DART AVGS Performance

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ABSTRACT

The Advanced Video Guidance Sensor (AVGS) was designed to be the proximity operations sensor for the Demonstration of Autonomous Rendezvous Technologies (DART). The DART mission flew in April of 2005 and was a partial success. The AVGS did not get the opportunity to operate in every mode in orbit, but those modes in which it did operate were completely successful. This paper will detail the development, testing, and on-orbit performance of the AVGS.

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

1. INTRODUCTION

The value of using sensors to automate rendezvous and docking of two spacecraft together has been recognized for decades, and although NASA has yet to demonstrate Automated Rendezvous and Docking (AR&D) operations in orbit, other nations have developed automated systems to support Space Station assembly and re-supply spacecraft, including Russia, Europe, and Japan. The challenge ahead of everyone developing automated rendezvous and docking vehicles is the development and thorough testing of their sensors and the integrated GN&C systems and operations. NASA recognized the value of the Video Guidance Sensor (VGS) to automate the guidance into docking mechanisms during the 1990's short lived Automated Rendezvous & Capture Project and flew the VGS proto-flight docking sensor on Space Shuttle Missions STS-87 and STS-95 in conjunction with the Rendezvous and Proximity Operations Display (RPOD) and used the integrated sensor and display to perform the retrieval of the Spartan 201 spacecraft. After the successful operation of the VGS, Defense Advanced Research Projects Agency requested help from NASA in placing VGS compatible retro-reflectors on the MUBLCOM (along other reflectors) in the ten weeks before its shipment for launch in 1999. The target devised for MUBLCOM had three Long Range Target (LRT) retro-reflectors on the rim of the MUBLCOM with the center one in front of the outer two and a Short Range Target (SRT) which has three retro-reflectors in a line with the center retro-reflector mounted out in front (to allow small pitch and yaw angles to be measured.) (See Figure 1)
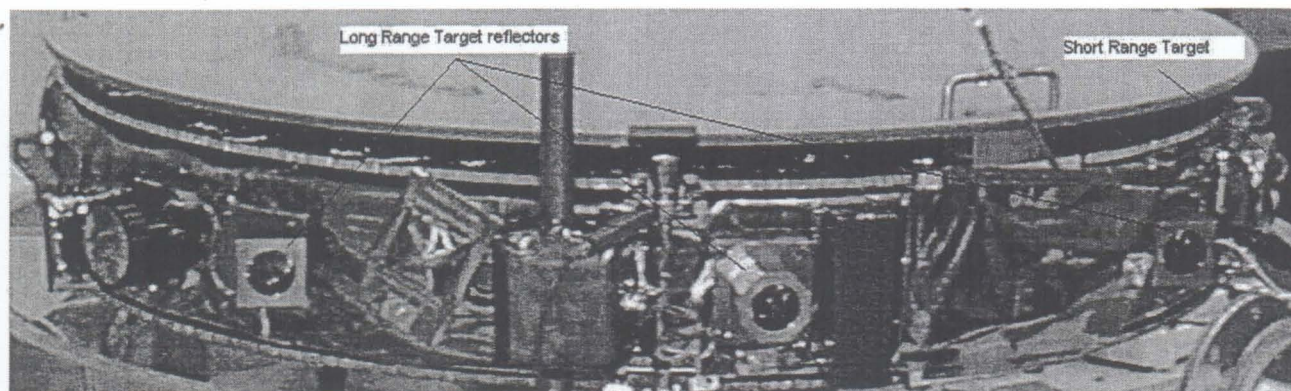

Figure 1: MUBLCOM target

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In 2001, Orbital Sciences proposed a low cost Class D flight experiment to fly up to MUBLCOM in its polar orbit in a Demonstration of Autonomous Rendezvous Technology (DART) using GPS receivers on both vehicles and left-over VGS sensors from the Shuttle. The Mission Objectives of DART included: (1) Transfer from Pegasus parking orbit to MUBLCOM orbit; (2) Approach MUBLCOM into 50 ft on V-bar; (3) Station-keep at 50 ft from MUBLCOM; (4) Depart safely from MUBLCOM; (5) Perform a retirement burn for re-entry in less than 25 years. This quickly changed when it was realized that the Spare VGS was the only unit that could be flown safely and the VGS unit that had already flown on the Shuttle twice could not be relied upon as a spare. The DART project decided to develop the Advanced Video Guidance Sensor (AVGS) as a follow on sensor to improve on the Video Guidance Sensor (VGS).

The initial AVGS design (both optical and electronic) was basically sound, and it was developed through various bread-board, brass-board, and prototype configurations before the flight units were built and tested extensively to ensure there were no hidden problems and that the actual performance was comparable to the predicted performance[6]. The AVGS was launched as the proximity operations sensor mounted on the front of the DART spacecraft in April of 2005.

The VGS and AVGS are sensors designed to acquire and track one or more patterns of retro-reflectors on another spacecraft at ranges from 1 meter out to 300 meters and calculate the relative position of the target. The sensor tracks targets that consist of corner-cube retro-reflectors with a filter that passes 850 nm light and absorbs 800 nm light. To sense the filtered reflectors, the sensor illuminates the target with 850 nm light and takes a picture, then illuminates the target with 800 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 2). 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. In addition to Tracking the target, while in Acquisition mode (hunting a target), and in Spot mode (a primitive mode with user-selectable laser powers and exposure times), the AVGS sensor sends out data about every spot that is within its field-of-view. This Spot mode data turned-out to be invaluable during ground testing and during flight. The operation of the sensor is described in more detail in the papers on the VGS[1,2,3] and on the AVGS[4].
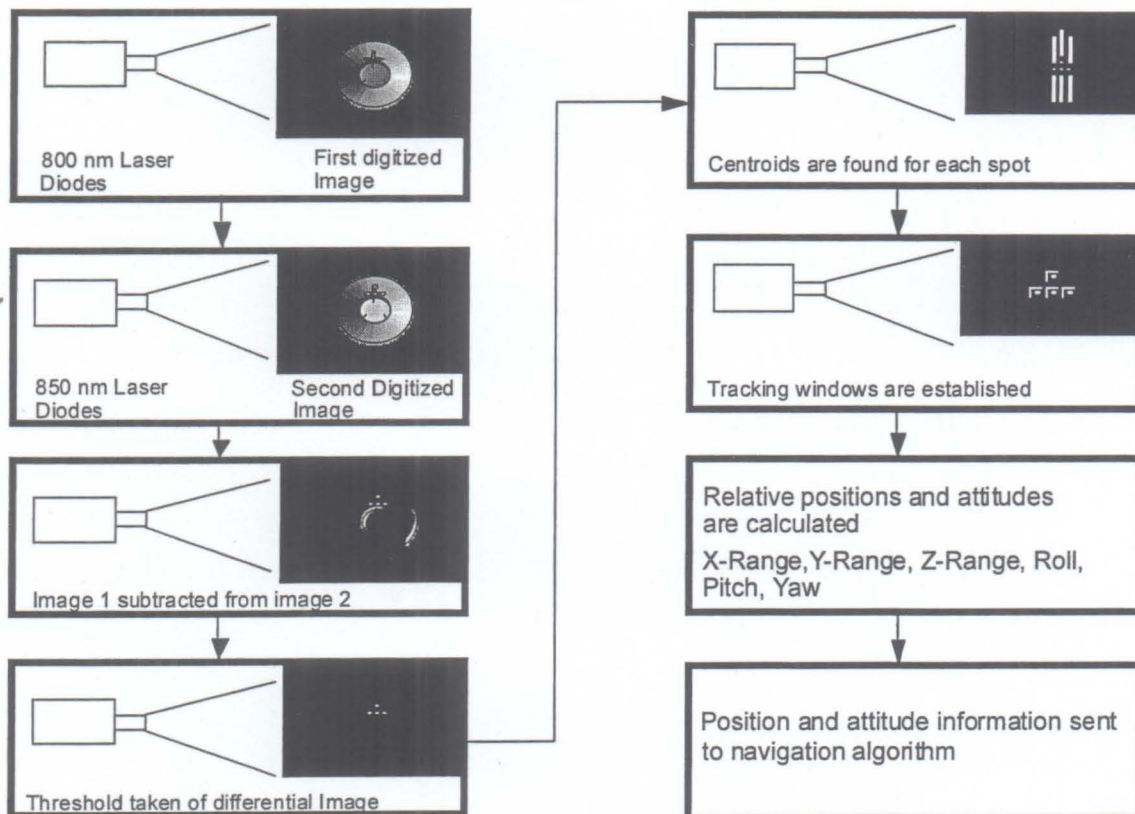

Figure 2: General processing flow of the Advanced Video Guidance Sensor

1.1 DART AVGS Goals, Requirements, Development, and Changes

When the VGS was replaced by the AVGS, three areas of improvement were higher speed, smaller volume & power, and longer range, with a goal of transforming the AVGS into a commercial product. MSFC contracted a local electro-optical systems company to build a breadboard of the AVGS while MSFC and Orbital Sciences worked on the requirements and the flight hardware transition. The breadboard consisted of a high-speed 1 Mega-pixel CMOS imager, a 12° x12° FOV imager Lens, a pierced mirror for injecting the laser outputs into the optical path to the target for mono-static return, 808nm & 940nm lasers, and a 14° fiber-optic guide for the lasers. This breadboard was used to estimate performance for the AVGS Specification before changing the fiber-optic guide/multiplexer FOV, switching the 940nm to 850nm lasers, and changing the Imager lens to 16° x 16° FOV. Also the DART Project put a "To Be Confirmed" 300m MUBLCOM tracking range requirement, a minimum spot size of 2-3 pixels, and the diagnostic Spot mode as a flight mode in the AVGS Specification. Each of innocent changes from the breadboard and the VGS specification would prove either challenging or redeeming later for DART.

One of the challenges to making the Proto-flight AVGS 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. This "dim Corner" problem may be traced back to changes in the lasers, the fiber-optic guide/multiplexer, misconceptions of corner-cube performance, different definitions of numerical aperture, and the overall change of the AVGS FOV. This sensor performance deficiency decreased the AVGS FOV beyond 100m and required additional analysis and testing and a change to the AVGS Spec.

Another unfilled AVGS requirement was the simultaneous tracking of the MUBLCOM Long Range reflectors and the Short Range Reflectors within the same frame 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. Since DART would not approach within 5m of MUBLCOM, this made no change to the DART mission design but required a change to the AVGS Spec.

Likewise, the AVGS was never able track the MUBLCOM target mock-up at 300m with any target reflector mock-up or any sensor configuration, (including IP, FP, and Proto-flight units). This tracking limit may be tracked to the interaction of the target reflector spacing, the AVGS FOV, and the minimum spot size of 2-3 pixels that grew into a focus requirement for an infinity spot to cover 2x2 to 3x3 pixels with 90% of its power, insuring a blurred spot from a reflector out to 2-3 kilometers and a merged blob from the MUBLCOM at 300m even with a 1 Mega-pixel imager. This required changes to the GN&C software and the mission sequence and a waiver to the AVGS Spec.

The three problems above were observed and verified during the Final Prototype testing and the Proto-Flight calibration and testing plans were modified.

The testing of the AVGS was vital to its successful development allowing problems to be identified in time for hardware, software, or operational changes. The testing began with the breadboard, which demonstrated that most of the expected performance was achievable. The Initial Prototype (IP) 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 (FP) (units that were to be just like the flight units.) These were used to continue testing and software development.

2. TYPES OF PROTO-FLIGHT UNIT TESTING

Each of the proto-flight units went through a series of tests after assembly to first optically align the lasers, mirror, lens, and imager and determine various optical parameters such as imager X, Y, and Roll offsets, Lens distortion and FOV, pixel defects and laser output, wavelength, and misalignment. After each vibration, shock, thermal vacuum, EMI/EMC, or other factory test, and after each shipment, a Limited Alignment Test and /or a Limited Short Range Performance Test was run to check for any focus or imager shift or other failure. Once the proto-flight units had passed their factory

environmental tests, they were shipped to MSFC for further testing focused on the measurement of the optical characteristics and the actual static and dynamic performance (including performance under solar lighting conditions). 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. Additionally, SN2 underwent early EMI tests, performance tests in long range vacuum facilities, and performance testing in dynamic situations, demonstrating both long range and dynamic tracking of the MUBLCOM target reflector pattern. More information about the testing can be found in a previous paper[4].

Since there was some variation between the different Proto-flight units (due to variations in individual lasers, differences in imager sensitivity, etc.), each AVGS had to be characterized separately. After OCT was performed on each 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, the spare flight unit (SN#3) 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.

2.1 Optical Characterization Testing and Calibration

The OCT testing consisted of first measuring the laser output power of the AVGS versus the commanded input power. Once the laser current commands that corresponded to the 10% and 100% of the derated output power levels were determined, then a 3rd order polynomial was computed to control the laser power versus the range to the target (from 5m to 100m). Beyond 99m, the laser power was held at the 100% power level. 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 plot shows the points at which the target tracked the sensor, and 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, one for ranges < 100 meters and one for ranges > 100 meters. The polynomials were chosen to create a smooth transition at 100 meters. These laser and IT polynomials and optical parameters were then put into the flight software. The completed and calibrated flight software was then used for the Tracking Performance Tests.
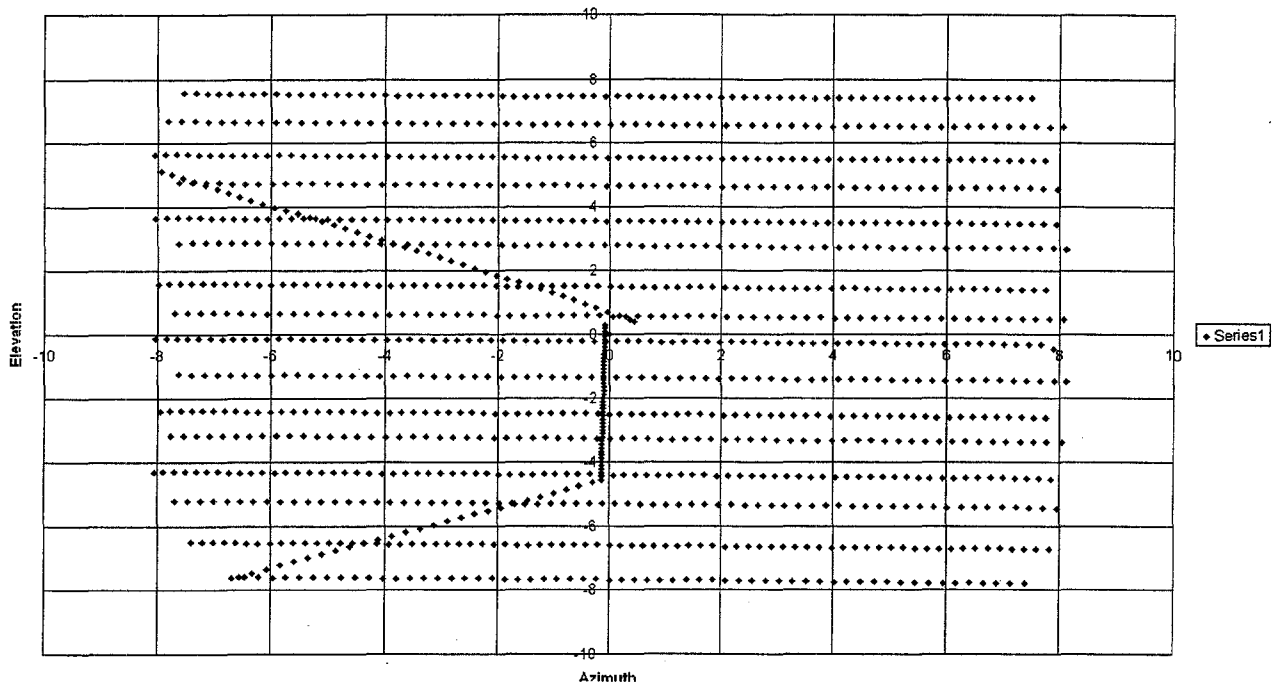
Figure 3: Plot of FOV test at 100 meters using SN3

2.2 Tracking Performance Tests

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 short range tests (from 15 meters in to 4 meters) were performed in MSFC's Flight Robotics Laboratory (FRL) and the long range tests (from 15 meters out to 300 meters) were performed in the 300m underground tunnel connected to NASA's Saturn 1 test stand.

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 and taking static data at four different combinations of target azimuth, elevation, and attitude as well as running some other tests to check the specified bounds of the sensor's performance. 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. This test data was also used for model development for GN&C and Vehicle level analysis and testing. Tables 1 and 2 shown below contain the sensor accuracy specifications.

The field-of-view was tested in various positions with either the sensor or the target pitched and yawed to determine the maximum angles at which the AVGS could still track the target at the range under test.

The Acquisition range tolerance was tested by setting the sensor to acquire the target at ranges of 80% and 120% of the actual range (the limits of the sensor specifications.)

Also, at several ranges from 50 meters out, the sensor was put into Spot mode and was scanned so the target went across the entire FOV (since part of the DART flight would use the sensor's Spot mode data.)

TABLE 1: DART AVGS POSITION MEASUREMENT ACCURACY REQUIREMENTS

Operating Range (m)	Range Overall Mean Accuracy (mm)	Range RMS noise About The Mean (mm)	Azimuth, Elevation Mean Accuracy (Degrees)	Azimuth, Elevation RMS Noise About The Mean (Degrees)
>4 – 30(LR)	±500	±10	±0.3	±0.0027
>30 – 50 (LR)	±1100	±20	±0.3	±0.003
>50 – 100 (LR)	±2200	±1300	±0.3	±0.0033
>100-300 (LR)	±11,000	±4000	±0.4	±0.0035

TABLE 2: DART AVGS ATTITUDE MEASUREMENT ACCURACY REQUIREMENTS

Operating Range (m)	Roll Mean Accuracy (Degrees)	Roll RMS Noise About The Mean (Degrees)	Pitch/Yaw Mean Accuracy (Degrees)	Pitch/Yaw RMS Noise About The Mean (Degrees)
>4 – 30(LR)	±0.5	±0.15	±2.0	±0.06
>30 – 50 (LR)	±0.5	±0.25	±2.5	±0.34
>50 – 100 (LR)	±0.5	±0.5	±2.5	±2.3
>100-300 (LR)	±0.5	±1.4	±7.5	±2.3

In addition to the accuracy and noise specifications, 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 circular FOV requirement for the AVGS (knowing that the available FOV is a 16 x 16 square).

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

Proto-Flight Unit Performance Testing Results:

SN003 is out of spec in the Roll axis – the imager is rolled 0.96 degrees relative to the case. The 0.96 degrees was subtracted from all of the roll measurements prior to analyzing them. Despite this, there were a number of cases that failed due to out-of-spec roll measurements. The failures were not very much out of spec, but they required a waiver in order to allow the AVGS to be accepted for flight.

> **15-100m** – Most of these failures were due to Roll being out of spec.
> **⁺250m** – The FOV test had intermittent dropouts, but it did track to the edges of the specified FOV.
> ***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.

Additionally, the Roll requirements are based on direct measurement from spot positions, and do not include the affect of conversions into and out of the Quaternion format used for the AVGS attitude outputs.

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 plot in Figure 5 shows an example of the smaller coverage of the AVGS at longer ranges.out of spec, and all of those at 50 meters and beyond
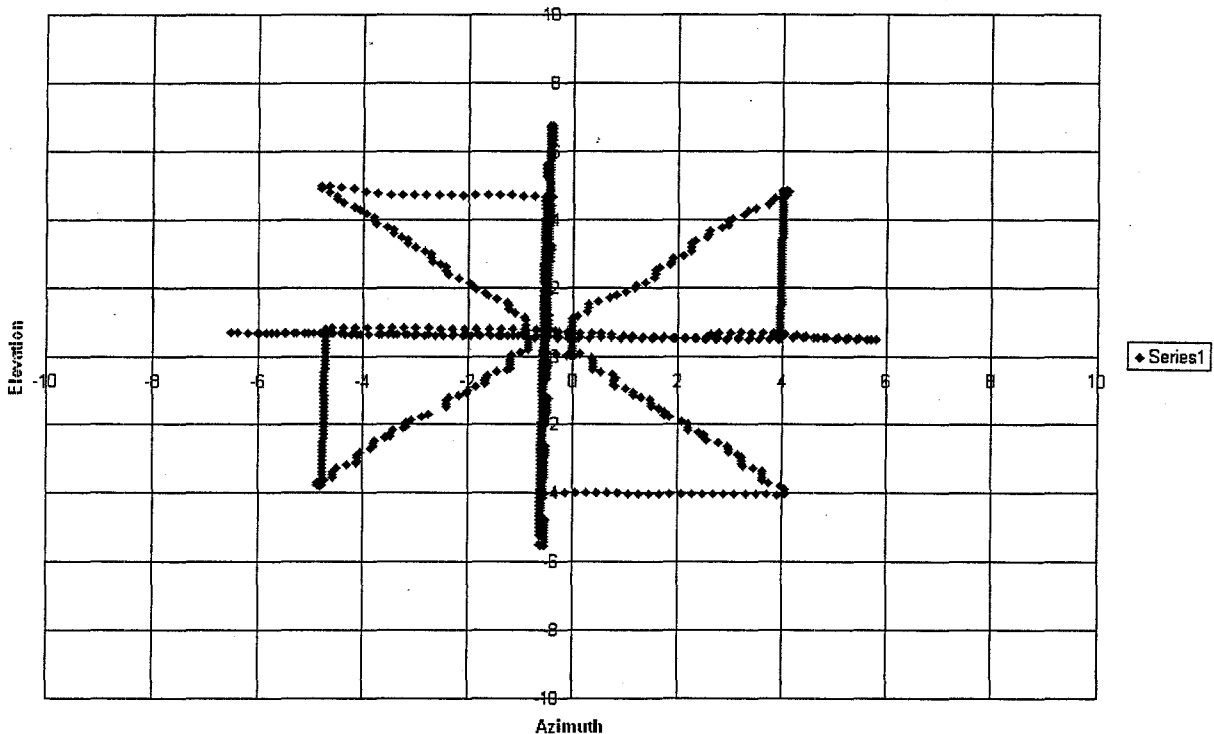
Figure 5: Tracking Performance Test FOV plot for SN3 at 200m

After its original lens was swapped out with a flight lens that not as close to designed lens prescription, SN4 performed even better and farther than SN3, only having three measurements.

2.3 Hardware-in-the-Loop Testing

One of the final tests performed with the actual flight unit was dynamic testing in Hardware-in-the-Loop (HWIL) simulations[5]. The flight sensor was connected to a flight computer from DART which generated DART thruster commands. The simulated thruster commands drove a dynamic model of the DART and the MUBLCOM vehicles and

the MSFC FRL overhead robot moved the MUBLCOM mock-up toward the AVGS in a closed-loop HWIL test. The unit worked well, allowing the DART mission to have all of its rendezvous and proximity operations performed successfully. The test was run several times with different aspects of the mission being simulated during each run, including sensor & return sensor dropouts and re-acquisition and collision avoidance maneuvers.

2.4 Solar Testing

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 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. At the right angle, a portion of the sensor's FOV was washed out by internal reflections of the solar light, but the unit could still acquire and track a target outside of that saturated area.

3. DART FLIGHT DATA AND RESULTS

On April 15, 2005 after a perfect launch, the Pegasus vehicle reached orbit and transferred control to the DART program that calculated and performed the orbital burns to successfully rendezvous with MUBLCOM in just over eight hours. Then the DART vehicle activated the AVGS in SPOT mode and started its forced approach toward MUBLCOM and determined it had run out of fuel and performed a retirement burn for re-entry in less than 25 years. Unknowingly, DART had flown past the planned 200m initiation range for AVGS Acquisition / Tracking and with only pointing data from AVGS, flown directly into MUBLCOM and knocked it into a higher orbit. The failure of the DART vehicle to complete any of its proximity operations with MUBLCOM before prematurely making its retirement burn resulted in the declaration of a Type A mishap and the convening of the DART Mishap Investigation Board. The Board released its report in October, 2005 for NASA headquarters review. NASA released an Overview of the DART Mishap Investigation Results in May of 2006.
http://www.nasa.gov/pdf/148072main_DART_mishap_overview.pdf

The five-month investigation following the mishap found that DART had used up its pressurized nitrogen gas maneuvering fuel before it could complete its Proximity operations. The investigation board determined that excessive thruster firings in response to incorrect GPS navigational data caused the spacecraft to run out of thruster fuel during its approach, and had a corrupted navigation solution so it could not avoid the low-velocity collision with MUBLCOM.

Causes of DART's Collision with MUBLCOM

The collision with MUBLCOM was caused by the inaccurate navigation system performance as described above coupled with increasingly accurate azimuth and elevation information from the AVGS. This had the effect of lining MUBLCOM up in the "cross hairs" of DART's guidance system at a time when the system did not have the ability to accurately control the distance between the two spacecraft. This condition existed because DART's pre-programmed logic for switching to AVGS distance measuring capability required the spacecraft to fly into an undersized, imaginary sphere (waypoint) along the flight path 200 meters behind MUBLCOM. The MIB's analysis of the telemetry data from the flight shows that DART missed this 6.3 meter radius spherical envelope by less than 2 meters. The reasons for this inadequately-designed logic include the unanticipated potential for navigational errors and a lack of adequate design review. When DART missed the critical waypoint for switching to full AVGS capability, it continued moving toward MUBLCOM. DART's design included a means of collision avoidance, but its capability proved to be ineffective. The software logic for collision avoidance was dependent on the same navigational data source as the guidance system. The impact of this dependency was that DART's calculated position and speed did not match its actual position and speed. In fact, at the time of collision, DART was flying toward MUBLCOM at 1.5 meters per second while its navigational system thought it was 130 meters away from MUBLCOM and retreating at 0.3 meters per second. The collision avoidance design approach never anticipated the possibility that the navigational data would be this inaccurate.

DART telemetry included the spot data for up six reflector returns and the AVGS sent data for the three passes over grounds before and immediately after the collision. The spot data was later analyzed and used by the investigation.

The initial spot azimuth & elevation data show that the DART was constantly changing its position relative to MUBLCOM, causing the spot to move into the AVGS FOV from one direction and move out of view diagonally. This is consistent with the estimated motions of DART responding to the fluctuating Navigation Filter solutions at a distance of around 2Km.

After a period of time, the DART appears to start pointing the AVGS (and the DART vehicle behind it) directly at MUBLCOM, keeping it centered in the FOV within a couple of degrees. Again this is consistent with the estimated DART initiation of the AVGS pointed forced motion toward the target while using the GPS navigation solution to calculate when to switch the AVGS from SPOT mode to Acquisition & Tracking mode.

When the AVGS was left in SPOT mode during the terminal approach into MUBLCOM, only the 850nm lasers were firing and the Imager Integration Time was extremely long, causing the Long Range Filter reflectors to merge together into a single big blob until other reflectors including the Short Range Reflectors and a Auto-Trac reflector on the right solar array started to appear (patterns of five Red dots on either side of MUBLCOM target mock-up in Photo 1). Since the DART telemetry contained data for up to six spots, the spacing between the various reflectors on different parts of MUBLCOM allowed its relative position to be calculated and simulated on a 6DOF robotic graphics simulator. The resulting series of positions allowed the calculation of the collision velocity of approximately 1.4 meters per second which closely agrees with the collision velocity calculated from the relative motions of MUBLCOM and Dart the orbital mechanisms and physics of the collision. Also the 6DOF animation generated from the relative positions of MUBLCOM seem to have MUBLCOM constantly changing it attitude, which is actually consistent with the estimated fluctuating motion of DART while keeping itself pointed toward MUBLCOM.

PHOTO 1: MUBLCOM Mockup with Three Long Range VGS reflectors and Two Auto-Trac Reflectors
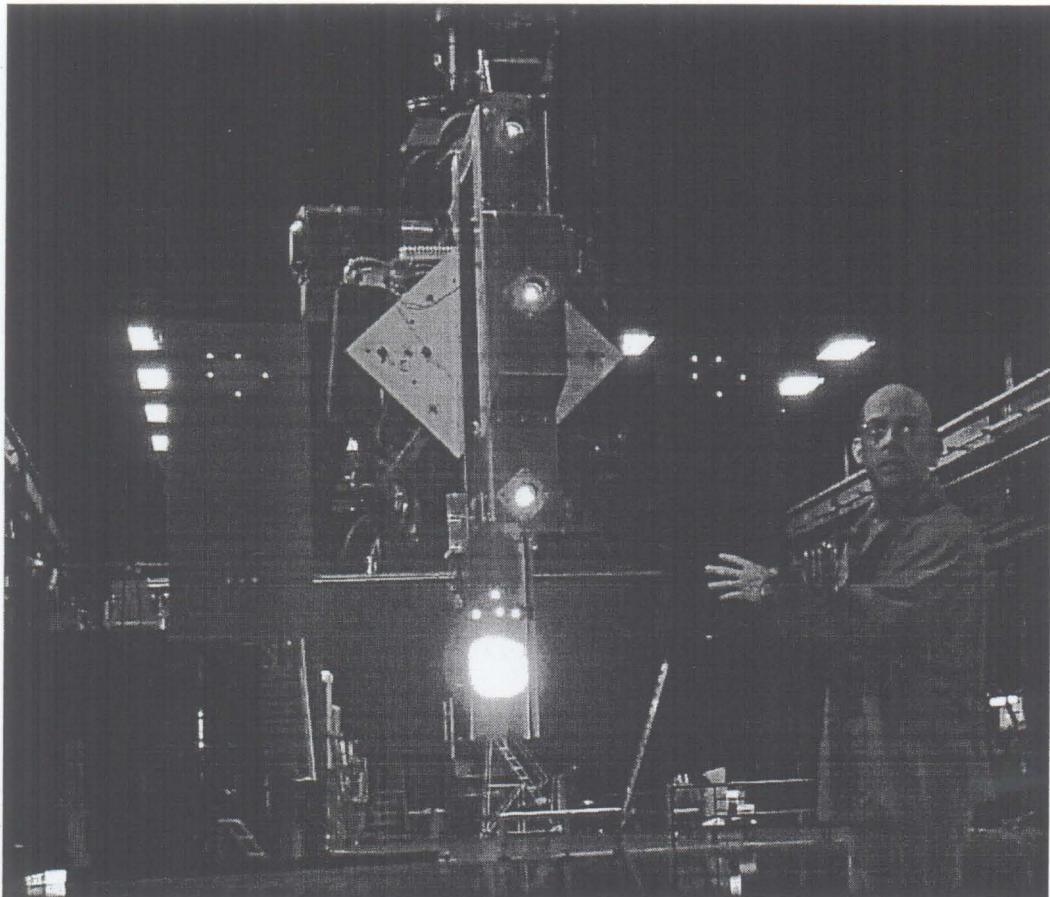
4. CONCLUSIONS

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.

Because of the insistence of the VGS engineers to have the SPOT mode and the numerous Spot data outputs in the telemetry, the AVGS data was able to help reconstruct the profile of the collision in this orbital game of billiards. Also, the activation of SPOT at long range allowed demonstration of the single spot range capability of the basic AVGS out to over a kilometer which will enable much longer tracking distances to support future ISS operations with the appropriate targets. However disappointing the DART mission was, valuable information was gained from the data generated in orbit and the extensive ground testing data which has already enhanced current and future sensors.

The true ability of the AVGS to guide automated docking operations will have to wait for the operations on Orbital Express which just launched into orbit just days ago and future generations of the VGS sensors.

ACKNOWLEDGMENTS

ACRONYMS AND ABBREVIATIONS

AR&C/D	Automatic Rendezvous & Capture/Docking	MIB	Mishap Investigation Board
AVGS	Advanced Video Guidance Sensor	MSFC	Marshall Space Flight Center
DART	Demonstration of Autonomous Rendezvous Technology	MUBLCOM	Multi-User Beyond-Line-of-sight COMmunications
DOF	Degrees of Freedom	NASA	National Aeronautics and Space Administration
DOTS	Dynamic Overhead Target Simulator	OCT	Optical Characterization Testing
FP	Final Prototype	SN	Serial Number
FRL	Flight Robotics Laboratory	VGS	Video Guidance Sensor
HWIL	Hardware-in-the-Loop		
IP	Initial Prototype		
ISS	International Space Station		

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