NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Demonstration of Autonomous Rendezvous Technology

Press Kit
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General Fact Sheet & Media Services Information

FACT SHEET

DART DEMONSTRATOR TO TEST FUTURE AUTONOMOUS RENDEZVOUS TECHNOLOGIES IN ORBIT

The Demonstration of Autonomous Rendezvous Technology (DART) is a flight demonstrator that provides a key step in establishing autonomous rendezvous capabilities for the U.S. space program and its Vision for Space Exploration. While previous rendezvous and docking efforts have been piloted by astronauts, the unmanned DART spacecraft will have only computers and sensors to perform all of its rendezvous functions.

Future applications of technologies developed by the DART project will benefit the nation in future space systems development requiring in-space assembly, services, or other autonomous rendezvous operations.

DART is designed to demonstrate technologies required for a spacecraft to locate and rendezvous, or maneuver close to, other craft in space. Developed by Orbital Sciences Corporation of Dulles, Va., the DART spacecraft will be launched on a Pegasus vehicle from its Stargazer L-1011 aircraft. At approximately 40,000 feet over the Pacific Ocean, the Pegasus vehicle will be released with the DART spacecraft. The vehicle will then boost the DART spacecraft into approximately a 472-by-479-mile polar orbit.

Once on orbit, DART will travel around the Earth to rendezvous with the target satellite -- the Multiple Paths, Beyond-Line-of-Sight Communications (MUBLCOM) satellite -- also built by Orbital Sciences. Launched in May 1999, the MUBLCOM satellite was used by the Department of Defense as an experimental communications satellite and was outfitted with optical retroreflectors designed for future use with a video guidance system such as the Advanced Video Guidance Sensor (AVGS) onboard DART.

The AVGS is an advanced version of the Video Guidance Sensor developed by the Marshall Space Flight Center in Huntsville, Ala., for NASA's Automated Rendezvous and Capture Project, which demonstrated these automated capabilities in the mid-1990s -- including two successful flight tests on board the Space Shuttle. The next-generation AVGS incorporates advanced optics and electronics and allows DART to communicate with and track the MUBLCOM satellite within a range of 5 to 250-plus meters.

Once DART reaches the MUBLCOM satellite, it will perform several autonomous rendezvous and close proximity operations, such as moving toward and away from the satellite using navigation data provided by the AVGS and Global Positioning System (GPS).

The Autonomous Rendezvous and Proximity Operations (ARPO) software on DART will test additional algorithms by calculating and executing collision avoidance maneuvers and circumnavigation -- navigating around the MUBLCOM satellite. To conclude the mission, DART will fly away from the MUBLCOM satellite. The entire 24-hour mission will be accomplished without human intervention.

The fourth stage of the Pegasus vehicle is an integral part of the DART spacecraft, sharing avionics and propulsion components while in orbit. The auxiliary propulsion system includes three hydrazine-fueled thrusters, and the reaction control system includes six nitrogen-fueled thrusters. The DART spacecraft also uses 16 nitrogen-fueled thrusters for proximity operations.

The DART spacecraft is about 6 feet long, with a diameter of 3 feet, and weighs approximately 800 pounds with fuel.

In June 2001, Orbital Sciences Corporation was awarded contracts to design and develop the DART flight demonstrator, including orbital flight test and integration and launch with a Pegasus vehicle. Software and hardware testing is underway. Assembly and integration of the DART spacecraft was completed summer 2004. Launch is scheduled for spring of 2005. The DART budget including launch services is approximately $110 million.

Flight demonstrators, like DART, have a critical role in demonstrating technologies that cannot be validated on the ground. DART will help lay groundwork for future reusable manned and unmanned launch vehicle missions using autonomous rendezvous operations. Future technology applications may aid in cargo delivery, servicing missions for the International Space Station and other on-orbit activities, such as satellite retrieval or servicing to enable future civil, defense and commercial space transportation. NASA is pursuing technologies that will enable the Agency to achieve its goals of establishing safe, reliable, affordable access to space.

The DART project is the first demonstration program selected by NASA's Exploration Systems Mission Directorate to develop technologies for tomorrow's exploration of the Solar System. The DART project is managed by the Marshall Space Flight Center. The Kennedy Space Center has oversight responsibilities for launch integration and launch services.

For more information on the DART project, including electronic images and animation, visit: **http://www.msfc.nasa.gov/news/dart/**

Media Services Information

NASA Television Transmission

NASA Television is broadcast on AMC-6, transponder 9C, C-band, at 72 degrees west longitude. The frequency is 3880.0 MHz. Polarization is vertical and audio is monaural at 6.80 MHz. The tentative schedule for television transmissions of mission activities is described below; updates will be available from the DART Public Affairs Office at Vandenberg AFB, California, the Media Services Group at John F. Kennedy Space Center, Florida, and from NASA Headquarters in Washington.

NASA TV Coverage of Briefings & Launch

The launch of the Demonstration for Autonomous Rendezvous Technology (DART) from Vandenberg AFB, California, is scheduled to occur during a 7-minute launch window which extends from 1:21 to 1:28 p.m. EDT (10:21 to 10:28 a.m. PDT) Friday, April 15, 2005. Live NASA TV coverage of the launch will begin at noon EDT (9 a.m. PDT) and will continue through spacecraft separation.
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Events carried live on NASA TV will also be accessible via Webcast at **http://www.ksc.nasa.gov/nasadirect/index.htm.** Please check the NASA TV schedule for updated dates and times of mission events.

Launch Media Credentialing for Vandenberg AFB

News media desiring accreditation for the launch of DART should fax their request on news organization letterhead to:

30th Space Wing Public Affairs
Vandenberg Air Force Base, California
Attention: Tech. Sgt. Rebecca Danet
Fax: 805/606-8303
Telephone: 805/606-3595

Internet Information

Information on the mission, including an electronic copy of this press kit, press releases, fact sheets, status reports and images, is available at http://www.nasa.gov/mission_pages/dart/main/index.html and at the Kennedy News Center on the Web at http://www.nasa.gov/centers/marshall/news. Launch coverage is available at http://www.nasa.gov/ntv.

Launch Site & Vehicle

The spacecraft and the Pegasus launch vehicle, carried under an L-1011 aircraft, will take off from Vandenberg Air Force Base, Calif., and dropped approximately 40,000 feet over the Pacific Ocean. The Pegasus XL launch vehicle is a winged, three-stage rocket booster weighing approximately 23,300 kg (51,300 pounds mass) and measuring 16.9 meters (55.5 feet) long and 1.27 meters (4.16 feet) in diameter. The DART is 1.829 meters (6 feet) long, 0.92 meters (3 feet) in diameter and weighs 363 kilograms (800 pounds).

Launch Period

The launch period opens on Friday, April 15, 2005, at 1:21 p.m. EDT (10:21 a.m. PDT). The second launch opportunity opens April 17 at 1:21 p.m. EDT.

Launch Time

There is a seven-minute launch window April 15 which extends from 1:21 EDT to 1:28 EDT.

DART Quick Facts

DART Spacecraft

Length	1.829 meters (6 feet)
Diameter	0.92 meters (3 feet)
Weight	363 kg (800 pounds)
Power	Six 50-amp hour batteries with twp 9-amp hour transient batteries
Batteries	Lithium Ion

Pegasus XL Launch Vehicle

Manufacturer & Type	Orbital Sciences Corp., Pegasus Stargazer L-1011 aircraft with Pegasus launch vehicle
Length	55 feet
Diameter	4 feet
Wingspan	22 feet
Weight	51,000 lbs.
Stages	4
Fuel	The Pegasus is an inertially guided three-stage solid rocket vehicle. The fourth stage includes an auxiliary propulsion system with three hydrazine fuel thrusters. The Pegasus reaction control system includes six nitrogen-fueled thrusters producing 150 pounds of force.

Mission

Launch Date	April 15, 2005
Site	Vandenberg Air Force Base, Lompoc, Calif.
Duration	Approximately 24 hours

Orbit

Characteristics	Approximately 472 mile x 479 mile polar orbit, passing over each pole every 99.7 minutes
Semi-major axis	7122.35 km (4422.98 mi)
Eccentricity	0.0004645
Apogee altitude	659.1 km (409.6 miles)
Perigee altitude	639.5 km (397.4 miles)
Inclination	97.7548°
Argument of Perigee	311.5608°
Right Ascension of ascending node	354.8294°
True Anomaly	288.7

Program

Duration	The DART Project authority is determined by the NRA 8-30 Source Evaluation Board (SEB), Cycle I Award. The DART Authority to Proceed (ATP) was initiated June 1, 2001, for Contract NAS8-01102. Contract completion date: June 2005.

Cost	The approximate cost of the DART project, including launch is $110 million.

DART Spacecraft

Diagrams of the DART vehicle configuration are shown in Figures 1 and 2. The vehicle combines two discrete systems into one: the DART spacecraft and the Pegasus launch vehicle. The aft portion is the Pegasus fourth stage including the avionics assembly and Hydrazine Auxiliary Propulsion System (HAPS). The forward portion, referred to as the Advanced Video Guidance Sensor (AVGS) bus, houses a propulsion tank, Reaction Control System (RCS) thrusters, batteries, communications equipment, and the AVGS that will be used for navigational data during proximity operations.

The AVGS sensor uses laser signals returned from retro-reflectors on the target vehicle to calculate relative bearing and range measurements. At ranges between 300 meters and at least 500 meters, the AVGS can provide bearing-only measurements to the target while operating in spot mode. Within a range of 300 meters, the AVGS is able to provide bearing, range, and relative attitude of the target in tracking mode.

The DART vehicle will be controlled using a combination of three propulsion subsystems. The HAPS system consists of three hydrazine thrusters, each producing approximately 222 newtons (50 pounds) 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. The HAPS tank is capable of holding 56.88 kilograms (125.4 pounds) of hydrazine.

The HAPS assembly also includes a set of 6 cold-gas nitrogen thrusters, producing 56 newtons (12.5 pounds) of thrust or 111 newtons (25 pounds) of thrust each, to provide three-axis attitude control during orbital drifts and roll control during HAPS burns. These thrusters are fed from a dedicated 5.77 kilograms (12.73 pounds) tank.

The AVGS bus includes a set of 16 cold-gas nitrogen thrusters (3.6 newtons or 0.8 pounds of force each) for translational and attitude control during proximity operations. The DART nitrogen tank will be capable of holding at least 22.68 kilograms (50 pounds) of propellant. The specific impulse of these thrusters will be 60 seconds.

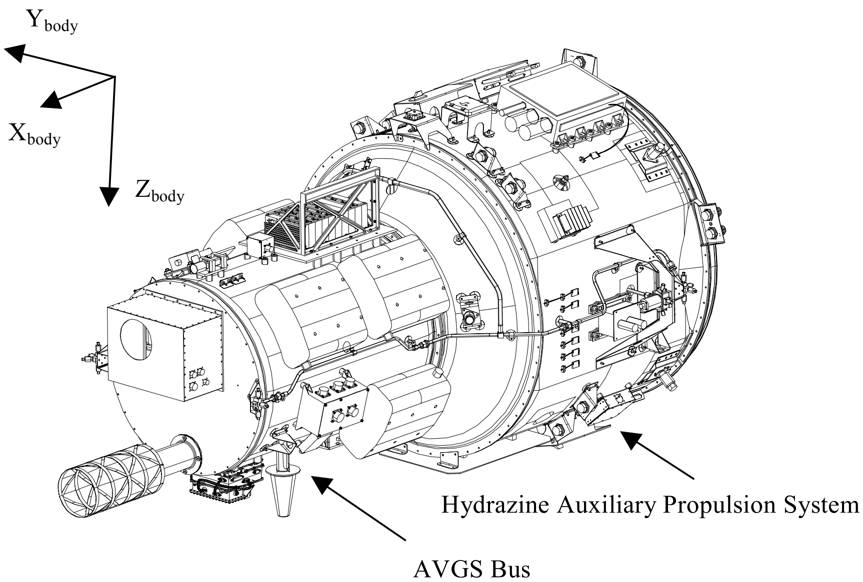

Figure 1. DART Vehicle Configuration

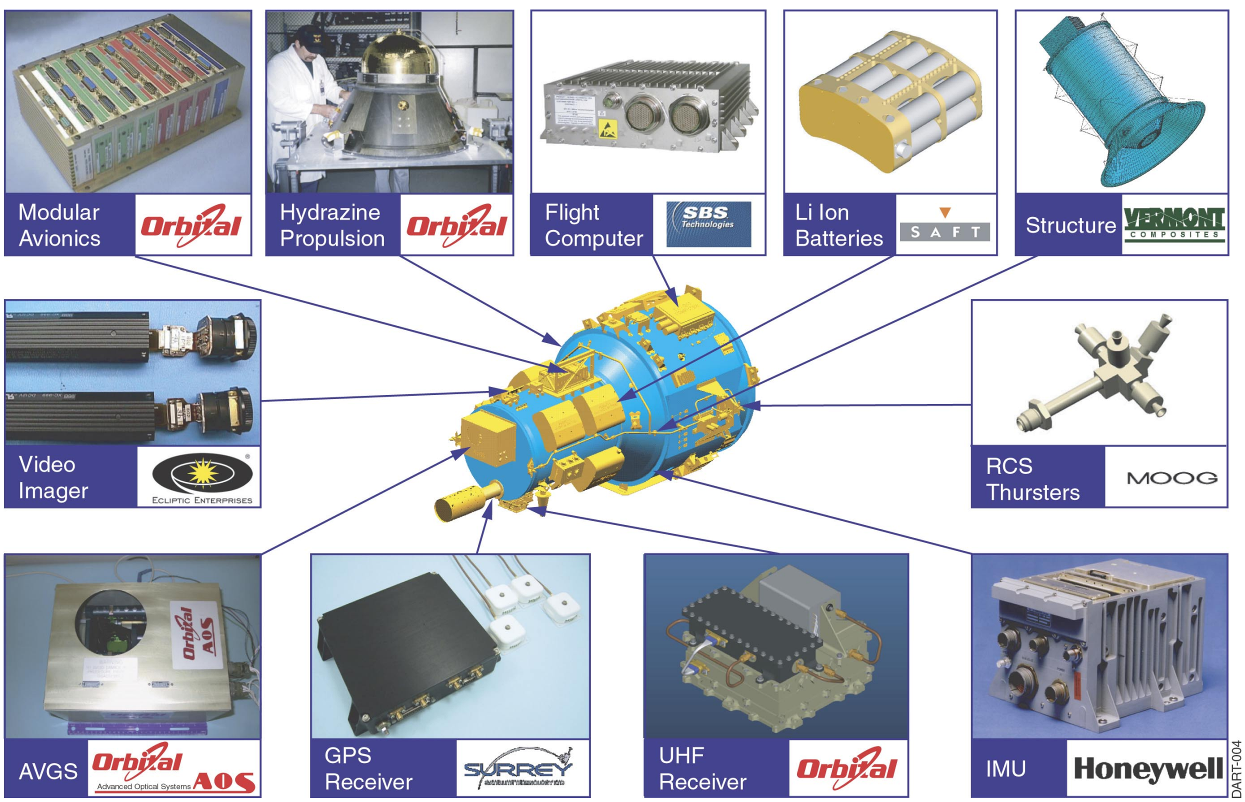

Figure 2. DART assembly and component diagram

The Target Vehicle

The target vehicle for the DART mission will be MUBLCOM, an experimental communications satellite launched for DARPA aboard a Pegasus launch vehicle in 1999. The MUBLCOM satellite design is shown in Figure 3.

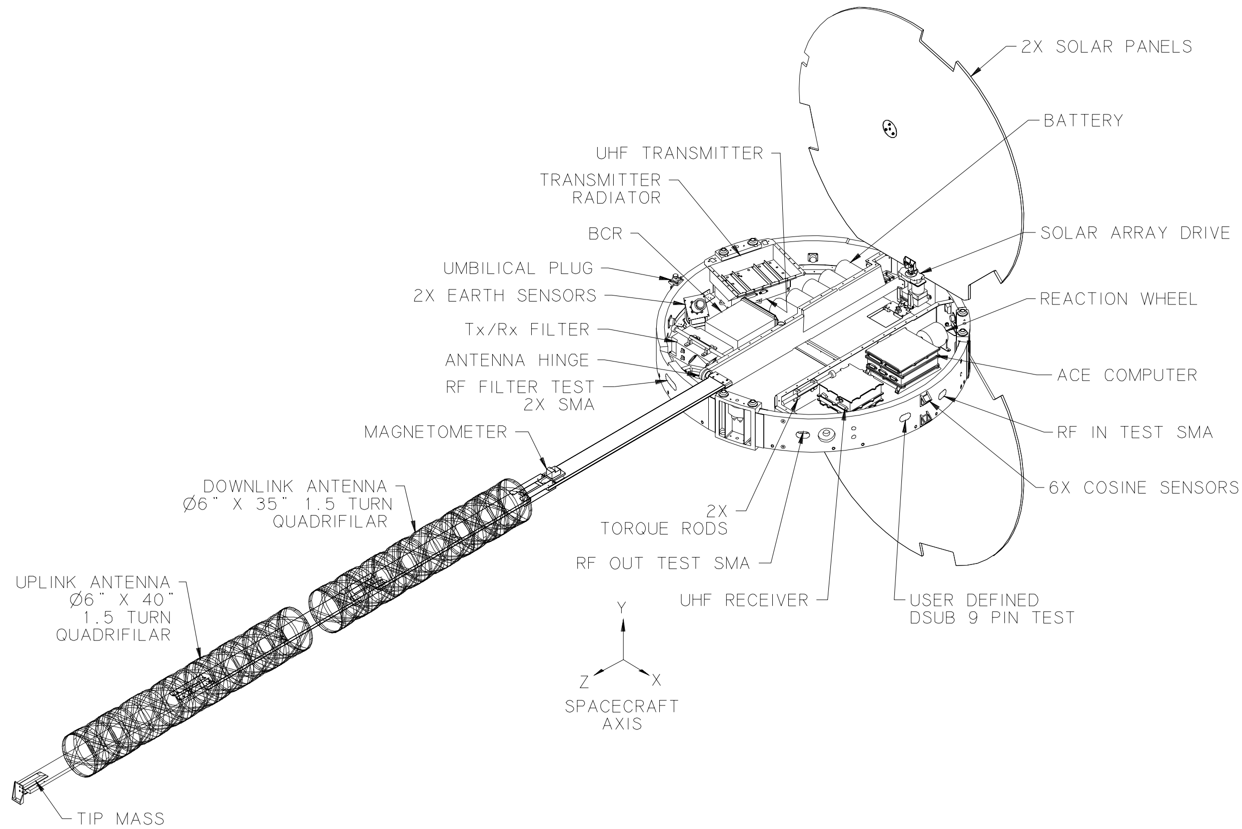

Figure 3. MUBLCOM Satellite Configuration

Retroreflectors designed for use with the Marshall Space Flight Center's Advanced Video Guidance Sensor (AVGS) have been installed along the edge of the central ring as shown in Figure 4. The long-range retroreflectors are consequently pointed 7° downward from the local horizontal when MUBLCOM is gravity-gradient stabilized. A set of short-range retroreflectors for use with the AVGS are available as well. The MUBLCOM satellite also includes a set of far-range retro-reflectors designed to allow laser tracking from a ground station. These are nearly symmetrically arranged around the nadir-pointing boom ($+Z_{sc}$ axis).

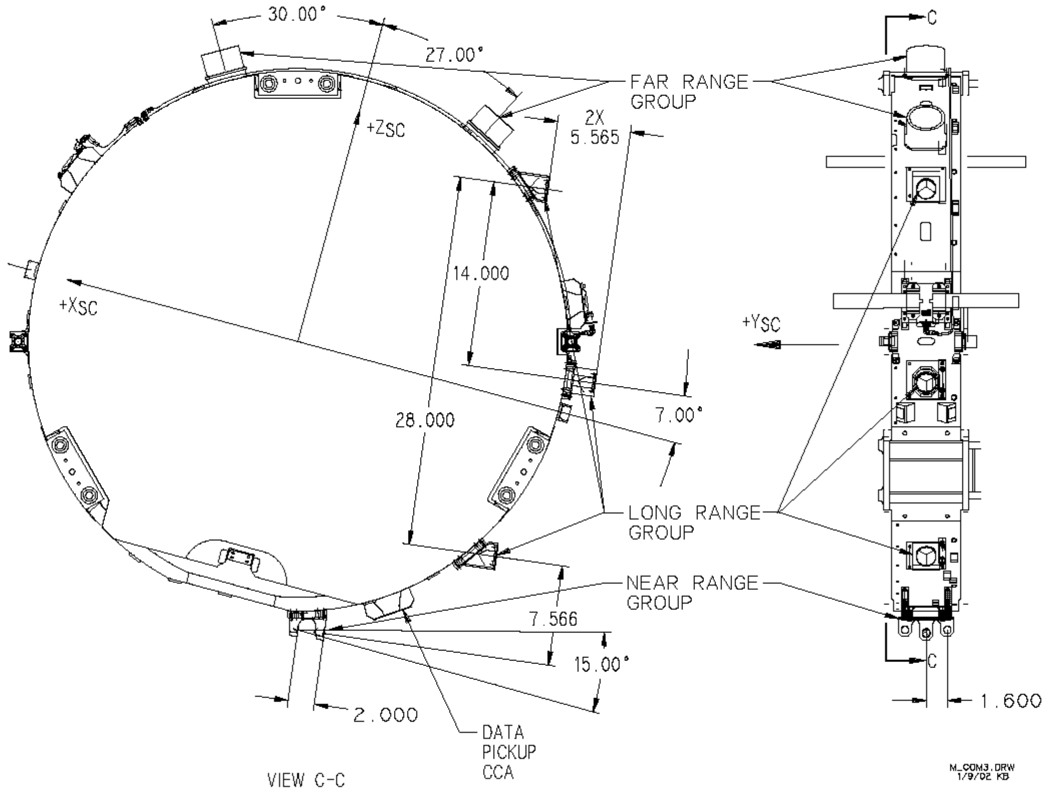

Figure 4. MUBLCOM AVGS Target Reflector Locations

A summary of the mean orbital characteristics of the MUBLCOM satellite are presented in Table 1. The basic data was obtained from the Satellite Toolkit (STK v4.2) satellite database, which contains a compilation of Two-Line Element (TLE) sets regularly updated by the U.S. Space Command. Additional orbital characteristics have been estimated analytically based on the STK data. Note that the apogee and perigee altitudes are referenced to the equatorial radius. The ground track for MUBLCOM over a 24-hour period is presented in Figure 5.

TABLE 1. PREDICTED MUBLCOM ORBIT CHARACTERISTICS AND TLE SET

TLE Epoch Year	2004
TLE Epoch Day of Year	292.5
Mean Motion	14.44335829
Eccentricity	0.0004645
Inclination	97.7548 deg
Argument of Perigee	311.5608 deg
Right Ascension of Ascending Node	354.8294 deg
Mean Anomaly	160.2497 deg
Mean Semimajor Axis	7122.35 km (4422.98 mi)
Mean Period	99.70 min

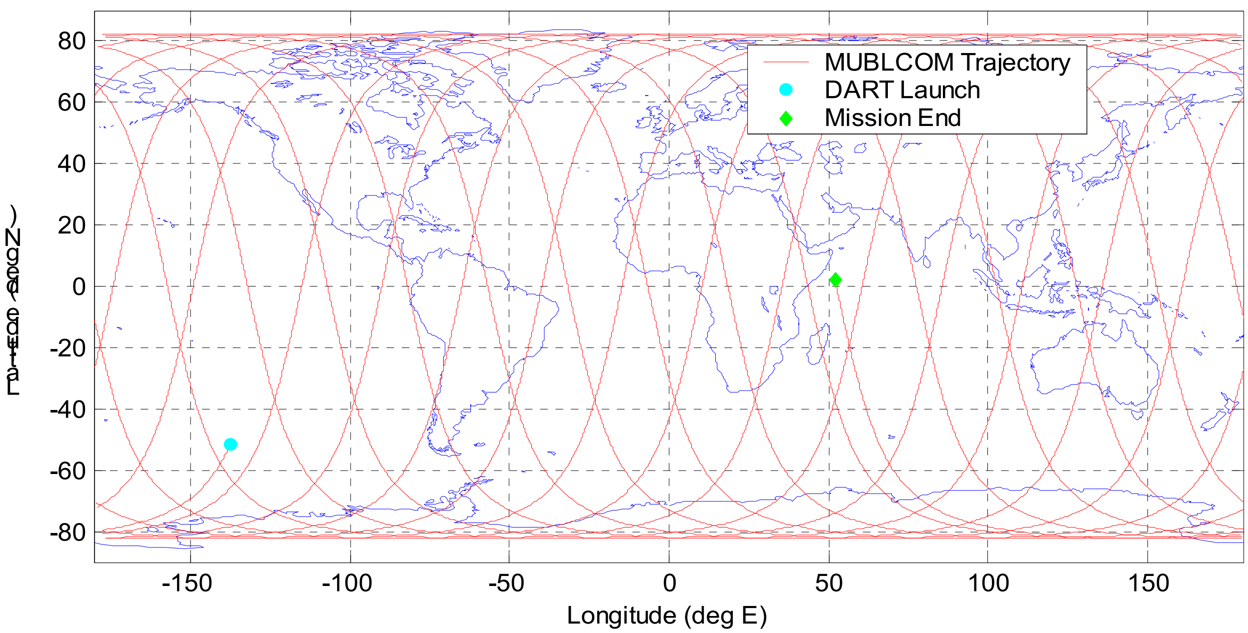

Figure 5. MUBLCOM Orbit Ground Track

DART Key Technologies

Advanced Video Guidance Sensor (AVGS)

The hardware element of the program -- AVGS -- is the primary sensor for close proximity operation in the DART mission. The success of the MSFC-developed Video Guidance Sensor (VGS) which flew successfully onboard two Space Shuttle missions (STS-87 and STS 95) as experiments led to the current work with the DART project, under which Orbital Sciences Corporation and NASA developed the next generation sensor.

AVGS development under the DART project has matured electrical and mechanical design, increased operational performance, reduced weight, decreased power consumption and qualified components for spacecraft use. The DART mission will mature the AVGS technology to track objects in space.

AVGS actively uses laser and image technology to find and measure a known configuration of passive retroflectors on a target, and hence is a two-part system. The AVGS utilizes geometric position of the return images from retroflectors to determine relative range, bearing, and attitude data when a valid target pattern is received. In the absence of a valid tracking target, the AVGS will return relative bearing information. The target geometric configuration contributes to the range performance characteristics of the system.

The AVGS will provide line of sight bearing from greater than one kilometer and provide 6 degreeof freedom (DOF) relative position and attitude data from 300 meters to dock. AVGS objectives during the DART mission are:

- Demonstrate AVGS capabilities.
- Demonstrate various approach techniques with an AVGS.
- Demonstrate bearing data at ranges beyond 300 meter.
- 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 meters from the target.
- Validate ground test results of the AVGS
- Validate ground simulations/test facilities with Flight Data.

Automated Rendezvous and Proximity Operations (ARPO)

The main functions of the ARPO system are guidance, navigation, control and mission management. In the past, vehicles have been guided by humans in the loop with programs to assist in the accomplishment of specific tasks. Future development of transportation systems requires the ability to assemble spacecraft in Earth orbit, or around other celestial bodies, and the ability to dock, refuel and transfer cargo between system elements. The technology of bringing two objects together in space safely and accurately without human intervention requires hardware and software that is robust, reliable and cost effective.

The DART vehicle navigation system fuses together multiple sensor data to obtain the best absolute and relative navigation solutions throughout the mission. The system's foundation is a Honeywell Inertial Navigation System (INS) of extremely accurate rate gyros and accelerometers. Data has a tendency to drift in accuracy over time, so the use of a modified terrestrial Global Positioning System (GPS) for long term stability and accuracy has been added to create a GPS/INS sensor. A GPS system can only be used in low Earth orbit (LEO), but other methods of navigational updates have been considered for use beyond LEO. Due to the space application of DART, a high performance, multi-channel, stand-alone Surrey GPS receiver was added as primary navigator for the mission. In LEO as many as 16 GPS satellites are available and can be used to increase the performance of the system. GPS state vector differencing is used in the DART mission to get within range of a proximity sensor. The close approach navigation of two vehicles requires the use of a high accuracy proximity sensor that can give not only position but relative attitude required for docking of the vehicles.

The DART mission fuses AVGS sensors, the primary proximity sensor, with sensors in its internal navigation filter to give the best possible navigation state, during all mission phases. This data is also used to create Keep Out Spheres (KOS) around the Target Vehicle, which are used to determine and incorporate Collision Avoidance Maneuvers (CAM) to ensure safety.

When two vehicles approach each other their initial orbits can be quite different. The altitude above a central body can be quite large. This difference in altitude allows the two vehicles to close so that docking can be accomplished, but also requires the on-board system to precisely adjust this altitude difference. The DART guidance uses both orbital altitude logic and proximity altitude logic to accomplish this. The orbital altitude guidance determines the difference between the two vehicles' altitude and what maneuver would accomplish the orbit raise (or lower) burn that would bring the two spacecraft into close proximity using a minimal amount of fuel. Orbital mechanics is used in both far field rendezvous and proximity operations. The chase vehicle must align both altitude and inclination to accomplish this. In the DART mission, DART is inserted into an orbit that is nearly 500 km (310 miles) circular and the target vehicle (the

MUBLCOM satellite) is at an altitude of 760 Km (472 miles). DART uses the altitude difference to “catch-up” to the MUBLCOM satellite. The main propulsion system on the DART vehicle is used to perform the orbit altitude burns and the out-of-plane burns required to align the two vehicles in proximity of each other.

Once the rendezvous is complete the proximity operation phase of the mission begins. This is the point at which inertial navigation changes to relative navigation. During this phase of the mission the guidance system uses algorithms that continue to bring the two vehicles closer together. Guidance designed for DART can perform station-keep maneuvers, circumnavigation, free-drift maneuvers, Clohesy-Whiltshire (CW) maneuvers (equations of motion used with spacecraft in circular orbit, defined with the target as the origin) and forced approaches along any approach path to the target vehicle. During the DART mission an approach along the velocity vector (Vbar) and radius vector (Rbar) are performed, along with the final docking approach along the docking axis of the target.

While the DART navigation system tells the vehicle where it is and where it wants to be, guidance determines how it want to get there. The control system takes the guidance commands and performs the burns. The control system consists of both a rotation and translation autopilot. During orbital altitude burns the control system points the vehicle in the correct direction for the main engines to burn. Much of rendezvous consists of drifting between burns. During this time the attitude autopilot controls the vehicle and points it in a direction that allows transmission to ground stations and controlled thermal heating from the Sun, Earth and deep space. Once rendezvous is complete the control system regulates both translation and rotation simultaneously until docking approach is complete. The most critical portion of the mission is during the docking maneuvers. The vehicle must be very agile and responsive. The control system is also used during the mission to scan an area of space to acquire and track the target.

The heart of the vehicle is the "mission manager," or software that determines how the mission is performed. The DART program goes beyond what has been done in the past, with the "mission manager" determining the running mode of the guidance, navigation and control system. It must determine the kind of maneuvers needed and when events require the system to back away and recover from anomalous situations. The "mission manager" is the replacement for the human or ground control used in the past. The intelligence level of the "mission manager" depends on the type of vehicle and system requirements.

The DART "mission manager" is at a level that allows autonomy with contingency. There are three levels of autonomy that this kind of system is capable of accomplishing. The first is commonly referred to as a Scripted Mission Manager. This type of system is linear and when problems arise the system will fail since it can only follow pre-programmed orders. The second level of autonomy, called Automated, allows for some level of replanning and contingency that has been pre-programmed by software designer. These types of systems are commonly called rule–based or expert systems. The last level of autonomy is referred to as Autonomous Systems. These types of systems are extremely complex and the software is difficult to verify because of its inherent non-linearity. The DART system is an Automated System that can handle a number of contingency, faults and anomalies. The DART "mission manager" has the ability to skip over events, change the order of operations, and replan the mission on the fly. The system has been run through thousands of possible scenarios and tuned to accomplish the mission with limited consumables. This type system is more reliable and deterministic than a completely autonomous system at the present time, but is the precursor to a system that can think for itself.

The DART Project will demonstrate the algorithms required to safely, robustly, and accurately accomplish the rendezvous and proximity operation of two vehicles in low Earth orbit. The ARPO algorithms are the first step in the ability to build smart vehicles that can accomplish the missions required to advance the transportation systems for the future.

The Mission
Mission Overview

NASA has performed numerous rendezvous and docking missions, but all have had the common element of being piloted by astronauts. The objective of the DART mission is to demonstrate, in space, the hardware and software necessary for autonomous rendezvous.

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. Under the AR&C Program, the AVGS was flown successfully on two flight tests on board the Space Shuttle.

The DART mission will mature AVGS and ARPO technology even further, increasing the Technology Readiness Level (TRL) from the current level of four to seven. Both technologies have developed from a basic research phase to a full-up system demonstration phase, taking several years of research to complete. DART has gone from a proof-of concept or idea, taking individual components and proving them in a laboratory environment and developing them to a system prototype that will be flown in space.

The DART mission will evolve the technology by integrating 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 a target currently in orbit.

The DART satellite will test technologies in orbit by moving toward a target satellite and performing several mission operations such as docking, circumnavigating and collision avoidance maneuvers

The DART vehicle will be launched aboard a Pegasus XL launch vehicle equipped with an option 4th stage, a Hydrazine Auxiliary Propulsion System (HAPS). Figure 6 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. 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.

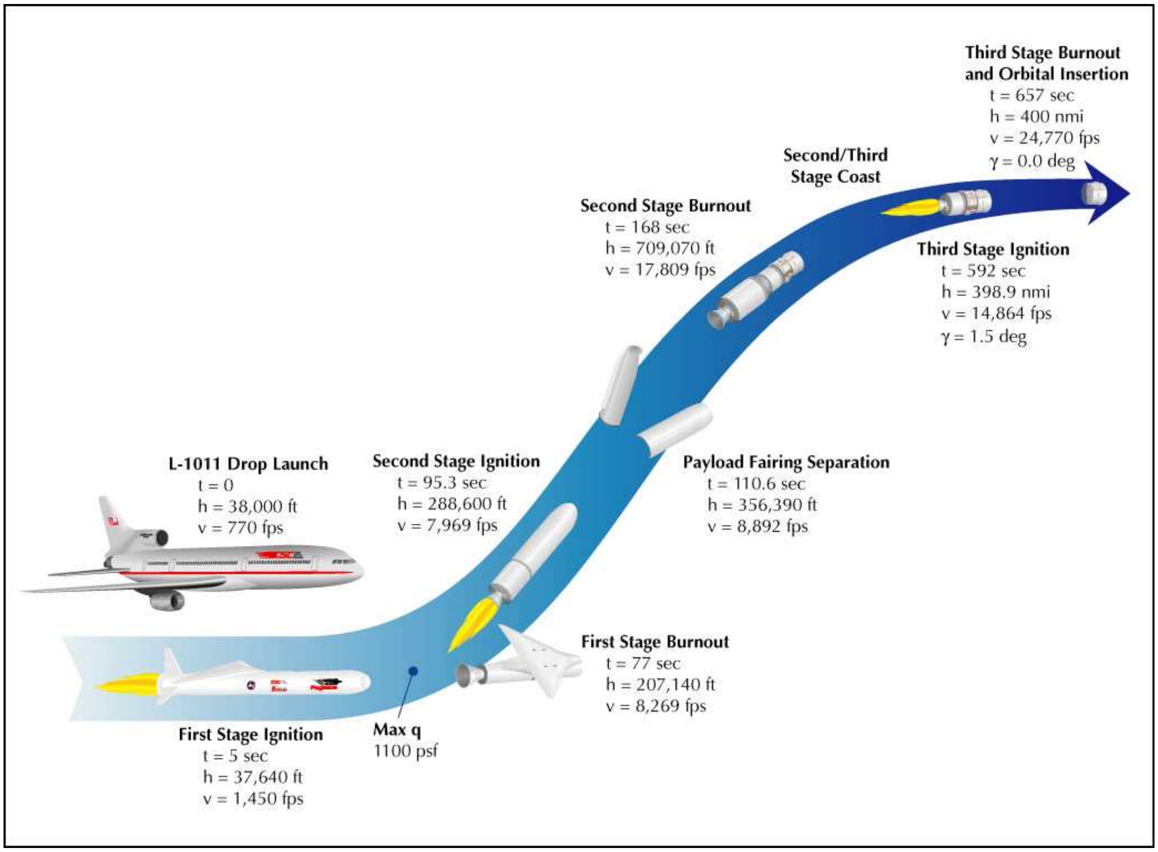

Figure 6. Pegasus XL Launch Operations for DART Mission

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 7.

This orbit will closely approximate a two-impulse Hohmann transfer, a fuel efficient way to transfer from one circular orbit to another circular orbit in the same plane and inclination but with a different altitude, 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, i.e., equations of motion used with spacecraft in circular orbits, defined with the target as the origin.

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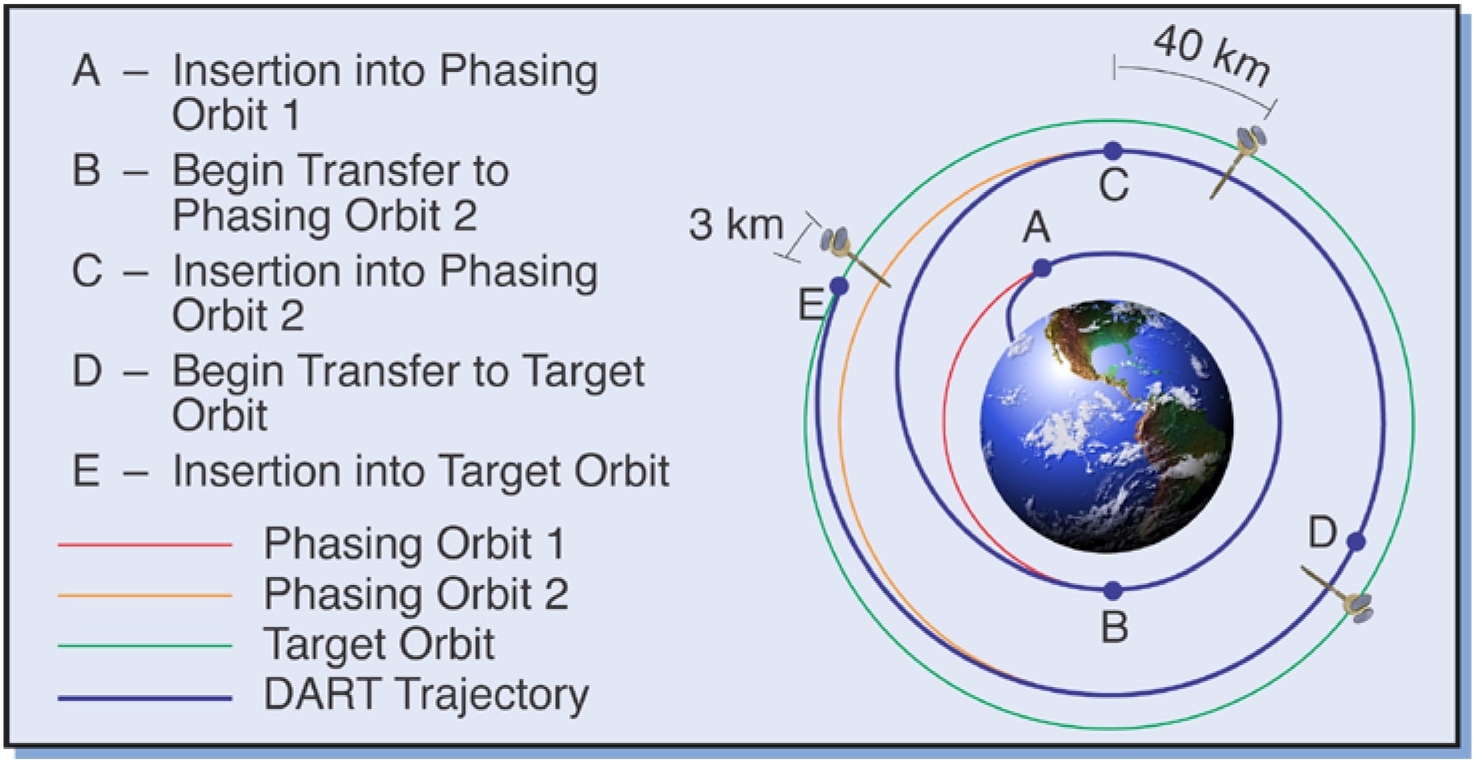


Figure 7. DART Phasing Orbits

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 Reaction Control System (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 8. 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 vehicle in the target orbit. DART will then perform another CW transfer to place it 1 km behind the target.

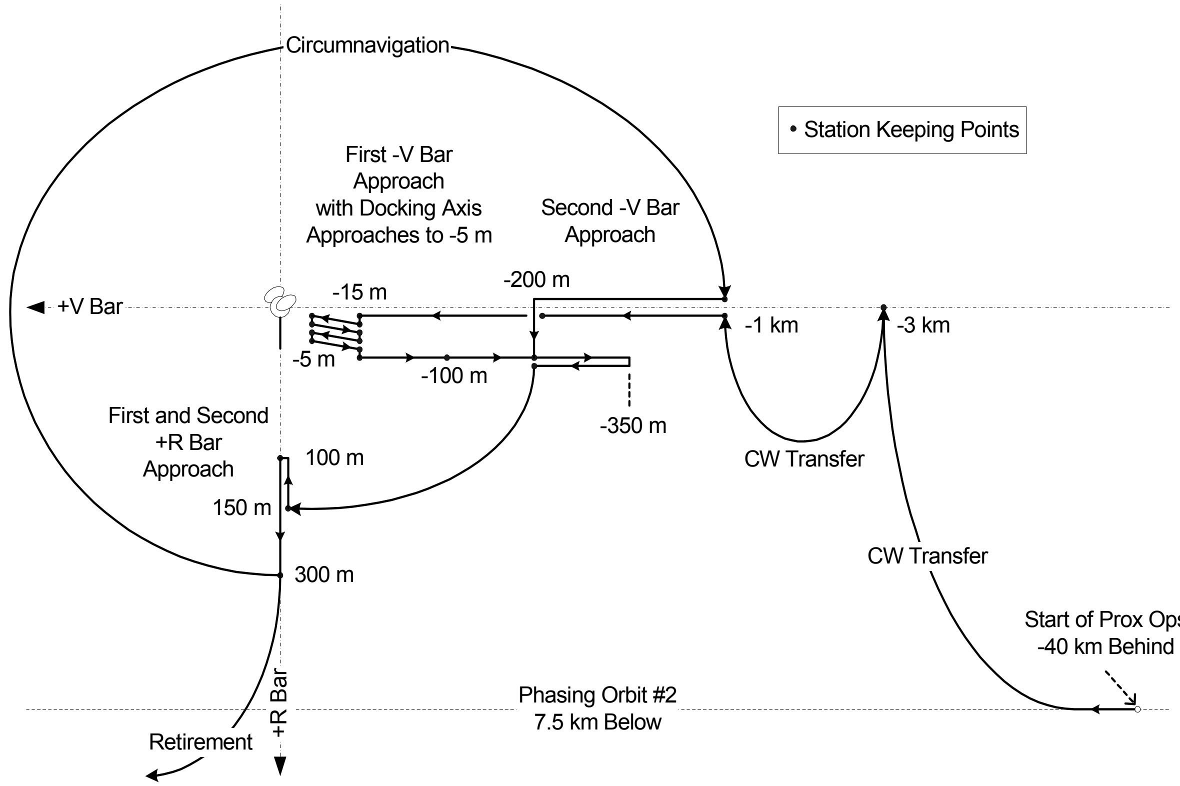


Figure 8. DART Proximity Operations

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.

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 Standards.

Mission Operations

Mission operations will be conducted from the DART Mission Operations Center (MOC) located at Vandenberg Air Force Base, Calif. Spacecraft communications will be conducted through NASA's Space Network, theTracking and Data Relay Satellite System (TDRSS).

Ground Station Visibility

The DART vehicle will employ an S-band transmitter to deliver telemetry data to the ground. This will be accomplished through the use of ground stations. Table 2 presents the locations of the S-band stations. The locations of these stations are shown in Figure 9 along with the DART vehicle ground track. Note that the current expectation is that the Vandenberg station only will be used to receive telemetry during launch operations.

TABLE 2. S-BAND GROUND STATION LOCATIONS

Station Name	Latitude (deg)	Longitude (deg)	Altitude (km)
Poker Flats, Alaska	65.12N	-147.46E	0.43
McMurdo, Antarctica	-77.84N	166.67E	0.15
Svalbard, Norway	78.22N	15.83E	0.46
Vandenburg, CA (VAFB)	34.57N	-120.5E	0.62

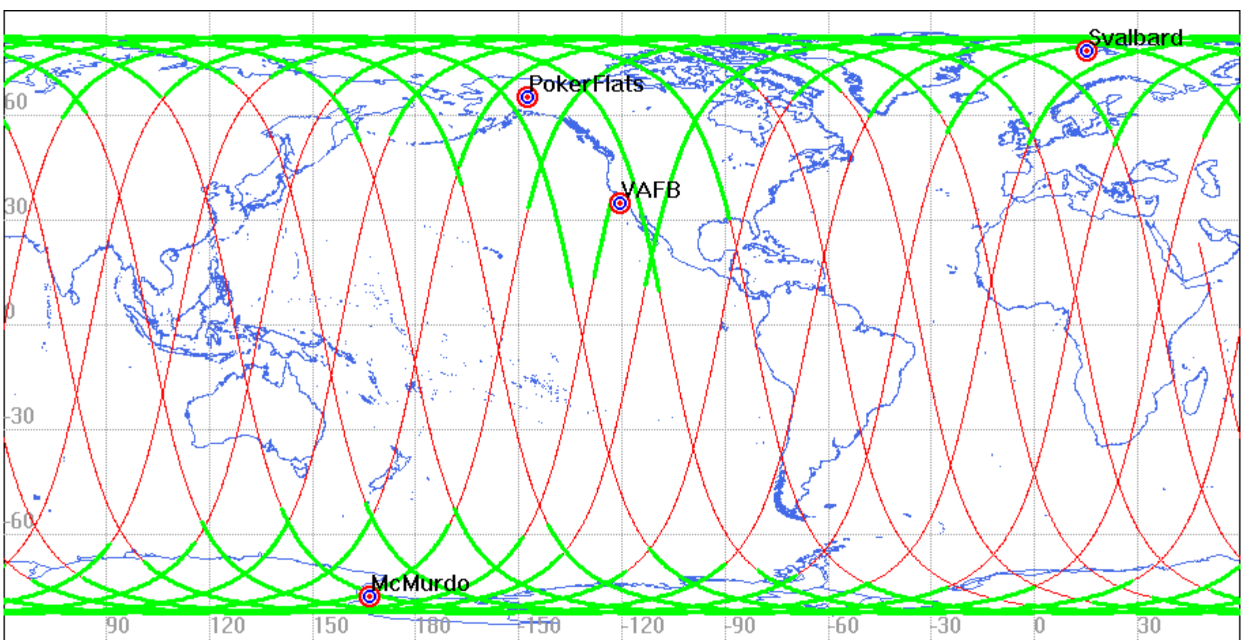


Figure 9. DART Mission Ground Station Access

Mission Time Line Summary

This mission time line is divided into four main phases:
1) Launch and Early Orbit (L&EO) Phase
2) Rendezvous Phase
3) Proximity Operations Phase
4) Retirement Phase.
Events occurring during each phase is shown in Figure 10 below.

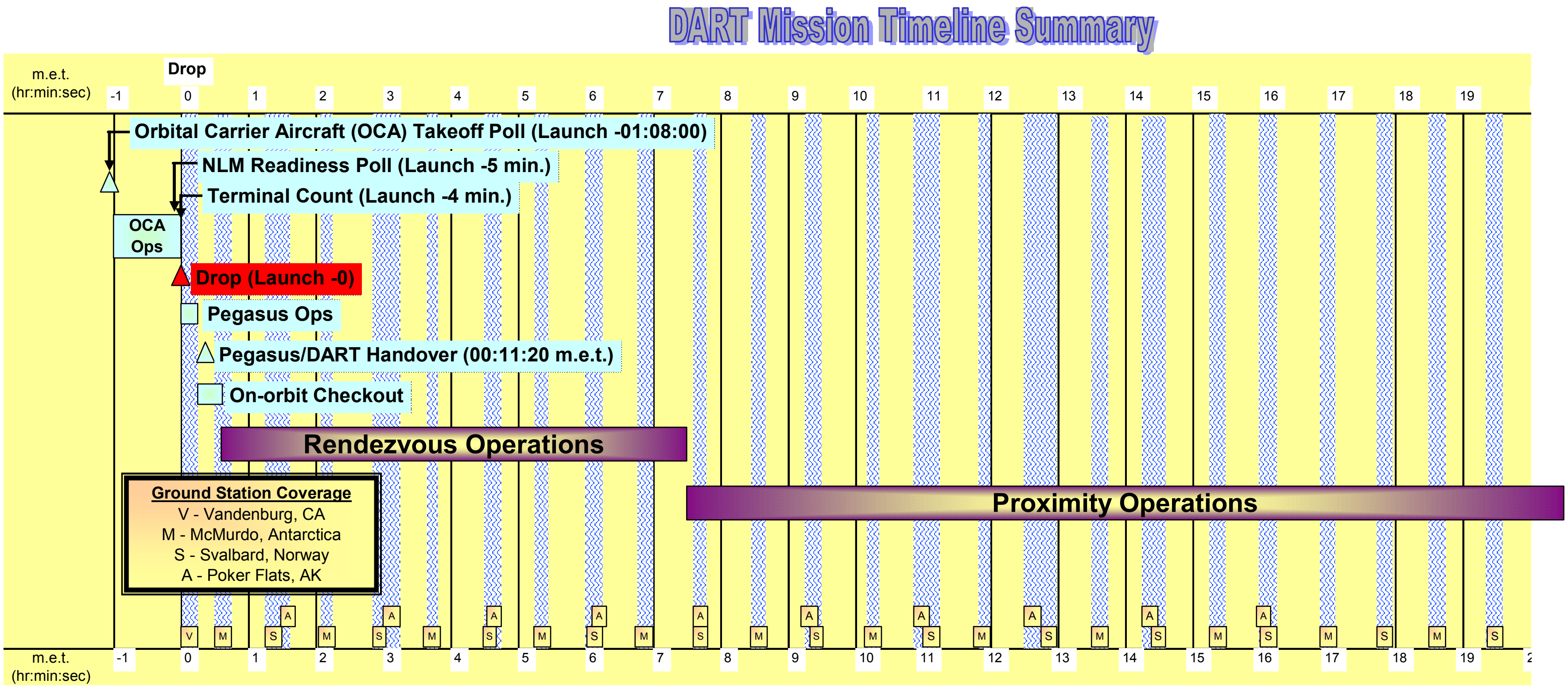
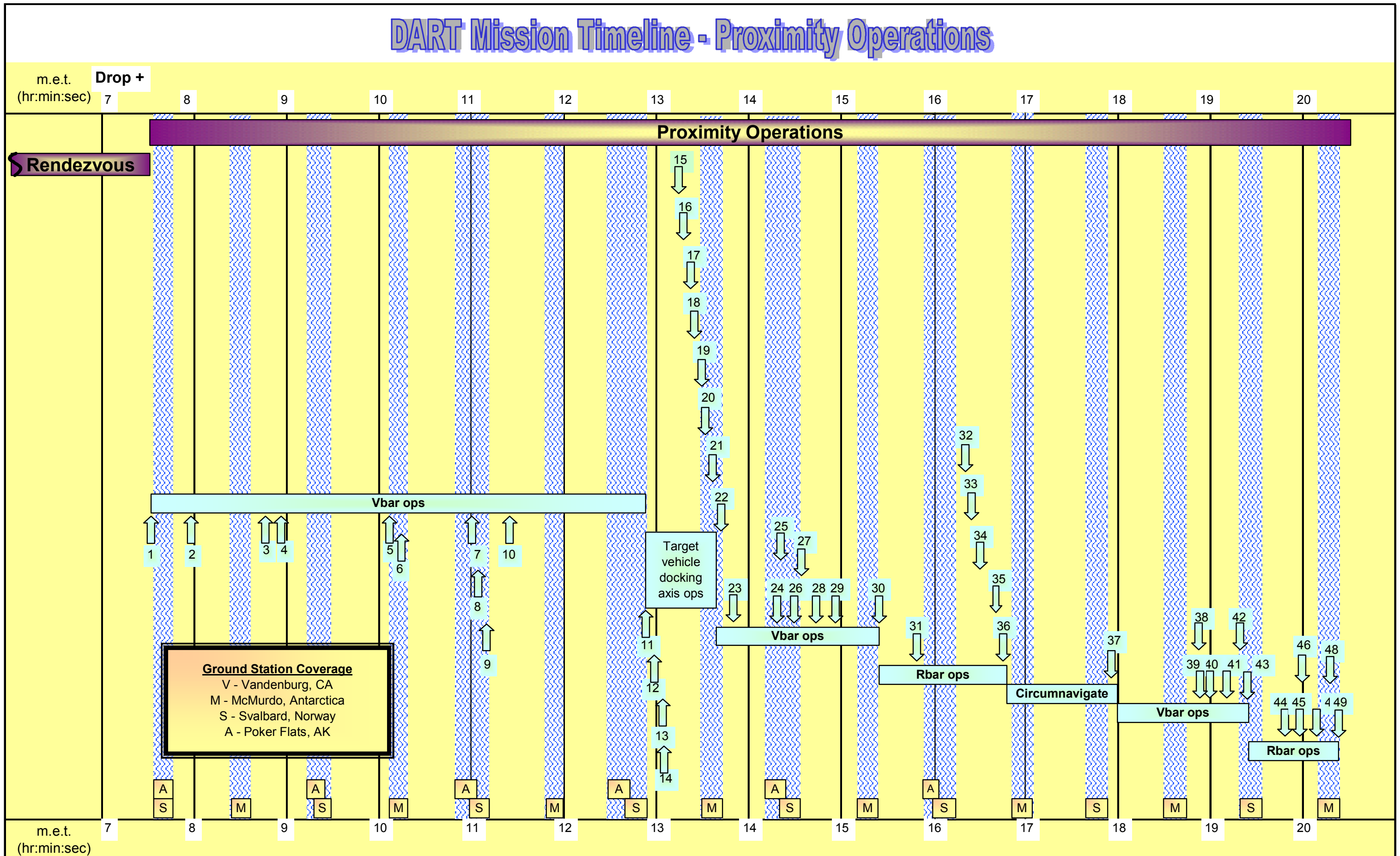


Figure 10. DART Mission Timeline Summary



DART On-Orbit Events

1 - Phasing Orbit 2 insertion (07:29:00 m.e.t.)
2 - CW transfer to -Vbar from -21km to -3km (07:55:42)
3 - Station-keep at -3km (08:46:49)
4 - CW transfer to -1km (08:51:49)
5 - Station-keep at -1km (10:08:05)
6 - Forced motion to -200m (10:13:05)
7 - AVGS acquisition scan (11:04:39)
8 - Station-keep at acquisition point (11:05:34)
9 - Forced motion to -15m (11:10:34)
10 - Station-keep at -15m (11:24:20)
11 - Transfer to target vehicle docking axis (12:54:20)
12 - Station-keep at -15m on docking axis (12:59:20)
13 - Docking axis approach to -5m (13:04:20)
14 - Station-keep at -5m on docking axis (13:06:31)
15 - Forced motion to -15m on docking axis (13:16:31)
16 - Station-keep at -15m on docking axis (13:18:45)
17 - Docking axis approach to -5m (13:23:45)
18 - Station-keep at -5m on docking axis (13:25:57)
19 - Forced motion to -15m on docking axis (13:30:57)
20 - Station-keep at -15m on docking axis (13:33:12)
21 - Transfer to -15m on Vbar (13:38:12)
22 - Forced motion to -100m (13:43:12)
23 - Station-keep at -100m (13:51:05)
24 - Begin approach to Target vehicle (14:21:05)
25 - Simulated CAM to -200m (14:21:35)
26 - Station-keep at -200m (14:29:53)

DART On-Orbit Events

27 - Depart to lose AVGS tracking (14:34:53)
28 - Return to -200m (14:44:42)
29 - Station-keep at -200m (14:53:48)
30 - CW transfer to Rbar (15:23:48)
31 - Station-keep at 150m on Rbar (15:49:50)
32 - Forced motion to 100m on Rbar (16:19:50)
33 - Station-keep at 100m on Rbar (16:23:58)
34 - Forced motion to 300m on Rbar (16:28:58)
35 - Station-keep at 300m on Rbar (16:38:43)
36 - CW transfer circumnavigation to -1km (16:43:43)
37 - Station-keep at -1km on Vbar (17:59:44)
38 - AVGS acquisition scan (18:55:01)
39 - Station-keep at acquisition point (18:55:56)
40 - Depart to lose AVGS tracking (19:00:56)
41 - Return to -200m (19:10:15)
42 - Station-keep at -200m (19:19:03)
43 - CW transfer to Rbar (19:24:03)
44 - Station-keep at 150m on Rbar (19:50:08)
45 - Forceed motion to 100m on Rbar (19:55:08)
46 - Station-keep at 100m on Rbar (19:59:23)
47 - Forced motion to 300m on Rbar (20:04:23)
48 - Station-keep at 300m on Rbar (20:15:21)
49 - Start retirement burn (20:22:26)

Launch and Early Orbit Phase

Launch Operations Overview

The DART vehicle will be launched aboard a Pegasus XL launch vehicle.

The Pegasus launch will deliver the DART vehicle to a circular orbit at an altitude of 500 kilometers and will be designed to match the inclination and ascending node of the MUBLCOM orbit, as summarized in Table 3. The 500 kilometer altitude is dictated by the performance of the Pegasus XL and HAPS systems.

TABLE 3. INITIAL DART ORBIT CHARACTERISTICS (PHASING ORBIT 1)

Mean Semimajor Axis (km)	6878.137
Mean Altitude (km)	500
Mean Inclination (deg)	97.7061
Mean Eccentricity	0.0
Mean Period (minutes)	94.6163
Mean Motion (deg/s)	0.063414
Mean Nodal Regression Rate (deg/s)	1.187420e-005

The DART vehicle will be launched off the coast of Vandenberg Air Force Base, California, along the ground track shown in Figure 12.

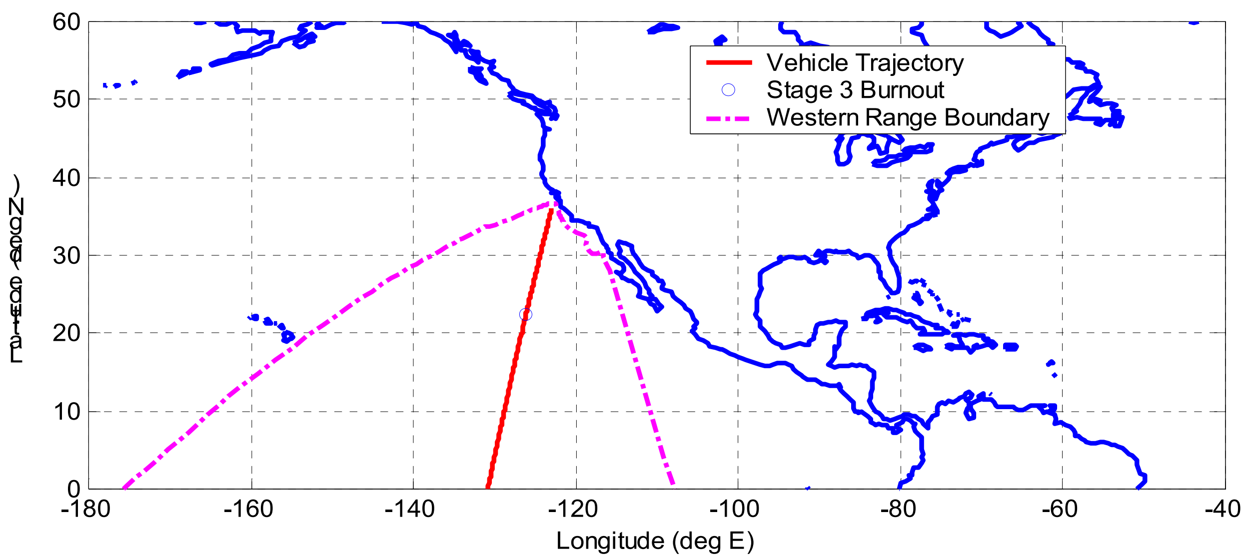


Figure 12. Pegasus XL Launch Ground Track

Pegasus launches typically target a specific drop point while allowing the drop time to vary by ±5 minutes. This has been acceptable in the past for payloads without tight ascending node requirements. For the DART mission, it will be critical for Pegasus to deliver DART to an orbit with an ascending node that closely matches that of MUBLCOM.

The nominal Pegasus launch trajectory has been designed to insert DART into the desired circular phasing orbit after stage 3 cutoff. Because the Pegasus guidance reserve is being carried onboard the HAPS, launch dispersions have the potential to significantly reduce the perigee of the initial phasing orbit. In these off-nominal situations, Pegasus will employ a HAPS burn to raise the perigee of the phasing orbit to the desired value.

The handoff between the Pegasus and DART mission will occur following stage 3 separation and the Pegasus HAPS burn to deliver DART to a nearly-circular, 500 kilometers altitude orbit.

Rendezvous Phase

Rendezvous Operations Overview

After being placed in the initial parking orbit, DART will begin the rendezvous phase of the mission. DART will remain in this orbit until the appropriate phasing exists between its position and MUBLCOM. DART will then use the HAPS to complete a transfer to phasing orbit 2, as shown in Figure 7. The approximate characteristics of phasing orbit 2 are summarized in Table 4. It should be noted that phasing orbit 2 is defined relative to the target vehicle orbit and consequently can vary significantly.

TABLE 4. APPROXIMATE DART ORBIT CHARACTERISTICS FOR PHASING ORBIT 2

Mean Semimajor Axis (km)	7134.5
Mean Altitude (km)	756.4
Mean Inclination (deg)	97.7061
Mean Eccentricity	0.00053
Mean Period (minutes)	99.9551
Mean Motion (deg/s)	0.060026
Mean Nodal Regression Rate (deg/s)	1.044672e-005

Proximity Operations Phase

The proximity operations trajectory chosen to accomplish the DART mission objectives is shown in Figure 11. The R Bar and V Bar axes correspond to a CW relative coordinate frame centered at the target vehicle with V Bar defined to point horizontally in the general direction of the MUBLCOM velocity vector and R Bar pointing towards nadir, or lowest point.

At the completion of rendezvous, the DART vehicle will nominally be located 40 km behind and 7.5 km below the target vehicle. After waiting for the required phasing, the DART vehicle will perform a CW transfer to place it 3 km behind the target vehicle in the target orbit. Following a station-keeping period, DART will perform another CW transfer to place it 1 km behind the target and then initiate two sets of –V Bar and +R Bar maneuvers intended to evaluate AVGS performance and proximity operations algorithms. This trajectory has been recommended by the Marshall Space Flight Center to maximize AVGS testing and exhaust the propellant available on the DART vehicle.

First –V Bar Approach

DART will move in from 1000 meters on the –V Bar to 300 meters as shown in Figure 10. The AVGS will initially be set to operate in spot mode but will be switched to acquisition mode at a range of 500 meters. At 300 meters, DART will station keep and, if necessary, perform a search procedure to locate and acquire the MUBLCOM vehicle in the AVGS field of view. Once the AVGS has begun tracking, DART will proceed directly to the 15 m point and station keep for 1.5 hours (approximately one orbital period). This will allow a thorough evaluation of AVGS performance under a range of lighting conditions and guarantee that useful camera images can be obtained for AVGS validation.

DART will next initiate a transfer from the –V Bar axis to the docking axis of the MUBLCOM satellite, defined as the boresight axis of the short and long-range AVGS retro-reflectors. A docking axis approach to a range of 5 m will be performed in which DART will track the attitude motion of MUBLCOM. After withdrawing to 15 m, the approach to 5 m will be repeated before withdrawing to 15 m again and transitioning back to the –V Bar axis.

DART will then withdraw to 100 m and, after a station-keeping interval, initiate another approach towards the target. After achieving a representative approach velocity, a simulated CAM will be initiated that will cause the vehicle to depart to 300 m. DART will station keep, reacquire MUBLCOM with the AVGS, and then proceed out along the –V Bar until AVGS tracking is lost to evaluate the maximum range of the sensor. For the purposes of the current reference mission, the maximum AVGS tracking range is assumed to be 500 m. Immediately after losing AVGS lock, DART will move back towards MUBLCOM to the 300 meter point and station keep prior to initiating a transfer to the R Bar.

+R Bar Approach

After completing the first –V Bar approach, DART will perform a CW transfer and maneuver to a range of 150 meters on the +R Bar. This transfer will be performed using a radial burn such that it will take approximately ¼ orbit (1500 seconds) to complete. During this transfer, DART will continue to point at the target vehicle to allow an evaluation of the angle at which the AVGS can no longer track the –V Bar MUBLCOM retro-reflectors.

DART will station keep on the R Bar at 150 meters and then initiate a forced motion approach to a range of 50 meters. While operating on the R Bar, AVGS tracking will not be possible so relative position data will be obtained from GPS state differencing. However, the MUBLCOM satellite does have two downward-facing retroreflectors intended for ground-based laser measurements that may allow use of the AVGS spot mode. After station keeping at 50 meters, DART will withdraw to 300 meters on the R Bar and station keep again.

Circumnavigation

Following the first +R Bar approach, DART will execute a CW transfer from 300 meters on the R Bar to –1 km on the V Bar. This will result in a circumnavigation of the target vehicle as shown in Figure 10. This circumnavigation will be designed to take 4500 seconds, or approximately ¾ of an orbital period. The DART vehicle will continue to point at the estimated position of the target vehicle throughout this maneuver.

Retirement Phase

After completing the mission objectives, the DART vehicle must be removed from the vicinity of MUBLCOM and perform a propellant depletion burn to reduce the orbital lifetime of the DART vehicle to less than 25 years. The DART mission will target a retirement orbit perigee altitude at or below 520 km to provide additional lifetime margin.

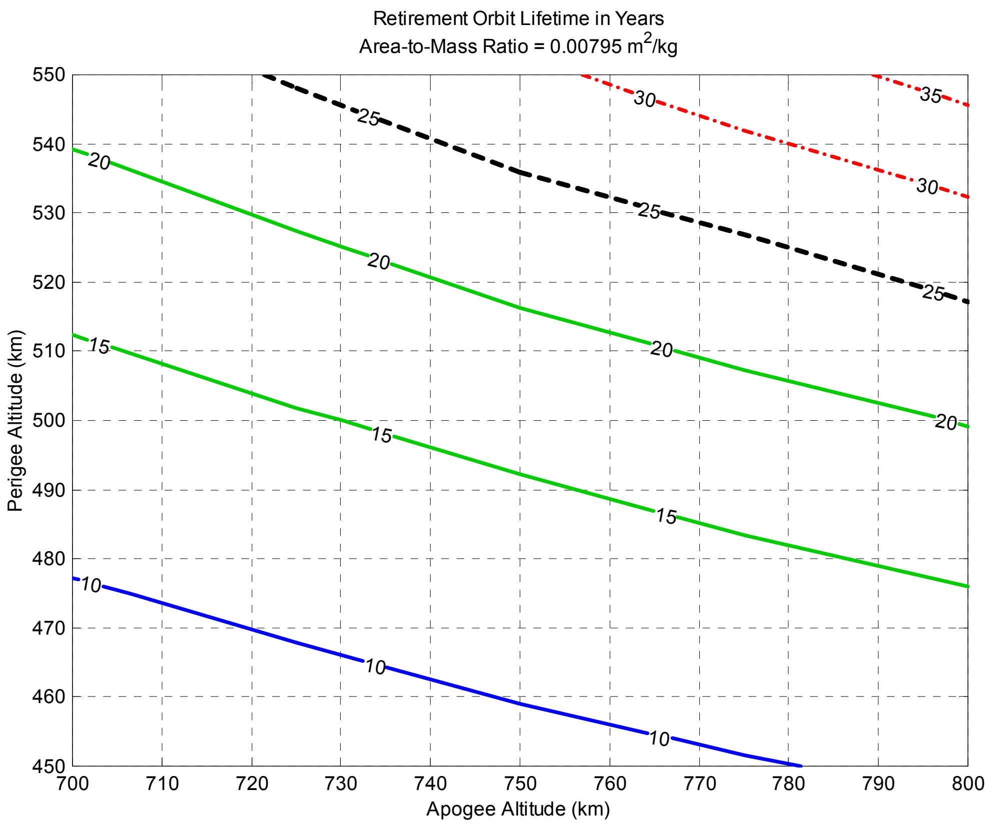


Figure 13. Retirement Orbit Lifetime Contours (Years)

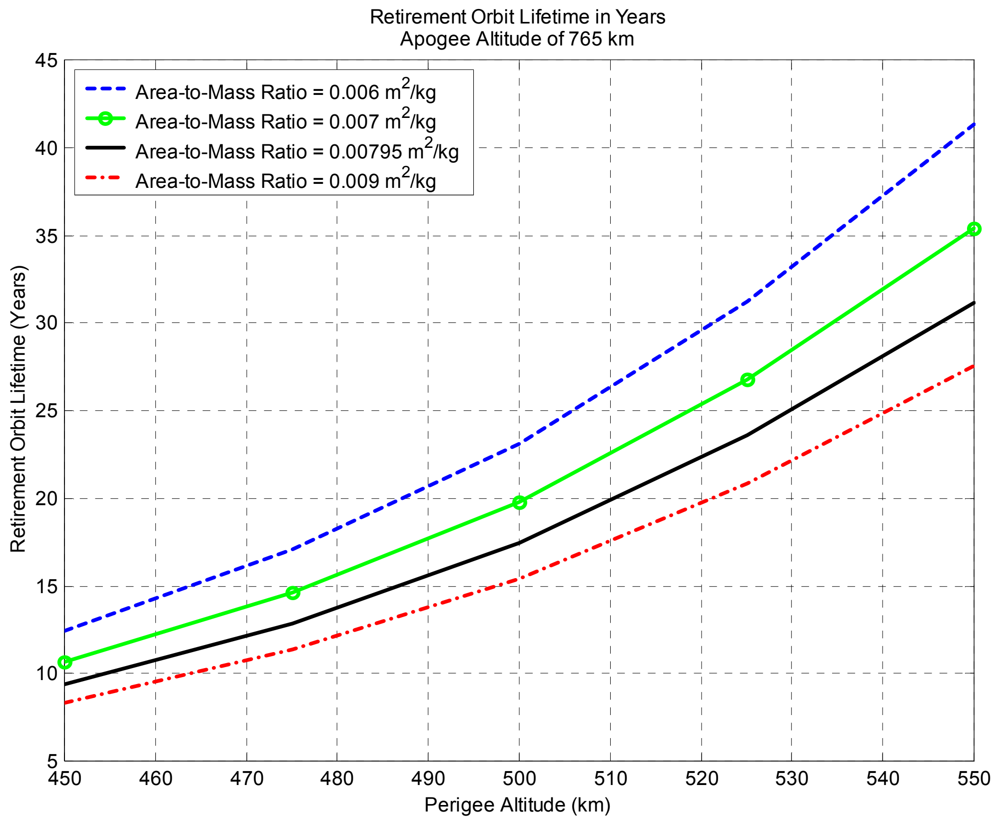


Figure 14. Retirement Orbit Lifetime Sensitivity to Area-to-Mass Ratio

Figure 13 presents the retirement trajectory that will be used to accomplish this task. From a position 300 meters below the target vehicle on the R bar, the DART vehicle will execute a HAPS burn to reduce the perigee altitude. This will involve a burn in the positive V bar direction that should not pose any risk to the MUBLCOM vehicle. Enough hydrazine has been budgeted to at least reduce the perigee altitude to 520 km. However, the duration of the retirement burn can increase significantly depending on the hydrazine remaining at the end of the mission. In the event that excess hydrazine is available, DART will continue to lower the perigee altitude to approximately 400 km and then turn out-of-plane to waste the remaining propellant by adjusting the orbit inclination and ascending node. This approach will ensure that the DART vehicle remains in orbit to allow multiple opportunities to downlink stored telemetry. This burn will be executed by scheduling the burn attitude as a function of predicted perigee altitude using standard Pegasus tables in the mission data load.

In the event that a contingency retirement burn is initiated prior to the nominal completion of the mission objectives, the standard retirement burn described above will be preceded by a 3 second out-of-plane HAPS burn. This will impart an out-of-plane velocity to the DART vehicle while minimizing the possibility of collision or plume impingement on the target vehicle. After waiting for 5 minutes to clear the vicinity of the target vehicle, DART will reorient to execute the standard retirement burn.

Future Applications of DART

DART will provide critical technologies that will benefit the Nation in future space systems development requiring in-space assembly, services, or other autonomous rendezvous operations.

The technology gained in the DART program will be shared with the Orbital Express Program managed by the Defense Advanced Research Projects Agency (DARPA). Orbital Express will validate the technical feasibility of robotic, autonomous on-orbit refueling, and reconfiguration of satellites to support a broad range of future U.S. and commercial space programs.

The technology gained with DART will also benefit the Experimental Small Satellite-11 (XSS-11) managed by the Air Force Research Laboratory program. The XSS-11 will advance the capabilities needed for a satellite to maintain operations on-orbit without intervention from ground-based mission control teams and assets.