LOCKHEED MARTIN

# Curio™ Small Spacecraft

## Mission and Payload User Guide

February 2025

| Release | Description |
| --- | --- |
| **February 2025** | Initial release |

## Contents

# 1 Introduction

**For Further Information**

- Deep space mission needs vary widely. Potential users should contact Lockheed Martin to explore how Curio™ can meet their specific mission objectives.
- curio.space@lmco.com
- www.lockheedmartin.com/en-us/news/features/2022/curio-small-mighty-spacecraft.html

The Curio product line is Lockheed Martin's smallest spacecraft designed for deep space missions.

Curio spacecraft are designed with a focus on science missions and instruments, that embraces both Lockheed Martin's planetary spacecraft heritage and the commercial SmallSat component supplier base. The spacecraft configuration is flexible, to accommodate a wide range of payloads, propulsion systems, and mission environments. The baseline Curio has a streamlined, single-string architecture, in line with a NASA Class D risk posture.

The Curio team recognizes that deep space SmallSat missions are still *deep space missions*, even with the increased risk tolerance and emphasis on low cost and rapid schedule. Design and operation of a deep space or cislunar mission requires special consideration of the mission environments. Curio incorporates lessons learned and staff from Lockheed Martin's multi-decade history supporting NASA planetary exploration.

The Curio family includes the Lunar Trailblazer and Janus SmallSats, built for NASA's Science Mission Directorate, as well as several in-development missions ranging from demos to commercial communications concepts.

## 1.1 Lockheed Martin's Relevant Capabilities

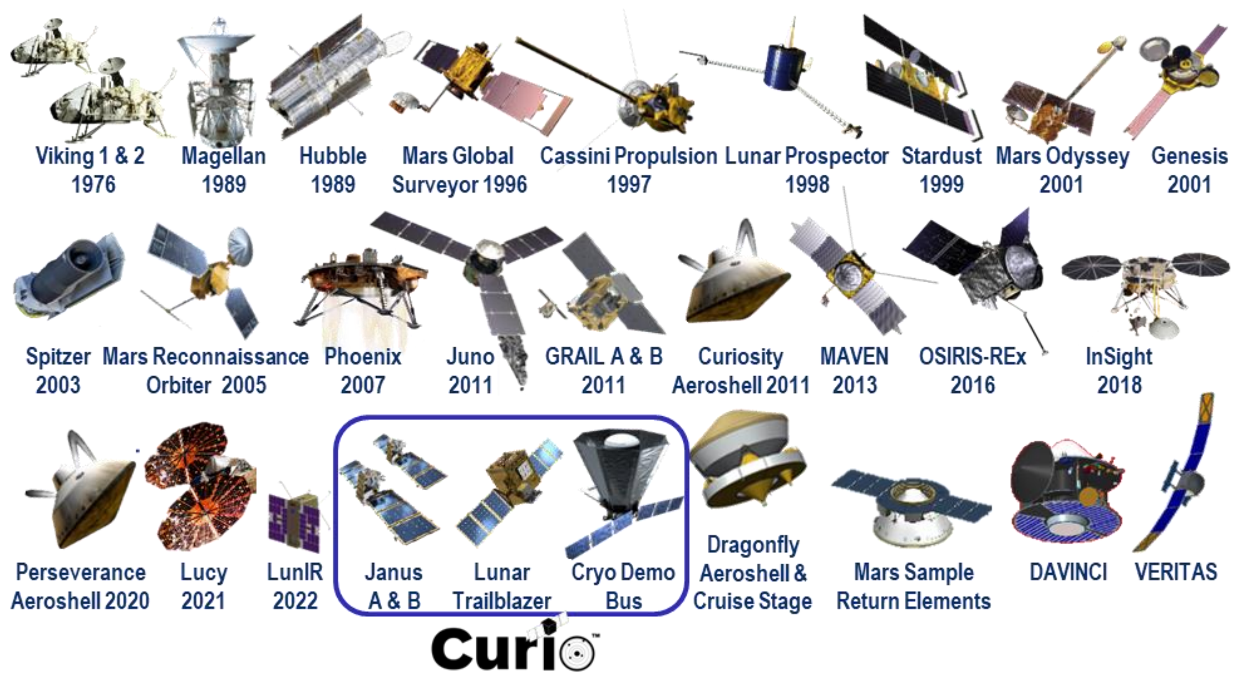


*Figure 1-1 Curio spacecraft are based on Lockheed Martin's experience developing, testing, and operating dozens of planetary spacecraft in collaboration with NASA and JPL. This graphic reflects announced missions through third quarter 2023.*

Lockheed Martin has been building planetary spacecraft since the Viking landers of the 1970s. Working with NASA and JPL, Lockheed Martin has sent planetary missions across the solar system, some of which are shown in Figure 1-1. Curio implementation includes elements of the same planetary exploration organization within Lockheed Martin that developed spacecraft like the OSIRIS-REx asteroid sample return spacecraft, GRAIL lunar orbiters, and Phoenix and InSight Mars landers. The team also incorporates commercial practices from the LM2100 product line. Curio leverages an experienced team, established facilities, and flight-proven subsystems for low-risk technical, schedule, and cost metrics.

## 2 Curio Spacecraft Overview

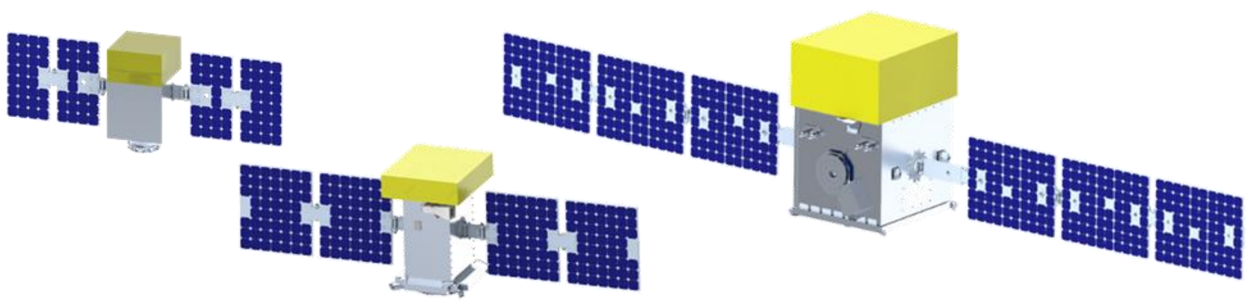

*Figure 2-1. Curio reference spacecraft: Mini (left), Medium (center), and Grande (right).*

Curio spacecraft have a common architecture, with discrete subsystem sizes and options. For example, the power distribution and control unit can accommodate different cards to match the modular solar array design and propulsion selections. Many subsystem components are commercial catalog items from SmallSat suppliers. Curio projects procure these products to standardized specifications, often the suppliers' own, to minimize development and realize low cost and rapid schedule. There are additional options to tailor the design to the mission. These options are based on a list of hardware compatible with the bus, maintaining the schedule and cost efficiency of a common design.

*Table 2-1. Curio spacecraft are designed for typical rideshare launch volumes and separation systems.*

| Point of departure | Launch volume | Payload (kg) | ΔV (m/s) | Payload power (W) | Battery (W hr) |
|---|---|---|---|---|---|
| **Mini** | Standard ESPA, half volume | 10 | 0 | 15* | 275 |
| **Medium** | Standard ESPA, full volume | 25 | 150 | 145* | 275 (*550 max*) |
| **Grande** | ESPA Grande | 50 | 575 (*650 max*) | 220* (*430 max*) | 550 (*1100 max*) |

*Notes:*

** Payload power estimate assumes full illumination of the solar arrays at 1 AU. Contact Lockheed Martin to discuss orbit average power for specific orbits or peak power states.*

Lockheed Martin offers three reference configurations of Curio spacecraft that may be used as-is or as points of departure, aligning to defined ESPA launch volumes: Mini, Medium, and Grande (Figure 2-1 and Table 2-1). Additional payload mass may be available on missions that do not require propulsion, or with structure configuration to carry increased loads. See Section 4.1.1 for further discussion of payload mass capabilities and Section 4.2.1 for payload power details. Also, higher ΔV capability may be available for smaller payloads or custom configurations. Interested users should contact Lockheed Martin with questions about modified or custom configurations beyond the reference capabilities in Table 2-1.

*Table 2-2. Curio spacecraft offer scalable subsystem options.*

| Subsystem | Catalog Options |
|---|---|
| **Structure** | Mini, Medium, Grande, or custom structure |
| **Power Distribution** | Number of switching cards, prop/pyro card |
| **Solar Array** | 2, 4, or 6 panels per wing |
| **Battery** | 275, 550, 825, or 1100 W hr |
| **Attitude Control** | 1 or 2 star trackers<br>3 or 4 reaction wheels, 0.5 – 8 Nms wheels<br>Magnetic torque rods |
| **Telecommunications** | S, X, or Ka band<br>Low, medium, or high gain antennas<br>Uplink encryption |
| **Mechanisms** | Solar array gimbal drive |
| **Propulsion** | Hydrazine propulsion<br>Configuration of attitude thrusters |

# 3 Mission Capabilities

Curio missions pair small spacecraft architecture with Lockheed Martin's demonstrated capabilities in executing ambitious science missions. The spacecraft is a central component of the overall mission. In Curio mission development, consideration is given to all mission phases, including test & integration, launch vehicle selection and launch site operations, and mission operations.

## 3.1 Trajectory and Mission Environment

Curio spacecraft support flyby, orbiter, and free-flyer missions to a variety of cislunar and inner solar system destinations. Example environments include Earth orbits, lunar orbits, Earth-trailing or -leading orbits, Earth/Moon Lagrange points, Earth/Sun Lagrange points, and near-Earth asteroid encounters. Curio variants can even support planetary missions to

Venus or Mars. Compatible Curio mission trajectories may start from a dedicated launch, including on a small launch vehicle; a rideshare launch to GEO transfer orbit, lunar transfer trajectory, or Earth/Sun Lagrange points; or an orbital transfer vehicle, tug, or kick stage. As every beyond-Earth-orbit mission has unique requirements and constraints, interested parties are strongly encouraged to contact Lockheed Martin to discuss the specifics of how Curio spacecraft may be able to support their missions.

In addition, Section 6.2: Mission Design discusses relevant Lockheed Martin trajectory design capabilities applicable to Curio missions.

### 3.1.1 Sun and Earth Range

Typical Curio spacecraft are designed to operate in near-Earth heliocentric space, including all of cislunar space. Curio variants may extend the operating Sun range through the inner Solar System. The designed Earth range extends up to 2.4 AU from the Earth. Longer ranges may be possible for certain mission concepts at lower data rates or with higher-gain telecommunication systems. Curio spacecraft are available for operation in Earth orbit, including low Earth orbit.

### 3.1.2 Lifetime

Curio spacecraft mission life is 2-5 years. Mission life depends on environment and operating assumptions, including radiation exposure along the mission trajectory, frequency of momentum offload maneuvers, component utilization during quiescent cruise, component utilization during nominal operations, and other factors. The Curio team encourages potential customers to contact Lockheed Martin for discussions about how their specific mission concept affects the expected spacecraft lifetime.

### 3.1.3 Propulsion

Curio Mini spacecraft typically include no propulsion. An option for a common bolt-on SmallSat-class propulsion system for limited orbit maintenance and end-of-mission deorbiting and momentum management is available.

Curio Medium and Grande may have a hydrazine monopropellant propulsion system with a single main engine and three-axis attitude control thrusters. The propulsion system improves upon the design successfully flown on GRAIL, XSS-11, and other missions. Thrusters, valves, and other components are qualified and well-characterized, including many previous spaceflights. Attitude control thrusters offer precise impulse and can be configured to prioritize mission needs. The standard configuration includes four attitude control thrusters, offering three-axis rotation control; eight or more thrusters can be placed around the spacecraft with a custom manifold. Additional thrusters may affect external payload usable volume. Tank options support up to 10 kg propellant fill on Curio Medium spacecraft and up to 85 kg propellant fill on typical Curio Grande spacecraft. Service valves are externally accessible for safe propellant fill, drain, and venting. Contact Lockheed Martin for options to increase propellant capacity and maneuver capability.

### 3.1.4 Typical ΔV Performance

Maneuver performance depends on maneuver design, spacecraft mass, and Solar System geometry, with interrelated tradeoffs. Table 2-1 gives ΔV performance for Curio spacecraft carrying representative payloads. Lockheed Martin's Deep Space Exploration organization has extensive experience with deep space maneuver design and propulsion system performance modeling. Curio customers are invited to contact Lockheed Martin for detailed discussions about mission design and Curio performance for specific payloads and destinations.

## 3.2 Launch Compatibility

### 3.2.1 Launch Interface

Curio spacecraft interface to an ESPA launch adapter with standard low-shock separation rings. Lockheed Martin can provide inputs, designs, and/or manufacturing of payload adapter plates as necessary.

### 3.2.2 Launch Vehicle Compatibility

Curio spacecraft are compatible with rideshare on a secondary payload adapter or dedicated launch on a small launch vehicle. The typical spacecraft design fits within the 38 by 28 by 24 inch Standard ESPA volume (for Curio Mini and Medium) or the 56 by 46 by 42 inch ESPA Grande volume (for Curio Grande). Figure 3-1 shows typical spacecraft inside these volumes. Externally mounted payloads will affect margins against the keep-in volume. The Curio Mini nominally occupies half of the launch volume, though mission-specific payloads may affect this. The Curio Grande, attached to an ESPA Grande adapter ring, assumes a 5 m launch vehicle fairing.

Standard Curio Grande spacecraft maintain the spacecraft fundamental frequency in the 40-60 Hz range. This is compatible with the minimum fundamental frequency of a variety of launch vehicles. Lockheed Martin supports coupled-loads analysis (CLA) cycles to confirm Curio compatibility with primary payloads on a rideshare launch. Spacecraft-level random vibration test profiles also include notches based on CLA results to further confirm fundamental frequencies and launch compatibility. The Medium and Mini Curio configurations have higher fundamental frequencies.

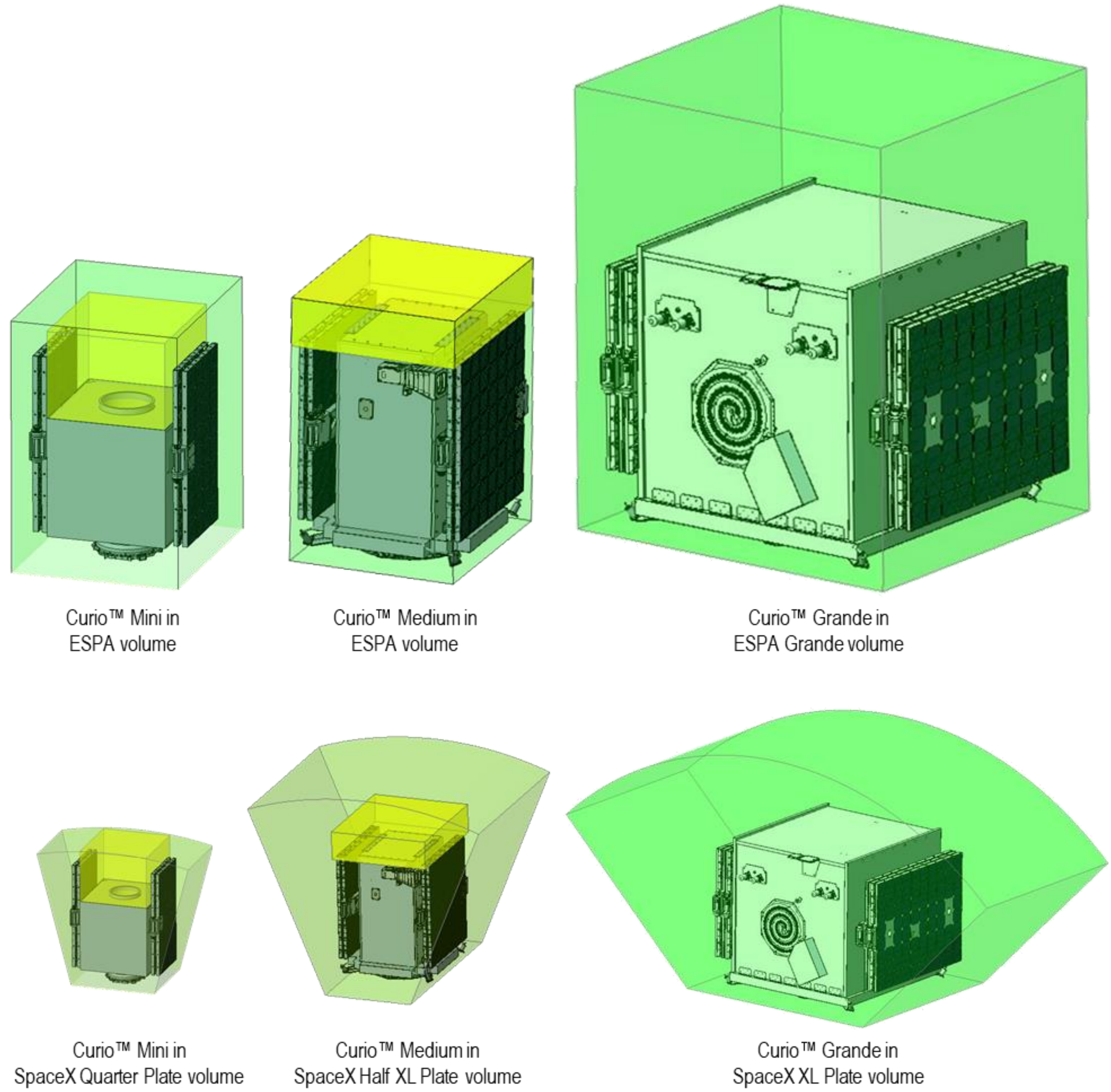


*Figure 3-1. Curio spacecraft stowed in ESPA volumes (top row) and SpaceX rideshare volumes (bottom row).*

### 3.2.3 Inhibits and Safety

Curio spacecraft comply with NASA Rideshare User Guide requirements, including independent inhibits in the Electrical Power Subsystem (EPS) and Command and Data Handling (CDH) to prevent the spacecraft from booting before launch vehicle separation. These inhibits prevent deployments, RF transmission, or other operations hazardous to launch and ascent.

Curio spacecraft with hydrazine propulsion have additional inhibits and safety features to prevent inadvertent thruster firing. A normally closed pyro valve seals the propulsion system against leakage. The attitude control thruster manifold and main engine have dual-seat valves. Pressure systems are qualified to levels in excess of flight pressures.

Lockheed Martin supports the development of hazard reports, hazard controls, and safety data packages (SDPs) for both primary and rideshare launch. See also Section 5.4 Launch Site Operations.

## 3.3 Attitude Control Performance

### 3.3.1 Pointing Knowledge and Control

Pointing knowledge includes attitude determination accuracy, star-tracker-to-payload alignment measurement knowledge, and environmental shifts. It may be possible to calibrate out static alignment knowledge contributions to this performance during payload commissioning, depending on payload concept. Worst-axis onboard pointing knowledge is typically <1.6 mrad (3σ) uncalibrated and <0.6 mrad (3σ) calibrated, including all effects above.

Pointing control includes attitude determination contributions as above, target commanding errors, attitude control errors, appendage articulation disturbances, and environmental disturbances. Pointing control capability may be looser when tracking dynamic targets in high-disturbance environments, or tighter when tracking inertially fixed targets in low-disturbance environments. Table 3-1 shows typical end-to-end pointing performance of a vector fixed in a payload (such as a boresight) for catalog Curio reference configurations. Pointing performance depends on the thermal environment, disturbance environment, concept of operations, and payload calibration accuracy. Custom Curio configurations may support tighter attitude performance. Contact Lockheed Martin for analysis and design options to support tighter pointing requirements.

*Table 3-1. Typical worst-axis payload attitude control performance.*

| | Typical | Best |
|---|---|---|
| **Nadir pointing from low lunar orbit (3σ)** | <1.88 mrad<br><0.11°<br><388 arcsec | <1.16 mrad<br><0.066°<br><239 arcsec |
| **Inertial pointing from Lagrange point halo (3σ)** | <0.92 mrad<br><0.053°<br><190 arcsec | <0.79 mrad<br><0.045°<br><163 arcsec |

In low Earth orbit (LEO) or medium Earth orbit (MEO), magnetic torque rods can be incorporated into the design for continuous momentum management.

### 3.3.2 Slew Rate

The Curio Mini was designed with a preferential slew axis that can achieve over 4°/s slew rates while maintaining sub-degree pointing accuracy about the slew axis. Typical slew rates for the larger Curio sizes are 0.5°/s or less. Larger reaction wheel options can support higher slew rates, though pointing performance during slews may not meet the same level as above.

### 3.3.3 Spin/Scan Rate

The Curio attitude control architecture is three-axis stabilized. The spacecraft can maintain a consistent roll rate up to about 2°/s without losing star tracker lock.

### 3.3.4 Other Attitude Needs and Constraints

Contact Lockheed Martin for additional discussion about payload pointing needs and constraints, such as gimbaled platforms, thermal constraints, or Sun keep-out zones.

## 3.4 Mission Automation

Curio onboard flight software modules are defined by configuration files that are tailored to the mission. Configuration files are text files in spacecraft nonvolatile memory that define the spacecraft and subsystem modes, telemetry, and behaviors, including the onboard sequence engine.

The sequence engine provides autonomous functionality by executing text file scripts, scheduled by time or event. Sequences make use of spacecraft commands, including subsystem and payload commands, as well as math libraries and flow control such as conditional statements and time delays. Sequences allow Curio spacecraft to perform operations out of contact due to ground station availability, solar conjunction, or antenna pointing. This includes spacecraft housekeeping tasks, maneuvers, safing, and payload operations.

Both configuration files and sequences can be updated during the mission without changing flight software.

### 3.4.1 Payload Automation

Sequences are resident in the spacecraft CDH and control functions at the spacecraft and subsystem level. Sequences can open and close load switches powering payload components, initiate slews to attitude targets, actuate mechanisms, and initiate communication events. Sequences can also send predefined commands to the payload (see Section 4.4.2) and monitor channelized payload telemetry for event triggers. The fault protection system (Section 3.4.2) provides another mechanism to monitor payload telemetry and initiate payload commands or sequences in response to detected conditions.

### 3.4.2 Spacecraft Fault Protection and Safe Mode

The Curio spacecraft is a single-string bus, with extensive software fault protection (FP) resident in the rad-hard CDH. The FP design is based on past deep space mission experience, evolved to meet the expectations of a small NASA Class D mission.

Spacecraft-level FP monitors system and subsystem performance and reacts by triggering an appropriate configurable sequence. The system handles some low-level faults by clearing or resetting individual components without interrupting mission activities. High-level faults result in FP placing the spacecraft in Safe Mode. The goal of Safe Mode is to establish and maintain a stable power, thermal, communication, payload, and attitude state so that ground intervention can diagnose issues and restore normal operations. The FP architecture accommodates the execution of time-critical mission events, such as orbit insertion burns or flybys, without interruption.

For details on component- or payload-specific fault protections, see Section 4.5.

## 3.5 Telecommunications

The Curio telecommunications solution is designed for compatibility with NASA (NSN and DSN) or commercial ground networks (KSAT and SSC, for example). The subsystem is designed to maximize flexibility in support of data volume requirements and navigation data requirements, including coherent Doppler data and/or ranging data.  The flexibility is enabled by the menu of heritage components available to meet the mission communication requirement needs. Patch antenna options include low-gain antennas (LGAs) for omnidirectional communications and directional medium- and high-gain antennas (MGAs or HGAs) for higher rates to support larger mission data volume needs. The software-defined radio is designed for operation on LEO, GEO, lunar, or interplanetary missions and includes two completely independent full-duplex channels.

### 3.5.1 Data Downlink

The telecommunications subsystem architecture provides multiple antenna paths to enable wide angle communications, with options for high-bandwidth communications via a high-gain antenna.

For details on mission data delivery from the Lockheed Martin Mission Support Area, see Section 6.1.2.

#### *3.5.1.1 Downlink Frequencies*

The Curio spacecraft software-defined radio provides options for S-Band, X-band, Ka-Band, or dual frequency channel downlink, subject to frequency allocation and ground station compatibility.

#### *3.5.1.2 Data Rates*

Table 3-2 lists representative downlink data rates to typical ground stations. Actual data rates require mission-specific link analysis. Please contact Lockheed Martin to discuss large data volumes and movement of those data volumes for downlink.

*Table 3-2. Downlink data rates.*

| | |
|---|---|
| **Earth-orbiting** | 100 kbps to 12.5 Mbps |
| **Interplanetary** | 30 bps to 1 Mbps* |

*Notes:*

** Achievable data rate depends on Earth range and may vary substantially over the mission*

### 3.5.2 Command Uplink

The Curio telecommunications subsystem typically includes multiple wide angle antennas to ensure near 4π steradian commandability to the spacecraft.  Higher uplink rates are enabled on MGAs or HGAs.

For details on payload commanding from the Lockheed Martin Mission Support Area, see Section 6.1.2.

##### 3.5.2.1 Uplink Frequencies

The Curio spacecraft software-defined radio enables options for S-Band, X-band, Ka-Band, or dual frequency channel uplink, subject to frequency allocation and ground station compatibility.

##### 3.5.2.2 Space System Protection

The Curio spacecraft telecommunications system has options to decrypt AES-256 uplinks before passing commands to CDH or the payloads.

### 3.5.3 Ground System Compatibility

The Curio spacecraft telecommunications system has heritage compatibility with NASA DSN ground stations and is designed for compatibility with the NSN and commercial ground networks.

# 4 Payload Accommodations

Curio spacecraft accommodate single payloads, multiple payloads, and single payloads with distributed sensing elements. Payloads may be mounted externally or internally.

The payload accommodation capabilities stated in this document are guidelines for mission concept development. The Curio team encourages any prospective users with similar mission needs to reach out for detailed discussions about special payload needs.

## 4.1 Mechanical Accommodation

### 4.1.1 Payload Mass

The following table provides a guideline of payload mass capability for the different Curio spacecraft sizes, without any change to the point-of-departure structure. Additional payload mass and volume may be available with a modified or custom structure, or for Curio Medium and Grande missions that require no or little propulsion. Payload size and configuration may affect various spacecraft performance parameters, including agility, ΔV, thermal dissipation, fundamental frequency, and others. Customers should contact Lockheed Martin for specific performance discussions.

*Table 4-1. Payload mass allocations without structure modification. ESPA limits depend on center of mass position.*

| | Mini | Medium | Grande |
|---|---|---|---|
| **Payload mass (kg)** | 10 | 25 | 50 |
| **Total launch mass (kg)** | 65 | 135 | 270 |
| ***ESPA limit (kg)*** | *180* | *180* | *465* |

 

### 4.1.2 Payload Volume

Curio spacecraft offer both external and internal payload accommodations. For more information about payload volume capabilities, please contact Lockheed Martin.

#### *4.1.2.1 Typical External Volume Available to Payload*

External payloads are mounted on exterior panels and exposed to the space environment. Figure 4-1 shows the representative external volumes available to payloads on typical Curio spacecraft. These configurations are typical designs based on the most restrictive ESPA keep-in volumes. Other payload configurations may be possible depending on launch, structural, and thermal needs.

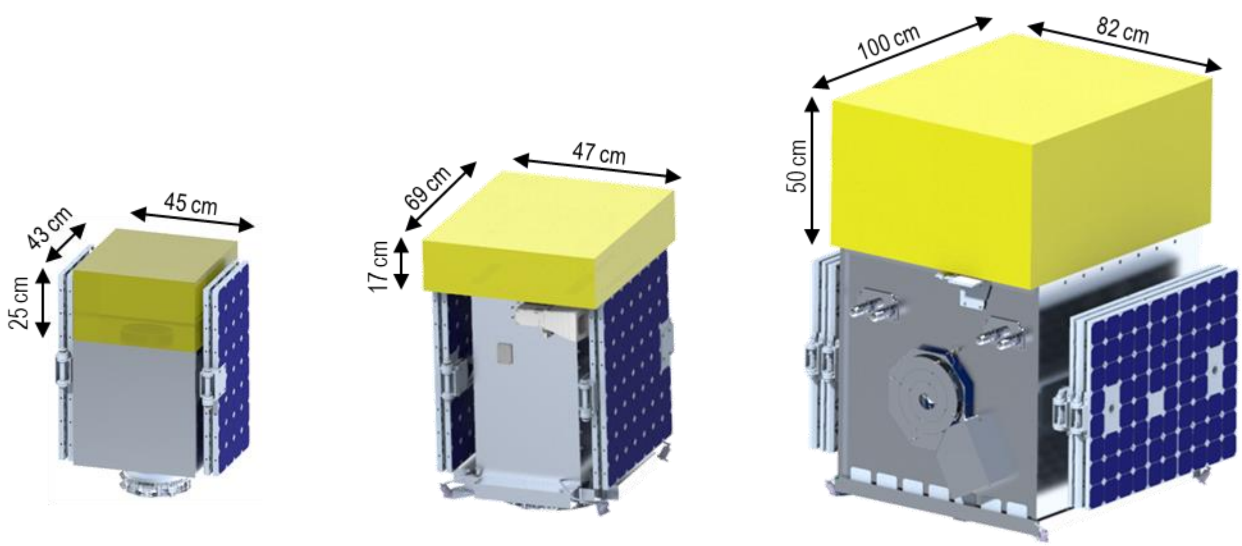


*Figure 4-1. Representative external payload volume on Curio Mini (left), Medium (middle), and Grande (right).*

#### *4.1.2.2 Typical Internal Volumes Available to Payload*

Internal payloads are mounted on structural panels with spacecraft avionics boxes. Table 4-2 describes the reserved internal volume available to payloads on typical Curio spacecraft. These configurations are typical designs and other payload configurations may be possible depending on structural, thermal, propulsion, and other subsystem needs.

*Table 4-2. Reserved internal payload volumes.*

| | **Mini** | **Medium** | **Grande** |
|---|---|---|---|
| **Internal payload shape** | cylinder | box | box |
| **Internal payload dimensions** | 17 cm diameter<br>17 cm long | 45 x 12 x 10 cm | 71 x 17 x 12 cm |

Other shapes and configurations of internal payload may be available. Contact Lockheed Martin for specifics of the internal volume and potential modifications of the internal configuration of the spacecraft.

#### 4.1.3 Payload Deployments

All fixed-base frequencies of deployable structures must be 1 Hz or higher, with frequencies 2.5 Hz or higher desired. Payloads must require a load switch activation or software command to initiate any deployment.

Portions of the spacecraft external volume may be reserved for radiator surfaces, antennas, thruster plumes, or sensor fields of view. The sizes and locations of these areas are not specified in the illustrated payload envelopes because they depend on mission-specific factors such as orbit geometry, pointing plan, and payload heat dissipation. Lockheed Martin will work with payload customers to develop acceptable payload accommodations.

#### 4.1.4 Mechanical Interfaces

The spacecraft structure panels offer adaptable positioning of fastener locations, without the need for standardized attachment locations or additional mounting adapter plates. Lockheed Martin will provide standard #8 or #10 mounting fasteners (NAS1351 or NAS1352, and material code "N" or similar), washers, shims, and thermal isolators if needed. Other fastener sizes are available per request.

### 4.2 Electrical Interfaces

Curio spacecraft are designed primarily to support a range of science experiments, complex instruments, and technology demonstrations. The solar array may be body-fixed or gimbaled to provide power generation in a variety of attitudes. The battery bank is sized to handle mission-specific eclipse environments and payload operations concepts. Customers are invited to contact Lockheed Martin for specific discussions about power utilization in different spacecraft and payload modes and under different mission operation conditions.

#### 4.2.1 Payload Power

Table 4-3 lists typical operating power available for payloads on a standard Curio spacecraft in consistent sunlight at the end of a 3 year mission. This assumes a 1 AU Sun range, no eclipse conditions, no changes to the spacecraft or payload power state, and no solar array offpointing. Curio spacecraft can supply payloads with higher power during transient cases, which may include battery discharge, as indicated.

Contact Lockheed Martin for detailed power modeling in relevant mission orbits or during transient conditions, as well as for thermal modeling during high power dissipation cases of payload operation.

*Table 4-3. Available payload power.*

| | Mini | Medium | Grande |
|---|---|---|---|
| **Payload power in sunlight, standard configuration (W)** | 15 | 145 | 220 |
| **Payload power in sunlight, maximum solar array size configuration (W)** | 15 | 145 | 430 |
| **Peak transient power to payload, standard configuration (W)** | 250* for <16 minutes† | 300* for <8 minutes† | 550* for <16 minutes† |
| **Peak transient power to payload, maximum battery configuration (W)** | 250* for <16 minutes† | 300* for <16 minutes† | 900* for <22 minutes† |

*Notes:*

** Peak power numbers are estimates and depend on thermal characteristics of the spacecraft and payload.*

*† Battery size and thermal design determines the duration a payload can sustain transient discharge.*

### 4.2.2 Switched Power and Voltage/Current Characteristics

The Curio spacecraft offers various standard electrical interfaces to payloads. All power available to payloads is switched power, controlled by spacecraft software. This includes payload-specific heater zones. Table 4-4 lists available switches without reconfiguration of the spacecraft channelization. *Some missions, such as those using electric propulsion or those requiring additional bus-controlled heater zones, may allocate a mission-specific number of the following channels to spacecraft components.* Lockheed Martin can advise potential customers about these options.

*Table 4-4. Power characteristics of available switches on Curio reference configurations.*

| Nominal voltage | Voltage range | Maximum current | Typical switches available for payload | | |
|---|---|---|---|---|---|
| | | | Baseline | Options (Medium) | Options (Grande) |
| **28 V** | 24-33.6 V | 8 A | - | up to 1 | up to 3 |
| **28 V** | 24-33.6 V | 6 A | - | up to 2 | up to 6 |
| **28 V** | 24-33.6 V | 4 A | 4 | up to 6 | up to 10 |
| **28 V** | 24-33.6 V | 2 A | - | up to 6 | up to 18 |
| **12 V** | 11.6-12.4 V | 4 A | 2 | up to 4 | up to 8 |
| **5 V** | 4.75-5.25 | 4 A | 4 | up to 6 | up to 10 |

In addition to the maximum current limits on individual switches, there are limitations on the maximum supported total current passing through the power system backplane. Spacecraft modes will manage device operation and duty cycles to respect overall limits.

All switches are equipped with overcurrent protection. Payload inrush current should not exceed the indicated maximum current for more than 50 µs after turn-on to avoid tripping the overcurrent protection limits.

## 4.3 Thermal Accommodation

The Curio thermal design is necessarily tailored to each mission. Thermal solutions are driven by payload locations and power profiles, and by the trajectory and pointing plan which determines which spacecraft surfaces are exposed to direct sunlight and the thermal loads of nearby planetary bodies. The spacecraft thermal design is primarily passive, using multi-layer insulation, surface coatings, and thermal doublers to manage heat loads and rejection. Heaters guard against low temperatures. High-power payloads can be accommodated via a combination of radiation from the payload itself, conduction via the spacecraft interface, and thoughtful mission planning.

Lockheed Martin will conduct an integrated thermal analysis for each mission to ensure each payload is maintained within allowable flight temperature (AFT) limits and is compatible with the mission concept. Payload providers are responsible for providing simplified component-level thermal models and payload upper and lower AFT limits, typically at the box level or at an interface. The spacecraft allocates heater power channels for each payload, controlled via mechanical thermostat control or software-defined temperature limits. If a payload uses internal heaters or thermo-electric coolers, they contribute to the payload's mass, power, and volume allocation. Heater power predictions, as determined in the flight system-level analysis, are incorporated into the flight system power budgets and models. The thermal design's performance is typically verified at a system-level thermal vacuum test.

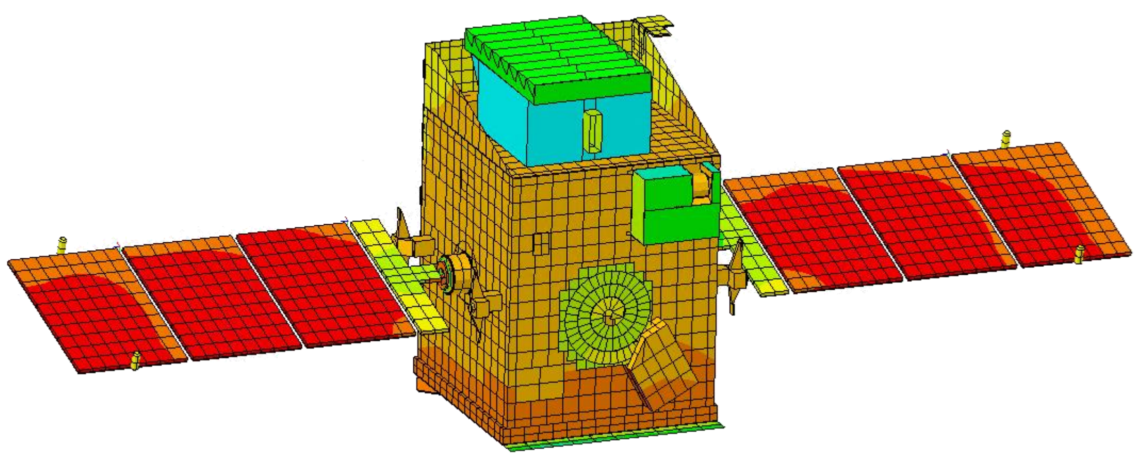

*Figure 4-2. Lockheed Martin applies integrated thermal modeling and design capabilities to ensure components are within allowable temperatures through all relevant mission scenarios.*

## 4.4 Data Interfaces and Services

### 4.4.1 Payload Data Interfaces

The Curio command and data handling (CDH) system offers the following standard payload data interfaces, with transfer speeds up to 90 Mbps:

*Table 4-5. Available payload command, telemetry, and data interfaces.*

| Interface | Number |
|---|---|
| **SpaceWire** | 2 |
| **RS-422 (synchronous)** | 2 |
| **RS-422 (asynchronous)** | 4 |
| **SPI** | 2 |
| **Analog voltage input (to CDH)** | 4 |
| **Discrete input (to CDH)** | 4 |
| **Discrete output (from CDH)** | 2 |
| **1 PPS clock** | n/a |

Especially at higher data rates, some interfaces will affect processor margin available on the flight computer.

Nonstandard interfaces can be implemented at additional cost. Lockheed Martin invites payload developers to contact us with details of other interface requests.

### 4.4.2 Payload Commanding and Telemetry

Curio spacecraft typically manage payload commanding through scheduled command sequences, which may include pass-through commands to the payload. Payload housekeeping telemetry and mission data is likewise passed through the spacecraft communications system as fixed-format or raw data, for the payload operations center to process. Payload telemetry can be channelized for processing in the mission operations center.

Commands and Telemetry use standard CCSDS telecommands and telemetry using SPP (CCSDS 133.0-B-2 Space Packet Protocol).[1] The commands and telemetry definitions are disseminated using the XTCE file format (CCSDS 660.2-G-2).[2]

### 4.4.3 Onboard Data Storage

The standard CDH offers 15 GB usable EDAC-protected NAND Flash nonvolatile storage. This storage is shared between the payload and spacecraft, with spacecraft usage estimated at <180 MB. Additional data storage options are available.

### 4.4.4 Time Services

The CDH provides a pulse-per-second (PPS) time synchronization signal that is available for payloads. The PPS signal in conjunction with time at tone data signal provides the spacecraft clock at the time of the PPS. The pulse is 3.3 V and active-high, normally low,

[1] https://public.ccsds.org/Pubs/133x0b2e1.pdf
[2] https://public.ccsds.org/Pubs/660x2g2.pdf

with pulse width of 1 μsec. The standard onboard clock drift rate, between correlations with the ground, is approximately 2 seconds per day. Contact Lockheed Martin to discuss options for more precise timekeeping, including GPS time synchronization in LEO.

### 4.4.5 Software Services

The 90 MHz standard Curio spacecraft CPU has >50% processor margin when running only spacecraft services, managers, and monitors. Some of this processing margin is available for implementation of mission- and payload-specific algorithms.

The payload management software module handles payload power state, commanding, housekeeping, data transfer, and telemetry, as well as interfaces to spacecraft-level sequences and fault protections. The payload management software can be customized to a wide range of payload interfaces and will provide data storage and forwarding. The spacecraft software can optionally provide functions such as payload data processing, fault protection, and some autonomous responses.

## 4.5 Component Fault Protection

Configurable fault protections can provide payload health monitoring and response. All fault protections are defined by configuration files that do not alter FSW and can be modified in flight. The general Curio FP philosophy is to bring devices into a safe state for ground intervention through simple actions such as a power cycle. However, it may be possible to design FP responses to autonomously recover compatible devices. The Curio team will work with payload and mission developers to define the appropriate FP responses to achieve mission goals for performance and robustness. All FP monitors, limits, parameters, and responses are defined in configuration files.

Representative FP monitors available for payload health monitoring include:

- Telemetry within fixed low/high limits,
- Telemetry within computed low/high limits,
- Telemetry matches last commanded states,
- Power states within low/high limits,
- Temperatures within low/high limits.

This is not a complete list. Monitors generally do not trigger a response until they are in fault for a configurable persistence time. FP responses are implemented via configurable sequences. Sequences (also described in Section 3.4) can take many actions, including:

- Setting telemetry flags for downlink to the ground,
- Removing power from a device,
- Power cycling a device,
- Commanding a device to change configuration or mode,
- Elevating flags to higher-level FP, such as spacecraft Safe Mode.

Sequences can also include basic logic flows, computations based on telemetry and math libraries, and delays.

Generally, spacecraft-level Safe Mode (Section 3.4.2) will interrupt payload operation and place payloads into a safe or standby mode, often by removing payload power. Spacecraft-controlled heaters will maintain payload temperatures in Safe Mode. Lockheed Martin will work with payload developers to understand requirements for safe and survival conditions.

# 5 Assembly, Integration, and Test Capabilities

Curio projects offer all the services and interfaces for successful integration and operation of many possible science and commercial payloads in various mission contexts.

A comprehensive and collaborative approach to mission integration shortens schedule, reduces cost and risk, and maximizes the opportunities to identify and resolve potential operational issues before launch. The initial focus of the experienced mission integration team is to cultivate strong engagement between payload, spacecraft, and mission operations teams to develop clear and accurate interface requirements. The team also defines expectations and activities to meet mission needs and blend the unique organizational cultures of the mission partners. This approach prepares the team for integration risk reduction (such as testbeds and fit checks), monitoring ICD compliance and managing changes, preparing for and completing integration with the spacecraft, supporting the payload in flight system testing, and conducting flight system testing in mission operational scenarios.

## 5.1 Test Programs

Curio spacecraft go through a test program that combines the best of heritage planetary mission test lessons learned with the streamlined processes used on commercial satellites. The sequence of tests includes fit checks, electrical tests, functional and performance tests, and environmental tests. The integrated spacecraft typically begins the environmental test program five months prior to launch, however the timeline can be compressed based on the mission's schedule and test requirements.

## 5.2 Facilities

Lockheed Martin's Denver facilities include all necessary test chambers, labs, and clean rooms on-site. Primary test facilities for planetary spacecraft are shown in Figure 5-1. The payload integration process prevents schedule slips by developing a test and verification schedule capable of absorbing delays, using risk-reduction activities for the interfaces prior to integration and test, and maintaining open lines of communications throughout the full program.

**Space Simulation Lab (SSL)**

- Highbay 40×40 ft
- Vacuum Chamber 29 ft Dia × 65 ft High
- 2× 40 Ton Cranes, 87 ft Hook Height
- Class 100,000 Clean Room

**Reverberant Acoustic Lab (RAL)**

- Highbay 47×36 ft
- 40 Ton Crane, 72 ft Hook Height
- Class 100,000 Clean Room
- Acoustic Chamber 18×19×68 ft High

**Multipurpose Test Facility (MTF)**

- Highbay
- Pressure Test
- 20 Ton Crane, 40 ft Hook Height
- Class 100,000 Clean Room

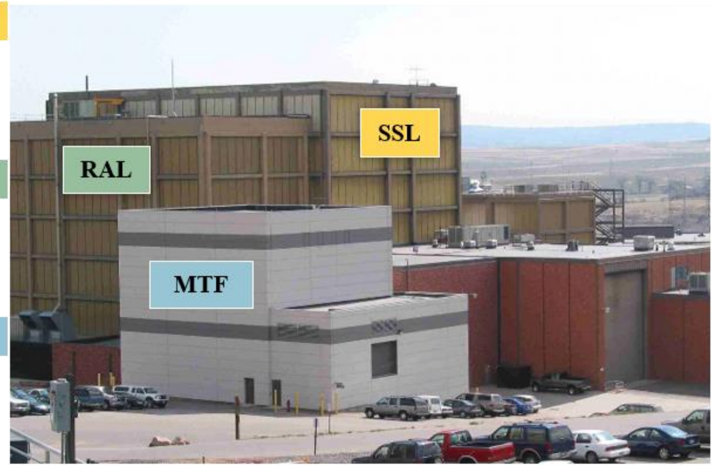


*Figure 5-1 Lockheed Martin has established facilities for planetary spacecraft assembly, functional tests, and environmental tests on the same campus, enabling efficient production of Curio spacecraft.*

### 5.2.1 Cleanliness

Standard operations occur in an ISO Class 8 (100,000) cleanroom environment. Facilities can be configured to support higher cleanliness (10,000) and additional requirements including planetary protection.

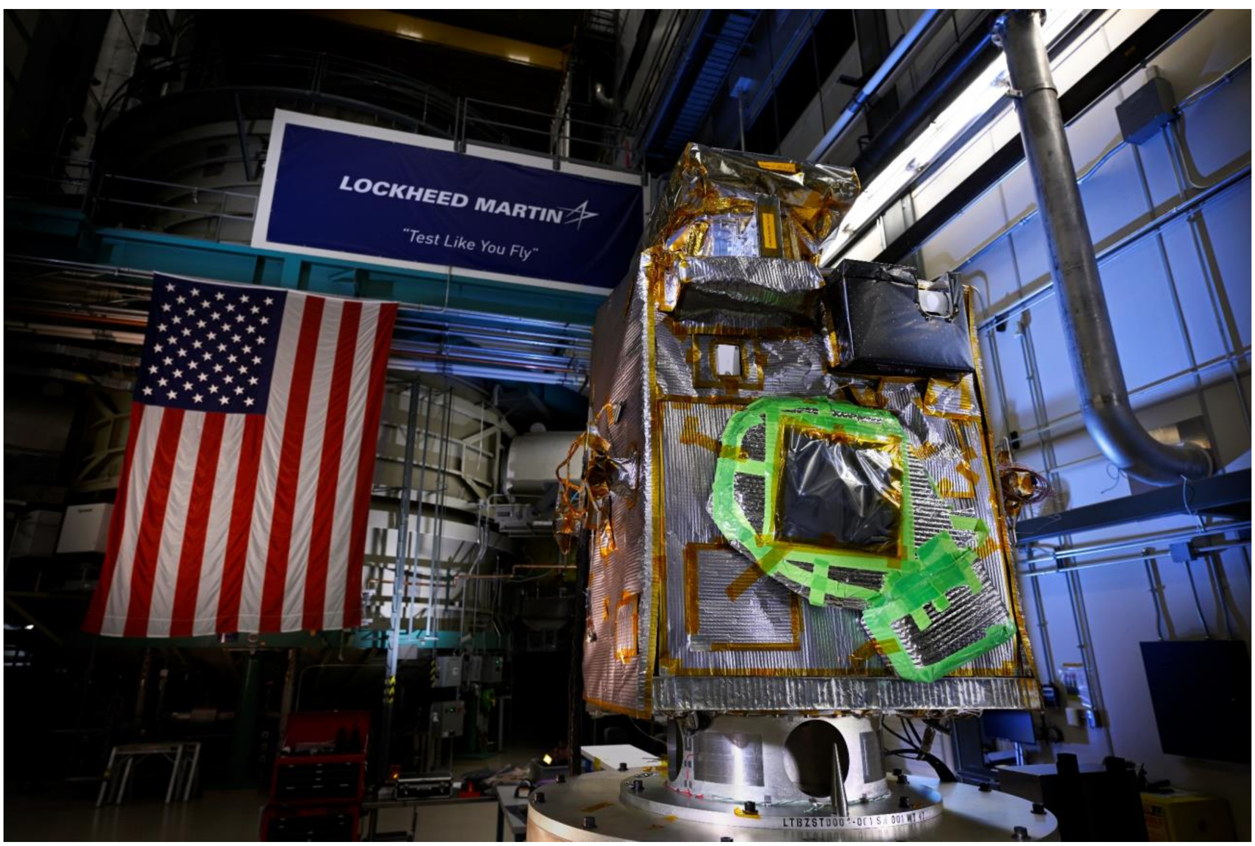


*Figure 5-2 Lunar Trailblazer in the SSL.*

### 5.3 FlatSat

The FlatSat is a real-time hardware-in-the-loop simulation environment based on emulator hardware corresponding to spacecraft components and subsystems, along with simulators or stimulators to mimic flightlike responses. The FlatSat runs spacecraft flight software, and ground control and telemetry systems interact with it through a flightlike interface. Typical uses of the FlatSat include assembly and test planning, benchtop checkout of components, mission operations planning, anomaly investigation, and software integration and troubleshooting. The FlatSat resides at Lockheed Martin's facility and can be integrated with payload emulator, EDUs, simulators, or flight components to facilitate the development and verification of hardware and software interfaces.

### 5.4 Launch Site Operations

Lockheed Martin has launched numerous planetary and Earth-orbiting satellites at Kennedy Space Center and Vandenburg Space Force Base. This experience results in launch operations that are highly integrated between assembly and test, mission operations, and the launch site. Lockheed Martin also has experience with commercial and government launch processing at other sites on A2100 and LM2100 missions.

Lockheed Martin can arrange air and ground transportation from Denver to the launch site, where the Curio team will support final performance testing and configuring for launch. The operations team participates in launch and ground working groups to develop clear requirements including schedule and resources. The spacecraft bus does not require special thermal, cleanliness, or EMI/EMC handling at the launch site. Lockheed Martin can facilitate propulsion system processing and propellant loading. Mission operations monitors spacecraft systems during launch operations and coordinates the handoff of spacecraft control from the launch vehicle post-separation.

## 6 Mission Operations Capabilities

### 6.1 The Mission Operations Center

Lockheed Martin's Deep Space Exploration Mission Operations group can operate Curio missions from the Mission Operations Center (MOC) in the Denver, Colorado facility. The MOC was first used to operate a planetary spacecraft in 1989 with Magellan and has now operated 17 planetary missions such as Mars Odyssey and Lucy. The team currently operates six planetary spacecraft from the MOC. Curio operations will share core processes and procedures, experienced personnel, facilities, and ops approach with a long history of successful flight missions.

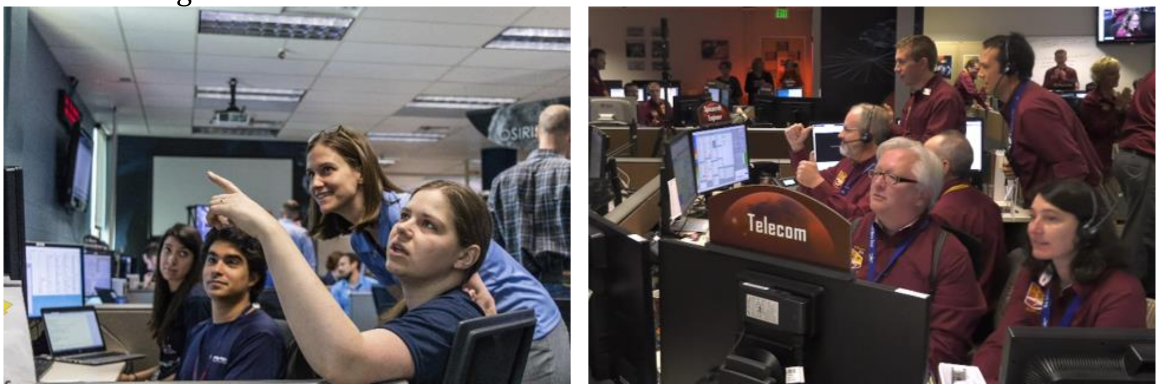


*Figure 6-1. Lockheed Martin's experienced Deep Space Exploration Mission Operations team and established Mission Operations Center operate Curio missions affordably and effectively. OSIRIS-REx (l) and InSight (r) mission operations shown.*

The Mission Ops team focuses on consistency, automation, personnel cross-training, and maximizing commonality to reduce cost and ensure mission success. Mission operations begin early in the development life cycle with Mission Ops staff participating in design reviews, developing and implementing engineering objectives, and supporting payload sequencing activities. They build, review, and test command products early in development to ensure successful program milestones, as well as a smooth transition to efficient day-to-day operations after launch. Flight-proven workstation displays, telemetry databases, and spacecraft performance analysis software are adapted from previous missions for flight operation of Curio spacecraft and payloads.

It is common for Mission Operations personnel to also support development and vice versa. Often development team members will follow a spacecraft into mission operations. The Ground Data Systems and Services Organization (GDSSO) works alongside development and mission operations to ensure data accountability, commanding, cybersecurity compliance, and overall ground system functionality. Lockheed Martin utilizes a multi-mission Mission Operations Network (MONET) as the backbone for GDSSO services.

### 6.1.1 Typical Operational Practices

Lockheed Martin's multi-mission organization is cost effective and efficient. Prior to Launch, as series of Thread Tests and Operational Readiness tests will occur to verify procedures and interfaces. Customers are welcome to participate in these events, as are the payload teams if the test involves instrument interfaces and/or operations. Specific needs of each mission are determined during development and refined during operations. This includes the duration of background sequences (typically 28 days), desat cadence, communication requirements, data integrity requirements, maneuver frequency, etc. The team typically conducts "lights out" operations, in which team members are not required on console outside of business hours unless the mission needs dictate otherwise. Proven tools will alert the team should a spacecraft issue occur and the team will respond accordingly. Typical durations for command generation is 2 weeks, however the team does have the ability to surge for a 24 hour turnaround or update of command products when needed.

### 6.1.2 Mission Data Handling

During flight, the Lockheed Martin MOC will receive payload telemetry over a secure network and transmit it to the customer's payload operations center. The customer can then provide payload operations command sequences for Lockheed Martin to radiate to the spacecraft. Payload uplinks are accomplished through pass-through commands that automatically route any instrument-level control data through the spacecraft RF link to the payload. Similarly, payload health & status and science telemetry is routed and stored on the spacecraft for downlink at the next opportunity. More complex control of a payload, such as autonomous response to an indicator, and higher-priority routing of data are available. Lockheed Martin can also provide additional payload operations and operations planning services. Customers who will perform complex near-real time operations with frequent commanding may consider locating an operations center at the Lockheed Martin facility for maximum efficiency.

## 6.2 Mission Design

Lockheed Martin has extensive mission and trajectory design capabilities to assist customers with developing their mission concept and planning operations. Curio mission designers have also supported NASA planetary missions including GRAIL in low lunar orbit; Lucy in interplanetary transfer to the Jupiter Trojans; and OSIRIS-REx in near-Earth space, low orbit of an asteroid, and entry, descent, and landing.

Relevant mission design capabilities include: ballistic transfer design, patched conic trajectory design, trajectory optimization, weak stability boundary design, low-thrust trajectory design, coverage analysis, stationkeeping and orbit maintenance analysis, disturbance prediction, aerocapture design, and planetary entry, descent, and landing with or without an atmosphere. Curio mission designs have included weak stability boundary lunar transfer designs, low lunar orbit analysis, highly elliptical lunar orbit design and analysis, Earth orbit design and analysis, near-Earth asteroid targeting, momentum accumulation prediction, and low-thrust trajectory design. Lockheed Martin has computing cluster assets that allow large-scale trajectory optimizations and searches, as demonstrated during the Janus mission science target selection from the population of all known near-Earth asteroids.

## 6.3 Deep Space Navigation

Curio missions have access to Lockheed Martin's deep space navigation capabilities, both in the mission formulation and mission operation phases. Deep space navigation includes interplanetary, cislunar, and Earth environment orbit determination, flyby geometry design and analysis, flight path correction maneuver design, mission operation trajectory redesign, relative navigation of multiple spacecraft, and navigation during descent and landing.

# 7 Project Execution

The Curio team takes Lockheed Martin's institutional knowledge and lessons learned from implementing robotic interplanetary missions and applies this deep expertise in an efficient development and testing process tailored to the mission class and needs of the payload. The team shares subject matter experts, many with experience on prior deep space missions, between Curio mission implementations.

Lockheed Martin has adopted standard practices and policies for Class C and D projects. The goal of Curio mission implementation is to prioritize the science, with appropriate risk tolerance including NASA Class D elements from Lockheed Martin's Mission Assurance Best Practices.

Curio projects execute streamlined procurements from subcontractors and suppliers. Generally, projects procure components to supplier-developed catalog specifications, limiting mission-specific development and allowing suppliers to maintain their own streamlined schedules and business rhythms.

While Curio projects must remain focused to enable performance at low cost, there are no boundaries between a Curio mission team and the rest of Lockheed Martin. Curio projects have access to the full breadth of Lockheed Martin facilities, personnel, analysis capabilities, and manufacturing centers. Curio projects tap these capabilities as needed to support specific mission requirements, with transparency to our customers about any scope impacts to the project. The Curio team has tailored typical aerospace processes to effectively utilize the deep experience available while maintaining a focus on cost and schedule execution. Customer interactions and products can be tailored depending upon the needs of the specific mission.

The Curio team encourages "systems thinking" among its members. Cross-discipline knowledge sharing is vital for each discipline engineer to understand the mission context and constraints of their subsystems. Systems thinking facilitates positive problem-solving, prevents information from concentrating in silos, and prevents hidden reserves from limiting project flexibility.

## 7.1 Systems Engineering

Lockheed Martin works with prospective mission teams to fully understand the overall science and mission goals to derive an achievable requirements baseline and mission architecture. The team applies extensive systems engineering experience to account for the specific mission goals and environments. Requirements development, traceability, and verification are key to successful missions in the complex science and deep space mission arenas. Lockheed Martin will develop spacecraft and subsystem level requirements based on the top level mission requirements, ensure traceability from mission requirements to subsystems, and ensure that verification plans are implemented to verify mission performance at the most appropriate phase of integration. Lockheed Martin uses aerospace industry standard tools to perform these systems engineering functions and can tailor toolsets and requirements management deliverables to suit the needs of the mission team.

## 7.2 Key Roles and Responsibilities

An overall Curio Portfolio Manager has broad visibility across Curio missions and facilitates resource distribution among them. The Portfolio Manager coordinates support and facility usage with the broader Lockheed Martin organization.

The overall Curio Chief Engineer manages technical efforts across Curio missions, including coordination of lessons learned and solutions to technical issues that impact all Curio projects.

A mission-specific Program Manager handles day to day execution of Curio mission implementation. This includes customer interfaces and task planning.

Each Curio project has several prominent systems engineering roles:

- The System Design Lead drives the overall technical solution for a mission, and chairs regular meetings of the System Design Team. Each Curio project has a full-time System Design Lead.
- Payload Systems Engineers coordinate payload interfaces, requirements, deliveries, and integration. (Individual Payload Systems Engineers may support more than one payload.)
- The Mission Operations Lead develops operations plans and procedures, as well as planning for onboard autonomous functions such as sequences. The Mission Operations Lead provides operations-focused inputs throughout the design life cycle of a project.

The Assembly, Test, Launch, and Operations Manager shepherds spacecraft integration and test activities including staff planning, facility usage planning, hardware receiving and test, payload integration, system-level testing, environmental testing, storage operations, and delivery to launch.

Subsystem and discipline engineering support (such as mechanical configuration, thermal, flight software, telecommunications, electrical power, stress and dynamics, and guidance, navigation, and control) is shared and distributed among Curio missions as needed. This both streamlines individual project staffing and allow ready transmission of common tools and implementation lessons learned between Curio projects.

## 7.3 Schedule

Due to the modular and streamlined architecture of Curio spacecraft, delivery to the launch site is possible in as little as 36 months from contract signing. The schedule will be developed as the spacecraft mission is defined and unique capabilities are identified. The Curio program management team will work with the customer to develop an achievable and optimized schedule that meets customer needs and will communicate progress throughout the life cycle of the mission.

| ***For Further Information*** |
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