor may use MIL-P-55110, as an alternative to the above referenced PWB manufacturing standards (note that this is not the current version, revisions F and later are not recommended for flight hardware).<br>o IPC A-600, Acceptability of Printed Boards<br>o IPC-6011, Generic Performance Specification for Printed Boards.<br>o IPC-6012, Qualification and Performance Specification for Rigid Printed Boards<br>o IPC-6013, Qualification and Performance Specification for Flexible Printed Boards<br>o MIL-P-55110, Printed Wiring Board, Rigid, General Specification for | MAY BE COMPLIED | need to check the requirements listed. |

# Compliance Matrix (13/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.3 | Active Thermal Control | Active thermal control employed on the HDV shall be redundant and testable in a 1-G environment. Thermal control heaters shall be controlled by the HDV, and shall be thermally sized for the entire operational bus voltage range. The survival heaters shall be sized for the minimum survival bus voltage range. | N/A | N/A |
| 4.1.3.1 | Thermal Environment | The Thermal Environment that shall be used for analysis is as follows:<br>Solar Constant: 1419 W/m2 (Hot) and 1287 W/m2 (Cold)<br>Albedo: 0.35 (Hot) and 0.25 (Cold)<br>Earth IR: 265 W/m2 (Hot) and 208 W/m2 (Cold) | MAY BE COMPLIED | |
| 4.1.4 | Guidance Navigation and Control | | - | Title |
| 4.1.4.1 | Attitude Control System | The HDV shall be capable of initial attitude determination after launch vehicle separation. The rate null shall be accomplished within 100 min (TBR). The HDV shall provide all necessary vehicle control modes to pursue, capture, dock, and dispose of the HST. These include control modes which enable solar power generation, thermal stability, orbit maneuvers, momentum management, HST acquisition and tracking, HST capture, HST rate null, and safe hold. The HDV shall provide all absolute and relative navigation capability to support the pursuit, capture, docking of HST. The HDV shall support on-board absolute and relative navigation. The HDV navigation system shall also support disposal by providing absolute navigation. If HST onboard attitude determination is functional, it will be made available to the HDV relative navigation system through the ground system. | COMPLY | |
| 4.1.4.1.1 | Altitude | The HDV shall be capable of rendezvous with an un-powered HST at a maximum altitude and orbital inclination as specified in Section 3.2.1. | COMPLY | |
| 4.1.4.1.2 | HST State | Capture and docking shall be accomplished without regard to the state of the HST. The HST in an un-powered state may have a worst-case drift body rate as specified in Section 3.2.1.1. | NOT COMPLY | Realistic condition should be coordinated. |
| 4.1.4.1.3 | Capture and Docking Attempts | The HDV shall be capable of capturing and docking as specified in Section 3.2.1.2. | COMPLY | |

# Compliance Matrix (14/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.4.1.4 | Plume Impingement | The HDV shall control thruster plume impingement on the HST per Sections 3.3.2.2.1. | -- | Thrust vector angle will be optimized considering GNC performance and plume impingement on HST. Evaluation and coordination are needed. |
| 4.1.4.1.5 | Physical Contact | The HDV shall not inadvertently contact any part of the HST. Sweep volumes as defined in Section 3.3.1.3.1 shall be avoided. | COMPLY | Stowing antenna and paddle should be coordinated. |
| 4.1.4.1.6 | HST Acceleration | The acceleration of the coupled HST/HDV system during propulsive burns shall be less than or equal to 0.1 g. | COMPLY | |
| 4.1.4.2 | Navigation | The HDV shall provide all necessary measurement data relative to HST during pursuit, capture, and docking using a minimum of two different sensor types. The HDV shall support on-board absolute and relative navigation. The HDV navigation system shall support disposal by providing absolute navigation. The relative navigation sensors and the GPS receiver shall make their raw data as well as any processed outputs available to the ground.<br>The HDV shall provide functionally redundant, independent relative navigation sensors that provide overlapping range and orientation data coverage from 100 m to 2 m and a minimum of one sensor down to 0.1 m (relative range to HST). The HDV shall provide range data at ranges less than or equal to 3 km relative to HST.<br>If HST onboard attitude determination is functional, it will be made available to the HDV relative navigation system through the ground system. | COMPLY | Sensor overlapping area is TBD. |
| 4.1.4.3 | Maneuver Control | The HDV control system shall be capable of executing ground up-linked maneuver commands during the pursuit and proximity operations phase. The HDV shall effect capture, and docking with HST with minimal ground interaction after in-orbit checkout.<br>The HDV shall be capable of on-board maneuver planning and execution during the proximity operations and capture. The transition from ground-based maneuver planning to on-board maneuver planning will occur during proximity operations. All disposal maneuvers will be planned from the ground. | COMPLY | |

| **HDV Requirements (NNG0461779R Attachment B)** | | | **Compliance** | **Note** |
|---|---|---|---|---|
| 4.1.5 | Ground System and Communications | The HDV shall provide forward and return link communications between the control center and the HDV through the Space Network (TDRSS) and the Ground Network (DSN and GSTDN). The system shall be capable of tracking up to four TDRSS satellites during pursuit, docking, and disposal operations. | COMPLY | |
| 4.1.5.1 | Security | The HDV command link shall utilize authentication and/or encryption for commands that could jeopardize the mission. | COMPLY | |
| 4.1.5.2 | Video | Real-time video transmission to the TDRSS shall be provided by the HDV. | COMPLY | |
| 4.1.5.3 | Bit Error Rate | The HDV shall provide bit error rates of less than 1 x 10-5 bits/sec and link margins of greater than +3 dB. | MAY BE COMPLIED | |
| 4.1.5.4 | Compatibility | The HDV ground system shall provide a set of application program interfaces via an IP interface that allows an external system to control HDV ground system functions, receive telemetry from the HDV, and send commands to the HDV. | MAY BE COMPLIED | New development |
| 4.1.5.5 | Ground Abort | The HDV shall provide ground abort capability per Section 5.9.2. | COMPLY | |
| 4.1.6 | Materials | | | |
| 4.1.6.1 | Materials and Processes | Materials and processes shall be in accordance with SMR-5000. In order to anticipate and minimize materials problems during space hardware development and operation, when selecting materials and lubricants, the developer shall consider potential problem areas such as radiation effects, thermal cycling, stress corrosion cracking, galvanic corrosion, hydrogen embrittlement, lubrication, contamination of cooled surfaces, composite materials, atomic oxygen, useful life, vacuum out gassing, toxic off gassing, flammability and fracture toughness, as well as the properties required by each material usage or application. A Materials List shall be submitted for approval. | MAY BE COMPLIED | |
| 4.1.6.2 | Corrosion of Metal Parts | Metal parts shall be protected from corrosion by stress relieving, plating, anodizing, chemical coatings, organic finishes, or combinations thereof. Such protection shall be compatible with the contamination constraints and operating/space environmental requirements. Applications involving dissimilar metals shall be evaluated to assure that galvanic corrosion is minimized. | MAY BE COMPLIED | |
| 4.1.6.4 | Castings | Castings shall not be used in the design without the prior consent of the GSFC Materials Assurance Engineer. | COMPLY | Not used |

## Compliance Matrix (16/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.7 | NATURAL ENVIRONMENT | The HDV shall be designed for the natural environments of NASA TMX-73331. | MAY BE COMPLIED | |
| 4.1.7.1 | Radiation Tolerance | HDV radiation tolerance shall be consistent with the orbit of the HST and the required lifetimes and functional reliability for the HDV. | MAY BE COMPLIED | |
| 4.1.7.2 | Component Selection | All electronic components shall be selected and/or shielded to minimize the potential impact of ionizing radiation, including Single Event Upsets (SEU). Components shall be capable of operating through mission life within specification after exposure to levels specified in Section 3.3.3.4 years. This requirement may be fulfilled through device tolerances and/or additional shielding. | MAY BE COMPLIED | |
| 4.1.7.3 | Control Circuitry SEU | Control circuitry shall be designed for less than one SEU in the entire system in 1 year for the HST orbit. For any device that is not immune to latch up or other potentially destructive conditions, protective circuitry shall be added to eliminate the possibility of damage and verified by test or analysis. | MAY BE COMPLIED | |
| 4.1.7.4 | Meteoroid Impact | The HDV shall be designed to minimize the effect of micrometeoroid impingement. External components shall be analyzed using the meteoroid flux model defined in NASA TMX-73331 (section 3.3.3.5). | | Need to analysis PNP |
| 4.1.7.5 | Atomic Oxygen | The design of critical external surfaces of the HDV shall take into consideration the atomic oxygen environment of the HST orbit. Reference TMX 73331.<br>The HDV shall not lose functionality due to AO exposure at HST orbital altitudes nor due to combined exposure with other environmental factors over the disposal lifetime defined in Section 3.2.2.2. | MAY BE COMPLIED | |
| 4.1.8 | SAFETY | The HDV shall conform to the safety requirements of the General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems, and Components (GEV-SE) and the Eastern and Western Range (EWR) 127-1 Range Safety Requirements. | MAY BE COMPLIED | |
| 4.1.8.1 | Hazardous Materials | All components of the HDV exposed to hazardous fluids shall meet the fluid compatibility requirements of Eastern and Western Range (EWR) 127-1 Range Safety Requirements, Chapter 3.10 Hazardous Materials. | MAY BE COMPLIED | |

# Compliance Matrix (17/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.8.1.1 | Test Requirements | Toxicity, reactivity, compatibility, flammability and/or combustibility testing requirements shall be determined by Range Safety on a case-by-case basis. | CASE BY CASE | Case by case |
| 4.1.8.2 | Range Operations Safety | Operations Safety General Design Requirements are defined in the Eastern and Western Range (EWR) 127-1 Range Safety Requirements, Chapter 3.5, Operations Safety Console. | MAY BE COMPLIED | Need to check the requirements. |
| 4.1.8.3 | Electrical System Safety | Electrical systems shall comply with Eastern and Western Range (EWR) 127-1 Range Safety Requirements, Chapter 3.14, Electrical and Electronic Equipment. | MAY BE COMPLIED | Need to check the requirements. |
| 4.1.8.3.1 | Connector Protection | Connectors shall be protected per the Eastern and Western Range (EWR) 127-1 Range Safety Requirements, Chapter 3.14.1.3, EGSE and Flight Hardware Connectors. | MAY BE COMPLIED | Need to check the requirements. |
| 4.1.8.4 | Ionizing Radiation | Ionizing Radiation flight hardware sources shall comply with Eastern and Western Range (EWR) 127-1 Range Safety Requirements, Chapter 3.9, Radioactive (Ionizing Radiation) Sources. | MAY BE COMPLIED | Need to check the requirements. |
| 4.1.8.5 | Pressurized Systems and Structures | HDV flight Hardware pressure systems and pressurized structures shall comply with Eastern and Western Range (EWR) 127-1 Range Safety Requirements, Chapter 3.12, Flight Hardware Pressure Systems and Pressurized Structures. | MAY BE COMPLIED | Need to check the requirements. |
| 4.1.9 | RELIABILITY | The reliability of the HDV design shall ensure that failure modes within the systems shall not propagate to other systems. The HDV shall provide better than 97% reliability, after orbit insertion, for achieving controlled disposal for the HST/HDV combined spacecraft. | NOT COMPLY | |
| 4.1.9.1 | Control Computer Configuration | The HDV C&DH shall have the capability to run in shadow mode with hot backup. | COMPLY | |
| 4.1.9.2 | Safe Hold Computer | The HDV C&DH shall provide an independent safe hold computer in the event of main and backup computer failure. | COMPLY | The third CDP will be added. |

# Compliance Matrix (18/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.9.1 | Fault Tolerance | The HDV design shall be redundant for all mission objectives. The HDV design shall preclude single point failures. | NOT COMPLY | Mechanical components like RMS have single point failures. |
| 4.1.9.1.1 | Disposal Command Protection | The HDV shall provide single fault tolerance to inadvertent activation of critical commands. The HDV shall provide two-fault tolerance to inadvertent activation of pyrotechnic commands. | COMPLY | |
| 4.1.10 | LIFE | At the HST EOM the HDV total life (shelf life + on-orbit life) shall satisfy all of its performance requirements. | NOT COMPLY | |

# Compliance Matrix (19/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.10.1 | Shelf Life | The HDV shall be designed for a three-year lifetime after delivery and before launch without any impact to performance. | NOT COMPLY | |
| 4.1.10.2 | Orbit Insertion Through Docking | The HDV shall provide pursuit, capture and docking capability for the period as defined in Section 3.2.1.6. At any time during this period, the HDV shall be able to continue with the later mission phases with no impact to performance. | NOT COMPLY | |
| 4.1.10.3 | HDV Life | The HDV shall be designed to safely dispose of the HST through disposal life per Section 3.2.2.2. | NOT COMPLY | |
| 4.1.11 | Ground Handling Environment | During all ground and prelaunch operations, the HDV environment will be maintained as specified in Section 3.3.3.7. | MAY BE COMPLIED | |
| 4.1.12 | Storage and Shipping | The HDV shall be designed for storage in environments listed in Section 3.3.3.7 of this document.<br>A suitable storage/shipping container shall be designed to permit the system to be stored and shipped via normal commercial transportation systems.<br>The HDV shall protect for the capability to be air transported and shall conform to the airworthy quasi-static G-factors and conditions described for the C-5A in MIL-STD-1791. HDV equipment and associated component shipping shall conform to Requirements for Packaging, Handling and Transportation for Aeronautical and Space Systems' Equipment and Associated Components, NPR 6000.1E. | MAY BE COMPLIED | |
| 4.1.13 | Identification and Marking | A parts identification and marking system shall be maintained. Each piece part, including flight spares and test items, shall be identified by a serial number. Parts lists shall be maintained at all subassembly and assembly levels to provide traceability.<br>Other markings to facilitate integration and testing shall be incorporated on the flight hardware as required. | MAY BE COMPLIED | |
| 4.1.14 | Documentation | All HDV engineering documentation (including drawings) shall be prepared, approved, released, and changed in accordance with SCM-1020. | COMPLY | New development |

# Compliance Matrix (20/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 4.1.15 | Electrical Ground Support Equipment | As a minimum, EGSE shall consist of a selected combination of unmodified COTS components conforming to NFPA 70, UL, and CSA certifications, and custom fabricated equipment conforming to NASA-STD-5005. Any EGSE directly interfacing the flight equipment on HDV shall have been verified as safe-to-mate prior to the application of power. Connector savers shall be used unless written rationale is provided. | COMPLY | New development |
| 4.1.16 | Technology Readiness Level | All HDV components shall be TRL 6 or greater, as defined in Mankins, John C., Technology Readiness Levels, White Paper, 06 Apr 1995, at proposal submittal. | COMPLY | New development |
| 4.1.17 | Capture Method | The HDV shall capture the HST as specified in section 3.2.1.2.1. | NOT COMPLY | |
| 4.1.18 | Capture Modes | The capture modes shall be as specified in Sections 3.3.1.2. | COMPLY | |
| 4.1.19 | SOFTWARE | Refer to Section 5.0 for HDV software requirements. | N/A | |
| **5.0** | **Flight Software** | | | |
| 5.1 | General Requirements | All flight software (FSW) programs and data for the HDV shall meet the requirements below.<br>The software component of firmware, consisting of computer programs and data loaded into a class of memory not dynamically modifiable by the computer during processing (e.g., Programmable Read-Only Memories (PROMs), Programmable Logic Arrays, Digital Signal Processors, Field Programmable Gate Arrays {FPGAs), etc.) shall be specified, designed, developed, reviewed, configuration controlled, and tested in the same rigorous manner as the flight software. | COMPLY | |
| 5.2 | Flight Software Modularity | The HDV flight software shall be written in modular or object-oriented form so that functional units of code can be modified on-orbit with minimal impact to operations. | COMPLY | |
| 5.2.1 | Software Module Upload | The flight software shall be capable of being uploaded in modules, units, segments, or objects that shall be usable immediately after completion of an upload of the modified modules, units, segments, or objects. Activation of the modified modules, units, segments, or objects shall not require completion of an upload of the entire flight software image. | COMPLY | |
| 5.3 | Flexibility and Ease of Software Modification | The HDV flight software design shall be flexible and table-driven for ease of operation and modification. It shall be capable of scheduling and prioritization of critical tasks to ensure their timely completion. Limits and triggers for anomaly responses shall be readily accessible and changeable by ground command. | COMPLY | |

# Compliance Matrix (21/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 5.3.1 | Tables | All HDV flight software data that are anticipated to be modified or examined by ground operators shall be organized into tables. The flight software shall have knowledge of the location of each table such that ground operators need only reference a table number (for the entire table), or a table number and position within the table (for a partial table). The flight software shall internally maintain table physical memory locations such that the ground can load and dump tables without the knowledge of where the data resides in physical memory, and no ground software or database change shall be required when the data is relocated due to a recompilation of the flight software. The FSW shall also accommodate a 30% table growth over the lifetime of the mission. | -- | Details should be coordinated. |
| 5.3.2 | Command Definition Independent from Processor Physical Memory Locations | The definition of HDV commands within the ground database shall not be dependent on physical memory addresses within the flight software. All commands processed by the flight software (with the exception of Section 5.11) shall be interpreted by the flight software without the use of any uploaded physical address. Existing command definitions in the database shall be unaffected when the flight software is recompiled. | -- | same as above |
| 5.4 | Version Identifiers in Embedded Code | All software and firmware shall be implemented with internal identifiers embedded in the executable program or image indicating the version of the currently installed software/firmware to ground operators. | -- | same as above |
| 5.5 | Flight Processor Resource Sizing | All multifunction flight software systems shall meet the resource utilization requirements identified in section 5.5.1. | -- | same as above |
| 5.5.1 | Multifunction Flight Processor Resource Sizing | During development, flight processors providing computing resources for HDV subsystems shall be sized for worst case utilization not to exceed the capacity shown below (measured as a percentage of total available resource capacity):<br>Multifunction Flight Processor Resource Utilization Limits<br>Resource/Phase S/W PDR S/W CDR S/W AR<br>Memory 40% 50% 60%<br>CPU 30% 40% 50%<br>I/O Bandwidth 30% 40% 50%<br>Bus Utilization 30% 40% 50% | -- | same as above |
| 5.5.1.1 | Resource Utilization Monitors | The flight software for multifunction software systems shall provide the capability to monitor the resource utilization by software subsystems or critical functions. The resource utilization monitors shall be available for downlink in telemetry. | -- | same as above |
| 5.6 | Responsiveness to Ground Originated Changes | The HDV flight software design shall accommodate processing of ground commands, on-orbit revisions to software and telemetry formats, computer self checks, redundancy management, and mode changes. | COMPLY | |
| 5.7 | Software Event Logging in Telemetry | The HDV flight software shall include time-tagged event logging in telemetry. The event messages shall capture anomalous events, redundancy management switching of components, and important system performance events. | NOT COMPLY | |

# Compliance Matrix (22/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 5.7.1 | Event Message Format | All flight software components shall utilize a common format for event messages. | -- | |
| 5.7.2 | Event Message Identification | Each event message shall have the means to identify the source processor, source software task or function, severity level, type of event (such as hardware, software, informational), a message number, and an optional text string that relates the cause of the event. | -- | |
| 5.7.3 | Event Message Queue | The flight software shall buffer a minimum of 300 event messages while the event messages are queued for telemetering to the ground. | -- | |
| 5.8 | Initialization | The flight software shall provide for separate Cold Restart and Warm Restart initialization processing. The contractor shall derive the Cold Restart and Warm Restart initialization functional, performance, and design requirements to satisfy all HDV requirements. | N/A | CDP and GCC are designed in the nonstop operation concept. |
| 5.8.1 | Cold Restart Initialization | The flight software shall execute the Cold Restart initialization processing when starting execution from a hardware reset. The Cold Restart initialization shall execute from non-volatile memory, shall reset the command counter, and shall restore default telemetry contents. | -- | |
| 5.8.1.1 | | The flight software shall provide a command that will affect a cold restart of the flight software. | -- | |
| 5.8.2 | Warm Restart Initialization | The flight software shall execute the Warm Restart initialization processing when restarting the flight software from software command. The Warm Restart Initialization shall preserve command processing statistics, and shall preserve memory tables and command sequences that were previously uploaded. | -- | |
| 5.8.2.1 | | The flight software shall provide a command that will affect a warm restart of the flight software. | -- | |
| 5.8.2.2 | | The flight software shall increment a Warm Restart counter by one (1) each time the Warm Restart software functionality is executed. | -- | |
| 5.8.2.3 | | The flight software shall report the Warm Restart counter in routine telemetry. | -- | |
| 5.8.2.4 | | The flight software shall provide a command to reset the Warm Restart counter to zero. | -- | |
| 5.8.3 | Avoid Warm Restart Loops | When the Warm Restart count equals or exceeds a commandable parameter, the flight software shall affect a Cold Restart in lieu of the Warm Restart. | -- | |

# Compliance Matrix (23/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 5.8.4 | Failsafe Recovery Mode | The flight software shall provide a failsafe recovery mode that depends on a minimal hardware configuration with all interrupts disabled and is capable of accepting and processing a minimal command subset that is sufficient to load memory and begin execution at a specified memory address. | -- | |
| 5.9 | On Board Autonomy | The HDV shall have the ability to autonomously perform reconfiguration of redundant components as required to enter into a safe mode. | COMPLY | |
| 5.9.1 | Autonomous Reconfiguration Limit | Autonomous reconfigurations shall not be required for normal operations of the HDV or its components. | COMPLY | |
| 5.9.2 | Ground Override of Autonomous Anomaly Responses | All flight software autonomous functions, automatic safing, or switchover capabilities shall be capable of being separately disabled, enabled, executed, or over-ridden, or aborted by ground command. | COMPLY | |
| 5.9.3 | Reconfiguration Notification | All autonomous equipment reconfigurations initiated by the flight software shall be reported in normal telemetry, and shall generate a critical event message. | COMPLY | |
| 5.9.4 | Component Status Determination | The flight software shall interrogate and determine the status of HDV components. | COMPLY | |
| 5.9.5 | Retain Component Status | The flight software shall retain knowledge of the status of redundant components following processor restart, processor failover, RAM memory loss, or bus under voltage so that the HDV avoids switching to previously failed components. | N/A | CDP and GCC are designed in the nonstop operation concept. |
| 5.10 | Failure Detection and Correction (FDC) | The flight software shall monitor component, subsystem, and housekeeping data, and shall have the ability to safely configure the HDV in the event of an anomaly. | COMPLY | |
| 5.10.1 | Flight Software Monitors | The flight software shall provide a table driven means for verifying proper execution of critical software tasks or functions, and shall perform a corrective action via stored command sequence(s) in the event that one or more of the critical tasks fails to meet performance requirements. | MAY BE COMPLIED | |
| 5.10.2 | Health and Safety Monitor Table | The flight software shall provide a table driven mechanism for defining anomalous conditions and the corrective action(s) to be performed in response for each condition. | -- | Table concepts should be coordinated. |
| 5.10.2.1 | Health and Safety Monitor Table Entries | The anomalous conditions defined in the Health and Safety Monitor table shall include software generated event messages, flight microprocessor component status data, and all subsystem, software, and housekeeping data. | -- | same as above |
| 5.10.2.2 | Ground Control of Health and Safety Monitor Table | The Health and Safety Monitor table as a whole, and single entries within the table, shall be enabled, disabled, loaded and dumped by ground command. | -- | same as above |

# Compliance Matrix (24/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 5.10.3 | Watchdog Timer | The flight software shall update the watchdog timer at a (TBD) rate when all critical software functions are executing nominally. | COMPLY | |
| 5.10.4 | Memory Tests | The flight software shall provide a mechanism to verify the contents of all memory areas. | COMPLY | All area memory dump |
| 5.11 | Memory Location Dump Capability | The flight software, and associated on-board computer hardware, shall provide the capability to dump any location of on-board memory to the ground upon command by referencing its physical memory address. | COMPLY | |
| 5.11.1 | Memory Dumps During Normal Operations | The flight software memory dump capability shall not disturb normal operations or HDV data processing. | COMPLY | |
| 5.12 | Memory Dwell | The flight software shall provide a mechanism to telemeter the contents of selected addresses in memory to support debugging efforts and provide additional telemetry points which may have been unanticipated at development time. | COMPLY | |
| 5.12.1 | Dwell Tables | The memory dwell function shall have the ability to sample selected memory addresses at rates exceeding the rate at which the dwell data is reported in the telemetry stream. | -- | Detail concepts should be coordinated. |
| 5.12.2 | Multiple Dwell Tables & Rates | The memory dwell function shall read memory values whose addresses are stored in TBS dwell tables of TBS addresses each. The data specified in each table shall be sampled at TBS-Hz. | -- | |
| 5.12.3 | Dwell Table Control | Each of the dwell tables, and each entry within each table, shall be capable of being enabled, disabled, loaded, or dumped via ground command. | -- | |
| 5.13 | Stored Commands | The HDV flight software shall provide two types of stored commanding: stored absolute-time command sequences, and stored relative-time command sequences. | NOT COMPLY | Absolute only |
| 5.13.1 | Absolute-Time and Relative-Time Stored Commands | All requirements in section 5.13.1 apply to both types of stored command sequences. | -- | |
| 5.13.1.1 | Stored Sequence Modifications | The absolute-time and relative-time stored command sequences shall be modifiable by ground command including the addition and deletion of separate command sequences. | -- | |
| 5.13.1.2 | Command Sequence Table Dumps | The absolute-time and relative-time stored command sequence capability shall be designed so that each stored command sequence table can be dumped to the ground by a single, simple command and not by an elaborate memory dump procedure. | -- | |

# Compliance Matrix (25/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 5.13.1.3 | Sequence Identification | Each absolute-time and relative-time stored command sequence shall have a unique identifying name or number. | -- | |
| 5.13.1.4 | Sequence Thread Identification | The HDV shall use the unique command sequence identifiers to report the status of each actively executing command sequence in telemetry. | -- | |
| 5.13.1.5 | Stored Sequence Control | Individual absolute-time and relative-time command sequences shall be enabled, disabled, paused, or cancelled by ground command. | -- | |
| 5.13.1.6 | Stored Command Sequence Timing Accuracy | The resolution of the least significant bit of the specified time shall be TBD*. The flight software shall send stored commands within TBD* seconds of the requested time.<br>* To be determined at contract award based upon successful proposal. | -- | |
| 5.13.2 | Absolute-time Stored Command Sequences | The HDV shall provide the capability to store multiple sequences of absolute-time time-tagged commands, and to execute those commands at the absolute time identified in the time-tag associated with each command in the sequence. | -- | |
| 5.13.2.1 | Concurrent Absolute-time Command Sequence Execution | The HDV shall have the ability to execute TBS (multiple) absolute-time stored command sequences concurrently. | -- | |
| 5.13.2.2 | Relative-time Sequence Activation | Absolute-time stored command sequences shall be capable of invoking relative-time stored command sequences. | -- | |
| 5.13.3 | Relative-time Stored Command Sequences | The HDV shall provide the capability to store multiple sequences of relative-time time-tagged commands, and to execute those commands at the time identified in the time-tag associated with each command in the sequence. | -- | |
| 5.13.3.1 | Concurrent Relative-time Command Sequence Execution | The HDV shall have the ability to execute TBS (multiple) relative-time stored command sequences concurrently. | -- | |
| 5.13.3.2 | Relative-time Command Time-Tags | Each command of a relative-time stored command sequence shall have a time-tag that specifies a variable delta time interval relative to the time that the previous command in the sequence was executed. A relative-time of zero for the first command of a relative-time command sequence shall indicate that it is to be executed immediately upon sequence activation. | -- | |

## Compliance Matrix (26/26)

| HDV Requirements (NNG0461779R Attachment B) | | | Compliance | Note |
|---|---|---|---|---|
| 5.14 | Software Development & Validation Facility (SDVF) | The fidelity of the HDV SDVF and its copy shall be such that all HDV flight software requirements may be validated. Hardware and simulation software shall provide all inputs and responses for validation of interface requirements and timing. All HDV subsystem functionality shall be modeled even if not actively controlled by flight software because of the requirements of 5.14.3 and 5.14.4 below. A Logic Analyzer and/or bus monitor shall be included for detailed FSW probing. | -- | |
| 5.14.1 | SDVF Flight Segment Simulation Performance | This test bed shall provide accurate simulation of software task execution, input/output functions, timing, dumps, and other engineering data. The test bed shall provide an accurate space environment and generate high fidelity engineering data for validation of the technical and operational requirements that are implemented by flight software. | -- | |
| 5.14.2 | SDVF Ground Segment Performance | Automated test procedures/scripts shall interact with the Flight Segment simulator to create a closed loop dynamic simulation system. Spacecraft or instrument anomalies shall be injected, and the performance of the flight software observed. The facility shall be capable of post-processing the engineering and science data, including multiple point plotting of flight processor memory, telemetry, and software simulation data. | -- | |
| 5.14.3 | Deliverable Spacecraft Simulator | The copy of the SDVF, delivered to the government, shall be used for Project V&V and for training of the Flight Operations Team personnel and validation of the HDV flight operations procedures. The fidelity of the software and hardware models shall be sufficiently high, and the performance shall match the performance of the HDV software and hardware, such that both nominal and anomalous HDV conditions may be created and observed. The Flight Operations Team commanding via the ground segment shall produce a flight-like response from the Simulator. | -- | |
| 5.14.4 | Similarities of Two Simulator Facilities | The Software Development & Validation Facility and the copy delivered to the government shall be based on a single set of operational and performance requirements that encompass the multiple uses of the simulators. The hardware elements shall be interchangeable to facilitate rapid response to equipment failure via component swapping. | -- | |

## Appendix-4 Abbreviations

| | |
|---|---|
| AI | Approach Initiation |
| C&DH | Command and Data Handling |
| ETS-VII | Engineering Test Satellite VII(7) |
| FOV | Field of View |
| FRS | Far-range Rendezvous Sensor |
| GPF | Grapple Fixture |
| GPS | Global Positioning System |
| GN&C | Guidance, Navigation and Control |
| HDV | HST De-orbit Vehicle |
| HRVDM | HST Robotic Vehicle De-orbit Module |
| HST | Hubble Space Telescope |
| HTV | H-II Transfer Vehicle |
| ISS | International Space Station |
| JAXA | Japan Aerospace Exploration Agency |
| JEM | Japanese Experiment Module of the International Space Station |
| JEMRMS | Japanese Experiment Module Remote Manipulator System |
| MFD | Manipulator Flight Demonstration |
| NASA | National Aeronautics and Space Agency |
| NASDA | National Space Development Agency of Japan |
| NRS | Near-range Rendezvous Sensor |
| ORU | Orbital Replacement Unit |
| RCS | Reaction Control System |
| RFP | Request for Proposal |
| RMS | Remote Manipulator System |
| TBD | To be defined |
| TBR | to be revised |
| TDRS | Tracking and Data Relay Satellite |

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