

The Sensor Test for Orion RelNav Risk Mitigation Development Test Objective

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The Sensor Test for Orion Relative-Navigation Risk Mitigation (STORRM) Development Test Objective (DTO) flew aboard the Space Shuttle Endeavour on STS-134, and was designed to characterize the performance of the flash LIDAR being developed for the Orion. This flash LIDAR, called the Vision Navigation Sensor (VNS), will be the primary navigation instrument used by the Orion vehicle during rendezvous, proximity operations, and docking. This paper provides an overview of the STORRM test objectives and the concept of operations. It continues with a description of the STORRM's major hardware components, which include the VNS and the docking camera. Next, an overview of crew and analyst training activities will describe how the STORRM team prepared for flight. Then an overview of how in-flight data collection and analysis actually went is presented. Key findings and results from this project are summarized, including a description of "truth" data. Finally, the paper concludes with lessons learned from the STORRM DTO.

I. Introduction

The Orion Crew Exploration Vehicle (CEV) is a new crewed vehicle being designed by NASA and Lockheed Martin to ferry humans to/from the International Space Station (ISS) and other possible exploration destinations. One particularly challenging flight phase of the Orion mission is rendezvous, proximity operations, and docking (RPOD). The unique requirements and constraints of the Orion vehicle make off-the-shelf relative navigation sensors insufficient for achieving the required relative navigation performance. Therefore, a new relative navigation sensor is being developed. The Vision Navigation Sensor (VNS) is a flash LIDAR and will be the primary navigation instrument used by the Orion during the RPOD flight phase.

Past experience suggests that on-orbit testing is critical to gaining confidence that the VNS will perform as expected. In fact, as is shown in Fig. 1, many previous relative navigation sensors have experienced difficulties on-orbit that were not predicted by ground testing. This need led the Orion GNC team to propose the Sensor Test for Orion Relative-Navigation Risk Mitigation (STORRM) Development Test Objective (DTO).

The STORRM DTO is scheduled to fly aboard the Space Shuttle Endeavour on STS 134, and will test the Orion Vision Navigation Sensor (VNS) and the high-resolution Docking Camera (DC) in an on-orbit environment. The objective is to collect data from these sensors to mitigate the loss-of-mission risk in upcoming Orion test flights and to increase the technology readiness level (TRL) of these sensors.

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Condition	Sensor												
	SVS	TCS	Rendezvous Radar	Star Tracker	ESA's RVS	HHL	OPTEC LIDAR	VGS/AVGS	Sandia LDRI	Neptec LCS	Kurs	RGPS-ESA	RGPS RME
Orbital lighting/reflections/shadows	■			■		■							
Background interference				■									
Longer range performance		■						■					
Acquisition range			■	■			■						
Higher velocities at longer range					■								
Modeling of real target vehicle in lab								■					
Potential hot spots		■	■	■	■			■					
Obscuration		■											
Multi-path												■	
Long-term exposure of targets to space environment		■											
Vehicle dynamics		■				■							
Dynamics of transitions during prox ops trajectory													
Performance in space environment		■			■		■	■				■	■
Coupling between dynamic and environmental effects							■	■				■	■
Sensor moding/transitioning								■				■	■

Figure 1. Historical survey of difficulties experienced by previous relative navigation sensors.

II. Mission Objectives & Concept of Operations

The overall STORM Mission Objectives are to test the on-orbit performance of the VNS and the DC on three different trajectories: (1) a nominal Orbiter RPOD trajectory to the ISS, (2) a nominal Orbiter undocking trajectory from the ISS, and (3) an Orion flight rendezvous/proximity operations trajectory to the ISS. To meet these objectives the Space Shuttle will separate from the ISS and then perform an unprecedented re-rendezvous with the ISS to within 1000 feet. The mission objectives are achieved by meeting the flight test objectives identified for each of the sensors. A summary of those flight test objectives are shown in Table 1 for the VNS, and in Table 2 for the DC.

To achieve these flight test objectives, plans were put into place with the Shuttle Program to allow for command and control of the sensors and recording rates from a laptop computer in the crew cabin. Various parameters that will eventually be controlled internally to the sensors were externally controlled for STORM. To facilitate the commands to the sensors, a STORM Software Application (SSA) was developed. This laptop application will be monitored by a Mission Specialist during the mission. One of

Table 1. Summary of VNS objectives.

Objective	Primary	Secondary
Characterize the ISS in the VNS wavelength (hot spots, reflectance map, etc.)	X	
Determine initial acquisition range	X	
Prove operation with large relative velocities	X	
Collect data through known break track and reacquire conditions	X	
Prove tracking through accelerations while maneuvering	X	
Demonstrate transition between 3-DoF and pose modes	X	
Allow for overlap with ground testing facilities	X	
Collect data to support pose calculation	X	
Characterize the ISS PMA2 augmented docking target	X	
Determine range of pose acquisition		X
Prove tracking through TPI-type maneuver		X
Long range "loss of signal"		X

Table 2. Summary of DC objectives.

Objective	Primary	Secondary
Prove operation in harsh orbital lighting conditions	X	
Collect images to support assessment of validity for piloting cues	X	
Assess DC as a potential backup to star tracker for mid-range bearings		X
Collect images to support Natural Feature Image Recognition analysis		X

the goals for the SSA was to minimize crew time and interaction, which lead to the implementation of a range-based control of the sensor settings. The range was obtained from either Orbiter onboard filtered range or from the Orbiter laser sensor, the Trajectory Control Sensor (TCS). The TCS data will later be used as “truth” measurements for comparison with the VNS data.

Primary STORRM data collection opportunities will take place on flight day 3 (day of rendezvous with ISS) and flight day 13 (day of undock) of the STS 134 mission. Preceding each data collection, a special procedure and software phase will be executed. This procedure is called “Tools Checkout.” Tools Checkout consists of a timed set of operations which mode the sensors and data recorders in a predetermined sequence. Completion of Tools Checkout assures the proper function of the STORRM equipment and all associated connections from onboard through the ground are properly made.

Data collection for the experiment is divided in to phases: Rendezvous, Undock, Re-Rendezvous and Separation. The phases, which are bounded by significant environmental or operational events, represent the highest level of decomposition of the mission time-line. The Orbiter trajectory, look-angle to ISS, ISS reflector assets, orbital lighting, sensor configuration, and various other parameters are unique to each phase. These differences provide a variety of collection opportunities from which to better evaluate the sensors. Astronaut action is required to place the SSA into the proper phase of data collection. Within each phase of data collection, the sensor settings are controlled through range bins. Upon entering a new range bin, a set of commands are sent to the sensors and data recorders to properly configure the system for data collection over that range. Sensor settings such as VNS gain, detector settings, field-of-view (FOV) size, and DC data recording are examples of range-based commands. Within each range bin, timed commanding also takes place. The timed commands control the region of interest upon which the DC is calculating automatic gain and exposure settings. This allows the STORRM team to collect valuable performance data on different region of interest sizes that will feed into Orion decisions for DC operations.

III. Overview of STORRM Hardware

The major components on the STORRM experiment are the Sensor Enclosure Assembly, Avionics Enclosure Assembly, Payload General Support Computer, Crew and Ground Operations Station. Each component and their major subsystems are described in the following paragraphs.

The Sensor Enclosure Assembly (SEA) is located on the Orbited Docking System (ODS) Truss adjacent to the relative navigation sensor used by the Orbiter, the Trajectory Control Sensor (TCS). The SEA enclosure contains a the VNS, DC, and keep-alive heaters. The SEA is co-located with the TCS for better truth comparison and to avoid line-of-sight limitations.

The Avionics Enclosure Assembly (AEA) is located on the port sidewall of Payload Bay 3. The AEA consists of data recorders that receive data from the sensors in the SEA, data storage units that store the collected data, and a Power Distribution Unit (PDU) that distributes power to the SEA and AEA. The AEA also passes sensor configuration commands to/from the PGSC and SEA.

The Payload General Support Computer (PGSC) is located in the flight deck of the Orbiter crew cabin. The PGSC is loaded with an application that will initiate data collection and allow the crew and the ground to monitor the health and status of the systems. The experiment is controlled via crew inputs to the PGSC application.

The Ground Operations Station (GOS) consists of computer terminals located in the Mission Control Center (MCC) in Houston, Texas, which also have access to real-time Orbiter telemetry and voice loops. The STORRM personnel monitor the sensor experiment data on the ground at the MCC.

An Orbiter crew member will configure the PGSC and initiate a PGSC application to allow data to be collected automatically. A crew member will also configure the system as necessary when phases of the

experiment have concluded.

Finally, power and data cables are routed from the SEA on the ODS Truss to the AEA on the payload bay sidewall and then through the Orbiter bulkhead into the STORRM PGSC in the crew cabin. Data from the experiment will be downlinked via Sequential Still Video (SSV) and the Orbiter Communications Adapter (OCA). An accurate time signature is provided from the Orbiter. This time signal, called the Payload Timing Buffer (PTB), is routed into the AEA from the Shuttle Payload Bay.

IV. Crew and Analyst Training Activities

The STORRM system interfaces with numerous Orbiter systems and levies unique trajectory requirements on the Orbiter. Because STORRM is highly embedded in the STS 134 mission plan the training activities for the experiment required a three pronged approach:

1. One-on-one sessions with the mission specialist
2. Stand-alone Simulations with all crew members
3. Joint Integrated Simulations with all the STS 134 ground personnel

The one-on-one sessions with the Mission Specialist assigned to STORRM were the primary opportunity to explain the experiment background, LIDAR operation, and the hardware architecture. Additionally, sensitivities relating to the Mission Objectives, and operational timeline were conveyed in these sessions.

The second approach used was Stand-alone Simulations. Stand-alone Simulations are crew training activities that involve all the Shuttle Crew and their timeline of activities as it would happen on the Orbiter during the mission. Stand-alone Simulations take place in the fixed base Shuttle Mission Simulator (SMS) at the NASA Johnson Space Center. The curriculum of these training opportunities focused on execution of the STORRM procedures and proper interface with the STORRM PGSC. Intentional failures are inserted into these training sessions. This training environment provides insight into the intersystem dependencies and helps identify crew workload issues.

The third training approach, the Joint Integrated Simulations, are large scale training opportunities for the entire ensemble of Flight Controllers and analysts involved in the mission. STORRM ground personnel used these opportunities to become accustomed to the voice loop protocols, the SSV telemetry path and various Mission Control resources provided for situational awareness. Joint Integrated Simulations provided end-to-end training for the STS 134 flight.

To carry out this suite of training activities a set of hardware and software components was developed to provide a functional equivalent of the AEA and SEA. This configuration of hardware and software is called the the STORRM Avionics Module. It mimics the physical and electrical interfaces between the PGSC and the AEA.

In addition to the suite of training activities described above, STORRM was given the opportunity to demonstrate the operation of the flight hardware and software to the crew members of STS 134. This training experience was extremely valuable to the crew in that it provided insight into the system timing and sensor image quality that was unachievable in other ground simulations.

This paper will discuss in greater detail the challenges encountered establishing and conducting the extensive training required to meet the STORRM objectives.

V. Data Downlink

Experimental data is transferred to analysts on the ground in two ways: in near real-time through a TV system called Sequential Still Video (SSV) and through a retrieval-downlink process which is called Data Retrieval Mode. The SSV data path employs the Orbiter Photo TV system and the PGSCs ability to render a virtual screen. This data path is configured such that high priority telemetry items are drawn to the virtual screen and then the virtual screen is interleaved into the Orbiter Photo TV stream to the Mission Control Center (MCC). Although the SSV data path is relatively fast (on the order of minutes), the information received is reduced significantly from the volume of data collected. The second way data is transferred to the ground, via Data Retrieval Mode, allows for all data, sensor image, and system health to be analyzed. In Data Retrieval Mode, the PGSC first copies unprocessed blocks of memory from the data storage drives in the Payload Bay on to the PGSC local disk drive. The blocks of data are copied to the from the PGSC disk drive to data storage in MCC via the Orbiter on-board network. The advantages, disadvantages, and

methods employed to maximize the information received will be discussed in greater detail in the full paper.

VI. Data Analysis

A number of tools were developed to quickly process the STORRM data collected on flight day 3 to determine if any modifications are necessary prior to the undocking and re-rendezvous that will occur on flight day 13. Upon receiving the data on the ground, data integrity checks are performed and the data is parsed into a “snapshot” format. This snapshot format means that each individual VNS or DC data file contains data collected at a single time, along with the appropriate header file. This snapshot data is then fed into either the VNS Quick Look Tool or the DC Quick Look Tool.

The VNS Quick Look Tool is capable of interpreting raw STORRM VNS snapshot data and plotting raw range and intensity images. It is also capable of performing image processing on raw STORRM data to provide bearings and ranges to centroids of candidate reflectors at a user specified rate. Data may be processed for only a single measurement, or a large volume of data may be processed in a batch format. The ability to process only a single measurement (which is actually created by processing a number of STORRM VNS images) is useful in helping the analyst understand the performance of the sensor. A user-defined region of interest may be defined in the VNS Quick Look Tool and the analyst can zoom in on a particular portion of the image. The tool provides summary statistics of the raw intensity, raw range, and processed image in this region of interest. For either the single-measurement or batch-processing modes, it is possible to save raw data, JPEG pictures, and movies. The output of the VNS Quick Look Tool may be used to qualitatively assess the performance of the STORRM VNS. A more quantitative assessment may be performed by comparing the VNS centroid results with the TCS measurements. Further, the outputs may be fed into a reflector identification algorithm, coupled with a relative navigation filter, to obtain an assessment of the resulting relative navigation performance.

The DC Quick Look Tool is capable of interpreting raw STORRM DC snapshot data and plotting raw and processed images. The raw DC data is still mosaiced (the detector uses a Bayer pattern), so the DC Quick Look Tool contains a demosaicing algorithm to reconstruct the color image (the user still has the option to either view a grayscale image or a color image). A number of image processing algorithms are available to the user to adjust the color gains, contrast, and brightness. The DC Quick Look Tool is capable of processing and saving a user defined set of data (e.g. a single image, an arbitrary set of selected images, all the images in a target folder, etc.). Additionally, the user can specify region of interest and the DC Quick Look Tool will provide a zoomed-in plot of this region. This is particularly useful in assessing the quality of the DC for piloting cues. The STORRM DC images will also be compared with images from the Orbiter’s docking camera.

The final version of this paper will include example VNS and DC images from the STORRM flight data.

VII. Lessons Learned

The final paper will include a thorough discussion of STORRM lessons learned. What follows are a few examples of some of the lessons that the team has learned:

1. Requirements should be written with emphasis on system capability, not for a specific concept of operations.
2. All procedures should be bookended (begin and end) at some stable state. They should be compartmentalized into indivisible sequences of events.
3. The philosophy of fault detection and troubleshooting measures should be chosen in the design phase.
4. Parallel test ports should be implemented on all flight hardware elements.