Presented to: SPIE's Space Systems Technology and Operations Conference, April 24, 2003 Orlando FL.

Demonstration of Autonomous Rendezvous Technology (DART) Project Summary

Timothy E. Rumford,
Orbital Sciences Corporation, Dulles, VA

ABSTRACT

The objective of the DART mission

Since the 1960s, NASA has performed numerous rendezvous and docking missions. The common element of all US rendezvous and docking is that the spacecraft has always been piloted by astronauts. Only the Russian Space Program has developed and demonstrated an autonomous capability. The Demonstration of Autonomous Rendezvous Technology (DART) project currently funded under NASA's Space Launch Initiative (SLI) Cycle I, provides a key step in establishing an autonomous rendezvous capability for the United States. DART's objective is to demonstrate, in space, the hardware and software necessary for autonomous rendezvous. Orbital Sciences Corporation intends to integrate an Advanced Video Guidance Sensor and Autonomous Rendezvous and Proximity Operations algorithms into a Pegasus upper stage in order to demonstrate the capability to autonomously rendezvous with an target currently in orbit. The DART mission will occur in April 2004. The launch site will be Vandenberg AFB and the launch vehicle will be a Pegasus XL equipped with a Hydrazine Auxiliary Propulsion System 4th Stage. All mission objectives will be completed within a 24 hour period. The paper provides a summary of mission objectives, mission overview and a discussion on the design features of the chase and target vehicles.

Keywords: Autonomous Rendezvous, Video Guidance Sensor, Proximity Operation.

1. INTRODUCTION

Orbital intends to integrate an Advanced Video Guidance Sensor (AVGS) and Autonomous Rendezvous and Proximity Operations (ARPO) algorithms into a Pegasus upper stage in order to demonstrate the capability to autonomously rendezvous with an object currently in orbit. An artist's illustration of the close approach between chase and target vehicles is shown in Figure 1.

This flight demonstration has the following objectives:

- Demonstrate autonomous orbit transfer and rendezvous from a parking orbit to a point in the vicinity of the target spacecraft at which the AVGS will be used for navigation.
- Demonstrate AVGS capabilities.
- Demonstrate various approach techniques (Rbar, Vbar, Circumnavigation).
- Demonstrate station keeping on the Rbar a distance of 50 meters from the target.
- Demonstrate station keeping on the Vbar at a distance of 15 meters from the target.
- Demonstrate station keeping on the docking port axis at a distance of 5 m from the target .
- Demonstrate autonomous operations following loss of AVGS lock and reacquisition, and
- Demonstrate Collision Avoidance Maneuver (CAM).
- Depart the vicinity of the MUBLCOM spacecraft and perform a propellant depletion sequence so as to reduce the orbital lifetime of the DART vehicle.
- Validate ground test results of the AVGS and ARPO algorithms.
- Validate ground simulations/test facilities with Flight Data

The Orbital-owned MUBLCOM satellite has been chosen as the target because it is currently in orbit, fully operational, and has reflectors that were expressly designed for use with the AVGS.

Figure 1. Demonstration of Autonomous Rendezvous Technology

The need for autonomous rendezvous capability has been recognized for some time. In the late 1980s and early 1990's the NASA/MSFC Automated Rendezvous and Capture (AR&C) Program was established to develop hardware and software to achieve safe, assured rendezvous and docking between a chase and target vehicle (REFERENCES 1,2,3). The hardware element of the program was the MSFC developed Video Guidance Sensor (VGS) which flew successfully onboard two shuttle missions (STS-87 and STS 95) as experiments (REFERENCES 4,5,6). The success of these experiments lead to the current work with the DART project, under which Orbital and NASA are developing the next generation sensor; the AVGS. The goal of the AVGS development under the DART project is to mature the electrical design and mechanical design to increase operational performance, reduce weight, decrease power consumption and qualify the sensor for spacecraft use.

Autonomous rendezvous and proximity operations are vital to the Level I objectives of SLI; namely reducing the cost of delivering payloads to orbit and reducing probability of loss of crew. A key element in the development of the SLI architectures has been the separation of crew and cargo missions. This separation affords cost and safety benefits in that the cargo missions do not need crew escape systems and life support systems. This represents a direct savings in available weight capacity to orbit. Furthermore, by reducing the overall number of manned missions, risks to humans are reduced. Autonomous capability is an enabling technology ingredient in all unmanned cargo missions. Over the lifecycle of 2nd Generation Reusable Launch Vehicle (2GRLV), significant infrastructure savings can be realized through reductions in cost of supporting ground operations.

In addition to enabling unmanned cargo missions, autonomous rendezvous and proximity operations also helps achieve SLI cost and safety objectives for manned vehicles. By reducing the reliance on piloting skills in the human occupants of manned vehicles, increased flexibility is achieved in mission planning and manifesting. Improvements in safety are afforded by enabling semi-autonomous retrieval and/or rescue scenarios, where vehicle occupants may not be capable of pilot functions. Finally, the AVGS technology can also be applied directly to existing and future avionics designs as a piloting aid. During proximity and docking operations, the AVGS can provide the pilot with accurate relative attitude information to aid in manual docking.

2. MISSION OVERVIEW

The DART vehicle will be launched aboard a Pegasus XL launch vehicle. Figure 2 presents the standard Pegasus launch procedure that will be employed to deliver the DART vehicle to orbit. Pegasus XL is a flight proven, 3 stage, solid rocket motor launch vehicle that is air launched from a L-1011 carrier aircraft at 39,000 feet altitude. The Pegasus utilized for the DART mission will include the option 4th stage, which is a

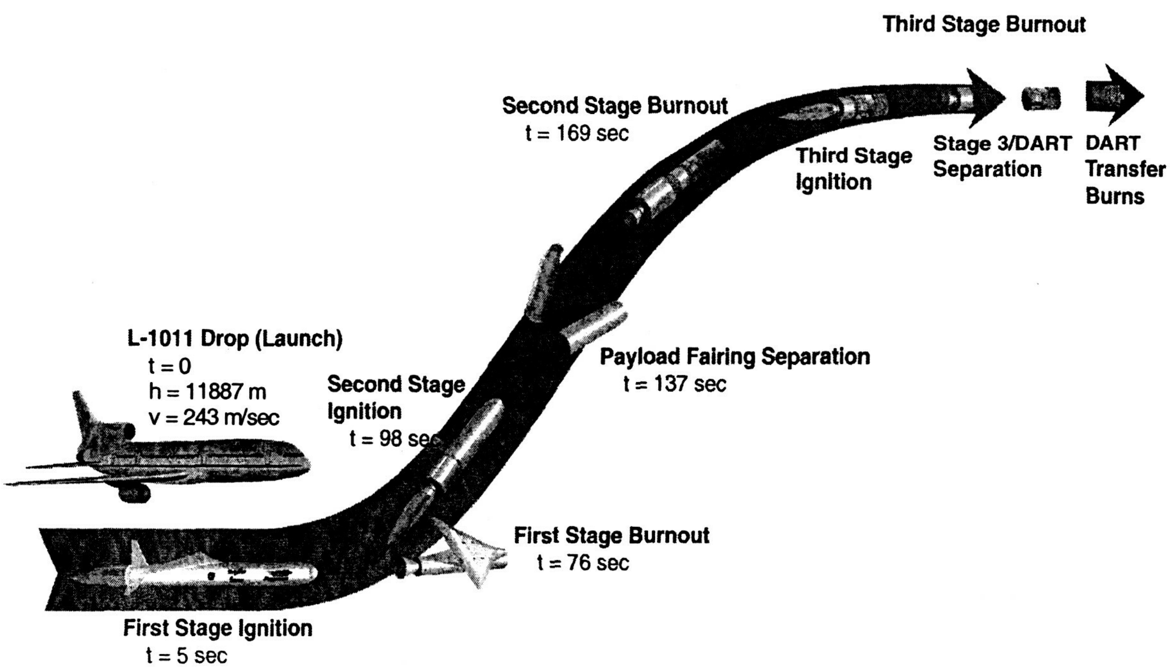

Figure 2. Pegasus Launch Profile

Hydrazine Auxiliary Propulsion System (HAPS). Approximately 10 minutes after launch, the Pegasus will deliver the DART vehicle to a circular parking orbit at an altitude of 500 km that will be designed to match the inclination and ascending node of the MUBLCOM orbit. At this point, the launch vehicle mission is complete and the DART space mission begins.

After being placed in the initial parking orbit, DART will complete the on-orbit checkout phase of the mission. This will involve verifying that valid navigation state estimates exist for the DART and target vehicles prior to beginning the rendezvous phase of the mission. DART will remain in this parking orbit until the appropriate phasing exists to initiate a HAPS burn that will begin a transfer to phasing orbit 2, as shown in Figure 3. This orbit will closely approximate a two-impulse Hohmann transfer, which theoretically requires the smallest velocity increment. The transfer will be mechanized using an adaptation of the existing Powered Explicit Guidance (PEG) algorithm, augmented by an explicit phasing calculation to control the downrange position at the end-of-rendezvous point. The start time of the transfer will be selected to deliver DART to a point 40 km behind and approximately 7.5 km below the target vehicle, measured in the Clohessy-Wiltshire (CW) frame defined with the target as the origin.

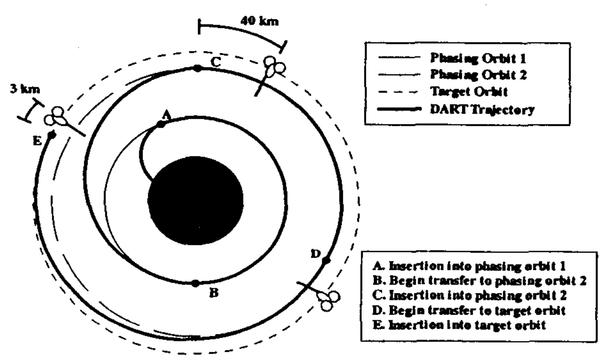

Figure 3. DART Phasing Orbits

At this point, the proximity operations phase of the mission begins; the attitude control system transitions from the existing Pegasus 3-axis cold-gas Attitude Control Subsystem (ACS), to the 16-thruster DART RCS. The DART RCS provides for precise and independent control of both 3-axis forces and moments, and this capability is used for all of the proximity-operations maneuvers. A diagram of the proximity operations necessary to support the DART mission objectives is shown in Figure 4. After waiting in phasing orbit 2, the DART vehicle will perform a CW transfer to place it 3 km behind the target vehicle in the target orbit. DART will then perform another CW transfer to place it 1 km behind the target.

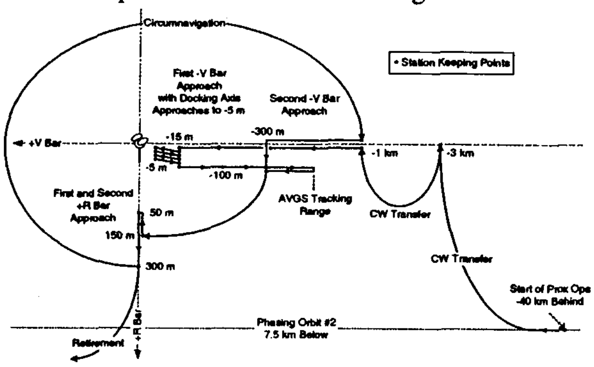

Figure 4. DART Proximity Operations

From this point, DART will initiate two sets of –V Bar and +R Bar maneuvers intended to evaluate AVGS performance and proximity operations algorithms. The –V Bar activities will include two approaches to 5 meters on the target vehicle docking axis, a simulated collision avoidance maneuver, and an evaluation of the maximum tracking range of the AVGS. A circumnavigation maneuver will be used to transition DART from the +R Bar to the –V Bar. Additional details on the DART trajectory can be found in RERERENCES 8 and 9.

After completion of the second +R Bar approach, DART will withdraw from MUBLCOM to 300 meters on the +R Bar and perform a retirement burn to exhaust the remaining hydrazine propellant and place the vehicle in an orbit with a lifetime less than 25 years as required by NASA Safety Standard 1740.14.

3. TARGET SPACECRAFT

The target vehicle for the DART mission will be MUBLCOM, an experimental communications satellite launched for DARPA aboard a Pegasus XL launch vehicle in 1999. The MUBLCOM satellite design is

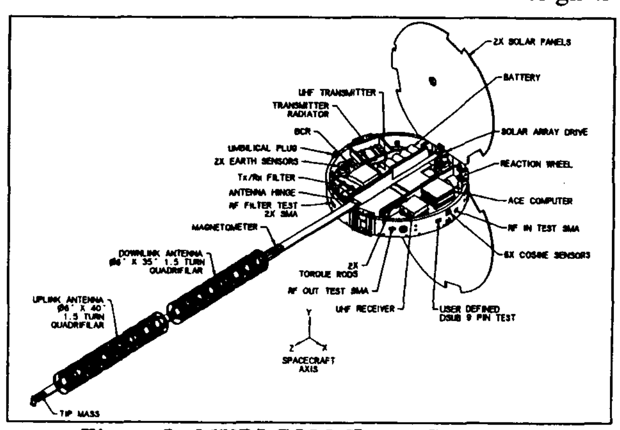

Figure 5. MUBLCOM, Target Spacecraft

shown in Figure 5.

Figure 6. Photograph of Stowed MUBLCOM Prior To Launch

Retroreflectors designed for use with the AVGS have been installed along the edge of the central ring (detail not visible in Figure 5, but shown pictorially in Figure 6). Note that the antenna boom extends along the Z_{sc} axis pointing towards the Earth. During the Mission, MUBLCOM will be 3 axis stabilized in a fixed yaw position with its X-axis aligned with the velocity vector. The retroreflectors are aligned with the MUBLCOM X-axis, such that the chase vehicle can approach from behind target (i.e., in the negative velocity vector). The retroreflectors are divided into two sets; a long range set and a short range set. The MUBLCOM satellite also includes a set of far-range retroreflectors designed to allow laser tracking from a ground station. These are nearly symmetrically arranged around the nadir-pointing boom ($+Z_{sc}$ axis). Salient interface requirements for the target vehicle are as follows: 1) must be three axis stabilized (within ±11° 3 sigma in yaw, 0.11 deg/sec yaw rate), 2) must have retroreflectors with known geometry (at least three with one out of plane), and 3) must broadcast its GPS position information to the chase vehicle.

Theory of operation for the AVGS is illustrated in Figure 7. This theory of operation is unchanged from the VGS technology as described in REFERENCES 4 and 6. The target vehicle is equipped with at least three retoflectors. These are specially designed, space-grade, corner cubes that will return reflect light back to its source. The chase vehicle will illuminate the target vehicle with two different wavelength inferred laser diodes. The target vehicle's retroreflectors are designed with an optical coating that is opaque to one wavelength (808nm) and transparent to the other

infrared?

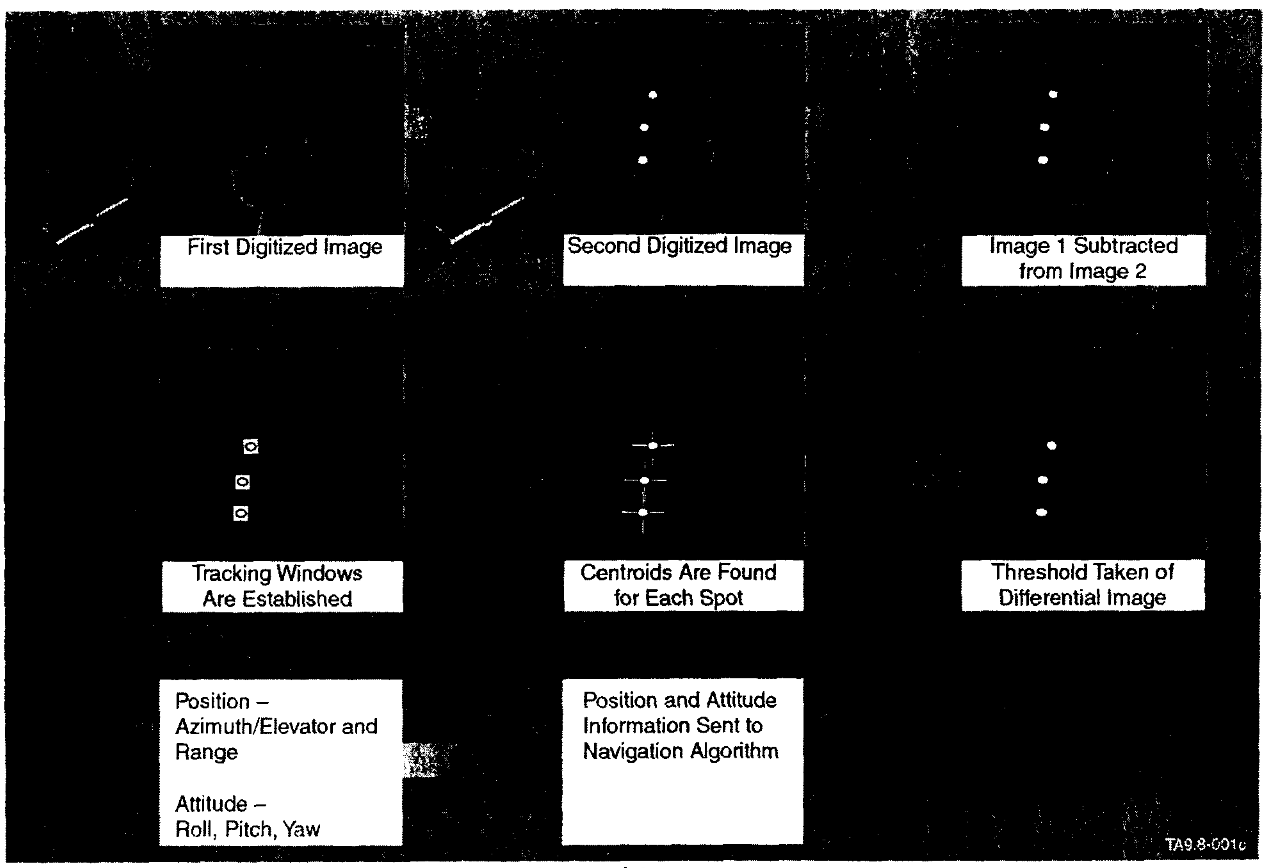

Figure 7. Theory of Operation, Averages

wavelength (850nm). This difference in return intensity is processed by the AVGS in order to filter out reflected light from other parts of the target vehicle, as well as background noise. Once the retroreflectors are filtered out from the background they can be processes by the AVGS as "dots" within a fixed field of view. The AVGS has onboard processors that can calculate relative range (based on how close the "dots" are to one another) and relative attitude (based on the pattern of the "dots"). The range and attitude data is then provided to the chase vehicle's On Board Computer (OBC) that, in turn uses the information in closed loop navigation and control to close in on the Target Vehicle.

4. CHASE VEHICLE DESCRIPTION

A diagram of the DART vehicle configuration is shown in Figure 8. The vehicle combines two discrete systems into one. The aft portion is the Pegasus 4^{th} stage including the avionics assembly and the HAPS. Orbital plans to use the HAPS design that has successfully flown seven times on board Pegasus as a precision injection fourth stage. The forward portion, referred to as the AVGS Bus, houses a propulsion tank, RCS thrusters, batteries, communications equipment, and the AVGS that will be used for navigational data during proximity operations.

4.1. Power Subsystem

The Power Subsystem diagram is provided in Figure 9. Due to the short duration of the mission, electrical power is provided solely from onboard batteries. No solar arrays were deemed necessary. Although not weight optimal, this approach greatly simplifies the design and reduces development costs. Two power busses are utilized; one for avionics and one for transient loads such as RCS thrusters. These two power subsystems are isolated from one another and tied to chassis and a single point ground. Batteries for both power subsystems are Li-Ion batteries supplied by SAFT America. The Avionics Bus uses six 50 Amp-hour batteries which are diode-steered together and distributed using two Battery Enable and Charge Assemblies (BECA). The Transient Bus uses a dual 9 Amp-hour (18 Amp-hour total) that is diode steered together inside the battery housing. Diode steering batteries provides a level of redundancy to the power buses. Both buses are switched using a Power Transfer Switch (PTS). This solid state design is heritage from Pegasus. Loads on the Transient bus include: Pyro Driver Units (PDUs), Thruster Driver Units (TDUs), a Hydrazine Thruster Driver Unit (HTDU) and Valve Driver Modules (VDMs). Loads on the Avionics Bus include the PCM Transmitter (Tx1), the Flight

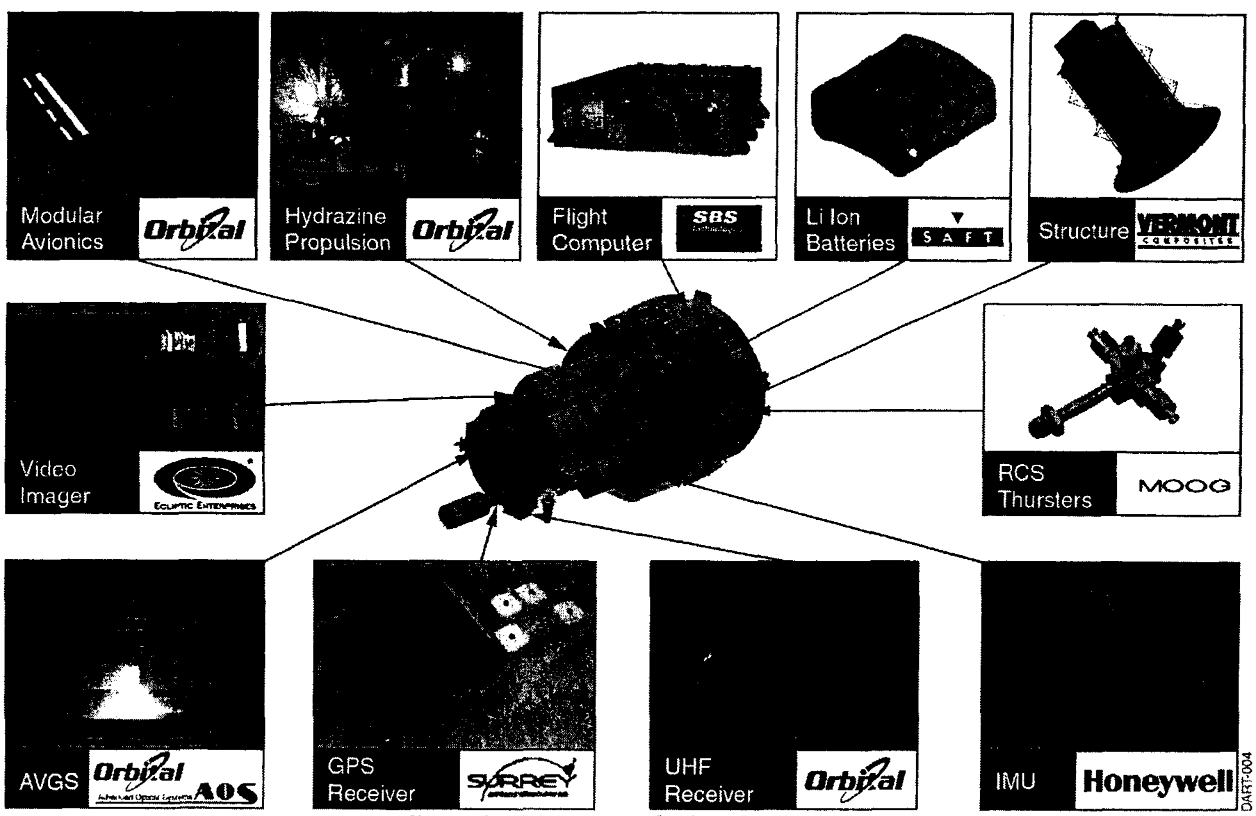

Figure 8. DART Vehicle Conffiguration

Computer (FC), a Stage 3 Multiplexer (MUX), Modular Avionics Control Hardware (MACH) Power Converter

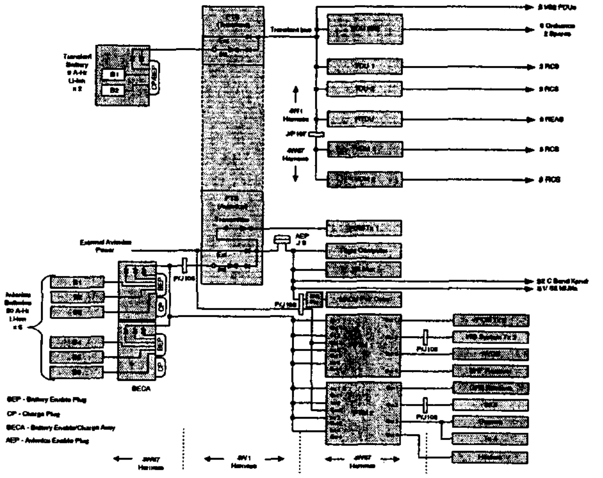

Figure 9. DART Power Block Diagram

and MACH Power Transfer Modules (PTMs). The PTMs provide for FC commanded in flight power cycling of other avionics components including: Transmitters (Tx2, Tx3 and Tx4), AVGS, UHF Receiver, Camera, Heaters, GPS Receiver, and the Space Integrated GPS/INS (SIGI).

4.2. Data and Control Subsystem

The Data and Control Subsystem diagram is provided in Figure 10. The On Board Computer (OBC) function is carried out by two separate components; the FC and the MACH. The FC, a Pegasus Heritage component manufactured by SBS-OR Industrial Computers, executes the Mission Data Load (MDL) Flight Code and runs the vehicle management functions. It is a ruggedized computer consisting of three VMEbus circuit boards mounted in a single chassis with a 32 MHz MC68030 CPU, two MC68302 I/O processors, 2 MB of SRAM and 1 MB of Flash RAM. For I/O, it supports up to 14 channels of RS-422 serial I/O ports and 16 opto-isolated discrete Inputs/Outputs. The discrete I/O is diagrammed in Figure 11. The MACH is a slave to the FC. Its purpose is to executes commands from the FC, store and forward telemetry, perform power switching, and serve as an A/D converter and multiplexer for analog instrumentation. The MACH is a modular stack of individual functional slices that are mounted together and share the same back plane and power. MACH is built by Orbital Sciences and has flown on several previous launch vehicles, including the OSP vehicle. For DART mission, the MACH is configured with the following ten slices: Two 10 MB Solid State Memory Modules used for store-forwarding telemetry data; Two Valve Driver Modules used to drive the 16 DART RCS thrusters (eight channels per slice); Two Power Transfer Modules used to power cycle various avionics components (four channels per slice); one Analog Input Module (AIM) used for collecting analog instrumentation; one Control Module and one Power Conversion Module. Note that the Figure 10 also depicts Pegasus specific components; the fin actuation system (FAS), thrust vector controllers (TVC2 and TVC3), pyrotechnic driver units (PDU1, PDU2, and PDU3), and stage 1 and 2 telemetry multiplexers (MUX1 and MUX2). These are shown for completeness and are used exclusively by the Pegasus launch vehicle and will not be required during the DART mission.

DART vehicle attitude and position data is provided by the Honeywell Space Integrated GPS/INS. SIGI is a self-contained, inertial strapdown navigation system.

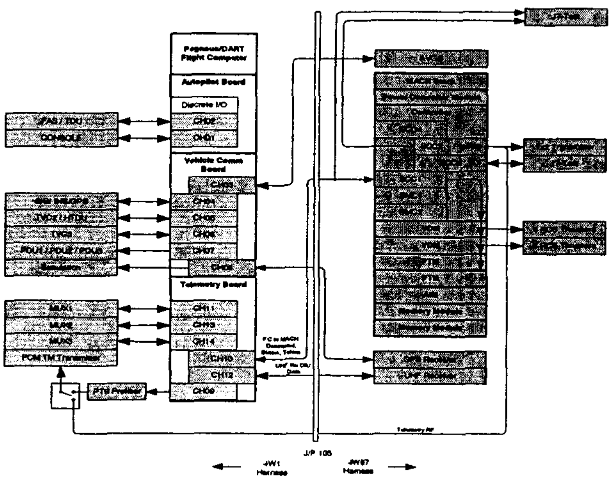

Figure 10. DART Data Flow Block Diagram

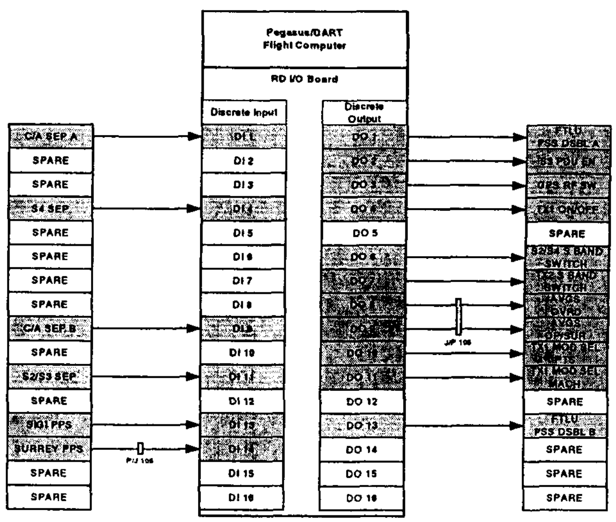

Figure 11. DART DO/DI Block Diagram

The SIGI consists of a microprocessor, ring-laser gyros, accelerometers, and a tightly-coupled integrated GPS receiver within a single chassis. SIGI provides outputs of linear and angular acceleration, linear and angular velocity, position, attitude (roll, pitch, and true heading), altitude, body angular rates, time tags, and Universal Time Coordinated (UTC) synchronized time. The SIGI has the capability to provide pure inertial, GPS-only, or blended GPS/INS navigation solutions. The SIGI includes a Collins GEM GPS receiver capable of tracking up to five GPS satellites simultaneously. However, the primary navigation data will be provided by an separate and external GPS receiver as discussed below. The SIGI will primarily be used to provide attitude data during the DART mission. The SIGI blended GPS/INS navigation solution will be available for use in the event of a failure in the primary GPS receiver.

The DART vehicle will include a stand-alone GPS receiver to provide the primary navigation data. A trade study was conducted to evaluate the various GPS receivers currently available. The SGR-10 receiver developed by Surrey Satellite Technology was identified as the best choice for the DART mission. The SGR-10 is a space-qualified receiver that has been flown on five satellites since 1998 and is scheduled to be flown on numerous upcoming missions including the Enterprise Module of the International Space Station. It provides C/A code tracking on 24 channels with support for 2 antennas. The SGR-10 also has a cold-start capability that provides a time to first fix from 2 to 10 minutes depending on initialization conditions.

As discussed earlier, the AVGS, being developed jointly by the Marshall Space Flight Center and Orbital Sciences Corporation is use during spacecraft rendezvous and docking operations and is the source of data for relative range and attitude between the chase and target vehicles. A block diagram of the AVGS is depicted in Figure 12. The AVGS contains lasers and a detector array that are used to measure the optical signal return from retroreflector arrays on the target spacecraft. Algorithms hosted within the AVGS process the resulting images and calculate the relative position and orientation of the target vehicle. The AVGS is capable of providing bearing data (azimuth and elevation) to the target at a range of at least 500 meters. Within 300 meters, the AVGS is capable of providing azimuth, elevation, range, and relative attitude measurements. The theory of operation is essentially the same as the VGS as discussed in the references. More detailed information on the AVGS can be found in the Advanced Video Guidance Sensor Specification (Orbital K60001).

4.3. RF Communication Subsystem

The RF Communication Subsystem is depicted in

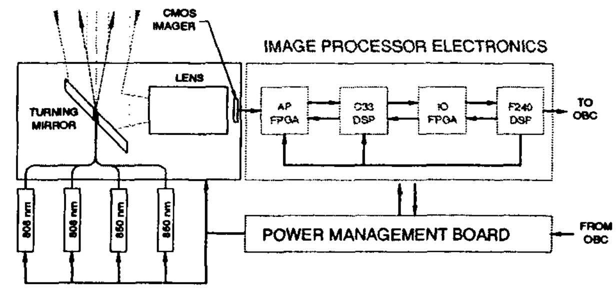

Figure 12. AVGS Block Diagram

Figure 13. Major components of this subsystem include: 1) Antennas for GPS (SIGI and Surrey), 2) UHF Receiver and Antenna, 3) Camera Subsystem, and 4) S-Band Subsystem.

The Surrey GPS Receiver supports two independent antennas. These have been separated by 180 degrees on the DART vehicle; one at 0 degrees and one at 180 degrees. This will provide optimum GPS constellation coverage. The SIGI supports one antenna input. This has been located at 0 degrees (pointing away from earth for most of the DART mission profile). There is a RF switch (SW-5) to switch to a down stage antenna during the Pegasus launch as the DART antenna is covered by a RF opaque fairing during launch. Note, the Surrey

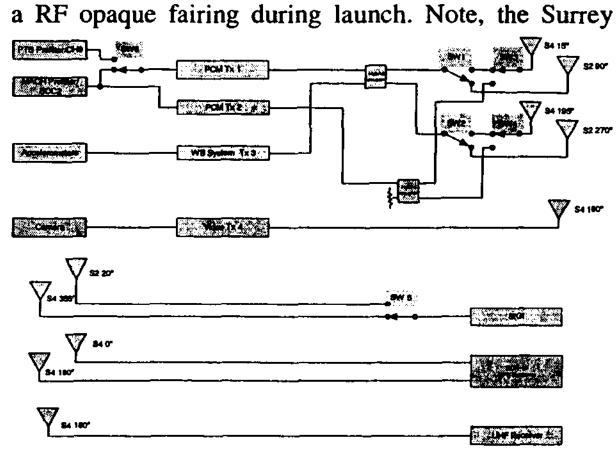

Figure 13. DART RF Block Diagram

GPS antennas are also covered during launch, therefore no GPS data will be collected from the SGR-10 during the launch phase; it will be initialized once in orbit.

The DART vehicle is equipped with a visual analog camera subsystem to provide real time down linked imagery during the DART mission. This will be used during post mission data processing as a source of truth data for the AVGS. The subsystem is comprised of a camera, a power supply (not shown), an S-Band video Transmitter (TX-4) and an S-band antenna. The camera subsystem is provided by Ecliptic Enterprises and is very similar to their heritage "rocket cam" that has flown of several recent launch vehicles.

The DART vehicle will include a UHF receiver and antenna used to gather state information transmitted by the target vehicle. Prior to launch of the DART mission, ephemeris data describing the target vehicle orbit will be entered into the DART flight computer. This target state data will then be propagated by the DART flight computer for the duration of the rendezvous. The state propagation is not expected to be accurate enough to allow a safe approach to AVGS acquisition range. The UHF system will be used to obtain near-realtime GPS updates as measured by the target spacecraft GPS receiver that can be used to improve the accuracy of the target vehicle state estimate. The minimum range of the UHF system has been conservatively estimated at 100 km. The UHF receiver has been developed by Orbital Science's Space Systems Group based on designs used in previous satellites.

The DART vehicle will include two 5 Watt S-Band transmitters to relay stored telemetry data to ground stations. The use of redundant transmitters will increase the probability that the science data required to verify mission success and evaluate AVGS performance will still be obtained in the unlikely event of a transmitter failure. The telemetry system will employ two hemispherical antennas placed on opposite sides of the DART vehicle to provide near-360° coverage. This antenna configuration will match the Pegasus baseline design with no changes anticipated for the DART mission.

4.4. Propulsion Subsystem

The DART vehicle will be controlled using a combination of three propulsion subsystems.

1) The HAPS consists of three hydrazine thrusters, each producing approximately 222 N (50 lbf) of thrust, to provide most of the delta-v capability for the mission. Off-pulsing of the thrusters provides pitch and yaw control during a HAPS burn. Thruster commands are sent from the flight computer to the HTDU which open or close the 3 thruster solenoid valves. The HAPS tank is capable of holding 56.88 kg (125.4 lbm) of hydrazine. The HAPS is heritage from Pegasus and only minor changes for thermal protection are planned. A block diagram of the HAPS is provided in Figure 14.

2) The HAPS also includes a set of 6 cold-gas nitrogen thrusters, producing 56 N (12.5 lbf) or 111 N (25 lbf) of thrust each, to provide 3-axis attitude control during orbital drifts and roll control during HAPS burns. The TDU drives the these RCS thrusters when commanded by the flight computer. The thrusters are fed from a dedicated 5.77 kg (12.73 lbm) tank. The HAPS RCS is heritage from Pegasus and no changes are being made for the DART mission. A block diagram of the HAPS RCS is provided in Figure 15.

3) The AVGS Bus includes a set of 16 cold-gas nitrogen thrusters (3.6 N or 0.8 lbf each) for translational and attitude control during proximity operations. These thrusters are driven by MACH VDMs when commanded by the Flight Computer. The DART nitrogen tank will be capable of holding at least 22.68 kg (50 lbm) of propellant. The specific impulse of these thrusters will be 60 seconds. A block diagram of the DART RCS is provided in Figure 16.

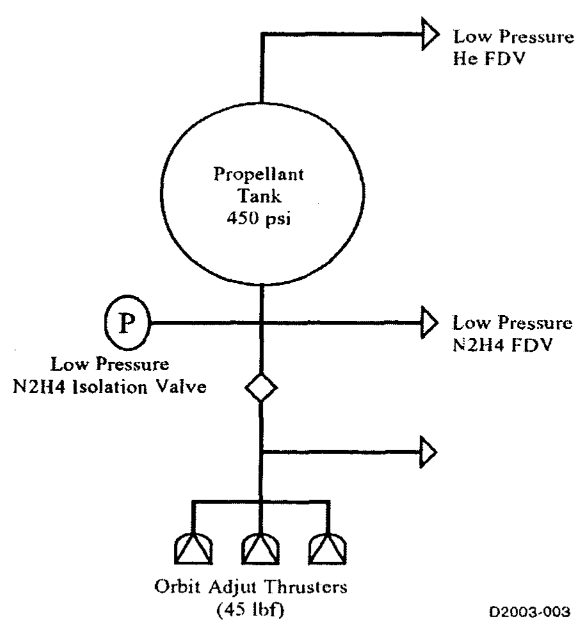

Figure 14. HAPS Block Diagram

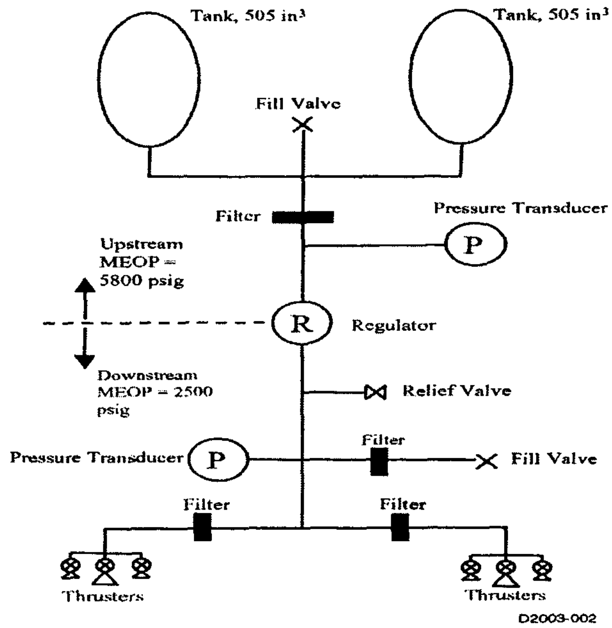

Figure 15. HAPS RCS Block Diagram

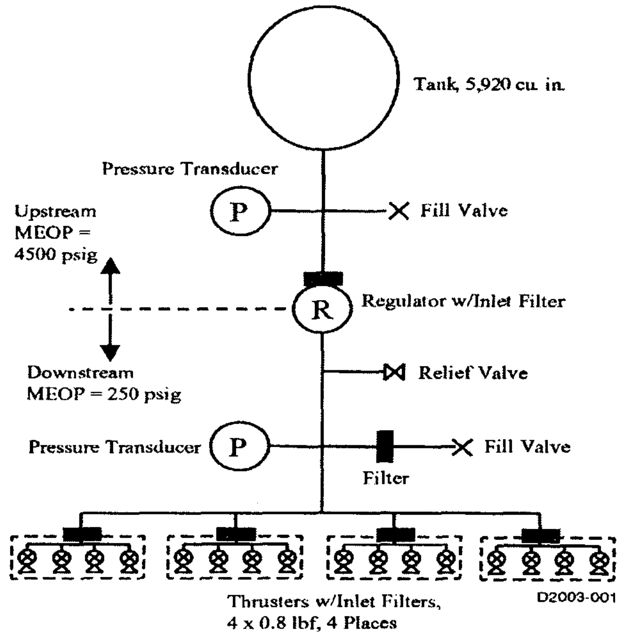

Figure 16. DART RCS Block Diagram

4.5. Structure Subsystem

The DART Vehicle Structure is predominantly a heritage Pegasus design consisting of an aluminum honeycomb core wrapped in Toray T-800/RS-17 composite facesheets. A solid composite cone connects the AVGS Bus to the Pegasus Avionics section. The front panel, which is machined aluminum, serves as the AVGS base plate.

4.6. Thermal Subsystem

The thermal control subsystem consists of Multilayer Insulating (MLI) blanket over most of the vehicle. Selected boxes (MACH, SIGI, Transmitters) also have thermal radiators with silver teflon tape to radiate excess heat to space. Some items (HAPS tubing, AVGS, antennas) have heaters that are controlled by thermostats.

5. CURRENT STATUS

The project was initiated in June 2001. SRR was held in Sept 2001. PDR was completed in August, 2002 and CDR was completed in Dec, 2002. The DART vehicle in currently in the build up and subsystem testing stage at Orbital's Satellite Manufacturing Facility in Dulles, VA. System level testing planned for summer and fall, 2003. Field site integration and testing with the Pegasus Launch vehicle at Vandenberg AFB, CA, is planned for the first quarter of 2004. Launch is planned for April 2004.

End to End mission simulations employing C-based flight code have been performed as part of CDR. These simulations have shown that the design is exceptionally tolerant to severe GN&C dispersions and stress cases, including Navigation outages. It is useful to view a typical simulation response with the current design. Figure 17 and Figure 18 and depict the DART response to a set of rendezvous guidance and proximity operations commands. On the plotted distance ranges of these Figures, several large-scale maneuvers can be seen: 1) The rendezvous from a phasing orbit approximately 250 km below the target to a point

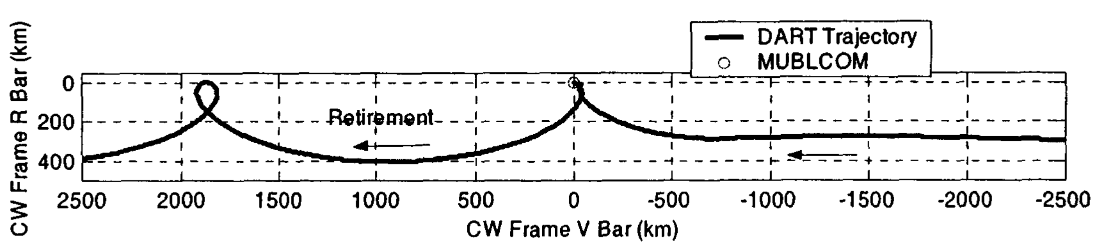

Figure 17. Rendezvous Simulation Results

approximately 7.5 km below and 40 km aft of the target, 2) A controlled drift phase, and 3) A transfer

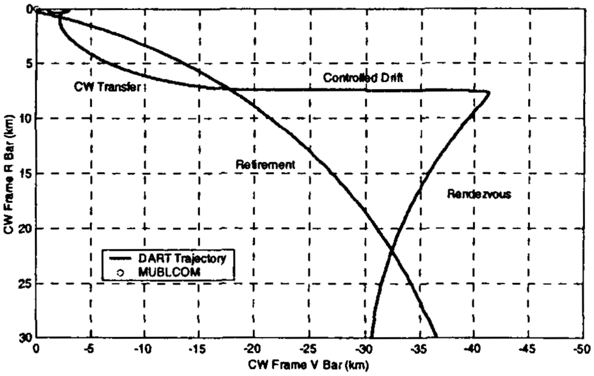

Figure 18. Rendezvous Simulation Results

from the controlled drift phase up to the –V Bar, to a point 3 km aft of the target. Figure 19 offers an expanded-scale version of the position response, focusing on proximity operations. For reference, Figure 20 depicts a representative stress-test result. The Figure provides a visual summary of the maturity of the current design. For this case, large dispersions to the guidance, control, and navigation parameters were applied to the simulation along with simulated GPS outages. The trajectory response is positive and stable throughout the mission, and provides confidence that additional performance analyses will continue to prove out the soundness of the GN&C design.

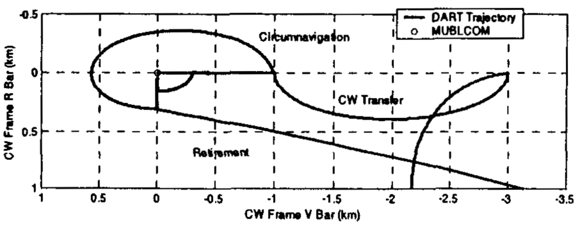

Figure 19. Proximity Operations Simulation Results

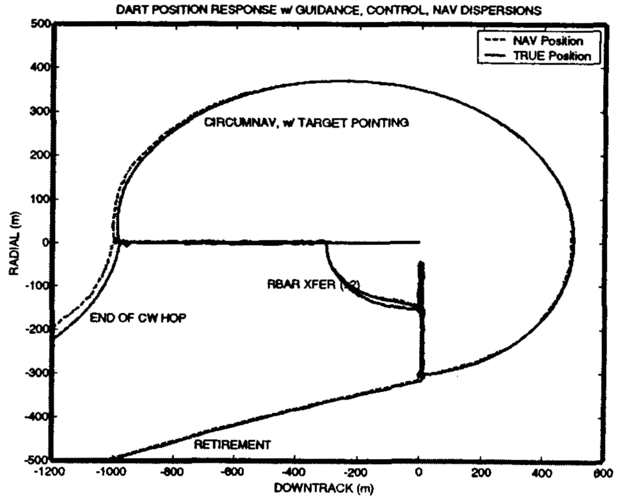

Figure 20. Proximity Operations Simulation Results with Stress Testing

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