Modeling, Simulation, Testing, and Verification of the Orbital Express Autonomous Rendezvous and Capture Sensor System (ARCSS)

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ABSTRACT

The Orbital Express Autonomous Rendezvous and Capture Sensor System (ARCSS) ALONG WITH ITS Vision-based Software for Track, Attitude and Ranging (Vis-STAR) provided relative target position and attitude measurements for guidance and relative navigation during autonomous vehicle proximity operations. The use of computer and physical models during simulation, ground testing and verification of ARCSS imaging camera and software performance prior to and during on-orbit operations is discussed.

Keywords: Modeling, simulation, testing, sensors, tracking, guidance, ARCSS, Vis-STAR, Orbital Express, rendezvous

1. INTRODUCTION

1.1. Orbital Express Overview

The Orbital Express is a Defense Advanced Research Projects Agency (DARPA) program to develop, demonstrate and validate key technologies required for on-orbit servicing of next generation satellites including the replacing of Orbital Replacement Units (ORUs) such as a battery and computer and the replenishment of propellant. A Boeing-led contractor team built two demonstration satellites which were launched March 8, 2007, then successfully demonstrated all on-orbit mission objectives in the four months following launch.

The two demonstration satellites were the Autonomous Space Transfer and Robotic Orbiter (ASTRO); a prototype servicing satellite built by Boeing Advanced Network and Space Systems and the Next Generation Satellite (NEXTSat) built by Ball Aerospace Corporation. The NEXTSat served dual roles; as a serviceable client satellite, as well as a Commodity Spacecraft which provided storage of spare ORUs and a propellant tank. The two satellites were launched together on March 8, 2007 in a mated configuration into a circular 492 km altitude, 46° inclination Low Earth Orbit.

In order to perform servicing operations, ASTRO needed to successfully demonstrate rendezvous and capture of NEXTSat. During the course of the Orbital Express mission, six unmated autonomous mission scenarios were completed to demonstrate (a) soft de-mate, safe separation and departure of ASTRO, (b) tracking of NEXTSat by ASTRO on-board sensors, (c) ASTRO on-board autonomous guidance and relative navigation and (d) soft capture of NEXTSat by either a three-pronged capture mechanism or a robotic arm. Six demonstration scenarios were performed, starting from ranges as short as 10 meters up to a maximum separation of over seven kilometers. Multiple approach trajectories were employed, including solar inertial, velocity vector (V-bar) and Earth radius vector (R-Bar), under varying daylight and nighttime lighting conditions. During the final End-of-Life (EOL) mission scenario, ASTRO departed to a maximum separation range of over 400 km and returned to within 1 km before proceeding to its final disposal orbit.

2. ORBITAL EXPRESS RENDEZVOUS SENSOR SYSTEM

2.1. ARCSS Flight System

The Autonomous Rendezvous and Capture Sensor System (ARCSS), along with the integrated Vis-STAR software, was ASTRO's primary relative navigation sensor system at mid- to long ranges and during fly-around, 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 was combined with the AVGS data stream to provide fully redundant measurements of bearing, range and relative attitude (pitch, roll, and yaw alignment).

ARCSS hardware consisted 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 at night or when lighting was poor. In addition to the imaging sensors, ARCSS featured a laser rangefinder (LRF), cued by the imaging sensors. The LRF provided direct ranging of NEXTSat from 6 km to 50 meters. A spotlight enabled visible sensor tracking during close-approach in darkness.

When the image of the client became extended across several pixels, Vis-STAR software independently calculated the attitude of the vehicle along with target range and bearing. This information was blended with AVGS data to ensure correct alignment to the NEXTSat during the final approach and capture phases of each mission scenario. Tracking algorithms were 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 optical bench, shown in Figure 1. The two visible sensors had radhard CMOS focal planes; chosen for their resistance to imaging artifacts, such as blooming and streaking, under harsh on-orbit lighting conditions. The IRS incorporated an uncooled microbolometer focal plane, providing sensitivity in the long wave (thermal) infrared, without need of a cryocooler.



Figure 1. ARCSS Flight Sensors on ASTRO Optical Bench

The sensor computers, ASTRO Computer 2 (AC2) and AC3, contained custom IEEE-1394a network interface cards (NICs), allowing all ARCSS sensor data to be accessed by either computer on the high speed 400 Mbps spacecraft network. 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. A functional block diagram of the ARCSS system and ASTRO computing architecture is shown in Figure 2.

2.2. 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 provided real-time relative target state measurements to AC1.

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



Figure 2. ARCSS and ASTRO Computing Architecture Functional Block Diagram

3. ARCSS MODELING, SIMULATION, TESTING AND VERIFICATION

3.1. ARCSS Test Overview

A rigorous component, subsystem and system test program was conducted to verify that ARCSS hardware would survive launch and the subsequent LEO space environment. In addition, an extensive combination of computer simulations and physical model testing was conducted in order to verify the performance of Vis-STAR algorithms and software prior to launch. During Orbital Express design, validation, and integration, computer simulations and lab models were combined to provide realistic imagery for algorithm and software testing. Completely synthesized images were injected into the AC2 computer; real-time synthetic camera data was generated for computer-in-the-loop testing; and cameras were shown combinations of model and projected scenes and realistic lighting, for full hardware-and-software-in-the-loop testing. Each of these test programs is discussed in further detail below.

3.2. Hardware Qualification Testing

To assure the proper operation of ARCSS in space, all flight hardware units had to pass vibration, thermal-cycle, thermal-vacuum, acoustic and EMI/EMC environmental tests either at the unit level or at an integrated subsystem/ system level. These tests were performed seamlessly across a number of supplier and Boeing sites using common processes and a rapid prototyping mindset to control costs. Hardware was tested to protoflight levels, with margin to expected flight maximum environments, but below normal qualification levels that would have rendered the hardware unsuitable for flight. Figure 3 presents an overview of the ARCSS hardware test and qualification process, both for Engineering Development Units (EDUs) and protoflight units. As described in sections 3 and 4, EDU sensors and computers were used extensively for flight software hardware in the loop testing and qualification. EDUs had the same form, fit, and function as the flight units but were built with commercial parts and were not subjected to environmental tests.



Figure 3. ARCSS Hardware Test and Qualification Flow

3.3. ARCSS Alignment and Optical Testing

3.3.1. Optical Testing Overview

The ARCSS sensor units were integrated on a single mechanically rigid optical bench in order to maintain precise alignment between sensor boresight and the ASTRO vehicle body axes. The body axes were defined by the alignment of the GPS/INS unit and the star tracker which were mounted on the same optical bench.

Iterative hardware characterization and testing was conducted at all stages of optical system development and integration using EDU sensors and other ARCSS components, model satellites with representative surface materials, and simulated lighting and backgrounds. This hardware in the loop (HWIL) testing (see section 4) was closely linked to sensor unit testing and ARCSS integration testing, subjects of this section. Early HWIL test results helped guide the sensor selection process, define characteristics important to autonomous operations in space, and establish component requirements that would ensure mission success. Later HWIL testing with EDU sensors ensured that each sensor interfaced properly with ARCSS, contained firmware features sufficient to successfully complete the mission, ensured sensor compatibility with other ARCSS components and software, and optimized values of variable sensor attributes.

The role of sensor unit level optical testing was to ensure that the imager (a complete "camera" with sensor electronics, firmware, lens, and structure) conformed to well defined requirements that were sufficient to ensure acceptable performance for the Orbital Express mission.

ARCSS integration optical testing was used to provide imager adjustment and calibration, confirm imager conformance to selected product requirements, and to perform functional testing throughout the series of ARCSS qualification and risk reduction environmental testing.

3.3.2. Component Unit Level Optical Testing

The imaging sensors were procured as complete, tested assemblies. As a consequence, product acceptance requirements were selected to be compatible with testing completed imagers. In addition to ensuring that specification requirements provided acceptable performance, they were selected to meet the following objectives:

- Test requirements needed to be easily understood and conducted at minimal expense.
- Test methods should be simple enough to be performed by technically capable, non-optical personnel.
- Test methods should be suitable for verifying function and performance before and after environmental tests without imager disassembly.
- Test criteria had to control attributes needed for integration, but not flow the prime contractor responsibility to the sensor vendor.

3.3.3. Visible Sensor Component Level Optical Testing

Visible optical test methods were adapted from IEC 1146-1⁰. Visible sensor specification requirements for Luminance sensitivity, resolution, signal to noise, gain uniformity, and gamma were relatively easily adapted from the IEC methods and tests could be completed using low cost materials and straightforward evaluation. Most of the tests involved simply placing the sensor in front of a standard test chart with specified illumination, adjusting the sensor, grabbing a digital image for evaluation and performing simple arithmetic (ratios, averages, etc) on pixel values using a computer. The simple test materials used are shown in Figure 4 shows typical test image and evaluation.



Figure 4. Visible sensor testing using inexpensive charts and simple LabView® applet image evaluation tools for tests such as the uniformity, linearity, and image quality

3.3.4. Infrared Sensor Component Level Optical Testing

Infrared imager (IRS) testing required thermal sources rather than normal photographic type lighting used to test visible imagers. Instead of methods based on industry standard video test charts, component level requirements included a noise equivalent delta temperature (NEDT) requirement to ensure acceptable sensor signal to noise ratio and an ensquared energy requirement to verify acceptable image quality. Specification limits were kept well below values achievable based on the sensor and lens specifications. This provided a balanced system design and maintained comfortable performance margins. The infrared imager vendor used a large-area blackbody source to verify conformance with the NEDT requirement and Boeing verified the ensquared energy requirement during integration. There was little risk in deferring the ensquared energy measurement because of the wide margin between nominal imager optical system capability and the specification requirement value. Image evaluation was generally performed using a LabView® applet similar to that shown in Figure 4.

3.3.5. Boresight Considerations

ARCSS boresight was achieved without physical adjustment using precision dowel pins to orient the laser rangefinder (LRF) and imagers. Variation was compensated in software after measuring the deviation of the imager line of sight from the LRF laser line of sight. Thus, the imager vendor was responsible for ARCSS interface features and for holding line of sight accuracy within a few percent of the instrument field of view, tasks easily accomplished using dimensional control. What remained was ensuring that the imager could withstand qualification, acceptance, and flight environments without significantly shifting the line of sight. Environmental stability, therefore, was monitored during environmental

testing by comparing the field center aimpoint both before and after each environmental exposure. Use of a simple ARCCS sensor mount emulator (loaned to the vendor by Boeing) and imaging the center cross on the vendor's IR source bar target plate was sufficient to complete the task. An ARCSS interface emulator similar to that used by the imager vendor and a typical image recorded using the wide field flight imager are shown in Figure 5.



Figure 5. Boresight monitoring. Typical ARCSS interface plate (left) and wide field sensor image of infrared target plate (right)

3.3.6. ARCSS Subsystem Testing During Integration

The flight optical sensors were received by Boeing in Huntsville and integrated with the flight optical bench assembly (OBA). The completed OBA was then shipped to Boeing Anaheim for final sensor adjustment and testing. Most of the adjustment and testing was performed at an optical test station which had a large diameter parabolic collimator that could be used for the visible and infrared imagers and for the near infrared laser rangefinder. Additionally, the flight bench was mounted on a cross-slide so that each sensor could be moved to the center of the collimator field without losing angular alignment between the bench and the collimator.



Figure 6. Collimator test station used for flight ARCSS sensor adjustment and test. Parfocal autocollimating microscope replaced with various sources and targets as required for UUT.

The collimator test station is shown in Figure 6. The only other optical test instrument used during integration was a visible focus test chart for focusing the wide field visible imager (VS2) at 10 m, which could not be achieved with the parabolic collimator.

Before use, the collimator was adjusted by autocollimation off of an Aerotech flat mirror. The parfocal microscope provided sufficient sensitivity to focus and alignment to achieve the required collimation error in the plane of the optical table and to position targets precisely on the collimator focal plane.

In the integration and test area, OBA and ARCSS flight sensor suite cleanliness was maintained by locating the test station within an ISO Class 6 clean tent. Before the OBA was removed from the clean tent for environmental testing, it was wrapped in clean, electrostatic discharge (ESD) safe packaging and taped.

3.3.7. Sensor Focus and Image Quality

VS2 nominal focus was set based on analysis supported by EDU hardware in the loop verification using a full scale NEXTSat mockup and prototype short range tracking software. Since a sufficiently short range was not feasible with the collimator, the large turning flat was used to point the sensor at a combination radial focus and bar target illuminated by a large integrating sphere source placed at the appropriate distance from the sensor.

The narrow field visible imager (VS1) nominal focus was based on analysis and testing similar to the method used for VS2. The collimator was used to establish focus using a back-illuminated Air Force bar target or a pinhole aperture. The point source target was most useful because images made with the target at longer and shorter ranges could be used to evaluate blur size vs. distance to target. The bar target was used to verify resolution and image contrast. IRS focus was set using a pinhole and blackbody source in a similar manner.

3.3.8. Sensor Optical Boresight

The stressing boresight requirement was that the sensors were required to establish the LRF laser aim point within the laser beam width to ensure an acceptable range success rate. To achieve this, the laser line of sight was defined as the ARCSS system line of sight and the pixel offsets from that line were measured for each of the imagers.

The first part of the task was to establish the coordinates in VS1 which correspond the laser hit point on a distant target. Since the laser had a wavelength in the near infrared, the sensor could not view the laser hit directly. Instead, a phosphorescent laser alignment card was placed at the focus of the collimator and the imager acquired the visible phosphorescence. A simple centroid calculation was performed on the image to determine the spot center to sub-pixel accuracy.

The OBA was then shifted using the cross-slide so that the VS1 and IRS apertures were simultaneously in the collimator field and the alignment card target was replaced with a pinhole target at the collimator focus. Images were then acquired using a visible source behind the pinhole with the narrow field sensor and with a thermal source behind the pinhole with the IR sensor. Resulting point images were evaluated by centroiding, the pixel offset was calculated, and the LRF boresight pixel was transferred to the IRS focal plane by incorporating the LRF to VS1 offset. Using this procedure, the boresight calculation was not sensitive to the position of the pinhole in the collimator focal plane.

The final step was to acquire pinhole images with VS2. Though VS1 and VS2 sensors could not fit in the collimator aperture simultaneously, past experience had shown that cross-slide errors were insignificant with respect to the boresight error allowance.

3.4. Vis-STAR Software Testing

Testing of the ARCSS software used a four phase, incremental capabilities, testing approach. Phase I addressed interface operability, data formats, communications protocols and error handling. This series of tests was performed using software emulation tools developed in house, in lieu of the physical hardware. This configuration also served as the ARCSS software functional test suite (Figure 7). Phase II addressed ARCSS interoperability between the two processors comprising the ARCSS redundant computer system (Figure 8). Phase III addressed timing latencies and data throughput associated with the ARCSS sensor inputs. These tests were conducted using engineering prototype sensor hardware (Figure 9). Finally, Phase IV addressed system track performance accuracy and was conducted using a

combination of hardware and software in a closed loop command and control configuration (Figure 10). Phases I through III were performed at the Boeing Anaheim facility utilizing EDU, control and sensor emulators and actual sensor hardware. Phase IV testing moved to the closed loop environment at the Boeing Huntington Beach OE System Integration Laboratory (OESIL).



Figure 7. Interface Emulator System Block Diagram

The Interface Emulator System (IES) provided necessary development stimuli for ARCSS testing through the use of inhouse developed software emulators. The emulators mimicked the commands and responses of the AC1 and ARCSS sensor components, including the LRF and AVGS. The IES supported the entire compliment of commands and responses that AC2 could expect to encounter during flight operations. In addition, the sensor emulators provided a subset of the actual sensor capabilities including image data transfers, State Of Health (SOH) and self test responses. Hardware in the loop testing was accomplished primarily at Boeing Anaheim's test laboratory with some additional testing at the Marshall Space Flight Center's Flight Robotics Laboratory (FRL). The majority of integration testing, excluding in-house simulation and unit testing, was accomplished at Boeing's Huntington Beach facility.



Figure 8. ARCSS Testing Phase I-II Interconnect Block Diagram

ARCSS software functional testing consisted of three main elements: Commanding, Input/Output and Track/Situational Awareness. Each capability as specified in the software requirements specification (SRS) was tested, to the extent possible, utilizing a static, repeatable testing environment. This environment consisted of the equipment depicted in Figure 9.



Figure 9. ARCSS Testing Phase III Interconnect Block Diagram

As specified in the ARCSS software test description (STD), four representative tracking scenarios were created for the purposes of statically testing the ARCSS track functionality. The scenarios, consisting of trajectory and imagery data, were created using the OE Sensor Simulator (SensorSIM) system. The SensorSIM PC mimicked the interfaces of the VS1, VS2 and IRS sensors using internal commercial off the shelf 1394 interface cards, presenting data to the AC2 and AC3 sensor computers as if actual cameras were connected. SensorSIM generated real time radiometrically accurate imagery representative of each ARCSS sensor, taking into account detailed sensor characteristics, geometry, NEXTSat material properties and lighting corresponding to a given orbital trajectory. Trajectories were created by a high fidelity closed loop Guidance and Relative Navigation (GR&N) simulation at Boeing's Houston facility.



Figure 10. ARCSS Testing Phase IV Interconnect Block Diagram

Each test scenario presented a specific set of trajectories and imagery which exercised specific capabilities within the track algorithms. Measurement data collected by the ARCSS software during test operations were compared to truth data contained within the scenario trajectory to compute measurement error data. The collected error data were compared to track measurement error requirements in the AC2 Software Requirements Specification, providing consistent and repeatable pass/fail criterion.

3.5. High Fidelity Modeling, Simulation and HWIL Testing

3.5.1. Cameras with Full and Sub-scale Models

An extensive suite of computer simulations and physical model tests were conducted in order to verify the performance of ARCSS hardware and software prior to launch. During Orbital Express design, validation and integration, computer simulations and lab models were combined to provide realistic imagery for algorithm and software testing. Completely synthesized images were injected into the AC2 computer; real-time synthetic camera data were generated for computer-in-the-loop testing; and cameras were shown combinations of model and projected scenes and realistic lighting, for full hardware-and-software-in-the-loop testing.

During Orbital Express development, realistic physical models of the NEXTSat, built with similar materials, were used in extensive testing with the Engineering Development Unit (EDU) sensors. These tests included capability for real time performance monitoring and comparison with data generated by truth instruments to assess sensor accuracy. Figure 11 shows a full scale mockup of the NEXTSat client vehicle and EDU sensor optical bench, during hardware in the loop testing in the Boeing ARCSS Sensor Integration Lab (ARCSIL) in Anaheim, Ca.



Figure 11. Sensor Hardware in the Loop Integration Testing in Anaheim

Operating at LEO altitude, in a short-period orbit, lighting conditions for the sensors changed rapidly over the course of each orbit and each scenario. Some of the most challenging aspects of the rendezvous and proximity operations for the optical sensors were operating against Earth and satellite structure backgrounds, operating at many different ranges with the same sensors, operating against changing and adverse sun angles, and operating smoothly through transition regions between different sensor and algorithm choices and settings.

The ARCSIL environment provided the capability to test both day lighting (with sun simulator) and spotlight-only night lighting conditions for dynamic sensor motion at ranges from capture to 16 meters distance. This allowed comprehensive testing of target plate tracking with the full-scale model for both visible sensors.



Figure 12. a) Computer Simulation with Background Image b) 1/8 Scale Lab Model with Plasma TV Background c) Full Scale Lab Model with Simulated Sunlight d) On-Orbit Visible Image, Passive Tracking in Daylight Against Earth

One of the most stressing system requirements was tracking against Earth backgrounds. To facilitate algorithm and sensor development and testing, different combinations of simulated and model scenes were used. Full simulation has the advantages of flexibility, repeatability, easily obtained truth data and most importantly the ability to readily conduct closed loop testing. Actual on-orbit performance of the Earth background suppression algorithm was excellent.



Figure 13. a) Computer Simulation of Docking Target b) Full Scale Lab Model with Simulated Sunlight c) On-Orbit Visible Image of Docking Target and Solar Panel

Figure 12a shows a fully simulated scene. To more accurately simulate the effects of lighting and materials, subscale and full size models, shown respectively in Figure 2b and Figure 2c, were used. The 1/8-scale model of NEXTSat could be placed in front of a plasma display in order to simulate a dynamic Earth background. The full-scale model allowed accurate simulation of the effects of sensor locations, vehicle details, and varying solar lighting angles. For comparison, an on-orbit image is shown in Figure 2d. Figure 13a-c similarly show computer-simulated, full scale model, and on-orbit images of the docking target against the clutter of the NEXTSat solar panel.

3.5.2. Hardware-In-The-Loop (HWIL) & Flight Robotics Lab (FRL) Testing

The FRL provides a Dynamic Overhead Target Simulator (DOTS), a flat floor facility, and a solar simulator that provides full solar illumination to test in simulated on-orbit conditions. Two accurate six degree-of freedom measuring devices (API laser tracker and Leica laser tracker) were used to provide independent "truth" reference data, in addition to the reference data provided by the DOTS command computer.



Figure 14. ARCSS EDU test fixture on DOTS tracking NEXTSat model in FRL

The FRL provided the capability to test ARCSS performance using a dynamic robotic arm (DOTS) to simulate relative sensor-to-target motion at ranges up to 30 meters. Useful performance data were obtained to verify both Vis-STAR target plate tracking and the various full-body tracking algorithms. AVGS tracking performance against both short-range and long range targets was also demonstrated. The ARCSS EDU equipment setup at FRL is shown in Figure 14.

4. ON-ORBIT EXPERIENCE

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.

During the second unmated scenario, on May 12, 2007 an opportunity presented itself that demonstrated the value of the ARCSS/Vis-STAR in-house lab and test capabilities. The scenario began routinely with successful corridor separation to 30 m and return to a 12 m stationkeep point prior to capture. At that point a transient sensor computer fault caused ASTRO to execute an autonomous abort maneuver. The two spacecraft remained separated for nearly 8 days at ranges of up to 6 km during which time several ARCSS issues came to light. The team's ability to rapidly reproduce the on-orbit conditions in the lab and test solutions prior to uploading updated software and I-Loads to the ASTRO spacecraft were key to rapid resolution and return to normal operations.

A summary of the conditions addressed by the team, and the role of the lab capabilities in their resolution is presented in Table 1.

| Condition | Lab Test and Verification Steps Taken | Vis-STAR Software Enhancements | On-Orbit Flight Test Results |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Measurement dropouts at close range at night due to spotlight glints from NEXTSat surfaces near Vis- STAR target | Modified full scale NEXTSat physical model to more accurately simulate orbital conditions. Verified updated exposure algorithms by EDU sensor test. | Updated I-Loads for exposure control and threshold parameters. | Restored in-corridor Vis- STAR operation under spotlight conditions |
| Higher than expected background noise from sun and earth for some lighting angles caused occasional measurement dropouts and spurious target reports | Setup solar simulator in ARCSIL to simulate Earth or Sun within exclusion zones. Verified updated exclusion angles by EDU sensor test. | Updated exclusion angles via I-Load, updated camera exposure control algorithms improved spurious target rejection parameters | Obtained consistent measurements as a function of sun and moon angles, spurious target measurements completely eliminated. |
| IR Sensor range performance met requirements but opportunity existed for significant improvement | Imported raw flight IR sensor data into PC desktop simulation. Verified noise and clutter improvement after implementing two point calibration routine. | Added two-point calibration for IR sensor to reduce sensor noise and improve probability of detection against space background. | Two point calibration resulted in a 5X reduction in sensor noise and clutter and corresponding improvement in detection range. |

Table 1. ARCSS Lab Role in Vis-STAR Software Updates, Enhancements

After the second unmated scenario, the flight data was analyzed, software and I-Load changes defined and coded, an updated version of Vis-STAR software was tested, qualified and uploaded to the ASTRO spacecraft, all within 16 days. These software changes resulted in significant performance improvements during nighttime visible extended object tracking and daylight long-range tracking. Long range IR sensor tracking, which had met specification previously, improved by a factor of five.

5. CONCLUSIONS

Extensive modeling, simulation and test of the ARCSS Sensors and Vis-STAR software definitely contributed to the overall success of the Orbital Express mission. Careful optical testing and alignment produced a stable boresight which was verified by on-orbit tests. Comprehensive simulated and physical model testing under varying lighting conditions averted many potential issues and were a valuable tool available to the team when issues did arise.

Ultimately, ARCSS/Vis-STAR on-orbit performance was excellent, fully warranting the investment in modeling, simulation and testing used to verify system performance prior to flight.

6. ACKNOWLEDGEMENTs

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