Next Generation Advanced Video Guidance Sensor: Low Risk Rendezvous and Docking Sensor

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The Next Generation Advanced Video Guidance Sensor (NGAVGS) is being built and tested at MSFC. This paper provides an overview of current work on the NGAVGS, a summary of the video guidance heritage, and the AVGS performance on the Orbital Express mission. This paper also provides a discussion of applications to ISS cargo delivery vehicles, CEV, and future lunar applications.

I. Introduction

RELATIVE navigation sensors are an enabling technology for exploration vehicles such as the National Aeronautics and Space Administration's (NASA's) Crew Exploration Vehicle (CEV), cargo vehicles for logistics delivery to the International Space Station (ISS), and lunar landers. Additional applications are lunar sample return missions, satellite servicing, and future on-orbit assembly of space structures. The Next Generation Advanced Video Guidance Sensor (NGAVGS) is a third generation relative navigation sensor that incorporates the basic functions developed and flight proven in the Advanced Video Guidance Sensor (AVGS). The AVGS was the primary proximity operations and docking sensor in the first autonomous docking in the history of the U.S. space program, which was accomplished on May 5, 2007 during the Orbital Express (OE) mission. However, the AVGS hardware cannot be reproduced due to parts obsolescence, which has provided Marshall Space Flight Center (MSFC) an opportunity to replace an obsolete imager and processor with radiation tolerant parts, and to address critical CEV and ISS cargo vehicle relative navigation sensor requirements. This paper provides a summary of the OE AVGS performance, an overview of the NGAVGS development underway at MSFC, and a discussion of NGAVGS applications to CEV and ISS cargo delivery vehicles.

II. Video Guidance Sensor History

The NGAVGS is the current video-based sensor being developed at MSFC. The NGAVGS builds on the prior successes and lessons learned from the previous design, development, testing, and flights of laser-based video sensors. The original Video Guidance Sensor (VGS), using laser illumination and video imagers, was built in-house after extensive laboratory development and testing. An Engineering Development Unit (EDU) was first built in the mid 1990s, and then two flight units (a flight and a spare) were built for flight on Space Transportation System (STS) 87 in 1998. The VGS Target assembly was designed, fabricated, and flight qualified at MSFC before mounting onto the Spartan 201 spacecraft. The close-range portion of the experiment was a success, and VGS

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obtained data out to 10 m (32.8 ft). However, an anomaly with the target spacecraft prevented measurements at longer ranges. The VGS was flown again in 1999 on STS-95, and it tracked the target spacecraft reliably from 150 m (492 ft) down to 2.5 m (8.2 ft), which is the closest approach allowed with the Shuttle bay.

The VGS solution was fed into the Rendezvous and Proximity Operations Display and the Remote Manipulator System (RMS) Situational Awareness Display for crew use, and the VGS video output was provided to the Shuttle aft flight deck. Commander Kurt Brown remarked during the mission debriefing that the VGS "performed exceedingly well." The VGS that was flown has been used in the MSFC Flight Robotics Laboratory (FRL) for closed-loop tests and demonstrations during the last eight years without failure.

The subsequent Demonstration of Autonomous Rendezvous Technology (DART) mission was designed to show that a spacecraft could rendezvous and perform proximity operations with a spacecraft already in orbit. Spare VGS retro-reflectors had been mounted on the Defense Advanced Research Projects Agency (DARPA) MUltiple path Beyond Line of sight Communication (MUBLCOM) satellite before launch. During extensive testing on the ground, the DART AVGS demonstrated acquisition and tracking the MUBLCOM target at ranges up to 300 m (984.3 ft). During the 24-hour DART mission, the AVGS operated in Spot Mode and was never commanded into Acquisition Mode. Spot Mode fires the lasers in the same sequence as the Acquisition and Track Modes, but it only measures and outputs the size, shape, intensity, and locations of all of the spots that it detects. This enabled the DART Guidance Navigation and Control (GN&C) system to maintain DART pointing control at the target spacecraft at ranges out to 2,000 m (6,562 ft). The accuracy of the bearing data output during Spot mode allowed the DART to approach the MUBLCOM spacecraft until contact. The data from the AVGS was vital in reconstructing the DART mishap, allowing calculation of the closing velocity to within 10% of the velocity calculated from ground-tracking measurements. Since the DART mission, the DART AVGS EDU has been used in testing at MSFC and Johnson Space Centers (JSC).

III. Summary of Orbital Express AVGS Performance

NGAVGS' predecessor is the AVGS, which was successfully demonstrated in on-orbit operations during DARPA's OE mission. Using relative navigation data from AVGS, OE performed the first U.S. fully autonomous rendezvous and capture in May 2007, followed by three months of multiple rendezvous and docking maneuvers and satellite servicing technology demonstrations. The experiment consisted of two separate spacecraft, the Boeing-built Autonomous Space Transport Robotic Orbiter (ASTRO) chase vehicle, and Next Generation Serviceable Satellite (NEXTSat) target vehicle built by Ball Aerospace. The OE AVGS was one of the near-field proximity operations and docking sensors integrated on the ASTRO.
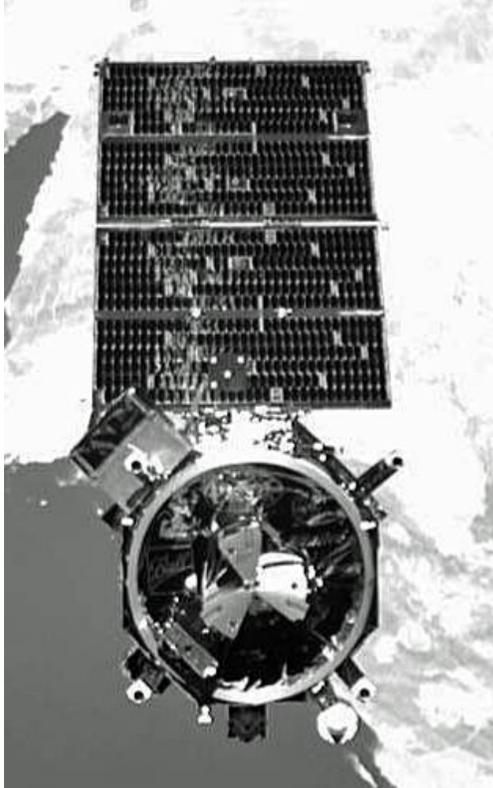
The AVGS' role on Orbital Express was to provide highly accurate 6 degrees-of-freedom (DOF) relative navigation data at ranges of 100 m to docking. Table 1 shows the accuracy specifications for the OE AVGS. Two specifications from 10 to 30 meters are given, since the AVGS tracked a Long Range Target (LRT) and Short Range Target (SRT) over different ranges of operation. The overlap region for tracking the two targets simultaneously was nominally

Table 1. Orbital Express AVGS Accuracy Requirements

Operating Range (m)	Range (mm)	Azimuth, Elevation (deg)	Roll (deg)	Pitch, Yaw (deg)
1-3	$\pm$12	$\pm$0.033	$\pm$0.13	$\pm$0.20
>3-5	$\pm$35	$\pm$0.033	$\pm$0.25	$\pm$0.33
>5-10	$\pm$150	$\pm$0.035	$\pm$0.45	$\pm$0.70
>10-30 (SRT)	$\pm$1500	$\pm$0.037	$\pm$1.30	$\pm$2.0
>10-30 (LRT)	$\pm$150	$\pm$0.027	$\pm$0.15	$\pm$0.70
>30-50	$\pm$400	$\pm$0.030	$\pm$0.25	$\pm$1.2
>50-100	$\pm$1666	$\pm$0.033	$\pm$0.50	$\pm$2.4
>100-300	$\pm$15,000	$\pm$0.033	$\pm$1.40	$\pm$7.0

from 10 meters to 30 meters. The data output rate of the OE AVGS was 5 Hz, although the sensor internally tracked the target at 10 Hz. The sensor had a field-of-view (FOV) of $\pm$8 degrees, and was required to track the target while it was within a seven degree cone about the center of the FOV.

Figure 1 is a photo of the NEXTSat spacecraft taken by one of the visible light cameras on ASTRO. The four AVGS LRT retro-reflectors are visible at the bottom left, bottom right, top right, and near the top left of the NEXTSat structure. The AVGS SRT, also containing four closely-spaced retro-reflectors, is a small gray cluster at the bottom center of the picture.

AVGS participated in a number of OE scenarios and operations, with over 56.8 hours in Track Mode or Acquisition Mode. Operations started and ended with tracking data while ASTRO and NEXTSat were mated, providing fixed-position data between AVGS and the SRT for assessing close-range performance. Three longer duration sets of mated-position data were also analyzed. The mated position data sets were the only ones that had nominal "truth" data, and post-flight analysis showed that the standard deviation of this data was an order of magnitude below the specifications. There were also several operations in which the AVGS tracked its target while NEXTSat was maneuvered on a robotic arm. The robotic arm maneuvers and the mated position data demonstrated high repeatability in AVGS' performance over the duration of the OE mission.

The most compelling OE AVGS data was obtained while the two spacecraft were separated. The AVGS provided 6-DOF relative navigation data to ASTRO's Guidance and Relative Navigation system. The SRT was tracked during every scenario out to the 30 m maximum range specification for the SRT and beyond; a 6-DOF solution was provided from SRT tracking at ranges from 1 m (3.3 ft) to 32.3 m (106 ft). In most scenarios, the ASTRO entered the NEXTSat approach corridor well inside the maximum range specification of 100 m for LRT tracking. The approach corridor was a 25-degree wide cone that started at 60 m (196.9 ft) between spacecraft. The LRT was tracked all the way in to approximately 8.7 m (28.5 ft), exceeding the LRT minimum range specification of 10 m. The AVGS typically tracked the LRT out to ranges between 100 and 110 meters (328 ft to 361 ft), while the ASTRO attitude kept the LRT in AVGS' FOV. Throughout the OE mission, the AVGS remained in Track Mode until a few minutes prior to leaving the departure corridor, or began tracking within a few minutes of entering the approach corridor. The OE scenarios involved separations as close as 11 m to as far as 5 km (3.1 miles). Scenario 3-1 recovery provided the longest range opportunity for the AVGS. The NEXTSat and ASTRO attitudes during Scenario 3-1 approach were planned to take advantage of AVGS tracking capabilities, and a 6-DOF solution was produced by AVGS starting at 150 m (492.1 ft) and continued in to docking.

Figure 1. NEXTSat Spacecraft in Orbit

The AVGS successfully tracked a large range of attitudes, azimuths and elevations. The mission did not test the AVGS tracking envelope, other than during sensor suite checkout. The data available for analysis encompasses a range of Pitch values from -26 through 26 degrees, Yaw from -23 through 10 degrees, Azimuth from -7 through 7 degrees and Elevation from -6 to 8 degrees. The maximum tilt angle on three scenarios exceeded the 25-degree requirement at ranges greater than 60 meters.

The AVGS played a vital role in the extremely successful Orbital Express mission. The sensor performed significantly better than required in a number of categories, particularly in SRT range capability and repeatability between different mated operations. The amount of data collected, both static and dynamic, was substantial, providing the basis for more analysis and a better understanding of on-orbit AR&D. The engineering, hardware and software development, testing, and flight experience from the OE AVGS is being applied to the NGAVGS.

IV. Next Generation Sensor

The next generation of AVGS is currently being developed and tested at MSFC, since parts obsolescence prevents the AVGS hardware from being reproduced. Its obsolete imager and processor are being upgraded with radiation-tolerant parts, and additional features are either being restored or included to satisfy new applications. The NGAVGS is a third-generation video guidance sensor that retains the basic functions developed and flight-proven for AVGS and applies invaluable lessons learned from on-orbit flight experience. MSFC has designed and assembled an NGAVGS breadboard, three brassboard units, a flight emulator, and a prototype unit, and has performed successful functional tests in the Flight Robotics Lab (FRL) and 300 m (980 ft) Tunnel at MSFC. In addition, preliminary MSFC outdoor range testing has been successfully performed with the NGAVGS and ISS-type

retro-reflector targets at distances out to 5 km (3.1 miles). NGAVGS flight hardware design and development are under way with the prototype unit being used as a pathfinder for the flight design. With a combination of targets such as those from OE and the ISS retro-reflectors, the NGAVGS will be capable of providing 6-DOF relative position and attitude solutions from 250 m (820.2 ft) to docking, as well as measuring range and bearing from 250 m all the way out to capability 5 km (3.1 miles) using the numerous existing retro-reflectors placed in widely spaced locations on ISS.

A. NGAVGS Features

The NGAVGS is a robust technology that employs laser-illumination, a video imager, and retro-reflector targets to measure relative positions and attitudes. The NGAVGS operational strengths are accuracy and reliability at the critical close ranges needed for docking and insensitivity to a variety of orbital lighting conditions. The 6-DOF solutions at critical close ranges are consistent over time, without spurious data or drop-outs that can negatively affect vehicle GN&C systems. NGAVGS is a lightweight, compact, and accurate sensor, providing a 5 Hz update rate. Previous generations of video sensor have required a range estimate that was within 25% of the actual range, but the NGAVGS can automatically acquire a target within the 6-DOF ranges of operation, expanding on the OE AVGS automatic acquisition within the 1 to 5 meter operational range. Also, the NGAVGS program memory is set up to have a "gold" code (unchangeable during flight) and room for another software load, allowing new software to be uploaded if necessary.

Four major components of the AVGS (imager, memory, Field Programmable Gate Array (FPGA), and processor) had to be replaced due to obsolescence. Modern parts with radiation tolerance were selected. The imager and image memory were specifically designed and built for space applications, and the next generation processor and FPGA have undergone radiation testing. All of these components are also used in commercial space processors and sensor avionics.

The NGAVGS has a built-in capability to output a digital video signal at a rate of at least 10 Hz. The signal will include constant light sources and reflections, which could be used by pilots as reference aids, in addition to the spots that are the reflections from the ISS retro-reflective targets. Spot patterns are a visual navigation aid that could provide pilots an instantaneous awareness of the docking port location at long distances without requiring them to assess target vehicle outlines and then estimate the docking port location. With crew training for spot pattern recognition, visual awareness of close-range positions and attitudes can assist other visual situational awareness sensors.

B. NGAVGS Design/Layout

The NGAVGS sensor layout and design evolved from the use of several custom components in a complex design to a configuration utilizing fewer, highly-integrated industrial components. These components include the lens, laser modules, laser and thermo-electric cooler (TEC) driver modules, and the single main processor. The integrated components have lowered the number of electrical and mechanical parts, simplified interconnections, and increased the adaptability and programmability of the new sensor. The NGAVGS simplified design with commercial parts will increase reliability and reduce the fabrication and operational costs.

To simplify the assembly, maintenance, and interconnections between components, the functions of the NGAVGS have been divided between an optical bench and a power/laser/electronics unit. This arrangement allows the lasers, with their power and temperature requirements, to be close to the power modules, the drivers, and the processor electronics. Only the laser light guide. the video imager, and the passive optical components are located on the optical bench, reducing weight, volume, and power requirements in the optical design. NGAVGS can be packaged in either one- or two-box configurations, providing options for mounting the sensor on vehicles. The current NGAVGS design configuration is shown in Fig. 2. NGAVGS design dimensions are 19.8 x 20.32 x 32.3 cm (7.8 x 8.0 x 12.7 inches), and the sensor mass is less than 7.3 kg (16 pounds). Power consumption is expected to similar or less than the AVGS, which consumed approximately 14 watts in Standby mode and 35 watts in Tracking mode, the most power-intensive mode of operation.
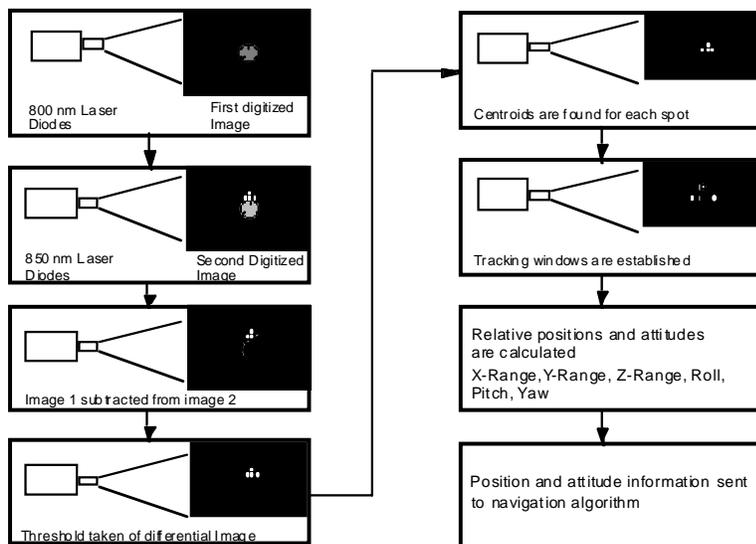
GEOMETRIC SIZE: 12.7(L) X 7.8(W) X 8(H) inches, MASS: ~16.0 lb
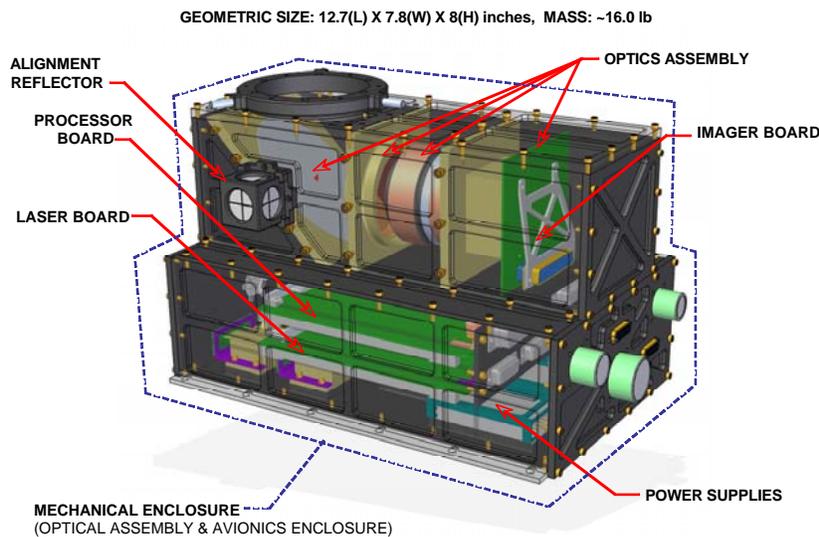
Figure 2. NGAVGS Design Configuration

C. NGAVGS Method of Operation

The Shuttle VGS, the DART AVGS, OE AVGS, and the NGAVGS all operate using the same original method of subtracted images with alternating illumination for reflector discrimination and target recognition. The NGAVGS uses two sets of laser diodes at wavelengths of 800 and 850 nanometers, a mirror through which the lasers fire, a camera that images the return from the lasers, and hardware, software, and firmware that process the returned images into relative position and attitude data. The sensor is designed to interact with a filtered retro-reflective target. The target has filters that allow one wavelength of NGAVGS laser to pass through and be reflected while blocking the other wavelength. The target retro-reflectors are arranged in a pattern known to the NGAVGS software. The sensor fires one set of lasers and captures an image. Then it fires the second set of lasers and captures a second image. When this first image is subtracted from the second image and an intensity threshold is used, virtually all of the background clutter is eliminated. This feature plays a significant role in overcoming challenging lighting conditions. The remaining data is converted into a set of spots, and the spots are compared to the target pattern. Once a set of spots matching the target pattern is found, the software computes the relative position and attitude between the target and the sensor. Figure 3 illustrates the laser illumination and processing sequence that the NGAVGS follows.

By modifying the standard mode of operation the NGAVGS can also be used to detect and track unfiltered retro-reflective targets. To enable tracking of unfiltered targets, the initial image is taken with no laser firings (a background image), and then the second image uses the usual laser illumination. This illumination sequence was employed in the DART AVGS to "spot" the MUBLCOM target spacecraft reflectors at ranges beyond 1000 m (3281 ft) and this method will work with the current ISS retro-reflectors.

Figure 3. NGAVGS Illumination and Processing Sequence

D. NGAVGS Functional and Performance Characteristics

NGAVGS will operate in the lighting conditions required for rendezvous and docking the CEV with the ISS. The NGAVGS FOV is ± 7 deg X ± 7 deg. The 6-DOF relative navigation data will be output at a 5 Hz rate. The NGAVGS is capable of Dual Track mode, in which solutions are generated for both the SRT and the LRT.

Figure 4 shows the NGAVGS block diagram. The NGAVGS operates at 28 volts Direct Current (DC) and can withstand continuous input voltage from the main bus of 20 to 36 volts DC. The NGAVGS flight interface is a single RS-422 Data Bus and is capable of receiving low-level discrete commands and serial digital commands from the vehicle system, including configure/safe commands for the lasers and power conservation. The RS-422 communications includes housekeeping parameters in all operating modes. NGAVGS will provide feedback verification to the vehicle that includes the internal status of the laser system. In addition to the RS422 data output, the NGAVGS also outputs real-time digital video images via a Camera-Link interface.
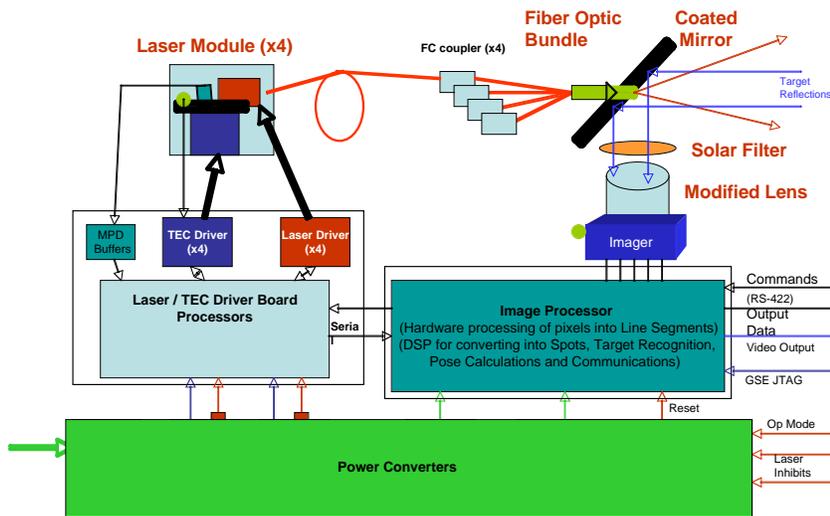

Figure 4. NGAVGS Block Diagram

E. NGAVGS Software

The NGAVGS software is the 4th Generation, with prior generations of software developed for the VGS, DART AVGS, and OE AVGS. The NGAVGS software is being built directly from the OE flight software and is being developed by the experienced MSFC software development organization whose personnel and processes have been certified to Capability Maturity Model Integration (CMMI) Level 3. The NGAVGS software, which executes on the NGAVGS hardware, implements complex target recognition and relative range/bearing/attitude determination algorithms. The NGAVGS software executes once every 200 msecs during a "Track" cycle to provide full 6-DOF solutions to the chase vehicle. The NGAVGS software also has the capability to be calibrated on-orbit by updates to the I-Load (initial load) table. New features that have been added to the NGAVGS software include auto-ranging acquisition.

F. NGAVGS Development and Test Status

The MSFC NGAVGS team is currently working on the hardware and software design, assembly, and testing. An NGAVGS breadboard was built for initial software porting and testing with the upgraded laser/lens/imager combination. Once the breadboard performance was quantified, two brassboard units were built. Part of the challenge of upgrading a well-performing sensor is identification of performance changes, such as resolution and exposure parameters, that may result from replacement parts. Performance characterization testing used OE SRT & LRT targets for the 1 to 200 m docking range, and two ISS-like hemispherical unfiltered reflectors from 3000 m in to 4m. The first brassboard was tested over ranges from 1 m to 300 m.

The close-range testing with the OE SRT was performed in the FRL, using a computer-controlled two-axis gimbal for sensor azimuth and elevation motion and a three-axis gimbal for target pitch, yaw, and roll positioning. These tests determine initial focus, alignment, resolution, and exposure parameters for various target angles in the center, edge, and corner of the sensor field of view, from 1 m out to 100 m.

Mid-range testing was performed in the 300 m tunnel facility equipped with a 4-axis Remote Automated Target Transport (RATT). The computer-controlled RATT positions target-mockups at a variety of yaw, pitch, and roll angles, and at distances from 5 m to 300 m in front of the sensor, which is pointed by a computerized pan & tilt unit.

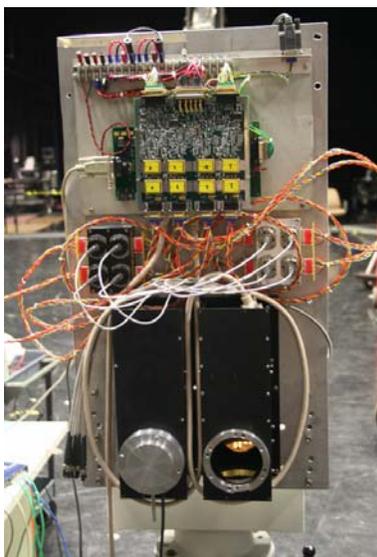American Institute of Aeronautics and Astronautics

The brassboard testing was performed with various retro-reflectors: including a pair of ISS-like hemispherical arrays, spaced like the ISS JEM reflectors, and shown in Fig. 5a at 7 m. Figs 5b and 5c show the background and foreground sensor images with the target at 300m. Both images contain the tunnel ceiling lights, but only the two target reflections are captured in the foreground image in Fig. 5c. Fig. 5-D is the subtracted image showing two very bright spots from the target reflectors, and very dim outlines of the lights.

Figure 5a

Figure 5b
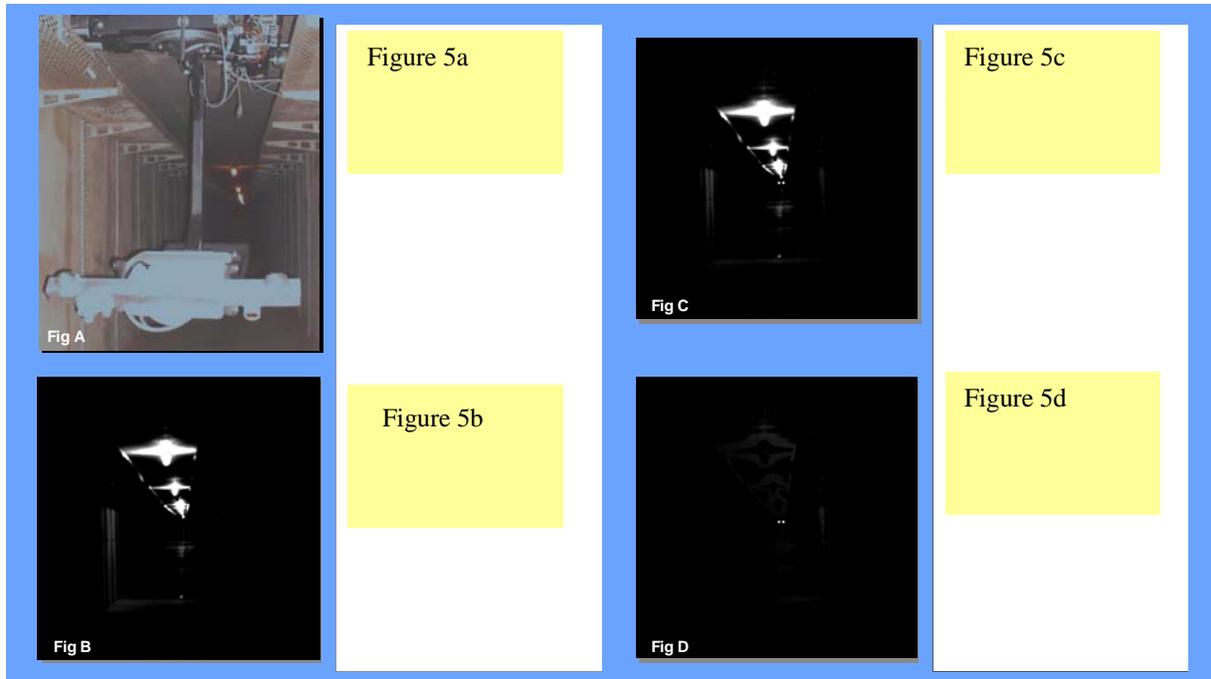
Figure 5c

Figure 5d

Figures 5a- 5d Testing in 300m Tunnel

Figure 6. NGAVGS Brassboards for Extended Range Testing

Longer range testing, at 300 m to 3,000 m, was performed outdoors at MSFC with the second brassboard. ISS-like hemispherical reflectors were mounted on Apollo-Saturn-era test stands and towers, at distances of about 2 km (1.24 miles) and 3 km (1.86 miles) south of the laser test tower, where the NGAVGS brassboard and an AVGS EDU for benchmarking were mounted. In spite of humidity greater than 80%, which produced significant atmospheric interference with the laser output and the return signal, both the 2 km target and the 3 km target were seen by the NGAVGS brassboard and the AVGS.

To test the sensor out to the CEV 5 km maximum range requirement, two modified brassboard configurations of the NGAVGS were fabricated, assembled, aligned, and tested. Two modified NGAVGS brassboard sensor heads with different sized imagers were mounted side by side on a computerized pointing gimbal, as shown in Fig. 6.

A target assembly was mounted on the Saturn I handrail for 3 km and 4.1 km testing, and on an Army test tower for 5 km testing. The target assembly consisted of two hemispherical retro-reflectors separated by 6.48 m (21 ft 3 inches), to simulate the separation between the ISS Japanese Experiment Module (JEM) and Pressurized Mating Adaptor 2 (PMA2) reflectors. The NGAVGS extended range brassboards and a DART AVGS flight unit, used as a baseline, were placed in the laser test tower for the 3 km and 5 km testing and on the top of Building 4200 for 4.1 km testing.
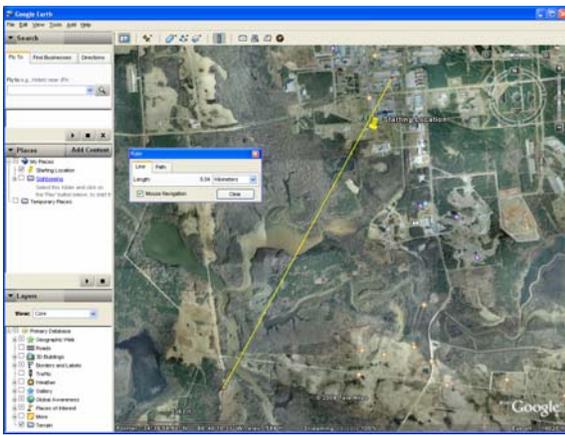
Figure 7a Test Direction and Distance

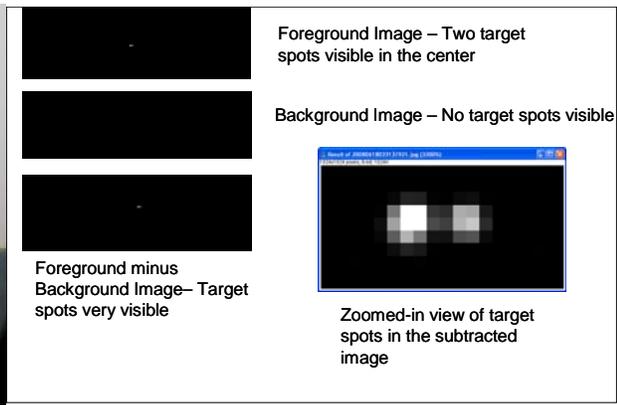Figure 7c Video Image

Figure 7b Target Location on tower

Figure 7d NGAVGS Image Sequence

Figures 7a-7d NGAVGS Outdoor 5 km Testing

Figure 7a shows the outdoor test direction and distance, with the target location from the test tower shown in Figure 7b, and the NGAVGS video image of the test target location in Figure 7c. Figure 7d shows the NGAVGS image sequence with the retro-reflector target spots. Test results showed that the higher resolution imager in the NGAVGS identified two spots at the 5 km range, and the AVGS also imaged two spots at that range. Both sensors provided intermittent data at 5 km, which can be attributed to the atmospheric conditions that are always present in outdoor ground testing. Test results from the NGAVGS were consistent with those from the AVGS. At the 4.1 km range, the higher resolution imager registered two spots, whereas the lower resolution imager registered only one spot. At the 3 km range, both imagers identified two spots.

In summary, the NGAVGS has successfully tracked a short-range target as close as 1 meter and tracked a two-spot ISS-like retro-reflector target out to 5 km.

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A NGAVGS prototype unit is being built and tested as a pathfinder for the flight design. The prototype has been designed to meet specifications based on the OE AVGS performance specifications. However, sensor performance is very dependent on the target configuration. Figure 8 shows the assembled NGAVGS prototype unit. The prototype can accommodate either the high resolution or lower resolution imagers. Imager selection will be made to match NGAVGS performance with mission-dependent operational requirements. Initial testing of the prototype at 3 km has been successful, and additional testing will identify settings for parameters that optimize performance.

Ground testing in the FRL, the 300 m tunnel, and outdoors has shown that NGAVGS is a single sensor with the capability to provide relative range and bearing from 5 km in to docking, and with suitable targets it can provide a full 6-DOF solution from 250 m to docking.
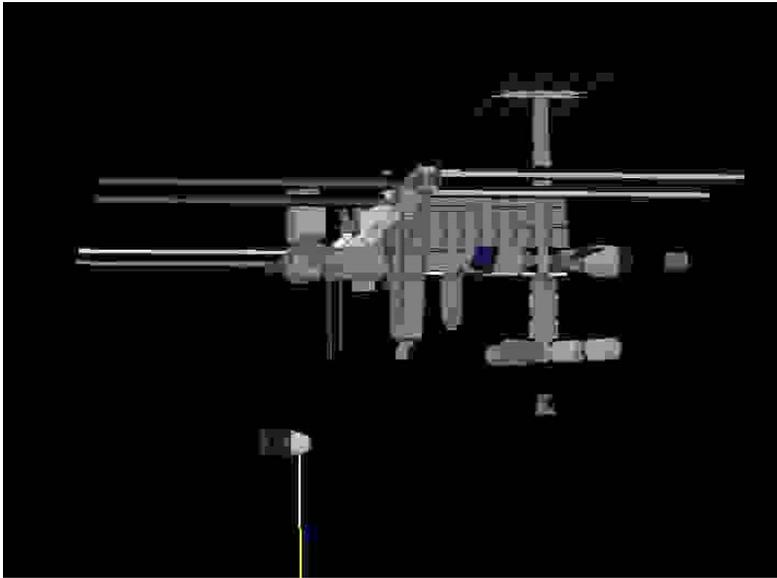

Figure 8. NGAVGS Prototype Unit

V. NGAVGS Applications

NGAVGS can meet the rendezvous sensor needs of ISS cargo delivery vehicles, CEV, satellite servicing vehicles, and other spacecraft with on-orbit proximity operations. NGAVGS uses retro-reflector targets in known patterns on the target vehicles, and is not incapacitated by the reflections from existing targets on ISS or other spacecraft. The NGAVGS can use existing unfiltered retro-reflectors on ISS to provide range and bearing for cargo delivery vehicles and for the CEV, and with the addition of a filtered close-range target at the docking or berthing port, NGAVGS can provide relative range, bearing, and attitude.

Rendezvous and berthing is a fundamental capability required for the delivery of cargo and supplies to the ISS by COTS vehicles. Three-degree-of-freedom (3-DOF) range and bearing information at midrange distances is required for relative navigation on ISS approach trajectories. Relative GPS can provide range and bearing outside of the Approach Ellipsoid around ISS, which is 4 km along the V-bar and 2 km along the R-bar and POP directions. Nominal COTS approaches to ISS are below and behind the ISS, transitioning to an R-bar approach outside of the 2 km Approach Ellipsoid. NGAVGS could provide primary sensor range and bearing data at this distance, with secondary data being provided by the relative GPS, up to a hold point along R-bar. At least one hold point is required for COTS vehicles, lying within the Approach Ellipsoid but outside the 200 m diameter Keep Out Sphere around ISS. If this hold point is close to the Keep Out Sphere and if a suitable set of ISS retro-reflectors is visible, the NGAVGS can provide six-degree-of-freedom (6-DOF) relative navigation data. While station keeping at the hold point, the COTS vehicle will receive the go command from either on-orbit or ground control crews, prompting the vehicle to fly up the R-bar to reach another hold point at a distance of approximately 30 m from ISS. At this second hold point, the NGAVGS could feed its video signal to the COTS vehicle's communication link to ISS, providing another visual aid to the on-board crew for approval to proceed. After the go command, the COTS vehicle will maneuver to the same berthing port used by the HTV, the nadir Node 2 Common Berthing Mechanism (CBM). If a short-range NGAVGS target with filtered corner cubes is mounted to this CBM, the NGAVGS could provide highly accurate 6-DOF relative navigation information as the COTS vehicle enters and maneuvers in the berthing approach corridor. The COTS vehicle slowly approaches the Node 2 CBM and is grappled by the Space Station Remote Manipulator System (SSRMS), which berths the vehicle. At departure, the COTS vehicle backs out and down along a corridor canted 15 degrees forward of nadir. The NGAVGS could provide 6-DOF relative navigation information and live video during the departure if the vehicle's departure attitude maintains target viewing angles in the sensor FOV. Figure 9 shows a representation of the SpaceX Dragon vehicle in the approach corridor to ISS.

Figure 9. Dragon in Approach Corridor to ISS (bdStudio Animation)

Applications for Orion include rendezvous and docking missions with ISS and the Earth Departure Stage (EDS) and Altair, the lunar lander. Orion will approach ISS from below and behind on a co-elliptical orbit. Docking is performed at either Pressurized Mating Adapter 3 (PMA3) on the nadir side of Node 1, or at PMA2 on the front of ISS. Figure 10 shows a representation of Orion approaching PMA2, from a bdStudio animation. For PMA3 docking, Orion will follow an R-bar approach to

ISS, and begin the transition to the docking axis orientation at approximately 300 m below and 90m behind the docking port. If a suitable set of ISS retro-reflectors is visible, NGAVGS

could provide range and bearing at this point, and angular alignment about the R-bar during the 180° roll maneuver to align Orion with PMA3. With a short-range NGAVGS target mounted on PMA3, NGAVGS could provide accurate 6-DOF relative navigation information to Orion at the Keep Out Sphere and in to docking, as well as provide real-time video output for crew monitoring. For PMA2 docking, Orion follows a trajectory from the R-bar up to the V-bar, and with a suitable Orion attitude the NGAVGS could provide range and bearing information from
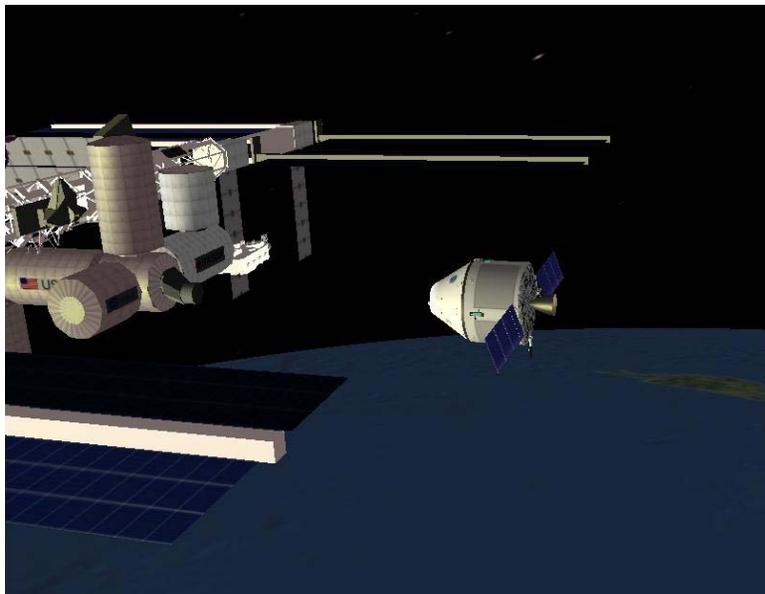
**Figure 10. Orion Approaching PMA2 on ISS (bdStudio Animation)**

the ISS reflectors. The approach corridor starts at approximately 150m from ISS, and if a suitable NGAVGS target were mounted on PMA2, the NGAVGS could provide 6DOF relative navigation information all the way in to docking.

Orion must also rendezvous and dock in low Earth orbit with the EDU/Altair stack after it is launched, and then again in lunar orbit with the lander ascent module after it returns with crew from the lunar surface. Figure 11 shows a typical lunar reference mission. Orion and the crew launch first on Ares I, followed by the EDU and Altair 90 minutes later. For rendezvous in low Earth orbit, the EDS/Altair vehicle is ahead and above Orion, and Orion is the chase vehicle. Terminal Phase Initiation (TPI) occurs 1.5 km behind and 1.4 km below the

EDS/Altair vehicle, and with NGAVGS targets on Altair and with a suitable Orion attitude to acquire and track those targets, the NGAVGS could provide range and bearing before the TPI burn is executed. An NGAVGS short-range target on the Altair docking adapter would enable accurate 6-DOF rendezvous and docking information from

NGAVGS. The same long and short-range targets on the Altair ascent module could be used later for the rendezvous and docking maneuvers in lunar orbit, after surface operations and before Earth return.
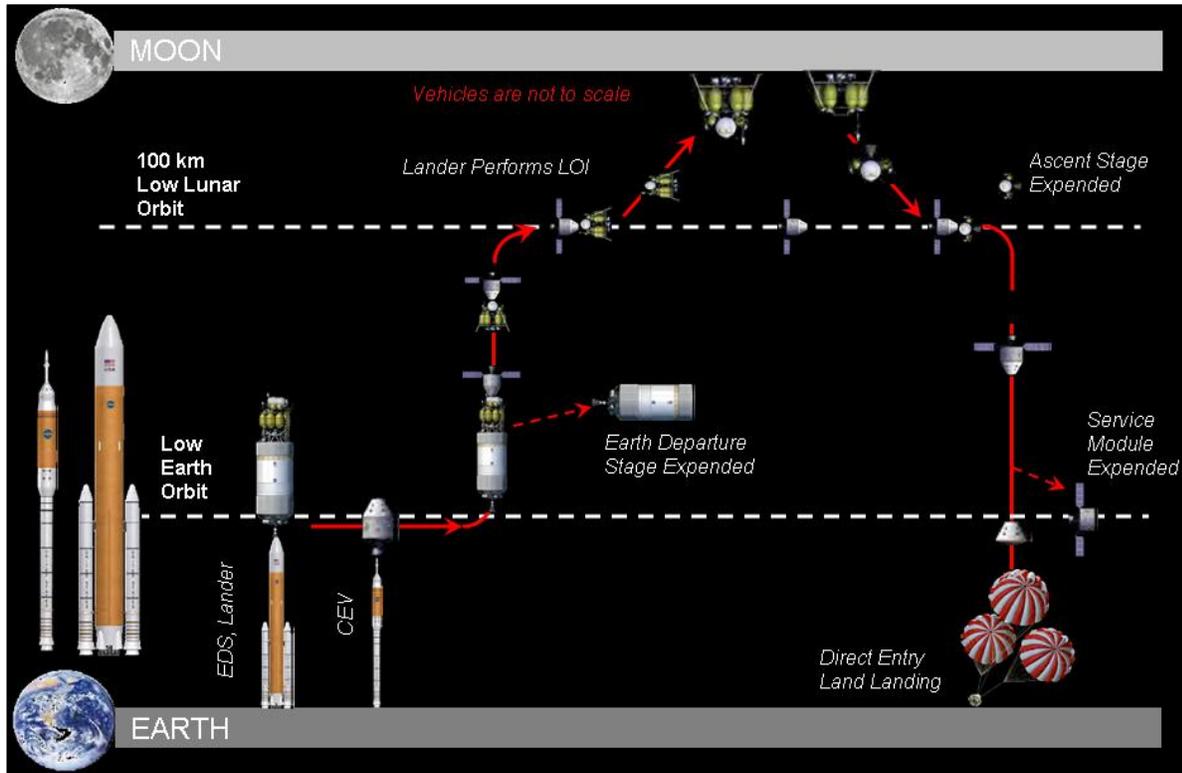
Figure 11. Typical Lunar Reference Mission

An accurate and reliable relative navigation sensor such as NGAVGS can provide confidence and safety assurances for not only man-rated vehicles like CEV and COTS, but also for unmanned vehicles to be used in lunar expeditions, for unmanned satellite servicing such as Orbital Express, and for unmanned space assembly. A reliable relative navigation sensor is critical for performing proximity operations near manned vehicles like ISS, permitting timely transitions to Collision Avoidance modes and other safety maneuvers, and is an enabling technology for unmanned rendezvous between space vehicles. In addition, accurate relative navigation sensors can save significant propellant on visiting vehicles by providing position and attitude information to their GN&C systems and enabling them to immediately correct deviations from the required trajectories and approach corridors, before those deviations become large.

VI.   Conclusions

The Next Generation AVGS is currently being built and tested at MSFC, using the hardware, software, testing, and flight operations experience from the AVGS on the recent Orbital Express mission. Ground testing with brassboard NGAVGS units has successfully imaged a short-range target as close as 1 m and a two-spot ISS-like retro-reflector target out to 5 km. A prototype is being built and tested as a pathfinder for the flight design. NGAVGS can meet the rendezvous sensor needs of ISS cargo delivery vehicles and CEV, and future applications in satellite servicing and lunar missions.