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# AVGS, AR&D for Satellites, ISS, the Moon, Mars and Beyond

Geoffrey C. Hintze [*], Keith G. Cornett[†], Michael H. Rahmatipour[‡] and Andrew F. Heaton[§]
*NASA Marshall Space Flight Center, Huntsville, Al, 35812*

Larry E. Newman[**]
*Miltec Systems, Huntsville, AL, 35806*

Kevin D. Fleischmann [††]
*Triumph Aerospace Systems, Huntsville, AL, 35812*

*and*

Byron J. Hamby [‡‡]
*Jacobs Technology, Incorporated, Huntsville, AL 35812*

**With the continuous need to rotate crew and re-supply the International Space Station (ISS) and the desire to return humans to the Moon and for the first time, place humans on Mars, NASA must develop a more robust and highly reliable capability to perform Autonomous Rendezvous and Capture (AR&C) because, unlike the Apollo missions, NASA plans to send the entire crew to the Lunar or Martian surface and must be able to dock with the Orion spacecraft upon return. In 1997, NASA developed the Video Guidance Sensor (VGS) which was flown and tested on STS-87 and STS-95. In 2001, NASA designed and built a more enhanced version of the VGS, called the Advanced Video Guidance Sensor (AVGS). The AVGS offered significant technology improvements to the precursor VGS design. This paper will describe the AVGS as it was in the DART mission of 2005 and the Orbital Express mission of 2007. The paper will describe the capabilities and design concepts of the AVGS as it was flown on the DART 2005 Mission and the DARPA Orbital Express Mission slated to fly in 2007. The paper will cover the Flight Software, problems encountered, testing for Orbital Express and where NASA is going in the future.**

## Nomenclature

AR&C = Autonomous Rendezvous and Capture
ASTRO = Autonomous Space Transport Robotic Operations satellite
AVGS = Advanced Video Guidance Sensor
CMOS = Complementary Metal Oxide Semiconductor
DART = Demonstration Autonomous Rendezvous Technology
FIFO = First In/First Out
ILOAD = Initial Load
ISS = International Space Station
LRT = Long Range Target

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[*] Orbital Express Software Design Lead, Space Systems Department, EI32, Senior Member AIAA.
[†] Orbital Express Software Project Lead, Space Systems Department, EI32
[‡] Software Engineer, Space Systems Department, EI32, Member AIAA
[§] Senior Engineer, Spacecraft & Vehicle Systems Department, EV40/GN&C, Member AIAA
[**] Senior Software Analyst, Space Systems Department, Building 4487/A252
[††] Software Engineer, Space Systems Department, Building 4487/A252
[‡‡] Senior Software Analyst, Spacecraft & Vehicle Systems Department, EV22

MUBLCOM = MUltiple-path Beyond Line-of-sight COMmunications
NASA = National Aeronautics and Space Administration
NEXTSat = Next Generation Satellite
OCT = Optical Calibration Table
OE = Orbital Express
ROI = Region Of Interest
SRT = Short Range Target
TBAV = Total Bearing and Angular Velocity
VGS = Video Guidance Sensor

## I. Introduction

As NASA enters the twenty first century, the need for AR&C in Space is clear. With trips to the International Space Station (ISS) plus the desire to return humans to the Moon and for the first time, place humans on Mars, NASA must develop a more robust Autonomous Rendezvous and Capture (AR&C) technology. The NASA Marshall Space Flight Center developed the Video Guidance Sensor (VGS)[1,2] which flew on STS-87 in 1997 and STS-95 in 1998. The Russians have used an automated docking system since 1967. The Russian docking system uses a KURS radar system that can be procured from only one source. Its electronics consume a lot of power and use vacuum tube technology.[2] The Russians are using their system on the ISS.

NASA has designed and built a more enhanced version of the VGS called the Advanced Video Guidance Sensor (AVGS). AVGS flew on the DART mission in April 2005. The AVGS is also scheduled to be a part of Orbital Express (OE), a Defense Advanced Research Project Agency (DARPA) project managed by Boeing. OE was launched on March 8, 2007. There are currently prototype efforts for next generation sensors for use in Lunar and Martian missions.

## II. AVGS

Orbital Sciences built the AVGS Flight Unit for the Demonstration Autonomous Rendezvous Technology (DART) mission. The Flight Unit was modified to be a part of Orbital Express (OE), a Defense Advanced Research Project Agency (DARPA) project managed by Boeing. OE is scheduled to fly in 2007.

Figure 1 shows the layout of the AVGS. The AVGS is composed of an Imager, two 850 nm Foreground Lasers, two 808 nm Background Lasers, two Field Programmable Gate Arrays (FPGA), and two Digital Signal Processors (DSPs). The Input Output Processor (IOP) is a Texas Instrument TMS320F240 DSP, a 16-bit fixed-point computer. The IOP communicates with the DART or OE Computer receiving commands and sending responses. The Application Processor (AP) is a Texas Instrument TMS320VC33, a 32-bit floating-point computer. The AP receives and processes commands from the IOP and returns results to the IOP. The IOP and AP communicate via the IOP FPGA. The AP communicates with the Imager via the AP FPGA. The AP FPGA takes the image from the Imager, reduces the image to Line Segments and sends the Line Segments to the AP via the Line Segment FIFO.

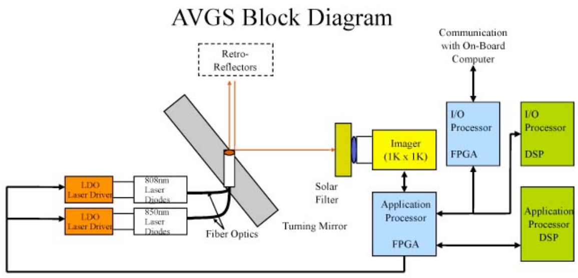

**Figure 1. Block Diagram of AVGS**

AVGS supports the following Modes:

- Standby
- Spot
- Acquisition
- Track
- Diagnostic
- Reset
- Maintenance
- Segment

The Maintenance and Segment Modes are only available in the Orbital Express version of the AVGS sensor. The Diagnostic Mode is also a non-Operational Mode. All of the Modes can be commanded from the ground except Track Mode, which is automatically invoked from Acquisition Mode whenever the Short or Long Range Targets are identified. Spot, Acquisition, Track, and Segment Modes all involve execution of an Image Processing Cycle (see below) which may be run at various synchronous and asynchronous data rates depending on mode and data rate selection (maximum of 50Hz for DART and 10 Hz for Orbital Express).

### AVGS Coordinate Systems

Figure 2 shows the relative alignments of the AVGS Sensor and Target coordinate systems when the Target coordinate system has Pitch, Yaw, and Roll angles of zero. The purpose of the AVGS sensor is to compute and report a 6-DOF-target vector for the AVGS Target coordinate system relative to the AVGS Sensor coordinate system. The 6-DOF-target vector consists of Range, Azimuth, and Elevation of the Target coordinate system origin, plus a quaternion set from which Pitch, Yaw, and Roll angles of the Target coordinate system can be derived. The CMOS Imager coordinate system XY axes are nominally aligned with the AVGS Sensor YZ axes as indicated in Fig. 2, with origin offset and small roll misalignment corrections applied in the Imager XY to Az/El transformation equations as described in the next section. Pitch, Yaw, and Roll rotations are performed in the classic Euler PYR rotation sequence.

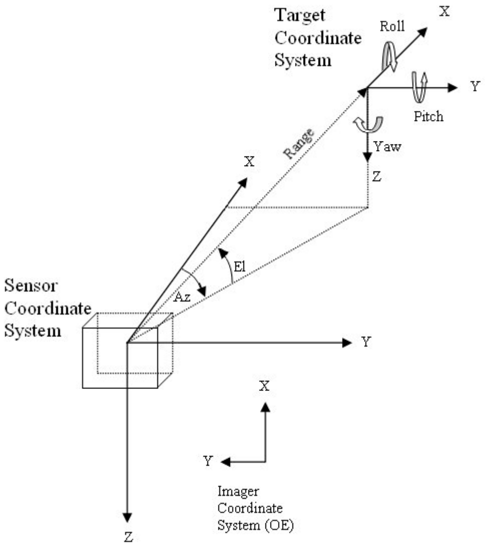

**Figure 2. AVGS Coordinate Systems**

### Image Processing Cycle

The Spot, Acquisition, Track, Diagnostic, and Segment modes all execute a common function or processing thread at the beginning of their cyclic task called the Image Processing Cycle. This is a task in which laser and imager control settings are sent to the laser drivers and imager electronics, and control operations are transferred to the AVGS firmware. The AVGS firmware fires the Foreground lasers and controls the exposure and retrieval of the Foreground laser image. It then fires the Background lasers and controls the exposure and retrieval of the Background laser image. The AVGS targets consists of an array of corner cube reflectors which return the light of the 850 nanometer wavelength Foreground lasers, but absorb the light of the 808 nanometer wavelength Background lasers, so that when the two images are differenced, only the images produced by the target reflectors are prominent in the difference image (see Fig. 3).

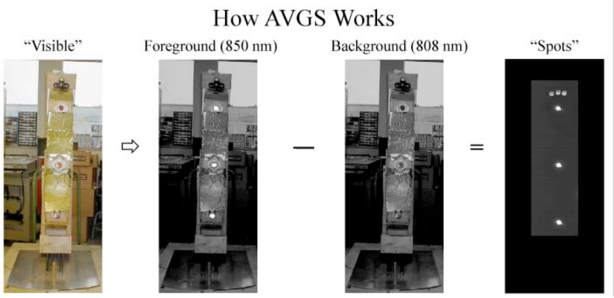

**Figure 3. How the AVGS Works**

In all but Track Mode, the imager is operated in full field of view mode in which all pixels in the image array are processed. In Track Mode, the field of view is reduced to four Regions of Interest or rectangular subregions of the field of view intended to exclude spots that are outside the reflector areas of the targets being tracked. The imaging firmware differences the pixel intensity of each pixel of the Foreground and Background images and determines whether the pixel is a "lit" pixel. A pixel is lit if its pixel intensity value (0-255) exceeds the Pixel Intensity Threshold value that was defined to it by the AVGS software at the beginning of the image cycle. The imaging firmware compresses lit pixel information into line segment packets which are reported to the AVGS software via a memory FIFO interface. A line segment packet reports contiguous lit pixel segments along each row of the 1024x1024 pixel array as depicted in Fig. 4 and consists of the following values:

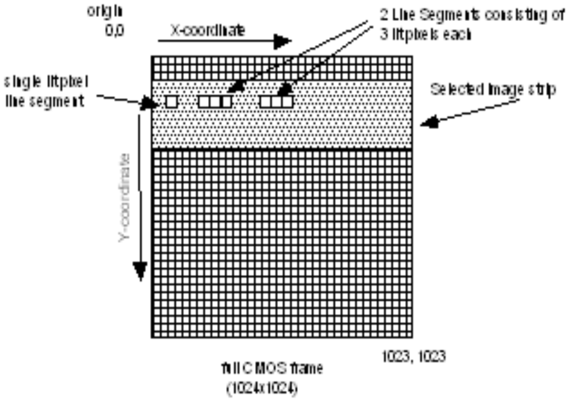

**Figure 4. Line Segments**

- Y Coordinate (0-1023)
- Starting X Coordinate (0-1023)
- Ending X Coordinate (0-1023)
- Summation of Pixel Intensities
- Summation of X Coordinate Times Pixel Intensity

In each operational mode, the AVGS software processes the line segment data reported to it by the imaging firmware into spot data. A single spot consists of a rectangular subregion of the image array containing lit pixels which are adjacent to one another (lumped together).

The AVGS software computes spot centroid coordinates for each spot which are the geometric averages of all lit pixel coordinates in the spot weighted by their pixel intensity values. The spot centroids are computed using the following equations, where i = index of each lit pixel in the spot:

$$\text{X Centroid} = \text{Sum of X Coordinate Times Pixel Intensity / Sum of Pixel Intensities} = \frac{\sum X_i I_i}{\sum I_i} \tag{1}$$

$$\text{Y Centroid} = \text{Sum of Y Coordinate Times Pixel Intensity / Sum of Pixel Intensities} = \frac{\sum Y_i I_i}{\sum I_i} \tag{2}$$

The transformation of X,Y spot centroid coordinates into Azimuth and Elevation spot centroid coordinates involves correction for spherical lens and corner cube distortion effects which are beyond the scope of this paper to detail. The following equations show the basic steps of the transformation without the detailed corrections for optical distortion:

Correct translational and rotational misalignments of the XY image plane to the AVGS Sensor azimuth and elevation axes:

$$\begin{vmatrix} X_M \\ Y_M \end{vmatrix} = \begin{vmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{vmatrix} \begin{vmatrix} X - X_0 \\ Y - Y_0 \end{vmatrix} \tag{3}$$

Correct X,Y coordinates for spherical lens and corner cube distortion effects:

$$\begin{aligned} X_C &= f(X_M, Y_M) \\ Y_C &= g(X_M, Y_M) \end{aligned} \tag{4}$$

Compute azimuth and elevation centroids:

$$\begin{aligned} Azimuth &= \tan^{-1}\left(\frac{-Y_C}{FL}\right) \\ Elevation &= \tan^{-1}\left(\frac{X_C}{\sqrt{{Y_C}^2 + FL^2}}\right) \end{aligned} \tag{5}$$

where:

$\theta$ = Small image plane rotational angle misalignment
$X_0$ = X coordinate of image plane optical center
$Y_0$ = Y coordinate of image plane optical center
$FL$ = Imager focal length in pixels
$X_M$ = Measured X pixel coordinate
$Y_M$ = Measured Y pixel coordinate
$X_C$ = Corrected X pixel coordinate
$Y_C$ = Corrected Y pixel coordinate

## AVGS Operational Modes

In normal flight operations, the AVGS can be commanded into one of several operational modes which are described in the following sections.

### A. Spot Mode

Spot Mode is initiated by the receipt of a Spot command from the host computer. Spot Mode is provided as a diagnostic tool for imaging and reporting up to 20 spots, ordered by decreasing spot size, that may appear in the imager field of view. Spot Mode can also be used, as in the case of the DART mission, to obtain bearing angles to the AVGS target cluster when individual target reflectors are not resolved into valid spots due to the distance of the target or because target range is unknown. The Spot command differs from the Acquisition command that is described in the following section in that it must specify all laser and imager control parameters such as Foreground and Background Laser Power, Image Exposure Time, and Pixel Intensity Threshold values. In Acquisition and Track modes, these parameters are automatically computed from an Optical Calibration Table (OCT) in the uploadable ILoad table as a function of target range. Spot Mode executes the Image Cycle processing functions described in the previous section at a 5 hertz rate. In addition to reporting individual spot parameters, it computes and reports a Summation of Spot Centroid parameter set.

The Spot Cluster Centroid coordinates represent the geometric center of all lit pixels weighted by their pixel intensity values as depicted in Fig. 5. The Summation of Spot Centroid parameters are computed from the individual spot parameters using the following equations, where k = index of each spot in the spot list:

$$\text{Total Number of Lit Pixels} = \sum N_k \tag{6}$$

$$\text{Sum of Pixel Intensities} = \sum (\sum I_i)_k \tag{7}$$

$$\text{Average Pixel Intensity} = \text{Sum of Pixel Intensities / Total Number of Lit Pixels} = \frac{\sum (\sum I_i)_k}{\sum N_k} \tag{8}$$

$$\text{Sum of X Times Pixel Intensity} = \sum (\sum X_i I_i)_k \tag{9}$$

$$\text{Sum of Y Times Pixel Intensity} = \sum (\sum Y_i I_i)_k \tag{10}$$

$$\text{X Centroid} = \text{Sum of X Times Pixel Intensity / Sum of Pixel Intensities} = \frac{\Sigma\left(\Sigma X_i I_i\right)_k}{\Sigma\left(\Sigma I_i\right)_k} \tag{11}$$

$$\text{Y Centroid} = \text{Sum of Y Times Pixel Intensity / Sum of Pixel Intensities} = \frac{\Sigma\left(\Sigma Y_i I_i\right)_k}{\Sigma\left(\Sigma I_i\right)_k} \tag{12}$$

Azimuth Centroid = fAzimuth(X Centroid, Y Centroid) (using Eqs. 3-5)
Elevation Centroid = fElevation(X Centroid, Y Centroid) (using Eqs. 3-5)

### B. Acquisition Mode

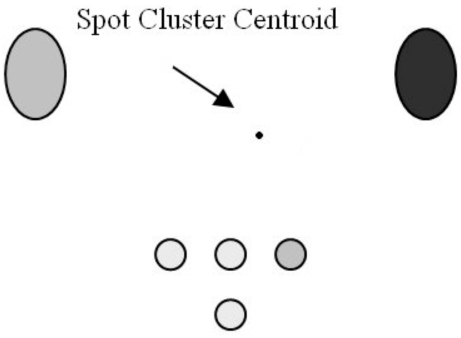

**Figure 5. Spot Cluster Centroid**

Acquisition Mode is an operational mode in which the AVGS software attempts to identify one or both of the AVGS targets from the reflector spots obtained from the pixel image array based on knowledge of the approximate range of the targets but without knowledge of the bearing or rotational attitude of the targets. The receipt of an Acquisition command from the host computer initiates Acquisition Mode. The Acquisition command differs from a Spot command in that it contains an estimate of the target range but does not contain laser power and imager control settings. The AVGS uses the estimated range to compute Foreground and Background Laser Power and Image Exposure Time settings that were determined by ground calibrations to be optimal for imaging the target at the estimated range. The range estimate is also used to compute an optimum Pixel Intensity Theshold value for determining lit pixels and the Minimum and Maximum SRT and LRT Spot Sizes (pixel count values) that are used to accept or reject spots that appear in the field of view. These values are interpolated from the Optical Calibration Table in the uploadable ILoad table, in which range is defined as an independent variable, and the Foreground/Background Laser Power, Image Exposure Time, Pixel Intensity Threshold, and Minimum and Maximum Spot Sizes are defined as dependent variables. The range estimate must be accurate to within 25% of the true target range. Any target vectors that are outside 25% of the range estimate are rejected by the AVGS software.

Both Acquisition and Track modes execute the same Pattern Recognition Algorithm, described in a later section of this paper, to match spots to corresponding reflectors of the target array in order to compute a 6-DOF target vector defining the orientation of the AVGS Target coordinate system relative to the AVGS Sensor coordinate system using the Inverse Perspective Algorithm, which is also described in a later section of this paper. If the estimated range of the target is greater than 30 meters, then only the LRT is searched. If the range is less than 8 meters, then only the SRT is searched. If the range is between 8 and 30 meters then both targets are searched.

Acquisition Mode outputs an Acquisition response message at a 5 Hz rate which contains spot and tracking status information for each target, but no target vectors. If one or both of the targets are found in an Acquisition cycle, then the software sets a flag in the Acquisition message to indicate which targets were found and automatically transitions to Track Mode in the next 5 Hz cycle. Similarly, in Track Mode, if neither the SRT or LRT target is found during a Track cycle, then the AVGS software sets flags to indicate neither target is found in the Track response message, and automatically transitions back to Acquisition Mode in the next 5 Hz cycle. Both modes require an estimated range to the target that is accurate to within 25% of the true target range. In Acquisition Mode, this range is the estimated range that was sent in the last Acquisition command that was received from the host computer, unless Acquisition Mode was automatically entered from Track Mode, in which case the estimated range is the last range in which one of the two targets was tracked with a Pattern Confidence flag set. If both targets were tracked with Pattern Confidence, then the range for the more accurate SRT solution is used over the range for the LRT solution when the target range is less than 10 meters. The Pattern Confidence flag is asserted for each target when the target is successfully tracked for 5 consequtive 10 Hz cycles without one of its target reflector spots intersecting the edge of the field of view or exceeding an angular rate of 2 degrees/second per axis.

### C. Track Mode

Track Mode is the primary operational mode of the AVGS sensor in which the sensor tracks one or both of the AVGS targets and reports a 6-DOF target vector for each target to the host computer at a 5 Hz rate. Track Mode is automatically entered from Acquisition Mode whenever an AVGS target is identified in a 5 Hz Acquisition cycle. The AVGS remains in Track Mode until either a new command is received from the host computer directing it to enter a new mode, or until the AVGS fails to identify either target in a Track cycle and Acquisition Mode is automatically entered in the next 5 Hz cycle. Track Mode is significantly different from Acquisition Mode in that Track Mode restricts the area in the field of view where each spot can be accepted for pattern recognition to a

Region Of Interest (ROI) area where the spot was found on the previous cycle plus a margin of 17 pixels around this area which is computed from the maximum expected angular rate between the sensor and target known as the Total Bearing and Angular Velocity (TBAV) parameter, which for the Orbital Express and DART missions is a value of 2 degrees/second per axis (azimuth or elevation). Another major difference between Track and Acquisition modes is that Acquisition Mode executes imaging and pattern recognition functions at a 5 Hz rate while Track Mode executes its imaging function at a 10 Hz rate and averages the spot data from every other cycle before performing its pattern recognition and attitude determination functions at a 5 Hz output rate.

### D. Other Modes

There are also four other Modes – Reset, Diagnostic, Segment and Maintenance Mode. The Segment and Maintenance Mode are new to Orbital Express. Diagnostic and Segment Mode are not used in Flight. Maintenance Mode is used to upload new versions of the AP and Initial Loads (ILOAD) while in flight. Reset Mode is used to reboot the entire AVGS system or reboot the AP (OE only). DART did not use the Reset command but it must be used in conjunction with Maintenance Mode in OE.

## Pattern Recognition Algorithm

The AVGS Acquisition and Track modes execute SRT and LRT Pattern Recognition Algorithms to identify the spots which originate from each reflector of the SRT and LRT targets in the CMOS image array. Pattern recognition is a crucial element of the AVGS tracking function. Accurate tracking can only result when each reflector that is defined in the 3 dimensional AVGS Target coordinate system can be mapped to its 2 dimensional projection in the CMOS image plane. Difficulties can arise when target reflectors are not spaced properly to form unique patterns in the 2 dimensional projection plane at all operational tilt angles. These difficulties are mitigated in AVGS by the use of corner cube reflectors which limit the pitch and yaw tilt angles between the AVGS Sensor and Target coordinate systems to approximately 18 degrees of line of sight tilt angle for the SRT reflectors and 27 degrees line of sight tilt angle for the LRT reflectors. Under these restricted tilt angles, it has been demonstrated with simulation and analysis software that unique mappings exist between the 3 dimensional SRT and LRT reflector coordinates and their 2 dimensional coordinates in the AVGS imaging system.

Figure 6 shows the numbering scheme assigned to the SRT and LRT target reflectors for the Orbital Express target configuration. SRT reflectors 1, 2, and 3 define a plane which is nominally parallel to and offset from the Target coordinate system YZ plane. The SRT 4 reflector is on a pole which is perpendicular to the SRT 123 plane in the negative X-axis direction. Similarly, LRT reflectors 1, 2, and 3 define a plane which is nominally parallel to and offset from the Target coordinate system YZ plane. The LRT 4 reflector is on a pole which is perpendicular to the LRT 123 plane in the positive X-axis direction. The Target coordinate system is nominally centered on the SRT 4 pole reflector. The purpose of the SRT and LRT Pattern Recognition algorithms is to positively identify the spot projection of each reflector in the CMOS image array. A Target Matrix is contained in the uploadable ILoad table which provides the XYZ coordinates in meters of each reflector in the AVGS Target coordinate system. The Pattern Recognition Algorithm uses the Target Matrix to compute key distances and ratios between the various reflectors that are used in identifying the targets.

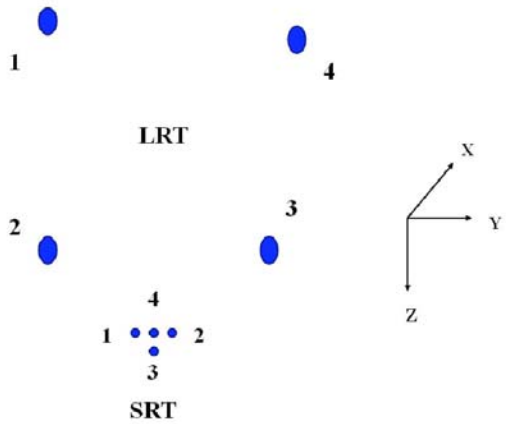

**Figure 6. Target Reflector Numbering Scheme**

The Pattern Recognition Algorithm for the SRT consist of identifying all four spots of the SRT and passing the azimuth and elevation coordinates of spots 1, 2, and 4 to the Inverse Perspective algorithm to compute the SRT target vector. The Inverse Perspective Algorithm computes a Spot Tolerance Angle for the unused SRT spot 3. This parameter is placed in the Track response packet as an indication of the amount of optical distortion that may be present in the imaging system. The Spot Tolerance Angle of a spot is the difference between the actual spot azimuth and elevation coordinates and the azimuth and elevation coordinates that are predicted for the reflector from the target vector. The detailed tests that are employed to identify the SRT target based on spot characteristics and the geometric perspective between the various spots are beyond the scope of this paper to describe.

The Pattern Recognition Algorithm for the LRT is similar to that of the SRT but is more complicated due to the possibility of false pattern identifications that arise under extreme tilt angles, such as when an SRT spot is close to LRT spots 2 or 3. The LRT Pattern Recognition Algorithm requires that LRT spots 1-4 be identified, plus one of the SRT spots. At long ranges, the SRT spots merge together into one or more spots depending on distance and target tilt angle and therefore the LRT Pattern Recognition Algorithm searches for a single spot in the region where the SRT is expected to be. The LRT Pattern Recognition Algorithm passes all viable three spot permutations of the four LRT spots (i.e. 412, 413, 423) to the Inverse Perspective algorithm and chooses the target vector solution having the smallest Spot Tolerance Angle to the unused fourth spot for its output solution. The detailed tests that are employed to identify the LRT target based on spot characteristics and the geometric perspective between the various spots are beyond the scope of this paper to describe.

## Inverse Perspective Algorithm

The Inverse Perspective Algorithm is employed to compute the 6 DOF vector of the AVGS Target coordinate system relative to the AVGS Sensor coordinate system from the azimuth and elevation angles of three reflectors of either the SRT or LRT target arrays. The algorithm requires the Target system coordinates of the SRT and LRT target reflectors be defined in a Target Matrix in the uploadable ILoad table. The range estimate for the target that was computed on the previous cycle or provided by the host computer is used to seed the initial guess of the deterministic Newton-Raphson numerical technique that is employed to solve the system of equations which results from the target geometry.

Referring to Fig. 7, $\mathbf{r}_1$, $\mathbf{r}_2$, $\mathbf{r}_3$ are the position vectors to the three reflectors in the Target coordinate system. In order to compute the 6 DOF vector, it is necessary to compute the $\mathbf{R}_1$, $\mathbf{R}_2$, $\mathbf{R}_3$ vectors to the three reflectors in the Sensor coordinate system. These vectors can be expressed in the Sensor XYZ coordinate system in terms of their unknown magnitudes $R_{i,}$ and their known azimuth and elevation angles $Az_i$ and $El_i$ as shown in Fig. 8 as follows:

$$\boldsymbol{R_i} = \quad R_i \begin{vmatrix} \cos(El_i)\cos(Az_i) \\ \cos(El_i)\sin(Az_i) \\ -\sin(El_i) \end{vmatrix} \tag{13}$$

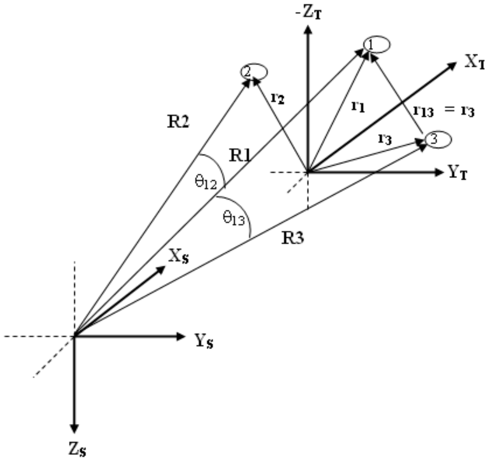

**Figure 7. Sensor Position Vectors to Three Reflectors**

The magnitudes of the vectors are computed as follows:

Compute cosines of the angles between the $\mathbf{R}_1$, $\mathbf{R}_2$, $\mathbf{R}_3$ vectors using the vector dot product relation:

$$\cos\theta_{12} = (\boldsymbol{R}_1 \bullet \boldsymbol{R}_2)/(R_1R_2) = \cos(\boldsymbol{El}_1)\cos(\boldsymbol{El}_2)\cos(\boldsymbol{Az}_1-\boldsymbol{Az}_2) + \sin(\boldsymbol{El}_1)\sin(\boldsymbol{El}_2)$$

$$\cos\theta_{13} = (\boldsymbol{R}_1 \bullet \boldsymbol{R}_3)/(R_1R_3) = \cos(\boldsymbol{El}_1)\cos(\boldsymbol{El}_3)\cos(\boldsymbol{Az}_1-\boldsymbol{Az}_3) + \sin(\boldsymbol{El}_1)\sin(\boldsymbol{El}_3) \tag{14}$$

$$\cos\theta_{23} = (\boldsymbol{R}_2 \bullet \boldsymbol{R}_3)/(R_2R_3) = \cos(\boldsymbol{El}_2)\cos(\boldsymbol{El}_3)\cos(\boldsymbol{Az}_2-\boldsymbol{Az}_3) + \sin(\boldsymbol{El}_2)\sin(\boldsymbol{El}_3)$$

Compute the difference vectors between the three reflectors in the Target coordinate system:

$$\boldsymbol{r}_{12} = \boldsymbol{r}_2 - r_1$$

$$\boldsymbol{r}_{13} = \boldsymbol{r}_3 - \boldsymbol{r}_1 \tag{15}$$

$$\boldsymbol{r}_{23} = \boldsymbol{r}_3 - \boldsymbol{r}_2$$

The law of cosines is then used to derive a system of equations which can be solved for the scalar ranges $R_1$, $R_2$, $R_3$ of these vectors in terms of the magnitudes of the difference vectors and cosine angles as follows:

$$\begin{aligned} r_{12}^2 &= R_1^2 + R_2^2 - 2R_1R_2\cos\theta_{12} \\ r_{13}^2 &= R_1^2 + R_3^2 - 2R_1R_3\cos\theta_{13} \\ r_{23}^2 &= R_2^2 + R_3^2 - 2R_2R_3\cos\theta_{23} \end{aligned} \tag{16}$$

The coupled quadratic equations in (16) are solved using a Newton-Raphson numerical technique. Calhoun and Dabney[3] describe the details of this technique.

After solving for the $R_i$ range scalars, the $\boldsymbol{R}_1$, $\boldsymbol{R}_2$, $\boldsymbol{R}_3$ vectors are completely determined, and from these vectors and the $\boldsymbol{r}_1$, $\boldsymbol{r}_2$, $\boldsymbol{r}_3$ vectors, the rotational transformation between the Target and Sensor coordinate system can be computed as follows:

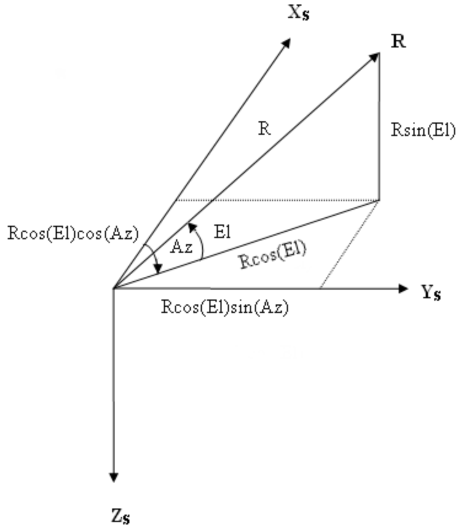

**Figure 8. Sensor Position Vector Components**

Compute the difference vectors between the three reflectors in the Sensor coordinate system:

$$\boldsymbol{R}_{12} = \boldsymbol{R}_2 - \boldsymbol{R}_1$$

$$\boldsymbol{R}_{13} = \boldsymbol{R}_3 - \boldsymbol{R}_1 \tag{17}$$

$$\boldsymbol{R}_{23} = \boldsymbol{R}_3 - \boldsymbol{R}_2$$

The rotational transformation from the Target to the Sensor coordinate system is defined by the equation:

$$\left|\boldsymbol{R}_{12} \quad \boldsymbol{R}_{13} \quad \boldsymbol{R}_{23}\right| = T \bullet \left|\boldsymbol{r}_{12} \quad \boldsymbol{r}_{13} \quad \boldsymbol{r}_{23}\right| \tag{18}$$

Expanded in matrix form, this equation is:

$$\begin{vmatrix} R_{12X} & R_{13X} & R_{23X} \\ R_{12Y} & R_{13Y} & R_{23Y} \\ R_{12Z} & R_{13Z} & R_{23Z} \end{vmatrix} = \begin{vmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{vmatrix} \begin{vmatrix} r_{12X} & r_{13X} & r_{23X} \\ r_{12Y} & r_{13Y} & r_{23Y} \\ r_{12Z} & r_{13Z} & r_{23Z} \end{vmatrix} \tag{19}$$

The solution for the rotation matrix T is:

$$\begin{vmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{vmatrix} = \begin{vmatrix} R_{12X} & R_{13X} & R_{23X} \\ R_{12Y} & R_{13Y} & R_{23Y} \\ R_{12Z} & R_{13Z} & R_{23Z} \end{vmatrix} \begin{vmatrix} r_{12X} & r_{13X} & r_{23X} \\ r_{12Y} & r_{13Y} & r_{23Y} \\ r_{12Z} & r_{13Z} & r_{23Z} \end{vmatrix}^{-1} \tag{20}$$

The solution for Eq. (20) is described in Calhoun and Dabney[3]. The quaternion defining the Target to Sensor rotational transformation is computed from the rotation matrix by the equations:

$$\begin{vmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{vmatrix} = \begin{vmatrix} \dfrac{(T_{23} - T_{32})\sqrt{1 + T_{11} - T_{22} - T_{33}}}{2\left|T_{23} - T_{32}\right|} \\ \dfrac{(T_{31} - T_{13})\sqrt{1 - T_{11} + T_{22} - T_{33}}}{2\left|T_{31} - T_{13}\right|} \\ \dfrac{(T_{12} - T_{21})\sqrt{1 - T_{11} - T_{22} + T_{33}}}{2\left|T_{12} - T_{21}\right|} \\ \dfrac{1}{2}\sqrt{1 + T_{11} + T_{22} + T_{33}} \end{vmatrix} \tag{21}$$

In order to compute the range, azimuth, and elevation angles of the Target coordinate system relative to the Sensor coordinate system, a vector ***R*** in the Sensor coordinate system must be formed to the Target coordinate system origin by differencing the $\boldsymbol{R}_1$ and $\boldsymbol{r}_1$ vector transformed to the Sensor coordinate system using the rotation matrix ***T*** as shown in Fig. 9 as follows:

$$\boldsymbol{R} = \boldsymbol{R}_1 - \boldsymbol{T}\,\boldsymbol{r}_1 \tag{22}$$

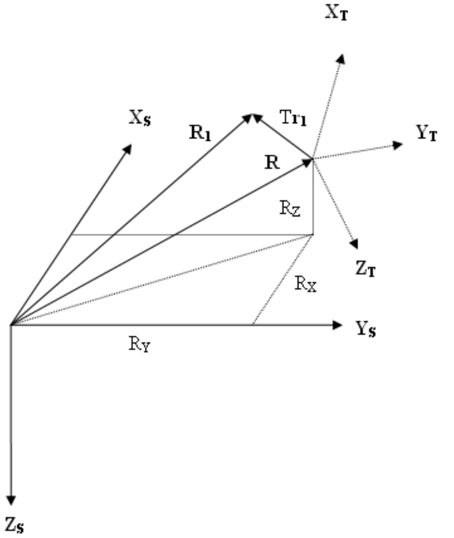

**Figure 9. Sensor Position Vector to Target Origin**

Range, Azimuth, and Elevation angles of the Target coordinate system relative to the Sensor coordinate system are computed from the target origin vector as follows:

$$\begin{aligned} Range &= \sqrt{R_X^2 + R_Y^2 + R_Z^2} \\ Azimuth &= \tan^{-1}\left(\frac{R_Y}{R_X}\right) \\ Elevation &= \sin^{-1}\left(\frac{-R_Z}{Range}\right) \end{aligned} \tag{23}$$

The final step of the Inverse Perspective Algorithm is to compute the Spot Tolerance Angle for the Inverse Perspective target vector solution (referred to as the Solution Noise parameter in the Acquisition and Track response messages), which is the error between the azimuth and elevation angles of the unused fourth reflector that was identified in the Pattern Recognition Algorithm but not designated for use in the Inverse Perspective Algorithm, and the predicted azimuth and elevation angles for the reflector that are computed from the Inverse Perspective Solution target vector. The predicted azimuth and elevation angles for the unused fourth reflector are computed as follows, where k = index of the unused reflector in the Target Matrix:

Compute the $\boldsymbol{R_k}$ predicted Sensor coordinate system position vector to the unused reflector from the Inverse Perspective Solution Target Origin vector $\boldsymbol{R}$, the Target to Sensor rotation matrix $\boldsymbol{T}$, and the Target coordinate system position vector to the unused reflector $\boldsymbol{r_k}$ which is defined in the ILoad Target Matrix table:

$$\boldsymbol{R}_{\mathrm{k}} = \boldsymbol{R} + \boldsymbol{T}\,\boldsymbol{r_k} \tag{24}$$

Compute the predicted azimuth and elevation angles for reflector k:

$$\begin{aligned} Az\_Pr\,ed_k &= tan^{-1}\left(\frac{R_{kY}}{R_{kX}}\right) \\ El\_Pr\,ed_k &= sin^{-1}\left(\frac{-R_{kZ}}{Range}\right) \end{aligned} \tag{25}$$

Compute the Spot Tolerance Angle between the predicted and actual unused reflector centroid locations:

$$Spot\ Tolerance\ Angle = \sqrt{(Az_k\ \text{-}\ Az\_Pred_k)^2 + (El_k\ \text{-}\ El\_Pred_k)^2} \tag{26}$$

## III. DART Mission

### A. Description

The DART mission was a 24-hour mission where the DART Spacecraft was required to approach the Multiple-path Beyond Line-of-sight COMmunications (MUBLCOM) satellite. MUBLCOM was placed in orbit in 1999. The target was mounted on the MUBLCOM (see Fig 10). There are two targets – a Short Range Target (SRT) and a Long Range Target (LRT). Each target has 3 reflectors. With the origin of the coordinate system being the base of the LRT, the center reflector of the LRT is offset -14.13 cm on the x-axis. The top and bottom reflectors are offset ±35.57 cm on the z-Axis. The center reflector of the SRT is positioned 30.7 cm on the X-axis and -54.77 cm on the Z-axis. The top and bottom reflectors are located 35.77 cm on the x-axis, -54.77 cm on the z-axis and ±4.06 cm on the y-axis.

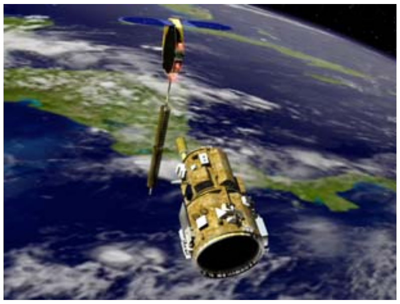

**Figure 10. DART Spacecraft and MUBLCOM Satellite**

### B. Testing

Testing was performed on the AVGS Flight Unit at the Marshall Space Flight Center. Most of the testing was performed at the MSFC Flight Robotics Lab (FRL) where the Advanced Sensor Optical Calibration Robot (ASOCR) provided automated target motion in the X and Y Target axes and manual positioning of the Sensor pitch and yaw rotational axes for target ranges between 1 and 9 meters. Longer ranges were tested in the FRL with ranges of 1-100 meters. Long-range tests of 1 to 290 meters were performed in a test stand cable tunnel using a fixed target. This tunnel is

**Figure 11. DART target during 500 meter vacuum tunnel testing**

mothballed but was reopened by MSFC Facilities to enable our testing. Figure 11 shows the DART target inside the tunnel. The DART Specifications required Acquisition and Tracking of the Long Range Target (LRT) at 500 meters. As the maximum range tested was 290 meters, a waiver was obtained on this specification prior to launch. Testing was also performed in the X-Ray Calibration Facility at MSFC. Testing was performed up to 483 meters[4].

All Short Range Target (SRT) testing and the LRT testing within 100 meters was performed in the FRL. There were two types of testing – Optical Characteristic Testing (OCT) and Verification Testing. The Sensors Group performed the OCT testing The OCT testing calculated Threshold, Laser Power and Integration Time. The calculations were second order polynomials as a function of range. These were performed for both the SRT and LRT. It was found that the LRT Integration Time did not fit very well with one polynomial so the DART AVGS software used one polynomial when the range was less than 100 meters and a second polynomial when the range was greater than 100 meters.

After the OCT testing was completed, the flight software was delivered to the test team. The test team performed formal testing in the FRL at ranges of 4, 15, 30, 50 and 100 meters. The SRT was tested at 4 and 15 meters. The LRT was tested from 15 to 100 meters. When these tests were completed, testing was moved to the test stand tunnel where the LRT testing continued at ranges of 150, 200, 250 and 290 meters.

Problems were discovered when tracking both targets inside 30 meters. All six reflectors could not be imaged at all positions across the Field of View and continuous tracking of both targets could not be achieved. As a result, the requirement to track the SRT was waived for the DART mission and the software was configured to track the LRT as the primary target. The DART AVGS was successful tracking the LRT in long-range tests out to 250 meters. At 290 meters, there was partial success, but AVGS could not maintain continuous tracking at all operational target attitudes.

### C. Results

The DART mission was not successful. AVGS was activated and Spot Mode worked but because of problems with the DART spacecraft, Acquisition and Tracking were never commanded. The Spot data helped the investigation team determine what caused the DART problems.

## IV. Orbital Express Mission

### A. Description

The OE mission is a longer duration mission than DART. An Atlas V launched the Autonomous Space Transport Robotic Operations (ASTRO) Satellite and the Next Generation Satellite (NEXTSat) (Fig. 12) on March 8, 2007. The OE Demonstration is scheduled for 3 months. Because of the length and complexity of the mission, AVGS added another Operational Mode – Maintenance Mode. AVGS also added an Initialization Load (ILOAD) to initialize parameters used by the AP. In Maintenance Mode, new versions of the AP and ILOAD can be uploaded. Since the AP must be halted while uploading the AP or ILOAD, the Reset Mode will now be used during Operations. It is not expected that new versions of the AP will be needed but there will be several ILOADS uploaded during the mission.

ASTRO and NEXTSat will be launched docked together. In orbit, they will separate by as much as 7 km. Other OE sensors will be used at these long distances but AVGS will be the primary sensor in close (less than 100 m). The OE mission will last about 3 months. The target AVGS will use is mounted on the NEXTSat. Unlike DART, the OE Target uses 4 reflectors for each of the SRT and LRT target arrays. A mockup of the target that was used to test AVGS is shown in Fig. 13. The SRT is located to the extreme right in Fig. 13. The four reflectors of the LRT are located to the left of the SRT.

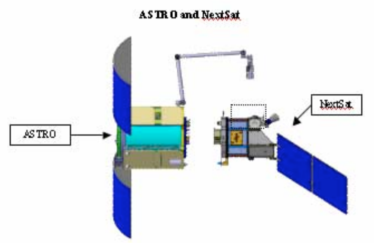

**Figure 12. The Astro and NextSat satellites**

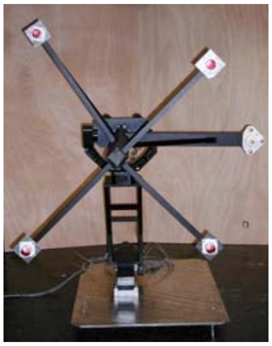

**Figure 13. Orbital Express Target**

### B. Testing

Since the OE mission has a shorter acquisition and tracking range requirement than the previous DART mission, the test approach for OE was different. All OE testing was performed in the Flight Robotics Lab at MSFC at ranges less than 100 meters. A new target mockup was developed, along with a robotic target positioning system. This target positioning system allowed the target to be controlled on four axes (roll, pitch, yaw and distance) with high precision, and allowed target dynamics to be programmed so that operational characteristics such as target bearing angular velocity (TBAV) could be tested. The sensor was mounted on a tripod with two axis positioning (azimuth and elevation) to enable testing across the field of view of the sensor.

Again, the sensors group performed OCT testing but the polynomials used in the DART Flight Software were replaced with tables. Once again, the Threshold, Laser Power and Integration Time were functions of range. To optimize the OCT target exposure parameters, test shots were taken as images and plotted using MATLAB. The images were then analyzed to determine if the OCT parameters were making best use of the imager's dynamic range.

Testing was then performed using a structured set of test cases combining target and sensor relative attitudes and ranges. In addition, testing was performed to simulate target acquisition and closure between the two vehicles. This verified that the range-based, table-driven OCT approach implemented for OE would work properly as range caused transition between table entries.

## V. The Moon, Mars and Beyond

NASA is currently evaluating enhancements of the AVGS technologies that will operate in the radiation environments that will be encountered during visits to the International Space Station by NASA's new Launch Vehicle – Ares and the new manned spacecraft – Orion; and that will be encountered during missions to the Moon and MARS. These enhancements will also provide an improved optical system, reduced mass and sensor footprint, and will add a capability to provide range and bearing solutions beyond 3km. A Prototype of this new AR&D system is currently underway.

## VI. Acknowledgments

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