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Operational concept evolution from HTV3 to HTV6 and future improvement up to HTV9

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Developed in Japan, the H-II Transfer Vehicle (HTV) "KOUNOTORI" is an unmanned cargo transfer spacecraft that has delivered a great deal of internal and external cargo to the International Space Station (ISS). Starting with its technical demonstration flight (HTV-1) launched in 2009, the subsequent HTV-2 to HTV-6 missions were all successfully completed on almost a yearly basis. As these HTV missions contribute to a stable resupply to the ISS, JAXA and NASA have learned many lessons and sometimes needed a change in operational concept due to a new configuration or constraints for the ISS and HTV. This paper introduces the evolution of operational concept in terms of HTV Guidance, Navigation and Control (GNC) as well as related ISS subsystems such as the Motion Control System.

1. Introduction

Developed and built in Japan, the H-II Transfer Vehicle (HTV) also known as "KOUNOTORI (meaning “white stork” in Japanese) is launched from the Tanegashima Space Center in Japan and controlled from the HTV Control Center in Tsukuba. After several days of rendezvous operation, the HTV is captured by the Space Station Remote Manipulator System (SSRMS) and then berthed to the ISS as shown in Fig. 1. The HTV carries up to 6,000 kg of supplies as cargo to the ISS and disposes of trash from the ISS via destructive reentry. Japan, the U.S., and Russia currently operate cargo transfers to the ISS. Among the supply vehicles, the HTV serves as the backbone of ISS operations with its world-leading largest supply capacity. HTV carries cargo with up to 6,000kg of supplies to the ISS and disposes of trash from the ISS via destructive reentry. Given its consistent on-time arrivals ever since the launch of the first technology demonstration mission, the HTV is now widely acknowledged as being a safe and reliable vehicle, for which the world has high expectations regarding its operations [1]. Table 1 summarizes the HTV mission heritage (with all dates based on Japan Standard Time). The current HTV series will be continued up to HTV-9, which is planned in 2020.

Table 1. Summary of HTV mission heritage [1]

HTV mission	Launch date	Capture date	Release date	Reentry date	Duration	Amount of cargo (kg)
HTV-1	2009/9/11	2009/9/18	2009/10/31	2009/11/2	53 days	4500
HTV-2	2011/1/22	2011/1/27	2011/3/29	2011/3/30	67 days	5300
HTV-3	2012/7/21	2012/7/27	2012/9/13	2012/9/14	56 days	4600
HTV-4	2013/8/4	2013/8/9	2013/9/5	2013/9/7	34 days	5400
HTV-5	2015/8/19	2015/8/24	2015/9/29	2015/9/30	42 days	5500
HTV-6	2016/12/9	2016/12/13	2017/1/28	2017/2/6	60 days	5500

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Fig. 1 HTV-5 berthed to the ISS in 2015(Image Credit: NASA)

2. RVS acquisition logic improvement

2.1 Overview of the HTV GNC system

The main objective of the HTV GNC system is to maintain and control the attitude of the HTV after its separation from H-IIB rocket, guide it safely to the proximity of the ISS, and then eventually to the capture point. This system also controls de-orbit and reentry sequences after departure from the ISS. The central processing unit of the GNC system is the Guidance and Control Computer (GCC) loaded with rendezvous flight software (RVFS). It collects navigation data from various sensors, determines time, position, velocity, attitude and attitude rate, and maintains proper attitude and trajectory by driving the thruster valves. The Abort Control Unit (ACU) is the processing unit that provides mission abort and safety capability in case of GCC failure [2].

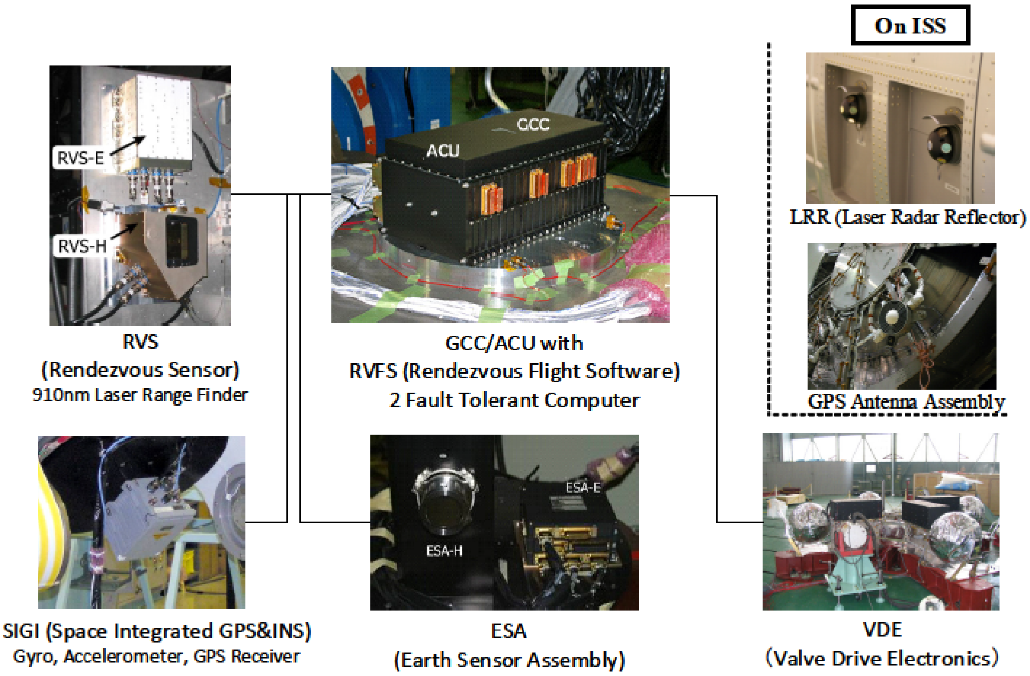


Fig. 2. Overview of HTV GNC components

For the attitude and attitude rate determination, the Earth Sensor Assembly (ESA) provides the roll and pitch angles with respect to the center of the Earth, while the Space Integrated GPS and Inertia Navigation System (SIGI), which is a hybrid sensor consisting of gyros, accelerometers and a GPS receiver, provides the 3-axis attitude rate. For the time, position and velocity determination, SIGI provides GPS standalone navigation solutions, pseudo ranges, pseudo-range rates, and receiver status, as well as 3-axis acceleration measurements. During the final phase of approach to the ISS when the relative range to the ISS is less than about 500 m, better navigation accuracy is required to meet the ISS safety requirements for capture; therefore, the HTV uses the Rendezvous Sensor (RVS) to determine the relative position and velocity to the ISS. The RVS provides laser ranging and line-of-sight (LOS) angle measurements against the Laser Radar Reflector (LRR), which is a retro-reflector installed on the nadir side of the JEM. Given the navigation data above, the GCC controls the HTV attitude and trajectory by driving the Valve Drive Electronics (VDE), which in turn control the thrust generated by the propulsion module [2].

2.2 Overview of RVS

The RVS is scanning-type LIDER (Light Detection and Ranging) that measures the range and LOS angle to the target reflector. The RVS was developed and manufactured by Jena Optronik GmbH (JOP) in Germany and co-developed by the ESA ATV/JAXA HTV program. The HTV has two RVSs on its zenith surface. It realizes laser-guided navigation at the final approach from the nadir direction of the ISS. The RVS provides range and LOS angle measurements using a two-dimensional mirror scan to target the retro-reflectors on the ISS. By using these retro-reflectors, the RVS can search and track the retro-reflectors within a range of 730 meters and has a maximum 40 degrees x 40 degrees field of view (FOV) in azimuth/elevation. After acquisition of the target, the FOV (scanned area) is shrunk around the target in order to realize frequent scans for tracking operation. Reflector selection is done several times during the R-bar approach. The first attempt known as “initial acquisition” is called AM0 (Acquisition Mode 0) and subsequently AM1 (Acquisition Mode 1) is at the beginning of the R-bar approach (340-700 m range). This is executed by RVFS using LOS angle information and the JEM retro-reflector is selected as the final target from among several retro-reflectors on the ISS. The second attempt is made during tracking mode by RVS firmware. This RVS firmware also selects the target during the subsequent HTV yaw 180-degree maneuver at the 250 m range, and during the transition of tracking mode to single reflector mode at the 55 m range. If lock loss occurs in an off-nominal case, the RVS will automatically transit to ReAM1 (Reacquisition Mode 1) by RVS firmware whose internal logic selects the JEM reflector based on range and LOS angle information. Unless acquisition is confirmed in ReAM1, then a secondary backup measure to transit to ReAM2 (Reacquisition Mode 2) will be conducted via a ground command and RVFS will finally select the JEM reflector based on LOS angle information. Table 2 summarizes the RVS mode patterns and acquisition logic.

Table 2. RVS mode patterns in acquisition logic (for ReAM2, as of HTV-5)

Operation	RVS mode	Who selects the JEM reflector?	Principle for selection	Max. number of reflectors
Initial reflector acquisition	AM0 & AM1	RVFS	LOS angle	8
Reacquisition (Auto)	ReAM1	RVS firmware	Range & LOS angle	8
Reacquisition (Manual backup)	ReAM2	RVFS	LOS angle	4

In 2013, NASA announced the first change of the reflector constellation on the ISS prior to the HTV-5 launch in 2015. This change included the installation of C2V2 P3 and S3 reflectors on the ISS truss, relocation of PMM on which the planar reflector is installed, installation of IDA2 on PMA2 with three retro-reflectors, and mounting a cover on the PMA2 reflector. As of 2018, all reconfigurations are complete as shown in Fig. 3, but there was an intermediate configuration change from HTV-5 to HTV-6. The HTV team needed to follow and assess the retro-reflector configuration at that point before each mission. The installation of IDA2 on PMA2 with two retro-reflectors and the mounting of a cover on the PMA2 reflector were not completed before HTV-5 mission due to a schedule delay, but were finally completed before the HTV-6 mission.

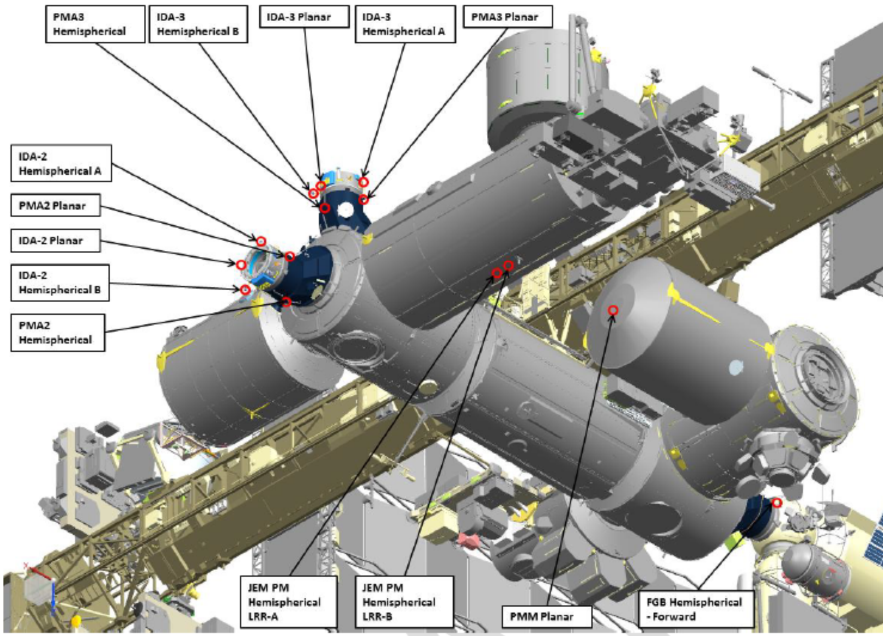


Fig. 3. ISS retro-reflector configuration (2018~present day)

2.3 RVS logic improvement

As a counterpart to this configuration change, JAXA decided to make some updates for HTV-5 in order to improve robustness. RVFS was modified to parameters related to "initial acquisition" on the R-bar approach. A patch on RVS firmware for updating the selection logic of ReAM1 was also loaded just prior to HTV-5's departure. During the HTV-5 departure operation, the RVS-A reacquisition demonstration by ReAM1 to confirm a correct lock on the JEM reflector worked as expected. This RVS firmware patch will be applied on-orbit to the RVS units for HTV-6 and HTV-7, and the RVS units for HTV-8 and HTV-9 will implement the patch in firmware so that the patch will no longer be required.

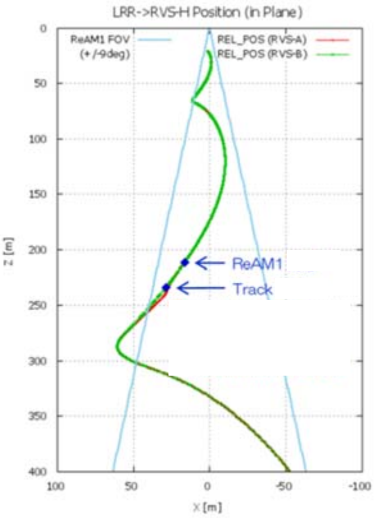
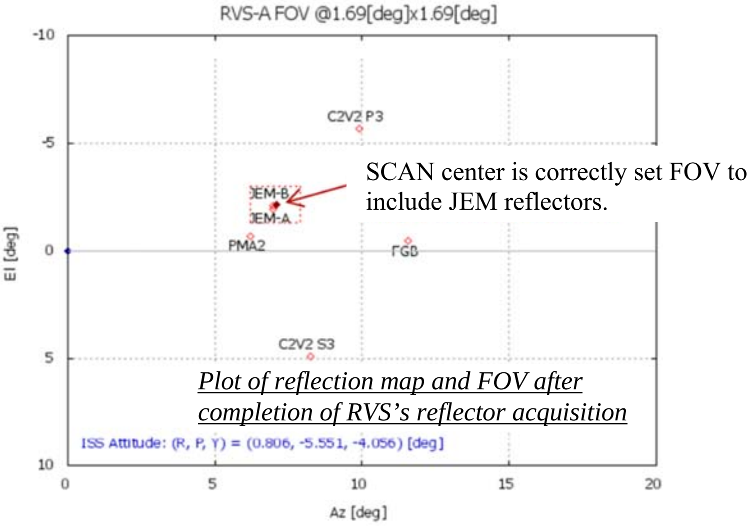


Fig. 4. ReAM1 demonstration results in HTV-5 (X-Z plane, with Hill coordinates)



SCAN center is correctly set FOV to include JEM reflectors.

Plot of reflection map and FOV after completion of RVS's reflector acquisition

Fig. 5. ReAM1 demonstration results in HTV-5 (RVS-A final tracking status)

To be more flexible in considering the uncertainty of new reflector installation prior to the HTV-6 mission, JAXA assumed that six retro-reflectors can be visible during acquisition because the existing ReAM2 covers up to four reflectors as listed in Table 2. The new ReAM2 utilizes a pattern matching logic, which is completely different from the previous version. The pattern matching logic compares the actual measured reflector vectors with the template vectors that are already registered in a reflector database in RVFS. The reflector database is set by a command (included in command parameters), and can be set at the launch site and updated on-orbit to reflect the latest ISS reflectors in a timely manner with flexible update. The criteria for success are also variable (and can be updated by commands). During the HTV-6 departure operation similar to that of HTV-5, the RVS-A reacquisition demonstration in ReAM2 to confirm a correct lock on the JEM reflector worked as expected. The success of the ReAM2 on-orbit demonstration resulted in the HTV flight control team deciding to utilizeg ReAM2 as the standard backup method on HTV-7 and subsequent flights. Thus, the new ReAM2 will be applied to RVFS for HTV-7 and subsequent flights. Consequently, additional patches and reprogramming on orbit are no longer necessary, and simply using and updating ReAM2 as necessary at any time will suffice. Even if the ISS reflector constellation should be changed in the future, JAXA can respond to such change by updating the reflector database (reflector layout and number) in RVFS.

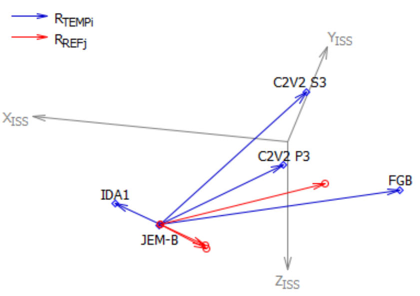


Fig. 6. New pattern matching logic in ReAM2

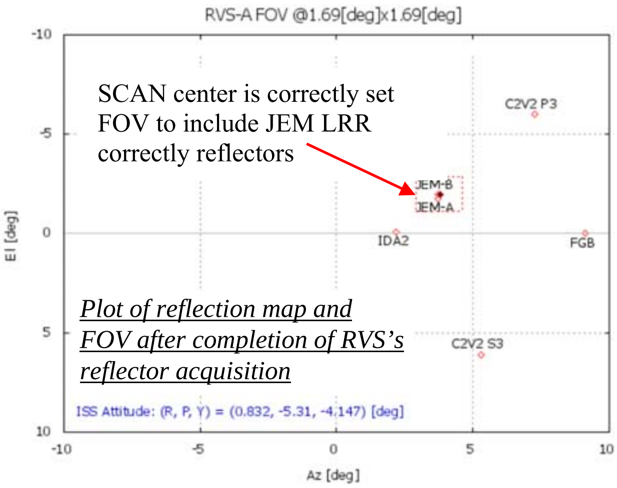


Fig. 7. ReAM2 demonstration results in HTV-6 (RVS-A final tracking status)

For the future vision regarding this new RVS acquisition logic with pattern matching, JAXA is investigating whether to apply this pattern matching logic to AM0 and AM1 (initial acquisition modes 1 and 2) in the subsequent HTV series as it affords much more flexibility for unknown ISS reconfigurations in the future.

3. GPS multipath mitigation

3.1 GPS navigation in HTV rendezvous operation

After the HTV is launched from the Tanegashima Space Center and then inserted into orbit, communications are initiated with the HTV Mission Control Room (MCR) via Tracking and Data Relay Satellites (TDRS). When the distance between the HTV and the ISS decreases enough to receive signals from the Proximity Communication System (PROX) in the JEM, the HTV directly establishes RF communications through what is called a PROX link. During HTV rendezvous operation, GPS is used in one of three ways. In absolute GPS (AGPS) navigation, the GPS data is collected by SIGI to provide current position and velocity measurements for the HTV. This data is only used for HTV standalone navigation and not for rendezvous with the ISS. To obtain a relative position and velocity with respect to the ISS, differential GPS or relative GPS navigation can be used. In differential GPS (DGPS) navigation, a state vector is obtained for both the ISS and HTV from absolute GPS navigation. These two state vectors are then subtracted to provide a relative position and velocity. In relative GPS (RGPS), the raw GPS data is provided from the ISS to the HTV via the PROX link, and a relative vector is computed using complicated calculations of the raw data. Of the three types of GPS use, RGPS provides the most accurate relative position and velocity measurements. The relative GPS navigation uses GPS raw measurement from the JEM GPS as part of the PROX hardware. Figure 8 shows the HTV flight profile with primary navigation.

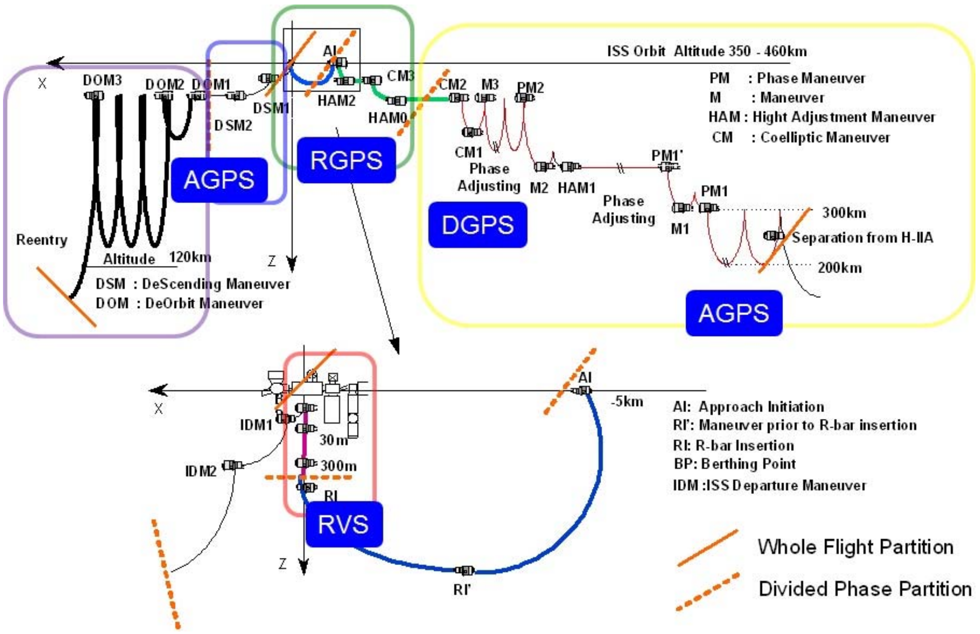


Fig. 8. HTV flight profile with navigation method

3.2 GPS multipath mitigation

The degradation of GPS performance caused by the multipath effect due to the ISS structure, such as its Solar Array configuration, was well known in analysis conducted before the start of the HTV mission. Prior to the HTV-1 flight, pre-launch analysis showed that the multipath effect on the GPS signal would be one source of serious degradation in HTV GPS navigation accuracy. In the HTV-4 mission, a clear degradation in RGPS accuracy was temporarily observed for the first time. As this degradation occurred right after RI maneuver final targeting was completed nominally and was soon recovered, there was no major impact on the following operation. After the post-flight evaluation, however, JAXA concluded that it was driven by the multipath effect on the JEM GPS-A receiver (primary GPS receiver) where the ISS solar panels were likely to have reflected the GPS signals, and thus needed to consider an appropriate ISS Solar Arrays panel configuration and identify necessary constraints to reduce the risk of initiating an Abort or RI point Hold. As shown in Fig. 9, the ISS Solar Array configurations were all different between HTV-2 and HTV-4.

Fig. 9. ISS Solar Array configurations during R-Bar Insertion (left: HTV-2, center: HTV-3, right: HTV-4)

After a long discussion, JAXA and NASA determined a new operation concept for HTV-5 and subsequent flights relative to a reconfiguration of ISS solar arrays (feathering timing and its angle) in considering the HTV maneuver sequence. The ISS solar arrays are maintained in auto track (i.e. rotating to point toward the sun) as long as possible to mitigate the GPS multipath effect, with the ISS initiating solar array feathering after MCF2 (as shown in Fig.10), which is the last maneuver before confirming the completion of R-bar injection, which was originally before the AI point (5 km to the ISS) departure. As a result of investigating the HTV-5 mission data, no degradation of RGPS navigation data was observed throughout the entire HTV-5 approach phase. And the number of multipath occurrences from AI through RI decreased drastically. There were 12 such occurrences at HTV-4 with the ISS feathered solar array, while there was no multipath effect on the ISS auto-tracked solar array. From these lessons learned, JAXA determined that this philosophy will be applied to HTV-6 and subsequent flights.

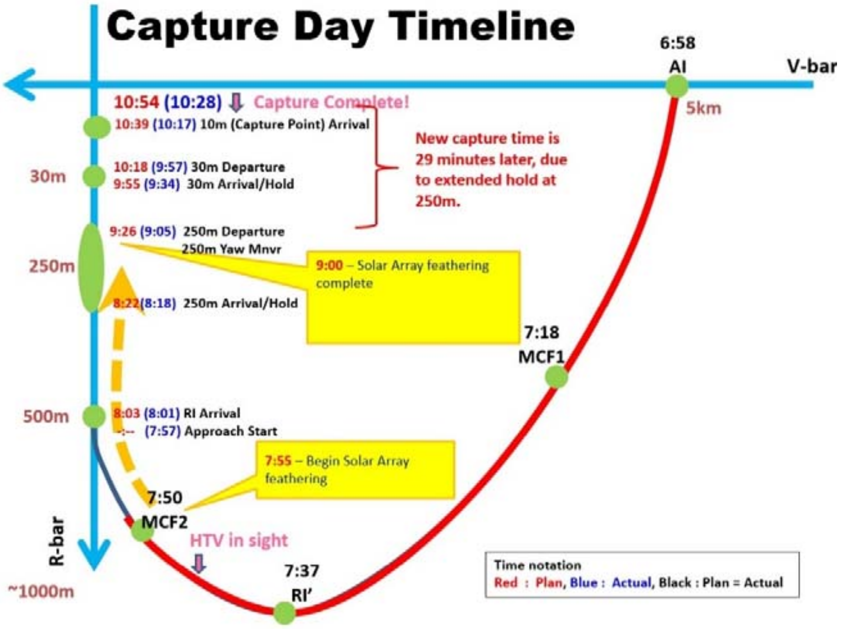


Fig. 10. HTV-5 R-Bar Insertion and Capture timeline plan and actual result

4. Conclusion

RVS acquisition logic was improved to enhance robustness. Both ReAM1 and ReAM2 were updated, and thus will be able to track the target JEM reflector correctly even if other retro-reflectors are reconfigured. Especially for ReAM2, JAXA updated RVFS to use new pattern matching logic. For the future vision, JAXA intends to apply this pattern matching logic to other AM0 and AM1 (initial acquisition modes 1 and 2) in the subsequent HTV series as it affords much more flexibility for unknown ISS reconfigurations in the future.

From the HTV-4 experience, JAXA tried to mitigate the GPS multipath effect as much as possible and successfully resolved the way that the ISS starts solar array feathering (keeping auto track until then) after MCF2. This operation concept will be applied to HTV-7 and subsequent flights.

Though we have not assumed frequent configuration updates of the ISS during HTV development, we actually experienced the addition of reflectors for new visiting vehicles using laser navigation and change requests for the ISS solar array setting, in order to comply with requests for more power generation. However, we learned that such configuration changes are always being made in the ISS mission that requires long-term operation. In order to respond to such frequent configuration changes, we need to have the ability to share the latest update plans with international partners and update the HTV function at the appropriate time.

References

[1] JAXA website: http://iss.jaxa.jp/en/htv/mission
[2] Satoshi, Ueda and Toru Kasai, "HTV Rendezvous Technique And GN&C Design Evaluation Based on 1st Flight On-orbit Operation Result," AIAA2010-7664, AIAA/AAS Astrodynamics Specialist Conference, 2 - 5 August 2010, Toronto, Ontario Canada.