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NEXT GENERATION ADVANCED VIDEO GUIDANCE SENSOR DEVELOPMENT AND TEST

Richard T. Howard,[*] Thomas C. Bryan,[†] Jimmy Lee,[‡] and Bryan Robertson[§]

The Advanced Video Guidance Sensor (AVGS) was the primary docking sensor for the Orbital Express mission. The sensor performed extremely well during the mission, and the technology has been proven on orbit in other flights too. Parts obsolescence issues prevented the construction of more AVGS units, so the next generation of sensor was designed with current parts and updated to support future programs. The Next Generation Advanced Video Guidance Sensor (NGAVGS) has been tested as a breadboard, two different brassboard units, and a prototype. The testing revealed further improvements that could be made and demonstrated capability beyond that ever demonstrated by the sensor on orbit. This paper presents some of the sensor history, parts obsolescence issues, radiation concerns, and software improvements to the NGAVGS. In addition, some of the testing and test results are presented. The NGAVGS has shown that it will meet the general requirements for any space proximity operations or docking need.

INTRODUCTION

The Next Generation Advanced Video Guidance Sensor (NGAVGS) is a sensor capable of supporting automated operations for spacecraft rendezvous, spacecraft proximity operations, spacecraft docking, spacecraft free-flyer capture, fluid transfers, and Orbital Replacement Unit (ORU) transfers. The sensor was developed by the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC). The NGAVGS builds on the technology of the AVGS, incorporating requirements to support the longer operational ranges required by the Crew Exploration Vehicle (CEV or Orion) (up to 5000 meters) and incorporating real-time video output. Since one of the key technologies required to support the International Space Station (ISS) re-supply as well as the NASA Constellation Program is Automated Rendezvous and Docking (AR&D), the robustness of an AR&D sensor is vital, so radiation is a bigger concern for the current sensor than it was for the Orbital Express (OE) Mission or any other previous mission.

As an in-house project, the technologies and testing required for VGS, AVGS and now the NGAVGS were developed by engineers within the MSFC Engineering Directorate, continuing the long AR&D heritage at MSFC. These engineers hold a number of patents on these sensors and related technologies. The NGAVGS flight hardware and software design is also being devel-

[*] Team Leader, AR&D Development and Test Branch (ES62), NASA - MSFC, Huntsville, AL 35812.
[†] Technical Assistant, AR&D Development and Test Branch (ES62), NASA - MSFC, Huntsville, AL 35812.
[‡] Project Manager, AR&D Projects Team (VP33), NASA - MSFC, Huntsville, AL 35812.
[§] Electrical Engineer, Data and RF Systems Branch (ES33), NASA - MSFC, Huntsville, AL 35812.

oped by the MSFC Engineering Directorate personnel. Since parts obsolescence issues were identified several years ago, an internal study was conducted in late 2006 to assess 13 different configuration options for the NGAVGS (the planned follow-on to the AVGS). The processor control board and the imager were key components assessed as a part of this trade study. The recommendation resulting from this trade was a two box configuration with a remote camera head and a laser/electronics box that could be internally mounted in the spacecraft to provide better radiation protection and thermal dissipation. In addition, a one-box option was also designed to provide an easier to integrate sensor solution. Two different NGAVGS brassboards were built based on the two-box configuration, and two prototypes were built based on the one-box configuration. The second brassboard, incorporating two different sensor heads side-by-side, is depicted below in Figure 1.

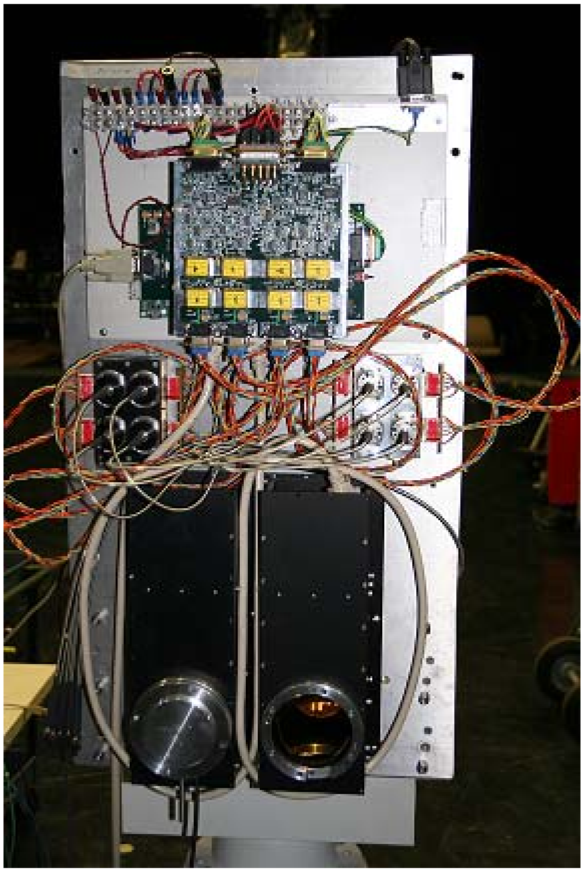

Figure 1. NGAVGS Brassboard 2/3 configuration.

FLIGHT HISTORY

The NGAVGS is the latest sensor in a line of video sensors developed at MSFC for automated rendezvous and docking. Early proto-type sensors were developed starting in 1988 and tested in the MSFC Flight Robotics Laboratory (FRL). They were initially used to guide a 3-degree-of-freedom (3-DOF) vehicle from an initial position 10 to 20 meters away from the sensor all the way into contact with the target location and throughout the closure of a docking mechanism.

The first sensor built for flight was the Video Guidance Sensor (VGS). It was based on a modified-for-space video camera, frame grabber, processor, and software. The VGS was designed as the sensor that would be used to guide a spacecraft the last 110 meters of its AR&D

mission (with the earlier portion of the mission guided by inertial navigation sensors and GPS.) The VGS was flown on the Shuttle on STS-87 and STS-95. It tracked a target that was mounted on a SPARTAN free-flyer. During STS-87, there were some problems with the SPARTAN release, so the VGS only got to track the SPARTAN while it was on the shuttle Remote Manipulator System (RMS). That limited the range to a maximum of about 13 meters. On STS-95, the full mission was carried out, and the VGS got to track the SPARTAN intermittently at 200 meters and constantly from 150 meters in to 10 meters (the minimum approach range). In addition, more data was taken with the SPARTAN mounted on the RMS.[1, 2] The VGS was also used in the FRL testing for both 3-DOF and 6-DOF simulations and in complete closed-loop AR&D system simulation and testing.[3] Figure 2 shows a picture of the VGS mounted on the Small Mobility Base in the FRL.

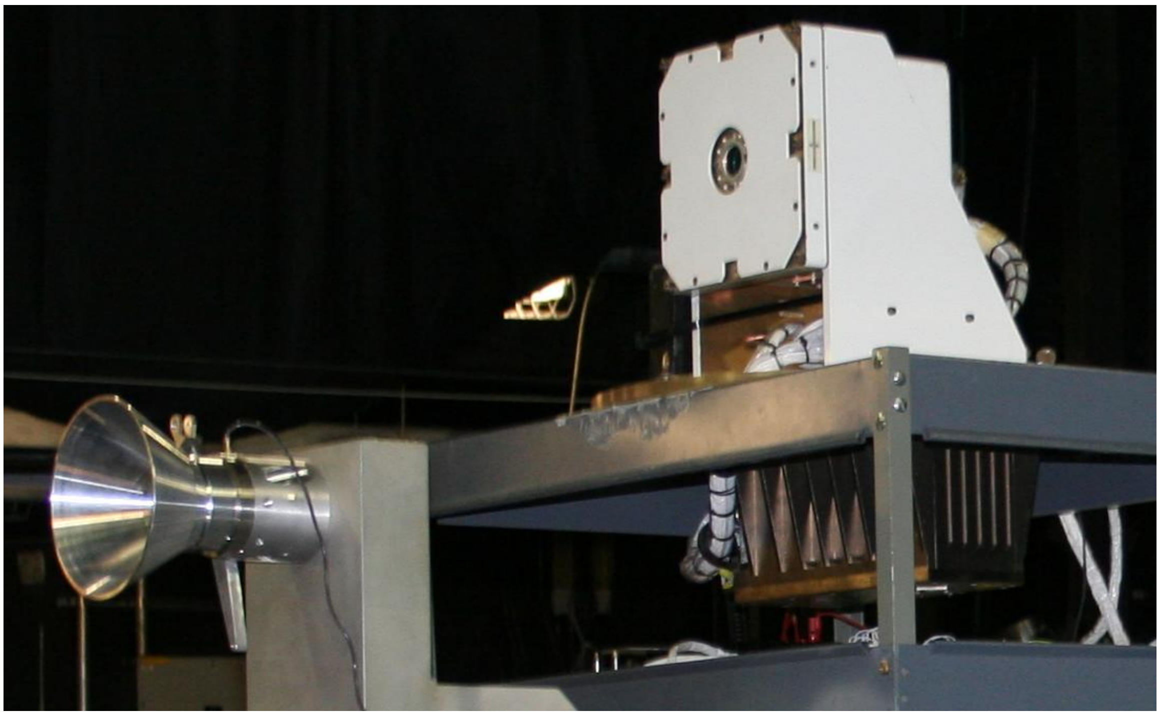

Figure 2. VGS flight unit mounted on Small Mobility Base in the Flight Robotics Laboratory.

The next generation of sensor hardware was initially developed in-house with some assistance from Advanced Optical Systems, and then the flight version of the hardware was built by Orbital Sciences Corporation. The software was all written, verified, and validated by MSFC's Flight Software group and the testing was carried out in the FRL as well as in the 300 meter tunnel. The Advanced Video Guidance Sensor (AVGS) shown in Figure 3 was 5 times faster than the VGS, used about 1/3 the power, and weighed less than half what the VGS weighed. It was the proximity operations sensor mounted on the front of the Demonstration of Autonomous Rendezvous Technologies (DART) vehicle. The AVGS was capable of acquiring and tracking a target from 300 meters in to docking range (but 4 meters was the closest planned approach range for DART.) While tracking a target, the AVGS provided all six pieces of relative position and attitude information. In addition, the AVGS had a Spot mode in which it would simply provide bearing information to any spots that it saw. This mode worked at ranges up to 2 kilometers during the DART mission, but unfortunately the sensor was never commanded into its tracking mode during the DART mission.[4, 5]

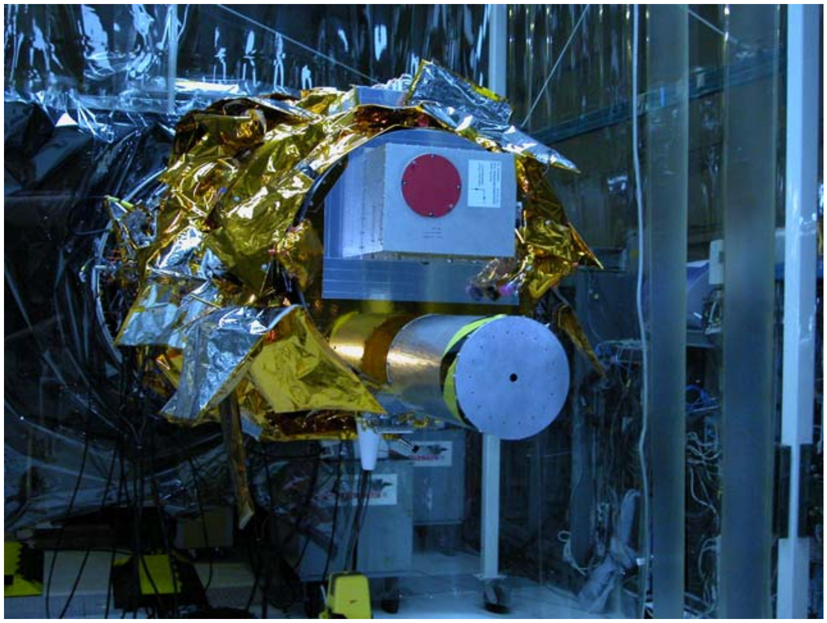

Figure 3. AVGS flight unit mounted on the front of the DART vehicle.

An upgraded version of the DART AVGS was desired by Boeing to be used on the Orbital Express (OE) mission. The changes to the sensor were minor, involving tighter thermal controls on some of the optical components and a new mounting location. The software underwent significant improvements, some due to lessons learned from the DART AVGS and some due to new requirements. The DART mission was only supposed to last 24 hours, so there was no need to update the software on orbit, while the OE mission was originally scheduled to be on orbit for up to one year, so the software needed to have the ability to be updated. In addition, there were a number of parameters that may have needed adjusting on-orbit, so an I-Load (Initial-Load) capability was created so some parameters could be quickly and easily changed without recompiling, validating, and loading a complete set of new software. Finally, due to the docking requirements that were not present on DART, a number of optical problems had to be overcome to generate the required accuracy.[6] The OE mission was extremely successful, with the AVGS being used from docking range (about 1 meter) all the way out to 150 meters (despite the fact that the planned use of AVGS was never to have been beyond 120 meters.)[7, 8]

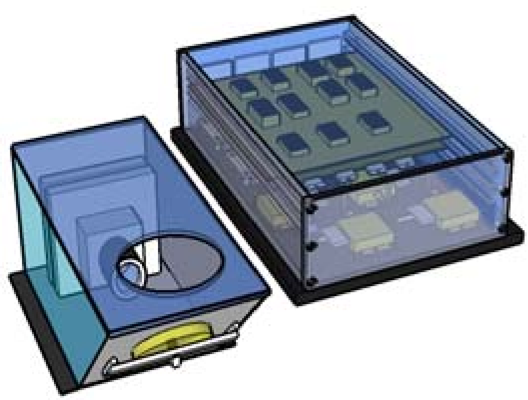

Figure 4. NGAVGS two-box design.

SENSOR CHARACTERISTICS

The AVGS weighed 20 lbs, was approximately 7 x 10 x 12 inches, and consumed approximately 14 Watts in Standby mode and 35 Watts in Tracking Mode (the most power intensive mode of operation). The AVGS was a single box that contained all of the necessary components. While working through design options for the NGAVGS, It became clear that to meet the needs of the various mission applications, the MSFC team needed to develop more flexibility into the NGAVGS sensor design packaging. As a result, there is a one box configuration which minimizes the weight and physical integration requirements and a two box design that allows the sensor head to be mounted externally and the laser and electronics box to be mounted internally to reduce environmental effects. The two box concept is shown in Figure 4 above. The NGAVGS one box design was pursued to the point of building two prototypes. The single box design measures 7 x 7.5 x 12 inches and weighs approximately 8 kg (17.5 pounds). It consumes about 20 Watts in Standby mode and an average of less than 30 W during tracking operations (the most power intense mode of operation). The NGAVGS one box design is shown in Figure 5 below, and the unit pictured is the second prototype unit built (the Block II Prototype).

Figure 5. NGAVGS Block II Prototype (one-box design).

The NGAVGS functions in a fashion similar to the AVGS – it takes two sequential pictures illuminated by different wavelengths of laser light, subtracts one picture from the other, creates spots from the lit pixel image data, matches spots to the known target geometry, and computes the relative position vector and relative attitude information.

During Acquisition or Tracking, image acquisition is initiated by the Digital Signal Processor (DSP). The DSP generates a command to the Field Programmable Gate Array (FPGA) to begin a cycle. The FPGA starts by issuing a fire laser command to the Laser Housekeeping Processor. The lasers are fired and the imager accumulates charge for a predetermined amount of time (the integration time or exposure time). Once the integration time is complete, the image is passed from the imager to the FPGA where it is stored in external memory. Two complete images are accumulated in this manner with each image being stored in separate memory. The differences in the two images are primarily caused by the difference in reflections of the two different wavelengths of lasers that were fired during each image's integration time. The two images are then compared by the FPGA, and the lit comparison data is compressed and passed to the DSP where pattern matching is performed. A final solution is calculated and transmitted out thru the RS-422 serial interface. The image can be seen in real time thru the Video Output port. A general block-diagram of the NGAVGS is shown below in Figure 6. The block diagram shows the basic components of the sensor, their functions, and the general I/O of the sensor.

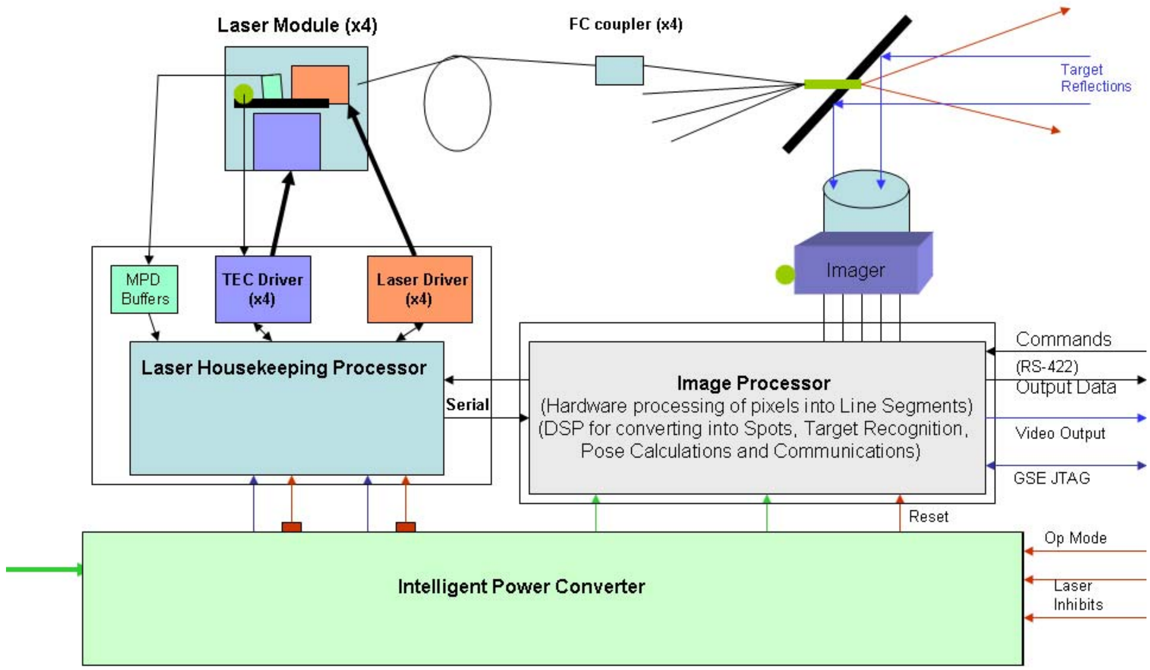

Figure 6. NGAVGS block diagram.

A breadboard version of the NGAVGS was built initially to test the new components that were chosen to replace the obsolete components. Once the breadboard had been successfully tested, two brassboard versions of the NGAVGS were built.

Part of the challenge of upgrading a well performing sensor is confirming any performance changes to the new sensor due to parts that have different performance or configuration. With a new imager and lens as well as a change in the laser illumination system, the resolution and exposure parameters of the new sensor needed to be verified with either old or new target configurations. For the NGAVGS, the Orbital Express Short Range Target and Long Range Target filtered reflectors (OE SRT & LRT reflectors) were selected for the 1 to 200m docking range and two International Space Station (ISS)-like hemi-spherical un-filtered reflectors were selected for use in berthing approaches from 5000m into 4m.

SENSOR DEVELOPMENT

Building on the AVGS laser illumination and imaging technology, the NGAVGS consists of two sets of laser diodes which operate at nominal wavelengths of 806 nm and 845 nm, 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 retro-reflective target. The target generally has filters that allow one wavelength of AVGS laser to pass through, while blocking the other wavelength. That arrangement causes reflections from the target to occur when one set of lasers is illuminating it, but not when the other set is. The target retro-reflectors are arranged in a pattern known to the AVGS software. The sensor fires the lasers that are passed by the filters and captures an image, and then it fires the second set of lasers and captures a second image. When this second image is subtracted from the first image and an intensity threshold is used, virtually all of the background clutter is eliminated. The remaining lit pixel 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 is found, the software computes the relative position and attitude between the target and the sensor. This data is output from the sensor and fed to the spacecraft Guidance and Navigation System. Figure 7 shows a picture taken down the 300 meter tunnel with the lights on and the lasers in the background mode. Figure 8 shows the same lights on but with the lasers in the foreground mode. Figure 9 is the image in Figure 7 subtracted from the image in Figure 8, showing how the extraneous light is removed and the two-spot target becomes clearly visible.

Figure 7. Background image (lights visible) with target at 300 meters.

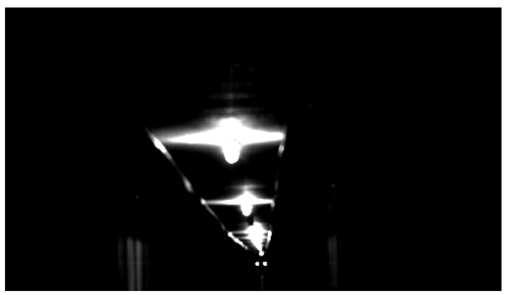

Figure 8. Foreground image (lights visible) with spots visible.

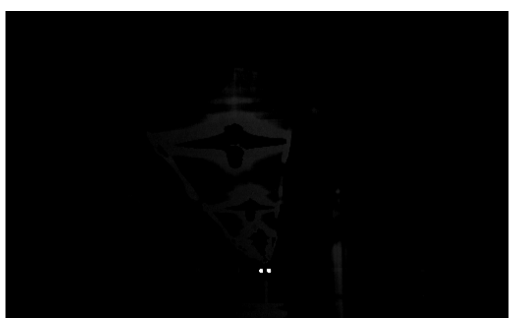

Figure 9. Subtracted image of target at 300 meters (background lighting eliminated).

As an in-house project, the NGAVGS hardware and software design work was performed by MSFC Engineering Directorate personnel. An initial study was conducted internally by the NGAVGS team in late 2006 to assess 13 different configuration options for the NGAVGS. The recommendation resulting from this trade was a two box configuration. There would be a remote camera head that would be relatively inexpensive and would be mounted outside the spacecraft and then there would be a laser/electronics box that could be internally mounted in the spacecraft to provide radiation protection and a better thermal environment. An NGAVGS brassboard was built based on this configuration, with two different imaging heads to allow for side-by-side performance comparison, and it is depicted in Figure 1.

The baseline NGAVGS performance requirements are similar to the OE AVGS requirements with regard to range of operation and accuracy (+/- 13mm range, +/- 0.033 degrees bearing, +/- 0.3 degrees attitude at docking ranges), but it must be noted that the sensor performance depends heavily on the target configuration used. The NGAVGS, like its predecessors, looks at the spots of light generated by illuminating a retro-reflective target. The accuracy at which the sensor tracks those spots is a function of reflector size, range, and position in the Field of View.

There are several modes of operation for the NGAVGS. The primary NGAVGS modes of operation, based on the OE AVGS modes are as follows: 1) Standby (in which the sensor sends out status messages while awaiting further commands), 2) Acquisition (in which the sensor is commanded to actively seek a target and go into Tracking once a valid target is found), and 3) Tracking (the sensor is actively tracking a target that was found during Acquisition). Other modes of operation include the Spot mode (which allows all of the operating parameters to be varied as desired) and Reset mode (which goes through an initialization sequence and automatically transitions to Standby).

An initial application for rendezvous and docking sensor technology for the space station will be on COTS. COTS will be able to re-supply the ISS and it could utilize ISS/JEM and Node 2 hemispherical targets to guide the approach and station-keeping. The NGAVGS will be able to guide a spacecraft into range to support berthing applications with ISS using the existing ISS Long Range Targets (LRT). As the ISS does not currently have Short Range Targets (SRTs), SRTs would need to be located on the ISS prior to docking applications. An SRT consists of a pattern of retro-reflectors designed to be used from docking range (around 1 meter) out to 15 to 30 meters (depending on the GN&C system requirements). The SRT shown in Figure 10 is the same size as that used on the OE mission. The AVGS could track that SRT and take relative position and attitude measurements from 1 meter out to 30 meters (demonstrated on orbit as well as in the laboratory.) MSFC has performed numerous target developments and in a new application, a target layout would need to be configured in coordination with the target geometry that would be programmed into the NGAVGS software/firmware. Testing would need to be completed prior to integration with ISS (or any other target spacecraft). ISS hemispherical retro-reflector and an SRT are shown together in Figure 10 below and are utilized in the NGAVGS Optical Characterization Tests (OCTs). Target development is key to the successful use of a sensor for AR&D. For each Constellation Design Reference Mission (DRM), target layout needs to be assessed and tested because it is integral to the sensor’s performance (and important to the performance of any active optical sensor).

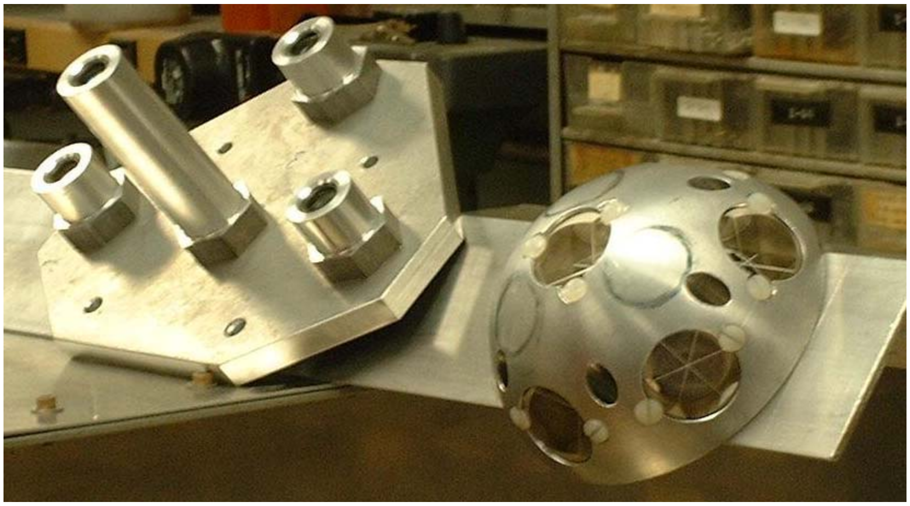

Figure 10. ISS Hemispherical target (right) with AVGS Short Range Target (left).

NGAVGS TESTING

The first brassboard was used for testing from ranges of 1 meter to 300 meters (the length of the test tunnel). The initial testing consisted primarily of imaging different retro-reflective targets at various ranges and angles to determine the probable overall performance of the initial NGAVGS. The results were that the sensor could see the two separate retro-reflectors at up to 300 meters with a wide variety of integration times and target tilt angles.

The close-range testing with the OE SRT occurred in the Flight Robotics Laboratory, which has a precise computer controlled a two axis sensor gimbal for sensor azimuth and elevation motion and a three axis target gimbal providing target pitch, yaw, and roll positioning. The repeatability and convenience of this testing capability is used for initial focus, alignment, resolution, and exposure parameter testing for various target angles in the center, edge, and corner of the sensor field of view from 1m out to 100m.

The middle range testing occurred in the 300 meter tunnel facility which has undergone renovations and upgrades of its own to turn it into a closed-loop computerized test capability. The Apollo-Saturn-era 300 m underground cable tunnel was cleared of 11,000 ft of cable trays and 200,000 to 300,000 ft of multi-conductor instrumentation cable. A four axis Remote Automated Target Transport (RATT) was designed and built. The RATT positions target mockups with desired yaw, pitch, and roll angles and at positions from 5 to 300m in front of the sensor. The sensor can be mounted on a two axis gimbal for testing any portion of the sensor's field-of-view. This facility is controlled by a computer that can move all six axes (range, azimuth, elevation, yaw, pitch, and roll) from static position or rate commands, multi-axis multi-step automated scripts, and simple sensor driven closed-loop dynamic testing. The middle range testing was performed with various retro-reflectors – an OE type SRT, 1.5 inch diameter OE corner-cube retro-reflectors, and a pair of ISS- like hemispherical arrays of seven 1-inch diameter retro-reflectors spaced apart similar to the pair on the bottom of the Japanese pressurized ISS laboratory module, as seen on the top in Figure 10. Figure 11 below shows all of the different targets mounted on the RATT in the 300 meter tunnel. Notice the lights along the ceiling – those are the constant light sources visible in Figures 7 and 8.

Figure 11. Two ISS-like hemispherical retro-reflectors, OE SRT (bottom left), and 1.5 inch diameter single retro-reflector (bottom right).

The second brassboard was used for testing at very long ranges (from 300 meters to 3000 meters). Because there were no available indoor test ranges with the distances required, this testing had to be performed outdoors. Prior to performing the outdoor testing, permission had to be acquired from the Army Redstone Arsenal and from the Federal Aviation Administration (FAA). The very long range testing used Apollo-Saturn-era test stands and towers and the surrounding roadways. This very long range testing was performed with the new sensor and an AVGS EDU shooting out of the eleventh floor window at the top of a test tower and an ISS- like hemispherical array of seven 1-inch diameter retro-reflectors mounted on the elevated handrail of a Saturn 5 engine test stand about 2000m south of the test tower and another hemi reflector array mounted on the elevated handrail of a Saturn 1 booster test stand about 3000m south of the test tower shown in Fig 12.

There was some definite atmospheric interference that caused the spots to vary in intensity and size for both the new sensor and the baseline sensor - the AVGS Engineering Development Unit (EDU). Spot varied from nothing being visible to a good, bright spot of about 15 pixels. The humidity was greater than 80%, and the high humidity and the dense air caused the atmosphere to interfere with the laser output and the return signal. At 2000 m, the new sensor saw the reflector array with just two lasers at about the same integration time as the AVGS EDU. However, to see the 3000 m reflector, the new sensor had to have the maximum integration time, which was several times longer than for 2000 m, to clearly see the spot in the center or the edge of the field of view, possibly due to atmospheric conditions or unknown sensor behavior. Successful integration times for 2000 meters were from 8.8 ms and longer, while at 3000 meters, the sensor only produced spot images at integration times of 65 ms (near the maximum integration time the sensor could handle).

Figure 12. View of 2 km and 3 km target stands from test-tower window.

Based on the initial brassboard tests, lens and laser changes were evaluated in the brassboard and an engineering unit was designed to meet specifications that were based on the Advanced Video Guidance Sensor performance specifications. A brassboard was first built with the updates to the lasers and lens as well as a higher resolution imager, and it was tested at ranges of 3000, 4000, and 5000 meters. Prior to retesting the unit at 3000+ meters, a second hemi reflector array was mounted, to allow range measurements also.

At 3000 meters, the atmospheric conditions were very good, and the sensor could track the target quite well. Both the Star-250 and the Star-1000 imagers were tested, and they measured (on the average) ranges within 50 meters of the true range. The standard deviation of the lower-resolution imager was 75 meters, and the standard deviation for the higher-resolution imager was 33 meters. The bearing data was extremely stable, with standard deviations of only 0.002 degrees in azimuth and elevation.

The target at 3000 meters in Figure 12 became the target used at 4000 meters when the sensor was tested from the roof of a different building. Images taken from the sensor during testing with targets at 4 km is shown in Figure 13. Despite the number of street lights and the occasional car, the target spots were clearly visible after the background was subtracted out. The results of the testing were positive. The sensor could detect two separate retro-reflectors at each range, it could give a range and bearing reading, and there was laser power and exposure time to spare. The laser power was set to maximum, but the sensor could see the retro-reflectors even when only one laser was actually used. That means that there is margin in the optical power of the sensor, and it means that the sensor could probably operate at even longer ranges were that a requirement.

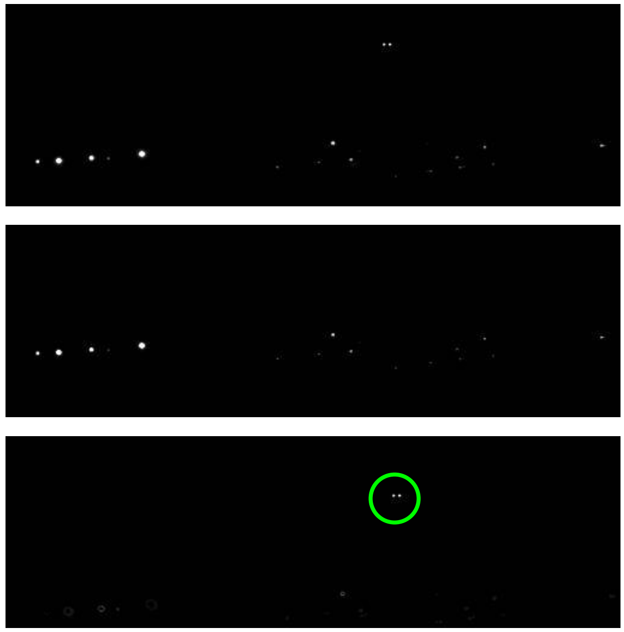

Figure 13. Foreground image (top), background image (middle), and subtracted image with target spots circled (bottom).

A picture of the target (on Hatton Mountain) at 5 km is shown in Figure 14. The picture was taken by the NGAVGS during the daytime, and the actual target is not visible in the picture (the target appears very small when it is 5 km away.) The testing was mostly successful. There was a great deal of atmospheric disturbance, causing wide variations in the return spots, but the sensor could image two individual spots and did intermittently track the target. Range values varied +/- 250 meters (with a static range of exactly 5000 meters) due to the atmospherically-caused noise.

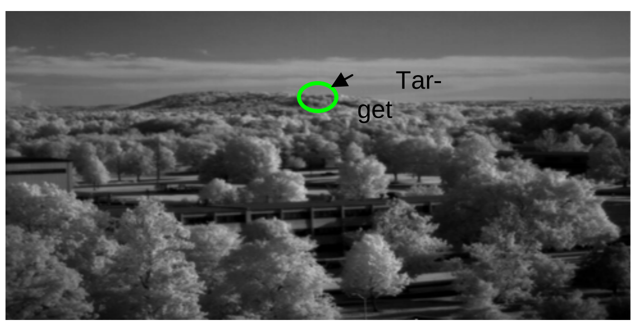

Figure 14. Image taken (using the NGAVGS) of 5 km target area during daytime.

During the course of the long range testing, an engineering unit was built. The engineering unit was the Block I prototype, and it was tested in the laboratory as well as in the long range test facility at 3 km. It also functioned well, demonstrating that it could see retro-reflectors at that long range, see two distinct retro-reflectors, and actually provide range and bearing data to a pair of retro-reflectors spaced the same distance apart as some of the retro-reflectors on the ISS.

CONCLUSIONS

The work performed in the design, development, and test of the NGAVGS has been quite successful. The hardware trades resulted in a promising design and the performance tests of the brassboards and prototypes have shown that the design was a good one. The NGAVGS has benefitted from the experiences gained from the successful OE AVGS and it is following in the footsteps of its successful progenitors, the DART AVGS and the VGS. The NGAVGS, with the ability to measure bearing out to 5 km and measure relative 6-DOF information at closer ranges, is able to support the Constellation and COTS programs as well as other systems requiring automated rendezvous and docking.

ACKNOWLEDGMENTS

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