1. Introduction

The HTV is a logistic supply and waste disposal vehicle for the ISS developed by the Japanese Aerospace Exploration Agency (JAXA). The HTV is designed to be launched on a new Japanese launch vehicle H-IIB, which is an enhanced version of the Japanese flagship launch vehicle, H-IIA. As its flight profile is shown in figure 1, it is loaded with pressurized and unpressurized cargo, including crew supplies, on the way to the ISS as a supply vehicle, and once docked with the ISS, the crew members will unload the cargo to the ISS. After about a month long stay at the ISS, the HTV will be loaded once again with unused and/or unnecessary items. It will then depart from the ISS and eventually reentry to the Earth atmosphere to dispose those items.

1.1. HTV-1 Flight Summary

The first flight article, HTV-1 was launched on September 10th, 2009 (GMT) and was captured by the Space Station Remote Manipulator System (SSRMS) on September 17th, 2009 (GMT). Figure 2 shows the actual photo taken by the ISS crew member during its rendezvous. During the eight-day endeavors to the ISS, the HTV-1 demonstrated its various safety features such as abort and retreat functions on top of the nominal performance to autonomously approach the ISS. After about 45-day long stay at the ISS, it departed from the ISS on October 30th, 2009 (GMT) and the eventual reentry was on November 1st, 2009, completing all of its mission objectives successfully. As the first flight, its main objective was to validated the flight performance and safety functions, which were verified on the ground prior to the flight, and to collect as much flight data as possible. Its flight data were analyzed thoroughly, and necessary modifications were made to its successive flight, HTV-2 (Kounotori-2) in order to improve its reliability and flight performance. For example, its rendezvous flight software (RVFS) was modified in 26 areas to ensure consecutive success.
1.2. HTV-2 Flight Summary

About one and a half years later, the HTV-2 was launched on January 22nd, 2011 (GMT) and was captured by the SSRMS on January 27th, 2011 (GMT). This time, it took only six days to reach the ISS because the launched date was delayed by two days by bad weather. We had to adjust its flight plan only two days prior to the actual launch date, but we proved that our rendezvous planning was flexible enough to accommodate the last minute launch delay. As a result, the arrival timing was unchanged and the HTV-2 reached the ISS as originally planned. Figure 3 shows the actual photo of the HTV-2 being captured by the ISS SSRMS.

While the HTV-1 was designed and developed as a demonstration flight, whose main objective was on-orbit validation, the HTV-2 was built as the first article of the HTV fleet as part of the ISS logistic program and its main objective was to maximize the cargo capability. The major difference between HTV-1 and 2 was the number of primary batteries (P-BAT) onboard. While the HTV-1 carried 11 P-BAT’s in order to accommodate various demonstration activities, the HTV-2 carried only seven P-BAT’s to maximize its cargo capability. Each P-BAT on the HTV-1 weighed about 130kg while that on the HTV-2 weighed 3~5% less with enhanced capability, which resulted in about 580kg saving in the total mass, and therefore, allowing total of 6 tons of cargo capability.

After about 60-day long stay at the ISS, it departed from the ISS on March 28th, 2011 (GMT) and the final reentry was on March 30th, 2011 (GMT). The HTV-2 flight was successful in its nominally planned flight events and performance, and moreover, it had additional demonstrations such as the zenith port relocation, domestically developed transponder validation and reentry data collection. All of those demonstrations were successful, and the HTV-2 had accomplished extra success in that sense. The results from those extra demonstrations are presented later in this paper.

1.3. HTV-3 and Beyond

After the successful flight of HTV-1 and 2, the HTV-3 is being built to be ready for launch early next year. The uniqueness of HTV-3 is that it carries full configuration of the domestically developed transponders and thrusters, which poses another level of challenge to the HTV-3 development. However, given the consecutive success of HTV-1 and 2, we will apply the proven method to the HTV-3 to reduce the risk, if any, and to ensure another successful flight to contribute to the ISS program as an international partner.

The future HTV fleet includes HTV-3 through HTV-7, and will be launched about once a year to support the ISS logistic program after the Space Shuttle retirement this year.

2. HTV-2 Flight Performance

In this section, the HTV-2 flight performance, especially in the guidance, navigation and control (GN&C) area, is evaluated based on the actual flight data, in comparison with that of the HTV-1 in some areas.

2.1. Guidance Results

After the HTV is separated from the H-IIB launch vehicle, the HTV onboard Guidance and Control Computer (GCC) calculates the necessary maneuver sequence based on the guidance parameters (the maneuver sequence is a series of thruster activations to obtain necessary acceleration to reach the ISS at higher altitude). Those guidance parameters are planned by the ground crew, and are tuned so that the expected maneuver sequence meets the rendezvous accuracy without having excessive thrust. After thorough verification of those parameters, including Monte Carlo simulations, they will be loaded to the GCC at the launch site just prior to the launch. Figures 4a and 4b show how we dealt with the sudden delay of the launch schedule by two days due to the weather. As shown in those figures, the eccentricity of the first phase adjustment was changed drastically to meet faster rendezvous so that the capture timing by the ISS would be unchanged even with the delayed launch. Through the HTV-1 and 2 experience, we have developed the guidance
planning and verification flow to accommodate even the last minute launch delay.

The rendezvous maneuver sequence consists of 31 maneuvers, and the departure and reentry sequence consists of 5 maneuvers. Actual maneuver plan calculated onboard will be checked against pre-calculated ground plan, such as expected maneuver duration and resulting orbital parameters, before the HTV actually initiates the maneuver.

Figures 5a and 5b show the pre-calculated ground plan (in red line) and the actual by the GCC (in green line) for the HTV-2 rendezvous and departure/reentry, respectively. As seen in those figures, the actual maneuver results precisely coincided with the planned, which means that the GCC calculated each maneuver correctly and the actual acceleration was consistent with the expected.

2.2. Navigation Results

The HTV primarily uses the Global Positioning System (GPS) for navigation during most of the rendezvous phase. Once it gets close to the ISS, namely, about 500m below the ISS, it starts to use the rendezvous sensor (RVS) for its final approach on the R-bar (approach along the radius vector). In this section, we focus on the GPS performance results.

Right after the separation from the launch vehicle, the HTV first stabilizes its attitude by damping its residual attitude rate and establishes Earth pointing attitude. The HTV will then start using the GPS data after proper initialization, and will use the standalone GPS navigation data (onboard data only, no real-time calibration) until it establishes the proximity communication link (PROX) with the ISS at about 250km behind the ISS.

The ISS carries similar GPS receivers as the HTV, and broadcasts its own position through the PROX link. Once the HTV gets close enough to establish the PROX link, it will start the differential GPS (DGPS) navigation. The DGPS navigation logic simply subtracts the ISS position from the HTV position and estimates the relative position and velocity. The DGPS is a useful tool to directly calculate the relative position and velocity, but is affected by the standalone GPS errors and has limited accuracy.

In order to improve the GPS navigation accuracy until the HTV starts using more accurate RVS navigation, it also has the relative GPS (RGPS) navigation system. The RGPS navigation logic uses the GPS measurements for those GPS satellites, which are in the common view for the HTV and the ISS. By subtracting measurements from the same GPS satellite, the RGPS eliminates the system errors, and therefore, improves the relative navigation accuracy.

Figures 6a and 6b show comparison between DGPS and RGPS in terms of position and velocity, respectively, for about 100km and less to the ISS. The position shows consistency with 1σ of a few meters, and the velocity shows that with 1σ of a few tens of centimeters except for those maneuver timings. Since the RGPS filter has a longer time constant than that of DGPS, its accuracy degrades for 15 minutes, at the worst case, right after the maneuver especially
in the z direction. This is because we focused on the 
coasting accuracy rather than the dynamic response. This 
temporal disturbance was not an issue because the RGPS 
converged prior to the next maneuver.

One interesting observation is that the bias term in the 
RGPS/DGPS x component we observed during the HTV-1 
mission was eliminated for the HTV-2 because of the RVFS 
modification we made as part of the improvement from the 
HTV-1.

2.3. Attitude Control Results

The HTV control system consists of the attitude control 
system and the translational control system on the R-bar for 
the final approach. In this section, the attitude control results 
are presented.

The HTV attitude control system consists mainly of two 
different modes, attitude control by the reaction control 
system (RCS) thrusters and that by the main engines (ME) 
with off-modulation. The RCS attitude control is used for 
most of the phase, and the ME attitude control is used during 
large maneuvers.

Figures 7a, b and c show the RCS attitude control results 
during one of the RCS maneuvers. This maneuver is called 
an RI’ maneuver and, in this case, it lasted about 140 seconds 
(indicated by the yellow line) in z direction. As shown in 
those figures, the attitude error was well below the 
requirement (indicated by the pink line) in pitch, roll and yaw.

Another good example is the ME attitude control during the 
de-orbit maneuver #3 (DOM3) as shown in figures 8a, b and c. 
The DOM3 maneuver is the last maneuver prior to the reentry 
and, in this case, lasted about 450 seconds (indicated by the 
yellow line). The roll and yaw angles were controlled well 
below the requirement (indicated by the pink line). Since 
this maneuver lasts so long in order to obtain sufficient 
deceleration for the reentry, the pitch angle maneuver is 
planned to achieve accurate deceleration vector in the inertial 
space. In fact, the HTV-2 DOM3 lasted over about 30 
degrees of the orbital arc. Figure 8b shows the commanded 
pitch angle in light blue and the actual pitch angle in dark blue, 
and the actual showed smooth transition along with the 
commanded.

2.4. Translational Control Results

Once the HTV approaches the R-bar insertion (RI) point, 
which is located at 500m below the ISS on the z axis, it 
acquires the reflected laser signal from the retro-reflectors 
installed on the nadir side of the Japanese Experimental 
Module (JEM). It will then start the RVS navigation to 
determine more accurate relative position with respect to the 
ISS. This accurate navigation logic, combined with precise 
translational control on the R-bar, allows the HTV to approach 
within the tight field of view (FOV) corridor of the RVS while 
complying with the strict safety requirements within the 
vicinity of the ISS.

Figures 9a and 9b show the actual approach profile for the 
HTV-2. Figure 9a is the xz plane (parallel to the orbital 
plane) projection and figure 9b is the yz plane (perpendicular 
to the orbital plane) projection. As shown in figure 9a, the 
HTV-2 flew from the right hand side and started the RVS 
navigation around 500m in z axis. It then started to “climb 
up” the R-bar using the R-bar translational control. The blue 
line is the actual flight trace, the green line is the commanded 
position and the red line is the approach corridor.

In order to check the HTV health status prior to the final 
approach, the 250m and 30m points on the z-axis are defined 
as “hold points (HP).” Those hold points are evident on the 
blue line as small glitches. Figure 9b, the out-of-plane plot, 
shows perturbation by the orbital motion and the control 
system’s counter-effort to stay along the R-bar.

Figures 10a and 10b show the z-position time histories for
After the HTV-2 mission, this anomaly was thoroughly analyzed and tested, and as part of the improvement to the PLS system, one PLS transponder was installed on the HTV-2 B-string. If an anomaly is detected on the A-string, the onboard logic will autonomously switch to the B-string. The Heart-Beat Failure Detection, Isolation and Recovery (HB FDIR) will autonomously switch to the B-string.

The HTV has two different communication paths during rendezvous in order to receive/send data from/to the ground, namely, the inter-orbit link system (IOS) which uses the Tracking and Data Relay Satellite (TDRS) and the proximity link system (PLS) which communicates with the ISS through the PROX link. As shown in figure 1, the IOS communicates directly with the TDRS while the PLS communicates with the ISS PROX, and the ISS, in turn, relays the data through its own link with the TDRS to the ground. In order to have the redundancy in each link system, the HTV has two independent strings for each link. The A-string is the primary string and the B-string is the backup. If any anomaly is detected on the A-string, the onboard logic called the Heart-Beat Failure Detection, Isolation and Recovery (HB FDIR) will autonomously switch to the B-string.

For the HTV-3 and subsequent flights, we have been developing our own transponders in order to improve the availability. Instead of installing and flying the newly developed transponders onto the HTV-3 for the first time, we decided to install one PLS transponder on the HTV-2 B-string in order to collect the flight data and validate prior to its serious debut.

After the HTV-2 was captured by the SSRMS and the condition was stabilized, we intentionally switched to the PLS B-string and confirmed that it communicated with the PROX as expected.

In addition to the data and command link functions, the PROX/PLS link is also used to measure the range and range rate in order to augment the RVS navigation. Figures 12a...
shows the PROX/PLS range measurements before and after the switchover, and figure 12b shows the range rate measurements (the switchover happened around 12:10 GMT). The range and range rate showed consistent results for both strings A and B, confirming the performance of the newly developed transponders.

During the departure phase, aforementioned HB FDIR was also demonstrated. This FDIR function detects any failure in the PROX/PLS link and autonomously switches to the backup string (B-string). This function has been thoroughly tested and verified on the ground, but has never been triggered during the actual flight, fortunately, and we decided to actually validate it on-orbit. After completing the descending maneuver #2 (DSM2), which was the last maneuver before leaving the ISS proximity, we intentionally turned off the PLS A-string and triggered the HB FDIR. The PROX/PLS string was switched from A to B as expected and the HTV-2 continued to communicate with the ISS PROX until about 265 km in distance from the ISS, which again provided comparable performance of the PLS B-string with the A-string.

3.2. Extended Data Collection Beyond the Reentry Point

During the deorbiting sequence, the HTV has three deceleration maneuvers, called DOM1, DOM2 and DOM3. After DOM3, which is the last maneuver before reentry, the HTV is put into tumbling in order to suppress airtift.

After analyzing the HTV-1 deorbit data, we decided that the tumbling was not necessary to ensure safe reentry, and decided to collect extended reentry data for the HTV-2 by controlling its attitude to its local horizon as long as possible even after the DOM3.

Figure 13a shows the ISS altitude and the HTV-2 altitude after the DOM3, which was completed around 2011/3/30 2:44 (GMT). While the ISS altitude was constant around 350 km, the HTV-2 altitude showed steady descent all the way down to 89 km where the communication link was lost. Figure 13b shows deceleration in the x axis due to the air drag, and it was apparent that the deceleration increased drastically after the HTV-2 passed the reentry interface point at 120 km altitude.

Figures 14a, b and c show the roll, pitch and yaw angles during the reentry. The attitude control system regulated the HTV-2 attitude even through the dense atmosphere.
We also evaluated the GPS navigation performance during the reentry. Figures 15a and 15b show the position and velocity comparison, respectively, between the GPS snapshot solution and the Kalman filter solution. As shown in figure 15b, the velocity solution from the Kalman filter started to diverge first due to the fact that the actual air drag started to grow beyond what was modeled in the Kalman filter below 100km in the altitude. The position solution started to diverge as well, as shown in figure 15a, about one minute prior to losing the communication link, partially due to the degraded PDOP.

These are a few examples of valuable data we obtained during the HTV-2 reentry. We are still analyzing the collected data and hope to present the findings in the near future.

3.3. Zenith Port Relocation

Once the HTV is captured by the SSRMS, it is designed to be attached to the nadir port of the ISS node2, in terms of the mechanical and electrical interfaces in addition to the environment such as thermal and solar conditions. Figure 16a shows the HTV-2 right after successful rendezvous and berthing.

The original HTV-2 plan was to stay at the nadir port for about 45 days and then depart as the HTV-1 did until the Shuttle launch schedule slipped to rendezvous with the ISS while the HTV-2 was attached. Because of the physical interference between the Shuttle once docked and the HTV-2 on the nadir port, NASA requested JAXA to relocate the HTV-2 from the nadir to the zenith port. In fact, that possibility was indicated by NASA even before the HTV-2 launch, and JAXA evaluated technical feasibility in advance. Although the HTV was not designed to be located at the zenith port, JAXA determined that the mechanical and electrical interfaces were compatible to an acceptable level, and JAXA, as an international partner, decided to help NASA launch the Shuttle, which ended up with a significant delay, by relocating the HTV-2 to the zenith port on February 18th, 2011 (GMT) as shown in figure 16b.

The HTV-2 stayed at the zenith port for three weeks, during which the Shuttle was launched and docked to the ISS on February 26th, 2011 (GMT). The Shuttle was undocked in ten days and the HTV-2 was moved back to the nadir port on March 10th, 2011 (GMT). While the HTV-2 was attached to the zenith port, three Russian vehicles (two Soyuz and one Progress vehicles) and one European vehicle (ATV2) were also present at the ISS in addition to the Shuttle, which means...
that six visiting vehicles were present at the ISS at the same time. Figure 16c shows a photo taken from the leaving Shuttle to capture this historical moment.

3.4. Recovery From the Earthquake

After the Shuttle left on March 7th, 2011 (GMT), the HTV-2 was moved back to the nadir port on March 10th, 2011 (GMT) for its final preparation for departure.

Then, it was around 5:46 (GMT) or 14:46 (Japanese Standard Time (JST)) on March 11th, 2011 when the earthquake hit. It caused considerable damage to the building where the HTV control center is located, and we had to evacuate the facility immediately. It took 11 days before the flight control team got back to the console as a full shift on March 22nd, 2011. We were fortunate enough to have completed most of the relocation tasks when the earthquake hit, and asked the NASA flight control team to monitor the HTV-2 status for us.

We were successful, in the end, to excute the HTV-2 departure and reentry as planned, but we were certain that we’ve been walking on a thin ice. We had learned valuable lessons from this experience, and will reflect in the future plan to reduce the risk in any way possible, including the backup control center, more flexible communication links, and so on.

4. Conclusion

The HTV-2 (Kounotori-2) completed its mission with a full success on March 30th, 2011 (GMT) after 2.5 months long endeavours. In addition to its nominally planned activities, the HTV-2 has demonstrated the zenith relocation capability, validated the newly developed transponder and collected valuable data during the reentry as extra success. We are currently analyzing those data thoroughly, and any findings will be reflected not only to the fleet of HTVs to improve the reliability and performance even further, but also to the future missions such as the HTV-R reentry and recovery (figure 17).

The HTV-3 (Kounotori-3) is currently under manufacturing and will be ready for launch early next year. The HTV-3 carries not only the full configuration of new transponders, but also a full set of RCS thrusters and MEs, which were domestically developed as well. They yet impose significant challenges, but we consider the HTV-3 as culmination of the technology developed for the HTV and ready to take on the challenges.

JAXA is committed to support the ISS program as an international partner, and hope to expand its horizon by further improving and developing the HTV technologies and know-hows.

Acknowledgments

The authors would like to express our sincere gratitude to the engineering support team of Mitsubishi Electric Corporation (MELCO) for its dedication to this project. They actually built the critical module, tested and verified thoroughly, supported the mission, provided valuable data, and were certainly a keystone for this entire success. We also would like to thank all the people who were associated with development of this unique vehicle. We hope to continue this teamwork for future HTV missions and beyond.

Lastly, but not the least, we express our deepest condolences to those suffered from this unprecedented earthquake. The Tsukuba area, including our control center, was damaged as well, and we all had to wonder what we could do. After we got back to the full shift in 11 days, it was our pledge to complete the mission as planned, as scheduled to show the spirit, and everybody in the world helped, including the crew members on the ISS.

We, in the deepest heart, dedicate this flight to the people in Japan with a promise to rise together.

References