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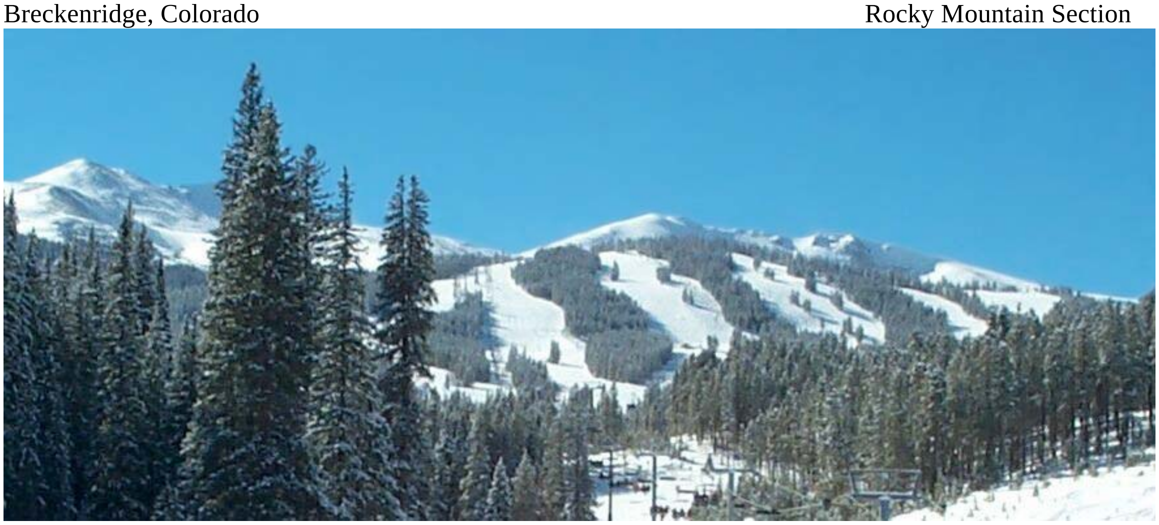

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FLIGHT RESULTS FROM THE HST SM4 RELATIVE NAVIGATION SENSOR SYSTEM

Bo J. Naasz,[*] John Van Eepoel,[†] Steven Z. Queen,[‡] and C. Michael Southward II,[§] Joel Hannah[¶]

On May 11, 2009, Space Shuttle Atlantis roared off of Launch Pad 39A enroute to the Hubble Space Telescope (HST) to undertake its final servicing of HST, Servicing Mission 4. Onboard Atlantis was a small payload called the Relative Navigation Sensor experiment, which included three cameras of varying focal ranges, avionics to record images and estimate, in real time, the relative position and attitude (aka "pose") of the telescope during rendezvous and deploy. The avionics package, known as SpaceCube and developed at the Goddard Space Flight Center, performed image processing using field programmable gate arrays to accelerate this process, and in addition executed two different pose algorithms in parallel, the Goddard Natural Feature Image Recognition and the ULTOR Passive Pose and Position Engine (P3E) algorithms.

INTRODUCTION

In May of 2009, the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) completed a successful on-orbit demonstration of its Relative Navigation Sensor (RNS) system. Flown in the cargo bay of Space Shuttle Atlantis during the highly successful Hubble Space Telescope (HST) Servicing Mission 4 (SM4), RNS captured and stored several hours of imagery of the telescope, as well as raw Global Positioning System (GPS) data, during the Rendezvous Proximity Operations and Docking (RPOD) and Deploy phases of the mission. The system also processed images of Hubble in real-time, estimating the position and orientation, or "pose" of the telescope relative to RNS's Shuttle-mounted cameras.

The RNS experiment on SM4 was originally conceived of in the course of developing a preliminary mission concept and spacecraft design for the Hubble Space Telescope Robotic Servicing and De-orbit Mission (HRSDM). Intended to successfully rendezvous and dock with an uncontrolled HST, the servicing vehicle required an autonomous means for real-time estimation of the relative position and attitude of HST. We refer to this relative state measurement, made directly from sensor data without consideration of the system dynamics, as the "pose" measurement.

The RNS experiment leveraged hardware procured prior to the cancellation of HRSDM to assemble a relative navigation sensor payload, RNS, to be installed in the Space Shuttle payload bay during SM4. Hosted on the Multi-use Logistic Equipment Carrier (MULE), RNS made real-time pose measurements during approach to and departure from HST during SM4. The objectives of RNS were: 1) to record images of HST, especially of a new Soft Capture Mechanism (SCM) being

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installed during SM4 to facilitate future RPOD with the Telescope; 2) to demonstrate the feasibility of generating real-time, on-board pose estimates under orbital lighting conditions; 3) to evaluate the performance of a comprehensive pose estimation system on orbit to assess its adequacy for possible future Autonomous Rendezvous and Docking (AR&D) operations with an uncontrolled HST. These objectives were subject to limitations, including that HST remained controlled during the entire SM4, and RNS could neither specify nor control the Shuttle trajectory or attitude relative to the HST.

RNS system hardware includes 3 cameras with varying optical ranges, a Navigator GPS receiver, an electronics box containing several commercial hard drives comprising the Mass Storage Module (MSM) to record camera images and raw GPS data, and an advanced microprocessor system called SpaceCube. Two pose estimation applications, the Goddard Natural Feature Image Recognition (GNFIR) and the ULTOR Passive Pose and Position Engine (P3E) (ULTOR), were executed in the SpaceCube. The primary requirements of these algorithms were to share the available processing resources—a Xilinx Virtex 4, each—and to produce pose estimates from each available camera (within their appropriate ranges) with sufficient precision to support evaluation of the accuracy goals stated in Table 1.

Table 1 RNS pose accuracy goals (3σ)

Target Range ft (m)	Lateral Accuracy ft (m)	Range Accuracy ft (m)	Roll Accuracy	Yaw/Pitch Accuracy
492 (150)	3.3 (1)	3.3 (1)	15°	15°
98 (30)	0.9 (0.3)	1.6 (0.5)	5°	5°
16.5 (5)	0.3 (0.1)	0.3 (.1)	1°	5°

NOTE: Goals expressed in individual camera frames

The focus of this paper is on pose estimation results, and on the comparisons of GNFIR and ULTOR algorithms to the best estimated trajectory provided by the Shuttle program. We first present a summary of the SM4 flight operations as they pertain to RNS, followed by additional details on the pose algorithms, and the first published pose estimation accuracy results from the SM4 flight. Details of the RNS sensor and avionics systems are described in detail in Ref. [1].

Flight Operations

RNS flight operations were conducted in the Payload Operations Control Center (POCC) at Johnson Space Center (JSC). While the prime method of commanding was via ground command, some commanding of the system could be performed by the crew. As described below, this backup mode of operation was critical during off-nominal operations in the Rendezvous phase of the mission. RNS flight operations consisted of the following major phases: Pre-Launch Operations; Activation; On-Orbit Checkout; Rendezvous; Post-Rendezvous; Deploy; Post-Deploy; De-Activation.

Pre-Launch Operations included pre-launch checkout of the RNS Ground Terminal (RGT) in the JSC POCC, performed by routing simulated RNS data (compressed imagery via Ku-band and telemetry data and RNS commanding via S-band) to the two RGTs.

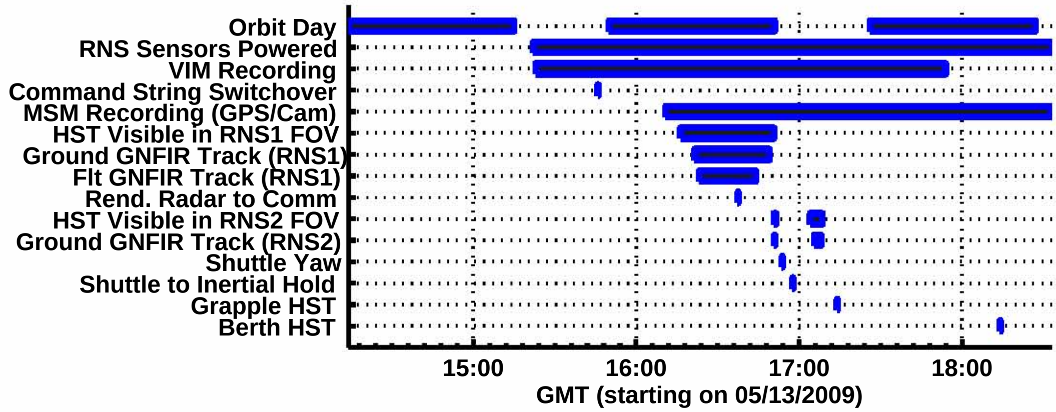


Figure 1 Rendezvous events timeline

Activation of the RNS Telemetry Module (TM) was perfomed at Mission Elapsed Time (MET) 0/02:33* (11 May 2009, 20:35 GMT). The TM remained powered for the remainder of the RNS operations, and provided health and safety telemetry during periods when SpaceCube–the primary source of RNS telemetry–was de-activated.

On-Orbit Checkout commenced at MET $0/14$:17 (12 May 2009, 08:19 GMT) via ground command from the RGT. Checkout included the first power-up of the RNS sensors† and avionics on orbit for verification. Proper operation of the system was verified when imagery of Earth, first recorded, and then live, were transmitted from the RNS system to the RGT via the Shuttle's Ku-band link. Power switching and sensor data recording via Atlantis Crew command were also verified at this point.

Rendezvous Operations commenced with power-up of the RNS operational heaters at MET $1/19$:40 (13 May 2009, 13:42 GMT) in preparation for rendezvous recording and pose estimation throughout the RPOD phase. Figure 1 shows the sequence of events during Rendezvous.

RNS imaging operations during the Rendezvous phase commenced just after the Shuttle MC4 burn – the final mid-course correction which targets the "R-bar" (HST nadir axis, as shown in Figure 2). At this point in the RPOD phase, the Atlantis crew had already commanded the Shuttle to a "target track" attitude, with the HST-target at approximately the 1000 ft range and positioned above the Shuttle payload bay as shown in Figure 2 (the original figure, and more thorough description of the RPOD phase are available in Ref. [2]). HST was operational, in the "rendezvous" attitude as shown in Figure 2, with Solar "Beta" angle of approximately -10^o.

At this point in the rendezvous sequence RNS heaters were bringing the system up to its operational temperature, the vehicles were passing through orbit night, and the ground team was debugging an issue with the Shuttle-HST S-band link, through which they needed to command HST to its final grapple configuration. After several other attempts failed, the ground team decided to switch over commanding of the Shuttle payloads to the backup hardware. While this did not resolve the

*MET, or Mission Elapsed Time format is D/HH:MM:SS. MET $0/00$:00:00 corresponds to HST SM4 liftoff at May 11, 2009 18:01:56 GMT. Detailed information on HST commanding during the servicing mission are available in the As Executed versions of the "Servicing Mission 4 Command Plan" and "HST Servicing Mission 4 Integrated Timeline (SMIT)".

†RNS sensors include 3 cameras, and the Navigator GPS receiver, always powered on and off simultaneously.

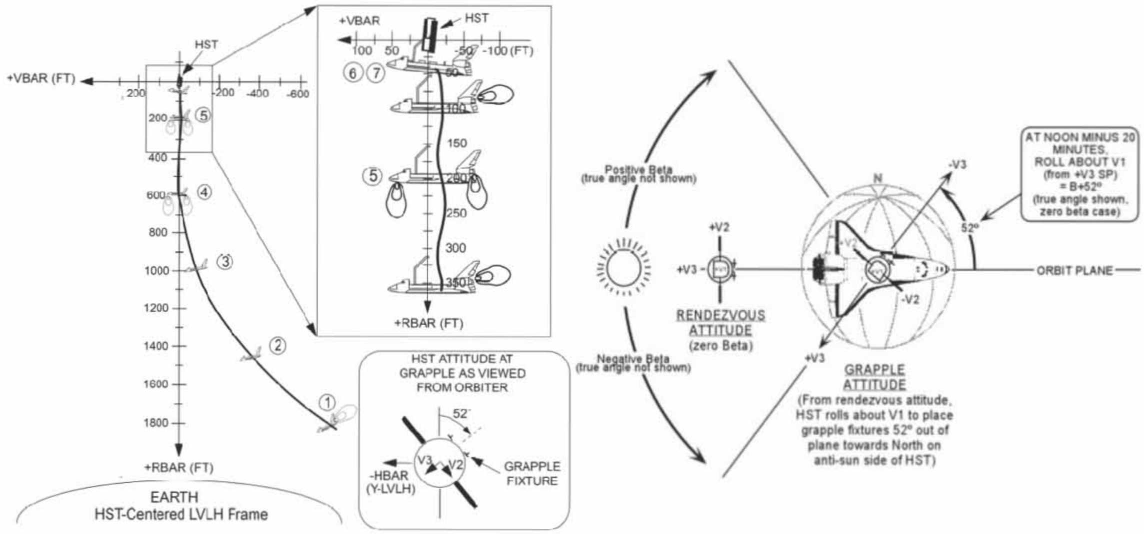


Figure 2 Shuttle R-Bar approach to HST and planned HST "rendezvous" and "grapple" attitudes (note that HST remained in the "rendezvous" attitude throughout the sequence, never maneuvering to the "grapple" attitude)

issue, it did remove any possibility of RNS ground commanding for the remainder of the sequence (RNS ground commanding was limited to the primary communication hardware).‡

A second consequence of the Shuttle-HST link issue was that HST ground controllers in the Space Telescope Operations Control Center (STOCC) opted to forgo the HST roll maneuver to the "grapple" attitude. This misalignment would be removed later in the sequence by a crew-commanded Shuttle yaw maneuver of about $45°$ about the Payload Bay (Shuttle zenith) axis, performed at an inter-vehicle range of approximately 150 ft at MET $1/22{:}51$ (13 May 2009, 16:53 GMT). This change to the relative approach attitude resulted in RNS being mis-configured for the initial pose acquisition. Ground commanding at this point could have adjusted the RNS pose algorithm acquisition modes. Unfortunately RNS commanding was not possible at this point due to the aforementioned command string switch over.

Upon notification that command switch over would occur, the RNS ground team powered up the system and executed those commands which could not be performed by the Crew (including initiation of compressed image recording on the SpaceCube Video Interface Module (VIM)§). Recording of uncompressed imagery and GPS recording would be initiated at the originally planned time via Crew command which was still possible after the command string switchover.

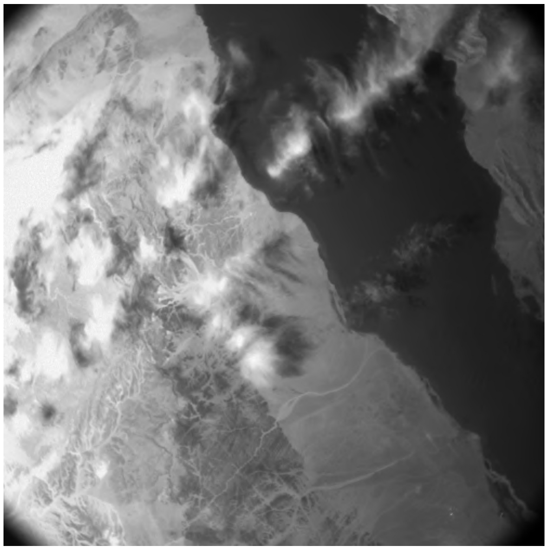
The remainder of the RPOD phase was nominal. The HST remained in an inertial hold throughout the sequence as the Atlantis Crew completed the "R-Bar" approach. The crew performed the yaw maneuver at approximately a range of 150 ft to align for grapple, transitioned the Shuttle's attitude control system to inertial hold at an inter-vehicle range of approximately 130 ft to match rates with HST, and performed the final grapple and berth of the telescope using the Shuttle Remote

‡The issue was later resolved by reconfiguration of the link parameters on the HST side and RNS commanding was restored.

§The VIM recording script commenced almost an hour earlier than planned. The script was to cycle through cameras in an open loop fashion, recording compressed imagery at the times when HST was expected to be in their field of view. Because the script started early, very little of the recorded imagery shows HST. One benefit of this timing change is that VIM-recorded imagery, intended to be a redundant backup to MSM-recorded imagery, is unique.

Manipulator System (SRMS). As with previous HST servicing missions, the grapple occurred well after sunset, and RNS imagery of the final 130 ft of the approach is quite dark, since the Shuttle floodlights were the only source of illumination during orbit night.

RNS rendezvous operations ceased with a crew-commanded stop recording and deactivation of the system at approximately 18:30 GMT.



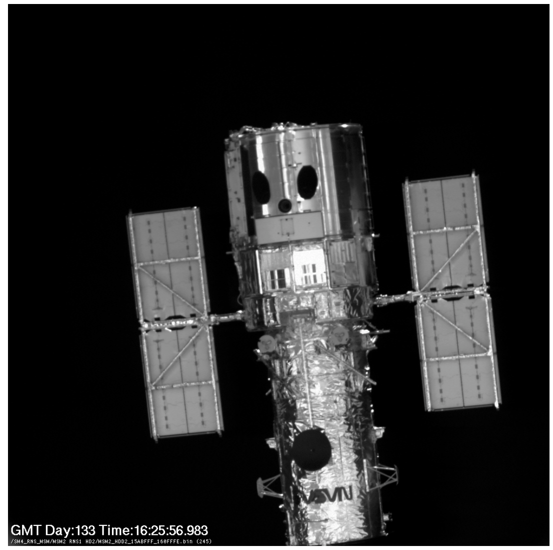


Figure 3 Image of Earth taken by RNS2 during RNS checkout (left), and of HST taken by RNS1 during rendezvous (right)

Post-Rendezvous operations consisted of Ku-band downlink of the rendezvous imagery, and commanding to prepare the RNS system for Deploy operations. In the days between Rendezvous and Deploy operations, the RNS team downlinked compressed imagery from all 3 cameras from the MSM using MSM playback, VIM compression, and SpaceCube transmission to the Shuttle Ku-band downlink system.

Ku downloads of recorded rendezvous images occurred on Flight Days (FD) 3, 4, 5, 6, 7 and 8. As a result of the downloads, approximately 81.5% of the recorded rendezvous images were downlinked for evaluation of camera Automatic Gain Control (AGC) performance. In total, 62,480 unique images were downlinked over the course of 6 nights, representing almost 6 hours of unique camera footage.

Evaluation of rendezvous imagery confirmed adequate performance with no updates to the camera AGC parameters necessary. Onboard storage space was confirmed to be adequate for deploy, the pose algorithms were commanded to Deploy Mode, and the system was ready for deploy operations.

Deploy Operations were a critical time for RNS for it was this time to meet its major requirement of imaging of the new SCM installed on the aft bulkhead of HST. To properly image the SCM, the RNS Intermediate Position (RIP) was added into the timeline as part of the nominal mission plan. Therefore, deploy operations began at MET 07/14:44 (19 May 2009, 08:46 GMT), ahead of the scheduled un-berthing of HST. Operational heaters and the SpaceCube were powered on via commands from the RGT. The sensors and MSMs were powered on at MET 07/15:48 (09:50 GMT), also via RGT command. Recording for deploy was initiated at MET 07/16:19 (10:21 GMT) via RGT command. The payload bay floodlights were turned on at MET 07/17:18 (11:20 GMT).

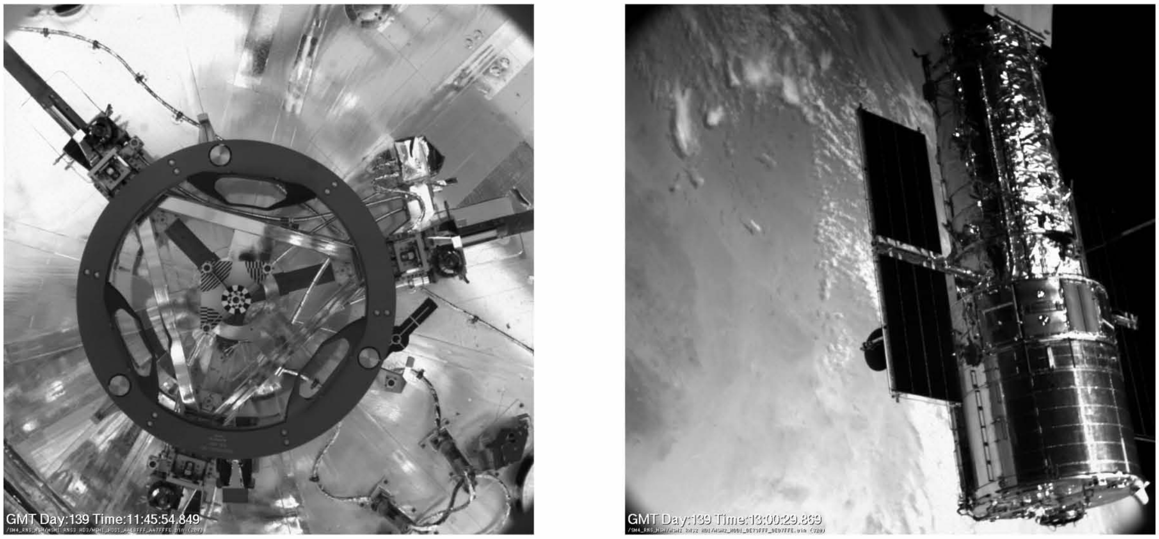


Figure 4 Image of HST Soft Capture Mechanism (SCM) taken by RNS3 during deploy, with SRMS at the RIP position (left) and by RNS2 after HST release (right)

Deploy operations events relevant to RNS are shown in Figure 5. The deployment sequence progressed as follows: Atlantis crew grappled HST with the SRMS; the HST ground team commanded de-mating of the HST umbilical, and opening of the three HST berthing latches on the Shuttle-mounted Flight Support Structure (FSS); the Atlantis crew then used the SRMS to maneuver the Telescope through a series of waypoints (see Figure 6), including the "FSS Hover" position, the "RIP" position, which centered the HST SCM in the field of view of the RNS short range camera, and the "HST Release Position". Once the HST ground team had opened the HST aperture door, and deployed the HST high gain antennas, the crew released the telescope at MET 7/19:02 (13:04 GMT), and performed two small separation burns to safely depart the neighborhood of HST. The RNS system continued to record during the final Shuttle-HST deployment.

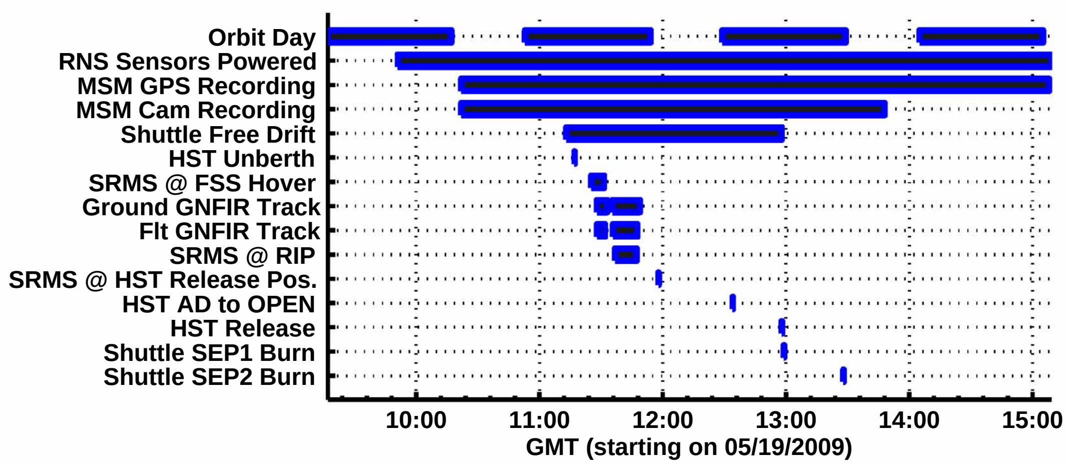


Figure 5 Deploy events timeline

At MET 07/19:46 (13:48 GMT), all camera hard drives were full, but the MSM continued to record GPS data. At MET 07/21:06, all recording was stopped. The sensors and MSMs were powered off at MET 07/21:07. The SpaceCube was left powered for the next 24 hours to perform radiation mitigation testing.

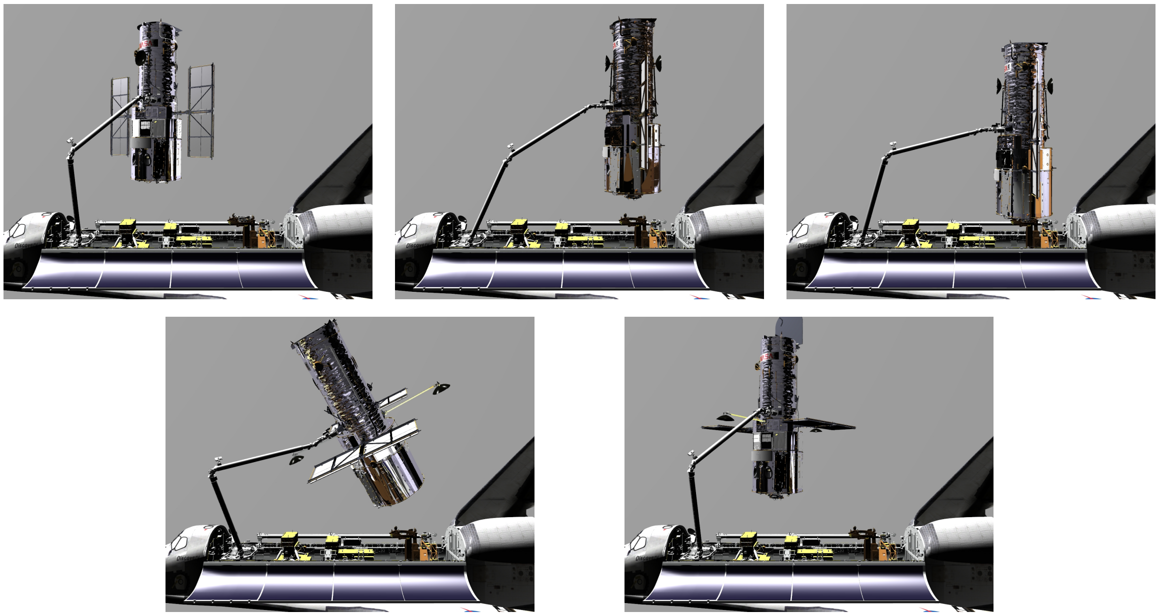


Figure 6 Port views of Shuttle and HST : (top row) Grapple (left), FSS Hover (center), and FSS Berth (right); (bottom row) RIP (left) and HST Deploy (right)

Post-Deploy Operations for downlink of deploy imagery and extended SpaceCube operations resumed during crew sleep after HST deploy. Ku downloads of recorded deploy images occurred during only one planning shift split between Flight Days (FD) 9 and 10. This was due to the fact that the majority of the remaining Shuttle payload was deactivated to conserve power for extended Shuttle operations. Mission managers made this decision on Flight Day 10 as forward forecasts of weather conditions at Kennedy Space Center (KSC) looked unfavorable for an on-time landing. As a result of this single night of downloads, approximately 15.3% of the recorded Deploy images were acquired.[¶]

In total, 16,990 unique images were downloaded of the HST deployment sequence for more than an hour and a half of unique camera footage.

De-Activation of the RNS TM occurred earlier than originally planned, at MET 8/21:12:53 to conserve energy onboard Shuttle. This was necessary due to inclement weather at the primary landing sight (KSC).

ALGORITHMS

GNFIR

The GNFIR is the latest mutation of RAPiD[3] - one of the first 3D trackers to run in real-time. As was the case with RAPiD and its numerous descendants, GNFIR utilizes natural features (edges) on its target and requires neither fiducials nor a cooperative target. GNFIR is built upon a RAPiD-derived edge-tracker re-parameterized using a Lie group formalism developed by Drummond and Cipolla[4] at the University of Cambridge. This approach assumes a monocular (single camera) system and requires an internal three-dimensional stick-model of the edge features of interest.

[¶]All Rendezvous and Deploy images are currently available in uncompressed format: they have been recovered from the MSMs during post-flight operations at GSFC.

As with all model-based methods, a correspondence is made between an image pixel and a 3D model point and the projection transformation between them is estimated. A component of that 3D to 2D transformation is the object's "pose" relative to the camera frame. For GNFIR, pose is defined as the three elements to describe the position, and four quaternion elements to parameterize the attitude, with q_4 as the scalar element.

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix}^{\substack{\text{projective}\\ \text{space}}} = \underbrace{\begin{bmatrix} \text{Viewport} \\ \text{Matrix} \end{bmatrix}_{3\times4} \begin{bmatrix} \text{Perspective} \\ \text{Matrix} \end{bmatrix}_{4\times4}^{\substack{\text{camera}\\ \text{space}}}}_{\text{Camera Matrix}} \underbrace{\begin{bmatrix} \text{Viewing} \\ \text{Matrix} \end{bmatrix}_{4\times4}^{\substack{\text{world}\\ \text{space}}} \begin{bmatrix} \text{Modeling} \\ \text{Matrix} \end{bmatrix}_{4\times4}^{\substack{\text{object}\\ \text{space}}}}_{\text{Pose Matrix}} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}_{object}$$

$$\begin{bmatrix} \tilde{u} \\ \tilde{v} \end{bmatrix}_{image} = \begin{bmatrix} \frac{u}{w} \\ \frac{v}{w} \end{bmatrix}_{proj}$$

Figure 7 *Object Space to Image Space Transformation*

Homogeneous coordinates and transformations are used throughout to account for the rotational and translational components of the pose. For this application, the Camera Matrix, shown in Figure 7, is assumed to be a known, fixed quantity. The flight cameras were rigorously tested to determine these parameters so that the only unknown is the Pose Matrix.

The pose estimation process, depicted in Figure 8, begins with a captured 10-bit camera image that is then processed using a standard edge-enhancing image (Sobel) filter. To realize realistic processing rates, this operation was moved into FPGA firmware which enabled increased the processing rate capability of the system from 0.5 Hz to 3 Hz. This enabled GNFIR to keep up with the RNS camera frame rate while in tracking mode.

Once the edge image has been generated, the tracking loop begins with an initial estimate of the target pose. This initial estimate, in the case of GNFIR, is generated by its internal acquisition mode. The GNFIR acquisition mode relies on scoring many stored (mission specific) pose estimates that were generated *a priori*. Therefore, it was imperative to have a coarse[‖] prediction of the relative motion of the Shuttle and HST during the rendezvous and deploy sequences to properly generate these initial pose estimates.[5] In addition to utilizing its own initial pose estimates, GNFIR was capable of utilizing pose seeds from ULTOR (or the ground) to aid in its attempt to acquire.

Given an initial pose estimate, the algorithm projects the wire-frame model edges into image space where they are dynamically segmented into control points. Next, the algorithm attempts to find edges in the actual camera image that match the control points and model edges. The edge search is a one dimensional search, normal to the projected edge in image space. Errors are then generated between the located edges and the edges in the image. The errors are then minimized in a least-squares fashion. The pose correction matrix is formed using a linearized attitude parameterization and then used to update the current pose estimate, and the process repeats for subsequent image frames.

If, at any time during tracking, the quality[**] metric falls below an established threshold, a re-acquisition is triggered.

[‖]Coarse trajectory design for acquisition is defined as 10° in attitude and 10 % of range

[**]GNFIR defines quality as a ratio of the features found vs the sought features

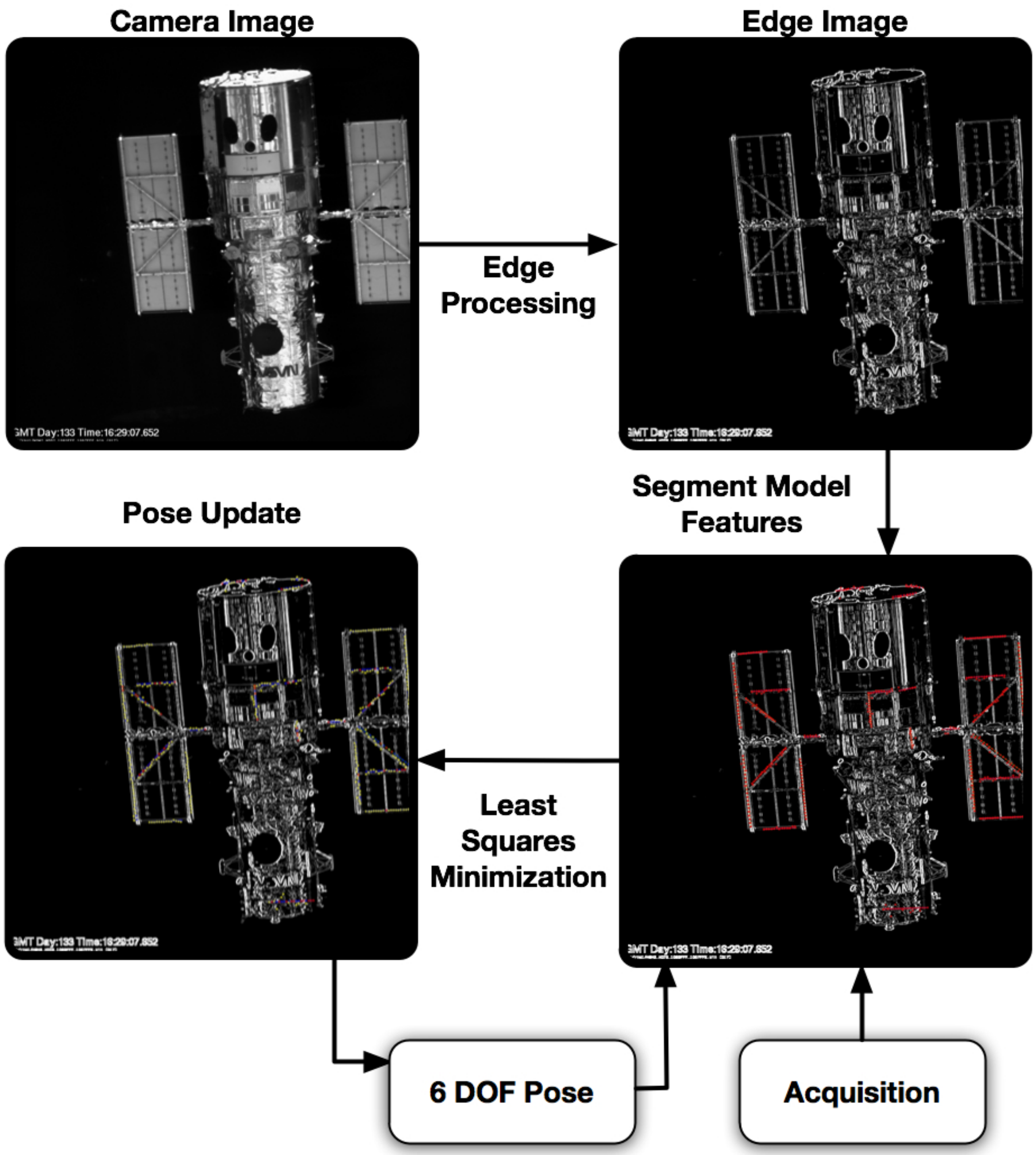


Figure 8 GNFIR Pose Process Loop

ULTOR®

Advanced Optical Systems (AOS) designed the ULTOR P3E (ULTOR)[6] to provide 6DOF state estimation of objects. ULTOR exists as VHDL firmware and is designed to be reconfigurable and portable. During RNS, ULTOR processed imagery from the RNS cameras to produce real-time results at full camera frame rates.

Simulated imagery of HST was developed to provide training data for ULTOR of specific features on HST in the camera field of view. The training data is processed to develop *filters* of the object to be measured. The ULTOR process is based on a spatial frequency analysis of a correlation between the filter and the actual object as viewed by the RNS camera. As shown in Figure 9, the relative positions of these features based on the HST mechanical model are used to evaluate the position and attitude of HST. An N-point perspective algorithm evaluates the spatial relationship of the estimated position features against the measured position to produce Six Degree of Freedom (6DOF) information of the object.

ULTOR acquires targets based on a search of the filter database to find the closest position and attitude. Once acquired, ULTOR transitions into tracking mode and processes through the filter database basd on the motion of the object. The filter database was designed to support the specified dispersion of trajectory angles based on the relative motion of the Shuttle and HST during rendezvous and deploy.

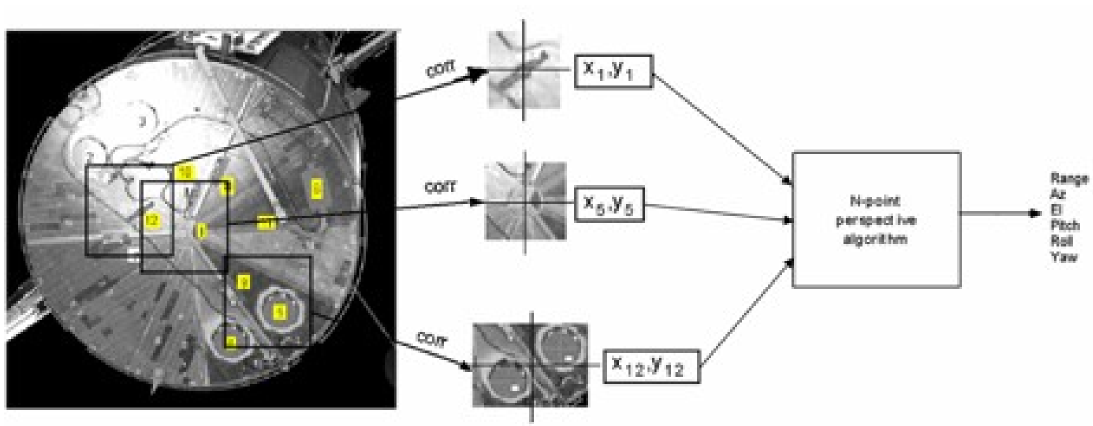


Figure 9 Feature based ULTOR ! (ULTOR !)P3E overview

TESTING

Alluded to in the previous algorithm section, the pose algorithms place importance on synthetic image generation. Test imagery is critical to have as an input for flight code development and verification, and to predict lighting of the target for proper model-feature selection. The pose algorithm performance is tightly coupled to the model features that are visible on the target, and therefore a system was developed to predict the on-orbit lighting conditions for the SM4 rendezvous and deploy trajectories.

This system encompasses a tool to model and animate 3D geometry, Geomod, a physical illumination and rendering system, Phillum. Phillum is a stochastic path tracer that uses Monte Carlo importance sampling to follow a large number of incoming light rays from a detector grid, through

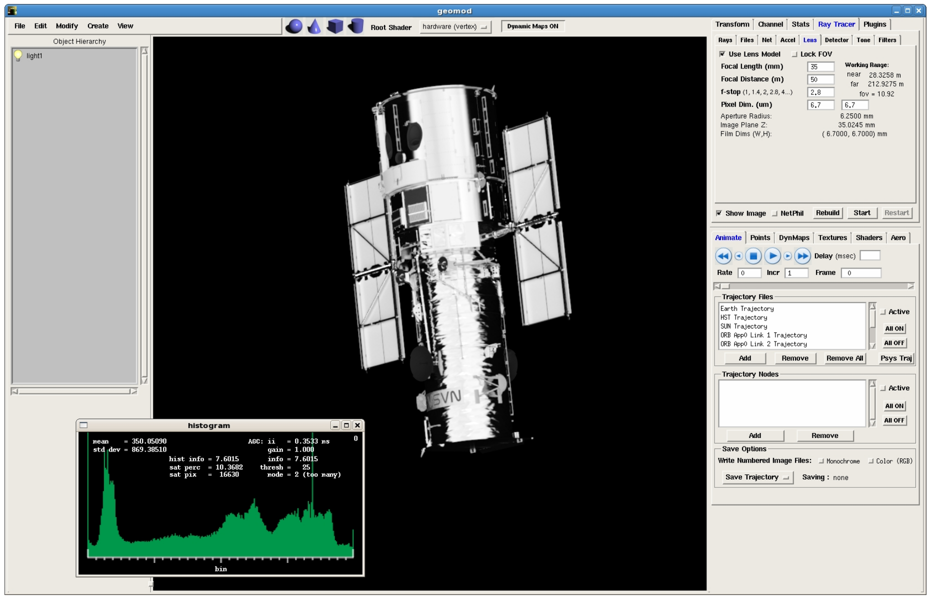


Figure 10   Geomod showing Phillum working on a SM4 Rendezvous Image

lenses and into a 3D geometry scene. It then traces the paths of the lights through the scene to determine the exposure at the detector. It uses radiometric light transport, geometric optics and statistically unbiased Monte Carlo integration. A screenshot of the application is shown in Figure 10.

For RNS, there is also an *Automatic Gain Control (AGC)* algorithm that determines the camera gain and integration interval, controlling the exposure of the next image by evaluating the information content of the current image. This creates a complex system that, without proper ground testing, could easily result in over/under-exposed images. The RNS team had the freedom to choose parameters for the AGC algorithm, but these could not be changed once the rendezvous or deploy sequence had started. Therefore, it was imperative to determine these settings *a priori* and the only way to achieve this was through simulation of the high dynamic range imagery with Phillum. As a testament to the accuracy of Phillum and the simulated SM4 trajectory, a comparison between a flight image and a Phillum generated image is provided in Figure 11.

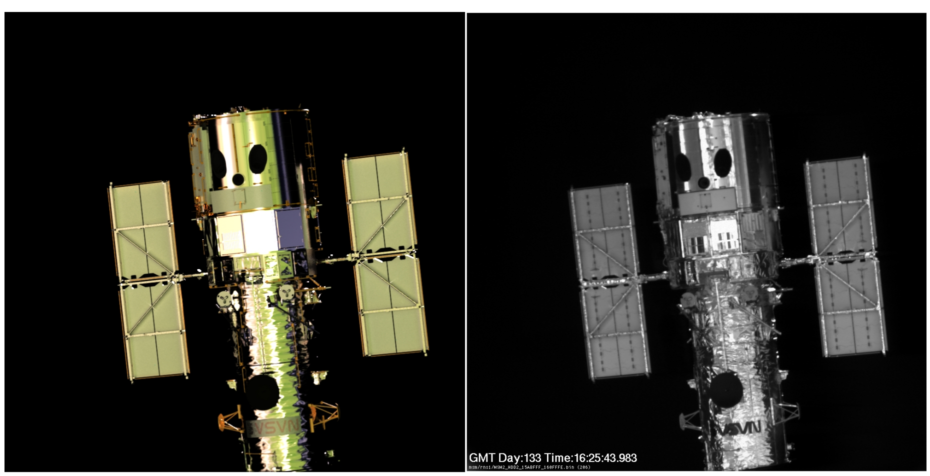


Figure 11   Comparison between Phillum synthetic image (left) and a Flight image from Rendezvous

POSE ESTIMATION FLIGHT RESULTS

This section presents a summary of on-orbit results of the pose algorithms, comparisons to a *truth* solution, and details the data analysis of the various pose solutions. The RNS hardware performed admirably during the HST SM4 mission by recording much of the rendezvous and deploy imagery of HST and returning it safely to the ground. During the rendezvous operations the GNFIR algorithm was able to track HST through the RNS1 camera from a range of 97 m (318 ft) to a range of 45 m (148 ft) with a peak quality of 99.2 % and maintained a continuous track for 20 minutes and 27 seconds. This success on rendezvous was mirrored in the deploy sequence of the telescope as GNFIR was able to track HST in the RNS3 camera at the hover position for 3 minutes and 48 seconds, and then at the RIP position for 11 minutes and 43 seconds with a peak quality of 87.1 %.

Recall from the Rendezvous Operations section, that the RNS team was unable to issue a command to the RNS system to change to a different operating mode that would have enabled better acquisition for the pose algorithms. In the case of ULTOR, this was critical as they were unable to track HST on-orbit. The appearance of HST in the RNS1 camera was at the edge of ULTOR's training data. ULTOR was able to produce several pose estimates with good confidence, but not enough to transition into tracking. ULTOR did pass an initial pose seed to GNFIR that enabled it to transition to tracking mode though. However, using the flight imagery, ULTOR was able to generate a post-processed ground solution by placing the algorithm in the correct operating mode. Doing this resulted in tracking HST for 13 minutes and 33 seconds.

The performance of the pose algorithms once the rendezvous took HST out of the field of view of RNS1 and into RNS2 was, unfortunately, not as successful. During rendezvous, GNFIR was only able to track for brief moments. The quality of the pose acquisition was enough to put the algorithm into tracking mode, but the acquisition time proved to be too long at 12 to 15 seconds to maintain tracking of HST as the relative range closed too quickly. Figure 12 shows the expected on-orbit lighting of HST on the left compared to the actual, on the right.

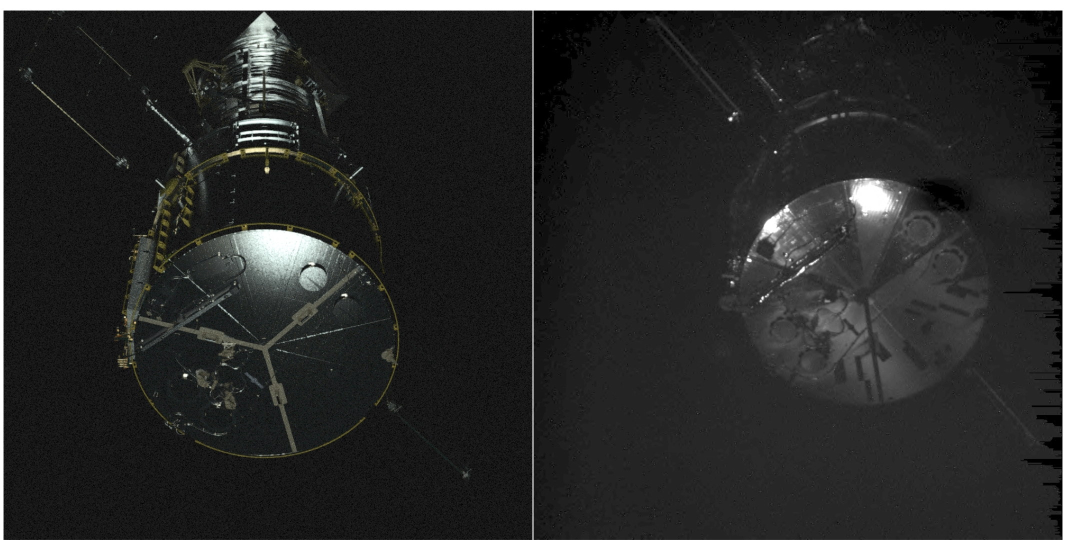


Figure 12 RNS2 with Phillum synthetic imagery (left), and Flight image (right) on Rendezvous

The combination of the variance in on-orbit lighting, the change in approach trajectory described in the Rendezvous Operations section, and the speed of the approach all combined to cause GNFIR to not acquire on-orbit. When the flight imagery was re-processed on the ground, the GNFIR algorithm was able to acquire and track HST in RNS2 for 1 minute and 43 seconds with a peak quality of $67.8\,\%$. To achieve this the GNFIR acquisition was modified to acquire the different trajectory followed on rendezvous, as well as some minor model simplifications. This underscores the fact that much of the RNS2 imagery was quite dark during rendezvous.

Finally, for RNS3, neither GNFIR nor ULTOR tracked HST during rendezvous when it was moved from the grapple position to the hover position above the FSS. This was due to a variance of $0.55\,\mathrm{m}$ and $3.6°$ in the expected motion of HST from the grapple position to the hover position. The features presented to the pose algorithms were similar to those expected, as shown in Figure 13. However, the differences in orientation and range were outside the expected search range and this was enough to cause GNFIR to not acquire HST during rendezvous. However, on deploy, GNFIR performed quite well by tracking HST at the FSS hover position and the RIP position for a total time of 15 minutes and 31 seconds with a peak quality of $87.1\,\%$.

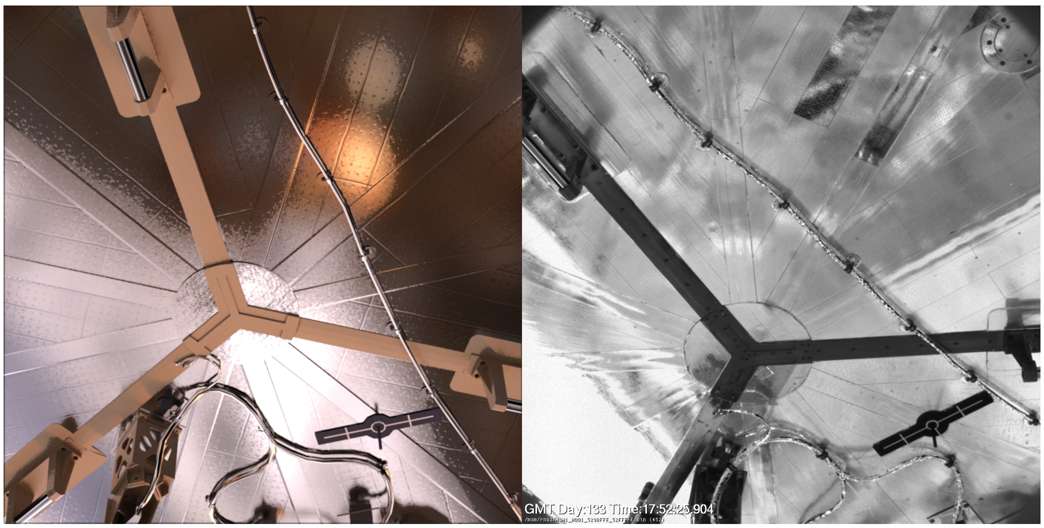


Figure 13 RNS3 with Phillum synthetic imagery (left), and Flight image (right) on Rendezvous

In light of these issues on-orbit, the RNS experiment met all of its objectives by: 1) imaging the newly installed SCM shown in Fig 4, 2) generating 32 minutes and 10 seconds of real-time pose estimates, 3) evaluating the performance of the pose estimation system (this paper).

Flight Data Comparison

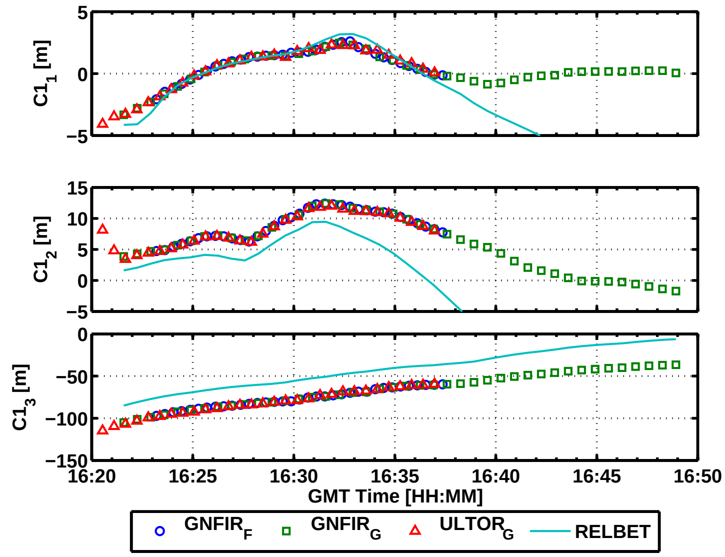
The initial undulation of success is now tempered with comparisons of the pose flight data to independent data sources, namely the Shuttle program's best estimated trajectory. The Shuttle program's Relative Best Estimate Trajectory (RELBET), was produced by JSC by filtering several different data sources such as onboard state estimates, rendezvous radar, COAS, IMU, and star tracker measurements, and taking into account timeline events such as maneuvers and corrections. RELBET's 3σ accuracies at $300\,\mathrm{m}$ are $2\,\mathrm{m}$ radial, $25\,\mathrm{m}$ in-track, and $2\,\mathrm{m}$ cross-track which is further discussed in the Interface Control Document (ICD) in Ref. 7. Shuttle attitude data was taken directly from instrument measurements, with an accuracy of $0.2°$ when Inertial Measurement Unit (IMU) data is available, and $0.75°$ otherwise, as given in the PATH ICD in Ref. 8. HST attitude was provided by the HST operations team, and the published accuracy of their solution is 1 arcsec during rendezvous. During the deploy sequence, the joint angles of SRMS are used to reconstruct the relative position of HST with respect to Shuttle, and eventually the RNS cameras. Accuracy of the joint encoders was not available at the time of publication.

The positions and attitudes of HST and the Shuttle are used to create a pose solution in the camera frame. This pose solution is then compared to the on-orbit and ground processed pose solutions for GNFIR and ULTOR. We will see discrepancies between the pose generated from Shuttle and HST position/attitude information, and the pose solutions from the RNS algorithms. To resolve this discrepancy, the RNS flight imagery was used to justify the pose solution from the RNS algorithms as the correct solution. As a result, the position data of the GNFIR post-processed solution will be compared to the GNFIR flight solution and the ULTOR post-processed solution. The attitude data of the Shuttle and HST does provide a valid *truth* solution, and will be used in comparing to the pose solutions.

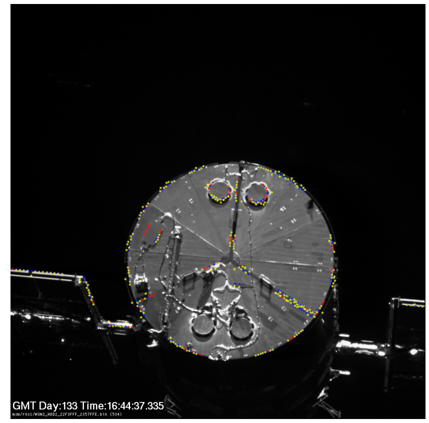
The comparison data is presented in the RNS camera frame. The camera frame is defined with $+X$ (Cn_1) to the right and $+Y$ (Cn_2) up in the image plane, where $n = 1, 2, 3$ for RNS1, RNS2, and RNS3, respectively. $+Z$ (Cn_3) completes the right handed triad by being into the camera boresight, thus making the $-Z$ axis correspond roughly to range to the target. The origin is placed at the theoretical center of the camera lens to correspond to a pin-hole camera model.

Figure 14(a) shows the different data sets of GNFIR(flight data and post-processed data), ULTOR post-processed data, and RELBET flight data. All pose solutions show the same trend for the rendezvous trajectory, however the RELBET solution shows a bias in all axes, most pronounced in the Z axis of the camera. Figures 15(a) and 15(b) detail the RELBET solution compared to the GNFIR flight solution. An ULTOR comparison is not possible as ULTOR did not track HST in flight, but did track HST when post-processing the flight imagery with the appropriate filters. The comparison plot and the RMS differences in Table 2 show a 20 m difference when compared to RELBET. However, when the pose solutions are cross-compared (GNFIR vs ULTOR), the position differences drop dramatically to less than 0.5 m for RNS1 (see Table 1). In Figure 15(b), the comparison of attitude data does not exhibit the same issues as position data. In this case, the attitude differences are $2.0°$ per axis, for a magnitude of $2.65°$ for GNFIR. This on-orbit difference is much better than the desired error of $15°$ stated in Table 1. The bottom plot of Figure 15(b) shows the principal angle that is generated from the quaternion comparison of the two solutions, and the quality metric of the GNFIR flight data. The quality during this time is exclusively greater than 85%, and peaks at 99.2% for a principal angle difference exclusively less than $5°$.

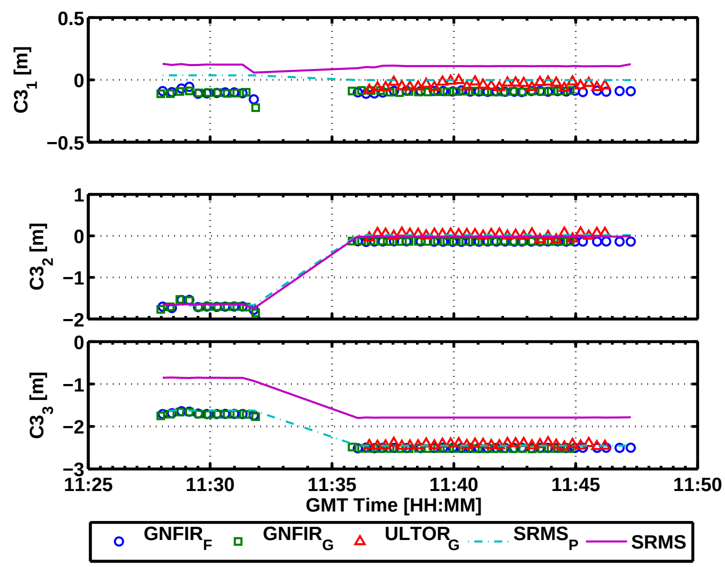
Figure 14(b) shows the different pose solutions, as well as pose data derived from RMS joint angle flight data and joint angles from the PDRS checklist,[9] denoted as ”published”. This plot demonstrates another error in the flight data for the RMS joint angles. While the pose from flight data, ground processing and predicted pose from the published joint angles all have differences in the centimeter range (Table 2), the comparison to RMS flight data shows a 0.75 m difference. The image in 14(d) shows the GNFIR post-processed pose solution overlayed on a flight image, which demonstrates, at least qualitatively, that a difference of this size cannot exist. Figures 15(c) and 15(d) show the comparison of GNFIR flight data to RMS flight data, and the SRMS published joint angles. Figure 15(c) shows the position difference mostly in the RNS3 $-Z$ axis. However, the comparison to the published joint angles show a difference of only 6 cm in range, which is well within the desired accuracy of 0.1 m stated in Table 1. The RSS subplot in this figure shows the bias removed when comparing to the published joint angles. Figure 15(d) compares the attitude solutions and shows only minor differences in attitude. The total angular error for roll is less than $1°$, as given in Table 2, which is better than the desired $5°$ stated in Table 1.



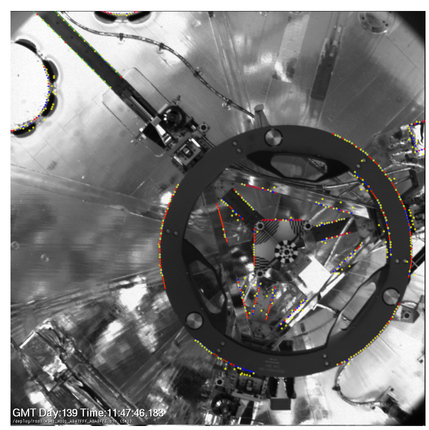
(a) Rendezvous



(c) Rendezvous - RNS1

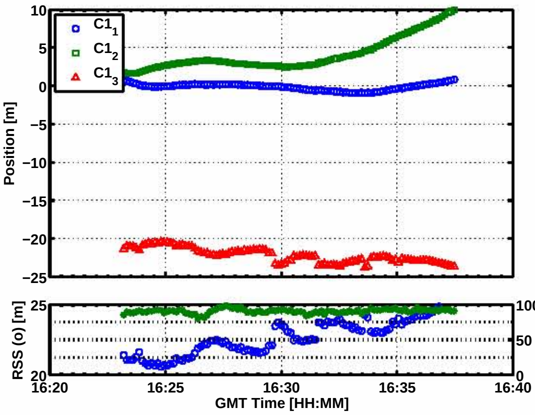


(b) Rendezvous

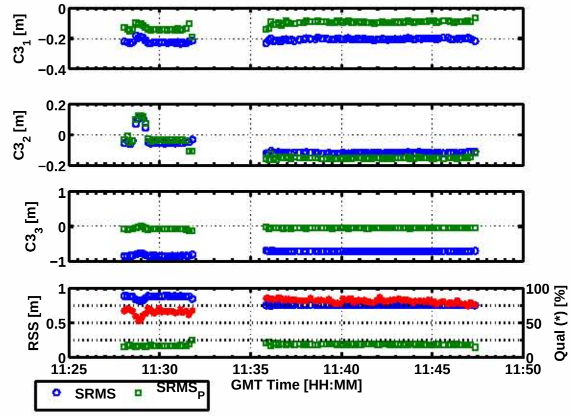


(d) Deploy - RNS3

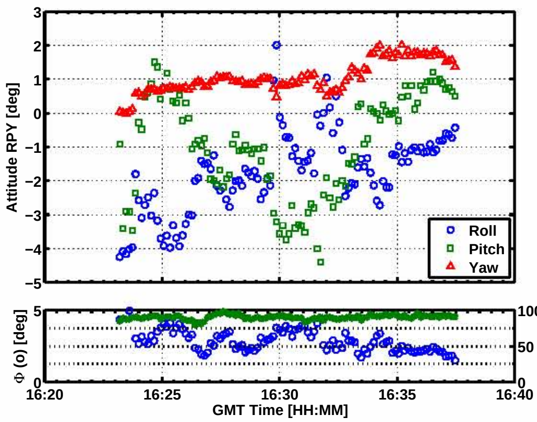
Figure 14 Pose Flight Data plotted with Shuttle RELBET and SRMS data (a & b); GNFIR pose solution with Flight Images (c & d)



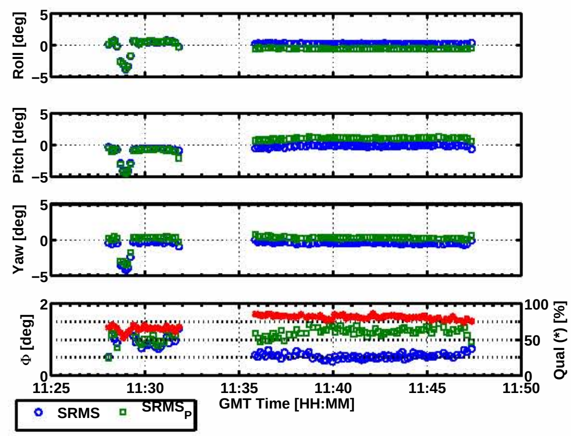
(a) Rendezvous Position



(c) Deploy Position



(b) Rendezvous Attitude



(d) Deploy Attitude

Figure 15 Pose Comparisons using GNFIR Flight data to : (a & b) RELBET, (c & d) RMS joint angles

Truth Reconstruction Issues

RELBET

Several issues arise when comparing a direct relative measurement to a filtered solution comprised of absolute and relative measurements as seen in the RELBET data. Notice that all relative trajectory comparisons to RELBET end at GMT 16:37:30 since at this point the Rendezvous Radar was configured for Ku-band communications and RELBET is no longer valid. Furthermore, the Rendezvous Radar was set to low power at 16:11:25 GMT which resulted in increased noise in the radar angles. The poor behavior of RELBET is illustrated in Figure 14(a) where RELBET and the GNFIR post-processed solution diverge at precisely the time at which the Ku-band is turned off. This can be seen in the $C1_1$ axis, and a few minutes earlier along the $C1_2$ axis. The $C1_3$ axis shows an approximate 20 m bias during the entire GNFIR tracking window. The rendezvous image shown in Figure 14(c) shows the GNFIRground solution overlayed on a flight image at 16:44:37 GMT. While errors on the order of a single-digit meter and degree may not be perceptible to the human eye in this image, the solution clearly does not contain an error of 20 m.

Table 2 Pose estimation differences from GNFIR and ULTOR solutions

Description		Position (meters)		Attitude (degrees)		
(R=Rendezvous, D=Deploy)		Range	Lateral	Roll	Pitch	Yaw
(R)	GNFIR Flight/RELBET	22.2[a]	4.60[a]	1.22[b]	1.53[b]	1.79[b]
(R)	GNFIR RNS1 Ground/RELBET	22.5[a]	4.62[a]	1.45[b]	1.25[b]	1.46[b]
(R)	GNFIR RNS2 Ground/RELBET	–	–	1.20[b]	8.69[b]	10.2[b]
(R)	ULTOR Ground/RELBET	22.7[a]	4.16[a]	0.75[b]	2.49[b]	1.99[b]
(R)	ULTOR Ground/GNFIR Ground	1.55	0.30	0.79	2.80	3.12
(R)	GNFIR Flight/GNFIR Ground	0.43	0.063	0.19	0.81	0.57
(D)	GNFIR Flight/SRMS	0.75[a]	0.24[a]	0.74[a]	0.92[a]	0.91[a]
(D)	GNFIR Ground/SRMS	0.76[a]	0.23[a]	0.75[a]	0.99[a]	0.93[a]
(D)	ULTOR Ground/SRMS	0.64[a]	0.18[a]	3.99[a]	3.77[a]	4.85[a]
(D)	GNFIR Flight/SRMS Published	0.061	0.17	0.84	1.33	0.74
(D)	GNFIR Ground/SRMS Published	0.078	0.18	0.82	1.43	0.74
(D)	ULTOR Ground/SRMS Published	0.048	0.091	3.42	3.02	4.2
(D)	ULTOR Ground/GNFIR Ground	0.10	0.19	5.40	1.89	3.90
(D)	GNFIR Flight/GNFIR Ground	0.015	0.022	0.60	0.40	0.30

[a]RELBET position and as flown SRMS-derived position and attitude are biased, as discussed in *Truth Reconstruction Issues*

[b]RELBET Attitude is valid (derived directly from Shuttle and HST onboard attitude solutions)

SRMS Joint Angles

A first glance at the deploy results shows GNFIR's pose estimate compared to pose reconstructed using SRMS joint angles with an error of 0.9 m. However, when comparing the Mission Evaluation Workstation Software (MEWS) SRMS joint angles to *published* SRMS joint angles in Ref 9, specifically at berth, a difference of 1-3° per joint was discovered. At berth, HST is physically constrained to the Shuttle so a discrepancy this size cannot be ignored. A 2° error on a 7 m arm length causes 0.25 m of error at the end of the arm. The discrepancy is illustrated in Figure 14(b) where a plot of the published SRMS joint angles lies near the GNFIR solution, and the MEWS SRMS data exhibits a bias. The SRMS published joint angles[9] placed HST directly on top of the latch and at the correct orientation, whereas the MEWS data places HST down into the latching mechanism by approximately 0.75 m.

Pose Algorithm Post-Processing Improvements

The post processed solutions for GNFIR and ULTOR sought to change as little as possible from the flight algorithms to generate comparison data. For either algorithm to successfully track HST during rendezvous, the algorithms had to be looking for it in the right place, as described in the Rendezvous Operations section. The changes to GNFIR to process rendezvous imagery in RNS1 entailed nothing else aside from allowing the algorithm to determine a pose for each image[††]. The result was slightly improved quality over the course of the rendezvous, and an extension of the tracking window to a total time of 27 minutes and 28 seconds. In the case of RNS2, the algorithm required minor modifications to the HST stick-model to increase the quality of the pose solution

[††]Flight processing by GNFIR was slightly less than 3Hz

using available features, and a modification to the acquisition to compensate for the shifted rendezvous trajectory. With these modifications, the algorithm was able to track for 1 minute and 43 seconds. No modifications were necessary to reprocess RNS3 imagery for deploy. The result was a tracking window of 18 minutes and 39 seconds.

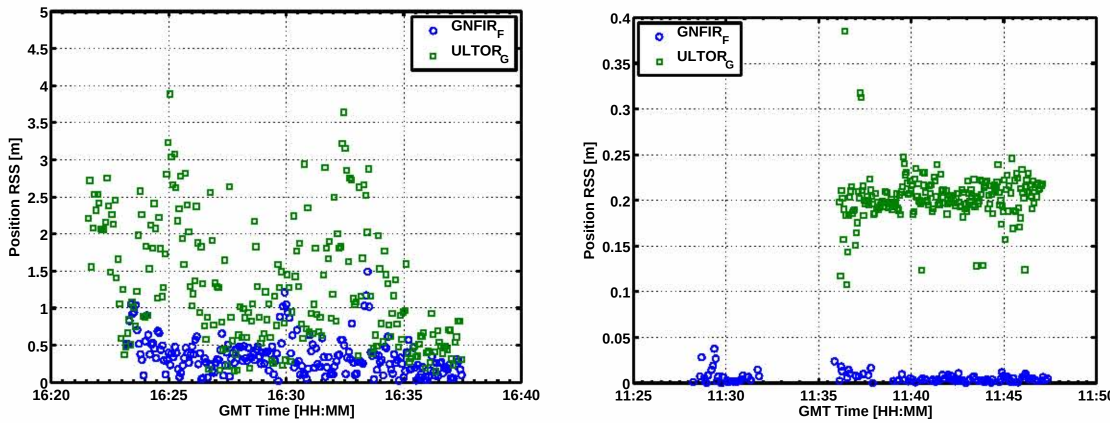
Regarding ULTOR, the AOS team discovered a software bug in the tracking mode that resulted in losing the track of HST midway through the RNS1 imagery on rendezvous. When corrected, ULTOR was able to track HST using rendezvous imagery for 20 minutes and 20 seconds. For deploy, AOS discovered that features selected from the training data, and their subsequent filters, were not optimal given the size of HST in the FOV of RNS3. Most of the features selected were associated with the center docking target. The training data used to develop these filters did not adequately model the lighting conditions, reflectivity and contrast encountered on-orbit. This resulted in only two or three features providing the tracking information, and ULTOR requires at least four features to produce a 6DOF pose estimate. To resolve this, ULTOR was placed into a higher resolution *windowing* mode for enhancing features on the target. This mode was not included in the flight version of the software. To create a post-processed solution, AOS modified the training imagery to more accurately reflect the actual contrast of the SCM features and enabled the *windowing* mode. This resulted in a consistent track of HST for 10 minutes and 44 seconds at the RIP position using deploy imagery.

Ground Results

In light of the issues with the flight data provided by the Shuttle, we are unable to provide a truly independent measure of the relative position of the Shuttle and HST. We now utilize the GNFIR post-processed solution as a measurement of the relative position. Figure 16(a) shows a comparison of the GNFIR flight pose and the ULTOR post-processed pose solutions to the GNFIR post-processed solution during rendezvous. This data shows improvement in the position differences. The RSS position error in Table 2 gives an error of 0.43 m in range for GNFIR and a 1.55 m error for ULTOR. Comparing these to the desired accuracy given in Table 1 of 1 m, GNFIR is better than the requirement, but ULTOR exceeds it. Figure 17(a) shows a comparison of the attitude solutions of the pose sources to the RELBET attitude solution using the principal angle between the two quaternion solutions. For rendezvous, we see for the GNFIR solutions, errors of 1.5° per axis from Table 2 and a total principal angle of 2.5°, and for the ULTOR solution, the accuracy resulted in 5° in roll and 2.5° for pitch/yaw from Table 2. Both solutions are much better than the desired accuracy of 15° stated in Table 1.

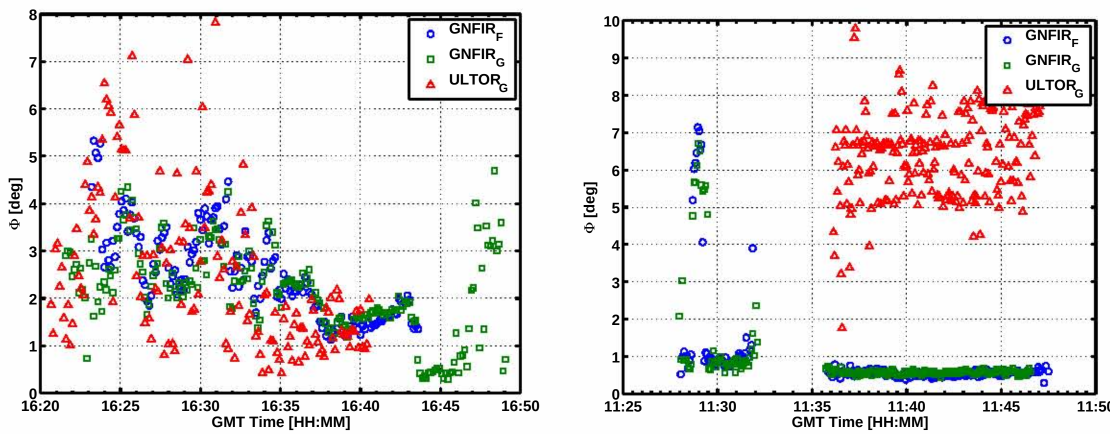
RNS2 is not presented in these plots due to the short time tracking window, but results were tabulated against the Postflight Attitude and Trajectory History (PATH) attitude solution. These errors of 1.2° in roll and greater than 8° in pitch and yaw did not meet the desired accuracy of 5° in Table 1. This again is due to the poor on-orbit lighting conditions as shown in Figure 12.

Figures 16(b) and 17(b) show comparisons of the deploy pose solutions. In the case of position, the GNFIR flight pose solution and the ULTOR pose solution are compared to the GNFIR post-processed solution. We see here that the error between the two GNFIR solutions is much smaller at 5 cm or less, whereas the ULTOR solution shows errors of 0.2 m. When compared to the *published* joint angles, the position solutions for both GNFIR and ULTOR show differences less than 10 cm. These differences are on par if not better than the desired accuracy of 0.1 m stated in Table 1. In comparing attitude solutions in Figure 17(b), we see less than 1° error for both sets of GNFIR pose solutions, however ULTOR shows a 7° error from the reconstructed pose solution from SRMS joint



(a) Rendezvous (b) Deploy

Figure 16 Position Comparison of GNFIR post-processed solution to GNFIR flight data and ULTOR post-processed solution



(a) Rendezvous (b) Deploy

Figure 17 Principal Angular Differences between Shuttle BET and GNFIR flight, GNFIR post-processed, and ULTOR post-processed

angles. The GNFIR solution is well under the desired accuracy of $1°$ and $5°$ for roll and pitch/yaw, respectively, from Table 1, however ULTOR exceeds the desired with a $4°$ difference in roll and a $6.14°$ difference in pitch/yaw.

A final note regarding the results presented here regards the accuracy of these relative measurements. The alignment of the RNS system to the Shuttle Atlantis can only be determined to approximately a degree. The alignment error of the RNS system to the MULE is well documented and determined to be $0.05°$. However, it was not possible to measure the alignment of the MULE to the Shuttle, but it is assumed to be on the order of one degree at worst.

CONCLUSIONS

The RNS system met its goal of imaging, recording and computing pose estimates of HST during its rendezvous with and deploy from Shuttle Atlantis for the SM4 mission. The GNFIR pose algorithm tracked HST on rendezvous for 20 minutes and 27 seconds with a peak solution quality of 99.2 %. During the deploy sequence, GNFIR tracked HST for a total of 15 minutes and 31 seconds with a peak quality of 87.1 %. The inability of the ULTOR algorithm to track HST during rendezvous is linked to the RNS system not being configured for the change in the relative trajectory detailed in the Rendezvous Operations section. In the case of the deploy sequence, AOS's oversight to not include the *windowing* mode in the ULTOR flight algorithm resulted in a lack of on-orbit tracking. However, in post-processing ULTOR was able to track HST for 20 minutes and 20 seconds using rendezvous imagery, and 10 minutes and 44 seconds using deploy imagery.

In determining the accuracy of the pose solutions, several issues arose in reconstructing *truth* data. The best estimated trajectory provided by the Shuttle program includes a 20 m error during rendezvous due to issues with the Rendezvous Radar, and a 0.75 m error during the deploy sequence from joint angle measurements of the SRMS. The attitude solutions using the PATH solution and SRMS joint angles offers a much better comparison.

Therefore, to determine position accuracy, it was necessary to use a post-processed solution from the GNFIR algorithm. This comparison resulted in range errors during rendezvous of 0.43 m for GNFIR and 1.55 m for ULTOR. Note that the peak quality for the GNFIR post-processed solution was 99.2 %. These results were in the regime of the desired accuracy given in Table 1 of 1 m. In the case of attitude errors during rendezvous, comparisons to the PATH data show an error of 2.4° RSSfor GNFIR and an error of 3.27° RSS for ULTOR. These values are well below the desired accuracy of 15°.

For the deploy comparison using RNS3, again the GNFIR post-processed solution was utilized to compare position estimates. Comparison to GNFIR flight data resulted in less than 5 cm error in position while ULTOR resulted in a 0.2 m error in position. The peak GNFIR quality for the post-processed solution was 87.1 %. Regarding attitude accuracy, the GNFIR solutions show a less than 1° principal angle error, while the ULTOR data shows a 7° error in the principal angle. This principal angle error is an error generated by comparing quaternions. The desired accuracy for the short range camera, RNS3, was given in Table 1 as 1° in roll and 5° in pitch/yaw. From Table 2, GNFIR meets these easily, however ULTOR, with errors larger than 5° Root Sum Squared (RSS) does not.

There is no denying the overall success of the RNS experiment on STS-125. When delving into the detailed comparison data, the success is somewhat tempered by the comparison to *truth* but was sufficient to meet the project's stated goals (Table 1). The lessons learned on RNS are directly applicable to future AR&D scenarios and the collected data is a valuable asset for pose algorithm development.

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ACRONYMS AND ABBREVIATIONS

6DOF Six Degree of Freedom

AR&D Autonomous Rendezvous and Docking

AGC Automatic Gain Control

AOS Advanced Optical Systems

COAS Crewman Optical Alignment Sight

FOV Field of View

FSS Flight Support Structure

Geomod Geometry Modeling Tool

GMT Greenwich Mean Time

GNFIR Goddard Natural Feature Image Recognition

GPS Global Positioning System

GSFC Goddard Space Flight Center

HST Hubble Space Telescope

HRSDM Hubble Space Telescope Robotic Servicing and De-orbit Mission

ICD Interface Control Document

IMU Inertial Measurement Unit

JSC Johnson Space Center

KSC Kennedy Space Center

MEWS Mission Evaluation Workstation Software

MET Mission Elapsed Time

MULE Multi-use Logistic Equipment Carrier

MSM Mass Storage Module

NASA National Aeronautics and Space Administration

P3E Passive Pose and Position Engine

PATH Postflight Attitude and Trajectory History

Phillum Physical Illumination

POCC Payload Operations Control Center

RELBET Relative Best Estimate Trajectory

RGT RNS Ground Terminal

RIP RNS Intermediate Position

RMS Root Mean Square

RNS Relative Navigation Sensor

RNS1 RNS Camera 1 (long range)

RNS2 RNS Camera 2 (medium range)

RNS3 RNS Camera 3 (short range)

RPOD Rendezvous Proximity Operations and Docking

RSS Root Sum Squared

SCM Soft Capture Mechanism

SM4 Servicing Mission 4

SMIT Servicing Mission 4 Integrated Timeline

SRMS Shuttle Remote Manipulator System

STOCC Space Telescope Operations Control Center

TM Telemetry Module

ULTOR ULTOR P3E

VIM Video Interface Module

VHDL VHSIC hardware description language