The Lucy Spacecraft

Matthew Cox[1], Cavan Cuddy[1], Jeremiah Schneider[1], Tom Kennedy[1], Jonathan Taylor[1], and Greg Bollendonk[1]
[1]Lockheed Martin Space, Littleton, Colorado

Abstract
The Lucy spacecraft is developed from a combination of heritage components used on other NASA deep space missions, combined with a set of newly developed hardware specific to Lucy's mission, most critically the solar arrays. These components are configured into a spacecraft capable of launching on the least expensive Atlas launch vehicle, deploying into a power-safe configuration, executing the high-precision Trojan asteroid encounters, and surviving the 12-year mission timeline.

1 Introduction

Prior to the Lucy Mission, no spacecraft in NASA's discovery program had travelled more than 2 AU from the Sun (Blume et al 2015) and no solar powered spacecraft had ever travelled beyond beyond the orbit of Jupiter (Bolton et al 2017). In order to survey the Jupiter Trojan asteroids (Levison et al submitted), Lucy required a spacecraft with the necessary power and propulsive capability to support operation in the outer solar system, while minimizing launch mass. Lockheed Martin, having a long history of planetary spacecraft configurations and hardware to choose from, drew on its expansive inventory of qualified deep space hardware and software elements to assembly the Lucy spacecraft system. The table below shows the most critical components and their development origin.

Component/Subsystem	**Heritage**
Structure	2001 Mars Odyssey Spacecraft (Saunders et al. 2004)
Bi-Propellant Propulsion System	2001 Mars Odyssey Spacecraft (Saunders et al 2004)
Electrical Solar Array Design	2011 Juno Mission to Jupiter (Bolton et al. 2017)
Mechanical Solar Array Design	2007 Mars Phoenix Lander Mission (Smith et al. 2008)
High Gain Antenna	2013 Mars MAVEN Mission (Jakosky et al. 2015)
Core Avionics	2011 Juno Mission to Jupiter (Bolton et al. 2017)
Instrument Pointing Platform	2013 Mars MAVEN Mission (Jakosky et al. 2015)
Instrument Pointing Platform Gimbal	2016 GOES-R Weather Spacecraft
Guidance, Navigation, Control Components	Commercial Products
Propulsion Components	Commercial Products
Flight Software	Lockheed Incremental Development over 20+ years of deep space missions

At launch, the spacecraft mass was 1500 kg, of which 712 kg is spacecraft dry mass, 50 kg is instrument dry mass, 438 kg is fuel, 297 kg is oxidizer, and 3 kg is helium pressurant.

2 Spacecraft Configuration

The Lucy spacecraft is comprised of five major elements, each accommodating a specific operational purpose. These five elements are assembled independently, and then combined and tested during the Assembly and Test phase, lasting the final 17 months of development prior to launch.

Element	**Location**	**Purpose**
Propulsion Module	Lower Half of Main Structure	Contain Propulsion Subsystem, Distribute Launch Loads
Equipment Module	Upper Half of Main Structure	Contain avionics and harnessing
Instrument Pointing Platform	Platform on top of Main Structure	Contain science instruments and navigation cameras, track Trojan asteroids during encounters
7.3 m Deployable Solar Arrays	Appendages on either side of main structure	Provide solar power throughout mission
2 m High Gain Antenna	Fixed dish antenna on one side of main structure	Provide high-rate communication to earth

Figures 1 thru 3, below, shows the primary elements and overall size of the Lucy spacecraft.
Figure 1 – Lucy Launch Configuration (inside Atlas-V Fairing)

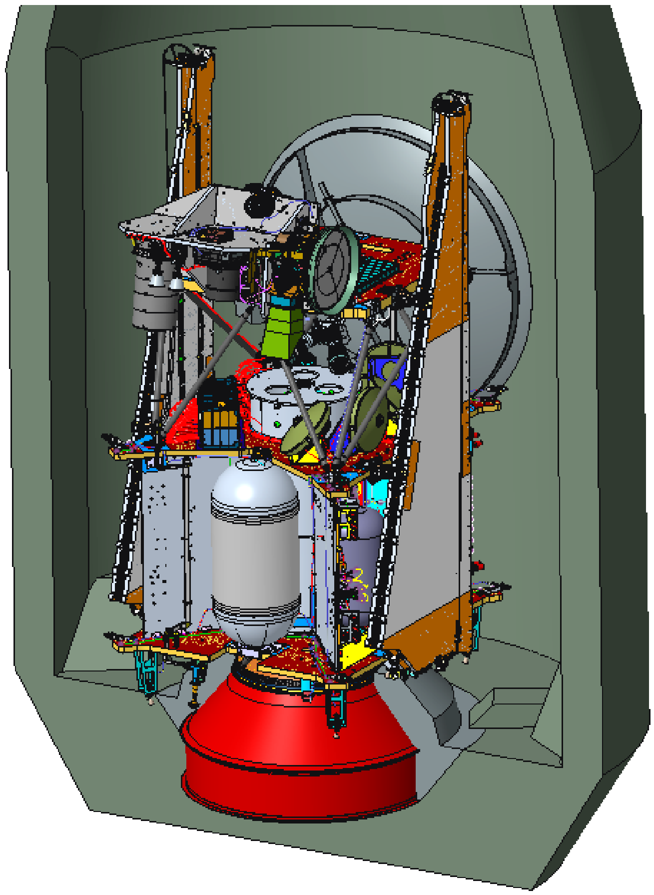


Figure 2 – Lucy Launch Configuration Dimensions

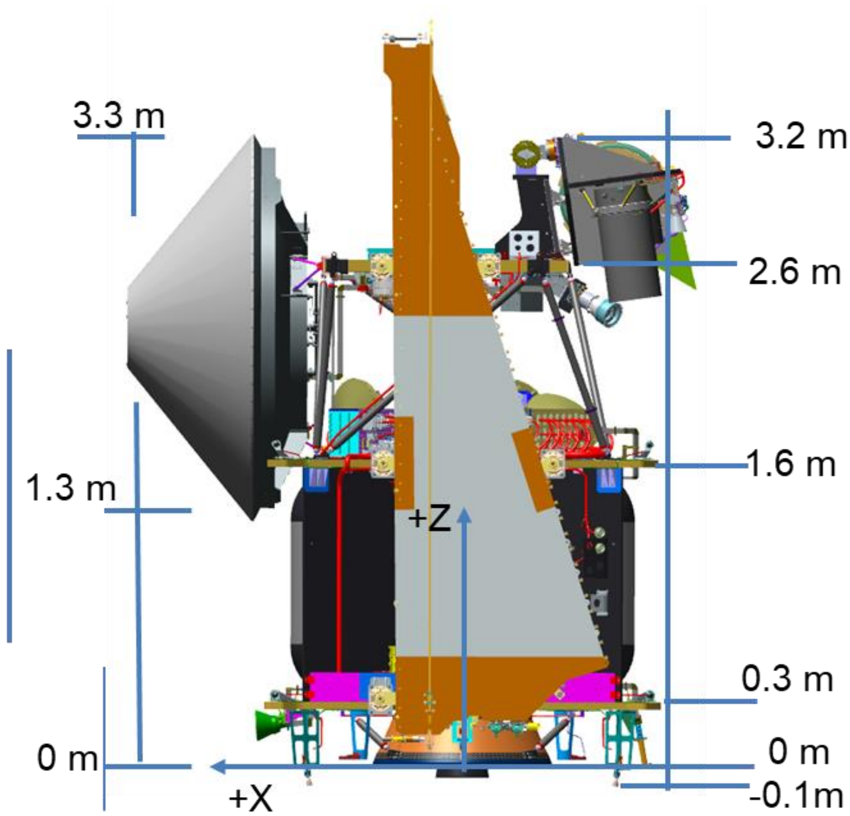
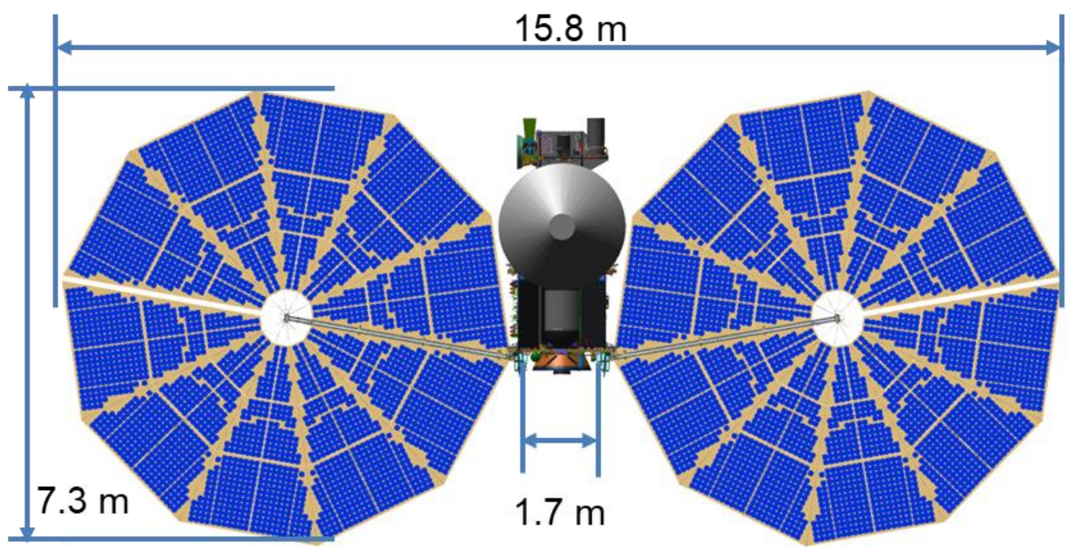


Figure 3 – Lucy In-Flight Configuration and Dimensions



3 Solar Arrays

Lucy utilizes "Ultraflex" solar arrays developed and manufactured by Northrop Grumman. The solar arrays deliver about 500 watts of power at the far sun range of the Trojan asteroid encounters (5.7 earth distances from the sun) and weigh 176 kg.

The solar cells are mounted on a mesh material formed by a group of composite spars radially connected to a rotating hub. After launch, the mechanisms rotate the assembly away from the spacecraft body, deploy the spars around the hub, and tension and latch the mesh elements into stiff solar panels. Figure 4, below, illustrates the solar array deployment sequence.

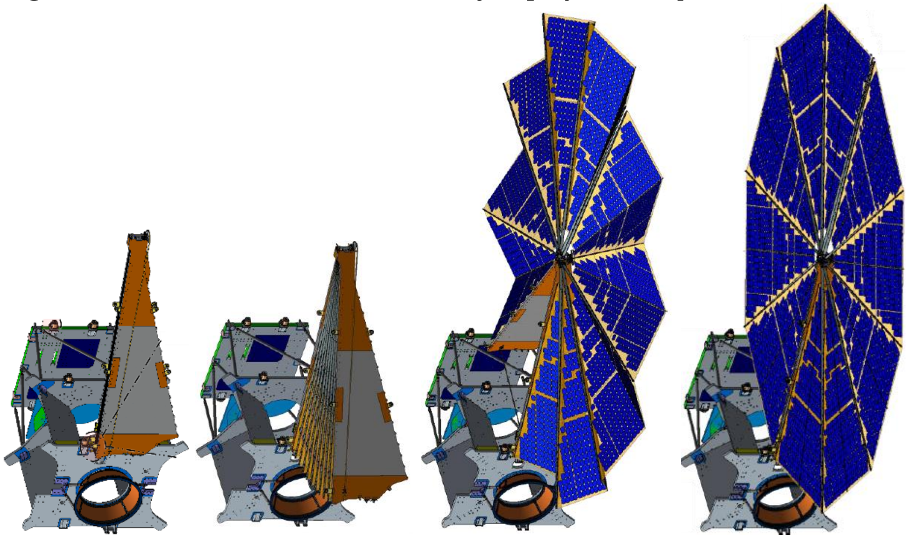


Figure 4 – Lucy Solar Array Deployment Sequence from stowed to fully deployed

3.1 Power Subsystem

The Lucy power subsystem consists of three main elements: Power Generation, Power Storage, and Power Distribution.

Power generations is provided by the most prominent feature of the Lucy spacecraft, two large 7.3 meter diameter solar arrays attached to the spacecraft's main body. Lucy will venture farther from the sun than any other solar-powered vehicle in history. Although the solar arrays are capable of producing up to 18,000 Watts in Earth orbit (enough to power several homes) at Jupiter's orbit Lucy will only generate 500 Watts (enough to almost power a hair dryer) due to the reduced solar irradiance at that distance. Solar irradiance, defined as power per unit area received from the Sun, reduces by the inverse square of the distance ($1/D^2$) from the Sun, so power diminishes rapidly as we travel into deep space at nearly 6 times the distance of Earth from the Sun. Lucy instruments, electronics, and thermal system have been carefully designed to consume as little power as possible in order to meet mission needs without breaking the 500 Watt power budget.

During certain mission activities, including launch and the Trojan asteroid encounters, the solar arrays cannot be maintained pointed at the sun, requiring stored energy to be supplied. When this occurs the battery comes into action. The single Lucy battery is a light weight design which uses an internally redundant small cell format (slightly larger than AA sized cells) strung up in an 8-series and 16-parallel string configuration to provide a nominal bus voltage of 32 V and an energy storage capacity of 44 Amp-hours. With this much energy the battery can power the spacecraft on its own for about 3 hours.

In order to get power from the solar arrays to the batteries and electronic loads, two electronics boxes are utilized, the Power Distribution and Power Unit (PDDU) and the Pyro and Propulsion Unit (PAPU).

The PDDU consists of circuit-card assemblies to manage solar array and battery power, switch on/off power to instruments, heater and other various loads, collect telemetry from the spacecraft, maintain housekeeping power for the PDDU and PAPU, and to provide a main power and grounding bus for the entire spacecraft.

The PAPU consists of four circuit card assemblies to provide energy to the pyrotechnic devices and valve control for the propulsion subsystem when commanded by the flight software.

Both the PDDU and PAPU have a high amount of heritage as versions of the units were used on other NASA missions including Juno, MAVEN, and OSIRIS-REx.

4 Instrument Pointing Platform

The Instrument Pointing Platform (IPP) provides volume accommodation and pointing of the 3 science instruments, L'Lorri, L'Ralph and L'TES, as well as the Terminal Tracking Camera (TTCam) assemblies that GN&C use to track the asteroid. The IPP is a gimbaled, carbon fiber sandwich panel construction platform.

The primary design consideration for the platform structure was co-alignment of each instrument. Instrument and IPP interface design had to account for thermal distortion, mounting pattern clearance and overall machining tolerances. The instruments are co-aligned to within about 0.5 milliradian. This angle is equivalent to the angle between the top and bottom of a silver dollar coin, when viewed from 100 yards away.

The science instrument boresights must remain steadily pointed at the asteroid targets while Lucy flies by. To maximize observational flexibility, the gimbals are used to point the instruments independent of the spacecraft orientation. Not only was instrument coalignment a big driver in design, so was instrument jitter, or how much the instruments shake due to the gimbals and other moving items on the spacecraft. The Lucy gimbals shake the instruments less than 5 microradians; or to put it another way the angle formed by the top and bottom of a quarter when viewed from 3 miles away.

The gimbals are a heritage design, tracing their lineage through the GOES weather satellites and several missions that are orbiting Mars. The smooth output motion of the gimbal is due to its high gear reduction zero-backlash harmonic drive, and a very fast feedback control loop of the motor. A high bandwidth control loop within the motor electronics ensures the gimbal is moving in the way the spacecraft has commanded, while an outer loop on the spacecraft monitors the gimbal positions and adjusts gimbal commands as necessary to maintain the desired pointing.

5 Guidance, Navigation, and Control Subsystem

Lucy's Guidance, Navigation and Control (GNC) Subsystem, is responsible for determining the attitude of the spacecraft (where it's pointing), controlling the attitude of the spacecraft and instrument pointing platform (where it points) and controlling the firing of the thrusters to change the trajectory of the spacecraft. Lucy is a 3-axis attitude stabilized spacecraft, meaning the GNC subsystem controls how all three axes of the spacecraft are oriented in inertial space.

For attitude determination (AD) Lucy employs gyroscopes, star trackers and sun sensors. The gyros are used to measure the relative rotation of the spacecraft. Even if the spacecraft doesn't know its exact orientation in space it can use the gyro rate measurement to maintain control of the spacecraft and move about to find the sun or to find stars with the star tracker. To determine the spacecraft absolute orientation in inertial space Lucy uses a dual headed start tracker. The Star tracker cameras take pictures of deep space, compare the stars it sees in the images to known stars in a catalog, and provides the spacecraft with its attitude orientation in inertial space. The final component used in determining the spacecraft attitude are the 4 head sun sensors which detect where the sun is relative to the spacecraft and are used to point the spacecraft solar arrays at the sun if the star trackers are not able to see stars.

For attitude control (AC) Lucy uses a variety of actuator components. For nominal control Lucy uses a suite of three reaction wheels, which use the principle of “equal and opposite action” to point the spacecraft. Applying torque to the reaction wheels produces an equal and opposite torque on the spacecraft body, turning it in a desired direction. Lucy uses three orthogonal reaction wheels for control, though they are not co-aligned with the spacecraft body axes. A fourth, spare wheel is not co-aligned with any of the other 3, allowing it to be used for three axis control in case of failure of one of the main wheels. The reaction wheels allow the spacecraft to pitch over and track the Trojans at rates up to 1 degree per second during encounters.

For attitude control during spacecraft emergencies and for changing the trajectory of the spacecraft, GNC controls the three types of thrusters on Lucy. The eight ACS (Attitude Control System) thrusters arranged such that a set of 4 thrusters can be fired to produce a pure torque about a principal axis of the spacecraft while producing very small residual force on the spacecraft. The six TCM (Trajectory Correction Maneuver) thrusters are used to impart small to medium forces on the spacecraft to change its trajectory and the single Main Engine is used for large trajectory corrections of the spacecraft, velocity changes greater than 50 meters per second.

During the flyby Encounters with the Trojan Asteroids, and the rehearsal flyby of the Main Belt Asteroids Dinkinesh and Donald Johansen, the GNC subsystem uses the AD and AC to coarsely point the spacecraft at the asteroids, pitching over about the Lucy Y axis as it passes by. GNC also controls the pointing of the Instrument Pointing Platform (IPP) for high accuracy pointing of the science instruments, to perform off-points and scans with the instruments, and, for the binary encounters, to rapidly retarget between the two asteroids.

Due to the large distances from Earth that the Trojan Encounters occur, about 5.7 A.U., the knowledge of where the Trojans are relative to the spacecraft will not be well known as the spacecraft approaches the targets. Even using the L’LORRI instrument in the months leading up to the Encounters to image and improve the location knowledge, there can still leave hundreds of kilometers of location uncertainty during the encounter. With the Trojans being about 15-100 km in diameter this uncertainty could cause the science instruments to completely miss the target at the ideal opportunity to image and collect data. For this reason, Lucy employs a Terminal Tracking System (TTS) to autonomously image the Trojans in the final hours of approach and to update the onboard knowledge of the target locations without intervention from the ground operators.

The Terminal Tracking System is comprised of a Terminal Tracking Camera (TTCam) to image the Trojans in the final hours and minutes of close approach, as well as on board software to update the knowledge location of the targets. The redundant TTCams’ field of view are wide enough to image the entirety of largest of the Trojans at their closest approach. The TTCam pixel resolution of 74 micro-radians is fine enough to allow it to resolve the smallest of the Trojans within the final hour of its closest approach.

Lucy uses a combination of Centroiding, State Estimation and Target Reference Generation software to update an onboard model of where the target will be relative to the spacecraft at any given time.

The first part of the TTS software, Centroiding, finds the target’s bright pixels in the image, determines the center of brightness (COB) of the brightly lit area of the target, and passes that information, along with an estimate of where the TTCam was inertially pointing at the time of the image, along to the next step in the TTS software, the Encounter State Estimator (ESE). The Encounter State Estimator, and the

Binary Encounter State Estimator used for the binary encounters, uses the Centroiding measurement of the Trojan location as inputs to its Kalman Filter, which mathematically converges on the unknown flyby parameters. These flyby parameters, the close approach distance, time of closest approach, and out of plane location of the target, are used by the final piece of software in TTS, the Target Reference Generator.

The Target Reference Generator (TRG) uses the ESE converged flyby parameters to provide a more accurate estimate of the location of both the Center of Mass (COM) of the Trojan at any point in time during the encounter as well as an estimate for where the Center of Brightness will be at any point in time. Either of these estimates, COM and COB, can be used to point the IPP and science instruments at the targets at any time during the close flyby. In general, COM is used when the full target is illuminated or when trying to image multiple portions of the target. COB is an important pointing method for the high sun incidence angle approaches of Leucus and Orus, where the targets can appear as thin crescents on approach and pointing at the illuminated portion of the Trojan will net the most successful science.

While the TTS method of imaging and updating an encounter target's flyby states has been used on other flyby missions, such as Stardust, Lucy will be the first mission to fly by a binary system and to not just update the flyby conditions but also autonomously estimate the orbital parameters of the binary system. As Lucy approaches the Patroclus and Menoetius near equal mass binary the two targets will initially both be in the field of view of TTCam and the science instruments. However, during the hours and minutes leading up to close approach, the angular separation between the two Trojans will increase, necessitating that the IPP move back and forth between them to obtain the desired science. The special binary version of ESE, BESE, uses images taken during the hours leading up to the close approach to update its onboard model of the binary system orbit parameters, feeding this to TRG in addition to its flyby estimates.

6 Main Structure

The Lucy Spacecraft is Lockheed Martin's seventh generation composite interplanetary Spacecraft and consists of a 26-inch diameter core cylinder with an integral launch vehicle adapter, aft and middle decks that interface to gusset panels tied to the core, and a forward deck supported by struts from the mid-deck. The aft and mid-decks provide radial shear load paths into the cylinder, while gussets serve to transfer vertical loads into the core cylinder. In addition to the primary structure, there is a variety of secondary structure on the Spacecraft such as component mounting brackets and the solar array hinge fittings.

The Lucy spacecraft main structure is primarily constructed from lightweight composite materials. The structure weighs a mere 135 kg and supports the entire spacecraft wet mass of 1,500 kg (3,307 lbs.). The efficient spacecraft structure accounts for amazingly small (9%) fraction of the spacecraft mass.

6.1 Propulsion Subsystem

The spacecraft propulsion system consists of the following key components, all of which are readily available within industry, with the exception of the fuel and oxidizer tanks, which are developed and built custom for Lucy:

- Two fuel tanks
- One oxidizer tank
- One helium pressurant tank
- One bi-propellant main engine assembly
- Six monopropellant trajectory correction maneuver thrusters
- Eight monopropellant attitude control thrusters

- One mechanical pressure regulator
- Numerous latch valves, pyro valves, service valves, and filters

The propulsion system stores the fuel and oxidizer needed for all propulsive events over the life of the mission. Lucy mission plan defined five deep space maneuvers utilizing the bi-propellant main engine, with a longest burn up to 2600 seconds. The propulsion system providing attitude control forces with small and trajectory correction maneuver ability.

6.2 Thermal Subsystem

The thermal subsystem maintains the Lucy spacecraft and its components within temperature specifications in the harsh environment of space across an extreme range of environments. A combination of temp sensors, heaters, multi-layer insulation blankets, special coatings, heat spreaders and isolators are leveraged on Lucy. The maximum flight system heater power utilization is projected to be less than 192 Watts.

6.3 Electrical Harness

The total length Lucy spacecraft electrical harness is a little over 2 miles of wire (average length of wire of about 15 to 20 feet). The biggest section of the harness bundle is about 4-inches in diameter at the splice area near the C&DH. One of the biggest challenges was optimizing harness routing to minimize 60 kgs (131 lbs.) wire mass.

The spacecraft electrical harness has 364 connectors and over 1,300 splices, with 12,847 electrical connections. There are 8 field joints and 40 field joint connectors. The aluminum foil overwrap weighs about 13 pounds.

7 Computation, Fault Protection, & Communications

7.1 Command & Data Handling Subsystem

The Lucy Spacecraft contains two fully redundant flight computers, or Command & Data Handling (C&DH) unit. The C&DH is responsible for all on-board computing logic, component communication, and data storage. The C&DH and related flight software control all aspects of spacecraft operation, relying on a raditioned hardened RAD750 PowerPC processor.

Different than terrestrial computers, space rated processors must tolerate an abundant spectrum of nasty high energy particles regularly found in the space environment. The central processor is complemented with dozens of radiation hard ASICs and FPGAs to provide reliable computing for the dozen year mission.

7.2 Flight Software & Fault Protection

The C&DH houses flight software that is responsible for all aspects of Spacecraft control. Onboard sequencing with high level language constructs achieve a programmable spacecraft without reloading flight software. The spacecraft flight software contains about 350K lines of code logic (with more than 1M total lines of code). The combination of target tracking and operational sequence programmability enables multiple encounters over mission life.

The flight software also includes logic to monitor, detect and respond to any on-board anomaly without ground controller intervention. The Spacecraft is designed to operate autonomously (with no mission operations controller intervention) for up to 30 days and thus requires a complex system to detect and respond to any issue that may arise.

7.3 Telecom Subsystem

Lucy's X-band telecommunication system is responsible for transmitting Spacecraft telemetry and receiving commands from the Mission Operations Center via the Deep Space Network. Lucy uses a 25 Watt tube amplifier and a 2 meter diameter high gain antenna to transmit data to Earth with data rates ranging from 2 kbps to 352 kbps. Lucy encounter science data return rates range from 10 kbps to 50 kbps and requires weeks of near continuous communications to receive the total data set. The Spacecraft also contains a low gain antenna and medium gain antenna which provide communication coverage over the wide range of Earth distances and Sun, Earth, and Spacecraft geometry. One way light time can be up to 55 minutes at far Earth ranges during Lucy's mission.

8. Conclusion

Like all planetary spacecraft, Lucy is designed to perform the scientific mission while minimizing mass and providing all necessary power and control resources to obtain the great science results. Through extensive use of qualified components combined into subsystems and a configuration supporting Lucy's unique Trojan encounters at outer-planet sun range, the Lucy spacecraft meets its requirements, within the cost requirements of a Discovery-class mission. A key contributor to this success is limiting custom development and qualification to the solar arrays and the GN&C algorithms necessary to execute the tracking asteroid encounters.

9 Acknowlegements

The Lucy Spacecraft is only possible due to the dedicated work of the hundreds of people and many orgnaziations involved in designing and building the spacecraft under the leadership of Hal Levison, Principal Investigator.

10 Compliance with Ethical Standards

The author affirms that there is no conflict of interest and that the subject of this manuscript did not involve research on human nor animals.

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Technical data about the Lucy Spacecraft is extracted from the Lucy Critical Design Review, conducted in October 2019.

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