ORBITAL EXPRESS AUTONOMOUS RENDEZVOUS AND CAPTURE SENSOR SYSTEM (ARCSS) FLIGHT TEST RESULTS

Manny R. Leinz[*], Chih-Tsai Chen, Michael W. Beaven, Thomas P. Weismuller, David L. Caballero, William B. Gaumer, Peter W. Sabasteanski, Peter A. Scott, Mark A. Lundgren

The Orbital Express flight demonstration was established by the Defense Advanced Research Projects Agency (DARPA) to develop and validate key technologies required for cost-effective servicing of next-generation satellites. A contractor team led by Boeing Advanced Network and Space Systems built two mated spacecraft launched atop an Atlas V rocket from Cape Canaveral, Florida, on March 8, 2007. The low earth orbit test flight demonstrated on orbit transfer of hydrazine propellant, transfer of a spare battery between spacecraft and the ability to replace a spacecraft computer on orbit. It also demonstrated autonomous rendezvous and capture (AR&C) using advanced sensor, guidance, and relative navigation hardware and software.

This paper summarizes the results of the on-orbit performance testing of the ARCSS (Autonomous Rendezvous and Capture Sensor System). ARCSS uses onboard visible, infrared and laser rangefinder sensors to provide real time data and imagery to the onboard sensor computer. The Boeing-developed Vis-STAR[†] software executing on the sensor computer uses the ARCSS data to provide precision real-time client bearing, range and attitude as needed, from long range to soft capture. The paper summarizes the ARCSS and Vis-STAR on orbit performance.

INTRODUCTION

Next generation satellites can be made more cost effective and provide additional mission utility by incorporating the capability for satellite servicing. Chief goals in a servicing system would be re-fueling and orbital replacement unit (ORU) upgrade, renewal, or repair. The Orbital Express flight demonstration was established by the Defense Advanced Research Projects Agency (DARPA) to develop and validate key technologies required for such servicing.

[*] Chief Segment Engineer, Electronic and Sensor Systems, The Boeing Company; 3370 Miraloma Ave. Anaheim, California 92807, AAS Member.

[†] Vision based Software for Track, Attitude and Ranging (U.S. Patent 6,954,441)

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A Boeing-led contractor team built the two-satellite Orbital Express Demonstration System (OEDS) which was launched March 8, 2007, aboard an Atlas V launch vehicle, to begin a four-month on orbit mission. OEDS included the Autonomous Space Transport Robotic Operations (ASTRO) Servicing satellite, built by Boeing Advanced Network and Space Systems and the Next Generation Serviceable Satellite (NEXTSat), serving as a client vehicle and as a Commodity Spacecraft (CSC), built by Ball Aerospace Corporation. The two vehicles were launched together in a mated configuration.

During the course of six unmated 'scenarios' the ASTRO spacecraft demonstrated completely autonomous rendezvous and capture (AR&C) of the NEXTSat from ranges of 10 meters to 100's of kilometers using advanced sensor, guidance, and relative navigation hardware and software technologies. Capture of NEXTSat was performed in two ways, via *direct* capture, using a three-pronged soft capture mechanism, developed by Starsys Research Corporation, and *free-flyer* capture, using a robotic arm developed by MacDonald-Dettwiler and Associates. The system also demonstrated transfer of hydrazine propellant, and the transfer of a battery and a computer unit between spacecraft on orbit.

Orbital Express accomplished numerous "firsts" in space, including: autonomous capture and servicing of a client satellite; fully autonomous capture of a free flying vehicle; autonomous component transfer using a closed-loop servo-vision system; fully autonomous on-board navigation and guidance to approach and station keep within 10 cm of a client using a passive vision system; fully autonomous "soft" capture of a satellite while station keeping; fully autonomous transfer of propellant from one vehicle to another on orbit with US technology; and on-orbit use of an IEEE-1394a (Firewire) network[‡].

ASTRO's Autonomous Rendezvous and Capture Sensor System (ARCSS) used onboard visible, infrared and laser rangefinder sensors to provide real-time data and imagery to an onboard sensor computer. Boeing-developed Vis-STAR software, executing on the sensor computer, provided precision real-time client bearing, range and attitude as needed, from ranges of over 200 km to soft capture. All the onboard sensor algorithms were successfully demonstrated, including algorithms for long range tracking against the stellar background, silhouette and edge tracking of the extended target against space and Earth background, and docking target plate track against NEXTSat vehicle clutter.

ORBITAL EXPRESS MISSION

Overview

[‡] Use of the embedded network enabled the AC3 computer ORU removal and replacement on the ASTRO spacecraft late in the mission.

Orbital Express Demonstration System program objectives included the design and development of the two demonstration servicing satellites, the ground stations, and the on-orbit demonstration operations. The Autonomous Rendezvous technologies, including sensors, guidance and relative navigation, and ground infrastructure for Orbital Express have been in development on Boeing IR&D since the year 2000. The system was designed from the beginning to be applicable to an operational spacecraft, where 'ground up rendezvous'; the transition from a ground-developed client ephemeris, to an onboard relative state is required.

The autonomous capabilities to be demonstrated included rendezvous and capture from long range without ground intervention; onboard and ground-commanded abort and collision avoidance; capabilities for soft direct-capture and grapple-berth; hydrazine propellant transfer; battery & computer component robotic transfer; and demonstration of a viable ground infrastructure with operator-friendly ground situational awareness.

The ASTRO and NEXTSat were launched together, to a 492 km, 46° inclination, circular Low Earth Orbit (LEO). Checkout of the satellites and the first set of propellant and battery ORU transfer scenarios were executed before de-mating. After these operations were completed, ASTRO and NEXTSat were de-mated, and began numerous unmated rendezvous and capture demonstrations.

Rendezvous Scenario Descriptions

A total of five unmated scenarios, plus an end of life (EOL) scenario were successfully completed during the course of the OEDS mission. These scenarios were designed to represent increasingly complex autonomous rendezvous trajectories, at ever increasing ranges.

After successfully completing a 10 m separation and capture on the first unmated scenario (2-1), scenario 3-1 was initiated on May 12. The operation proceeded normally with solar inertial separation to 30 m and return to station keep at 12 m. At this time a sensor computer fault occurred, which caused loss of relative navigation data from the ARCSS sensors. The ASTRO spacecraft executed an autonomous abort sequence which took it to 120 m. Over the next days the range between the two spacecraft increased to up to 6 km. Following a period of data analysis, sensor software was updated to improve performance and the scenario was successfully completed using the backup sensor computer.

ARCSS performance was excellent for all subsequent scenarios with tracking to ranges greater than 300 km achieved during EOL.

A summary of key unmated scenario milestones is provided in Table 1, below.

Table 1. Key Orbital Express Demonstration Milestones

March 8	Launch
March 9-April 15	Initial spacecraft checkout, propellant and battery ORU transfers

April 16	Launch ring ejection, ARCSS rendezvous sensor checkout followed by berthing of NEXTSat to ASTRO using robotic arm.
May 6	Scenario 2-1: First unmated scenario, solar inertial separation to 12 meters over a period of 1 hr, 57 min.
May 12-20	Scenario 3-1: Second unmated scenario. Successfully separated to 30 m and returned to 12 m as planned. Computer fault at 12 m caused autonomous abort. Spacecraft remained separated for nearly 8 days at ranges of up to 6 km during anomaly resolution, followed by rendezvous and capture. First demonstration of free-flyer capture and berthing. Scenario 4 and 6 objectives completed, therefore these were eliminated from the plan.
June 16	Scenario 5-1: Third unmated scenario. Fully autonomous separation, 120 x 60 m elliptical fly around of NEXTSat, -R bar approach (Earth in background). Duration: 4 hrs, 51 minutes.
June 23	Scenario 7-1: Fourth unmated scenario. Fully autonomous solar inertial separation to 4 km behind NEXTSat, followed by 120 m -V-bar (velocity vector) station keep, 100 m circular fly around, solar inertial approach to free flyer capture.
June 27-29	Scenario 8-2: Fifth unmated scenario. Fully autonomous solar inertial separation, phasing to 7 km behind NEXTSat, 4 km standoff for 6 hrs, 43 min., 100 m 3X orbital rate circular fly around, solar inertial approach to free flyer capture.
July 17-20	End of Life (EOL) Scenario: Sixth unmated scenario. Fully autonomous solar inertial separation to 410 km behind NEXTSat, return to 1 km – 500 m standoff, final egress to 15 km above NEXTSat, 1.25 km crosstrack. Total duration > 3 days inside 1000 km.
July 22	Mission complete with 100% mission success. ASTRO and NEXTSat decommissioned.

ARCSS SYSTEM DESCRIPTION

The ARCSS system, along with the integrated Vis-STAR software, is ASTRO's primary relative navigation sensor system at mid to long ranges, providing relative state information for NEXTSat from ranges of hundreds of kilometers. The capability of ARCSS to acquire and track NEXTSat at long range is key to the ground up rendezvous capability mentioned earlier.

At short range, less than 200 m and in the approach corridor, the Advanced Video Guidance Sensor (AVGS) provides 6 degree of freedom navigation data to GN&C. AVGS was developed by NASA Marshall Spaceflight Center and industry partners and performed well on OEDS. ARCSS provides fully redundant measurements of bearing, range and attitude up to and including soft capture. ARCSS and AVGS performance will be compared in a future technical paper.

ARCSS consists of three imaging sensors: a narrow field of view acquisition and track sensor (VS1), a mid to short-range wide field of view visible track sensor (VS2) and long wave infrared sensor (IRS) for continuous situational awareness during day and particularly nighttime operations or when lighting is poor. In addition to the imaging sensors, ARCSS features a precision laser rangefinder, cued by the imaging sensors, which is designed for mid range tracking of NEXTSat from 7 km.

ARCSS is designed to acquire the NEXTSat client satellite at ranges beyond two hundred kilometers using VS1, at which point it appears as a point source. VS1 tracks NEXTSat during periods of favorable lighting, providing bearing data to GN&C. The infrared sensor was designed to provide bearing data beginning at a range of 5 km.

When the image of the client becomes sufficiently extended, Vis-STAR software is used to independently calculate the attitude of the vehicle in addition to the range and

bearing. This information is conjunction with AVGS to ensure correct alignment to the client vehicle during the final approach and capture phases of the mission scenario. The wide field of view visible sensor is used during the final thirty meters of the approach to provide additional visible imagery while keeping the entire client vehicle in the field of view. The tracking algorithms are designed to run interchangeably with either the visible or infrared cameras. In this way, seamless coverage is provided over a wide range of lighting, range, and background conditions.

All of the imaging sensors are similar in function and exhibit largely common features, which helps to reduce program cost. The two visible sensors are built around the same rad-hard focal plane, and use the same rad-tolerant electronics to reduce complexity. CMOS focal planes were chosen because of their resistance to artifacts, such as blooming and streaking under harsh on-orbit lighting conditions. Each sensor has a similar housing with comparable footprints, as well as common electronics components, such as power converters and signal conditioners. Other common features include the IEEE-1394a digital data bus interface, triggering, and integration time control functions. The LWIR sensor incorporates a microbolometer focal plane and the design replicates 70% of the electronics, and packaging of the visible sensors. The microbolometer approach reduces cost and complexity, requiring no cryo-cooling. All three sensors used the same IEEE-1394a network interface.

The sensor computers, ASTRO Computer 2 (AC2) and AC3 include Boeing-designed and built IEEE-1394a network interface cards (NICs) which allow all ARCSS sensor data to be available to either AC2 or AC3, as needed. AC3 (mounted in an ORU container) was used as the primary sensor computer subsequent to the scenario 3-1 anomaly.

ASTRO Computer 1 (AC1), also on the 1394 network, incorporates command and data handling, Guidance, Navigation and Control (GN&C) and other satellite servicing software functions.

All of the ARCSS sensors are mounted on a common optical bench, shown in Figure 1. The optical bench formed one of the eight exterior panels that made up ASTRO's structure. ARCSS is shown installed on the ASTRO spacecraft in Figure 2. A spotlight (lower left) was provided to facilitate using the visible sensors for tracking during close-approach in darkness.

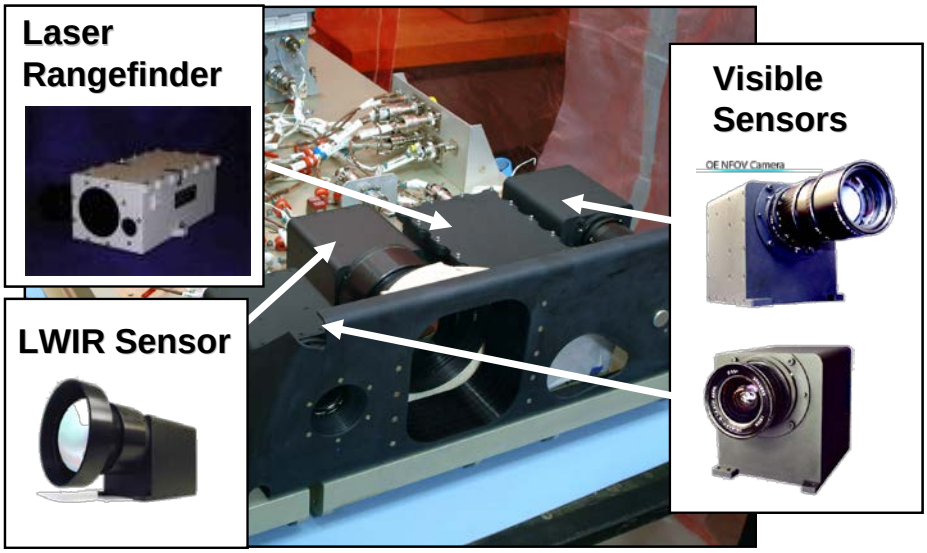


Figure1. ARCSS Flight Sensors on ASTRO Optical Bench

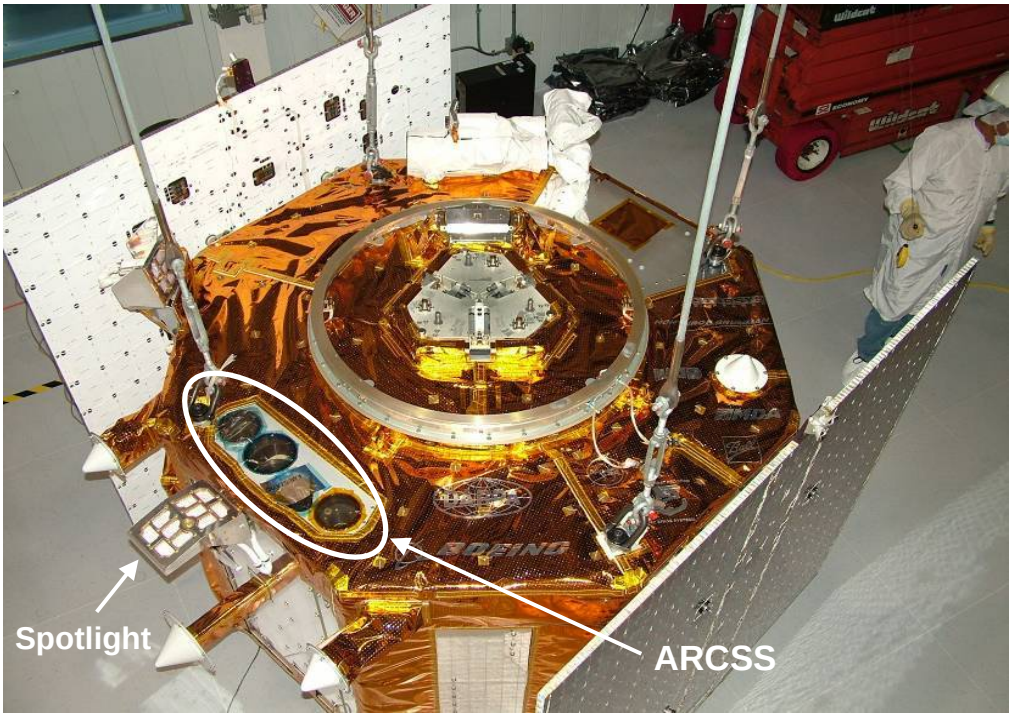


Figure 2. ARCSS Mounting in ASTRO Spacecraft

Vis-STAR Software

The Vis-STAR Software, which includes Long Range Track (LRT), Extended Target Track (ETT), target plate track and sensor control/interface functions, provides real-time relative target measurements to the guidance and relative navigation (G&RN) function of ASTRO's GN&C system.

The Vis-STAR software, illustrated 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, enabling relative navigation with respect to a completely passive client. In the Orbital Express application, virtually identical software operates with all ARCSS imaging sensors so that no additional hardware is required. Vis-STAR is highly scaleable to different sensor formats and fields of view, and therefore operating range can be selected by sensor optics, with matching software parameters. Because of Vis-STAR flexibility, processing speed and accuracy can be tailored and scaled target image characteristics and precision requirements.

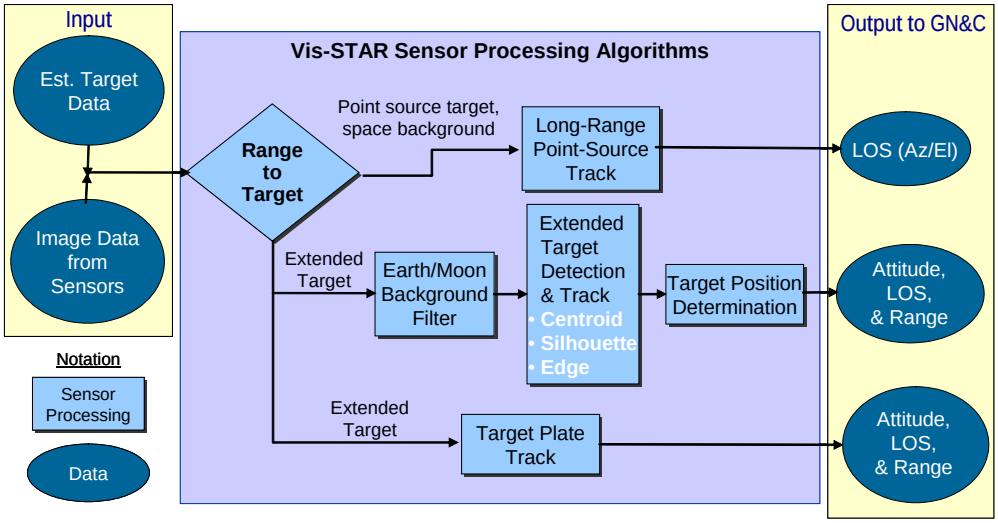


Figure 3. Overview of Vis-STAR Processing Flow

All of the 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 Figure 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 size of the observed target 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 faint point sources, this tracker can improve the signal to noise ratio of the target to allow detection at extended ranges.

If the target is extended, it will be processed by either the extended target tracker, or for very close ranges in corridor, the target plate tracker. The extended target tracker has the capability of filtering out the highly cluttered background of the earth or other

celestial bodies if they are behind the target. It can also determine the position and attitude of the target, whether in or out of corridor, by use of a silhouette matching algorithm. It can also give range estimates based upon the extent of the target. If the object is in corridor, a secondary edge matching algorithm can be used to provide target position, attitude, and range. A centroid tracker is available as well for estimating target position.

The target plate tracker is used when the target is very close and especially when it overfills the field of view. This tracker evaluates the positions of four dots positioned on a small passive plate mounted over NEXTSat's solar panel to determine the attitude, range, and position of the target from a mated position up to a range of about ten meters.

GROUND STATION

The ARCSS Ground Station (ARCSS-GS) is a personal computer based application, developed by Boeing which runs under the Microsoft Windows-XP operating system. ARCSS-GS was used by the sensor system engineers during the OEDS mission to monitor the health, status and performance of the onboard sensors and to observe real time situational imagery from the ASTRO spacecraft. Several instantiations of the ARCSS-GS were operating during the mission, both at the primary mission ground control site at the Air Force Research Lab in Albuquerque, NM and at the Engineering Support Room (ESR) at the Boeing Advanced Network and Space Systems facility in Huntington Beach, Ca.

The ARCSS Ground Station graphical user interface is shown in Figure 4. Key features are

1. Status updates from ASTRO and NEXTSat vehicles
2. Sensor condition including temperature, power, and commanded state
3. Sensor processor software status
4. Tracking and attitude measurement data in sensor or docking mechanism coordinate systems
5. Real-time situational awareness imagery
6. Current Sun and Earth angles and lighting conditions

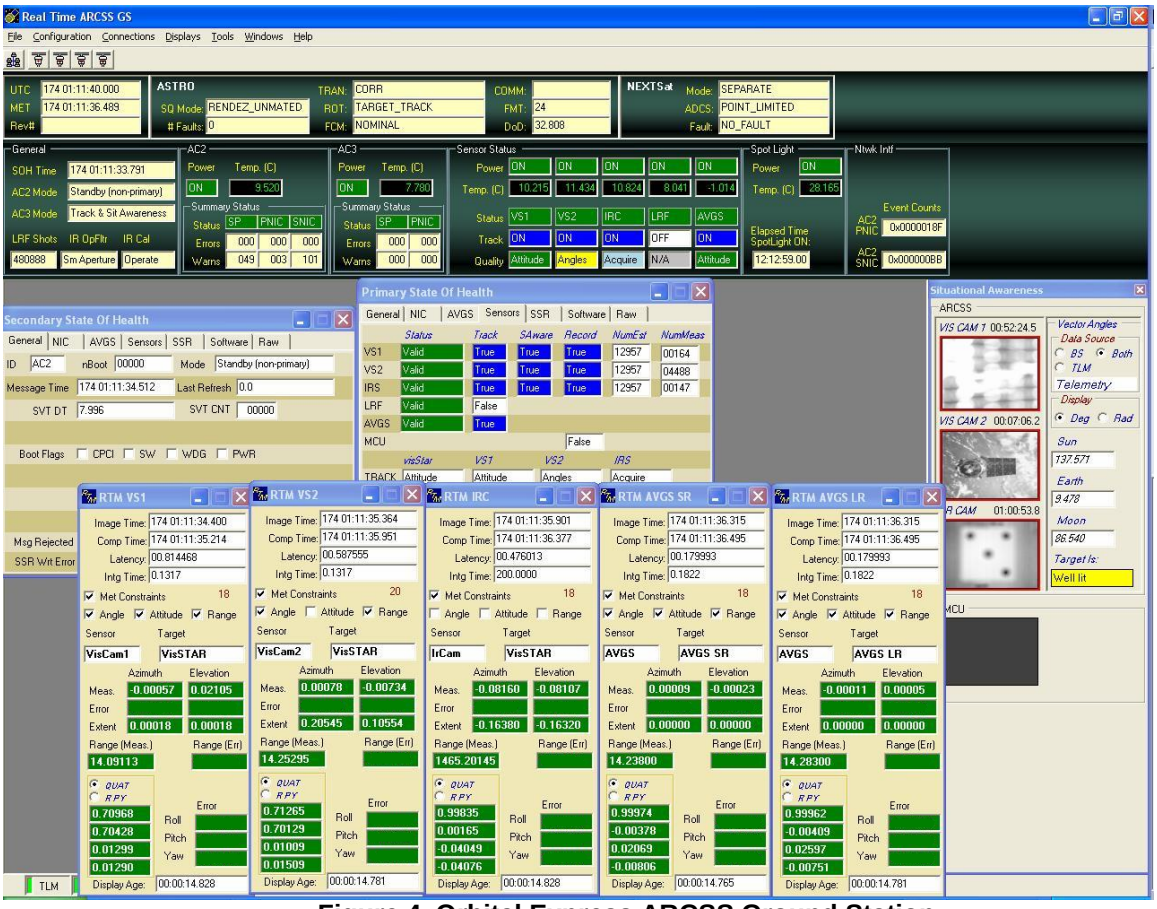
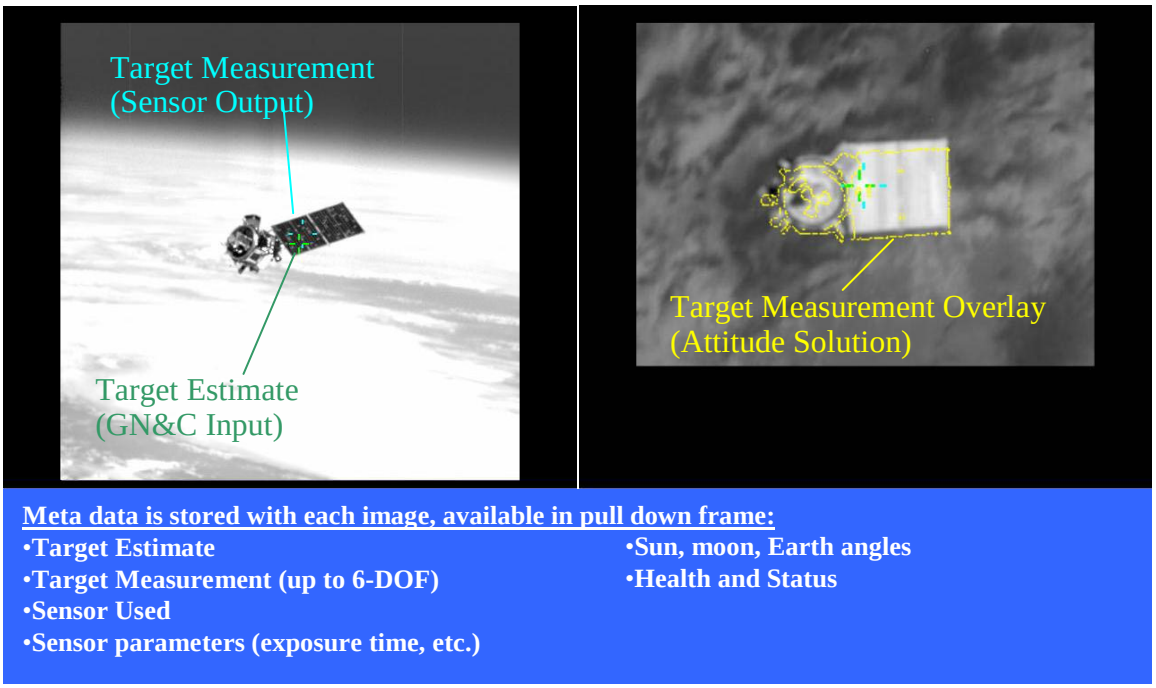


Figure 4. Orbital Express ARCSS Ground Station

For each sensor, independent pop-up windows, examples of which are shown in Figures 5 a and b, allow the ARCSS sensor operator, with a simple mouse click to the thumbnails on the main screen, to observe full-size real-time sensor images along with correlated tracking and Vis-STAR data. Controllers can visually monitor the performance of specific sensors and analyze the current situation via their access to a user selectable amount of additional data. Temporal displays of sensor track data (e. g. bearing, range and relative attitude) can also be displayed if desired.

The image in Figure 5a shows the instantaneous single-sensor track measurement in blue, and the total navigation solution (target estimate) in green. The image in Figure 5b adds to the tracking cross-hairs a projected Vis-STAR attitude solution superimposed on the sensor image as a predicted NEXTSat outline in yellow. Real-time graphical displays of simultaneous raw and processed data allow controllers to make quick, insightful decisions regarding the validity of sensor and GN&C data.



Figures 5. a) Tracking Data b) Tracking and Attitude data, Meta Available for All Images in Pull-Down Window

HIGH FIDELITY MODELING, SIMULATION, AND HWIL TESTING

A robust combination of computer simulations and physical model testing was conducted in order to successfully 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 6 shows a full scale mockup of the NEXTSat client vehicle and EDU sensor optical bench, during hardware in the loop testing in the ARCSS Sensor Integration Lab (ARCSIL) in Anaheim, Ca.

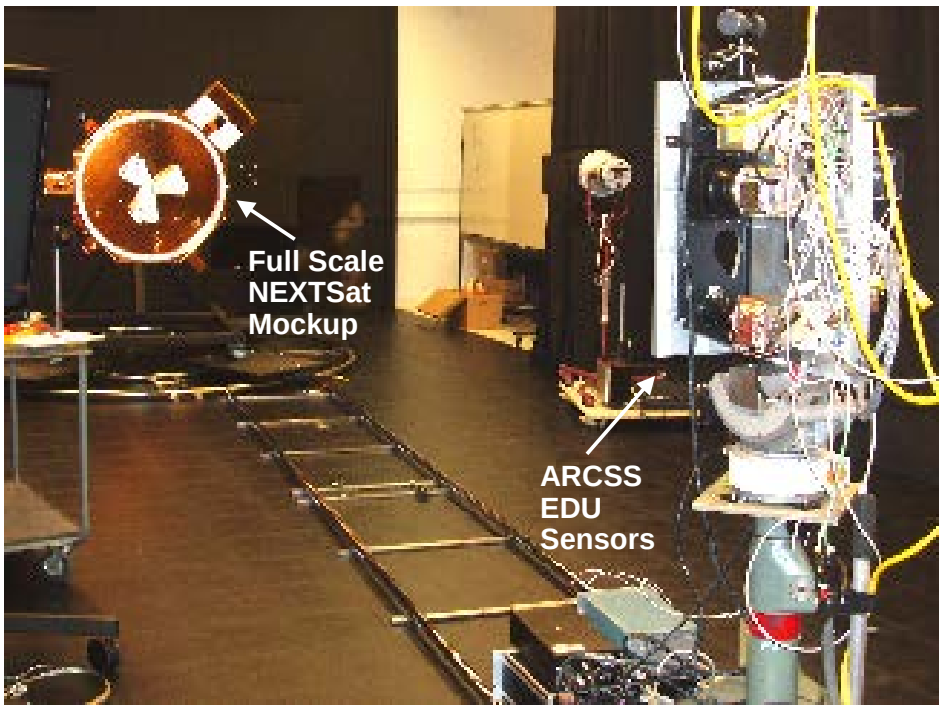


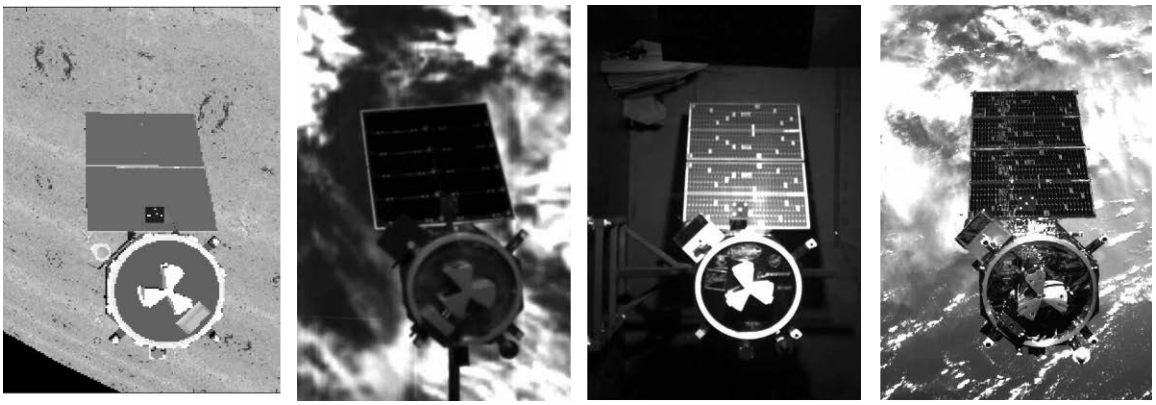
Figure 6. Sensor Hardware in the Loop Integration Testing in Anaheim

Lighting and Background Conditions

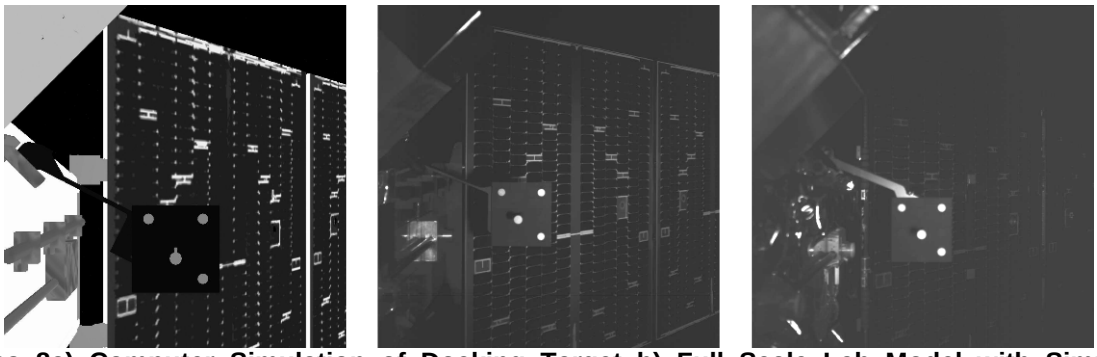
Operating at LEO altitude, in a short-period orbit, lighting conditions for the sensors changed rapidly over the course of each orbit and each scenario. Some of the most challenging aspects of the rendezvous and proximity operations for the optical sensors were operating against Earth and satellite structure 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.

Simulations Validating Visible Tracking with Earth Background

One of the most stressing system requirements was tracking against Earth backgrounds. In order to facilitate algorithm and sensor development and testing, different combinations of simulated and model scenes were used. Figure 7a shows a fully simulated scene. Full simulation has the advantages of flexibility, repeatability, easily obtained truth data and most importantly the ability to readily conduct closed loop testing. In order to more accurately simulate the effects of lighting and materials, subscale and full size models, shown respectively in Figures 7b and 7c, 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 7d. Figures 8a – c similarly show computer-simulated, full scale model, and on-orbit images of the docking target against the clutter of the NEXTSat solar panel.



Figures 7a) 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



Figures 8a) Computer Simulation of Docking Target b) Full Scale Lab Model with Simulated Sunlight c) On-Orbit Visible Image of Docking Target and Solar Panel

FLIGHT TEST RESULTS

Vis-STAR Statistical Performance Summary

More than 50 GB of flight sensor data was collected over the course of the OE flight demonstration program and all flight data, particularly EOL has not yet been analyzed. Over the last three unmated scenarios prior to EOL (5-1, 7-1 and 8-2), Vis-STAR measurements were recorded over ranges varying from 0 m to 7 km. Of these measurements, over 78% returned bearing data with a high confidence level. Range and attitude measurements, which are only required to be reported at short ranges and thus have lower validity rates, also performed well over their effective ranges at rates of 56.6% and 72.2% respectively. These reporting rates are well within system requirements.

Because the sensor computer controls sensor scheduling, depending on the lighting conditions, range, background, and other factors, aggregate sensor-use statistics can be an overly conservative measure of sensor utility. However, breaking down the bins we find that VS1 under well-lit conditions had an angle valid rate of 95% and a range valid rate of 79.3% during scenario 5-1. VS2 performed almost as well reaching a peak performance of

over 89% angle and range valid and 87% attitude valid under well-lit conditions and over 89% angle, range and attitude valid while in eclipse under spot lit conditions (during scenarios 5-1 and 8-2 respectively). Finally, the IR sensor was valid on over 98% of angle measurements in eclipse during scenario 5-1 and 92% during well lit conditions during scenario 7-1 and 71% while the target was backlit also during scenario 7-1. It reached a peak performance of 80% range valid while well lit during scenario 5-1.

As the system is designed to use the sensors with the best performance under a given set of conditions, the most accurate measure of the validity indicators, from a system view, is over the ranges where each sensor is employed. A representative sample of these is shown in Figures 9a to 9i. [§] The data was partitioned by range, using 10m bins from 0-500m in range and 650m bins from there out to a maximum 7km in range. In the figures, the independent variable range is plotted at the midpoint of each bin.

In Figure 9a, we see that VS2, under well-lit conditions works extremely well out to a range of approximately 70m. After that, until about 120m there is a lack of measurements by VS2 as VS1 and IRC are scheduled 99.75% of the time. Additionally, attitude measurements are only required to 60m so the charts do not include attitude data beyond that range. Figure 9b illustrates that IRC is an effective tool for deciding bearing out to at least 1.5km while eclipsed and Figure 9c shows that it is also effective close in (0-150m) with good lighting conditions. However, as Figure 9b shows a slight drop in performance while the Earth is in the background, Figure 9i data is from the same configuration but with a space background only. This has a much better performance level, except for a slight drop when transitioning from short range track to long range track (or vice versa). Figure 9d illustrates the performance of VS1 at intermediate ranges. Figures 9e and 9f show that track measurement availability remains high, even under the stressing condition where Earth is in the background. Finally, Figures 9g and 9h show the efficacy of IRC and VS1 at long range. Note that the IRC has a remarkable effectiveness rate. Each bin in Figure 9g has an average of 1400 and a minimum of 360 measurements, so these validity rates are based on significant numbers of data points. Although VS1's performance was not as good, reflecting an opportunity to further optimize the algorithm's track parameters, the data provided is more than enough to allow GN&C to maintain a highly accurate relative state for the NEXTSat

[§] Subsequent to Scenario 3-1, an on-orbit software upgrade (a capability designed into the OE system) allowed an algorithm change in IR Sensor detection, which significantly increased its effective tracking range / performance.

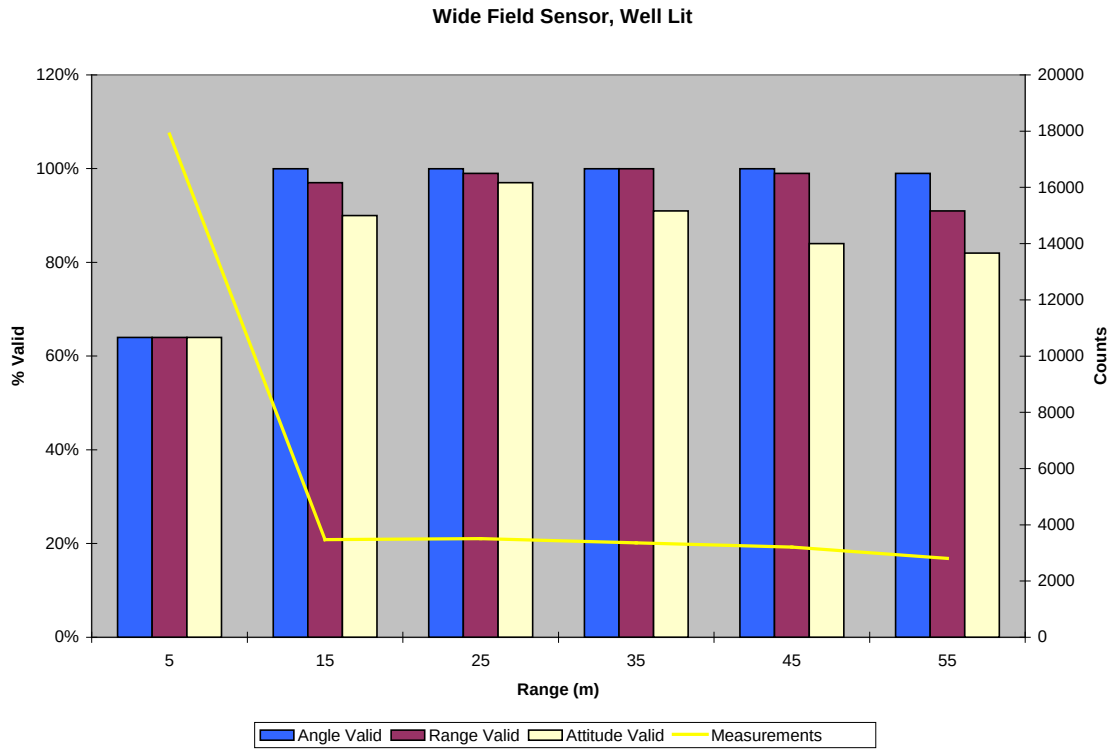


Figure 9a. Validity rates for VS2 under good lighting conditions

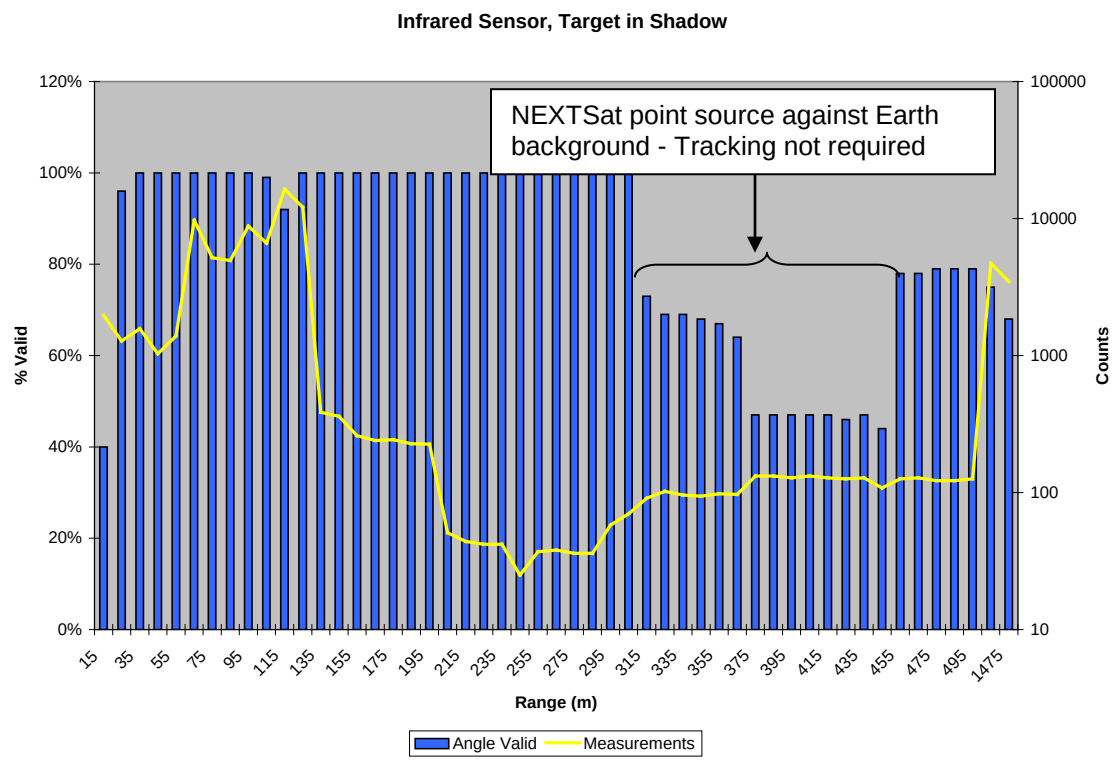


Figure 9b. Validity rates for IRC while the target is in shadow

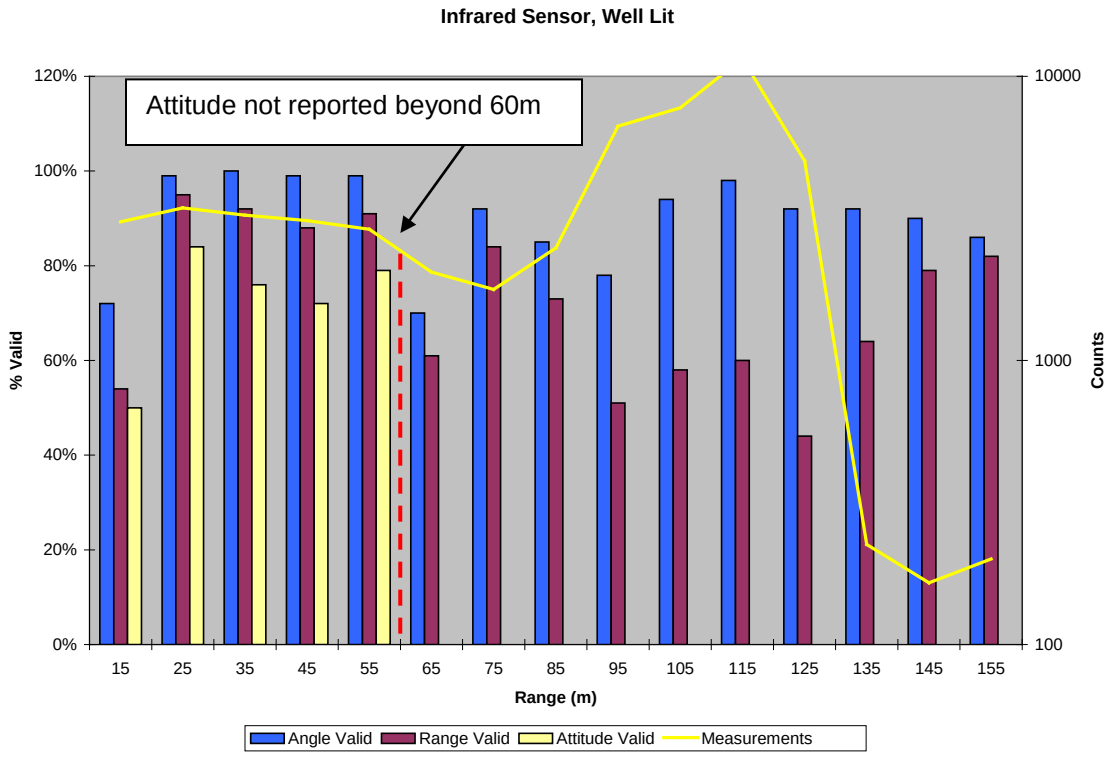


Figure 9c. Validity rates for IRC under good lighting conditions

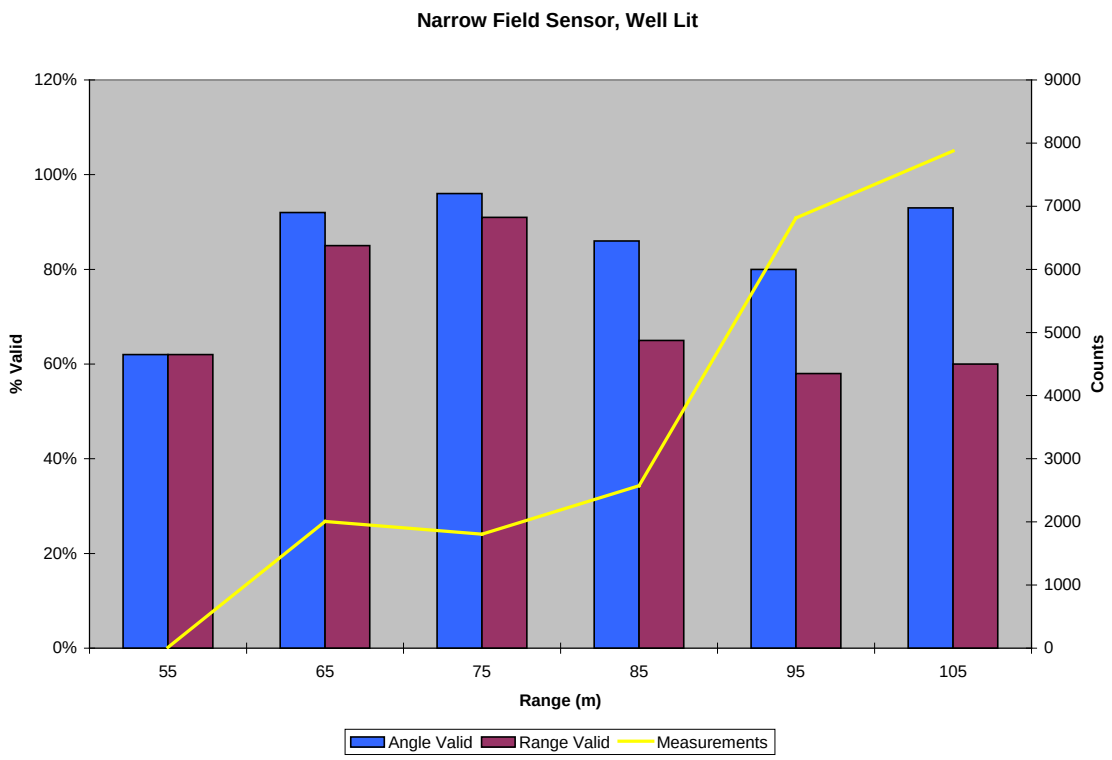


Figure 9d. Validity rates for VS1 under good lighting conditions

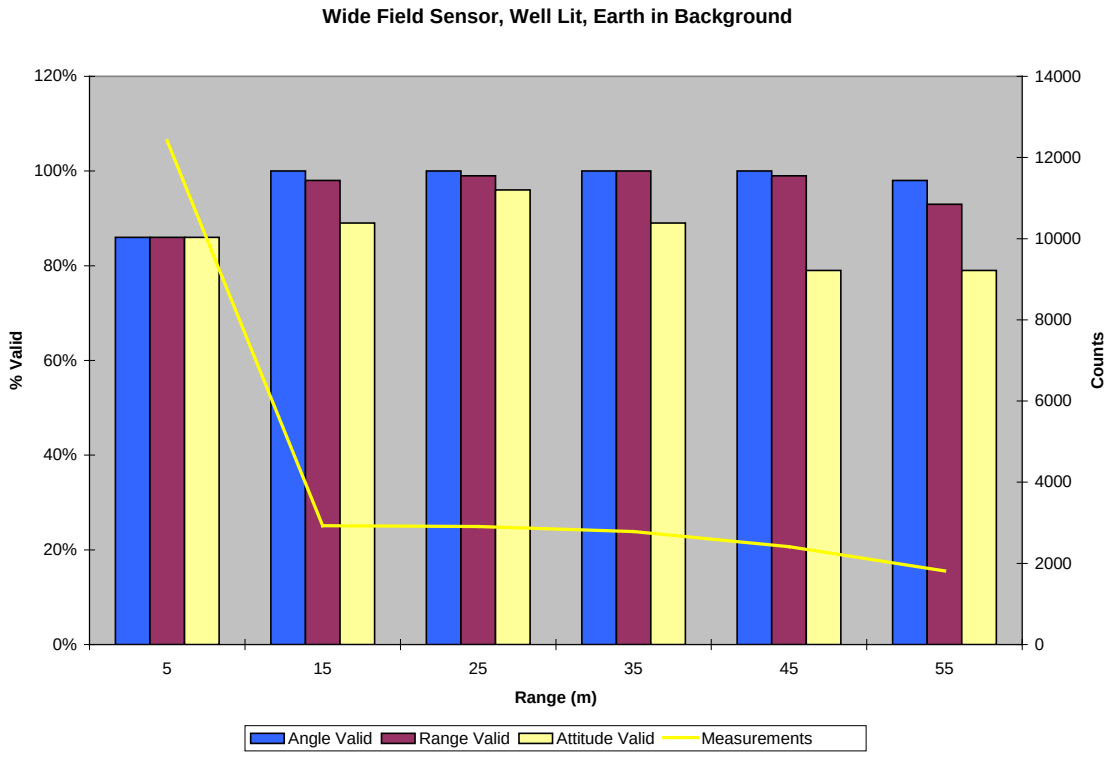


Figure 9e. Validity rates for VS2 well lit but with Earth in the background

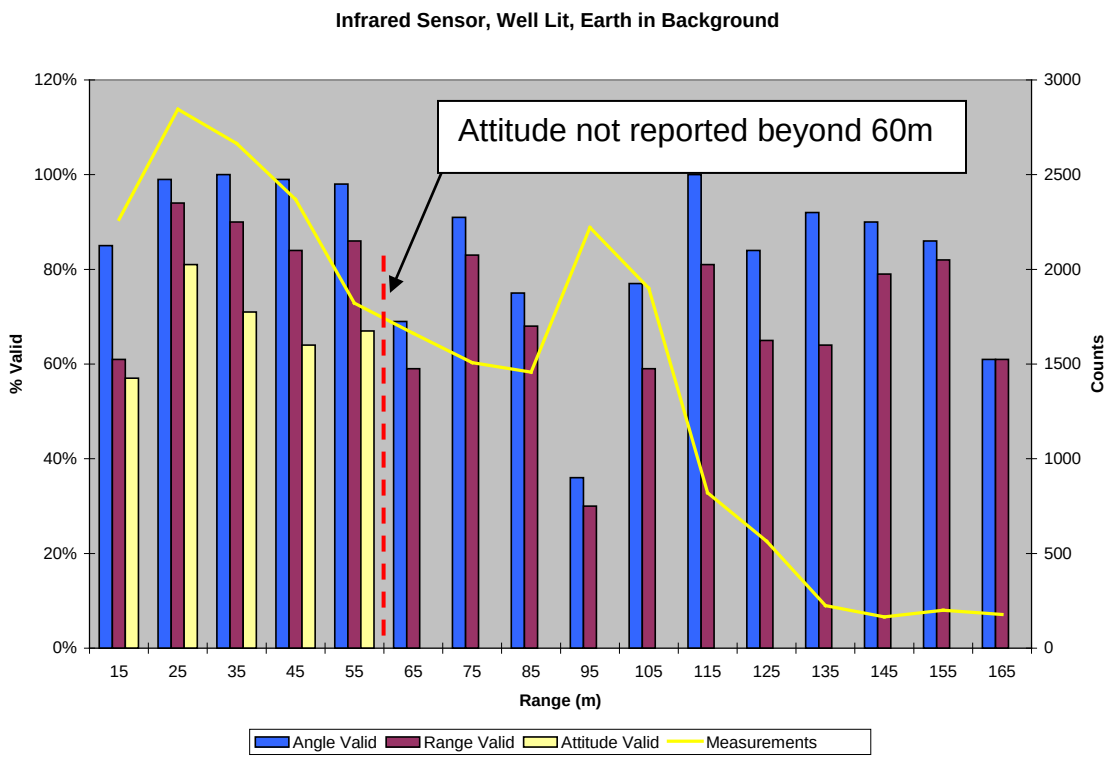


Figure 9f. Validity rates for IRC well lit but with Earth in the background

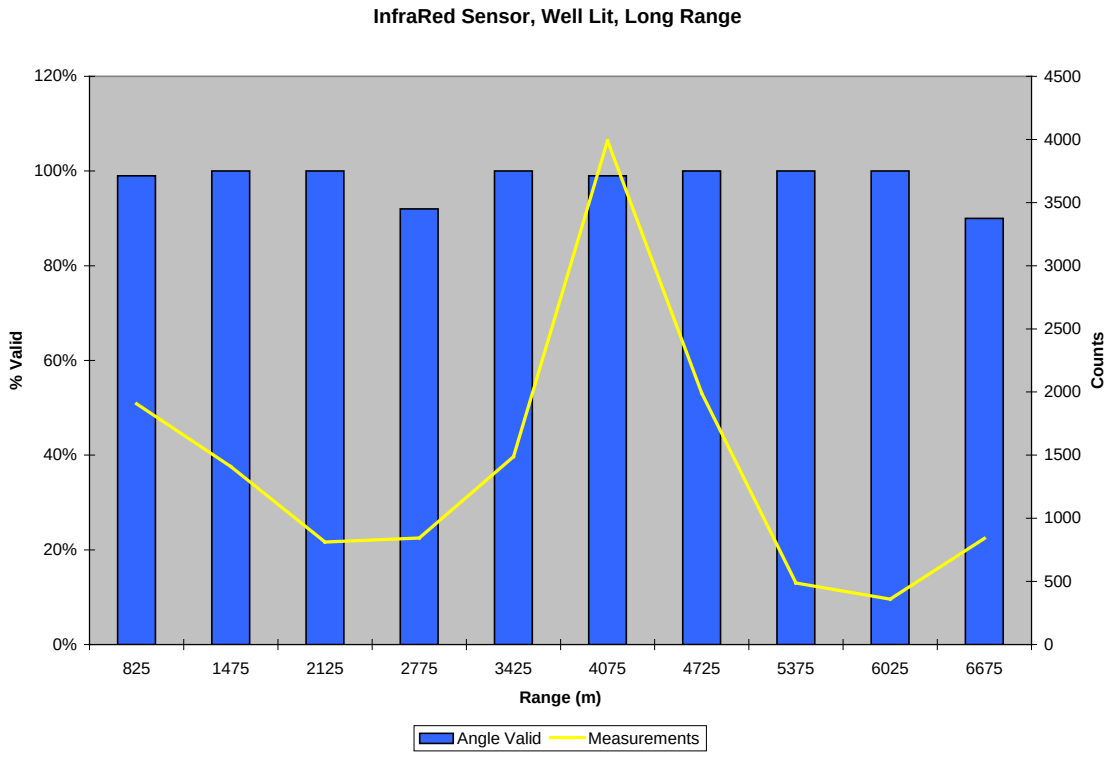


Figure 9g. Validity rates for IRC well lit from long range (0.5km-7km)

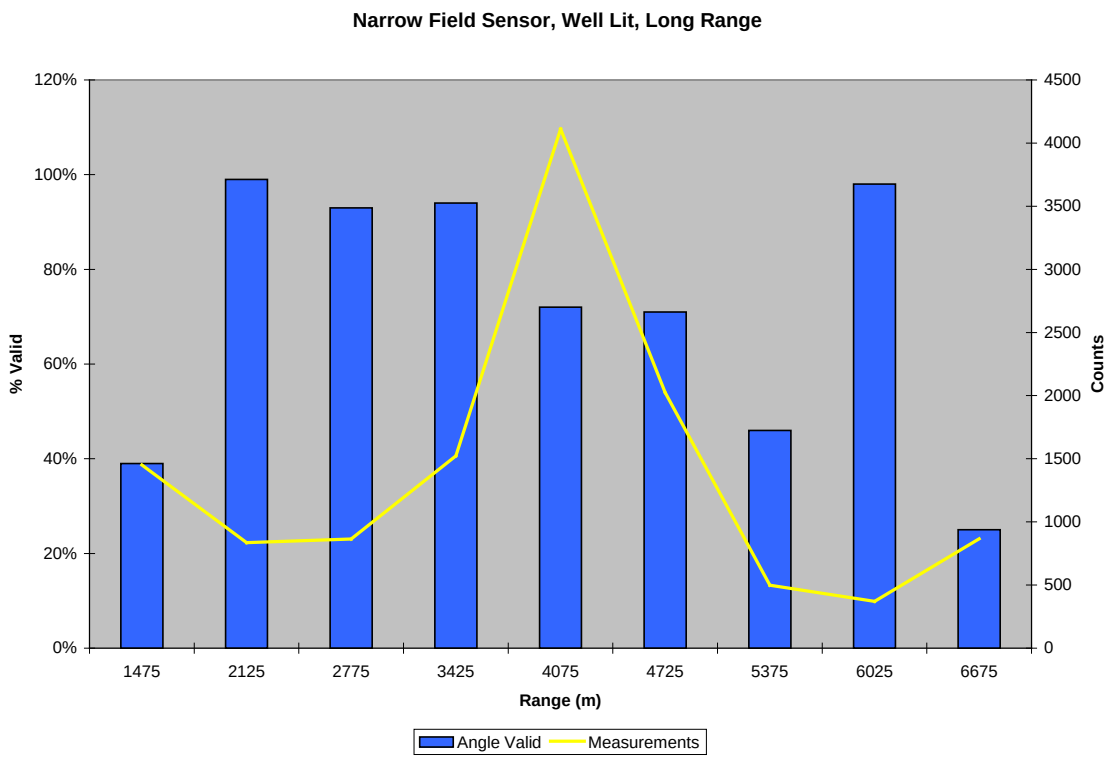


Figure 9h. Validity rates for VS1 well lit from long range (1.15km-7km)

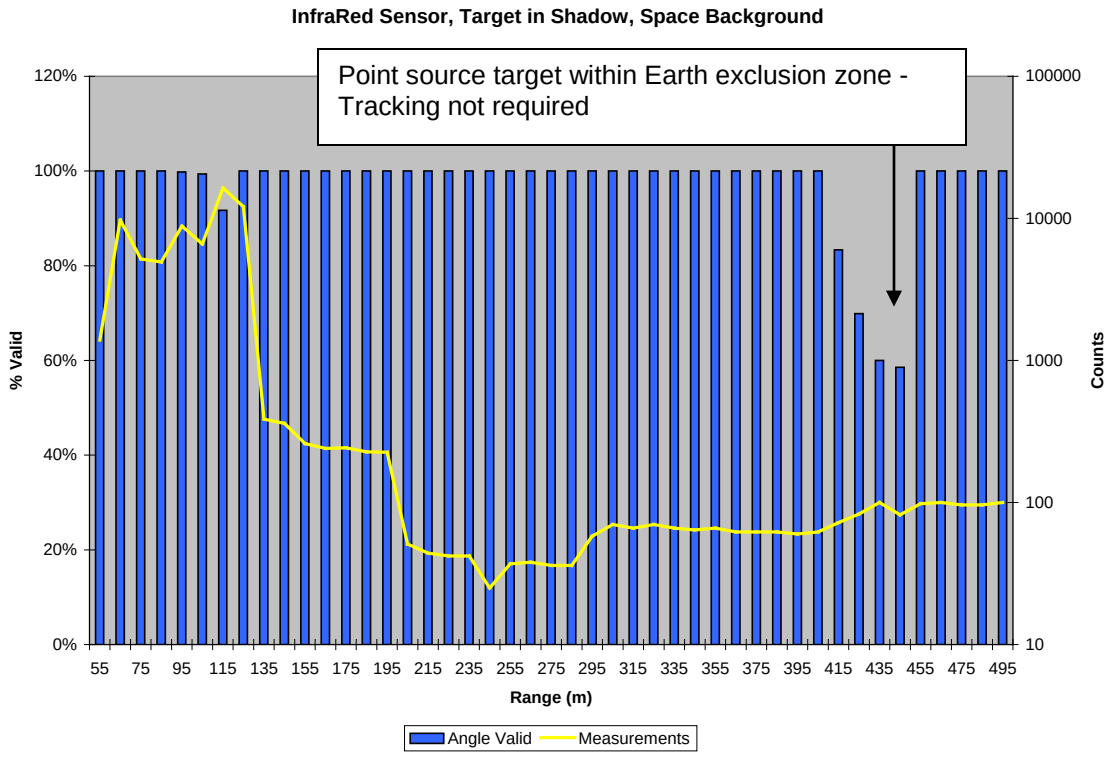


Figure 9i. Validity rates for IRC, target in shadow against a space background.

Long Range Track Performance

The ARCSS system was designed to enable point source tracking of the NEXTSat against a stellar background to enable generation of an onboard relative state vector. This capability facilitates flying deterministic approach trajectories, increasing client safety and reducing fuel usage.

Long range track performance was evaluated during four OEDS scenarios; 3-1, 7-1, 8-2 and EOL.

The long range tracking (LRT) precision results from each sensor was found to be excellent, exceeding requirements for all cases analyzed to date. An example of LRT bearing data, from the LWIR sensor in Scenario 7-1 is shown in Figure 10. This plot shows the normalized measured line of sight bearing (azimuth and elevation) angles. Azimuth and elevation are plotted in radians, and time is in seconds Note that there is no truth information available, thus the measured value contains two prominent sources of deviation; the error in the sensor measurement and the actual motion of NEXTSat in the sensor focal plane array (FPA) as the ASTRO guidance tries to maintain NEXTSat centered in the field of view.

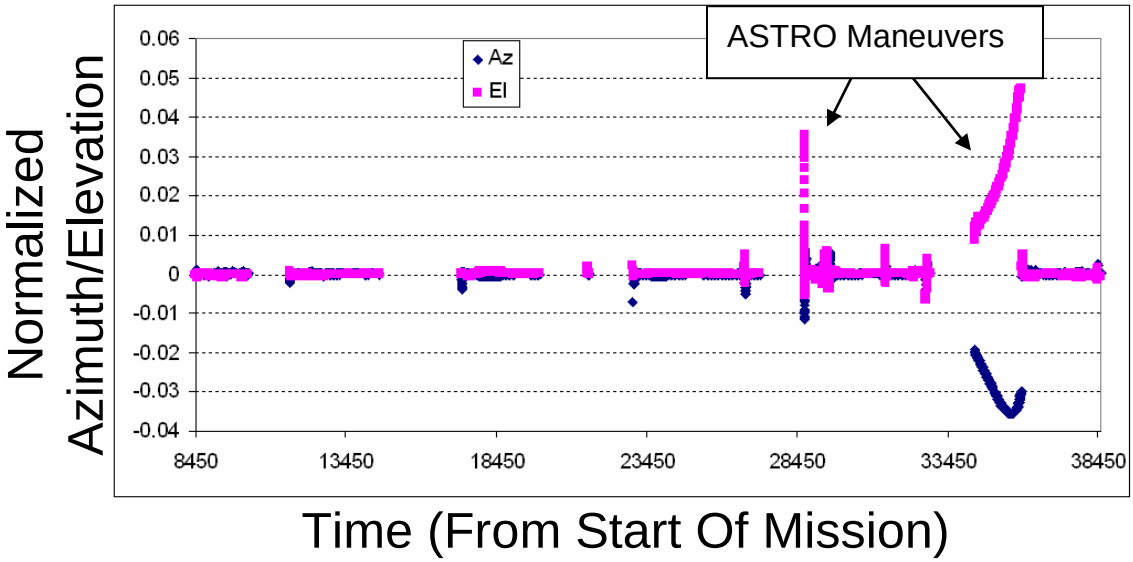


Figure 10. Infrared Sensor LRT Performance, Bearing vs. Time, Scenario 7-1

Places where the ASTRO satellite performed a maneuver are seen in this plot by the large deviations from the zero-horizontal axis. From the plot it can be seen that in the non-maneuvering periods the LRT bearing (angle) measurement precision was excellent. Note that although precision cannot be computed for the maneuver periods, the deviations shown in the plot track the actual motion of NEXTSat across the FPA.

The LRT algorithm was successfully demonstrated by precision tracking of NEXTSat against the stellar background. When tracking, the LRT computed NEXTSat FPA positions that corresponded to the position of the target with minimal precision error. GRN was then able to update and enhance its NEXTSat estimated position in subsequent frames. This allowed for a smooth transition from LRT tracking to NEXTSat tracking, range and attitude determination.

Vis-STAR Proximity Performance

Figure 11 shows three pairs of data plots from the IR camera, from scenario 8-2, operating at a range of within 60m of NEXTSat, with very little relative motion. The IR sensor was found to be particularly effective during OEDS due to its sun immunity and ability to track in both daylight and darkness.

The plot pairs are the normalized reported values. The data are client bearing (azimuth and elevation - top), client relative attitude (pitch, yaw and roll - center), and range deviation (bottom). Azimuth and elevation are plotted in radians, yaw, pitch and roll in degrees, range deviation in meters and time in seconds.

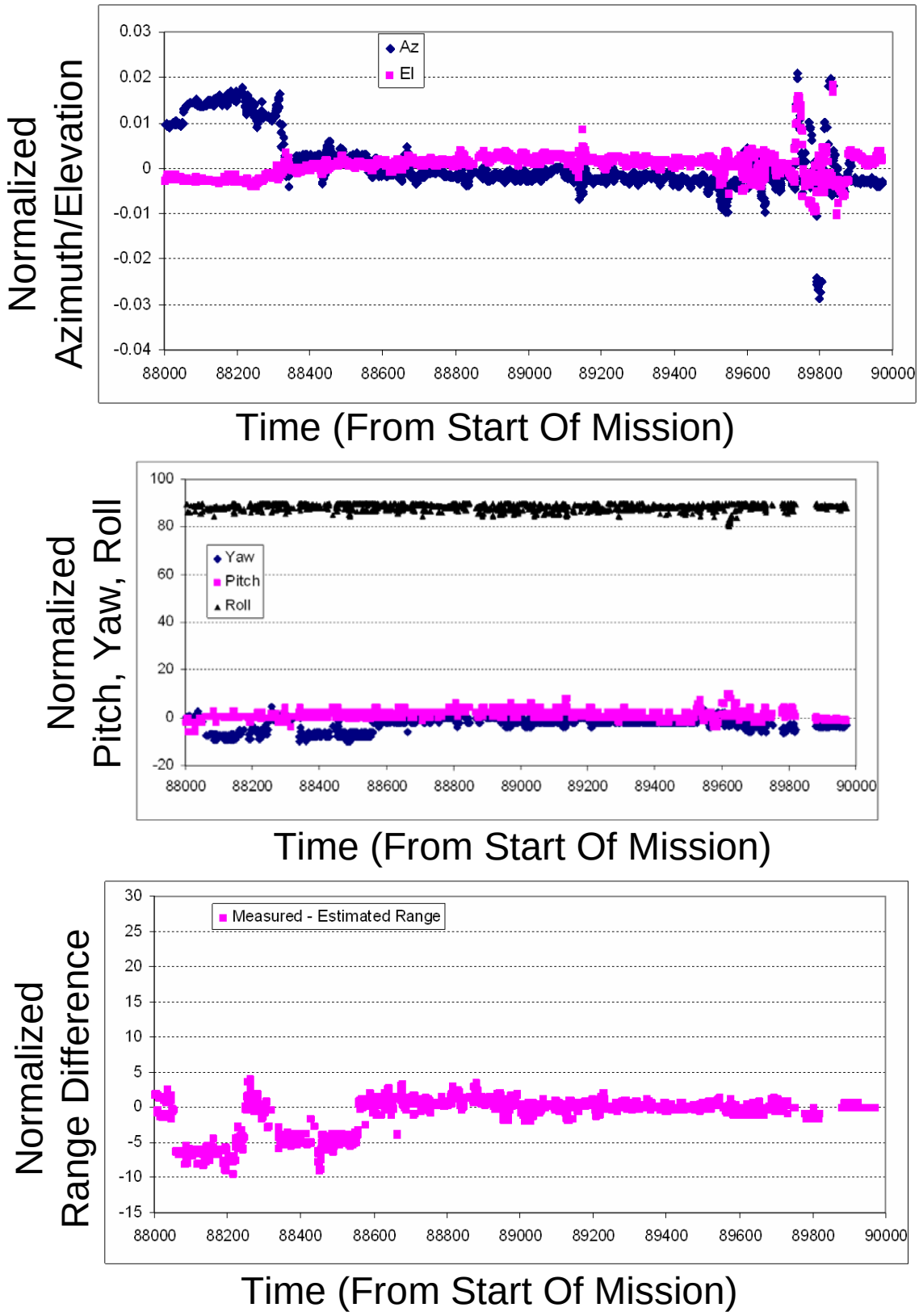


Figure 11. Scenario 8-2, NEXTSat Bearing a), Relative Attitude (b) and Range Deviation (c) Vis-STAR Capture Performance

As in the previous measurement graphs, the deviations in these plots occur during ASTRO maneuvers as the measurements follow the actual NEXTSat position in the FPA very well. The sensor precision performance is excellent as can be seen in the non-maneuver periods.

The position, range and attitude determination algorithm was successfully demonstrated by precision tracking and attitude determination of NEXTSat against the stellar and Earth background. The algorithm computed NEXTSat position, attitude and range that corresponded to the target with minimal precision error. GRN was able to update and enhance its NEXTSat estimated position, attitude and range estimates in subsequent frames. This allowed for a smooth transition from proximity tracking and attitude determination to Vis-STAR tracking using the target plate.

Figure 12 shows three sets of normalized data plots from VS1, from scenario 7-1, operating at a capture range from the client NEXTSat, with subtle client motion. The data are client bearing (azimuth and elevation - top), relative attitude (pitch, yaw and roll - center), and range deviation (bottom). Azimuth and elevation are plotted in radians, yaw, pitch and roll in degrees, range deviation in meters and time in seconds.

In these plots the ASTRO vehicle was maneuvering throughout as indicated by the sloped regions of the elevation curve given in the top graph. Also as can be seen from the plots the sensors reflect two significant maneuvers approximately one third and two thirds into the data set. These deviations track the actual motion of NEXTSat across the FPA.

The Vis-STAR target plate position, range and attitude determination algorithm was successfully demonstrated by precision tracking and attitude determination of NEXTSat at close range. The algorithm computed NEXTSat position, attitude and range that corresponded to the target with minimal precision error. GRN was able to update and enhance its NEXTSat estimated position, attitude and range estimates in subsequent frames.

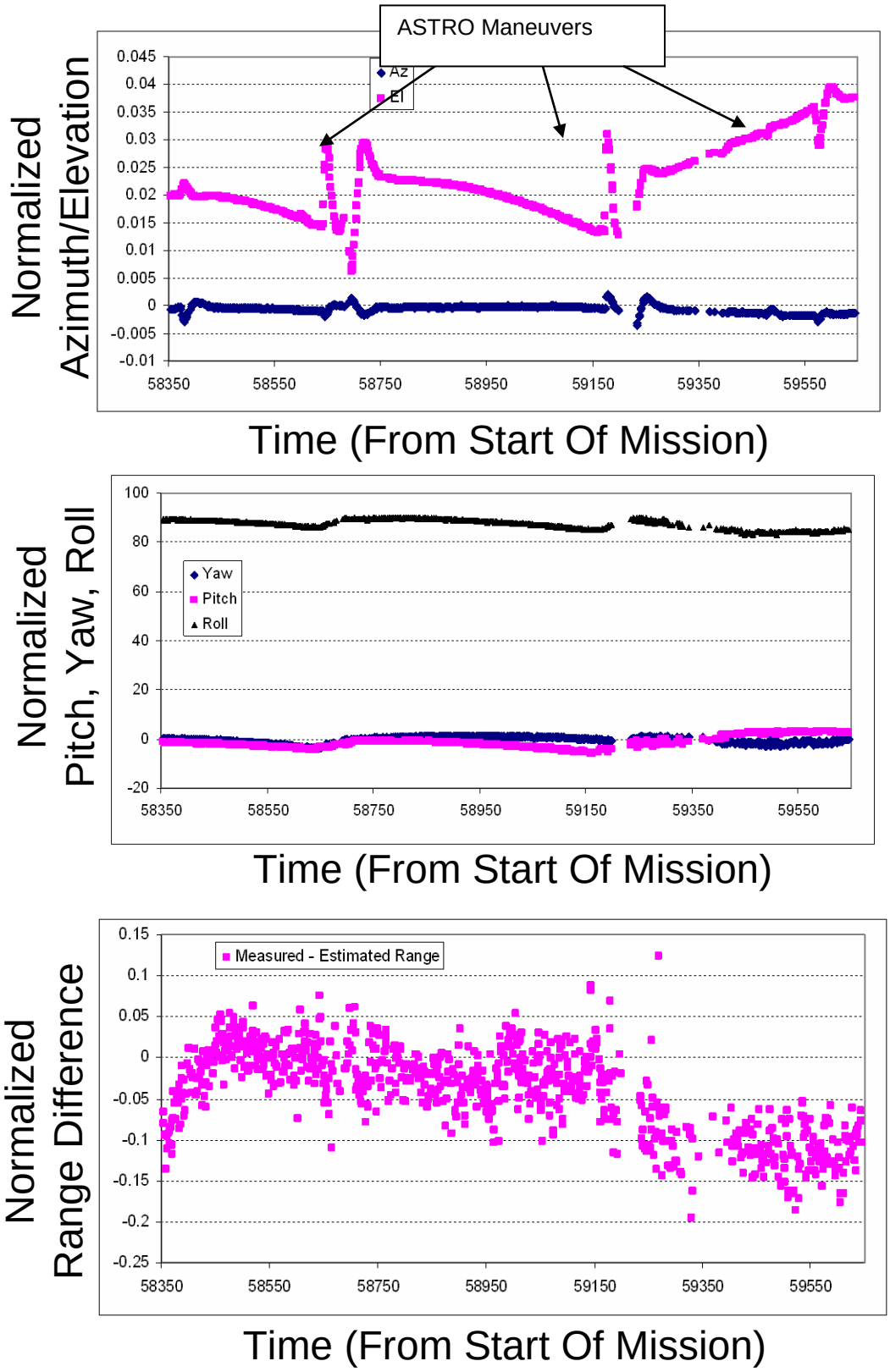


Figure 12. Scenario 7-1, VS1 Prox Ops Performance

CONCLUSION

On-orbit test results during the OEDS mission confirmed that passive optical tracking is a highly effective means of providing navigation data for autonomous rendezvous missions. The ARCSS sensors with integrated Vis-STAR software provided precision bearing, range and attitude measurements at all ranges under stressing on-orbit lighting and background conditions over the course of all six unmated scenarios enabling both direct and free-flyer capture of NEXTSat.

ARCSS and Vis-STAR as well as the guidance and relative navigation algorithms and software are highly applicable to near term and future spacecraft rendezvous missions. The ability to autonomously approach another vehicle without the need for direct closed loop operator control enhances system utility, increases safety, and reduces operator workload. In the case of robotic deep space rendezvous and capture, such as may be required for planetary sample return missions, autonomous rendezvous may be the only way to accomplish mission objectives, as communication delays preclude tele-operation. Passive optical systems such as ARCSS/Vis-STAR are uniquely suited to space science, as well as exploration missions due to their small size and weight, minimal power demands and high mission utility. These sensors provide high precision navigation inputs, and inherently provide operator situational awareness in daylight and darkness, covering up to 100% of the orbital period. Because Vis-STAR takes advantage of the known physical geometry of the client vehicle, it eliminates the need for optical aids (e. g. retro-reflectors) on the client vehicle, reducing cost and complexity. In the case of clients that are already on orbit, such as the International Space Station, this cost avoidance could be significant.

REFERENCES

1. Vis-STAR software is derived from US patent 6,954,551, Method of Determining Attitude of an Object, to Thomas Weismuller, October 11, 2005, assigned to The Boeing Company

2. Paper No. AAS 06-016, GN&C Technology Demonstrated by the Orbital Express Autonomous Rendezvous and Capture Sensor System, T. Weismuller, M. Leinz, The Boeing Company, Anaheim, CA 92803, Presented at the 29th Annual AAS Guidance and Control Conference, Breckenridge, Co., February 4-6, 2006.