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A Summary of the Rendezvous, Proximity Operations, Docking, and Undocking (RPODU) Lessons Learned from the Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) Demonstration System Mission

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April 2011

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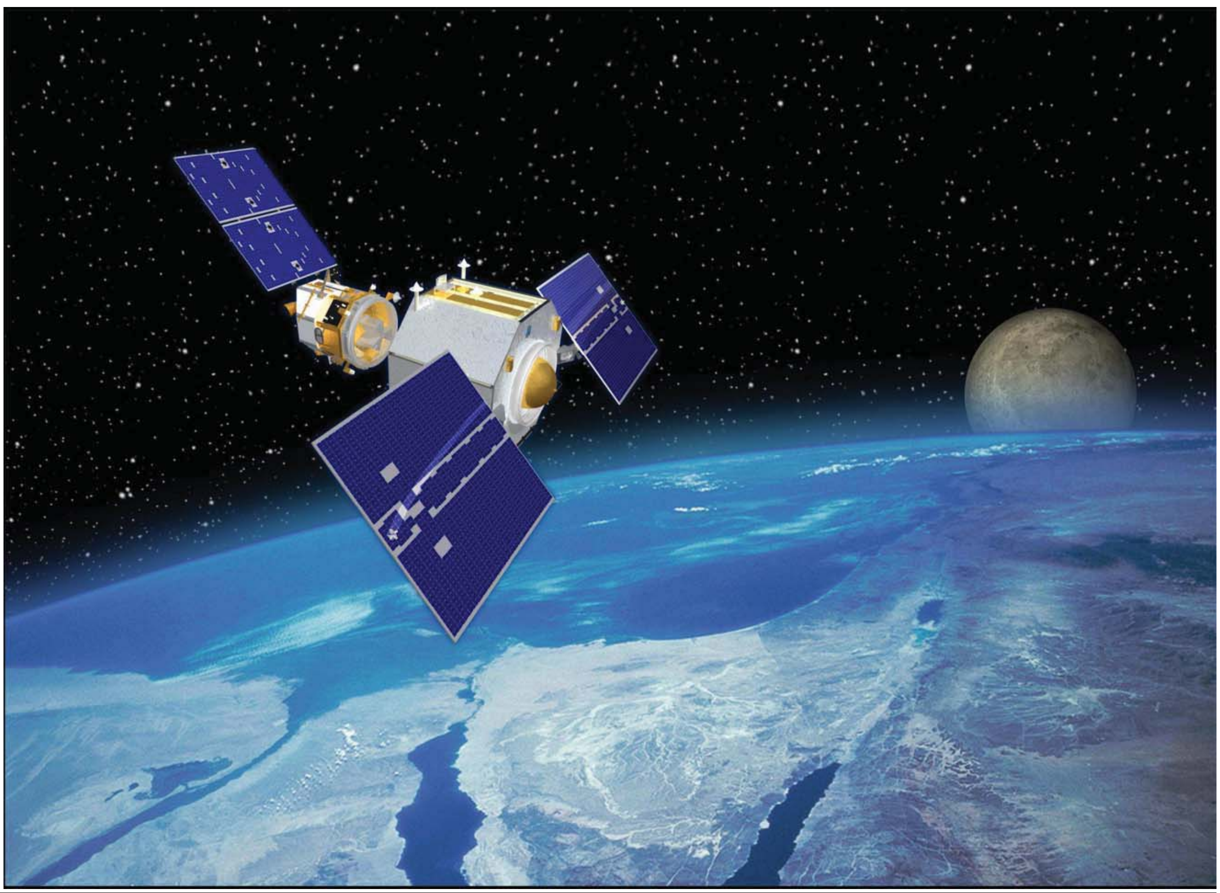

April 4, 2011

Report Approval and Revision History

Approval and Document Revision History

NOTE: This document was approved at the March 31, 2011, NRB. This document was submitted to the NESC Director on April 11, 2011, for configuration control.

Approved:	*Original Signature on File*	4/14/11
	NESC Director	Date

Version	Description of Revision	Author	Effective Date
1.0	Initial Release	Neil Dennehy, NASA Technical Fellow for Guidance, Navigation, and Control	4/4/11

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Volume I: Assessment Report

1.0 Authorization and Notification

The Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT) sponsored Dr. J. Russell Carpenter, a Navigation and Rendezvous Subject Matter Expert (SME) from NASA's Goddard Space Flight Center (GSFC), to provide support to the Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) rendezvous and docking flight test that was conducted in 2007. When that DARPA OE mission was completed, Mr. Neil Dennehy, NASA Technical Fellow for GN&C, requested Dr. Carpenter document his findings (lessons learned) and recommendations for future rendezvous missions resulting from his OE support experience. This report captures lessons specifically from anomalies that occurred during one of OE's unmated operations. It was anticipated the Constellation Program (CxP) Orion Project, NASA's commercial crew and cargo partners, International Space Station (ISS) visiting vehicles, and any space vehicles performing rendezvous and docking would benefit from these findings, observations, lessons learned, and NESC recommendations.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 4/18/11

Mr. Cornelius J. Dennehy Date

Significant Contributor:

Dr. J. Russell Carpenter Date

Signatories declare the findings and observations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, technical discussions, and open literature, and/or generated from independently conducted or observed tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization/Location
Core Team		
Neil Dennehy	NASA Technical Fellow for GN&C	GSFC
Russell Carpenter	Navigation and Rendezvous SME (Member of the NESC GN&C TDT)	GSFC
Administrative Support Personnel		
Patricia Pahlavani	MTSO Program Analyst	LaRC
Christina Williams	Technical Writer	ATK/LaRC

4.0 Executive Summary

Over the period from late calendar year (CY) 2005 through the middle of CY 2007, the NASA Engineering and Safety Center (NESC) Guidance Navigation and Control (GN&C) Technical Discipline Team (TDT) member, Dr. J. Russell Carpenter, provided specialized engineering technical support to the Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) Demonstration System mission. In particular, Dr. Carpenter served as a member of the OE Independent Readiness Review Team (IRRT) that was led by Brigadier General (Retired) Peter Worden.

Dr. Carpenter, a NASA civil servant at NASA's Goddard Space Flight Center (GSFC), is a senior navigation specialist. He had previously served as the Deputy Chairman on the Mishap Investigation Board (MIB) that convened in April 2005 to determine the causes and contributing factors relating to the NASA Demonstration of Autonomous Rendezvous Technology (DART) mission. In that role, Dr. Carpenter provided the necessary program-independent rendezvous and navigation engineering expertise needed by the DART MIB. His NESC-sponsored work as a member of the OE IRRT was a logical outgrowth of his DART MIB leadership.

The OE IRRT was formed in late CY 2005 with the charter to independently identify, assess, and advise the DARPA Director (Dr. Tony Tether) on urgent issues that would impact the OE mission's technical success, cost, and schedule. The IRRT was tasked to focus on developing recommendations for pragmatic solutions to issues that would minimize cost and schedule impacts, while increasing the probability of accomplishing the OE mission objectives. Following the OE launch, the IRRT activity was maintained with an augmented charter which included: reviewing the results from on-orbit operations; resolving on-orbit anomalies and recommending corrective actions; and providing guidance on the performance of on-orbit test scenarios.

The driving events for this report were a sequence of navigation and sensor problems that occurred during one of OE's unmated operations. Although OE successfully recovered from these anomalies, the DARPA Director suspended further unmated operations, and requested Dr. Carpenter to chair a review of the issues that led to these anomalies. This report captures findings, observations, lessons learned, and NESC recommendations that resulted from this review, as well as NESC's participation both in the recovery activities themselves, and more generally with the IRRT throughout the final 2 years of the OE Project.

5.0 Problem Description

5.1 Orbital Express Background

The purpose of the DARPA OE system was to demonstrate the operational utility, cost effectiveness, and technical feasibility of autonomous techniques for on-orbit satellite servicing. A primary OE objective was to develop and demonstrate an on-orbit autonomous GN&C system that would provide the autonomous non-cooperative rendezvous, proximity operations, and capture functions and capabilities needed to support on-orbit satellite servicing.

The OE demonstration system consisted of two satellites, launched simultaneously on March 8, 2007, aboard an Atlas V booster from the Cape Canaveral Air Force Base into a 492-km circular orbit at 46-degree inclination. The satellite that performed the servicing was designated as the autonomous space transfer and robotic orbiter (ASTRO). The next generation satellite/commodity spacecraft (NextSat/CSC) functioned as the satellite being serviced by ASTRO. The mission demonstrated autonomous rendezvous, proximity operations, and servicing, including transfers of hydrazine fuel, and battery and flight computer orbital replacement units. ASTRO was the active (chaser) vehicle with the NextSat/CSC as the passive (target) vehicle.

The block diagram of the OE autonomous GN&C (AGN&C) system is provided in Figure 5.1-1. As described in Reference 1, the specific key features of the AGN&C system on-board the ASTRO spacecraft were:

1. Fully-autonomous guidance software to perform demate, separation, departure, rendezvous, proximity operations, and capture.
2. Fully-autonomous attitude software to orient the vehicle in required directions during each segment of approach and separation.
3. Onboard guidance sequencer to progress through translation and pointing modes during approach and separation.
4. Functionally-redundant rendezvous sensors to track the target from over 200 km to capture.
5. Fully-autonomous navigation filters to sort and weight data from multiple sensor input sources.
6. Internal sanity checks and rendezvous abort capabilities if safety or hazard thresholds were exceeded.

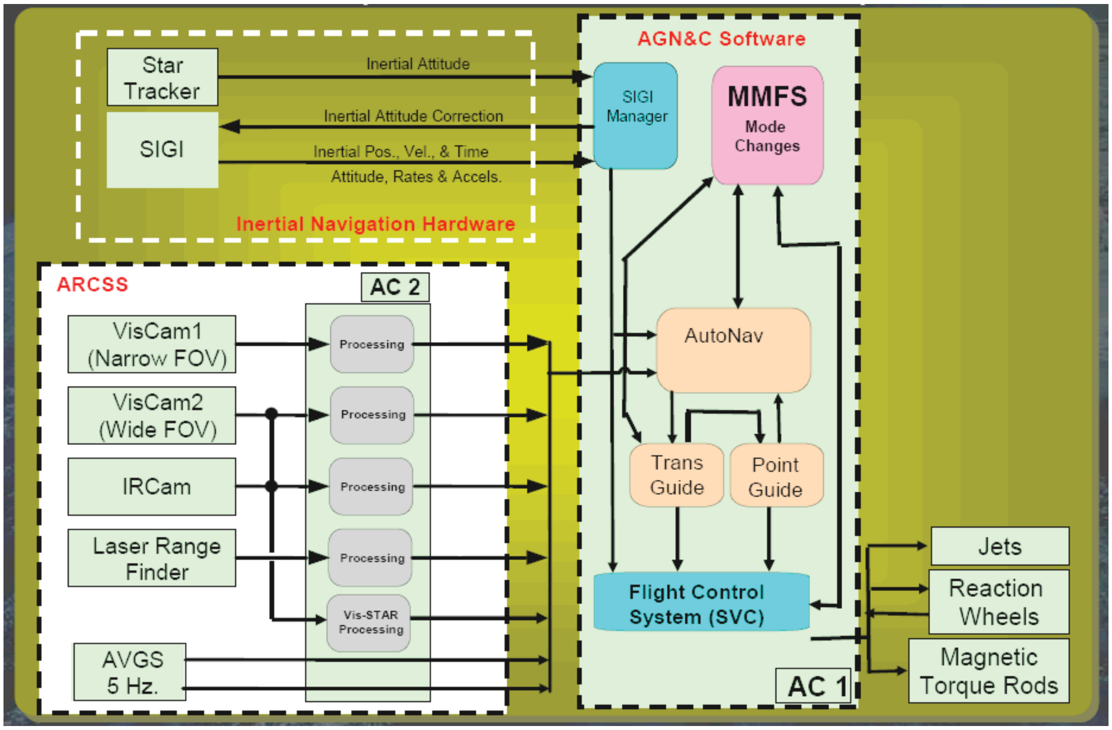

Figure 5.1-1. OE AGN&C System Block Diagram (from ref.1)

Many of the OE rendezvous, proximity operations, docking and undocking (RPODU) lessons learned reported in this paper were concerned with the suite of navigation sensors employed on the ASTRO spacecraft. Background information on these sensors will assist in understanding those sensor-related lessons learned.

The ASTRO spacecraft was equipped with an autonomous rendezvous and capture sensor system (ARCSS). A detailed ARCSS description is provided in Reference 2. The ARCSS consisted of five different sensors, which were mounted on a common optical bench. The ARCSS consists of three imaging sensors:

1. Narrow field-of-view (NFoV) visible acquisition and tracking sensor, referred to as VS1.
2. Mid-to short-range side field-of-view (WFoV) visible tracking sensor, referred to as VS2.
3. Infrared (IR) sensor, referred to as IRS, for use during orbital "night" (eclipse) or periods of poor lighting conditions.

In addition to the visible and IR imaging sensors, the ARCSS included a precision laser rangefinder (LRF), which was used for mid-range target spacecraft tracking purposes. Lastly, the advanced video guidance sensor (AVGS) laser-based tracking system was employed to provide target attitude, range, and bearing during the chaser's short-range proximity maneuvering and docking operations that occurred in the last few hundred meters of flight down the approach corridor. The AVGS evolved from the video guidance sensor (VGS) technology developed by the NASA Marshall Space Flight Center (MSFC) in the mid 1990's and flown as a flight experiment on the space transportation system (STS)-87 and STS-95 Space Shuttle missions. The AVGS was designed to be an autonomous docking sensor using the same basic functional concept as the VGS, but with updated electronics, increased range, reduced mass, and improved dynamic tracking capability. The AVGS had previously flown on the DART spacecraft in CY 2005.

The ARCSS system provided NextSat/CSC target spacecraft state information to the AGN&C flight software over a range from a hundred kilometers to close proximity/docking. The ARCSS sensors each have a different effective operational range. Together this sensor suite provided overlapping target range coverage as depicted in Figure 5.1-2.

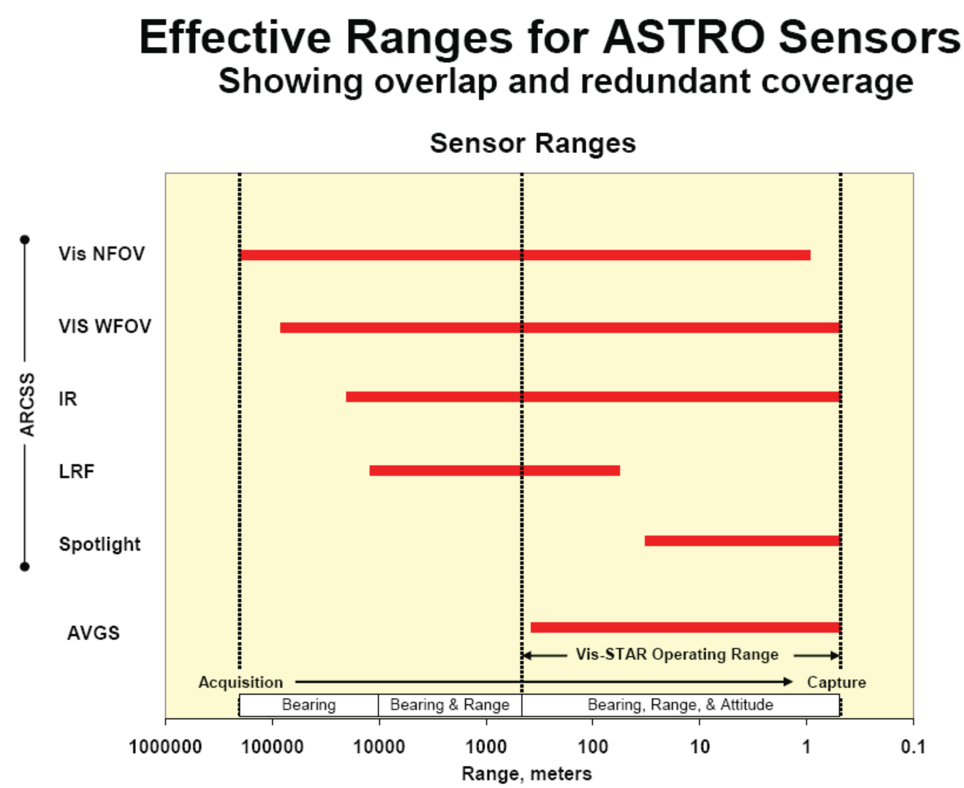

Figure 5.1-2. Effective Operational Ranges of the OE ARCSS (from ref. 2)

During May and June of 2007 after initial on-orbit system checkouts, the OE spacecraft conducted five unmated operations. The spacecraft conducted one additional long-range rendezvous demonstration in July 2007 as part of the decommissioning sequence.

The ASTRO spacecraft was decommissioned on July 20, 2007. The Next Sat/CSC spacecraft decommissioning occurred on July 21, 2007. References 3 and 4 discuss post-flight analysis of ARCSS and AVGS performance, respectively. References 5 and 6 provide detailed summaries of flight operations.

5.2 Summary of the Driving OE Event

During the second OE unmated operation, also known as Scenario 3-1, ASTRO "… was nearly crippled [sic] by a major failure in its sensor computer, which processes data gathered by the craft's rendezvous instruments, including cameras, an advanced video guidance sensor and a laser rangefinder."[1] With assistance from ground controllers, ASTRO eventually re-mated with NextSat. The contractor, with assistance from a panel of external experts chaired by the NESC representative, developed solutions and work-arounds for the problems ASTRO encountered, and OE performed its remaining unmated scenarios without significant further issues.

Section 6.0 of this report reviews and summarizes OE's problems during Scenario 3-1. Reference 5 may be consulted for further details. Section 7.0 captures findings, observations, lessons learned, and NESC recommendations that resulted from the NESC's participation both in the recovery activities arising from the problems that occurred in Scenario 3-1, and with DARPA's IRRT throughout the final 2 years of the OE Project. This report serves as an expedient means for concisely sharing, with the NASA GN&C community of practice (CoP), the engineering knowledge gained from OE's on-orbit spacecraft RPODU flight test experience. The report will be posted to the NASA Engineering Network (NEN) GN&C CoP website for future reference (https://nen.nasa.gov/web/gnc).

5.3 Relevance to Future Spaceflight RPODU System Design, Development, Test, and Operation Activities

Space rendezvous subsystem technologies, and the systems engineering to effectively integrate them together, will be essential to execute future NASA human and robotic spaceflight missions. There will be a continued trend towards designing and developing autonomous rendezvous and docking systems to perform routine RPODU flight operations routinely, safely, efficiently, and affordably.

In the future, NASA will require GN&C capabilities for space rendezvous and docking to satisfy mission requirements for both crewed spacecraft (e.g., CxP Orion Crew Exploration Vehicle

[1] http://www.spaceflightnow.com/news/n0707/04orbitalexpress/, accessed July 5, 2007. "[N]early crippled" is an overstatement; the mission was able to use a backup sensor computer to recover from the anomaly, which was a due to a series of failures in the integrated sensor/computer subsystem. It should be noted that data from these subsystems was processed with a set of rules and monitored with respect to preset parameters. A number of these monitors had inappropriate values, and contributed to the series of failures that led to the anomaly. These issues were evident in other unmated operations, but did not have such negative outcomes.

(CEV) rendezvous with the ISS in Earth orbit, and CEV rendezvous with the Altair ascent stage in Lunar orbit) and robotic spacecraft (e.g., Mars sample return and other targets of scientific interest). In addition, the ISS will continue to host a number of different "visiting vehicles" that will have some form of RPODU GN&C interaction. It will be critical to ISS safety that GN&C engineers understand both the nominal RPODU operations and potential RPODU failure modes on these visiting vehicles. Figure 5.3-1 illustrates this wide range of RPODU mission applications. RPODU is also an enabling technology for crewed and robotic satellite servicing missions.

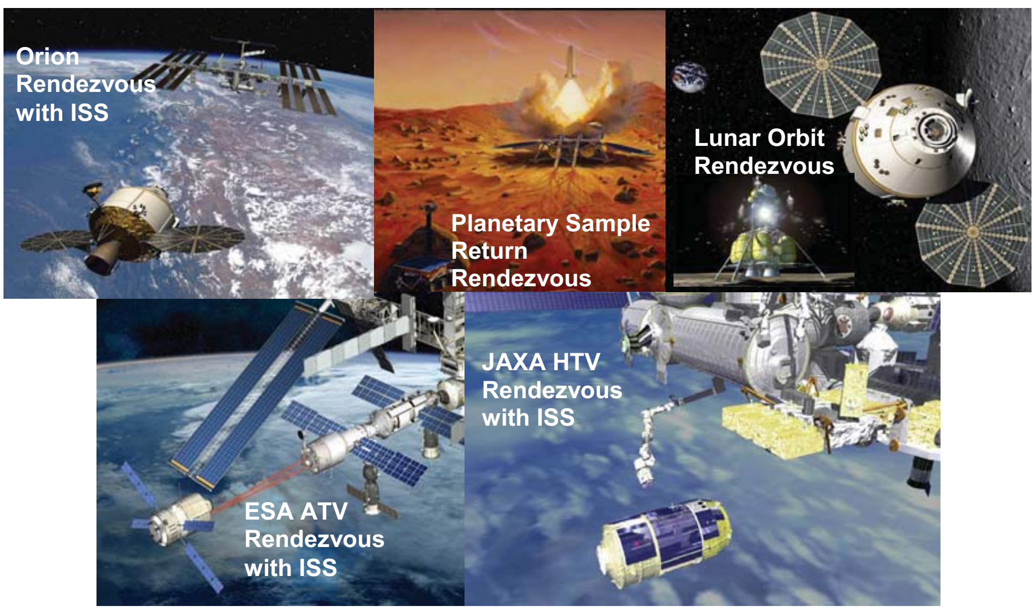

Figure 5.3-1. Some Examples of NASA's RPODU Mission Applications in Human and Robotic Spaceflight

Future RPODU capabilities will require a high degree of system engineering to successfully architect and integrate the various sensors, GN&C algorithms, autonomous software, mechanisms, actuators, and other subsystems into a spacecraft safely, efficiently, and affordably. The engineering and economic tradeoffs between manual, automated, supervised autonomy, and fully autonomous RPODU systems will need to be investigated for each specific mission application. The use of common hardware and software system elements will need to be considered. Fully integrated RPODU systems, and their multiple spacecraft dynamic interactions, will be difficult to test on the ground. Non-operational space rendezvous and docking flight testing opportunities for future RPODU systems should be emphasized, but these will likely be limited in number and complexity.

Effectively addressing the autonomous RPODU problem will be a significant technical challenge involving complex, and sometimes hazardous, dynamic interactions across multiple spaceflight regimes. It should be recognized that DARPA's RPODU technology and engineering interests have significant overlap with NASA activities. The key point is that the OE Demonstration System architecture, concept of operations, and GN&C design (i.e., RPODU sensors, algorithms, mechanisms, actuators) flight tested by the DARPA/industry OE team will likely have a strong and direct impact on NASA's future GN&C system design and development activities for crewed and robotic spacecraft. It is advantageous for NASA to learn as much as possible from the DARPA OE GN&C design, development, and flight test experience. Capturing and disseminating OE lessons learned is an important step and allows NASA to leverage the significant DARPA investment in performing the OE orbital flight tests.

6.0 Data Analysis and Review

This section reviews aspects of OE's second unmated operation, Scenario 3-1, which are germane to NESC's analyses. The source of the data presented is Reference 5.

During Scenario 3-1, ASTRO had been intended to follow a similar profile to that used during its first unmated operation, during which it performed a successful in-plane circumnavigation of NextSat at an approximate radius of 10 meters. For Scenario 3-1, separation to 30 m was planned to extend the range over which OE's sensors would be demonstrated. As ASTRO returned from its planned maximum separation of 30 m to a 10 m standoff, the aforementioned sensor computer failure occurred[2]. This failure was the proximate cause of the set of problems OE encountered in the operation. In response, ASTRO executed an abort procedure in which it flew through a pre-planned separation corridor, then retreated to a safe-hold station-keeping box 120 m trailing NextSat. ARCSS data were lost due to the failure of the sensor computer, but AVGS continued tracking throughout the separation corridor. The trajectory ASTRO followed after departing the separation corridor exceeded AVGS visibility constraints, so no relative navigation data were available, and relative navigation accuracy began degrading. Once ARCSS was recovered using a backup sensor computer, data from the IR sensor became available as ASTRO neared the 120 m station-keep box. However, the navigation filter began rejecting this data, and ground operators elected to place ASTRO into coasting flight mode until the navigation problems could be resolved. While troubleshooting continued, ASTRO drifted without relative state measurements over the next day, eventually reaching approximately 2.5 km following NextSat, an estimate based on ASTRO's Global Positioning System (GPS) solutions and ground tracking of NextSat.

[2] No root cause was identified for the failure of the sensor computer. Identical software was used for the remainder of the mission in a backup sensor computer.

At this point, ground operators attempted to arrest ASTRO's drift rate. Unfortunately, data from ASTRO's accelerometers was improperly processed by ASTRO's software, leading to an anomalous burn[3]. This anomaly corrupted the onboard navigation state, and put ASTRO onto a trajectory that repositioned it from 2.5 km following to what was eventually estimated to be 6 km ahead of NextSat.

Over the next several days, ASTRO remained in coasting flight mode, while ground operators experimented with various navigation settings to overcome numerous flight conditions that significantly differed from pre-flight expectations. Sensor performance was one area of difficulty. Due to the abort, the geometry of the sun, Earth, and spacecraft were different from any configurations contemplated during pre-flight planning. In addition, the sun glare in particular was worse than any encountered in pre-flight testing. The sensors had furthermore not been calibrated under such stressful conditions, leading to numerous faulty observations being reported to the navigation filter. The navigation filter itself had never been tested under such stressful conditions, and its performance during the recovery phase of the scenario also led to a great deal of consternation on the part of the operators. Unfortunately, many of the sensors relied on feedback from the navigation filter for acquisition aiding, so the filter's poor performance interfered with ability of the sensors to facilitate recovery from the abort.

Eventually, operators found a configuration that would allow data from the IR sensor to be accepted by the navigation filter. Using this data, ASTRO maneuvered to within 2.5 km of NextSat, from which point LRF range data could be reliably acquired and processed. The successful processing of the combination of IR and LRF data by the navigation filter allowed an approach to 150 m. The subsequent trajectory was planned to ensure that AVGS data would be continuously available. With the AVGS continuing to meet performance expectations, and despite a thermal issue with one of the thrusters that nearly led to another abort, the recovery was completed eight days after the operation began.

Prior to resumption of unmated operations, the DARPA Director requested the NESC to chair a review of the navigation and sensor problems OE experienced on Scenario 3-1. This review panel identified a set of liens against a return to unmated operations that the OE team successfully addressed. These liens primarily involved additional on-orbit sensor calibration, and navigation filter re-tuning. The panel identified additional deficiencies in the navigation filter design, but did not view correcting these as an imperative for a return to unmated operations. As References 5 and 6 describe, with these adjustments, OE resumed unmated operations and completed its mission successfully.

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[3] The software fault was associated with a unique untested system configuration that occurred as a result of the combination of the sensor computer reset and the type of ground-loaded burn that was used for the drift-stop maneuver.

7.0 NESC Determinations

This section describes findings, observations, lessons learned, and NESC recommendations that resulted from the NESC's participation in the recovery activities arising from the problems that occurred in Scenario 3-1, and with DARPA's IRRT throughout the final 2 years of the OE Project.

7.1 Findings, Observations, and Lessons Learned

The following findings are based on facts established during NESC's involvement with the OE Project.

F-1. The autonomous abort to 120 m did not establish an adequately stable and safe standoff in the presence of degraded navigation, necessitating additional maneuvers that further degraded the navigation state.

As described previously, the original issue that began the series of events leading to the contingency during Scenario 3-1 was a re-boot of the computer that hosted the sensor processing software. OE's flight software, performing as programmed for this circumstance, automatically triggered an autonomous abort. The intent of this abort was to place ASTRO at a stable stationkeeping point 120 m following NextSat, at the same orbital altitude and inclination. However, the stability of this type of stationkeeping declines as relative navigation accuracy degrades, and the particular contingency that initiated the abort had resulted in a loss of onboard relative navigation. Hence, the abort put ASTRO at risk of being unable to autonomously maintain a stable and safe separation from NextSat, necessitating additional ground intervention. With these actions, ground operators attempted to increase the margin of safety by allowing ASTRO to drift further from NextSat. As described previously, the drift rate that resulted was high enough to cause additional concern, and an attempted drift stop maneuver by ground operators triggered a latent defect in ASTRO's flight software related to accelerometer processing, which further degraded relative navigation. The resulting decline in relative state knowledge significantly hampered ground operators' situational awareness, and impeded subsequent recovery operations.

F-2. The AVGS "spot" (acquisition) mode would likely have provided critical navigation measurements when the other sensors were unavailable.

The AVGS provided range and angular position information, and relative attitude information, to about 200 m, when the AVGS retro-reflector targets were in the sensor's field of view. AVGS is also capable of providing angular position information via its "spot" or "acquisition" mode, to about 2 km, based on whatever laser returns are available (multiple "spots" are centroided). This mode was successfully used in the DART mission. OE did not provide proper interfaces to AVGS to make use of the spot (acquisition) mode. Since AVGS was unaffected by the problems occurring with the other relative navigation sensors, its ability to provide angular positions at ranges to 2 km would have proved valuable in the recovery from the contingency during Scenario 3-1.

F-3. The navigation filter underestimated its uncertainty.

All successful rendezvous missions to date, including OE, have used a type of sequential navigation filter known as the extended Kalman filter (EKF). A primary advantage of this type of navigation algorithm is that it maintains an online, adaptive estimate of the uncertainty in its navigation state estimate.

In OE's case, the filter had intentionally been tuned in such a way that it typically underestimated this uncertainty (i.e., the filter was always "over-confident" about how well it was navigating). The rationale given for this tuning was that it was required for adequate performance in long-range rendezvous scenarios. Although pre-flight simulations had indicated this issue to a smaller degree, in-flight experience showed that the OE navigation filter often underestimated its uncertainty by an order of magnitude or more. Due to OE Project resource limitations, it was not deemed possible to make the types of changes to the filter that would have been required to remedy this issue. There were multiple consequences of this design, several of which are described in other section of this report.

The most fundamental consequence, improper weighting of sensor data, is the focus of this finding. One way to understand how the EKF uses its uncertainty estimates is by analogy to the methods historically used by sailors. A shipboard navigator maintains a track log that is updated regularly by a combination of dead reckoning and making fixes. A fix consists of observing a celestial object or a known landmark with an instrument that measures some component of the ship's position. In between fixes, the navigator dead reckons the ship's position by extrapolating from the previous fix using an estimate of the ship's speed and heading. When updating the track with a new fix, the navigator judges the accuracy of the fix against the accuracy of the dead reckoning, accounting for uncertainty in tides and currents, compass errors, helm errors, etc., and makes an adjustment to the track log.

There are no fundamental differences between the shipboard navigation described and the functioning of the EKF. If the EKF inaccurately estimates its uncertainty, then it will not be able to adequately "judge" how best to combine new observations from the sensors with its previously "dead reckoned" extrapolation track. If the EKF consistently overstates the accuracy of its estimates, then it will tend to undervalue the information provided by new sensor data, and get increasingly "locked in" to a track based on ever-older information.

F-4. Pre-flight testing did not reveal the sensor and navigation issues that occurred in flight.

The OE Project determined it was infeasible for the spacecraft sensor suite and navigation software to be tested in a fully integrated, hardware-in-the-loop fashion. Further, the facility used for testing the navigation cameras was unable to simulate the dynamic range and diversity of optical effects that might be expected to occur in space[4].

Although it is not possible to say definitively that such pre-flight testing would unequivocally have discovered the issues with the sensors, the navigation filter, and their interactions that led to the contingency during Scenario 3-1, such testing "as you fly" may have helped to detect them prior to flight. There was a Government facility available that could have assisted with this type of testing, which the OE Project elected not to utilize.

F-5. Pre-flight navigation system stress testing did not account for extreme sensor data outliers.

The OE team performed a significant amount of software simulation prior to the mission, much of which included random noise and bias-like output perturbations to reasonably high-fidelity sensor models. However, the noise models generally assumed "well-behaved" statistics (i.e., the distribution of the noise was assumed to be Gaussian).

In flight, due to a variety of problems with the sensors, their outputs were different from what had been simulated. The laser range finder would occasionally report extreme outliers several kilometers out of family from the rest of its measurements, and the cameras often reported false targets resulting from misidentification of optical artifacts. In effect, the sensor data that occurred in flight had a higher probability of occurring far from their mean values than the Gaussian distribution was capable of producing. Subsequent consultation with the laser vendor revealed that the outliers were an expected feature of the sensor's design.

F-6. Testing of ground uplink abort commands did not reveal the issues that occurred in flight.

Late in the development program, the OE team added a capability to uplink ground initiated abort commands. Because these were not initially contemplated, the manner in which they had to be introduced required a re-initialization of the navigation filter.

Critical to the anomaly that occurred in Scenario 3-1 is that some of the states in the navigation filter tracked the accumulated biases in the inertial measurement unit's accelerometers. When the filter was reset, so were these states, which corrupted their

[4] It is not clear that any existing facility can accurately model the full range of optical effects that occur in space.

estimate of the accelerometer bias. The navigation system could quickly recover from this condition, so long as a burn did not begin at the same time. However, if a burn did initiate concurrently, the system would try to correct the error in the navigation filter's accelerometer bias state, which in flight was large immediately after a reset.

In flight, this resulted in a larger than intended abort maneuver, which was also improperly directed. The difference between the flight occurrence of this issue and when this capability was tested on the ground pre-flight was the duration of the time that had elapsed prior to the reset. The reason the time elapsed was important was that over a short interval, the accelerometer bias does not accumulate to a large enough value to affect the burn.

F-7. There was no consistently available and accurate backup to OE's onboard navigation system.

Soon after OE lost its onboard navigation knowledge during Scenario 3-1, the ground operators realized that ground orbit determination solutions based on ranging data from the Air Force Satellite Control Network (AFSCN) stations would not be accurate enough to support recovery operations. As this eventuality had been contemplated prior to launch, OE had prior arrangements with the AFSCN imaging radar site operators to provide contingency support if needed. Unfortunately, due to maintenance at one of these facilities, the amount of tracking from these sites was limited. In addition, AFSCN were unable to provide a full state orbit determination solution. Nevertheless, the range estimates and other data the AFSCN provided proved to be invaluable in supporting the recovery from the contingency.

The following observations are factors, events, or circumstances that the NESC team identified which did not contribute directly to the problems occurring during Scenario 3-1, but nonetheless, have the potential to cause or increase the severity of similar problems for future RPODU activities.

O-1. Final approach along the radius and velocity vectors tended to cause unanticipated thruster duty cycles and subsequent over-heating.

As is typical for most rendezvous missions, during the final meters of the ASTRO's approach to NextSat, ASTRO would fly through a conical corridor extending along NextSat's docking axis. This trajectory segment would in general not correspond to any natural, coasting orbital motion, and hence would require more frequent thruster firings to maintain than had the rest of the rendezvous and proximity operations profile.

Depending on the objectives of the current operation, sometimes NextSat would remain sun pointing during the approach, and sometimes NextSat would point along either its velocity or radius vectors. In the latter two cases, somewhat more frequent effort was required to fight against orbital mechanics to remain inside the corridor.

The thruster firing logic design was such that when small and frequent maneuvers were commanded, unexpected chattering would occur when the commanded thrust was larger than the minimum thruster firing allowed by the logic. In such cases, the subset of thrusters (usually only one) bearing the brunt of the duty cycle would approach its operating temperature limit. Consequently, during the last moments of the recovery from the Scenario 3-1 abort, one thruster was within a few degrees of reaching its temperature limit and thus triggering an abort.

O-2. The process of dumping the onboard recorders and extracting the data from the downlinked files proved cumbersome during contingencies.

Real-time telemetry was stored by ground operators and was readily available for post-processing and fact-finding during the trouble-shooting surrounding anomalies. However, the full telemetry set was only available during AFSCN contacts, and the Tracking and Data Relay Satellite System (TDRSS) coverage was not continuous, so that gaps existed in the real-time telemetry record. All of the data were stored in OE's onboard recorders, but retrieving this data proved difficult. First, dumping the recorders required re-configuring the telemetry, which was not always feasible or advisable, due to other demands occurring during the anomaly (e.g., commanding and downlinking of situational awareness imagery). More significantly, once the data was downlinked, the process of extracting the guidance and relative navigation data occurred slower than real-time. These limitations conspired with the high tempo of contingency operations to effectively prevent the ground team from being able to make use of the data from the onboard recorders during trouble-shooting surrounding anomalies.

O-3. Possible evidence of ASTRO absolute position radial biasing.

During the recovery from the Scenario 3-1 contingency, analysis of the real-time telemetry indicated the possible existence of radial biases in ASTRO's absolute position. Since no "truth" trajectory was available for comparison, this evidence was inconclusive. What was observed was that the differences between ASTRO's GPS receiver's position point solutions and the navigation filter's estimate of ASTRO's absolute position were biased by approximately 10 to 15 m when no other data were being processed by the navigation filter. Once the filter began to ingest data from the IR camera, the bias appeared to increase to approximately 20 to 30 m. The large number of gaps and a strong time-varying signature present in the data make these conclusions on the bias somewhat speculative. Nevertheless, it remains plausible that at OE's altitude of approximately 500 km, ionospheric biasing of the GPS measurements could have been present.

O-4. Spacecraft collision was possibly prevented by the unintentional presence of out of plane motion.

When OE lost all navigation information during Scenario 3-1, ASTRO unintentionally passed from one side of NextSat to the other without real-time knowledge of ground operators. Although onboard navigation was not available during this time frame, later analysis of less accurate ground-based orbit determination solutions suggested that the in-plane projection of ASTRO's motion might have passed within 10 m or less of NextSat in the process of switching sides. Prior to this, as a consequence of an improper ground-initiated abort maneuver, several dozen meters of out of plane motion had unintentionally been introduced into ASTRO's orbit relative to NextSat. The ground-based solutions suggest that, thanks to this unintentional out of plane maneuver, at the time when ASTRO's in-plane motion was close to NextSat, it probably had a reasonably safe out-of-plane separation.

O-5. The navigation filter's model of how NextSat's orbit propagated during sensor outages introduced significant relative state errors.

The navigation filter modeled NextSat's orbit using a gravity model that only included central-body and equatorial oblateness terms. No atmospheric drag, solar radiation pressure, third-body gravity, or other perturbations were modeled. When relative measurements were available, pre-flight analysis had shown this model to be adequate for OE's mission. However, such a model can be expected to introduce errors on the order of 10 to 20 km per day [ref. 7][5], depending primarily on the atmospheric density. Since ASTRO's orbit was constantly updated with GPS, this propagation error would directly contribute to errors in the relative state, when relative measurements were not available. Although such outages of relative measurements were never intended to occur, the contingency during Scenario 3-1 led to more than a day without any direct measurements of the relative state. In this circumstance, the OE ground team had to rely on infrequent updates by various ground tracking assets to maintain safe separations between the vehicles with ground-commanded thruster firings.

O-6. The navigation filter's relative state estimate was biased after long periods of angles-only tracking.

During the unmated scenarios that extended beyond a few kilometers, it was typical that the only data type available to the navigation filter was angular position information, primarily from the IR camera. In these cases, the filter had to rely on a combination of fairly inaccurate target state propagation, and correlations between angular observables and actual range. Such correlations become evident to the navigation filter as relative motion normal to the line-of-sight to the target occurs. The biasing problem was clear to the OE ground operators, who could often observe laser rangefinder measurements that were a kilometer or more different from the navigation filter's range estimate. At times, the ground operators had to restart the filter to enable it to ingest the laser rangefinder measurements, which operators had come to realize were indicating a more accurate representation of the true range. Such filter restarts had the potential to interfere with previously planned maneuvers.

[5] The example quoted is for a low Earth orbit (LEO) satellite (LACE) at solar maximum, that used a higher-fidelity model than OE's navigation filter used.

The following lessons learned summarize the knowledge or understanding that the Automated Rendezvous and Docking (AR&D) CoP has gained from the OE experience.

LL-1. System designers and operators should be mindful of implicit assumptions concerning the availability of a navigation state.

There were times during the recovery from the abort during Scenario 3-1 in which there was significant confusion among OE's ground operators concerning ASTRO's position relative to NextSat. After the anomalous drift stop maneuver, extended time was required to establish a coarse characterization as to whether ASTRO was leading or following NextSat. Once the recovery was underway and accurate navigation knowledge was restored, a member of the OE operations team, who had also been one of the principal system designers, made the off-hand comment that "Nav is really important". This comment succinctly summarized a lesson that the OE team appear to have learned from their OE mission experience. These individuals gained a heightened appreciation of the degree to which at least some coarse knowledge of the navigation state may be taken for granted. Although NASA's AR&D CoP includes navigation experts, such expertise can sometimes be compartmentalized, and even experienced experts can take situational awareness for granted. More generally, most people have never been caught at sea in a fog, or found themselves alone at the controls of an aircraft in instrument meteorological conditions, and hence have never truly experienced what it is like to lose the usual cues that lead to situational awareness. Such experiences reinforce that navigation should never be taken for granted. The OE operations team did have this experience when OE lost navigation information during the aforementioned contingency.

LL-2. IR sensors can enhance system robustness to unanticipated lighting variations.

Prior to the abort in Scenario 3-1, many members of the OE team appeared to view the IR sensor as a secondary or supplemental sensor. The lesson learned was that because the IR sensor was less susceptible to unanticipated variations in lighting conditions, it provided a robust and capable alternative to sensors operating in the visible light band. Although the OE IR camera was not without its problems (primarily associated with calibration; this topic is discussed further in the recommendations), it was the primary sensor through which the mission accomplished its recovery from the contingency. Furthermore, it was the sensor that most reliably tracked during a majority of the operations that occurred outside of AVGS range.

LL-3. A coupling between sensor and navigation software is susceptible to mutually reinforcing problems.

The software controlling the OE sensor suite and the navigation filter software were tightly coupled in a number of ways that led to some of the problems that occurred during Scenario 3-1. This interdependence caused precipitous system performance degradation as the subsystem performance declined. The lesson learned was that tight coupling might reduce overall system robustness, since problems may mutually and negatively reinforce each other.

The navigation filter aided the sensor software with a target ephemeris message, and the sensor software aided the navigation filter with measurement validity information. This coupling, when it occurred in the presence of spurious sensor measurements, led to a feedback that prevented OE from recovering its navigation state, even when ground operators could see via downlink imagery that NextSat was in the sensors' fields of view.

The feedback began when optical artifacts (e.g., glints, glares, saturations, hot pixels) appeared in the sensors' fields of view. Due to faulty target selection logic, these were at times reported as target tracks. The navigation filter would ingest these measurements, which resulted in biasing its state estimate, while at the same time decreasing the filter's state uncertainty. The improper reduction in uncertainty occurred because the filter "believed" these were valid measurements on the basis of the measurement validity information from the sensor software. The filter would begin reporting biased target ephemerides to the sensor software, which prevented the sensor software from subsequently associating the image of NextSat with a successful target track.

Another example was that some of the relative navigation sensors needed a range estimate seed to set operating parameters when acquiring NextSat. In some cases, this seed was to have been provided by other relative navigation sensors. When these other sensors had either spurious or no measurements, the range-estimate seed was not provided, which prevented acquisition with other sensors. In some cases, this significantly reduced the number of sensors operating at the same time.

LL-4. To achieve an effective sensor calibration on-orbit, the target vehicle should not be present in the sensors' fields of view, and possible sources of image corruption should be included.

Prior to commencing unmated operations, OE performed two sets of on-orbit sensor calibrations. Pre-flight calibration had been performed in a contractor facility prior to launch integration. However, the facility was unable to simulate the dynamic range and diversity of optical effects that might be expected to occur in space. The on-orbit calibrations consisted of demating ASTRO and NextSat using the robotic arm, moving NextSat while remaining on the arm, performing the calibration, and then remating. NextSat remained in the sensors' fields of view during this procedure, and other bright objects (e.g., the Earth limb and the moon) were excluded from the fields of view.

This calibration procedure failed to reveal the optical artifacts that contributed to the loss of navigation during Scenario 3-1. Prior to initiating further unmated operations, the calibration procedure was repeated, but with the change that NextSat was moved out of the sensor field of view, and bright objects were imaged. This proved to be a more effective calibration procedure. The data from this calibration, in combination with the data previously gathered during the aborted Scenario 3-1, allowed the OE ground team to retune the sensor software to remove a majority of the optical artifacts.

LL-5. Situational awareness imagery can be critically important in aiding the ground operations team's recovery from an abort, and since ground-based assets provide limited coverage, providing such data via the TDRSS should be a system capability.

As originally configured, OE was only capable of downlinking situational awareness imagery from its cameras via the AFSCN. In general, the AFSCN contacts were shorter and sparser than TDRSS contacts, but the TDRSS contacts had a lower bandwidth. Despite the limited bandwidth of the TDRSS link, the OE team was able to reconfigure the telemetry during the contingency so that limited situational awareness imagery could be downlinked continuously during TDRSS contacts. This imagery was crucial to ground decision-making during the recovery operation. Unfortunately, at critical times, the availability of such telemetry to engineering support areas outside of the operations center was sometimes limited.

LL-6. The navigation filter must be able to identify and screen out erroneous sensor data without affecting the filter's processing of valid sensor data.

This capability depends on the filter's accuracy in modeling the time-evolution of the navigation state vector, predicting the sensor measurements, and computing the statistics of the states and measurements. As mentioned previously, successful rendezvous missions to date, including OE, have used the EKF. A known attribute of such filters is that "… large values of the prediction residual relative to the prediction standard deviation may be an indication of bad tracking data and hence may be used to edit data from the solution" [ref. 8][6]. The efficacy of such editing is hindered when the filter does not accurately compute the aforementioned residual standard deviation. In OE's case, the filter typically underestimated the residual standard deviation. For the reasons previously mentioned, the core of this issue was not addressed, but the mission was flown first without editing, and later with unusually large editing thresholds (i.e., roughly corresponding to ten or more standard deviations). When editing was disabled, the filter ingested spurious measurements that ultimately led to a total loss of onboard state knowledge. When editing was enabled with the large thresholds, filter performance also suffered, and periods of filter divergence sometimes occurred.

7.2 NESC Recommendations

The following recommendations were identified from the NESC's findings, observations, and lessons learned. They are directed towards the development of future non-human rated RPODU missions[7].

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[6] The residual is the difference between the observed and expected measurement.

[7] Reference 11 offers detailed recommendations concerning RPODU for piloted spacecraft based on Space Shuttle Program experiences.

R-1. Consider ground operators' role in real-time reaction to autonomous aborts.

The overall success of OE's RPODU operations is attributable to provisions in OE's design that allowed ground operators to fully control the recovery from contingencies. The OE design avoided limitations that precluded ground intervention. In general, OE limited autonomous contingency responses to those cases when it was not practical for ground operators to intervene in a timeframe consistent with the mission's operational tempo. OE's operators could generally over-ride any autonomous abort response. Future missions should allow and encourage involvement from ground operators during aborts in similar fashion where feasible. Additionally, to avoid the problems OE experienced in Scenario 3-1, future RPODU missions should, where feasible, adopt the following strategies.

a. **Design autonomous contingency responses to rapidly place the vehicles into a stable, safe, coasting flight configuration.**

   This will allow the ground sufficient time to recover the mission, without unduly stressing the ground operations tempo. Although OE used such a strategy in Scenario 3-1 after the abort to 120 m proved unsustainable, it was a ground-commanded fallback action, not an autonomous response.

b. **Perform pre-flight systems engineering design activities that plan scenarios of how ground operators will interact with mission elements both onboard and on the ground to accommodate anomalies.**

   Such activities typically do not occur until pre-flight mission simulations and operator training exercises. Performing these activities during system design can identify design issues.

R-2. Plan for the generation of independently derived "best-estimated" trajectories (BET's).

Although true absolute and relative trajectories of RPODU missions can never be accurately known, it is generally possible to derive a post facto "best-estimate" of the full set of relevant trajectory parameters by combining available data in an estimation process. Cost and schedule constraints may drive missions not to implement a robust capability in this area. Due to a number of factors and circumstances previously described, OE's ability to provide such data were limited. These limitations detracted from the assessment of OE's readiness for resumption of unmated operations. To avoid such problems, future RPODU missions should, where feasible, plan for the following activities.

a. **Derive BET's using a combination of onboard- and ground-based sensor data.**

b. **Validate navigation subsystems by comparison to BET's.**

c. **Assess performance of navigation subsystems by comparison to BET's.**

d. **Provide for the availability of BET's within a timeframe consistent with supporting investigations associated with mishaps and recoveries from contingencies.**

R-3. Seek to design sensor suites so that they perform their functions as independently from each other as possible.

Because OE was designed with a navigation sensor suite that had a diversity of data types, and dissimilarly redundant components, it was able to recover from the unanticipated issues that led to the abort in Scenario 3-1. However, coupling between the sensors and the navigation filter allowed problems occurring in different sensors to negatively reinforce each other.

R-4. Consider off-nominal conditions when planning sensor calibrations.

Many of the issues that led to OE's difficulties in Scenario 3-1 centered on sensor calibration issues that became evident during the ensuing off-nominal conditions. The following summarize how calibration practices OE adopted during its anomaly recovery could be applied in future RPODU missions.

a. **Calibrate sensors on-orbit, with and without targets in the field of view, during at least the initial mission checkout phase.**

b. **Calibrate sensors on-orbit under all possible lighting conditions that might reasonably encountered, including off-nominal conditions that might occur due to contingencies.**

c. **Calibrate sensors on-ground and on-orbit over their full range of specifications (e.g., expected range, relative attitude, field-of-view, and dynamics), and over a sufficient dynamic range to cover off-nominal lighting conditions (e.g., bloom and glint).**

R-5. Apply appropriate fidelity to pre-flight simulation and testing.

As previously described, OE performed a significant amount of high-fidelity pre-flight testing, yet problems still occurred that were not discovered during testing. To better mitigate such risks, future RPODU missions should attempt to incorporate the following guidelines for pre-flight testing.

a. **Complete high-fidelity integrated simulations of GN&C algorithms using realistic mission profiles, which model the range of variation expected in the spaceflight environment, *prior to* the final implementation of the algorithms as flight software.**

This allows the opportunity for modification of the algorithms based on discoveries from the integrated simulations. If instead the flight software design has already been largely completed when such issues are discovered, then it becomes difficult to make significant changes. Cost and schedule pressure can result in less-than-ideal solutions to such problems.

b. **Consult with sensor and actuator vendors to ensure that simulations model performance effects that might reasonably be expected to occur.**

Special attention should be given to discovering and modeling outliers, biases, non-Gaussian noise characteristics, and other output features that might differ from GN&C system designers' expectations.

c. **Derive performance estimates based on integrated GN&C simulations from statistically significant sets of simulation runs, and include confidence intervals or similar measures based on the data set size.**

d. **Validate software-only GN&C simulations using closed-loop feedback from hardware-in-the-loop emulators.**

e. **Conduct hardware-in-the-loop testing of the sensors, software, and actuators to verify the closed loop response of system interactions, and the overall system timing and latency.**

Such tests should include stress cases, control mode transitions, and flight- or flight-like processors.

f. **Perform pre-flight testing with durations representative of flight operations in an effort to identify unanticipated failure modes that may only develop after such time intervals have elapsed.**

R-6. Consider anomaly resolution when deriving telemetry bandwidth and coverage requirements.

a. **Consider anomaly characterization and resolution in the system design of the telemetry bandwidth and coverage.**

b. **Design the onboard recorder with sufficient data downlink and archival capabilities to provide timely support for anomaly investigation.**

c. **Ensure adequate bandwidth between ground facilities to retrieve anomaly data.**

R-7. Provide capabilities for ground operators' situational awareness in system design.

a. **Design diverse communications paths to deliver critical flight data to ground operators.**

Where feasible, including TDRS in the system design can facilitate optimized situational awareness and data gathering.

b. **Include compressed low-resolution optical imagery as presented to optical sensors in the communications downlink**.

c. **If a separate situational awareness camera is used, then it should be mounted on the same navigation bench as the optical sensors.**

R-8. When using AVGS or derivative sensors, fully utilize all capabilities of the system.

a. **Employ "spot mode" so as to receive bearing information when outside the range at which AVGS can provide a full set of range, bearing, and relative attitude measurements.**

b. **Ensure that range seeds sent to the sensor have adequate precision.**

R-9. Include propulsion system constraints (e.g., temperature limits) in pre-flight analysis of non-coasting flight segments (e.g., the corridor approach used by OE).

R-10. Implement robust strategies to ensure timely and effective communications concerning program status across program elements during all operational phases, including contingency response activities.

R-11. Employ rendezvous navigation algorithms of sufficient fidelity to allow for the propagation of the target vehicle's orbit over longer intervals than nominally planned.

This allows for support of contingency operations, since during such operations, the time over which such propagations may occur without any relative sensor updates may significantly exceed nominal expectations.

R-12. Abort strategies should accommodate the loss or degradation of onboard navigation.

An example of such a strategy is to avoid introducing relative motion that re-intersects with the target vehicle's orbit track (V-bar) at any point in subsequent orbits. Such a strategy is effective because small errors in relative orbit period arising from loss of navigation can result in such intersections violating close approach criteria. This strategy would also minimize the sensitivity of the abort to problems occurring from feedback control of the orbit that depends on accurate relative navigation data (e.g., such as ASTRO used for station-keeping 120 m following NextSat).

R-13. Provide a robust method for ensuring timely availability of sufficiently accurate target vehicle orbit state information.

Possible sources of information include: GPS on the target vehicle and a chaser-target communications link to relay the GPS data; wide field-of-view, long-range sensors that do not rely on precise pointing information to acquire the target (e.g., a rendezvous radar; ground-based relative orbit solutions based on sufficiently accurate ground-based tracking and/or TDRSS tracking); and a wide field-of-view transponder or beacon on the target vehicle.

R-14. Utilize best practices for rendezvous navigation filter design.

a. **Maintain an accurate representation of the target-chaser relative state estimation errors, including an accurate variance-covariance matrix.**

This allows the filter to compute an appropriate gain matrix. It also aids the filter in appropriately editing unsuitable measurements.

b. **Provide a capability for measurement underweighting that adapts to the current uncertainty in the filter's state estimation error, as required to be consistent with the suboptimality of the navigation filter's measurement update.**

Effective means for accomplishing this have been found to include:

i. Modified second-order Gaussian state update method [ref. 9];

ii. Multiplicative adjustment of the mapping of the state error covariance matrix into the measurement subspace, which occurs within the computation of the residual covariance [ref. 12]; and

iii. Schmidt-Kalman state update [ref. 10] that utilizes the covariance matrix of "consider" parameters (i.e., states that the filter does not update, but for which it maintains a covariance).

Multiplicative adjustment of the measurement noise covariance matrix within the computation of the residual covariance (the "bump up *R*" method [ref. 10]) has been found to be less effective, and is not recommended unless other methods are not feasible.

c. **Estimate states that model biases in sensor measurements and account for un-modeled accelerations.**

Gauss-Markov models for these biases have been found to be more effective than random constant or random walk models. Random constant models can become stale, and random walk models can overflow during long periods without measurement updates.

d. **Provide commands that allow for selective processing of individual measurement types.**

If the filter utilizes an automated residual edit process, then the recommended command capability should be able to override the residual edit test.

e. **Maintain a backup ephemeris, unaltered by measurement updates since initialization, which can be used to restart the filter without uplink of a new state vector.**

f. **Provide a capability for reinitializing the covariance matrix without altering the current state estimate.**

g. **Ensure tuning parameters are uplinkable to the spacecraft, and capable of being introduced to the filter without loss of onboard navigation data.**

h. **Provide flexibility to take advantage of sensors and sensor suites' full capability over all operating ranges.**

R-15. Seek independent review by discipline expertise throughout the project life cycle.

a. **Proactively seek the advice and recommendations of independent rendezvous experts with experience in developing and operating rendezvous missions.**

b. **Maintain independent rendezvous expertise continuity throughout the project life cycle, particularly *but not only* at key milestone reviews.**

c. **Engage independent rendezvous experts in the development of post-mission analysis studies and lessons learned activities.**

R-16. Use caution with angles-only rendezvous.

a. **Weigh the risks of angles-only rendezvous techniques against the cost of mitigating the constraints that preclude the use of active sensors.**

b. **Study and incorporate lessons learned from the flight history of relevant missions.**

Some occurrences of angles-only rendezvous include the following: radar-fail cases on Gemini X, XI, and XII, STS-92, and some Soyuz missions; mishaps on Progress-Mir, Engineering Test Satellite (ETS)-VII, and DART; and during difficulties experienced by OE and Experimental Satellite System (XSS)-11. Reference 13 provides information on many of these missions. Reference 14 addresses the Gemini rendezvous experiences in particular. A summary of the Japanese ETS-VII rendezvous and docking technology in-space experiment results is given in Reference 15. The publically released overview of the DART mishap investigation results is provided in Reference 16. Lastly, Reference 17 describes how the XSS-11 mission demonstrated capabilities and technologies for autonomous rendezvous and proximity operations.

R-17. Plan for post-mortem.

a. **Archive detailed post-flight analyses of rendezvous and proximity operations.**

A partial list of such activities includes: archival of flight data, both real-time telemetry and data from onboard recorders; determination of actual performance by comparison of flight data to post-facto best-estimated parameters; comparisons between predicted and actual performance; and archival and documentation of results in form and content suitable for varying levels of disclosure consistent with applicable laws, rules, and guidelines.

b. **Plan to ensure data archives are readily available to support resolution of contingencies during operations.**

8.0 Alternate Viewpoints

There were no alternate viewpoints expressed during this assessment.

9.0 Other Deliverables

There were no other deliverables for this assessment.

10.0 Acronyms List

AGN&C	Autonomous Guidance, Navigation and Control
AR&D	Automated Rendezvous and Docking
ARCSS	Autonomous Rendezvous and Capture Sensor System
ASTRO	Autonomous Space Transfer and Robotic Orbiter
AVGS	Advanced Video Guidance Sensor
CEV	Crew Exploration Vehicle
CoP	Community of Practice
CY	Calendar Year
DARPA	Defense Advanced Research Project Agency
DART	Demonstration of Autonomous Rendezvous Technology
EKF	Extended Kalman Filter
GN&C	Guidance, Navigation and Control
GSFC	Goddard Space Flight Center
IR	Infrared
IRRT	Independent Readiness Review Team
ISS	International Space Station
LRF	Laser Rangefinder
MIB	Mishap Investigation Board
MSFC	Marshall Space Flight Center
NEN	NASA Engineering Network
Next/CSC	Next Generation Satellite/Commodity Spacecraft
NFoV	Narrow field-of-view
OE	Orbital Express
RPODU	Rendezvous, Proximity Operations, Docking & Undocking
TDT	Technical Disciple Team
VGS	Video Guidance Sensor
WFoV	Wide Field-of-View

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14. ABSTRACT
The Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT) sponsored Dr. J. Russell Carpenter, a Navigation and Rendezvous Subject Matter Expert (SME) from NASA's Goddard Space Flight Center (GSFC), to provide support to the Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) rendezvous and docking flight test that was conducted in 2007. When that DARPA OE mission was completed, Mr. Neil Dennehy, NASA Technical Fellow for GN&C, requested Dr. Carpenter document his findings (lessons learned) and recommendations for future rendezvous missions resulting from his OE support experience. This report captures lessons specifically from anomalies that occurred during one of OE's unmated operations.

15. SUBJECT TERMS
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