Comparison of Navigation Solutions for Autonomous Spacecraft from Multiple Sensor Systems

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ABSTRACT

The Orbital Express ASTRO spacecraft carried multiple independent sensor systems for estimating relative state in autonomous vehicle proximity operations. The on-orbit performance of pose-estimation imaging and dedicated-target navigation solution methods are compared, for ranges between 150 meters and spacecraft capture. Variations between performance expectations from pre-flight ground tests and actual on-orbit performance are discussed. Analysis results indicate the sources of solution variations.

Keywords: spacecraft, navigation, proximity operations, capture, sensor

1 INTRODUCTION

The Orbital Express program was developed to demonstrate key technologies for autonomous operations of space vehicles, including autonomy in proximity operations, capture and vehicle resupply. One enabling technology developed for the Orbital Express demonstration was a system of proximity operations navigation instruments capable of providing stable and accurate relative state estimates for spacecraft approach and capture.

1.1 Orbital Express spacecraft design

The Orbital Express mission flew two spacecraft, the Autonomous Space Transport Robotics Operations (ASTRO) servicing spacecraft and a prototype next-generation serviceable spacecraft, NEXTSat. NEXTSat carried the passive half of the STARSYS capture mechanism, and optical targets to facilitate proximity operations guidance. The guidance sensor suite developed for ASTRO was equipped with multiple sensors, to provide functional redundancy for proximity operations guidance. ASTRO's functional redundancy makes it possible to compare navigation solutions from the available sensor sets, and thereby evaluate the effectiveness of each sensor system's performance.

1.2 Rendezvous and capture mission scenarios

The Orbital Express mission was designed to exercise progressively more complex and independent levels of autonomy. These sequences of operations were grouped into scenarios. The initial scenario provided for sensor and systems checkout and on-orbit calibration while the ASTRO/NEXTSat satellites were attached in the launch configuration. Subsequent scenarios provided for operational checkout in various lighting and approach corridor configurations. Rendezvous and capture scenarios contained pre-planned moves to contingency "safe" points to be used in case off-nominal conditions occurred. Demonstration scenarios were evolved and refined throughout the OE development, and at launch eight scenarios were planned. Not all planned scenarios were executed due to time constraints and because data obtained from those executed satisfied all mission objectives.

2 ASTRO VEHICLE NAVIGATION SENSOR ARCHITECTURE

ASTRO flew with navigation sensors located in two structural bays, with the forward section of panel one housing the Advanced Video Guidance Sensor (AVGS). ASTRO panel five housed the navigation system optical bench, which provided a stable platform for the remaining navigation sensor components:

- Honeywell Space Integrated GPS and Inertial Navigation System (SIGI)
- Jena Optronik ASTRO Star Tracker and interface unit (ST)
- L3-ALST Eye-safe Laser Range Finder (ELRF)

- Three Boeing-developed imaging sensors, including narrow- and wide-field visible light cameras (VS1 and VS2) and an infrared sensor (IRS)
- An LED-based spotlight (for night time approach and capture)



Fig. 1. ASTRO (lower) and NEXTSat spacecraft at vehicle integration. The AVGS Short Range Target is visible at the top.

2.1 Inertial Navigation Sensors

The SIGI and Star tracker provided inertial navigation data to ASTRO guidance computers. The remainder of the optical bench systems, and the AVGS, were dedicated to providing navigation for vehicle proximity operations leading to capture.



Fig. 2. ASTRO optical bench assembly with ARCSS Sensors in Foreground (Left) and AVGS Sensor (Right)

2.2 Autonomous Rendezvous and Capture Sensor System (ARCSS)

The automated rendezvous and capture sensor system (ARCSS), along with the integrated Vis-STAR software, is ASTRO's primary relative navigation sensor system at mid- to long ranges and during fly-around at about 100 meters, providing relative state information for NEXTSat at ranges up to several hundred kilometers. At short range, in an approach corridor from 60 meters to capture, ARCSS data is combined with the AVGS data stream to provide fully redundant measurements of bearing, range and relative attitude (pitch, roll, and yaw alignment).

ARCSS hardware consists of three imaging sensors: a narrow field of view visible sensor (VS1) for long range acquisition and track, a wide field of view visible sensor (VS2) for mid- to short-range operations, and a long wave infrared sensor (IRS) for continuous tracking and situational awareness during operations when lighting is poor. In addition to the imaging sensors, ARCSS features a laser rangefinder, cued by the imaging sensors, which provides two-meter resolution for mid range tracking of NEXTSat from 7 km to 50 meters. A spotlight enables visible sensor tracking during close-approach in darkness.

ARCSS acquires the NEXTSat client at ranges beyond two hundred kilometers using VS1. At initial acquisition ranges NEXTSat presents a point source image. VS1 tracks NEXTSat during periods of favorable lighting, providing bearing data to GN&C. The infrared sensor begins providing bearing data at a range of 5 km.

When the image of the client becomes extended across several pixels, Vis-STAR software independently calculates the attitude of the vehicle along with target range and bearing. This information is blended with AVGS data to ensure correct alignment to the NEXTSat during the final approach and capture phases of each mission scenario. VS2 is used during the final sixty meters of the approach to provide Vis-STAR imagery by keeping the entire NEXTSat vehicle in the sensor field of view. Tracking algorithms are designed to run interchangeably with any of the sensors, providing seamless coverage over a wide range of lighting, range, and background conditions.

ASTRO imaging sensors were built on a common platform. The two visible sensors had rad-hard CMOS focal planes. CMOS focal planes were chosen for resistance to imaging artifacts, such as blooming and streaking, under harsh on-orbit lighting conditions. Sensor data and control was through an IEEE-1394a digital data bus interface. The IRS incorporates an uncooled microbolometer focal plane.

The sensor computers, ASTRO Computer 2 (AC2) and AC3 contained custom IEEE-1394a network interface cards (NICs), and the spacecraft network allowed all ARCSS sensor data to be accessed by either AC2 or AC3. AC3 (mounted in an ORU container) was included for redundancy and to demonstrate on-orbit replacement of an electronics unit. ASTRO Computer 1 (AC1), also on the 1394 network, provided command and data handling, Guidance, Navigation and Control (GN&C) and mission manager software functions to control the spacecraft.

2.3 Vis-STAR Software

The Vis-STAR Software includes Long Range Track (LRT), Extended Target Track (ETT), target plate track and sensor control/interface modules. Vis-STAR provides real-time relative target state measurements to AC1.

The Vis-STAR software, outlined in Figure 3, provides the capability for passive relative range and attitude determination of a target, based on imaging sensor data only. A real-time image correlation algorithm takes advantage of a priori knowledge of client vehicle physical configuration, enabling relative navigation with respect to a completely passive client. Vis-STAR is scaleable to different sensor formats and fields of view, and therefore operating range can be selected by sensor optical prescription. Vis-STAR image processing can be tailored for specific target image characteristics and precision requirements.



Fig. 3. Schematic of Vis-STAR navigation solution process flow

All available Vis-STAR processing modes were successfully verified and met performance requirements during the OEDS mission.

The process flow of the Vis-STAR algorithms is highlighted in Fig. 3. The inputs to the routine include an estimate of the target data, including position, and imagery from the visible and infrared sensors. The target position allows motion stabilization of the target on the focal plane image. The target range is first used to determine the mode of operation (whether the target is a point source or extended). If it is a point source, the long-range tracker is employed to determine the target position in terms of azimuth and elevation. For longer range targets (faint point sources), an image calibration algorithm improves the signal to noise ratio of the target to allow detection at extended ranges.

2.4 AVGS sensor system operation

The AVGS sensor system consists of the AVGS sensor on the ASTRO spacecraft and two sets of optical target arrays on the NEXTSat spacecraft. The AVGS was designed to detect the optical signal return from retroreflector target arrays on the target spacecraft to determine range and relative attitude information for guidance and close proximity operations. The AVGS sensor is comprised of a lens and CMOS imager, two pairs of laser diodes (808 nm and 845 nm wavelengths), and associated data processing and electronics.

AVGS operation may be summarized as follows. First, the AVGS illuminates the target at 808 nm and acquires an image; this is immediately repeated using the 845 nm lasers illumination. The first image is then digitally subtracted from the second image and the result is thresholded to set low-level pixels to zero. Since the retroreflector targets on the NEXTSat are filtered such that only the 845 nm light is returned, the subtraction yields an image limited to the reflective

target spots on NEXTSat. AVGS performs a perspective inversion calculation on this spot data to calculate relative target navigation state.

The AVGS functions at ranges from 200 meters to dock in both day and night-time operations. The AVGS was designed to provide a solution from the short range target set from capture out to a range of about 10 meters. From 10 meters to 30 meters, AVGS supplies a dual solution (from both the short range target set and the long range target), and from about 30 meters to the max operational range the AVGS supplies the long range target solution only.



Fig. 4. AVGS Block Diagram

3 ASTRO NAVIGATION AND GUIDANCE OPERATIONS

Navigation error limits were allocated to the navigation sensors based on systems analysis of orbital operations. At long ranges, excess navigation errors would lead to excessive propellant consumption. At capture ranges the vehicle error limits were defined by the misalignment limits of the capture mechanism. During detail guidance system design, Monte Carlo simulations and closed-loop simulations showed that larger range and track angle noise limits would provide acceptable performance. On-orbit operations confirmed that relative nav could absorb somewhat larger sensor errors than the initial allocation and maintain performance margins.

Navigation performance on-orbit real-time was evaluated with the use of down-linked telemetry, observing guidance, navigation, and control (GNC) filter output, sensor input and intermediate states. No measurement sources available either on-board or externally could provide an independent assessment of relative navigation accuracy.

The relative navigation on-orbit performance was evaluated by comparing the consistency of the navigation estimates with the measurement data available from on-board sensors, including the multiple relative target sensors and the inertial guidance system (SIGI). Small differences, or residuals, between nav filter states and raw sensor measurements indicated good performance. Comparison of data from the redundant vehicle sensors increased confidence in the navigation performance estimates.

During occasional measurement dropout intervals, obtaining a range measurement from the laser rangefinder confirmed that target estimate angles were valid and that range estimates errors were valid. Subsequent sensor measurements reduced the estimation errors to desired levels as the ASTRO continued to close in on NEXTSat.

The target state estimate provided by the guidance and relative navigation (G&RN) relative navigation filter is the best available data to use as "truth" data for evaluating unmated sensor data. The relative navigation filter provides a blended solution of all available sensor data continuously. During on-orbit operations, GNC provided target state estimates in sensor coordinates to ARCSS for direct comparison with VS1, VS2 and IR sensor data. Ground processing converted AVGS and Vis-STAR measurements to common coordinates to compare AVGS and Vis-STAR sensor data during capture & mate on-orbit.

The major difficulty with critical evaluation of the performance of the navigation sensor systems is the lack of objective measurement data to compare sensor data against. Post-flight analysis of AVGS data revealed how limiting this lack of "truth" data can be.

The AVGS demonstrated highly repeatable and accurate measurements throughout the ground testing, particularly after exhaustive ground calibration processes. Since the AVGS design is inherently insensitive to errors caused by adverse lighting or off-nominal target perspectives, AVGS solutions were predicted to provide reliable measurements during operations within the approach and departure corridors. Because of the expected accuracy, ASTRO navigation filters heavily weighted the AVGS contribution to the nav solution for all operations with blended solutions. For post-flight analysis, the filter weighting limited the usefulness of comparing AVGS data to the filtered navigation solutions. Since ~90% of the nav solution is based on AVGS data, correlation to the GNC solution appears excellent, but is not particularly meaningful.

	Requirement	Expected	Actual Performance
		Capability	
Usable Range	200 meters	200 meters	150 meters demonstrated
Range accuracy (within capture box)	+/- 15 mm	+/- 15 mm	+/- 6 mm
Lateral alignment measurement error	+/- 15 mm	+/- 15 mm	+/- 6 mm
(within capture box)			
Relative attitude measurement accuracy	0.4 degrees	0.2 degrees	<0.2 degrees

Table 1. AVGS measurement requirements and actual performance



Fig. 5. ASTRO guidance and control data flow

3.1 ASTRO vehicle operational modes for proximity operations

Three relative navigation operational modes were available for ASTRO proximity operations – AVGS, Vis-STAR and a blended solution. In practice, only the blended mode was used. The blended mode used all available position and attitude measurement data from all sensors including AVGS, VS1, VS2, IR and LRF.

3.2 Detail methods applied (Kalman filtering) to blend navigation solutions.

The relative navigation software utilized two Kalman filters to estimate the relative target state. A fourteen-state inertial state filter was used to estimate ASTRO position and velocity (six states) and NEXTSat position and velocity (six states) in inertial coordinates. An additional two states were used to remove sensor biases.

The state estimate and error covariance were updated using measurements sequentially from each sensor, blending the multiple sensors measurements into a composite relative target state. Weighting of sensor measurements was determined from ARCSS-provided measurement error estimates with the target state estimate error covariances. Measurement sets that were incorporated included LRF range only, angles only from VS1, VS2 or IR, and range/angles from AVGS and Vis-STAR (VS1, VS2, IR).

The vehicle states were propagated with a Super-G integrator incorporating delta sensed velocity input and a J2 gravity model. Data editing was used to remove measurements that might adversely affect the target state estimate accuracy. The data editing ensured that spurious target reports from the navigation sensors would be dropped. SIGI state updates were used to maintain accuracy of absolute ASTRO state, without diluting accuracy of the NEXTSat state.

A separate Kalman filter was used to estimate inertial attitude of both ASTRO and NEXTSat. The nine-element state included NEXTSat attitude difference (roll, pitch, yaw), NEXTSat inertial rate, and ASTRO inertial attitude. Target attitude measurements were used to update the NEXTSat attitude when available.

On-orbit calibration was performed to compute mean measurements (position and attitude) at mate for the AVGS shortrange target and the Vis-STAR target. Calibration reduced the measurement bias at capture. The calibration procedure was repeated after corrected parameters were loaded to confirm that the calibration provided the expected reduction in measurement error.

4 FLIGHT PERFORMANCE FOR ASTRO NAVIGATION SYSTEMS

The AVGS performed well throughout the majority of the OE mission. The AVGS output was especially useful in the unmated scenarios. The AVGS was active for all six of the unmated operations, three of which ended in capture, two in free-flier capture, and the last was the end-of-life separation. Additionally, the AVGS collected data during ARCSS sensor checkout and separation ring ejection. The AVGS took significant amounts of data during the two mated calibration procedures (AT-UTIL-25) and a 5-hour sensor stress test prior to Scenario 5-1. The AVGS contributed significantly to the successful direct and free-flier captures during all Orbital Express unmated operations. AVGS tracked continuously during all proximity operations and capture inside of 60 meters, while on the approach corridor. The AVGS tracked its Short Range Target (SRT) consistently from the docked position (1.2 meters) out to about 31 meters, while the Long Range Target (LRT) was tracked from about 8.8 meters out to as far as the scenario allowed.



Fig. 6. AVGS Data from mission scenario 2-1 depicts excellent correlation between short range and long-range solutions. Long-range solutions were only available at ranges greater than 8.8 m.

During each unmated scenario, the ASTRO would depart from the NEXTSat along the Approach Corridor (which extended along the target boresight out to 60 meters), and would then move off the Approach Corridor into a more fuelfriendly trajectory. Since the NEXTSat was in Solar Inertial pointing mode for the majority of the mission, the fuel requirements for staying on the boresight of the NEXTSat targets became progressively larger as the relative range increased. The AVGS tracked the NEXTSat during both the departure along the Approach Corridor as well as during the approach and capture, but corridor departure limited the AVGS to tracking only within 60 meters for most scenarios. During one scenario (Scenario 3-1), the approach to the NEXTSat was on the target boresight at longer ranges, and in this case the AVGS provided accurate navigation data from 150 meters in to capture. The AVGS maximum range specification was 200 meters, but ground testing was never performed beyond 100 meters, so the optical parameters were extrapolated and resulted in 150 meters tracking rather than 200 meters.



Fig. 7. AVGS Data from mission scenario 7-1 depicts excellent correlation between the short range solution (red) and the ASTRO G&RN target estimate (green).

The AVGS had several operation modes. During the mission the AVGS was primarily operated in Track Mode or Acquisition Mode, the two modes in which the sensor is interacting with or attempting to acquire the target. Standby Mode was used for approximately half an orbit prior to each scenario, to thermally stabilize the optical bench within the instrument. Throughout the mission Diagnostic Mode, Maintenance Mode and Reset Mode were also exercised. All of these modes operated successfully each time they were called. While the AVGS was in Track Mode, the output data rate was 5 Hz. Twice during the mission, a new initialization data load (I-load) was developed on the ground and uploaded to the AVGS. The I-load generation and upload processes were thoroughly exercised during ground testing and went smoothly during mission operations. The AVGS operated with four one-watt system lasers firing in Track Mode or Acquisition Mode for almost 57 hours while on orbit.

There were some anomalies in the AVGS performance during some of the longer-range opportunities (i.e. when the AVGS could image the targets at ranges from 80 to 120 meters.) The sensor experienced an error that was the result of one of its internal processors taking too much time to process an image. This error was traced to a combination of events: a large number of spots being visible at certain solar angles and software that had not been tested at great enough extremes. The software was fixed on the ground and a new load readied for the unit on orbit. However, since the problem only occurred at ranges outside the approach corridor (0 to 60 meters), the problem was not deemed significant enough to upload new software into the AVGS.

The ARCSS sensors with associated Vis-STAR software provided relative navigation data from hundreds of kilometers to capture. During proximity operations, range, position and attitude angles were provided within required accuracy and measurement rates against both space and earth background, in day and eclipse lighting conditions.

Accurate Vis-STAR position state measurements were obtained both within the nominal approach corridor and out-ofcorridor for a wide range of lighting and target orientation angles. Attitude measurements were constrained by software limits to in-corridor operations inside 60 meters range. Vis-STAR measurement accuracy matched well with ground simulation results. Some measurement dropouts were observed in early unmated scenarios due to glints off NEXTSat. Dropouts were substantially eliminated for later engagements by modification of camera exposure control and threshold parameters in I-loads for those sensors.

From 10 meters to 15 meters, all sensors (VS1, VS2 and IR) were used to provide Vis-STAR measurements. The VS1 sensor provided measurements using a dedicated Vis-STAR target. The IR sensor used edge tracking at these ranges and VS2 sensor used both silhouette track and edge track to provide target data.

Some sensor measurement dropouts occurred during corridor departure and approach. VS1 measurement dropouts were sometimes observed at an edge of the 10 meter station-keeping box in later scenarios during eclipse. This was due to reduced target signal at the longer spotlight illumination ranges. Vis-STAR position and attitude measurements were provided by VS2 and IR sensors during the VS1 dropout intervals, so that no Vis-STAR measurement dropouts exceeded allowed time intervals for proximity operations. During non-solar inertial (LVLH attitude) scenarios, dropouts also occurred briefly during the period where strong shadows crossed the target plate.

For future applications, further enhancements to the exposure control algorithm and slight modifications to the target plate design will eliminate these dropouts.

For ranges from 15 meters to 60 meters in-corridor, some combination of sensors (VS1, VS2 and IR), depending on range and lighting, were used with silhouette track, edge track and earth background removal algorithms to provide position and attitude measurements. Earth background removal worked extremely well, with performance corresponding to simulation estimations. Occasional short data dropouts due to target merging with earth background never exceeded allowed time periods.

At ranges from 60 meters to 150 meters, both in-corridor and during fly-around maneuvers, Vis-STAR provided position angle and passive range measurements with good relative navigation performance. A laser range finder was also used to provide an active range sensor at greater than 50 meters.

After the second unmated scenario, an updated version of Vis-STAR was uploaded to the ASTRO spacecraft. Track algorithm and I-Load changes resulted in improvements in long-range (greater than 150 meters) tracking. Performance improvements for ranges less than 150 meters (the subject of this paper) were accomplished with I-load parameter adjustments only. See the following table for a summary of on-orbit Vis-STAR track software updates and associated improvements in on-orbit system performance.

Condition	Vis-STAR Software	On-Orbit Flight Test Results	
	Enhancements		
Measurement dropouts at close range at	Updated I-Loads for exposure	Restored in-corridor Vis-STAR	
night due to spotlight glints from	control and threshold parameters.	operation under spotlight	
NEXTSat surfaces near Vis-STAR		conditions	
target			
Higher than expected background noise	Updated exclusion angles via I-	Obtained consistent measurements	
from sun and earth for some lighting	Load, updated camera exposure	as a function of sun and moon	
angles caused occasional measurement	control algorithms improved	angles, spurious target measure-	
dropouts and spurious target reports	spurious target rejection parameters	ments completely eliminated	
IR Sensor range performance met	Added two-point calibration for IR	Two point calibration resulted in a	
requirements but opportunity existed	sensor to reduce sensor noise and	5X reduction in sensor noise and	
for significant improvement	improve probability of detection	clutter and corresponding	
	against space background	improvement in detection range	

Table 2.	Vis-STAR	Software	Enhancements



Fig. 8. Vis-STAR range & bearing plot: Scenario 7-1 free-flyer capture, VS2 measurements - blue, G&RN estimates - green



Fig. 9. VIS-STAR attitude plot for Scenario 7-1 free-flyer capture, VS2 measurements - blue, G&RN estimates - green

5 VARIATIONS BETWEEN DESIGN EXPECTATIONS AND FLIGHT PERFORMANCE

Pre-flight predictions of navigation performance were made using a combination of Monte Carlo simulations performed with sensor math models based on sensor design requirements and closed-loop simulations using Vis-STAR sensor software operating on simulated sensor imagery in conjunction with AVGS and LRF math models.

The AVGS sensor math model applied the ground-test-verified AVGS error characteristics for both bias and noise values. On-orbit navigation performance was observed to be considerably smoother than the same performance in the pre-flight simulations, when AVGS measurements were provided in-corridor. This appears to imply that the on-orbit AVGS sensor measurement errors were noticeably better than the math model values, despite the validated error sources. This finding is attributed to the better environment thermal stability on orbit and the lack of atmosphere-induced optical path disturbances.

The on-orbit Vis-STAR statistical measurement error performance was well predicted by the ground simulations. Measurement dropouts that initially occurred at close range were corrected with software updates. The measurement error performance was similar to the separate Vis-STAR computer model performance predictions, meeting the design requirements as stated in the ARCSS software specifications.

6 CONCLUSIONS AND RECOMMENDATIONS

Reviewing the mission data from Orbital Express, two findings are clear. First, solutions from both target-imageanalysis-based and dedicated-optical-target navigation instruments can provide proximity operations navigation sufficiently accurate and reliable for autonomous vehicle approach and capture. This finding is a major justification of the investment made in developing and flying the Orbital Express spacecraft.

Second, the inclusion of long range sensors, such as the ARCSS imagers and rangefinder, significantly improved the GN&C relative navigation state, resulting in safer, more deterministic and more accurately flown rendezvous trajectories.

The third major finding was that extensive ground testing is required to evaluate and tune sensor performance, and even with hundreds of hours of ground testing, some surprises will be experienced on-orbit. Vis-STAR developers had to retune software settings, especially camera exposure settings, to react to the challenging on-orbit lighting that is essentially impossible to accurately simulate in ground testing. AVGS developers were happy with the instrument's lower-than-predicted measurement noise, but this deviation from expected performance may indicate that ground testing of future proximity navigation instruments should include at least limited operations against targets in a vacuum environment.

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