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THE RENDEZVOUS MONITORING DISPLAY CAPABILITIES OF THE RENDEZVOUS AND PROXIMITY OPERATIONS PROGRAM

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The Rendezvous and Proximity Operations Program (RPOP) is a laptop computer-based relative navigation tool and piloting aid that was developed during the Space Shuttle program. RPOP displays a graphical representation of the relative motion between the target and chaser vehicles in a rendezvous, proximity operations and capture scenario. After being used in over 60 Shuttle rendezvous missions, some of the RPOP display concepts have become recognized as a minimum standard for cockpit displays for monitoring the rendezvous task. To support International Space Station (ISS) based crews in monitoring incoming visiting vehicles, RPOP has been modified to allow crews to compare the Cygnus visiting vehicle's onboard navigated state to processed range measurements from an ISS-based, crew-operated Hand Held Lidar sensor. This paper will discuss the display concepts of RPOP that have proven useful in performing and monitoring rendezvous and proximity operations.

INTRODUCTION

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RPOP DESCRIPTION

RPOP is a rendezvous and proximity operations situational awareness tool. It is a Windows application, tailored for the IBM/Lenovo Thinkpad laptop computers used by NASA. RPOP acquires visiting vehicle and target vehicle state information (position, velocity, attitude, and attitude rates) from its host vehicle and graphically displays the relative state between the two vehicles. The display can include a plot of the relative motion from multiple measurement sources, display of vehicle and target attitudes, time-graduated coasting trajectory predictions, and piloting overlays tailored to the demands of the mission (approach corridors, hold points, etc). RPOP also contains an input interface to the Hand Held Lidar (HHL) sensor.

RPOP HISTORY

Initial development of requirements for RPOP occurred in 1992 specifically to support Orbiter docking to Mir and ISS. The concept was to develop an application that runs on laptop computer

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in the Orbiter cockpit to provide the pilot relative trajectory information not available on the Orbiter's main computers. The primary purpose of RPOP was to help the Orbiter pilot meet operational flight constraints by providing a common location to view and evaluate data from multiple sensors.

Once the requirements were approved, the RPOP development team used an existing program, Payload Bay (PLBAY), as a baseline that was developed by astronaut Rick Hieb and already certified to run on the laptop computers in the Orbiter cockpit. PLBAY had flown on STS-49 – it allowed the crew to manually enter raw radar data and camera angle data to compute and display in-plane motion of the Orbiter relative to the rendezvous target. This capability was functional, but very constraining from a crew workload perspective. With Rick Hieb's consent, the RPOP team selected PLBAY as the foundation for RPOP development.

The evolution of PLBAY into RPOP began by implementing two extremely important requirements for navigation: 1) ability to process continuous payload-bay laser data, and 2) ability to process data from the Orbiter's General Purpose Computer (GPC). STS-51 was the first developmental flight of the payload-bay laser known as the Trajectory Control Sensor (TCS) and the GPC data extraction program known as PCDecom (later renamed WinDecom). The RPOP team modified PLABAY to add an interface to accept and process these two new sources of data via serial connection and performing a flight test on STS-51. This flight test of RPOP proved that multiple sources of data could be processed, thereby alleviating the previously heavy workload required to manually input data. The successful flight test of RPOP on STS-51 proved the feasibility of displaying navigation data on a laptop computer, while minimizing crew workload.

RPOP was flown and used by Orbiter pilots on every rendezvous mission since STS-51 in 1992 until Orbiter retirement in 2010. This included <??> docking missions with Mir and ISS, as well as <??> small satellite deploy and retrieve missions. Several modifications were made to RPOP during this time, including improved displays, upgrades for new laptop operating systems, and guidance capability to provide the pilot with suggested translational hand controller inputs.

WHY RPOP FOR ISS?

The first block of the Orbital Cygnus vehicle did not meet crew monitoring requirements due to its sensor suite. Cygnus had three identical LIDAR sensors, but the fact that they are identical caused concern over whether all three sensors are susceptible to a common mode failure. NASA required an independent source of range and range rate. The Crew Monitoring Working Group performed trade studies on how to address this issue and proposed to use a Hand Held Lidar (HHL) sensor, which had previously been used during rendezvous for the Space Shuttle program and had been transferred to the ISS.

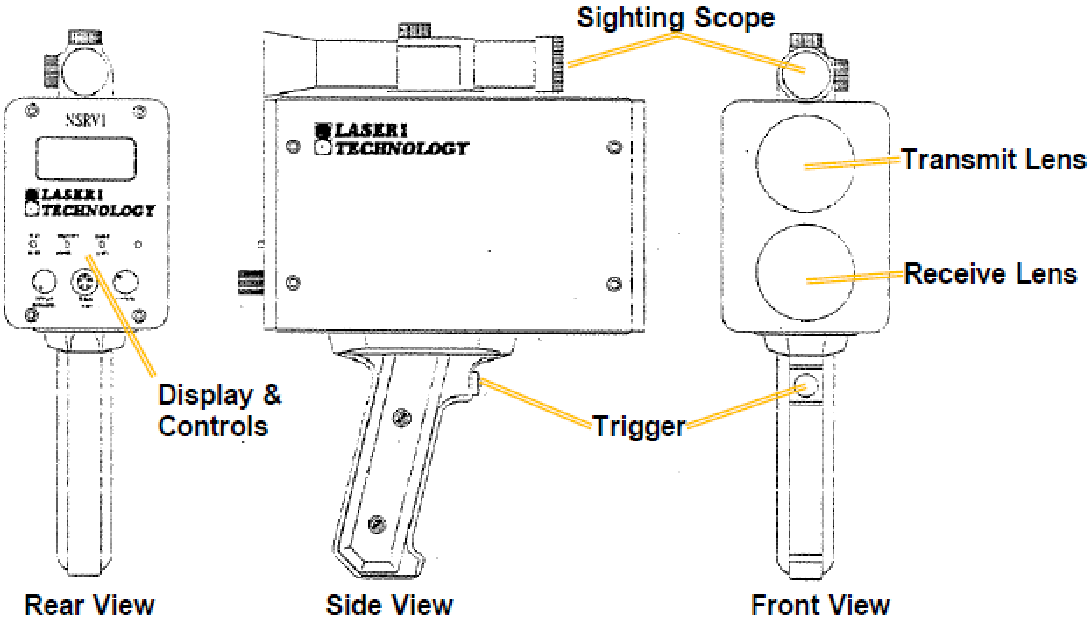


Figure 1. The Hand Held Lidar (HHL) Sensor.

While the HHL provides an independent source of range and range rate, by itself it does not meet crew interface requirements for ISS. The display on the back of the HHL unit displays the range and range rate in units of feet and feet per second, whereas the ISS requirement is for all crew displays to be in Systeme Internationale (SI) units of meters and meters per second.

The Crew Monitoring Working Group proposed using RPOP with the HHL to satisfy the independent range/range rate requirement. Modifications would be necessary to convert RPOP's display to SI units and to make the comparison between the HHL measurements and Cygnus's onboard navigation easier to interpret. To provide data for this comparison, RPOP would need to be modified to enable it to read data from the ISS's telemetry system. It was found in the trade study that even with these modifications, adapting RPOP to a new role held advantages over developing an all-new program to compare the HHL data with the onboard navigation data.

First, RPOP already has an interface to the HHL that allows the HHL to input its measurement via serial cable. This capability was used extensively for the Space Shuttle program, as the HHL was the backup sensor to the Orbiter's main rendezvous sensor for ISS missions. The interface allows the crew to connect the HHL to the laptop with an RS-232 serial cable, and the RPOP software will automatically display, process, and record HHL measurement data whenever the trigger is pulled.

Another advantage to using RPOP is that, once the modifications are made to allow the input of data from the ISS telemetry system, all of the graphics and display concepts that made RPOP valuable during the piloting of a Space Shuttle rendezvous (such as the relative motion plot, predicted trajectory, etc) are immediately operational and available. These displays present data differently than the existing rendezvous monitoring displays and make a good supplement to the required displays.

A final advantage to RPOP is that ISS crews that have previously flown on Space Shuttle missions are familiar with the RPOP user interface, reducing the training necessary to use it in a new application.

RPOP FOR SPACE SHUTTLE

For the Space Shuttle program, RPOP was used as an aid during the piloting task for rendezvous missions. RPOP processed and displayed data from multiple data sources to improve the situational awareness of the rendezvous pilot.

RPOP read GN&C data from the Shuttle Orbiter's GPC such as onboard state vector estimates, measurements from the rendezvous radar and Inertial Measurement Unit (IMU), the Trajectory Control Sensor (a scanning LIDAR) and the Hand Held Lidar. RPOP processed the data from all of these sources and displayed the resulting trajectory from each source on its relative motion plot. This allowed the user to easily compare the results from each measurement source to assess the health of the navigation estimate and to determine if any of the measurement sources were providing unreliable results.

RPOP also included an extended Kalman filter to process measurements from the Trajectory Control Sensor (TCS). The TCS Navigation filter (TCS NAV) allowed RPOP to improve the accuracy of its state estimate well enough to satisfy the rate envelope for the docking mechanism.

RPOP also included some rendezvous guidance capability. Based on the navigation data from either the onboard state vector or TCS NAV, the guidance provided the crew with piloting suggestions to fly a more propellant-efficient trajectory.

In addition, RPOP was run in NASA's Mission Control Center using space-to-ground telemetry as an input. This gave ground operators insight into what information and cues the crew was using to decide how to fly their approaches.

RPOP FOR ISS

A key difference in RPOP's role on the International Space Station is that RPOP would be used as a monitoring aid rather than as a piloting aid. Despite this difference, the functionality of the display is largely the same, with the same displays of relative motion, attitude, trajectory predictions, and static overlays. The key difference that tailors RPOP specifically for the monitoring capability is the transformation of the Cygnus relative state into an equivalent HHL range measurement for comparison. In dedicated part of the display, the HHL Measurement and RPOP's transformed estimate are both displayed along with the absolute and percentage differences between the two. Color coding indicates whether or not the difference is within pre-set margins of error.

RPOP Requirements

The modifications to RPOP had to satisfy the following requirements:

- RPOP shall run on a Lenovo Thinkpad T61p model laptop. These are the laptops that are used by the crew onboard the ISS. This was a difference from the laptop model that was used for the Space Shuttle program, especially in the screen size. The layout of the information of the screen had to be changed to be compatible with the aspect ratio of the T61p.
- The units of all data on the display shall be in SI units, due to ISS cockpit display requirements.
- The RPOP program shall read data from the ISS telemetry system.
- RPOP shall calculate and display a comparison between the HHL measurement and the visiting vehicle's state vector.
- RPOP shall correctly operate while the visiting vehicle is closer than 1 km.

HHL PERFORMANCE

1. Computation of the Cygnus state vector-derived range rate

Consulting figure 1, we see that the position vector from the HHL to the aim point on Cygnus is

$$\mathbf{r}^{(LVLH)}_{HHL\ to\ aimpt|Cygnus} = \mathbf{r}^{(LVLH)}_{ISS\ CG\ to\ Cygnus\ CG} + \mathbf{r}^{(LVLH)}_{Cygnus\ CG\ to\ aimpt} - \mathbf{r}^{(LVLH)}_{ISS\ CG\ to\ HHL}$$

All of the vectors in the previous equation are expressed in the LVLH reference frame. Note that the last two vectors on the right-hand side are fixed in their respective bodies; therefore, neglecting small attitude errors we have $\delta\mathbf{r}_{HHL\ to\ aimpt|Cygnus} = \delta\mathbf{r}_{ISS\ CG\ to\ Cygnus\ CG}$. Then it follows that

$$\mathrm{Cov}(\mathbf{r}_{HHL\ to\ aimpt|Cygnus}) = \mathrm{Cov}(\mathbf{r}_{ISS\ CG\ to\ Cygnus\ CG})$$

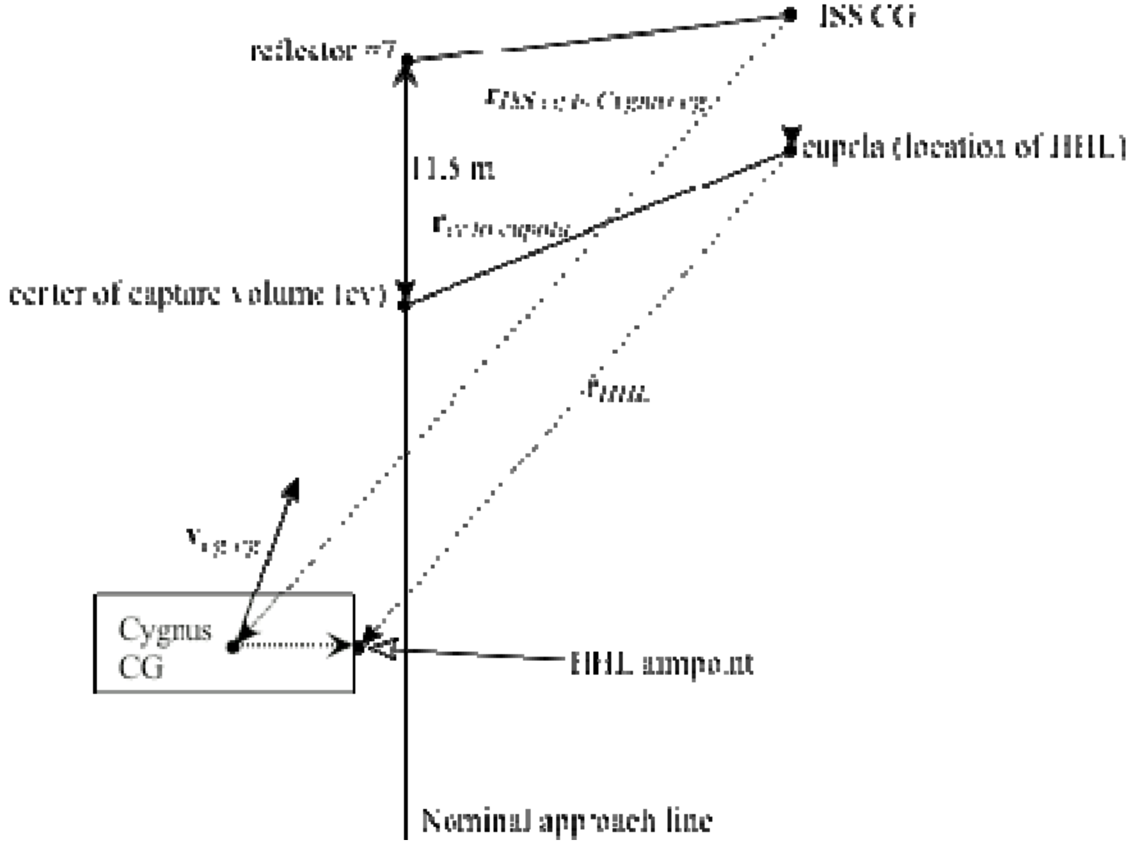


Figure 1: More HHL measurement geometry

It can be shown that the range rate compatible with the HHL range rate measurements, but derived from the Cygnus data is approximately

$$\dot{r}_{HHL|Cygnus} \approx \frac{\mathbf{v}^{(LVLH)}_{Cygnus\ cg\ \mathrm{wrt}\ ISS\ cg} \bullet \mathbf{r}^{(LVLH)}_{HHL\ to\ aimpt|Cygnus}}{r_{HHL\ to\ aimpt|Cygnus}}$$

Here, the notation “|Cygnus” indicates that the computation is done with the Cygnus data.

We give a comparison of the range rate that would be measured by the Cygnus LIDAR tracking reflector #7, and the range rate of Cygnus with respect to the HHL’s location at the cupola. Figure 2 shows this comparison from 30 m to the capture point. This shows why we transform the Cygnus-computed range rate to a range rate compatible with the HHL measurement.

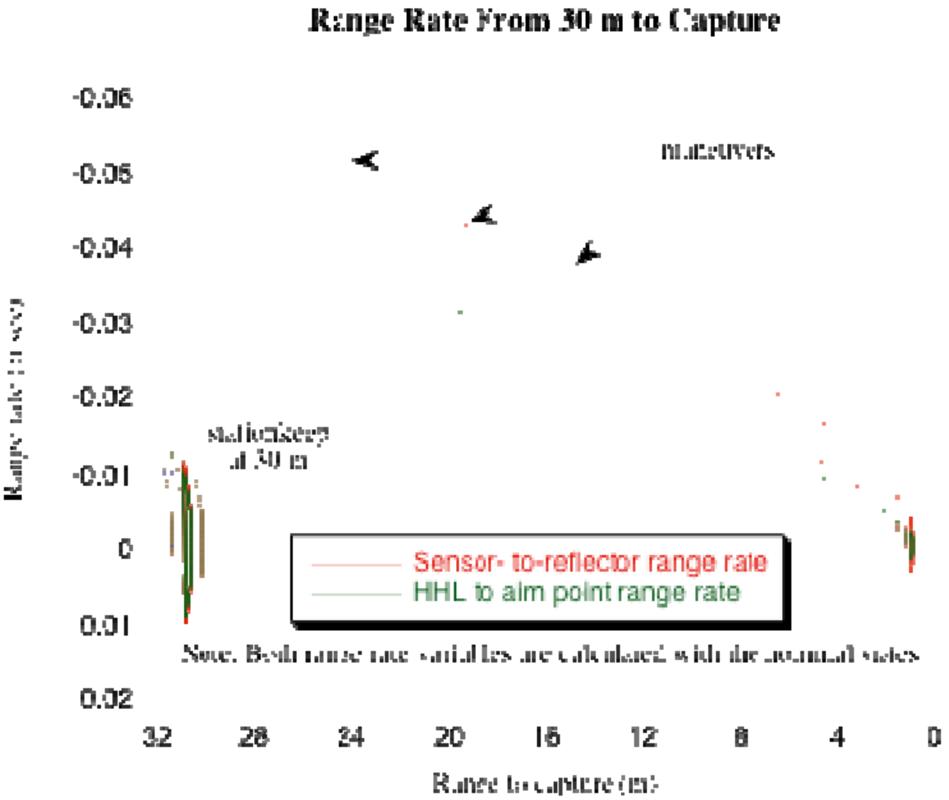


Figure 2: Nominal range rate from 30 m to capture

2. An expression for the variance of the Cygnus-derived range rate

Henceforth, we suppress the “|Cygnus” designation for brevity (except when needed for clarity). Also, we denote the CG-to-CG state by simply $\mathbf{v}_{cg\text{-}cg}$, and $\mathbf{r}_{HHL\ to\ aimpt}$ is replaced by $\mathbf{r}_{HHL}$. From the last equation in the preceding section we find that the error in the range rate estimated from the Cygnus state vectors can be expressed as

$$\delta\dot{r}_{HHL|Cygnus} = \frac{\partial\dot{r}_{HHL}}{\partial\mathbf{r}_{HHL}}\delta\mathbf{r}_{HHL} + \frac{\partial\dot{r}_{HHL}}{\partial\mathbf{v}_{cg-cg}}\delta\mathbf{v}_{cg-cg}$$

After computing the partial derivatives (defined as row vectors), substituting into the previous equation, and computing the variance of the error we obtain

$$\begin{aligned}\mathrm{Var}(\delta\dot{r}_{HHL|Cygnus}) = {} & \left[\frac{\mathbf{v}_{cg-cg}}{r_{HHL}} - \frac{\mathbf{r}_{HHL}}{r^3_{HHL}}(\mathbf{r}_{HHL} \bullet \mathbf{v}_{cg-cg})\right]\mathrm{Cov}(\delta\mathbf{r}_{cg-cg})\left[\frac{\mathbf{v}_{cg-cg}}{r_{HHL}} - \frac{\mathbf{r}_{HHL}}{r^3_{HHL}}(\mathbf{r}_{HHL} \bullet \mathbf{v}_{cg-cg})\right]^T \\ & + \frac{\mathbf{r}_{HHL}}{r_{HHL}}\mathrm{Cov}(\delta\mathbf{v}_{cg-cg})\frac{\mathbf{r}^T_{HHL}}{r_{HHL}} - \left[\frac{\mathbf{v}_{cg-cg}}{r_{HHL}} - \frac{\mathbf{r}_{HHL}}{r^3_{HHL}}(\mathbf{r}_{HHL} \bullet \mathbf{v}_{cg-cg})\right]\mathrm{Cov}(\delta\mathbf{r}_{cg-cg}, \delta\mathbf{v}_{cg-cg})\frac{\mathbf{r}^T_{HHL}}{r_{HHL}}\end{aligned}$$

The preceding expression is the variance of the Cygnus filter's estimate of the range rate to the HHL.

The error in the HHL/DT range rate measurement derived by RPOP from the HHL range measurements is independent of the error in the estimate derived from the Cygnus state vector. Denote the error in the measurement by $\delta\dot{r}_{HHL/DT}$. The variance of the difference of the two estimates is

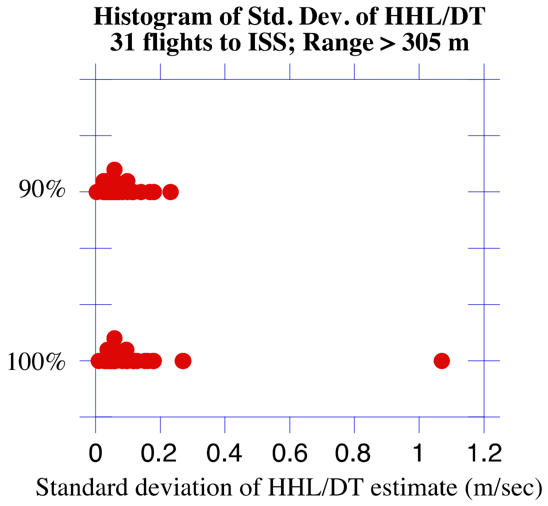
$$\mathrm{Var}(\delta\dot{r}_{diff}) = \mathrm{Var}(\delta\dot{r}_{HHL|Cygnus}) + \mathrm{Var}(\delta\dot{r}_{HHL/DT})$$

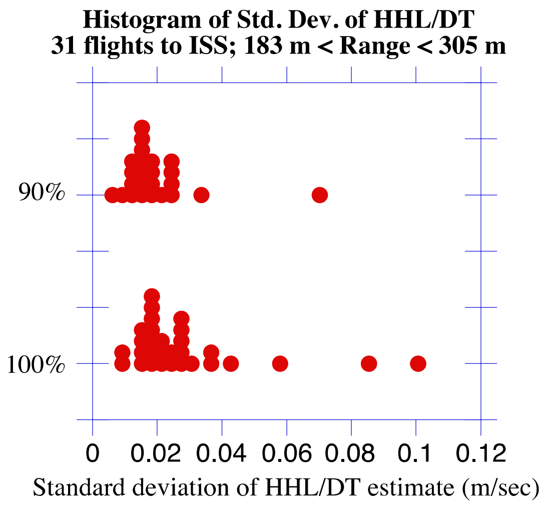
The variance of the error in the HHL/DT calculation was estimated on 31 of the last 32 flights of the Space Shuttle to the ISS (ref. 1). The variance differs between HHL operators, but the envelope of values is known. Not surprisingly, the variance is a function of range.

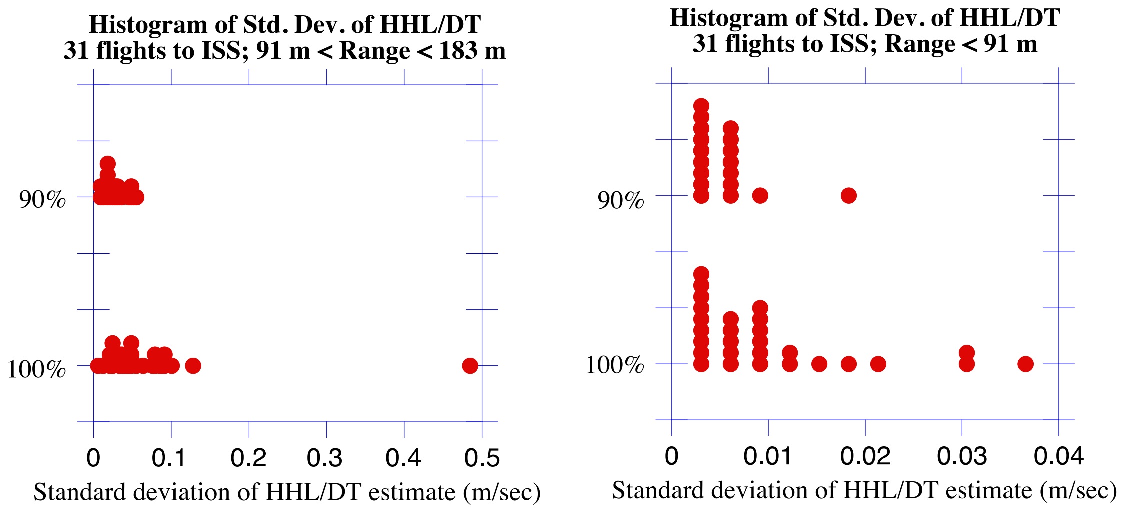
3. HHL/DT accuracy

Thus far, we have not discussed the accuracy of the HHL measurements. We did extensive analysis of the performance of the HHL after many Space Shuttle flights. There is no guarantee that the performance of the HHL will be the same with Cygnus as our experience with shuttle astronauts shooting the HHL at the ISS. Considering that Cygnus is a much smaller target, it may be more difficult to obtain a laser return at long range.

Also, accuracy of the HHL on Space Shuttle flights varied considerably from operator to operator. Figures 3–6 each show two histograms. The bottom histogram shows all of the data, and the top histogram shows the data with the 5 percent most extreme points from each tail deleted (the same as in the tables). Each dot in each histogram represents the standard deviation of the HHL/DT for a single flight at the given range.


Histogram of Std. Dev. of HHL/DT
31 flights to ISS; Range > 305 m


Histogram of Std. Dev. of HHL/DT
31 flights to ISS; 183 m < Range < 305 m



Figures 3–6: Histograms of the standard deviation of HHL/DT at various ranges

4. Other considerations in developing thresholds

Data on the Cygnus display will be colored yellow if the Cygnus-derived estimate differs from the HHL estimate by a threshold. If the threshold is too small, the crew will be frequently given what amounts to an alarm, when actually there is no degradation of the Cygnus navigation (i.e., a false alarm, corresponding to a Type I error in statistics). If the threshold is too large, use of HHL on ISS will have little capability to detect an error in the Cygnus navigation (i.e., a false negative, corresponding to a Type II error in statistics). The goal is to choose a threshold that has adequate capability to detect a Cygnus navigation error, but does not lead to frequent false alarms. We expect that the threshold should be a function of range.

The operator data presented in this report are taken from HHL measurements of the very large ISS target taken from the Space Shuttle Orbiter. Very large errors are obtained when the operator was not aiming at the assumed point on the ISS. Cygnus is much smaller than the ISS, being about 5 m in length and 3 m in diameter. An “error” caused by a change in aim point cannot be greater than the size of Cygnus.

If the operator executes a 5-second trigger pull with the HHL, the average change in range would be half the nominal range rate × 5 sec. At 1 km, the nominal range rate is –1.6 m/sec. Therefore, this effect contributes up to 4 m. We assume that the HHL instrument noise may be 1 m. An analysis showed a worst-case range error is about 9.3 m when relative GPS is the source of navigation. Adding these error sources, we obtain 1.5 m (size) + 4 m (movement) + 9.35 m (Cygnus and HHL RSS noise) = 14.85 m. We round this to 15 m. At close range, the three-standard deviation poor operator may see a difference of just less than 3 m. We choose this for the threshold inside a range of 100 m. The threshold varies linearly between ranges of 500 m and 100 m. Therefore, we arrive at the range threshold shown in figure 7 below.

Now we turn to the range rate threshold. As with the range data, the operator data used to derive the expected difference between the HHL and Cygnus estimates are of HHL measurements from the Orbiter to the ISS. Because HHL/DT = $(\mathrm{range}_i - \mathrm{range}_{i-1})/\Delta t$, large range errors affect the HHL/DT calculation. Cygnus is about 5 m in length. But even if the HHL operator were to obtain a return from opposite ends of the vehicle, the difference in range would be small until very close to capture. This leads us to think that the results based on HHL measurements of ISS from the Orbiter are very conservative. Adding 0.02 m/sec (3σ) Cygnus error, 0.04 m/sec pointing error (2 m/50 sec), and a maximum 0.1 m/sec bias at long range results in a sum of 0.16 m/sec. The preceding rationale does not account for additional operator error. Doubling the 0.16 m/sec and rounding, we arrive at 0.3 m/sec. Setting the threshold to 0.03 m/sec at 100 m and varying linearly between 0.3 m/sec at 500 m we arrive at the threshold function shown in figure 8.

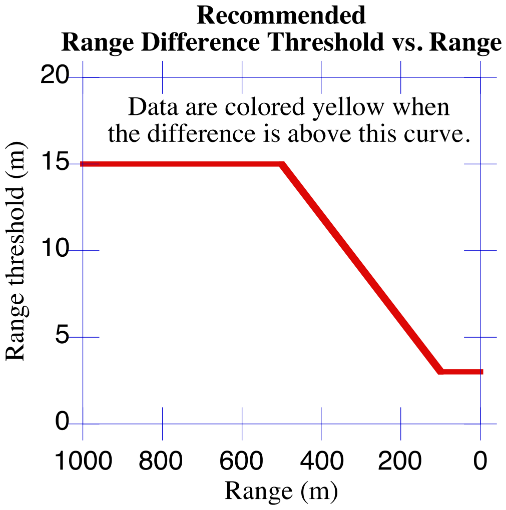


Figure 7: Range threshold vs. range

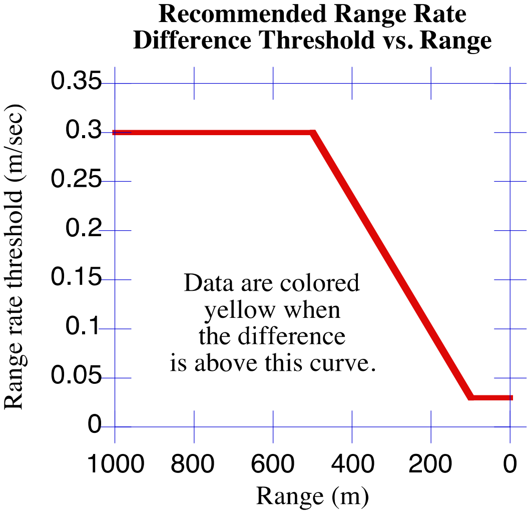


Figure 8: Range rate threshold vs. range

SIMULATION AND TESTING

An essential element required for the development, certification, and ultimately, the operational success of RPOP is a computer simulation test bed capable of feeding RPOP realistic data for operational relevant test scenarios. The Interactive Control and Dynamics Simulation (ICDS) is the primary simulation test bed used in the development and testing of RPOP. ICDS is a high-fidelity two-vehicle earth orbital GN&C simulation capable of simulating visiting vehicle rendezvous and proximity operations with the ISS. ICDS contains sensor models, effector models, and functional GN&C software allowing accurate simulation of mission specific approach and separation trajectories. A very detailed HHL performance model was developed in ICDS to support RPOP development for the Space Shuttle program. This HHL model has been verified with flight data from numerous Space Shuttle flights. This same HHL model was used for RPOP for ISS development and testing, where its simulated location instead was moved to be based onboard the ISS tracking and measuring the visiting vehicle. ICDS also includes serial and Ethernet network communication for sending both the simulated HHL data as well as the Cygnus onboard GN&C telemetry data required by RPOP.

For RPOP certification, a series of functional, performance and interface test cases were developed in ICDS for each required scenario. In the actual testing, ICDS serial and network communication cables were connected to RPOP while the test was being executed. During this time, RPOP is running just as it would onboard the ISS, taking in and processing telemetry from Cygnus, the ISS, and measurement data from the HHL. In this setup, RPOP does not know it is connected to a simulation, and responds to data and user interaction inputs just like it would in flight.

OPERATIONAL CONCEPT

The ISS crew will be using several tools to gather information about the relative trajectory of the approaching visiting vehicle. RPOP will supplement these tools to provide additional information that can be used to confirm the position of the visiting vehicle.

RPOP receives relative state (position an velocity) data continuously via telemetry from the visiting vehicle. This data is processed and displayed graphically on an LVLH relative motion plot and updated continuously. The relative motion plot depicts several important pieces of information, including: 1) the current position and attitude of the visiting vehicle relative to the ISS, 2) the history of relative position creating a relative trajectory, 3) a prediction of future positions otherwise known as predicted trajectory in one-minute increments, 4) reference trajectory and constraint overlays, and 5) digital relative position and velocity data. The ISS crew can quickly look at this display and ascertain the current state of the visiting vehicle relative to trajectory constraints.

<Decide how to describe/organize paragraphs for generic RPOP capability versus Cygnus-specific capability using HHL.>

For Cygnus, RPOP will run on a laptop computer positioned in the cupola of the ISS attached via RS-232 serial cable to the hand-held LIDAR (HHL). <Add an ISS figure showing the cupola.> An ISS crewmember will periodically aim and shoot the HHL through the cupola window at the approaching Cygnus vehicle. The range and range-rate measurements from the HHL will be sent to RPOP and processed. The Cygnus-computed relative navigation state will be sent to RPOP via PCS-DAS. RPOP will display the Cygnus-computed relative range and range-rate and the HHL-derived relative range and range-rate so that the ISS crewmember can compare the two sources of data. <Add Rdot window display from RPOP.> <Add figure of Cygnus relative trajectory.>

The ISS flight rules are unchanged with the addition of RPOP to the toolset used by the ISS crew for monitoring. RPOP is considered situational awareness only – it is not safety or mission critical. While, the ISS crew will use information from RPOP to supplement other tools and data, the crew will not make an abort call based on RPOP information only. However, if RPOP provided information that indicated the visiting vehicle was out of positional limits, the crew could contact the ground controllers to inquire.

<Add paragraph about RWS and other tools used to monitor.>

References

1. Clark, F. D., “HHL Range Rate Performance Analysis for STS-135,” SSV-11-009, GCD-11-490, 14 Jul 2011.