H-II TRANSFER VEHICLE TRAJECTORY PLANNING AND FLIGHT OPERATION RESULTS

Shigeki Hotta [(1)], **Koji Yamanaka** [(2)], **Keiichi Wada** [(3)], **and Issei Kawashima** [(4)]
[(1)] *Japan Aerospace Exploration Agency, Tsukuba-City, Ibaraki-ken, 305-8505, Japan, +81-503362-5510, hotta.shigeki@jaxa.jp*
[(2)] *Japan Aerospace Exploration Agency, Tsukuba-City, Ibaraki-ken, 305-8505, Japan, +81-503362-5707, yamanaka.koji@jaxa.jp*
[(3)] *Japan Aerospace Exploration Agency, Tsukuba-City, Ibaraki-ken, 305-8505, Japan, +81-503362-2765, wada.keiichi@jaxa.jp*
[(4)] *Japan Aerospace Exploration Agency, Tsukuba-City, Ibaraki-ken, 305-8505, Japan, +81-503362-3875, kawashima.issei@jaxa.jp*

Abstract: *The H-II Transfer Vehicle (HTV) is the cargo transportation vehicle to the International Space Station (ISS), which is developed and operated by Japan Aerospace Exploration Agency (JAXA). Three flights of HTV were successfully completed in 2009, 2011 and 2012. Subsequent flights are scheduled once per a year. In this paper, HTV flight planning activities are presented. First, trajectory planning is discussed based on experiences from the accomplished three HTV flights. It discusses the trajectory planning process how to harmonize with the ongoing ISS operation and other mission constraints, to realize safe and on-time flight. Secondary, determination and validation process for mission specific parameters loaded to the flight software is presented. HTV has the flexible attitude and maneuver control capability to allow wide range of cargo mass property, realizing the versatile cargo transportation and disposal service to ISS. Lastly, the real-time operation aspect is presented. As a visiting vehicle to the ISS, HTV operation is jointly conducted by both of HTV/ISS operation teams. It is discussed what activities are conducted by the ground control team to ensure the safe and on-time flight, from the viewpoint of real-time trajectory operation.*

Keywords: *Trajectory planning, Rendezvous, Reentry, Flight operation*

1. Introduction

The H-II Transfer Vehicle (HTV) is the cargo transportation vehicle to the International Space Station (ISS), which is developed and operated by Japan Aerospace Exploration Agency (JAXA). The HTV1, HTV2 and HTV3 were successfully flown in 2009, 2011 and 2012 respectively, and completed the cargo transportation service to ISS as planned. Additional four subsequent flights are scheduled once per a year.

As the results of three successful flights, it was impressed to the international partners joining the ISS mission operation that the HTV provides safe and on-time flight for cargo transportation. Also, the HTV flight operation was well harmonized with the ongoing ISS mission operation, where it is important to match the ISS crew working timeline and ensure the ISS crew safety.

Figure 1 illustrates the overview of HTV flight operation. The HTV is launched by the H-IIB Japanese rocket from Tanegashima Space Center. The HTV is inserted to the orbit of which inclination is the same as the ISS. On-time launch is conducted at the timing when the ISS orbit passes over the launch site. After the separation from the rocket, HTV mission control center at Tsukuba Space Center takes over the mission control. The HTV flies adjusting the phase distance to the ISS for several days, in order to realize on-time arrival. The rendezvous trajectory and maneuvers are planned prior to the launch and the ground operators monitor that the vehicle follows the planned trajectory. The maneuver delta-V and ignition time are automatically calculated by onboard flight software using the latest state vectors of the ISS and the HTV, and each maneuver is conducted with Go command from the ground operator. When the HTV comes into the region of approximate 100km backward from the ISS, the proximity operation is initiated as the joint operation between HTV and ISS teams. Since there is a risk of HTV collision to the ISS during the proximity operation, the ISS safety is prioritized as the most important factor to conduct the rendezvous flight. Therefore, the proximity operation trajectory to approach the ISS is strictly determined ensuring the safety under any contingency scenario, and deviation from the pre-determined approach trajectory is not allowed. Maneuvers are conducted to follow the safety ensuring trajectory. The HTV flies to the point 500m below the ISS, and the final approach along R-bar is conducted to the capture point 10m below the ISS. Finally, the HTV is captured by the robotics arm on the ISS and berthed to the nadir port of the ISS. After completion of cargo unloading and disposal loading, the HTV departs from the ISS. To ensure the safety to the ISS, the HTV departs following the pre-determined departure trajectory to the orbit 5km below the ISS with four maneuvers. Reentry is conducted with three separated maneuvers. Since reentry destruction of the HTV needs to be done within the allowed region on the south pacific ocean, the HTV waits for the appropriate timing to perform the first de-orbit maneuver. The reentry trajectory after completion of the last third de-orbit maneuver is monitored to confirm the safe reentry to the specified region.

The photograph of the HTV3 arrival below the ISS is shown in Fig. 2. The HTV3 is located at approximate 10m below the ISS and waiting for the capture by the robotics arm. The rendezvous flight of the HTV3 was on time as planned and the HTV3 was safely captured by the robotics arm.

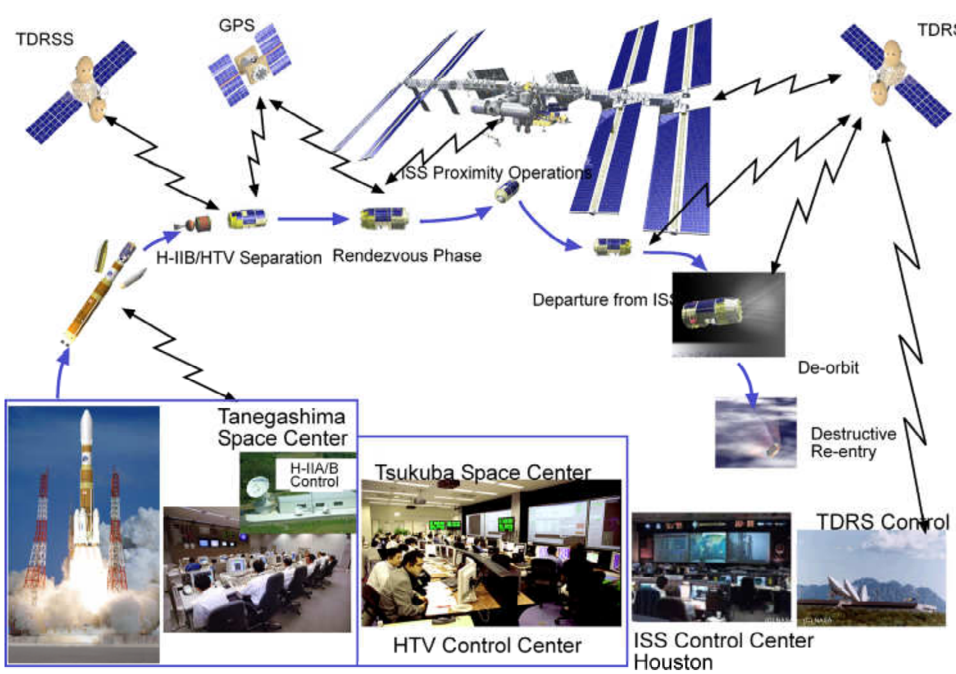

Figure 1. Overview of the HTV flight operation

Figure 2. Photograph of HTV3 arrival below ISS

2. Flight Planning Activities

2.1 Overview of Pre-flight Planning Process

This paper focuses on the following items of pre-flight planning process, which are major activities related to HTV flight operation.

- To determine rendezvous and reentry trajectory
- To determine onboard software parameters specific to each flight
- To prepare operation procedures used for flight operation

As for the rendezvous flight, the pre-flight planning process is started approximately six months prior to the launch and continued until two days before the launch. For the reentry flight, the preliminary flight planning is done before launch, and the final planning process starts one month prior to departure from the ISS and continued until two days before the departure. Since all the conditions (such as ISS trajectory ephemeris, HTV mass property, and so on) used for the pre-flight planning process are not fully fixed yet at the early stage of six months prior to the launch, the pre-flight planning process is repeated and the planning results are matured through the process repetition.

The trajectory planning is conducted seven times for rendezvous and six times for reentry. The process to determine onboard software parameters takes approximate one month to complete the verification. It is conducted twice; the first cycle is conducted at the early stage to confirm that there are any technical issues or not, and the second cycle is conducted approximate two months before the launch, when all the conditions are fixed and the onboard software parameters are valid for the actual flight. The operation procedures are continuously maintained until the flight, and the major updates are done to incorporate the onboard software parameters update. Figure 3 illustrates the pre-flight planning process for rendezvous, and Fig. 4 illustrates that for reentry. The pre-flight planning process is conducted sequentially, since the results of previous process is necessary to conduct the next process. The required inputs for the rendezvous flight planning are as follows.

- ISS ephemeris: ISS mission operation team provides the estimated orbit including duration of the HTV rendezvous
- Arrival date/time at ISS: ISS program and mission operation team request data/time of the HTV arrival based on the situation of the ISS mission operation
- Flight duration: HTV mission operation team determines it considering all the constraints of the ISS, the launch rocket and the HTV
- Launch day: Launch rocket program and HTV program determine allowable launch period
- HTV mass property at launch: HTV system integration team provides the data

Using the above-mentioned inputs, the following tasks are sequentially conducted as the pre-flight planning process for the rendezvous flight.

1) Trajectory planning: Using the inputs of ISS ephemeris, arrival date/time at ISS, flight duration and launch day, the rendezvous trajectory is generated from the launch rocket separation to the ISS arrival. In this process, the launch time is also determined as the timing when the ISS trajectory passes over the launch site.
2) Maneuver delta-V and fuel consumption evaluation: The plan for all the maneuvers is generated, based on the trajectory planning results. Also, fuel consumption profile is evaluated based on the maneuver plan, and it is used for mass property evaluation.
3) HTV mass property profile during flight: Fuel consumption profile is reflected to generate HTV mass property profile during flight. The mass property information includes total mass, moment of inertia and center of gravity of the vehicle.
4) Determination of onboard software parameters: Based on HTV mass property profile during flight, control parameters are determined to realize stable attitude and translational control. The variation of HTV mass property during flight is taken into account, and two sets of control parameters are determined. The first set covers the flight from rocket separation to the end of orbital phase adjustment period (approximately 500km phase distance from the ISS), and the second set covers the flight to the ISS arrival after the transition from the first set of control parameters. Also, guidance parameters are determined based on the trajectory planning results.
5) Validation test for onboard software parameters: Validation tests for the determined onboard software parameters are conducted using the flight equivalent software simulator. The validation tests simulate the same flight profile as the planned trajectory. The variation of mass property and the off-nominal scenario are incorporated to the test conditions to confirm the robustness of the onboard software parameters.
6) Operation procedures generation: All the results of planning process are incorporated to operation procedures. The execution timing and duration of each operation procedure are considered to be consistent with the planned trajectory.

As for the reentry planning process, the inputs are different from the rendezvous planning process, however the same tasks are applied to the planning process as the rendezvous flight. As the first planning process, the reentry trajectory is generated. Based on the reentry trajectory, the maneuver plan, onboard software parameters and operation procedures are generated. The inputs for reentry planning are different from those of rendezvous planning. Each input item is explained as below.

- ISS ephemeris: ISS mission operation team provides the ISS orbit for the HTV release. It is used for reentry trajectory planning.
- Departure date/time from ISS: ISS program and mission operation team request data/time of the HTV departure
- Reentry location on the south pacific ocean: Reentry location needs to be within the safe region allowed by Japanese government and related countries
- HTV mass property at ISS departure: ISS mission operation team (responsible to manage disposal cargo) and HTV system integration team provide the data

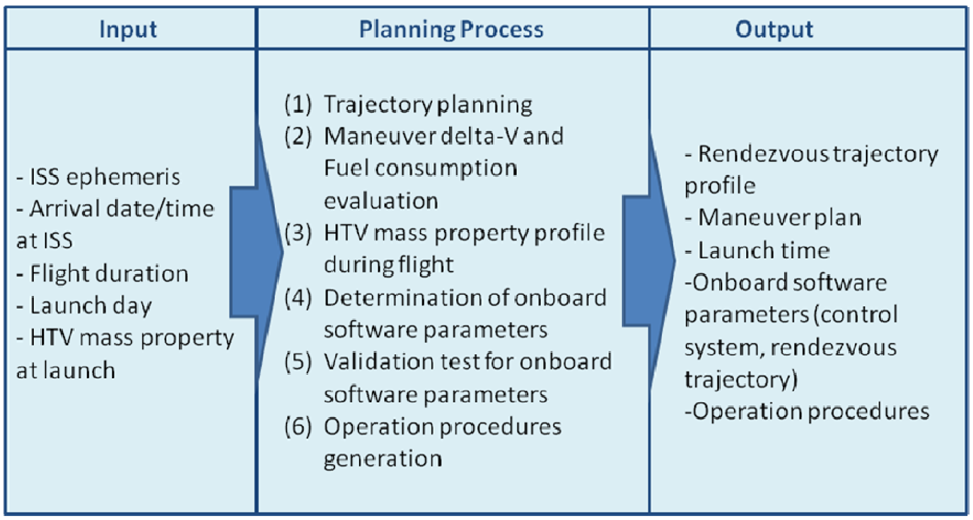

Figure 3. Pre-flight Planning Process for Rendezvous

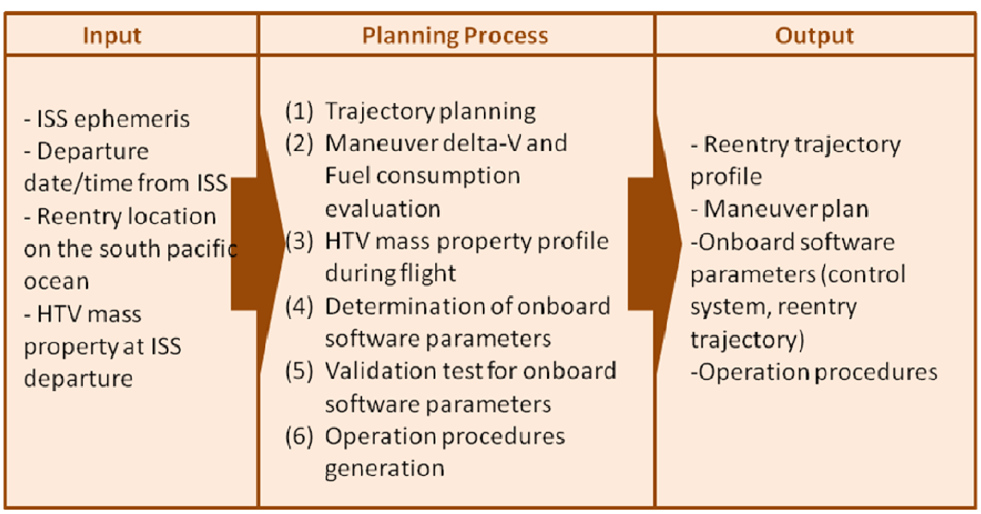

Figure 4. Pre-flight Planning Process for Reentry

2.2 Rendezvous Trajectory Planning

Rendezvous trajectory planning is categorized to two phases.

1) Far-field rendezvous phase (launch ~ approx. 200km range from ISS)

2) Proximity rendezvous phase (approx. 200km range ~ berthing on ISS)

The proximity rendezvous trajectory is fixed and cannot be varied for each flight due to the reasons for safe trajectory assurance to ISS and consistency of integrated proximity operation involving ISS crew, Houston and Tsukuba operation teams. Therefore, the far-field rendezvous trajectory is adjusted and optimized for each flight to satisfy trajectory planning constraints.

As explained in the previous section, the rendezvous trajectory is generated to satisfy the following constraints; ISS orbit, Arrival date/time at ISS, Flight duration, and Launch day. Since on-time arrival at ISS is the highest priority to harmonize with ongoing ISS crew activities, the rendezvous trajectory needs to be managed under the condition of the other constraints. The basic method to realize on-time arrival is to determine the appropriate phase adjusting orbit. The phase distance of the HTV relative to the ISS can be decreased by the difference of orbital rate. The initial phase distance is determined from the HTV launch day/time and the ISS orbit at the launch time. The initial phase distance is managed to be zero at the time of ISS arrival. There are two periods for the phase distance management for the HTV rendezvous trajectory. The majority of phase distance is reduced during the first phase management period. Figure 5 shows the rendezvous trajectory plan for HTV3. It indicates the relative position of the HTV with respect to the ISS (Hill’s coordinates). The most phase distance is reduced while the HTV is flying 120km-160km below the ISS. During the second period of phase distance management, the HTV is flying 40km below the ISS, and phase distance is more precisely managed to achieve on-time flight.

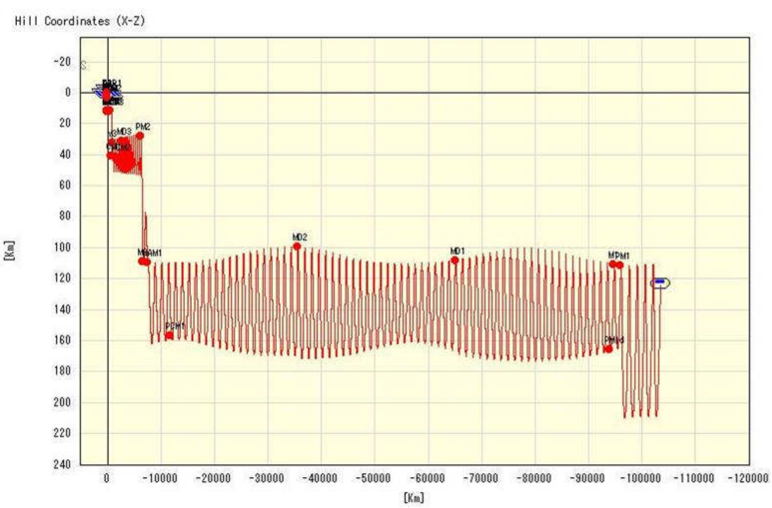

Figure 5. Rendezvous Trajectory Plan for HTV3

Discussing the actual rendezvous trajectory planning, the input conditions used for planning can be frequently changed. For example, the ISS orbit may change due to the debris avoidance maneuver, the arrival date/time on ISS may change due to re-schedule of the ISS crew activities, and launch day may slip due to weather condition on the launch site. The rendezvous trajectory planning is required to handle these changes. Through the experiences of rendezvous trajectory planning to handle such a significant condition change for the HTV1, HTV2 and HTV3, the capability of planning is improved. Figure 6 and Fig. 7 are the actual outputs of rendezvous trajectory planning for the HTV2. For the HTV2 case, the launch was slipped by two days due to weather condition. Since it was decided to keep the same arrival day/time on the ISS even in the case of launch slip, the rendezvous trajectory was re-planned to realize the same arrival day/time. As comparing between Fig. 6 and Fig. 7, the large difference of altitude is shown during the phase distance management period. The phase rate between the ISS and the HTV was decreased by increasing the altitude. For the case of rendezvous trajectory before launch slip (Fig. 6), the HTV passes below the ISS twice and more than 720deg phase angle is managed with large difference of altitude between the ISS and the HTV. On the other hand, for the case of rendezvous trajectory after launch slip (Fig. 7), the managed phase angle is less than 360deg with small difference of altitude between the ISS and the HTV, because the flight duration is shortened from 7days to 5days.

Based on the accumulated knowledge through the HTV1, HTV2, and HTV3 mission operation, the capability is obtained to conduct the rendezvous trajectory planning in a timely and flexible manner.

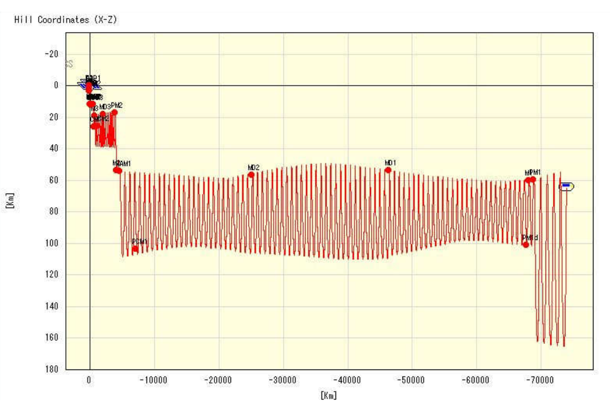

Figure 6. HTV2 Rendezvous Trajectory Plan, Launch on 1/22/2011, Capture on 1/27/2011 (Before launch slip)

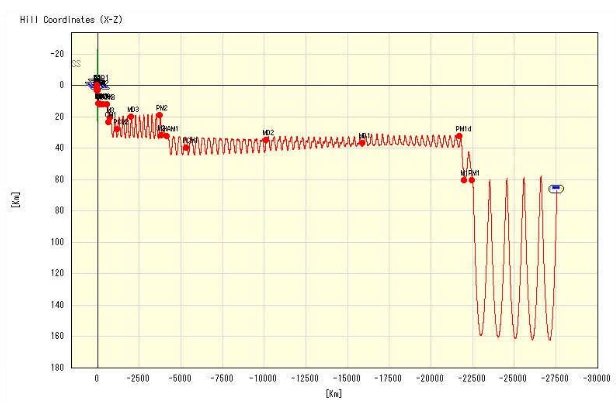

Figure 7. HTV2 Rendezvous Trajectory Plan, Launch on 1/24/2011, Capture on 1/27/2011 (Two days launch slip)

Figure 8 and Fig. 9 illustrate the proximity rendezvous trajectory. The trajectory is defined in Hill's coordinates, and fixed for all mission flights. In order to ensure the ISS safety from the collision risk, the proximity rendezvous trajectory is required to meet the safety requirements. In case of emergency on the HTV, rendezvous flight needs to be terminated and abort is conducted. The trajectory after abort shall be safe to the ISS. Specifically, the drift trajectory (i.e. without control) after abort shall not violate the specified region around the ISS (4km x 2km ellipsoid) during 24 hours. The proximity rendezvous trajectory is determined to meet the safety requirement. The number, interval and target location of maneuvers are fixed, and each maneuver is conducted to follow the specified proximity rendezvous trajectory.

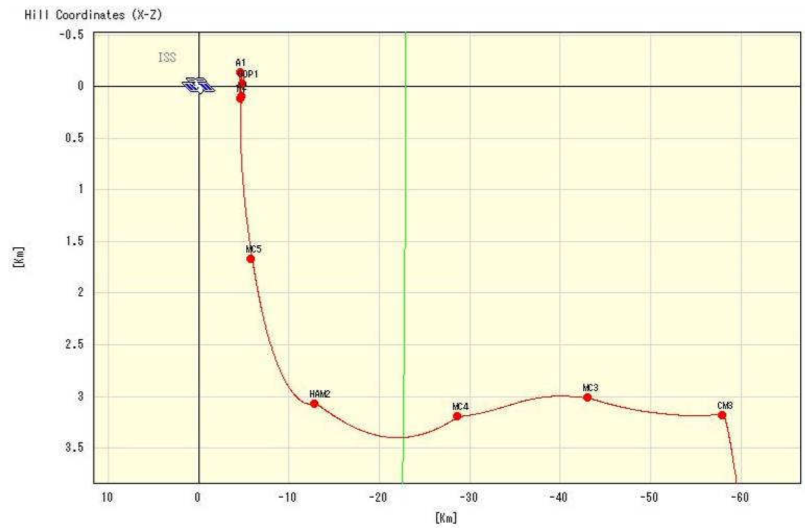

Figure 8. Proximity rendezvous trajectory (up to 5km range from ISS)

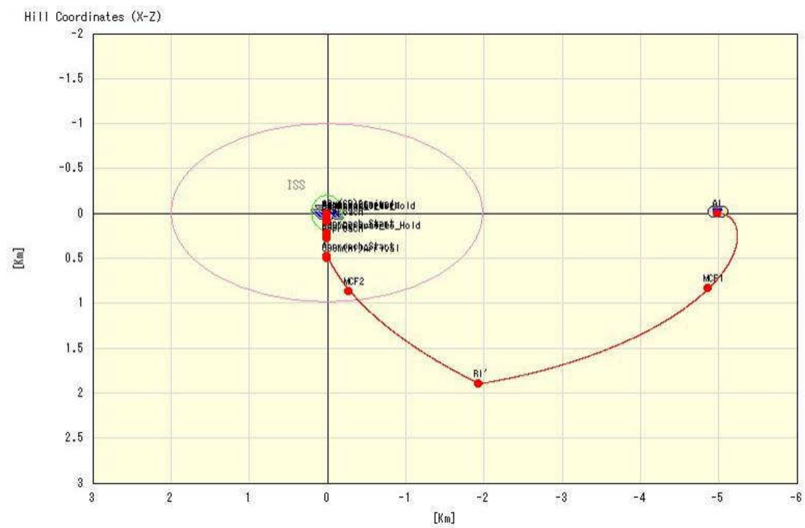

Figure 9. Proximity rendezvous trajectory (less than 5km range)

2.3 Reentry Trajectory Planning

To ensure safe reentry to the earth, the restricted area is allowed on the south pacific ocean for the splashdown of destruct vehicle. Reentry trajectory is planned not to violate the restricted area. Figure 10 shows the overview of reentry trajectory and the restricted area for splashdown of destruct vehicle. The earth trace is generated using the telemetry data from the HTV, and the trace disappears before the splashdown area due to break of communication link. However, it is confirmed that the destruct vehicle stays within the restricted area by analysis of destructive reentry.

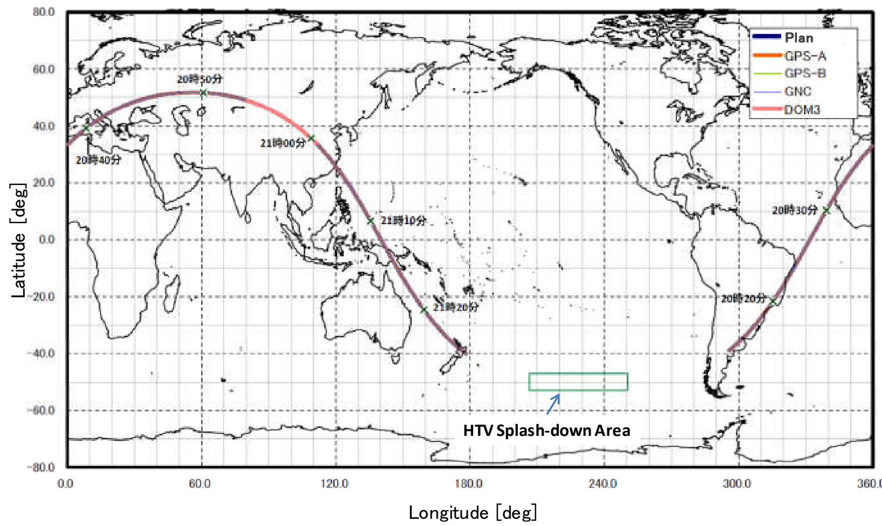

Figure 10. Overview of reentry trajectory and restricted area for splashdown of destruct vehicle

Reentry trajectory is generated from the inputs of ISS ephemeris, departure date/time from ISS and the reentry location on the south pacific ocean. Since the earth trace of the HTV after departure from the ISS depends on ISS ephemeris and departure date/time, the HTV waits for the appropriate timing for the earth trace of the HTV to cross over the reentry location on the south pacific ocean, staying on the orbit 5km below the ISS. Therefore, the reentry time is varied up to 2days after departure from the ISS. The reentry to the earth is conducted by three de-orbit maneuvers due to restriction of burn duration for each maneuver. The altitude of perigee is equally decreased to the reentry altitude with three de-orbit maneuvers. Figure 11 illustrates the reentry trajectory plan for the HTV3. For this case, the reentry is performed after one and a half days from the ISS departure.

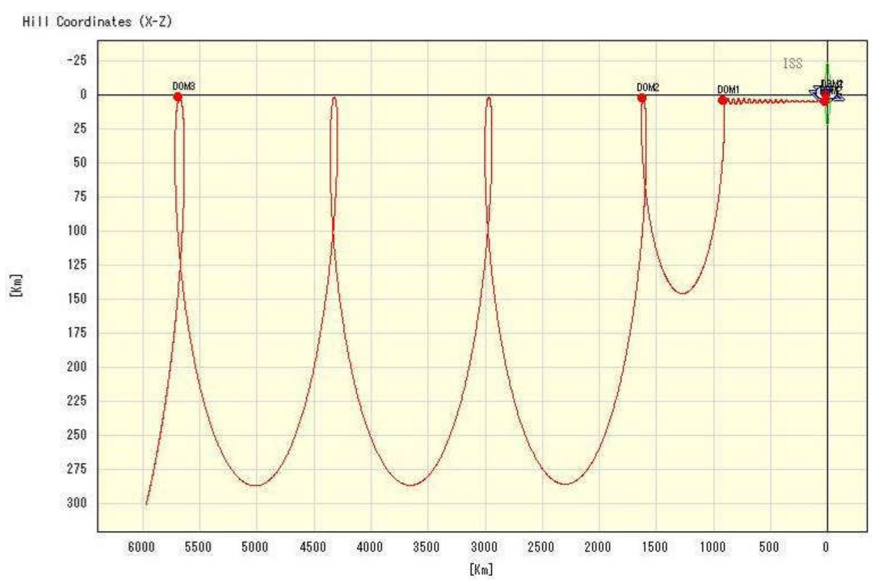

Figure 11. Reentry Trajectory Plan for HTV3

2.4 Determination of Mission Specific Parameters

One of major flight planning activities is determination of mission specific parameters and validation test. For every flight, the HTV mass property varies due to difference of delivery and disposal cargo, and rendezvous and reentry trajectory is different depending on the ISS orbit, arrival/departure day and time, and launch day. In order to provide flexible service of cargo delivery/disposal and to maximize flight opportunities, the HTV flight system is developed to accommodate large differences. Safe and reliable flight is realized by loading appropriate parameters into the onboard software.

The mission specific parameters are summarized in Table 1. There are two categories for mission parameters; one is related to trajectory and the other is related to control. Also, there are three sets for the trajectory parameters; rendezvous trajectory, proximity operation trajectory and departure/reentry trajectory.

Table 1. List of Mission Specific Parameters

Mission parameters	Detailed items
Rendezvous Trajectory parameters	• Arrival time to proximity operation interface point • Arrival location to proximity operation interface point • Interval revolutions between maneuvers (note) Maneuver delta-V and ignition time is automatically calculated.
Proximity Operation Trajectory parameters	• Pre-defined relative location to ISS for each maneuver • Interval revolutions between maneuvers • Arrival time at Approach Initiation point (5km aft ISS) • Departure time from Approach Initiation point (5km aft ISS) (note) Maneuver delta-V and ignition time is automatically calculated.
Departure and Reentry Trajectory parameters	• Departure maneuvers delta-V and ignition time relative to release • Reentry orbit angle at reentry interface point • De-orbit maneuver sequence initialization time (note) Reentry interface point is defined as altitude and latitude. Reentry maneuver delta-V and ignition time is automatically calculated.
Control parameters	• Attitude controller gains • Modulators for thruster control • Translational controller gains (note) Parameters are updated before proximity operation and release from ISS to accommodate variation of mass property.

2.4.1 Rendezvous trajectory parameters

Onboard software is capable to automatically calculate the maneuver delta-V and ignition time and manage the timeline sequence for maneuver execution. During the actual flight operation, the ground team confirms the onboard maneuver solution comparing with the planned solution, and send Go command to continue the automatic maneuver sequence. As far as the rendezvous flight continues nominally, the ground team can concentrate on monitoring the automatic maneuver execution, and workload of ground operation can be reduced. Following parameters are required for the automatic onboard function.

- Arrival time to proximity operation interface point
- Arrival location to proximity operation interface point

- Interval revolutions between maneuvers

These parameters are generated as the results of rendezvous trajectory planning process, and uploaded to the onboard software prior to launch.

2.4.2 Proximity operation trajectory parameters

Onboard software is capable to automatically calculate the maneuver delta-V and ignition time and manage the timeline sequence for maneuver execution. Proximity operation trajectory is fixed and there is no difference between flights. Maneuver calculation is straightforward based on CW(Clohessy-Wiltshire) equation. The ground team confirms that the onboard maneuver solution is within the allowable variation range and send Go command to continue the automatic maneuver sequence. Following parameters are required for the automatic onboard function.

- Pre-defined relative location to the ISS for each maneuver
- Interval revolutions between maneuvers
- Arrival time at Approach Initiation point (5km aft ISS)
- Departure time from Approach Initiation point (5km aft ISS)

Regarding the first two items, the same parameters are used for each flight to realize the same safe trajectory. Since the proximity operation trajectory is the same for all the flights, the operation timeline can be the same for all mission operation. It is beneficial that the ground operation team can improve the skill and operation efficiency based on lessons learned from the previous flights.

The last two items are the actual onboard software parameters corresponding with arrival date/time on the ISS.

2.4.3 Departure and Reentry trajectory parameters

As for departure trajectory from release by the robotics arm to the reentry preparation orbit 5km below ISS, the delta-V and ignition time for maneuvers are fixed and related parameters are uploaded from the ground. For reentry trajectory, onboard software is capable to automatically calculate the maneuver delta-V and ignition time and manage the timeline sequence for maneuver execution. In order to satisfy safety requirement of the reentry trajectory, the trajectory needs to be generated to ensure the splashdown of destruct vehicle on the restricted area. It is managed by setting reentry interface point and start time of de-orbit maneuver sequence. Reentry interface point defines the altitude and latitude of the reentry trajectory, and start time of de-orbit maneuver sequence determines the appropriate orbit pass crossing over the restricted splashdown area. During the actual flight operation, the ground team confirms the onboard maneuver solution comparing with the planned solution and send Go command to continue the automatic maneuver sequence. Following parameters are required for the automatic onboard function.

- Departure maneuvers delta-V and ignition time relative to release
- Reentry orbit angle at reentry interface point
- De-orbit maneuver sequence initialization time

These parameters are generated as the results of departure and reentry trajectory planning process, and uploaded to the onboard software prior to departure from ISS.

2.4.4 Control parameters

Control parameters are determined based on the HTV mass property for each mission. Also, considering the change of mass property due to propellant consumption and delivery/disposal cargo difference, control parameters are determined for three flight phases. They are far-rendezvous, proximity rendezvous and departure/reentry flight phases and uploaded to the onboard software before launch, start of proximity operation and ISS departure, respectively. Table 2 indicates the mass property at launch and ISS departure for the HTV1, HTV2 and HTV3. It can be known that there is large difference of mass property for flight phases and individual flights. Control parameters include the following items.

- Attitude controller gains
- Modulators for thruster control
- Translational controller gains

Since these parameters are fundamental to stable flight, sufficient validation tests are performed before they are uploaded to the onboard software.

Table 2. Difference of mass property at launch and ISS departure for each flight

	HTV1	HTV2	HTV3
Total mass at launch	16000 kg	16000 kg	15400 kg
Moment of Inertia at launch	Ixx: 36900 kgm^2 Iyy: 168000 kgm^2 Izz: 168000 kgm^2	Ixx: 36000 kgm^2 Iyy: 155000 kgm^2 Izz: 152000 kgm^2	Ixx: 33000 kgm^2 Iyy: 151000 kgm^2 Izz: 150000 kgm^2
Total mass at ISS departure	12400 kg	13000 kg	12700 kg
Moment of Inertia at ISS departure	Ixx: 32200 kgm^2 Iyy: 138000 kgm^2 Izz: 138000 kgm^2	Ixx: 30700 kgm^2 Iyy: 128000 kgm^2 Izz: 128000 kgm^2	Ixx: 28900 kgm^2 Iyy: 124000 kgm^2 Izz: 123000 kgm^2

2.4.5 Validation test for the mission specific parameters

Validation test is conducted before the launch and the ISS departure. The actual mission flight is simulated by the flight equivalent software simulator, and the performance is quantitatively evaluated to verify the parameters. Also, the robustness is confirmed considering any uncertainties like estimation error of mass property, performance variation of sensors and thrusters. In addition to the nominal flight test cases, off-nominal test cases are conducted to confirm the correct behavior to failures. It takes approximate one month for the validation test before launch, and half a month before ISS departure. Regarding the validation test before the ISS departure, the mass property at ISS departure can not be finalized at the time of half a month before the ISS departure, since disposal cargo may increase depending on the situation of ongoing ISS mission operation. To resolve the situation, the control parameters are validated to allow some increase of disposal cargo. This approach contributes to the disposal management of the ISS, where storage volume is limited.

Figure 12 through 15 show the results of validation test and actual flight data for the HTV2. The validation test results are compared with the actual flight data, and it can be seen that they match very well. Figure 12 and Fig. 13 are the plots of pitch attitude time-history from AI(5km point) departure to R-bar injection. Figure 14 and Fig. 15 are the plots of R-bar approach trajectory in XZ Hill's frame. From these plots, it can be said that the actual flight performance is sufficiently evaluated using the flight equivalent software simulator for the validation.

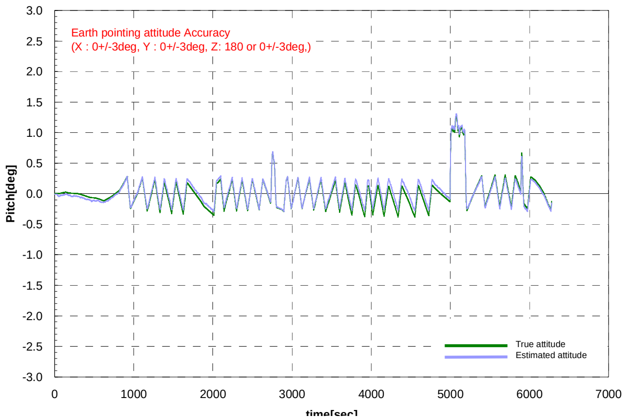

Figure 12. Result of SW parameters validation test for HTV2 (pitch attitude time-history during proximity operation)

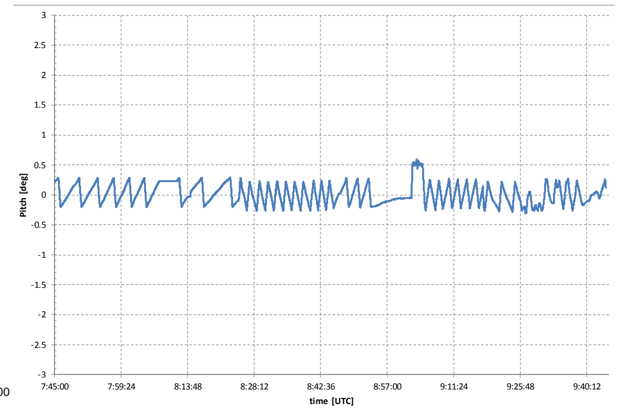

Figure 13. HTV2 Flight data (pitch attitude time-history during proximity operation)

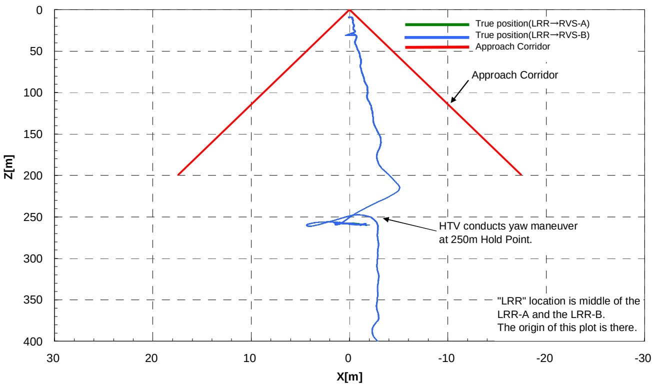

Figure 14. Result of SW parameters validation test for HTV2 (R-bar approach trajectory)

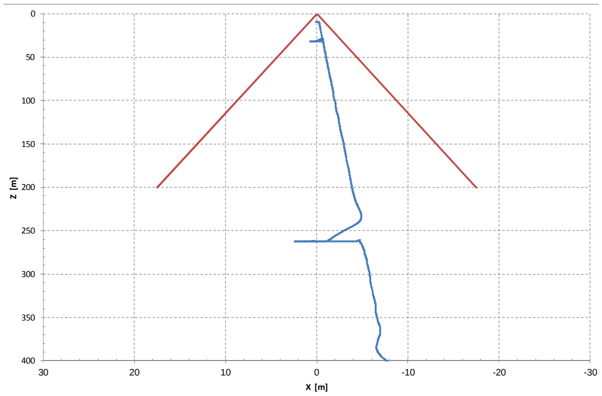

Figure 15. HTV2 Flight data (R-bar approach trajectory)

3. Real-time Trajectory Operation

The major tasks of real-time trajectory operation are 1) Trajectory monitoring and 2) Maneuver plan update. Trajectory is always monitored and detailed evaluation is conducted after each maneuver execution to ensure on-time arrival at the ISS, safe trajectory to the ISS and safe reentry to the earth. The trajectory is confirmed to follow the planned trajectory in real-time basis, and in case of unacceptable deviation from the planned trajectory, corrective action is taken promptly. The maneuver plan is periodically updated based on the current state of the HTV and the ISS trajectory. The updated maneuver plan can be used to evaluate the future trajectory, and it is used as the reference data for evaluation of onboard calculation results for maneuvers.

Since the relative orbital motion between the ISS and the HTV is important for safe rendezvous operation and the same situation awareness is necessary between both of the ISS and the HTV operation teams to ensure safe flight, the framework of HTV/ISS integrated trajectory operation is established.

The schematic figure of HTV/ISS integrated operation is shown in Fig. 16. The HTV operation team is located at Tsukuba Space Center in Japan and the ISS operation team is located at Johnson Space Center in Houston. The real-time telemetry data is shared for both teams and voice communication is available to exchange any information.

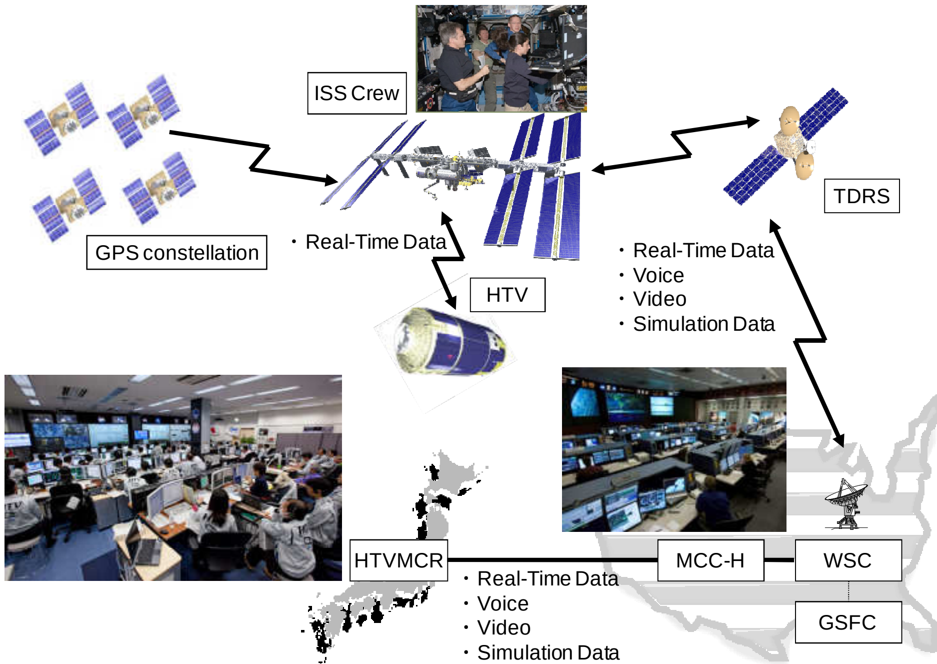

Figure 16. Schematic of HTV/ISS Integrated Operation

Figure 17 illustrates the typical real-time trajectory operation for maneuver execution. This kind of voice and data exchange is conducted between the HTV and the ISS operation teams for every maneuver. Though the automatic maneuver execution sequence is implemented to onboard software to reduce the ground operation workload, 'Go' command is required from the ground for maneuver execution and the ground teams makes the decision based on the trajectory evaluation results, since the ground team is responsible for the safe rendezvous flight to the manned ISS. When making a decision, it is important for both teams to have the same understanding on the trajectory situation. After maneuver completion, trajectory is evaluated as soon as possible whether the resulted trajectory is as expected to the planned trajectory, and the post-maneuver trajectory state vector of the HTV is sent to the ISS operation team for the purpose of updating TDRS communication link schedule. Maneuver plan is updated after every maneuver in order to manage the trajectory precisely. Even if there is small deviation from the planned maneuver, it is confirmed that the future trajectory can be recovered by adjusting the next maneuvers as the result of maneuver plan update. If there is large deviation that can not be recovered by the following planned maneuvers, it is possible to introduce a correcting maneuver as contingency operation. From the experiences of three HTV flights, the performance of HTV/ISS integrated operation is improved and both operation teams have enough confidence to ensure on-time and safe flight for the subsequent HTV missions.

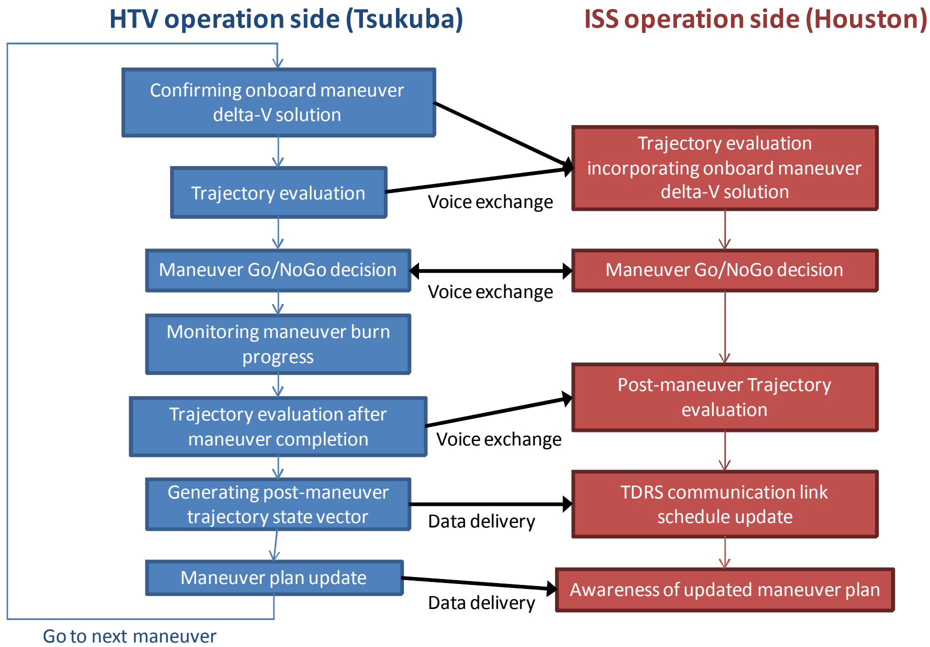

Figure 17. HTV/ISS Integrated Real-time Trajectory Operation for Maneuver Execution

4. Conclusion

In this paper, the HTV flight planning activities and trajectory operation aspect are presented based on the actual experiences obtained by successful flights of the HTV1, HTV2 and HTV3. Clearly, the flight planning is basis of safe flight and mission success, and it is a great opportunity to improve the capability of flight planning for rendezvous mission through the international partnership for the ISS mission operation. Even though three HTV flights were successfully completed, there were specific difficulties to conduct the flight planning activities for each flight. Especially, day-by-day change of the ISS status imposes many difficulties on the HTV flight planning. For example, the condition of the ISS orbit was degraded for the HTV flight due to precedence to the Space Shuttle and Soyuz vehicle considering importance of manned flights, and any ISS orbit change had to be considered for flight planning caused by potential debris avoidance maneuver of the ISS. Through those experiences and lessons learned, our capability of flight planning is improved in step-by-step manner, and we would continue the contribution to the ISS mission operation by providing cargo delivery/disposal service on time and safely with the frame of international partnership. Moreover, it is believed that the acquired knowledge of the HTV flight planning activities would be the basis for the future challenging rendezvous/reentry vehicle.

5. Reference

[1] Tanabe, K., Uchiyama, T., Maeda, M. and Kato, A. "HTV-2 Flight Operation Results" 28th ISTS, Okinawa, Japan, 2011
[2] Yamanaka, K., Sasaki, H., Fukatu, T. and Tanabe, K. “HTV Flight Operation Results” 61th International Astronautical Congress, Cape Town, South Africa, 2011
[3] Wada, K., Yamanaka, K., Uematsu, H., Suzuki, Y. and Sasaki, H. “Evaluation Results of the HTV Atmospheric Reentry Trajectory” 61th International Astronautical Congress, Cape Town, South Africa, 2011