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Simulation and Ground Testing with the AVGS

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ABSTRACT

The Advanced Video Guidance Sensor (AVGS), an active sensor system that provides near-range 6-degree-of-freedom sensor data, has been developed as part of an automatic rendezvous and docking system for the Demonstration of Autonomous Rendezvous Technology (DART). The sensor determines the relative positions and attitudes between the active sensor and the passive target at ranges up to 300 meters. The AVGS uses laser diodes to illuminate retro-reflectors in the target, a solid-state imager to detect the light returned from the target, and image capture electronics and a digital signal processor to convert the video information into the relative positions and attitudes. The development of the sensor, through initial prototypes, final prototypes, and three flight units, has required a great deal of testing at every phase, and the different types of testing, their effectiveness, and their results, are presented in this paper, focusing on the testing of the flight units. Testing has improved the sensor's performance.

Keywords: Automated Rendezvous and Docking, video guidance sensor, AR&C, AR&D, VGS, AVGS

1. INTRODUCTION

The Advanced Video Guidance Sensor (AVGS) was developed as a follow on sensor that was to improve on the Video Guidance Sensor (VGS). The basic hardware design (both optical and electronic) showed great promise, but the design had to be tested to ensure there were no hidden problems and that the actual performance was comparable to the predicted performance. The continuous testing of the AVGS led to greater understanding of its capabilities as well as its limitations. After testing at each stage of development, the sensor's design was improved, and a new unit was built, culminating in the flight units.

The AVGS is a sensor designed to acquire and track up to two targets at ranges from ½ meter out to 300 meters. The sensor tracks targets that consist of corner-cube retro-reflectors with a filter that passes 848 nm light and absorbs 808 nm light. The target used for the Demonstration of Autonomous Rendezvous Technologies (DART) has a Long Range Target (LRT) and a Short Range Target (SRT), each of which has three retro-reflectors in a line with the center retro-reflector mounted on a pole (to allow small pitch and yaw angles to be measured.) The sensor illuminates the target with 848 nm light and takes a picture, then illuminates the target with 808 nm light and takes another picture. The second picture is subtracted from the first picture, and a threshold is subtracted from that value to leave pixels that (mostly) belong to the retro-reflective target (see Figure 1). These target spots are processed, and the information from the spots is used to compute the relative position and attitude between the target and the sensor. This information is sent out through a serial data port. The sensor's field-of-view is 16 degrees by 16 degrees. The operation of the sensor is described in more detail in the papers on the VGS[1,2,3] and on the AVGS[4].

One of the challenges to making the sensor work to its full capability was the fact that the sensor's laser output is in a Gaussian beam that drops to about 1/6 power in the corners of the field-of-view (FOV), and the retro-reflective targets return less light as they are tilted away from the sensor. The AVGS can track targets at up to a 50 Hz internal rate, but to save power, it can also track at a 10 Hz rate. The data from two track cycles is averaged together and then sent out serially at 25 Hz or 5 Hz (depending on the rate chosen.)

The testing of the AVGS was vital to its successful development. The AVGS is to fly as a part of DART on April 15, 2005. The AVGS will be the proximity sensor used for the final 300 meters of the approach of the chase vehicle to the target vehicle, a MUBLCOM satellite that was launched in 1999. This target was launched with a modified VGS target mounted on the side. This target is now referred to as the MUBLCOM target (see Figure 2).

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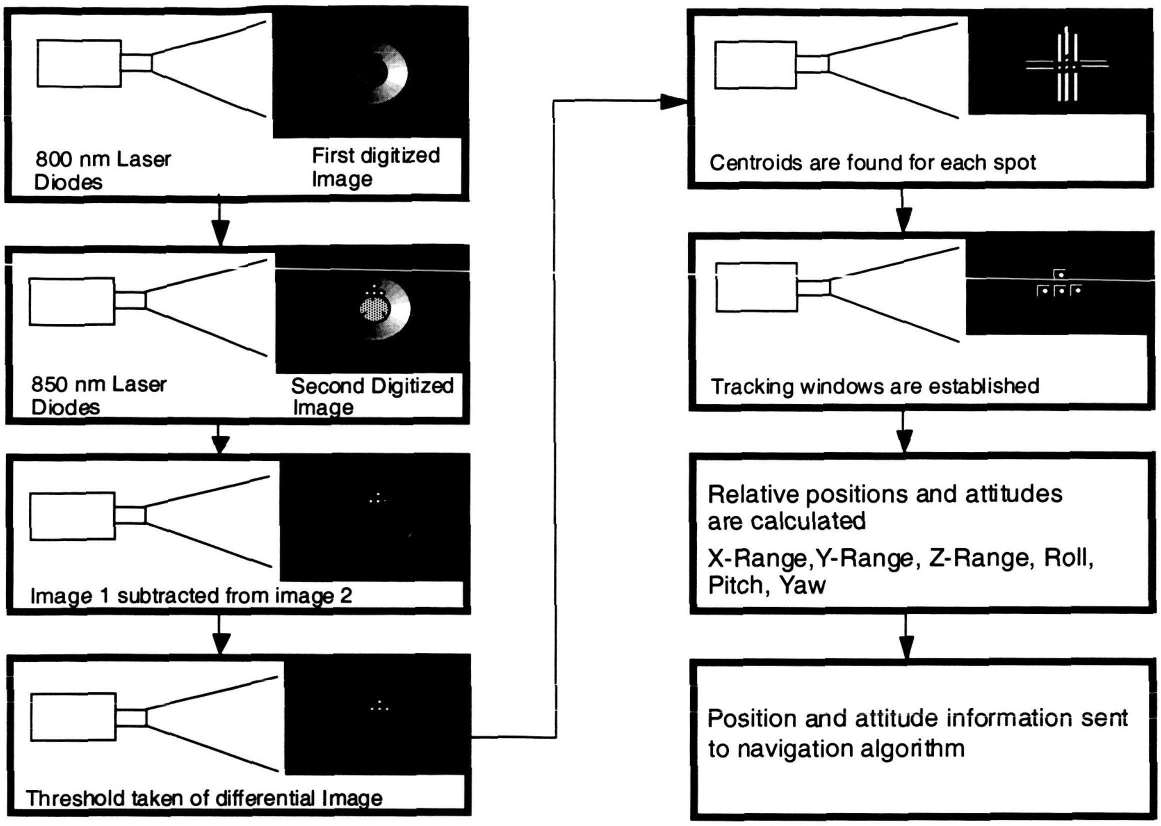

Figure 1: General processing flow of the Advanced Video Guidance Sensor

The testing began with the breadboard, which demonstrated that the expected performance was achievable. The Initial Prototype was designed and built as a complete sensor, and it allowed the initial development of software to be built. This unit was followed by the Final Prototypes (unit that were to be just like the flight units.) These were used to continue testing and software development. Finally, the first flight unit was delivered in January, 2004. Serial Number 2 (SN2) was that first flight unit, and it went through the most extensive tests on the ground, paving the way for the actual flight units (SN3 and SN4) that would follow. Once the actual flight units had passed their EMI and thermal vacuum tests, further testing was focused on the measurement of the optical characteristics and the actual performance (including performance under solar lighting conditions).

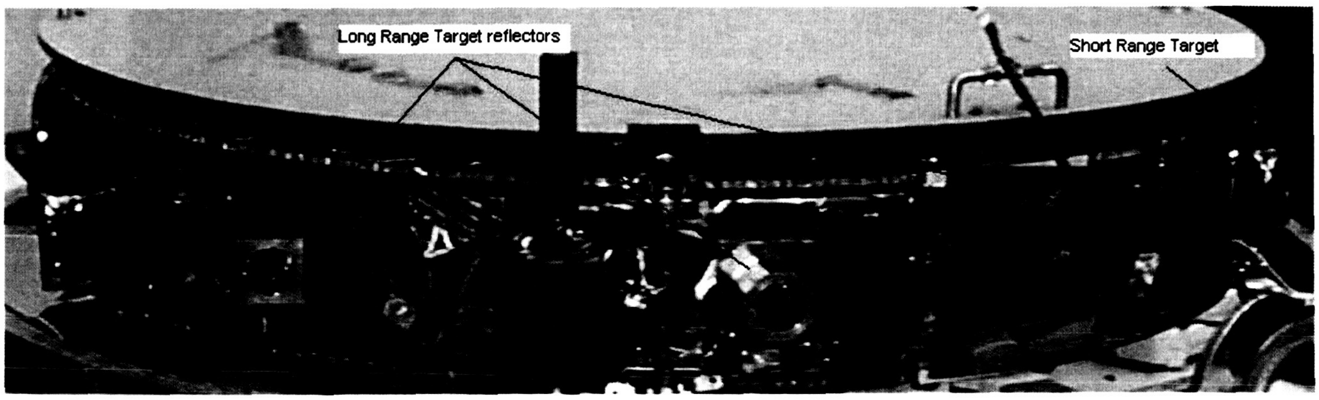

Figure 2: MUBLCOM target

The whole test effort for the different units included characterization of the optical performance with a duplicate of the intended target, thermal vacuum testing, performance tests in long range vacuum facilities, EMI/EMC tests, and performance testing in dynamic situations. The sensor has been shown to track a target at ranges of up to 300 meters, both in vacuum and ambient conditions, to survive and operate during the thermal vacuum cycling required by the DART mission, and to perform well in dynamic situations. More information about the testing can be found in a previous paper[4].

2. TYPES OF FLIGHT UNIT TESTING

Three flight Advanced Video Guidance Sensors were built: SN2, SN3, and SN4 (SN1 was canceled due to schedule and funding constraints.) Of these three, SN3 was designated as the flight unit and SN4 was designated the flight backup. SN2 and SN3 went through Optical Characterization Testing (OCT) in order to determine the laser powers, integration times, and thresholds that the software should use at each range of operation. Since there was some variation between the various units, each AVGS had to be characterized separately. After OCT was performed on the unit and the flight software was loaded, then the two designated flight units had to undergo performance testing to ensure that they met the specifications in the requirements documents (ranges, accuracies, and noise across the FOV). In addition to the performance testing, one of the flight units was tested using solar light at specified angles in order to prove that the sensor could still function properly with the Sun one degree outside of the sensor's FOV.

The OCT testing consisted of first measuring the laser output power of the AVGS versus the commanded input power. Those measurements were then used to compute a 3rd order polynomial that governed the laser power versus the range from the sensor to the target. The threshold was fixed at a value of 90 for the entire set of ranges (a value that had been arrived at after much testing – this value ensured that there was no noise from external sources and yet the target spots were clearly visible to the sensor.) Then, at a series of ranges from 5 meters out to 100 meters, the sensor was run through a series of pre-generated scripts after first aiming the sensor such that the target was in a corner of the FOV and the target was tilted at 25 degrees to the sensor (causing the least amount of light to be returned to the sensor). The scripts would fire the lasers at the commanded level for an increasing amount of integration time (essentially keeping the shutter open for longer and longer exposure times.) This data was analyzed, and the lowest integration time for which the full target could be acquired was chosen as the best value for that range. Due to the fact that there was some variation in performance over time, the entire procedure was run twice and the results were averaged. From 100 to 300 meters, the procedure was modified slightly – the target was placed in the center of the FOV, and an average between the lowest working integration time and the highest working integration time was picked as the best choice for that range. After the ideal integration time (IT) was chosen for a range, the unit was commanded to acquire and track the target (using the newly discovered IT), and the sensor was pitched and yawed to cause the target to go across the entire FOV. A sample FOV plot from the 100 meter data is shown below in Figure 3. The points at which the target tracked the sensor are in blue – as can be seen, the sensor tracked the target across the entire FOV except for the very corners, which are outside of the required tracking envelope. The FOV test was used to make sure the choice of IT was indeed good.

Once the entire range of integration times was found from the OCT, the data would be used to generate two different 3rd order polynomials that the sensor would use at ranges < 100 meters and ranges > 100 meters. The polynomials were chosen to create a smooth transition at 100 meters. This polynomial was then put into the flight software. The completed flight software was then used for the Tracking Performance Tests. The Tracking Performance Tests were performed in order to quantify several measures of the sensor's performance, such as the noise levels of the sensor at different ranges, angles, and target attitudes. These tests consisted of running the sensor in Track mode at approximately 25 different combinations of target azimuth, elevation, and attitude as well as running some special tests to determine the bounds of the sensor's performance. The special tests were different types of field-of-view tests in which either the sensor or the target was pitched and yawed to determine the maximum angles at which the AVGS could still track the target at the range under test. The Tracking Performance Tests were run at 10 different ranges, from 4 meters out to 300 meters. The tests were performed in two parts: the long range tests (from 15 meters out to 300 meters) were performed in a cable tray tunnel in MSFC's test stands, and the short range tests (from 15 meters in to 4 meters) were performed in the Flight Robotics Laboratory at MSFC.

The sensor accuracy specifications for range, azimuth, elevation, roll, pitch, and yaw are shown below in Tables 1 and 2 (taken from the document K60001 Rev E - Advanced Video Guidance Sensor (AVGS) Specification).

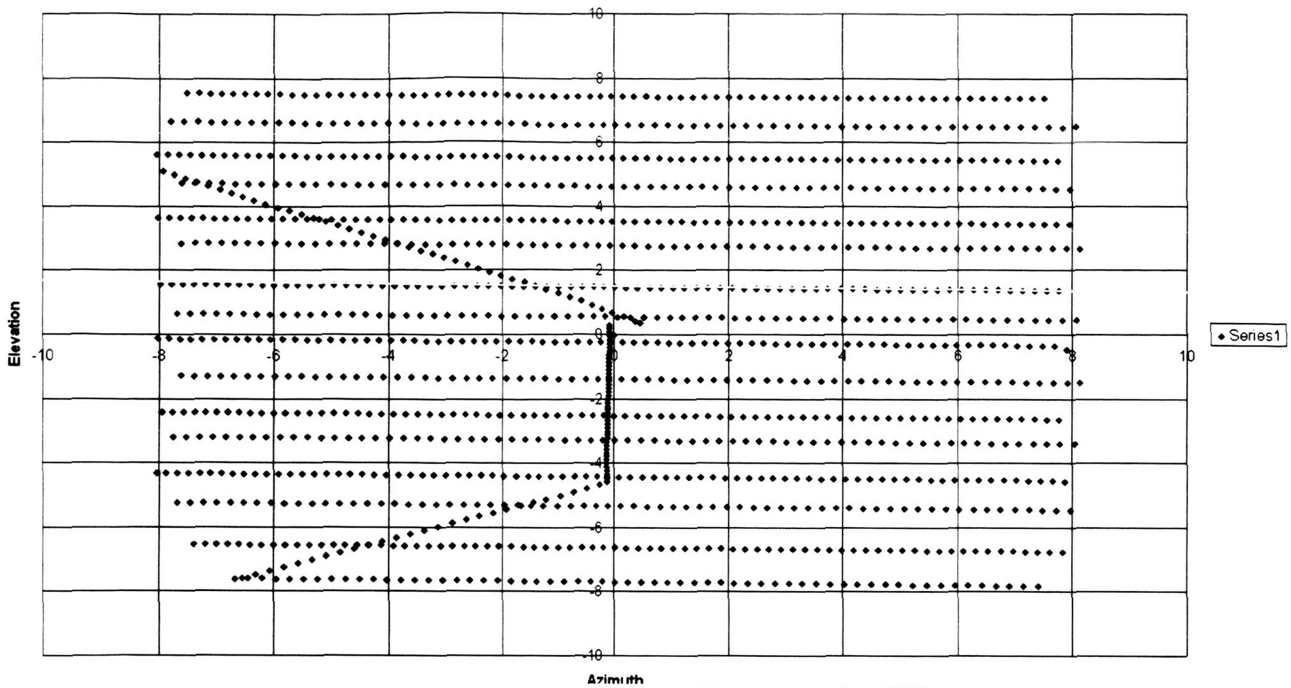

Figure 3: Plot of FOV test at 100 meters using SN3

TABLE 1: AVGS MODIFIED MUBLCOM MEASUREMENT ACCURACY REQUIREMENTS

Operating Range (m)	Range Overall Mean Accuracy (mm)	Range RMS Noise About The Mean (mm)	Azimuth, Elevation Mean Accuracy (Radians) {Degrees}	Azimuth, Elevation RMS Noise About The Mean (Radians) {Degrees}
1 – 3 (SR)	±12	±5	±0.0052 {±0.3}	±0.000058 {±0.0033}
> 3 – 5 (SR)	±35	±15	±0.0052 {±0.3}	±0.000058 {±0.0033}
> 5 – 10 (SR)	±150	±75	±0.0052 {±0.3}	±0.000061 {±0.0035}
> 10 – 15(SR)	±1500	±500	±0.0052 {±0.3}	±0.000065 {±0.0037}
> 4 – 30(LR)	±500	±10	±0.0052 {±0.3}	±0.000047 {±0.0027}
> 30 – 50 (LR)	± 1100	±20	±0.0052 {±0.3}	±0.000052 {±0.003}
> 50 – 100 (LR)	±2200	±1300	±0.0052 {±0.3}	±0.000058 {±0.0033}
>100-300 (LR)	± 11,000	±4000	±0.0070 {± 0.4}	±0.000061 {± 0.0035}

TABLE 2: AVGS MODIFIED MUBLCOM MEASUREMENT ACCURACY REQUIREMENTS

Operating Range (m)	Roll Mean Accuracy (Radians) {Degrees}	Roll RMS Noise About The Mean (Radians) {Degrees}	Pitch/Yaw Mean Accuracy (Radians) {Degrees}	Pitch/Yaw RMS Noise About The Mean (Radians) {Degrees}
1 – 3 (SR)	±0.0088 {±0.5}	±0.00227 {±0.13}	±0.0349 {±2}	±0.001 {± 0.06}
> 3 – 5 (SR)	±0.0088 {±0.5}	±0.00436 {±0.25}	±0.0349 {±2}	±0.001 {± 0.06}
> 5 – 10 (SR)	±0.0088 {±0.5}	±0.00785 {±0.45}	±0.0349 {±2}	±0.001 {± 0.06}
> 10 – 15(SR)	±0.0088 {±0.5}	±0.02269 {±1.3}	±0.04363 {± 2.5}	±0.006 {± 0.34}
> 4 – 30(LR)	±0.0088 {±0.5}	±0.00262 {±0.15}	±0.0349 {±02.0}	±0.001 {± 0.06}
> 30 – 50 (LR)	±0.0088 {±0.5}	±0.00436 {±0.25}	±0.04363 {± 2.5}	±0.006 {± 0.34}
> 50 – 100 (LR)	±0.0088 {±0.5}	±0.00873 {±0.5}	±0.04363 {±2.5}	±0.040 {± 2.3}
>100-300 (LR)	±0.0088 {±0.5}	±0.02443 {±1.4}	±0.13090 {± 7.5}	±0.040 {± 2.3}

For the DART mission, the DART spacecraft would be commanded to approach the MUBLCOM no closer than 5 meters, so the Short Range Target (SRT) would not be needed for the entire mission. And since the SRT retro-reflectors had lenses in front, their optical performance was markedly different from the LRT targets. The decision was made to not even attempt to track the SRT target during the DART mission. This decision was made late in the program, so the SRT performance requirements were still in the specification document, but a waiver was generated to release the AVGS from its requirement to track the SRT and the LRT simultaneously.

The AVGS is required to operate (acquire and track the MUBLCOM target) within a conical FOV, and the radius of that cone gets smaller as range increases. Table 3 covers the FOV requirement for the AVGS. For the Tracking Performance Tests, in the interest of time, the FOV plot was performed in a windmill pattern, making sure that the edges (left, right, top, bottom, and each 45 degree angle) were checked. The FOV plots in Figures 4 and 5 show examples of the smaller coverage of the AVGS at longer ranges.

TABLE 3: AVGS FOV REQUIREMENT

Range	FOV
5-100m	10 degree radius
100-150m	8 degree radius
150-200m	7 degree radius
200-250m	6 degree radius
250m +	3 degree radius

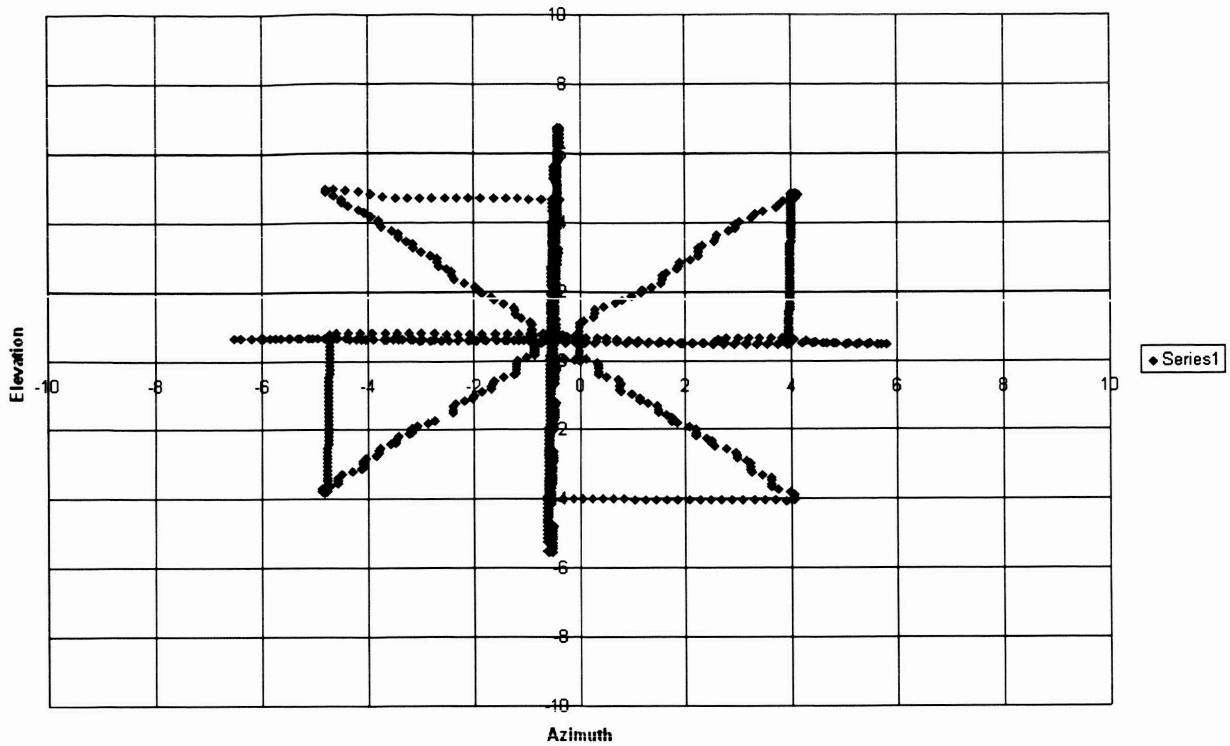

Figure 4: Tracking Performance Test FOV plot for SN3 at 200m

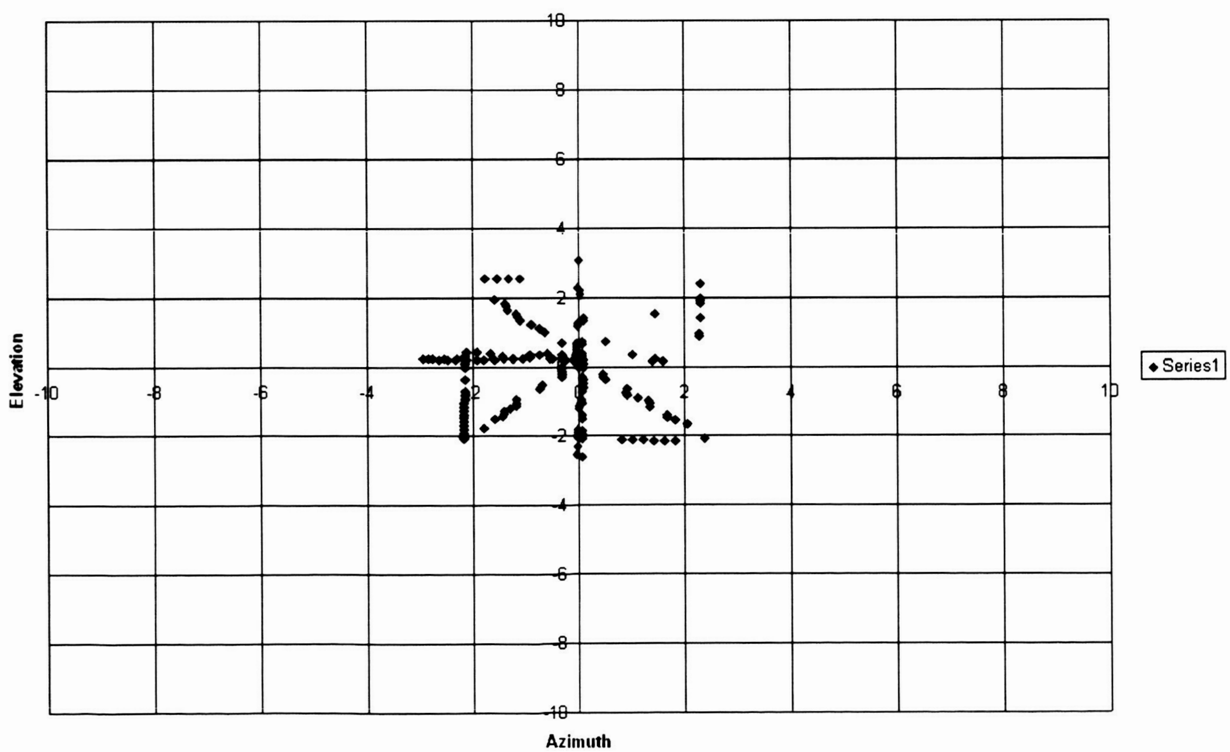

Figure 5: Tracking Performance Test FOV plot for SN3 at 250m – notice dropouts in tracking

The Tracking Performance Tests took static data, with the target at fixed positions and attitudes relative to the AVGS. The static data (approximately 600 samples per position) was used to compute means and standard deviations for demonstrating that the sensor met (or didn't meet) its performance requirements.

Solar testing was performed to ensure the unit could still track under the solar lighting conditions specified in the requirements document. A lamp whose output matched the Sun (in both intensity and spectrum) was set at the required angle relative to the lens aperture on the AVGS, and a target was placed in the AVGS FOV in order to test acquisition and tracking.

The final test performed with the actual flight unit was dynamic testing in Hardware-in-the-Loop (HWIL) simulations[6].

3. DATA AND RESULTS

3.1 OCT

The results of the OCT testing were ultimately a 3rd order polynomial describing the integration time used by the sensor as a function of range. The intermediate results of the testing are shown below in Table 4 for both SN3 and SN4.

TABLE 4: Integration Time Results from OCT of SN3 and SN4

OCT Range (m)	SN3 Integration Time (uS)	SN4 Integration Time (uS)
5	58	48
15	58	58
30	65	68
50	164	136
100	328	328
150	78	149
175	78	111
200	53.75	82.5
250	55.5	63
300	63	68

3.2 Tracking Performance Tests

This data is summarized (as Pass/Fail) in the table below (taken from an internal report on AVGS performance).

Table 5: Summary of analysis results.

Test Range	Pass/Fail	Pages
4m Fast Track FRL	PASS all 50 measurements	3-4
4m Slow Track FRL	PASS all 50	5-6
15m Fast Track FRL	**FAIL** – 2 Rolls of 50 measurements	7-8
15m Slow Track FRL	**FAIL** – 2 Rolls of 50 measurements	9-10
15m Fast Track	**FAIL** – 1 Roll, 1 Az of 50 measurements	11-12
15m Slow Track	**FAIL** – 1 Roll, 1 Az of 50 measurements	13
30m	**FAIL** – 1 Roll, 1 Range noise of 50 measurements	14-15
50m	**FAIL** – 1 Roll, 1 Az, 1 Range noise of 50 measurements	16-17
100m	**FAIL** – 1 Roll, 1 Range noise of 52 measurements	18-19
150m	PASS all 26 measurements	20-21
200m	PASS all 28 measurements	22-23
250m	PASS all 13 measurements	24-25
300m	PASS* – this range was waived	26-27

Note: SN003 is out of spec in the Roll axis – the imager is rolled 0.96 degrees relative to the case. This value was subtracted from each of the roll values measured during the tests.

Failure or Anomaly Summaries:

4-100m – Most of these failures were due to Roll being out of spec.

* **300m** – The Integration Time (IT) polynomial causes the IT to drop to zero at about 270 meters, so no range past 270m will Acquire or Track. This is acceptable according to the FOV waiver T813-760-D-002.

3.3 Hardware-in-the-Loop Testing

The unit worked well, allowing the DART mission to have all of its rendezvous and proximity operations performed successfully.

3.4 Solar Testing

The AVGS could acquire and track targets from close range out to about 40 meters (the limit of the facility during this test) despite having solar-equivalent light illuminating the face of the sensor at an angle just outside the sensor's FOV.

4. CONCLUSIONS

Testing is vital to the development and characterization of hardware. The tests performed on the AVGS during its various stages of development helped define its performance and show its limitations as well as uncover unexpected pitfalls. The behaviors uncovered during testing have helped improve the overall sensor performance and robustness. Extensive testing should be performed whenever possible in order to improve the unit under development.

ACKNOWLEDGMENTS

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ACRONYMS AND ABBREVIATIONS

AR&C/D/M	Automatic Rendezvous & Capture/Docking/Mating
AVGS	Advanced Video Guidance Sensor
DART	Demonstration Automatic Rendezvous Technology
DOF	Degrees of Freedom
DOTS	Dynamic Overhead Target Simulator
FP	Final Prototype
FRL	Flight Robotics Laboratory
GN&C	Guidance Navigation and Control
GPS	Global Positioning System
HWIL	Hardware-in-the-Loop
IP	Initial Prototype
ISS	International Space Station
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OCT	Optical Characterization Testing
SN	Serial Number
STS	Space Transportation System
VGS	Video Guidance Sensor
XRCF	X-Ray Calibration Facility

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