TROPICS Project Plan

Lincoln Laboratory
Massachusetts Institute of Technology
Lexington, Massachusetts
June 14, 2017

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Revision History

Revision	Description of Change	Author	Date
1.0	Initial Release	S. Michael	1/6/2017
1.1	Update for SRR	S. Michael	4/24/2017
1.2	Additional updates for SRR	S. Michael	5/3/2017
2.0	Post SRR Updates	S. Michael	5/18/2017
2.1	Corrected typos	S. Michael	5/25/2017
2.2	updated cover plot with 3-3-0 constellation and fixed altitude on ground scan pattern plot and incorporated review comments from Greg Stover and John Rogers	S. Michael	6/6/2017
2.3	Kristin Clark listed as new PM ; additional typo corrections	S. Michael	6/9/2017
2.4	Incorporate changes from NASA program office and update Technology Development Plan	S. Michael	6/14/2017

Contents

1 Project Overview

1.1 Introduction

The "Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats" (TROPICS) project was selected by NASA's Science Mission Directorate (SMD)/Earth Science Division (ESD) on March 10, 2016, in response to the Second Stand Alone Mission of Opportunity Notice (SALMON-2), Program Element Appendix (PEA) P: Earth Venture Instrument-3 (EVI-3), NNH12ZDA006O solicitation.

The Principal Investigator (PI) is Dr. William J. Blackwell from MIT Lincoln Laboratory (MIT LL); he is responsible for the TROPICS mission development and activities necessary to deliver the science as proposed and subsequently selected by NASA's selection authority. The Principal Investigator is responsible for scientific success, design, development, test, mission operations, and data verification tasks and will coordinate the work of all contractors and science team members. The TROPICS project will implement a spaceborne Earth observation mission designed to collect measurements over the tropical latitudes that allow for observation of the thermodynamics and precipitation structures of Tropical Cyclones (TCs) over much of the storm systems' life cycles. The measurements will provide nearly all-weather observations of 3-D temperature and humidity, as well as cloud ice, precipitation horizontal structure, and instantaneous surface rain rates. These measurements and the increased temporal resolution provided by the constellation are needed to better understand the TC life cycles and the environmental factors that affect the intensification of TCs. The TROPICS Space Vehicles (SVs) will be launched on one or more NASA-provided expendable launch vehicles to form a multi-plane constellation capable of providing the the median observation revisit rates necessary to fulfill all baseline science requirements.

The scientific goal of TROPICS is to provide nearly all-weather observations of 3-D temperature and humidity, as well as cloud ice and precipitation horizontal structure, at high temporal resolution (compared to current Passive Microwave (PMW) measurements) that allow for high-value science investigations of TCs. Critical science questions to be addressed include:

1. What are the relationships between upper-level warm-core evolution and storm intensity and structure change?
2. What is the role of rapidly evolving storm structure in TC formation and intensity change?
3. How does environmental moisture impact TC structure, size, and intensity?
4. Can TC intensity forecasts be improved through utilization of rapid-update microwave information?

In accordance with `NASA Procedural Requirement (NPR) 7120.5E`, *NASA Space Flight Program and Project Management Requirements*, TROPICS is designated a Category 3 project, with program authority delegated from the Associate Administrator for the Science Mission Directorate (AA/SMD) through the Earth Science Division within SMD to the Earth System Science Pathfinder (ESSP) Program Manager at Langley Research Center (LaRC). The TROPICS satellites will be developed as Class D per `NPR 8705.4`, *Risk Classification for NASA Payloads*.

1.2 Objectives

TROPICS will demonstrate that science payloads on low-cost CubeSats can push the frontiers of spaceborne monitoring of the Earth. TROPICS will enable system science and fill gaps in our knowledge of the short time scale — on the order of hourly — evolution of tropical cyclones, where current capabilities are considerably slower. The TROPICS project will implement a spaceborne Earth-observation mission designed to collect measurements over the tropical latitudes to observe the thermodynamics and precipitation structures of TCs over much of the storm life cycle. The measurements will provide nearly all-weather observations of 3-D temperature and humidity, as well as cloud ice and precipitation horizontal structure. These measurements and the increased temporal resolution provided by the constellation are needed to better understand the TC life cycles and the environmental factors that affect the intensification of TCs.

The TROPICS science program is directly relevant to three of the six NASA Earth Science Focus Areas: Weather, Water and Energy Cycle, and Climate Variability and Change. TROPICS addresses goals and objectives from the 2014 NASA Strategic Plan including advancing the understanding of Earth and developing technologies to improve the quality of life on our home planet (Strategic Goal 2) and advancing knowledge of Earth as a system to meet the challenges of environmental change and to improve life on our planet (Objective 2.2). Furthermore, the TROPICS measurements intersect with the 2014 NASA Science Plan, including improving the capability to predict weather and extreme weather events, and furthering the use of Earth system science research to inform decisions and provide benefits to society. Finally, the TROPICS mission directly addresses the need for rapid-update observations with cloud-penetrating capability, cited in the National Research Council (NRC) recommendation to fly the PATH decadal survey mission. TROPICS will contribute to some of the PATH mission objectives to improve understanding of fundamental severe storm thermodynamic processes.

1.3 Mission Description and Technical Approach

The TROPICS core instrument is a cross-track scanning passive microwave spectrometer that provides measurements of upwelling thermal emission and scattering of the earth's atmosphere. Measurements are taken in approximately 12 channels (finalized by trade study, see Section 4.3) near atmospheric absorption features of oxygen and water vapor. Processing of the raw radiance values measured by the spectrometer yields atmospheric temperature, moisture, rain rates, and other information relevant to precipitation structure and storm intensity. Instrumentation needed to make these measurements has been used in space for decades, and ultra-compact instrumentation for CubeSat implementation is now available with high technology readiness level. TROPICS will provide the first publicly-available space-based measurements of brightness temperature near the 118 GHz oxygen line.

1.3.1 Science Objectives

The fundamental physical parameters required to address the science objectives are 3-D atmospheric temperature and humidity, storm intensity, and horizontal precipitation structure. These parameters have a long heritage of being derived from spaceborne Passive Microwave (PMW) imagery and sounding channels (e.g., AMSU, ATMS, SSMIS). Practical considerations of antenna and instrument size and mass for a 3U CubeSat system guide the selection of PMW channels for TROPICS.

Temperature and moisture profiles are retrievable from seven channels near 118 GHz and three near 183 GHz, respectively. The precipitation structure is obtained from a combination of 90 GHz, 206 GHz, and the temperature and moisture channels, with horizontal resolution matching that of the moisture data due to the high sensitivity to precipitation hydrometeors at 183 GHz. The 206 GHz channel will be sensitive to smaller ice particles than 90 GHz and will produce a stronger signal. These observables link back to science requirements and to the primary sensor requirements (horizontal and vertical resolution and sensitivity).

The key linkages between the primary TROPICS observables and science objectives are summarized below.

- **Objective 1: "Relate precipitation structure evolution, including the diurnal cycle, to the evolution of the upper-level warm core and associated intensity changes."**
  Temperature sounding performance of 2 K RMS up to 50 hPa (approximately 20 km altitude) provided

by TROPICS allows sensing of upper tropospheric Tropical Cyclone (TC) warm cores, important since a fully resolvable TC warm core is desired for objective estimates of storm intensity. The ATMS temperature sounding requirement drives the TROPICS sensor sensitivity requirement to approximately 0.5 K at the native sensor horizontal resolution, as determined using simulations of temperature profile retrieval performance with the TROPICS bands. Techniques developed to estimate the intensity of TCs from microwave sounder information have greatly aided TC satellite analysts and warning centers around the globe. All TROPICS channels together provide some information on vertical structure and will allow the derivation of proxies for intensity of precipitation in the TCs.

These techniques measure the upper-level warm-core anomaly and relate it to TC intensity assuming hydrostatic principles and statistical relationships. The upper-level thermal anomalies associated with the TC warm core are computed from brightness temperature (T_b) fields for selected microwave channels. To compute the local anomaly, a core radiance value is taken from the warmest pixel near the TC center. Environmental values are selected from a filtered pattern surrounding the TC and averaged. The resulting T_b anomalies are then correlated with publicly-available coincident in-situ aircraft intensity data to develop regression equations.

- **Objective 2: "Relate the occurrence of intense precipitation cores (convective bursts) to storm intensity evolution"**
  High-frequency PMW observations have the potential to provide a wealth of information on scattering by precipitation-sized ice particles. The novel 206 GHz channel will be particularly sensitive to ice particle scattering and will provide an opportunity to better identify and map convective precipitation. All TROPICS channels together provide some information on vertical structure and will allow the derivation of proxies for intensity of precipitation in TCs. These methodologies will be modified to use the combination of 90 GHz, 118 GHz, 183 GHz, and 206 GHz channels to arrive at brightness temperature depressions and differential scattering parameters between different channels with different gas absorption strength. Scattering signatures will be tied back to hydrometeor content and height of the scattering layer using a set of high-resolution simulations of tropical storms derived from the state-of-the-art 3-D modeling system.

- **Objective 3: "Relate retrieved environmental moisture measurements to coincident measures of storm structure (including size) and intensity"**
  A major unknown is whether dry air acts to potentially weaken TCs through modification of precipitation structure or overall convective activity. TROPICS will provide coupled measurements of the more slowly varying environmental humidity profiles around a TC, and heretofore unresolvable short-term variations in the vortex-scale horizontal precipitation structure over the lifetime of storms, that will enhance our ability to determine the extent of environmental humidity control on TC precipitation and intensity.

- **Objective 4: "Assimilate microwave radiances and/or retrievals in mesoscale and global scale models to assess impacts on storm track and intensity"**
  A unified resolution brightness temperature product allows for retrievals to use both the 183 GHz band and the 118 GHz band at exactly the same spatial resolution. This will result in an increased accuracy of clear-sky and cloudy temperature and water vapor soundings and will also increase the utility of those channels for data assimilation purposes.

- **Objective 5: "Utilize microwave parameters as input into statistical storm intensity models"**
  TROPICS data will be used as input to numerical (HWRF, GEOS-5) and statistical models to examine the impacts of the data in Observing System Experiments (OSE) and statistical forecasts. The impact of the data in the statistical model will shed light on the correlations between upper-level warm-core temperature, environmental moisture, and precipitation and/or cloud horizontal structure with storm intensification. HWRF and GEOS-5 simulations will be analyzed along with the observations to examine the processes responsible for storm intensification and structure.

1.3.2 TECHNICAL APPROACH

TROPICS comprises a constellation of six identical Space Vehicles (SVs) conforming to the 3U CubeSat form factor and hosting a passive microwave spectrometer payload. The constellation members will be flown in a circular Low Earth Orbit (LEO) in nearly equally-spaced orbital planes, with multiple satellites populating each orbital plane. Each orbit inclination will be roughly 30°. The constellation will allow for rapid-revisit sampling of vertical temperature and moisture profiles of TCs.

The PMW spectrometer antenna is mounted on a rotating axis that will spin about the long axis of the SV. The long axis is aligned to the satellite velocity vector such that the spectrometer will record measurements along a line perpendicular to the satellite velocity in a "pushbroom" fashion that maximizes the area scan rate of the instrument. Each SV will record the raw passive microwave data and relay the raw data to the ground, where the data will be processed to produce the temperature and moisture profiles.

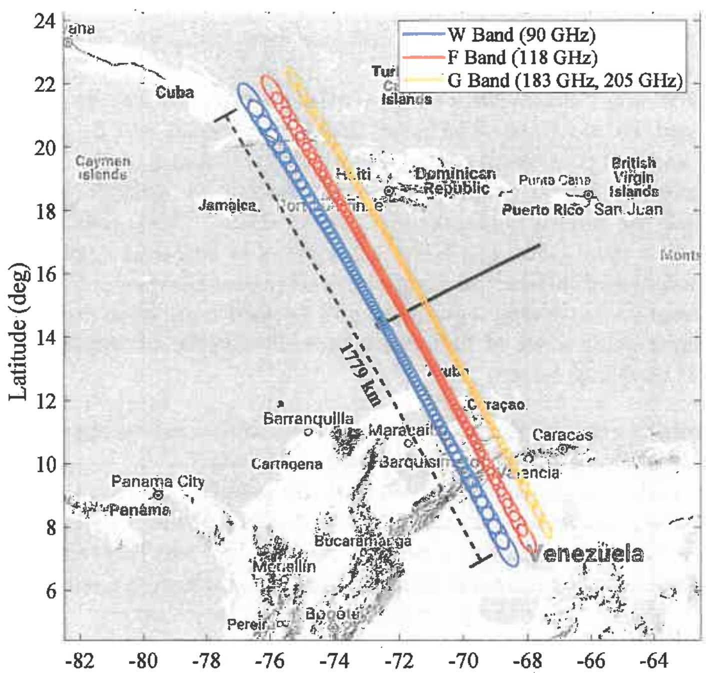

Figure 1: *TROPICS ground scan pattern for supported frequency bands (500 km altitude)*

TROPICS will follow a risk-informed management design-to-cost and build-to-cost philosophy. Single-string design approaches will be used, as some system redundancy will result through the constellation implementation (see Section 4.5). Parts selection (including COTS) will be guided by the *TROPICS Mission Assurance Plan*, TRPCS-PL-002, and will be commensurate with cost, mission lifetime, criticality, de-rating and redundancy. Final selection is entirely at the discretion of the PI/Project Manager (PM). Implementation will rely on a thorough test program with a full qualification unit, limited use of engineering models, and a limited SV flight-spares mentality (See Section 4.5). TROPICS will use a low-overhead approach to design and execution, and most importantly strive for an unwavering commitment to timely decisions at all levels of the organization to preserve the schedule and budget commitments.

Key components of the mission are described below:

1.3.2.1 SPACE VEHICLE

Each SV in the 6-member TROPICS constellation is an identical 3U CubeSat consisting of a MIT LL-built spectrometer payload integrated onto a commercially-procured bus.

The spectrometer payload consists of a rotating passive Radio Frequency (RF) antenna measuring spectral radiance as it rotates about the SV velocity vector. A detailed description of the payload is given in the TROPICS proposal document.

The payload is based upon a similar payload previously designed by MIT LL for the MicroMAS-2 mission (see Figure 2). The engineering team will modify the design in order to meet TROPICS performance and mission reliability requirements. The redesign includes:

- Antenna modification to optimize ground profile while minimizing side lobes
- Noise reduction in analog front end
- Higher-dynamic-range analog-to-digital converter
- Modifications to spectrometer channel center frequencies and bandwidths
- Higher-reliability control electronics
- Higher-reliability and lower-power motor-scanner assembly (potential redesign)

The redesign effort does not include any high-risk modifications, and should simplify the build and calibration of the payload relative to the MicroMAS-2 baseline design.

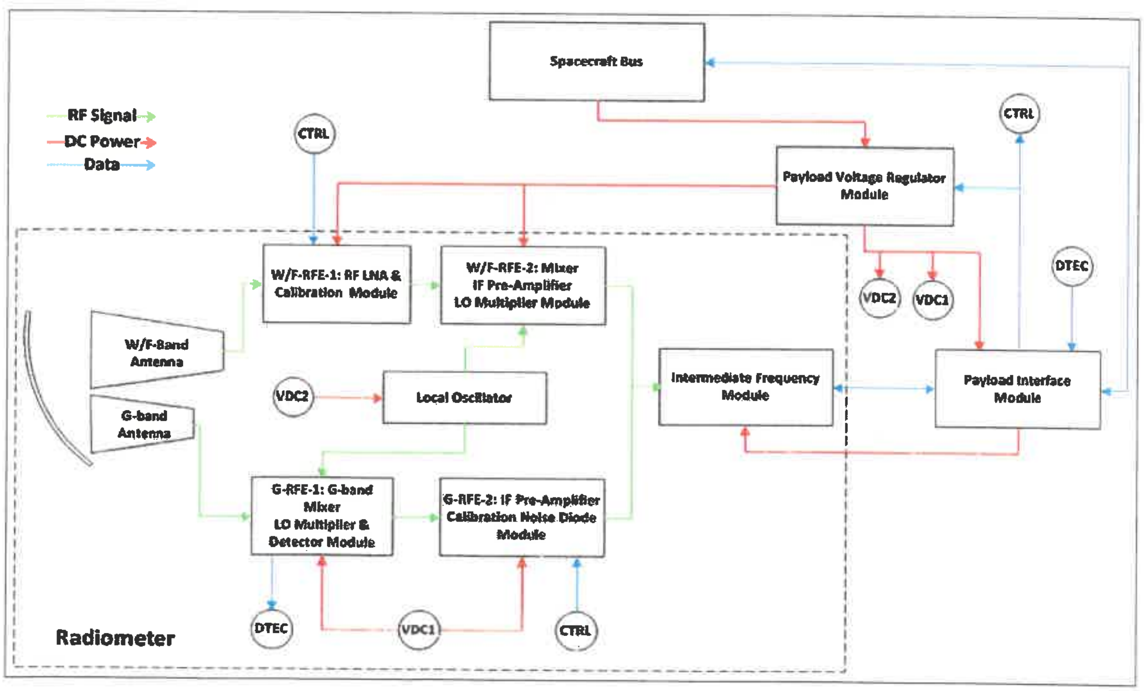

Figure 2: *MicroMAS-2 Payload Block Diagram*

A notional SV including the bus and payload is shown in Figure 3. The MicroMAS-2 bus does not have sufficient pointing accuracy or power generation capability to meet the TROPICS mission requirements. The TROPICS bus will match much of the functionality of the MicroMAS-2 bus, but will take advantage of recent commercial advances in CubeSat reliability and bus technology. In particular, making use of available GPS receivers for position knowledge and star cameras for attitude knowledge will greatly enhance the data product geolocation accuracy.

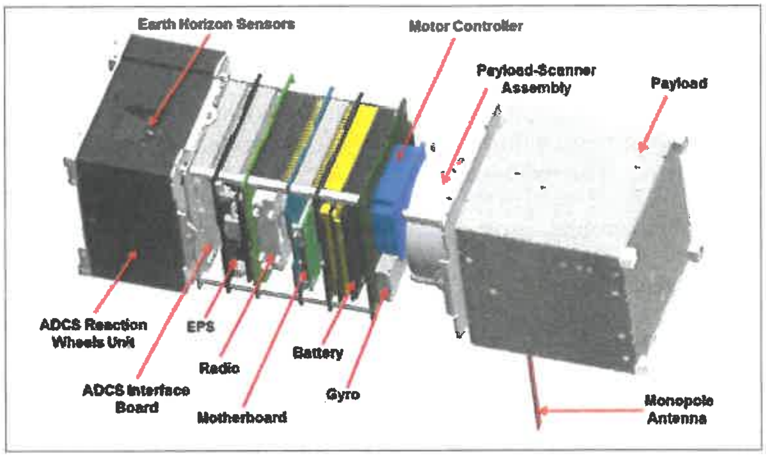

Figure 3: *MicroMAS-2 Space Vehicle (without solar panels)*

MIT LL will procure the bus from a commercial vendor, using a design that includes minimal changes (most likely in the power generation system) to existing buses with flight heritage. The bus will provide power & power conditioning, communications, on-board processing, thermal management, and Attitude Determination & Control System (ADCS) to the satellite. The bus vendor will be responsible for payload integration, environmental testing, and SV integration into the CubeSat dispenser mechanism.

The MIT LL role will include technical and programmatic oversight of the bus procurement. MIT LL will also be developing custom software that will be hosted on the bus avionics system (see Section 2.2.2 of TRPCS-PL-007, *TROPICS Software Management & Development Plan*). This software will provide command and control of the payload, and will interface with the bus communications system to manage payload commands and prepare payload telemetry for downlink. Additional custom software tasks for link management and ADCS commanding may be included depending upon the capabilities of the delivered bus system.

1.3.2.2 Launch Interface

The launch interface segment will ensure that the space vehicles demonstrate mechanical and electrical compatibility with the chosen CubeSat dispenser mechanism. The dispenser typically defines the mechanical environment, and the dispenser vendor ensures that the defined environment is consistent with the chosen launch vehicle. MIT LL will work with both the dispenser vendor and the launch vehicle provider to ensure system compatibility.

Prior to NASA selection of the launch vehicle the SV design shall be guided by a well-defined 3U CubeSat dispenser Interface Control Documents (ICDs). To reduce overall system risk MIT LLs will leverage the flexibility provided by dispensers such as the Canisterized Satellite Dispenser (CSD) that provide for mass and volume above the P-POD standard. This decision will be made in conjunction with the NASA program office.

1.3.2.3 Ground Station

The TROPICS SVs will interface with a ground station network to allow for SV command and control and downlink of bus and payload telemetry for each member of the constellation.

Choice of ground station is an open trade discussed further in Section 4.6.

1.3.2.4 Mission Operations

MIT LL will leverage existing systems developed by the chosen bus vendor to command and control the constellation of satellites. The bus vendors have existing mission operations software that interacts with their existing buses, is scalable to operate constellations, and can be customized to provide command and control of the spectrometer payload.

More detail is provided in Sections 3.11 and 3.14.

1.3.2.5 Data Processing

MIT LL will interact with the mission operations provider to acquire the down-linked raw science data and format it into data products that can be shared with the data processing center at University of Wisconsin (UW).

The data products will be made available to the data processing center via a secured connection. The data will be stored at MIT LL in a Structured Query Language (SQL) database on a MIT LL computer system that includes disk redundancy and daily data backups. The entire mission data set will be stored at MIT LL for the duration of the TROPICS project.

UW Space Science & Engineering Center (SSEC) as the data processing lead will archive the data to an Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Center (DAAC) in a format approved by NASA Earth Science Data Systems (ESDS). Further detail is provided in Section 3.11.5.

1.4 Project Authority, Governance Structure, Management Structure, and Implementation Approach

1.4.1 Project Authority & Governance Structure

The TROPICS project management shall report to the ESSP program office at LaRC. As the host NASA Center for the program office, LaRC shall provide the Engineering Technical Authority (TA) and Safety and Mission Assurance TA functions to the project.

The TROPICS project will be led by the PI, Dr. William J. Blackwell (MIT LL), who has overall responsibility for the mission and its associated objectives. Dr. Scott Braun (GSFC) will serve as Project Scientist (PS).

The instrument team will be led by the PM, Kristin Clark. The management team includes the Deputy Project Manager (DPM) Steven Michael. The Project Systems Engineer (PSE) is Linda Fuhrman. The PSE is responsible for developing the requirements for the hardware starting with the Level 1 science requirements documented in the NASA Program-Level Requirements Appendix (PLRA).

The PI is responsible for decisions relating to the science mission objectives. The PI will make the final decision on science, technology, and release of reserves, but will rely on the PS, PSE, Chief Engineer (CE), PM, and DPM, respectively. All decisions related to technical or programmatic changes will be made by the PI in consultation with the PM.

The PI shall report to NASA according to Figure 4.

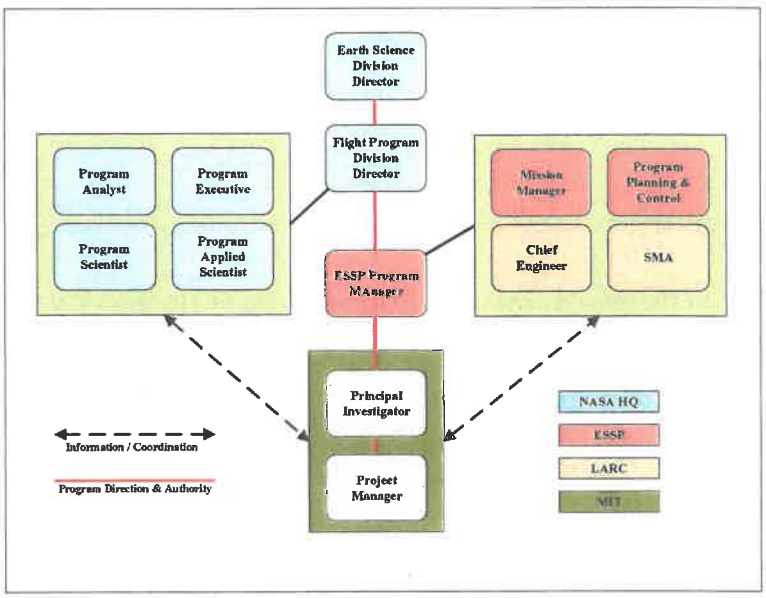

Figure 4: *TROPICS Lines of Authority & Coordination*

1.4.2 Management Structure

The overall TROPICS project organization is shown in Figure 5.

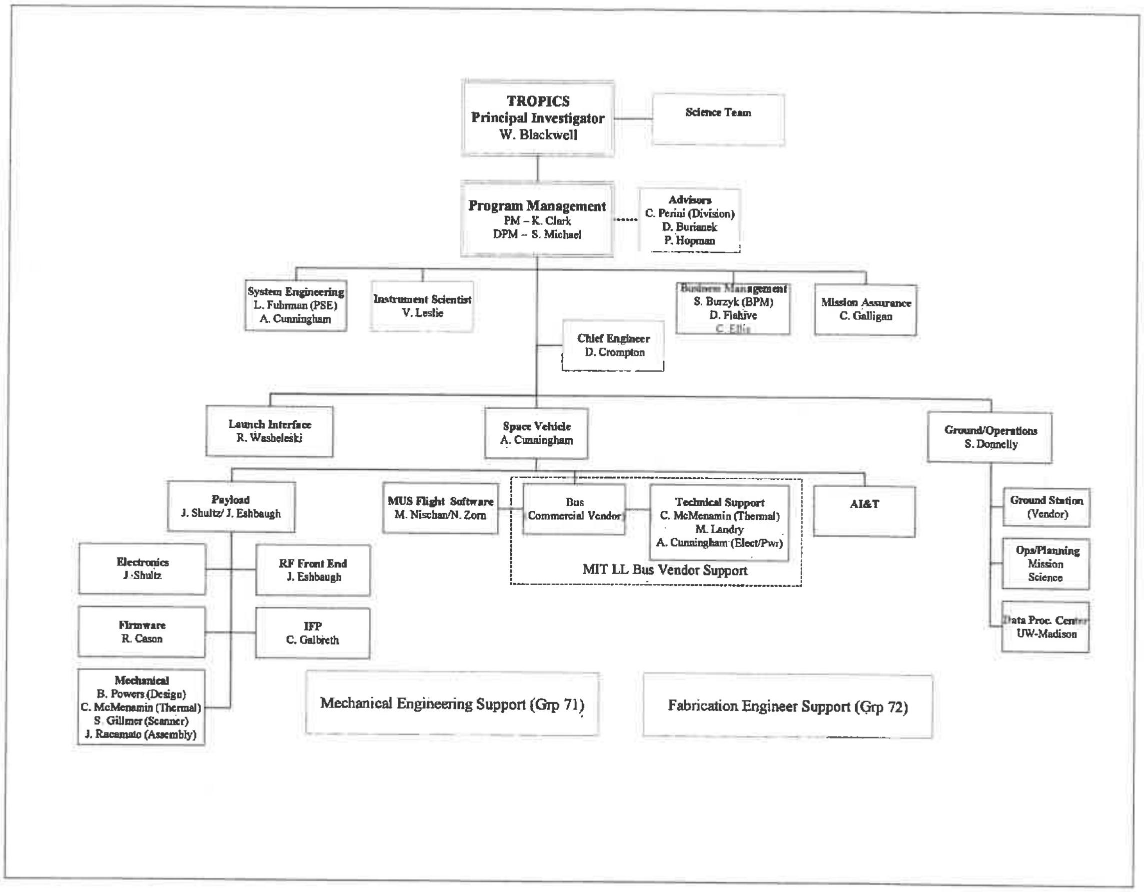

Figure 5: *TROPICS Organization Chart as of May 19 2017*

The PI hosts a weekly meeting with the project office that include the Program Executive, PM, the DPMs, the PS, and appropriate project personnel. At this meeting the team reviews the current technical and programmatic status of the project and any issues that have arisen. The same team also has a weekly teleconference with the NASA ESSP mission manager and his team to discuss the current status.

The PM has oversight of the instrument development team along with the DPM and the PSE. The PM has a weekly meeting of the unit engineers and leads on the program where status is reported and discussed. At MIT LL the unit engineer is assigned to a specific portion of the project and assumes overall responsibility for making sure that his/her unit satisfies the requirements as documented by the PSE. Each unit engineer holds discussions with his/her team as necessary to meet the program technical and schedule milestones.

The PI coordinates the science team and instrument team activities in close cooperation with the Project Scientist. In close coordination with the PI, the Project Scientist will lead the science team activities, monitor progress toward fulfilling the mission science requirements, plan and track science data product development, and communicate mission goals and plans to the research and applications communities. Periodic meetings are held (approximately once every two weeks prior to Critical Design Review (CDR) and weekly after CDR) that include the PI, PS, Level 1 and Level 2 Algorithm leads, and the Data Processing Center lead.

The Chief Engineer (CE) is tasked with providing engineering oversight to the program as whole. The CE will be accountable for the overall engineering quality of the system. The CE role is filled by a senior engineer who can use his or her significant technical expertise and prior experience to guide the unit engineers in making high-level decisions.

The project management team (PM, PI, DPM, PSE, CE) will review and report to NASA monthly the state of the budget and schedule. Project technical status including status and trending of Key Performance Metrics (KPMs) and major procurements shall also included in the monthly reports.

1.4.3 Implementation Approach

The TROPICS science team executes the TROPICS science objectives. The TROPICS team is responsible for development and testing of required science algorithms, pre- and post-launch calibration and validation of TROPICS observations and the delivery and validation of TROPICS data products.

MIT LL achieves the mission and science objectives using a management approach based on best practices and lessons learned from over 50 years of developing prototype hardware including numerous spacecraft and space instruments. MIT LL management processes are compatible with NASA project management requirements as described in `NPR 7120.5E`.

Most space-flight projects at MIT LL, including this one, are designated as “Level-1”. This designation invokes a close partnership between the execution team and the MIT LL Mission Assurance Office (MAO). The MAO is responsible for ensuring best practices are followed for quality management, parts procurement, and use of fabrication and test infrastructure. The MAO will also be deeply involved in major procurements, scrutinizing vendors to understand and validate their Quality Management System (QMS). For more information see `TRPCS-PL-002`, the *TROPICS Mission Assurance Plan.*

Microsoft Project will be used to track the development schedule, major milestones and critical path items. Milestones will include programmatic/technical reviews, internal hardware deliveries, test events, interim design reviews, and other significant demonstrations. The schedule will be baselined 30 days prior to Preliminary Design Review (PDR), updated as necessary on a monthly basis, and formally re-baselined at formal design reviews (PDR, CDR) and other major programmatic milestones.

While the project schedule will be utilized to track schedule performance, a separate financial spreadsheet will track actual expenditures against the spend plan. This spreadsheet will track both staffing and procurements. Though tracked in separate documents, the project business management team will ensure the schedule and budget remain well aligned.

Due to the high importance and schedule constraints of the program, a specially designated mechanical and electronics procurements representative will track all procurements associated with the program. This person will facilitate purchases through the MIT LL procurement process as well as monitor vendor delivery of equipment and parts. They will report status of procurements through internal meetings and reports.

1.5 Stakeholder Definition

NASA, MIT LL, and the Earth science communities are the primary stakeholders on the TROPICS mission. Stakeholder advocacy is achieved through interactions with the Earth science community and with the general public interested in Earth science. These interactions involve ESD, advisory committees, and non-scientific user groups. Advocacy for this broad and diverse community of TROPICS program stakeholders is led by the ESD TROPICS program scientist in consultation with the TROPICS Program Executive (PE), ESSP Mission Manager (MM), PI, and PM. Additional programmatic advocacy comes from the ESD director, the SMD AA, and NASA Administrator in their budgetary submittals to Congress and by Congress via its appropriation of the funding necessary to implement the program.

2 Project Baselines

2.1 Requirements Baseline

The systems engineering team has developed a requirements flow-down matrix that imposes technical requirements on TROPICS subsystems and components based upon the mission requirements called out in the PLRA.

Each system requirement has an antecedent that can be traced to the PLRA, a proposed technique for requirement verification, and a requirement verification status.

The tracked Technical Performance Measures (TPMs) described in Section 3.1.2 will be used to internally trade system requirements against one another should relief be requested by an external contractor or unit engineer.

The system requirements are maintained in a Microsoft Excel spreadsheet, and are configuration controlled via the process described in Section 3.16. The requirements hierarchy is shown in Figure 6 below.

Requirements will be formally tracked down to Level 4. Requirements down to Level 4 will be baselined at PDR. Once requirements are baselined modifications will require a formal process and documentation. The Level-1 requirements contained in the PLRA are controlled by NASA. All subsequent levels are controlled by MIT LL. After the requirements are baselined, any changes to the level-2 and below requirements will be reviewed by the PI, the PM, and the PSE to determine the impact and provide approval, if appropriate.

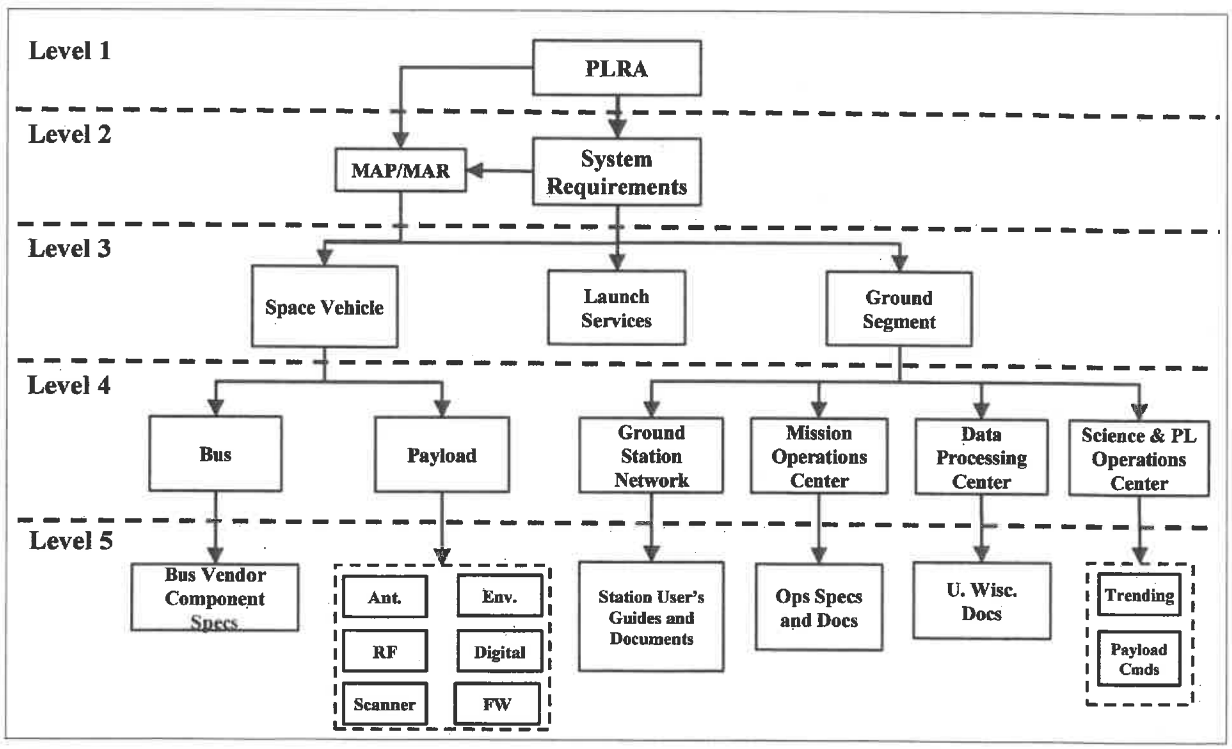

Figure 6: *Requirements Flowdown*

2.2 WBS Baseline

The Work Breakdown Structure (WBS) for the TROPICS project has seven elements at Level 2: Mission Science (-1), Program Management (-2), Safety and Mission Assurance (-3), Systems Engineering (-4), Space Vehicle (-6), Ground and Operations (-7), and Launch Vehicle Interface (-8). Progress and budget reporting will be done at Level 2 for all WBS elements except for Space Vehicle (-6). The Space Vehicle WBS will be reported at Level 3 for the Payload (-61) and the Spacecraft Bus (-62). Each element is tied directly to the budget and schedule elements, and aligns closely with the management structure in Figure 5.

The WBS dictionary is provided in Table 1. MIT LL is the responsible organization for all WBS elements. The WBS does not conform to the NASA standard; however, the WBS does adhere to a standard used internally by MIT LL to successfully execute many space-flight programs. As the organization responsible for executing the project, MIT LL will use its own WBS format.

NOTE: The WBS is expected to evolve over time. The current WBS is maintained by the MIT LL TROPICS Project Office.

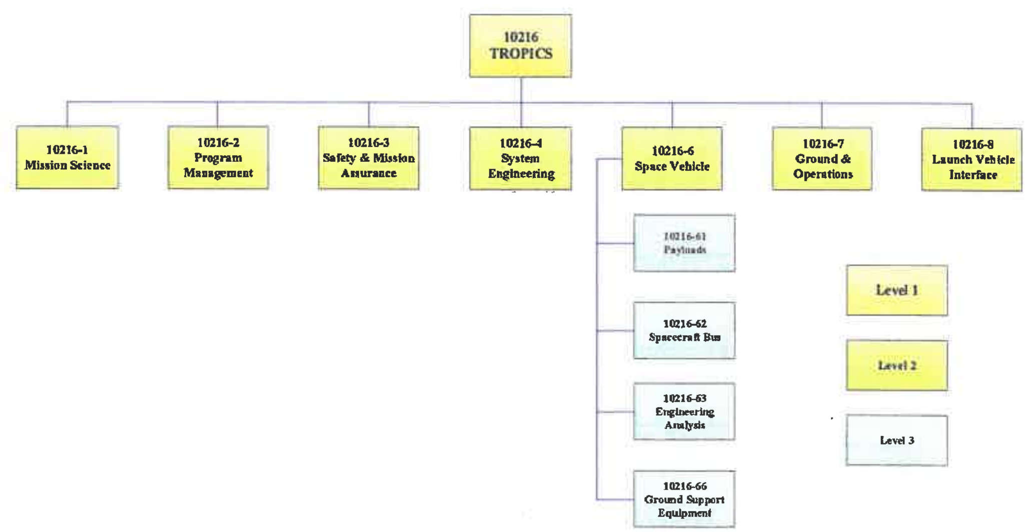

Figure 7: *TROPICS Top-Level WBS as of 4-15-17*

WBS	Title	Description
10216	TROPICS (Top Level)	Summary Element: This element includes planning, organizing, directing, coordinating, analyzing, controlling, administrating, and approval processes required to accomplish overall TROPICS project objectives. It has programmatic authority over, and responsibility for, all of the other WBS elements listed here or as may be assigned hereafter to this project.
10216.1	Mission Science	This WBS group provides for the managing, directing, and controlling of the science investigation aspects. The costs incurred to cover the science team members are included. Specific responsibilities include defining the science; ensuring the integration of these requirements with the instrument, spacecraft, ground systems, and mission operations; providing the algorithms for data processing and analyses; and performing data analysis, follow-up observations, and archiving. This element excludes hardware and software for the on-board science instrument or the ground systems for data analysis, instrument operations, or data archiving.
10216.2	Program Management	This element includes the planning, organizing, directing, coordinating, analyzing, controlling, administrating, and approval processes required to accomplish overall TROPICS project objectives. This element includes program technical and business management support. This element supports the creation and maintenance of budgets, the Integrated Master Schedule (IMS), earned value analysis and reporting, technical, and business programmatic reporting. This element also includes staffing for reviews & travel.
10216.3	Safety and Mission Assurance	This element includes the technical and management efforts of directing and controlling the safety and mission assurance elements of the project. This includes design, development, review, and verification of practices and procedures and mission success criteria intended to ensure that the delivered spacecraft, ground systems, mission operations, and instrument meets performance requirements and function for their intended lifetimes.
10216.4	Systems Engineering	This element includes efforts required for directing and controlling an integrated engineering effort for the project. Leads the overall system architecture, definition and engineering function such as the PSE. Includes spacecraft-ground system interface definition, trade studies, integrated planning and control of technical efforts by design/software/specialty engineering ; system architecture development and integrated test planning ; system requirements writing, configuration control, technical oversight, and risk management activities.
10216.6	Space Vehicle	This element includes both Payload and Spacecraft development, fabrication, assembly, & test.
10216.61	Payload	This element includes payload development, fabrication, assembly, and test. This element includes engineering, fabrication, and assembly labor support, payload subassembly procurements, testing and calibration services, and fixtures for assembly, test, and calibration.

. . . Table Continued

WBS	Title	Description
10216.62	Spacecraft Bus	This element includes spacecraft development, assembly, and test. This element includes engineering, fabrication, and assembly labor support, bus procurements, testing services, and fixtures for assembly and test.
10216.63	Engineering Analysis	This element includes all spacecraft & payload engineering analysis resources required to perform structural and thermal model development & analysis.
10216.66	Ground Support	This element includes all resources for the design, procurement, fabrication, assembly, and where required test of Ground Support Equipment (GSE).
10216.7	Ground & Operations	This element includes all labor, subcontracts, materials, and other direct costs to provide command and control of the spacecraft bus and instrument, maintain spacecraft health and safety, provide science data to the end users during mission lifetime, and prepare the ground systems prior to launch.
10216.8	Launch Vehicle Interface	Includes all subcontracts, labor, material, and other direct costs from integration with the launch vehicle, including CubeSat dispenser mechanism. These costs should include items such as safety documentation, launch site procedure development, range safety support for hazardous procedure reviews, launch rehearsals, and launch site-to-ground control center interface testing.

Table 1: *WBS Dictionary*

2.3 Schedule Baseline

A detailed schedule is part of the Data Requirements Description (DRD), and has been delivered to NASA (document `TRPCS-PL-005`, *TROPICS Integrated Master Schedule*) in the required Microsoft Project format. The complete schedule will be updated as required with the monthly reports.

A high-level overview is provided in Figure 8 below:

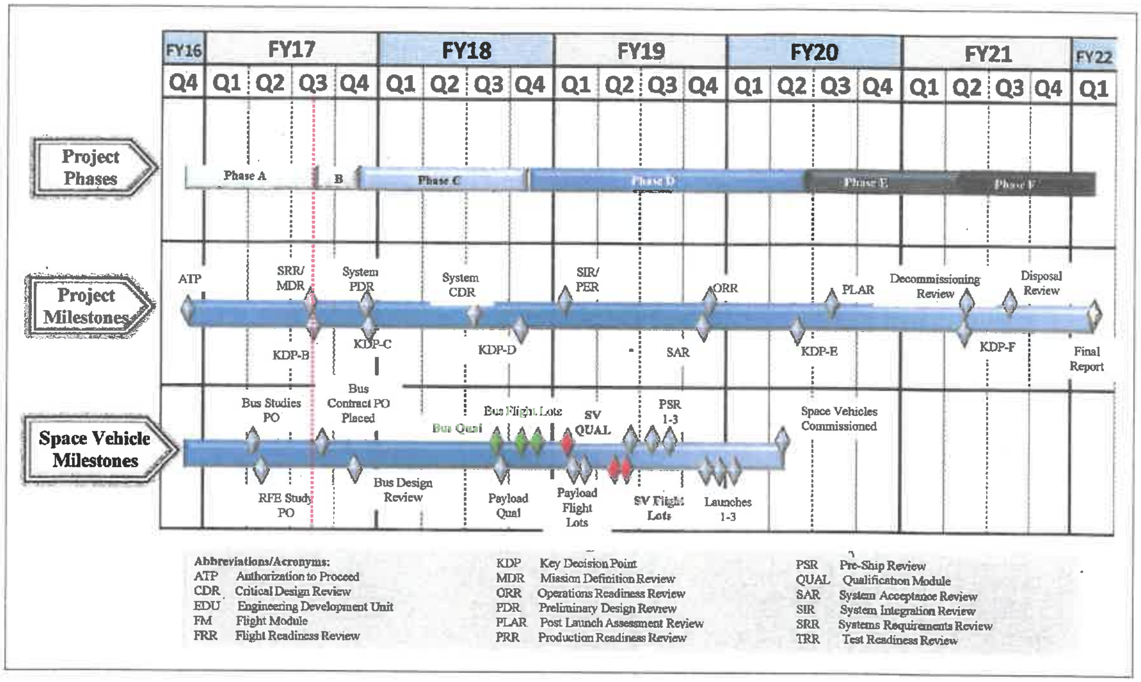

Figure 8: *Representative High-Level Schedule (see IMS for current schedule)*

2.4 Resource

2.4.1 Budget

Table 2 shows the TROPICS high-level budget with spending as a function of fiscal year both with and without management reserves.

Total Program - LL + NASA + Partners	FY16	FY17	FY18	FY19	FY20	FY 21	FY 22	Total thru Closeout (Nov 2021)
Science/Exploitation	$0	$958	$790	$701	$644	$763	$0	$3,857
Program Management	$56	$938	$962	$708	$158	$104	$10	$2,937
Safety + Mission Assurance	$0	$119	$116	$102	$0	$0	$0	$337
Systems Engineering	$20	$380	$376	$288	$407	$299	$6	$1,776
Space Vehicle	$23	$8,631	$2,423	$1,099	$0	$0	$0	$12,176
Ground + Mission OPs	$0	$236	$450	$307	$306	$218	$0	$1,518
Launch Vehicle/Services	$0	$0	$0	$0	$0	$0	$0	$0
Ground Systems	$0	$0	$0	$0	$0	$0	$0	$0
System I+T (support at vendor)	$0	$0	$0	$0	$0	$0	$0	$0
Total LL	**$99**	**$11,262**	**$5,116**	**$3,207**	**$1,516**	**$1,384**	**$16**	**$22,600**
NASA	$0	$293	$84	$262	$253	$243	$0	$1,135
NOAA	$0	$289	$80	$236	$267	$245	$0	$1,117
Total Funding (to NASA + NOAA)	**$0**	**$582**	**$164**	**$499**	**$519**	**$488**	**$0**	**$2,251**
Total - All	**$99**	**$11,844**	**$5,280**	**$3,705**	**$2,035**	**$1,871**	**$16**	**$24,852**
Reserve	$12	$2,302	$1,197	$847	$510	$478	$2	$5,348
Total with Reserve	**$112**	**$14,146**	**$6,477**	**$4,553**	**$2,546**	**$2,349**	**$18**	**$30,200**

Table 2: *High-Level Budget (See monthly program status report for current budget)*

The TROPICS project includes several open trade studies. Section 4 describes the trade studies and baseline assumptions for study outcomes. These baselines are included in both the delivered budget and schedule.

A detailed budget reporting out spending to lower levels is supplied in a separate Microsoft Excel workbook.

2.4.2 Staffing

Staffing for the TROPICS project is consistent with the size and scope for the project and is based on experience from previous efforts. Figure 9 shows the full-time equivalents for the project, by fiscal year, based on the existing schedule and budget. This includes only MIT LL staff equivalents and not those of our subcontractors. The highest staffing occurs early in the project (FY17) and is focused on the design and fabrication of the hardware as well as oversight of the external vendors building the spacecraft bus. Staffing tapers off as the hardware is built and integrated with relatively lower staffing to cover the operations and science data management.

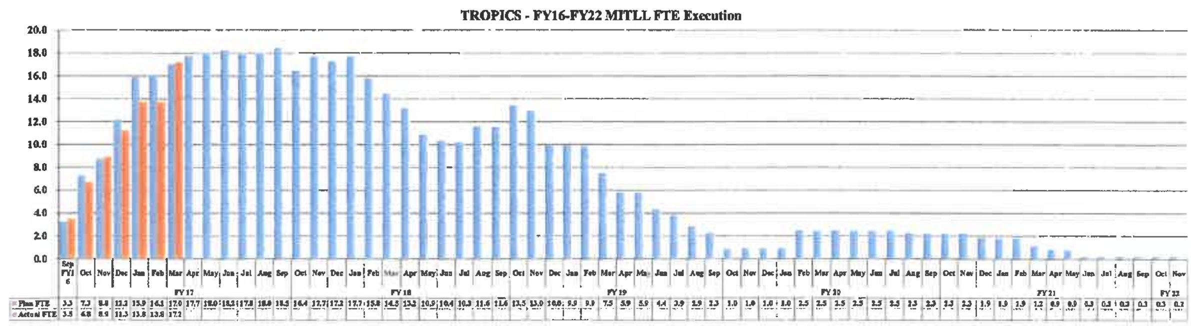

Figure 9: *Notional Staffing Plan for MIT LL Support)*

Figure 9 represents MIT LL staffing only. Additional staffing will be provided by the bus vendor (e.g. launch vehicle support) and partners for the ground segment (mission operator, data processing center, science operations center). Note that it is assumed a mission partner will execute the ground operations, hence the low MIT LL staffing in FY21 and FY22.

2.4.3 Infrastructure

The payloads for the constellation will be built at MIT LL. Laboratory leadership has allocated sufficient laboratory space and equipment (e.g., thermal-vacuum chambers, vibration tables, etc...) to ensure successful execution of the project. Further, the team will be leveraging previous MicroMAS investments in capital equipment (e.g. blackbody source) to aid with build and calibration of the payload hardware.

2.4.3.1 Space Vehicle

The space vehicle consists of an externally-procured bus and a MIT LL-built payload. MIT LL will ensure as part of the bus procurement process (Section 3.4.1) that the chosen vendor has the capability to execute the bus build at the necessary scale. The baseline plan includes both integration of the radio spectrometer payload and environmental testing of the full SV by the bus vendor. Again, MIT LL will ensure as part of the bus procurement process that the bus vendor has the necessary infrastructure to support integration and test of the full space vehicle. Multiple informational visits to potential bus vendors suggest that this is an area of low risk.

The payload will be developed internally at MIT LL. The laboratory has a long history of spaceborne payload development, and has the infrastructure necessary to build the payload at scale. This includes both the personnel and laboratory space necessary to build payloads at the necessary scale.

2.4.3.2 Ground Operations

MIT LL will make use of an existing ground station network to communicate with the constellation. Details of the necessary ground infrastructure are discussed throughout this document.

2.4.4 Procurements

Most major procurements and contracts, including the SV bus, major payload subsystems, and the science support teams are to be awarded via a Firm Fixed-Price (FFP) contract. The ground station network may include costing on a per-contact basis. However, the contact costs are well known and can be bounded by knowing the constellation size and mission duration. In addition, a Fixed-Price Level-of-Effort (FPLOE) contracting mechanism may be used for In-Orbit Checkout (IOC) support and anomaly resolution due to the inherent uncertainty in resourcing these tasks.

Due to long leads, several procurements are being initiated prior to program PDR. These include most significantly the SV bus as described in Section 3.4.1 as well as critical components for the payload spectrometer Receiver Front End (RFE) as described in Section 4.11.

2.5 Joint Cost & Schedule Confidence Level

Not Applicable (Project Cost < $250M).

3 Project Control Plans

3.1 Technical, Schedule, & Cost Control Plan

3.1.1 Schedule & Cost

The budget and IMS describe the expected level of spending and technical progress as a function of time. These will be monitored internally (and externally, via the monthly reports) to ensure potential cost and scheduled risks are identified early.

Each major section of the budget includes management reserve level appropriate for the uncertainty and risk. Budgeted reserve levels as of March 2017 are provided below:

NASA, NOAA, Science	25%
Management, SysEng, Mission Assurance	13%
Payload	25%
Bus	20%
Ground Station & Operations	25%
Program Total	**22%**

Table 3: *Budget Reserve Levels, March 2017*

The reserve levels in Table 3 are consistent with the level of risk and maturity in each section. Details for areas with reserve levels below 25% are provided below:

- **Management, Systems Engineering, & Mission Assurance**
  The project includes a baseline execution plan, a budget, and a schedule. With the scope of the project now well known, oversight costs are well predicted by comparisons to many programs of similar scope. As such, exposure to management cost overruns is minimal.

- **Bus**
  MIT LL will be contracting with a bus vendor that will execute on a FFP contract, as described in Section 4.1. MIT LL has already issued an Request for Information (RFI) and Request for Proposals (RFPs) for a study to multiple vendors (Section 3.4.1). Conservative estimates from bus vendors have been used for budget planning. Due to the maturity of the estimate the margin on the bus has been reduced to 20%.

The project includes a mechanism for graceful de-scoping as necessitated by schedule and/or cost pressures. The baseline plan includes procurement of 6 flight satellites and a qualification unit. Only 5 satellites are required to meet baseline mission requirements (4 satellites are required for threshold). This allows the final number of procured satellites to be reduced while still meeting baseline mission requirements. Section 4.5 discusses this trade in more detail.

Cost and schedule will be monitored by MIT LL using a tailored version of earned value that is consistent with the size and scope of the project as well as MIT LL's financial management system. Each WBS element at Level 2 (Level 3 for the -6 element for the spacecraft) has a budget associated with it, as captured in the project-level budget. In addition, the IMS has schedule and task elements for each section of the MIT LL. Prior to Preliminary Design Review (PDR), the MIT LL PI and PM will assign costs to each major task. On a monthly basis, the unit engineers will review progress on each task in their area and assign a percent complete (either 0%, 25%, 50%, 75%, or 100%). The unit engineers estimate of work completed and the expenditures data from the Lincoln financial system will be used to calculate a budgeted cost of work performed and a scheduled cost of work performed. These will be incorporated into the budget and schedule monthly reports.

MIT LL seeks to procure components from trusted subcontractors with a minimum of Non-Recurring Engineering (NRE) and make use of FFP contracting mechanisms to minimize procurement risk to both schedule and budget.

3.1.2 Technical Performance Measures

The TROPICS team will be tracking several TPMs that ensure key system components are capable of meeting requirements. Where relevant, the TPM will include both an allocation, or not to exceed number, and a Current Best Estimate (CBE). Appropriate margin will be added to each allocation based upon the engineering judgment of the unit engineer and PSE. The PSE will ultimately hold and allocate margin. MIT LL will consult NASA Goddard "GOLD" rules (GSFC-STD-1000) for guidance in determining appropriate margin, modulating as necessary according to system maturity. Margins will be reduced and allocated values will converge to the CBE as laboratory measurements confirm unit specifications.

No.	Title
TPM-001	Median Revisit Rate
TPM-002	Space Vehicle Mass
TPM-003	Reserved
TPM-004	Reserved
TPM-005	Space Vehicle Power
TPM-006	RF Link Budget
TPM-007	Downlink Data Capacity
TPM-008	Geo-location Error
TPM-009	Horizontal Spatial Resolution
TPM-010	Radiometric Precision ($NEdT$)
TPM-011	Calibration Accuracy
TPM-012	Level-2b Performance
TPM-013	Ground Data Latency

Table 4: *TROPICS Technical Performance Measures*

A subset of these TPMs will be identified as KPMs. As called out in the DRD, these will be agreed upon by the government and will be reported out monthly.

Technical performance measures will be configuration controlled per the process described in Section 3.16.

3.2 Safety and Mission Assurance Plan

MIT LL has developed a Safety and Mission Assurance Plan (TRPCS-PL-002) consistent with the NASA Langley Mission Assurance Requirements document. The latest copy of the TROPICS contract deliverable, *TROPICS Mission Assurance Plan*, document TRPCS-PL-002, fulfills the requirements of the safety and mission assurance plan.

3.3 Risk Management Plan

TROPICS has been classified as a NASA Class-D (per NPR 8705.4), category 3 (per NPR7120.5) CubeSat mission. The risk management approach will focus on risks that could impact the ability to meet the Level 1 mission success criteria. This section is being written in lieu of delivery of DRD PM-8.

The governing document for Risk Management in the Lincoln QMS is LLP-8. The TROPICS team will utilize a standard 5x5 Likelihood vs. Consequence matrix. An example is shown in Figure 10. The threshold levels for the likelihood and consequence are shown in Tables 5 and 6, respectively.

Each unit engineer will develop and discuss a set of risks based on their subsystem. The risks will be reviewed by the project management team (PM, DPM, PSE, PI, CE) and a baseline risk placed in the project risk spreadsheet. For each credible risk, the project management team will make an assessment of the following items:

- Likelihood (based on the criteria in Table 5)
- Consequence (based on the criteria in Table 6)

- Category (Cost, Schedule, Technical)
- Action (Accept, Monitor, Mitigate, etc.)

A mitigation plan will be put in place, if appropriate. The list of top risks will be presented and discussed in the project monthly report. It is expected that this will encompass roughly 10 risk items and will include all risks that can impact the Level 1 Science Requirements. If a risk requires additional resources or time from the unencumbered reserves, it will be reported and documented.

The risk matrix will be reviewed and updated once per month and included in the overall monthly report, along with any mitigation options.

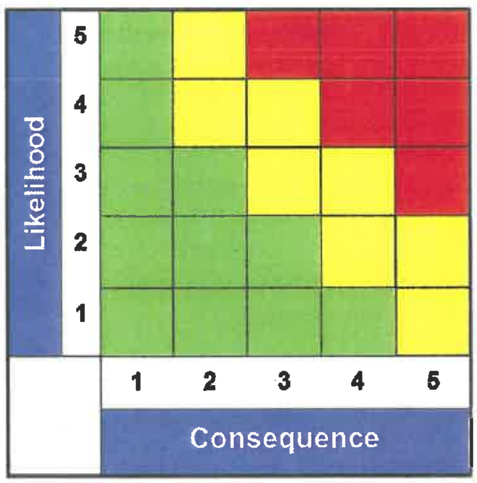

Figure 10: *Risk Matrix*

1	Remote	5% - 20%
2	Unlikely	21% - 40%
3	Possible	41% - 60%
4	Likely	61% - 80%
5	Probable	81% - 100%

Table 5: *Likelihood Rating*

1	Minimal	Meet PLRA, <1%, non-critical schedule
2	Acceptable	Meets L2, 1% cost, < 2 week slack from critical path
3	Significant	PLRA deviation, 1-5% cost, major milestone slip
4	Serious	PLRA failure, 5% cost, launch slip
5	Catastrophic	Safety, No Utility, 10% cost, miss PLRA need date

Table 6: *Consequence Rating*

3.4 Acquisition Plan

3.4.1 Bus

The TROPICS bus will be procured from an outside vendor. The vendor selection will be done via a competitive bid process managed by the MIT LL Contracting Services Department. Oversight of the selected vendor will be conducted by the project team and will consist, at minimum, of weekly updates and monthly status reports by the contractor. Major reviews will be scheduled as part of the contract consisting of at least one design review and a test readiness review.

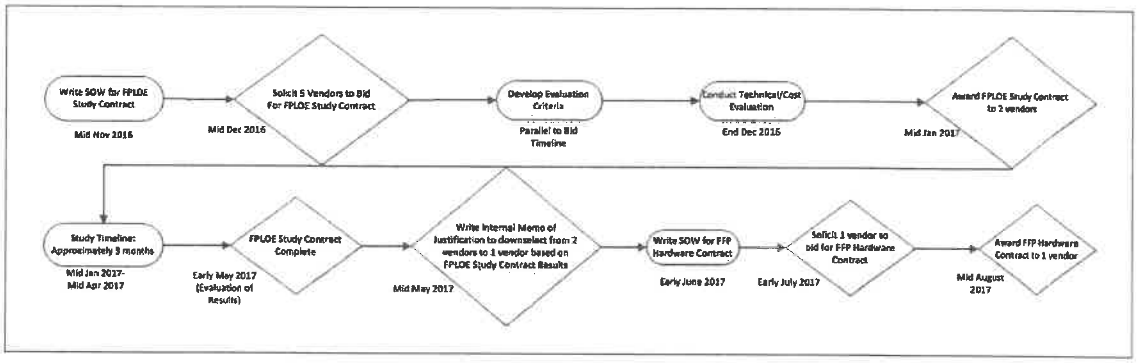

Figure 11: *Bus Acquisition Strategy*

More detail is provided in Section 4.1.

3.4.2 Payload

The payload will include a number of externally-procured components. A competitive bid process will be used where necessary. However, a number of the procurements involve highly-specialized components and leverage technology development efforts undertaken to support prior MIT LL CubeSat radio spectrometer missions (MicroMAS, MiRaTA). For these, a sole-source procurement may be justified.

As with the bus, all payload procurements will be managed by the MIT LL Contract Service Department and will include technical and programmatic oversight by the MIT LL team. The level of oversight will vary by component but may include regular technical updates and at least one major review of the technical design and testing plan. Payload parts will be procured via FFPs contracts with external vendors.

3.5 Technology Development Plan

This section is used as the Project Technology Development Plan, in lieu of a separate document, as indicated in the tailored `7120.5E` compliance matrix.

The SV bus will be procured from an outside vendor. MIT LL will contract with a vendor that has flight heritage for the bus system and requires minimal NRE to complete a mature design. The TROPICS payload is based on the existing design of the space-qualified MicroMAS-2 spectrometer payload with modifications to the RF front end and digital signal processing. The process is described in detail throughout this document.

Though the design is not yet complete, given the heritage of both the bus and the payload, all components in TROPICS SV are expected to be at Technical Readiness Level (TRL) 6 or greater by PDR.

For subsystems and components not currently at a TRL $\geq$ 6 a summary of qualification plans is provided below:

- BCT Bus
  The BCT bus has been qualified to TRL 6 and above as part of other missions, including the on-orbit RAVAN mission. The lone exception is the Inertial Measurement Unit (IMU), which is being qualified in Thermal Vacuum (TVAC) by BCT this summer to support another mission.

- Tyvak Bus
  The Tyvak bus has been qualified to TRL 6 and above as part of the CPOD and PropCube missions. The lone exception is the complex panel deployment mechanism. However, as part of a separate mission Tyvak is qualifying a deployment mechanism with sufficient similarity to the TROPICS design that TRL 6 can be claimed for TROPICS.

- Payload
  The payload is based upon designs with qualification heritage from the MicroMAS and MicroMAS-2a missions. However, upgrades are being planned to both improve reliability and reduce system complexity. Upgrades that will require additional qualification include:

  - Digital / Analog Video Board
    Analog video and digital chain are being redesigned to use higher-reliability parts. All parts are at TRL-6 or above, with exception of a new analog switch. The switch is latch-up immune by design, and will undergo Total Integrated Dose (TID) testing in July 2017. Full board prototype is in fabrication with planned thermal testing in late summer 2017.

  - W/F Intermediate Frequency Processor (IFP)
    The W/F-band IFP is similar to the MicroMAS-2a design. New higher-gain COTS amplifiers have been identified and the system is making use of a new 24-bit Analog / Digital Converter (A/D). The high-dynamic-range A/D will eliminate the need for difficult hand tuning of gains in the analog chain. The A/D and supporting voltage reference have recently been TID tested by MIT LL. There are no inherently vacuum-sensitive components on the board, and oven testing of a prototype board is scheduled for 2017.

  - G IFP
    The G-band IFP is similar to the MicroMAS-2a design. Like the W/F-band IFP, the G-band IFP uses improved amplifiers and the same 24-bit A/D. There are no inherently vacuum-sensitive components on the board, and oven testing of a prototype board is scheduled for 2017.

  - G RFE 2
    The G RFE 2 board is similar in design to that qualified for MicroMAS-2a. Component upgrades include a new more capable amplifier, coupler, and noise diode. These will be qualified at the component level to TRL 6 prior to PDR.

  –

3.6 Systems Engineering Management Plan

The *TROPICS Systems Engineering Management Plan*, document TRPCS-PL-003, outlines the methodology for requirements flowdown for PLRA at Level 1 through subsystems at Level 4. It also documents the configuration management and change process for the requirements after they are baselined. NASA is the owner of the Level 1 PLRA Science Requirements ; MIT LL owns all subsequent levels. The Systems

Engineering Management Plan (SEMP) and requirements flowdown will be baselined by PDR. The SEMP also outlines all interfaces for the TROPICS mission and the necessary interface control plans.

3.7 Information Technology Plan

MIT LL maintains an internal network, the Lincoln Local-Area Network (LLAN). The LLAN is firewalled from the Internet and complies with DoD requirements for information security. All TROPICS development efforts will be performed on MIT LL systems that operate only on this network.

The MIT LL Information Technology Security Department is a key component to ensuring the success and continuity of the Laboratory's mission and projects. The Information Technology Security Council (ITSC), in collaboration with Laboratory technical staff, is tasked with developing policies and procedures to keep Laboratory systems and data secure. The procedures provide risk management strategies to mitigate known vulnerabilities and attack vectors. System users contribute to the security of Laboratory information systems by familiarizing themselves with procedures, employing safeguards and controls for protecting information, and promptly reporting any suspected compromise related to the confidentiality, integrity and availability of Laboratory information and systems. The MIT LL Data Security Plan (DSP) provides a process for identifying, assessing, tracking, and implementing mitigations for risk at Lincoln Laboratory. The DSP was developed to streamline and improve monitoring of processes that were previously handled through manual efforts.

Information technology is discussed in more detail in TRPCS-PL-007, *TROPICS Software Management and Development Plan.*

3.8 Software Management Plan

The latest copy of the TROPICS contract deliverable, *TROPICS Software Management & Development Plan*, document TRPCS-PL-007, fulfills the requirements of the Software Management Plan.

3.9 Verification and Validation Plan

This section summaries the standalone plan that will be baselined at the TROPICS system PDR. As stated in 2.1, the system requirements Excel spreadsheet has each requirement's PLRA antecedent, proposed technique for requirement verification, and a requirement verification status. The verification technique options are inspection, analysis, demonstration, and test. Inspection is by visual examination of drawings, data, or part without special test equipment. For example, the mass can be inspected by using a calibrated scale. Analysis consists of using statistics, modeling, similarity, simulation, or other accepted analytical techniques. Demonstration relies on observing or recording a functional aspect of the requirement, e.g., access panel or verifying a data latency. Finally, test verification uses special test equipment with a quantitative measurement beyond the simple measurements available under inspection. Testing is the preferred method if schedule and cost constraints allow it and the test is warranted for the particular requirement. Section 3.15 describes SV verification during integration & test.

Validation of the PLRA data products occurs at each step from antenna temperature (i.e., NEdT) through geophysical retrievals. Data product validation is an important step to ensure that the science requirements are met. A validated Level-1b product will be publicly available 90 days after launch, and the remaining products will be validated 180 days after launch. Validation refinements will continue throughout the mission.

- **Level 1**

For Level 1 validation, the use of residuals from data assimilation (observations minus background fields) provides a simple, straightforward, and relatively low-cost method to identify and ascertain calibration differences between constellation members. The residuals can also be averaged over each pixel position or view angle to identify potential cross-track biases.

- **Level 2**
  The TROPICS core geophysical products (vertical temperature and moisture profiles and precipitation estimates) will be validated and optimized by using a variety of proven methods and ancillary datasets, including inter-satellite match-ups, global comparison with radiosondes and numerical analysis fields, and comparisons with ground sensors (e.g., Integrated Multi-satellite Retrievals for GPM (IMERG)). Efforts will focus on identifying and collecting high-quality in situ datasets, ground-based radiometer, and GPS-RO observations. The proposal team is exceptionally experienced in such validation efforts and current and planned work will be leveraged to implement a comprehensive TROPICS program and relatively low cost and risk.

Inter-calibration of the TROPICS CubeSat radio spectrometers is a critically important element of the validation program. This inter-calibration will be carried out using global comparisons with NWP atmospheric fields, synoptic radiosondes, GPS radio occultation measurements, and comparisons with other orbiting passive microwave sensors such as ATMS using Simultaneous Nadir Overpass (SNO) and double differencing techniques as applied by the GPM inter-calibration effort. To verify the individual calibration of the TROPICS CubeSats during payload TVAC calibration, a Level-1B intra-calibration between TROPICS CubeSats will be performed to identify potential problems and to ensure that the observations are physically consistent between them.

3.10 Review Plan

The TROPICS project plans to have a streamlined review process. The major reviews with the NASA Standing Review Board (SRB) are captured in this section. There will be a number of other informal reviews throughout the project as needed, as described in the Systems Engineering Management Plan TRPCS-PL-003. The major reviews that will be conducted with the SRB per the TROPICS Terms of Reference are:

- System Requirements Review (SRR) / Mission Definition Review (MDR)
- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- System Integration Review (SIR) / Pre-Environmental Review (PER)
- Operations Readiness Review (ORR)

For the five reviews in the list above, a formal, in-person review with the SRB will be held unless an alternate plan is agreed to by the stakeholders. Two months prior to the review, the TROPICS management team, the ESSP Program Office, and the SRB chair will develop a set of entrance and exit criteria for the review. The program office and the SRB chair will communicate the criteria to the SRB and the relevant NASA and center administration. As part of the criteria, a deliverables list and due date will be developed.

During the review, the TROPICS team will present the current status of all aspects of the project. All requests for action (RFA) will be managed by the SRB chair. At the conclusion of the review, the SRB chair, the PM, the Mission Manager, and the PI will discuss each action and its relevance to TROPICS mission success. Those deemed relevant will be formally submitted and the project will determine a response date for each action.

Per the TROPICS Statement of Work (SOW) Data Requirements List (DRL) and DRD, there are two additional review packages due to NASA beyond the SRB reviews above. They are the Pre-Ship Review (PSR) and The Post-Launch Assessment Review (PLAR) packages, which are led by MIT LL. Furthermore, there are additional major non-SRB reviews in the TROPICS Terms of Reference baseline, which will be led by NASA:

- Mission Readiness Review
- Decommissioning Review
- Disposal Readiness Review (DRR)

The TROPICS team will hold peer reviews as they are deemed necessary. Likely candidates for review include a peer review of the bus-hosted software, a peer review of the payload hardware, and a peer review of the mission operations. Peer reviews shall draw from subject matter experts within the MIT LL community. Invitations may also be extended to the NASA sponsors and relevant members of the SRB.

Though the details are not yet determined, the TROPICS team shall also support launch vehicle-related reviews as required.

3.11 Mission Operations Plan

Figure 12 provides a high-level overview of the mission operations plan, with more details below:

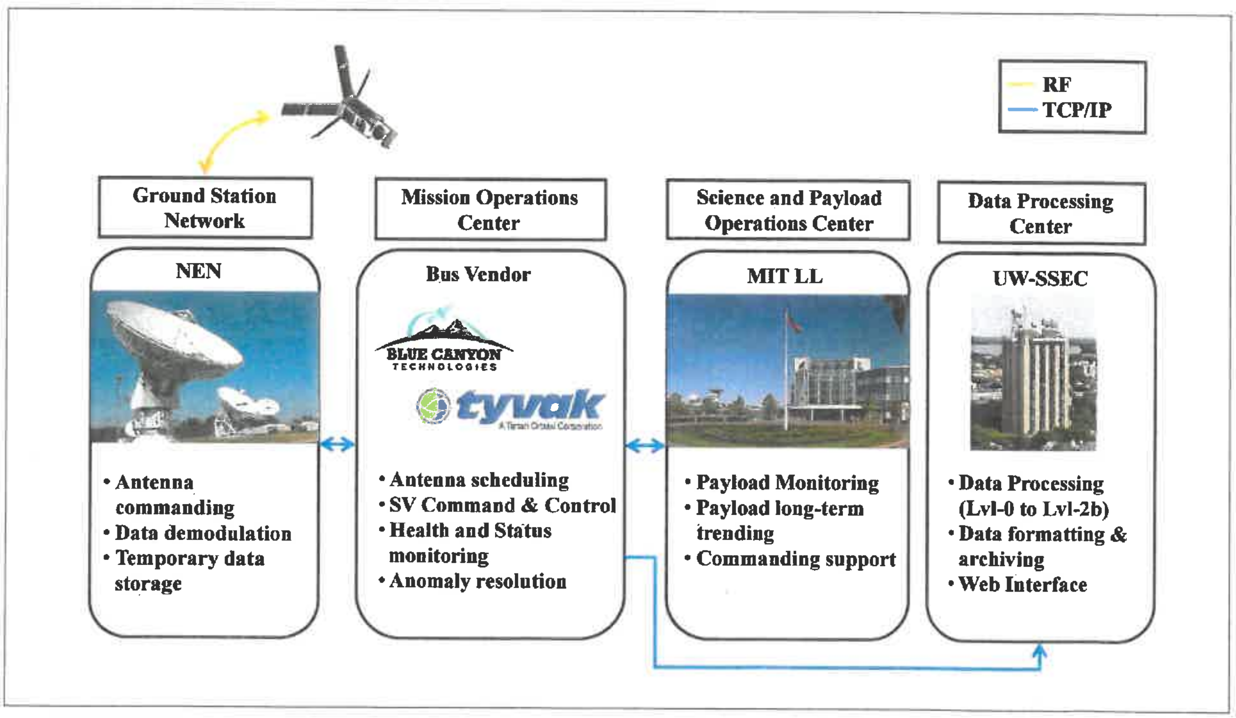

Figure 12: *Mission Operations*

3.11.1 Orbit

The TROPICS baseline plan calls for launch of 6 satellites. Three launches, concurrent to within 60 days would be required to populate each of the three orbital planes. The required launch parameters were analyzed using a comprehensive simulation analysis and are shown below:

Parameter	Value
Semi-major Axis	550 km ($\pm$ 50 km)
Inclination	30° ($\pm$ 3°)
Plane Spacing (RAAN)	120° ($\pm$ 1°)
Intra-Plane Satellite Phasing	Random

Table 7: *SV Orbital Elements*

3.11.2 Ground Station Network

The TROPICS project will chose a Ground Station Network before PDR out of the following options:

1. NASA Near-Earth Network (NEN) + Wallops / Morehead
2. NRO Mobile CubeSat Command & Control (MC3)
3. Konsberg Satellite Services (KSAT Lite)

All three options meet our data downlink/uplink requirements; final decision will be impacted by bus vendor down-selection. This system trade is described in Section 4.6.

Mission operations will be described in more detail in document `TRPCS-PL-011`, the *TROPICS Mission Operations Plan.*

3.11.3 Mission Operations Center

Potential bus vendors have the capability to operate a constellation of their satellites more efficiently than can be done internally at MIT LL. Therefore the baseline plan is for the Mission Operations Center (MOC) to be operated by the bus vendor from their facility. Both potential bus vendors have mission operations as a demonstrated company capability and have provided initial costing for operation of the constellation.

The MOC will connect directly to the ground station network. The MOC will coordinate with the Science & Payload Operations Center (SPOC) for daily operations. In addition, the MOC will receive telemetry from each spacecraft and store it as Level 0 data with redundant off-site backup. The MOC can support the operation of the TROPICS CubeSats including contact scheduling and executing the Early Orbit Activation and Checkout and Science Operations during Phase E Operations and Sustainment. The MOC with support from the SPOC will resolve on-orbit anomalies.

3.11.4 Science & Payload Operations Center

The SPOC, led by MIT LL, will generate the commanding required for early orbit activation and check-out for each SV payload. The SPOC will also monitor the health and status of the operational SVs and take appropriate action on any anomalies that may impact the data products by long-term trending SV data.

3.11.5 Data Processing Center

TROPICS will capitalize on many successful prior programs to build a comprehensive ground segment and Data Processing Center (DPC). The TROPICS DPC will leverage existing architecture and experience with the NPP Atmosphere PEATE project and the International MODIS/AIRS Processing Package (IMAPP). The DPC will make all data products available on anonymous FTP servers, HTTP, scriptable Web Application Programming Interface (API), and an interactive Web search and order system. All data products will be archived locally for the lifetime of the project. UW SSEC will archive the data to an EOSDIS DAAC in a format approved by NASA ESDS. The TROPICS threshold data processing latency requirement for Levels 0 through L2 is within 60 minutes of downlink (goal is 10 minutes). UW SSEC expects 20 to 30 minute latency.

3.12 Environmental Management Plan

The NASA HQ NASA National Environmental Policy Act (NEPA) Manager, SMD NEPA Liaison, and Office of General Counsel (OGC) have reviewed the scope of the TROPICS program and confirmed that the current scope falls within the 2011 NASA Routine Payload (NRP) Environmental Assessment (EA). Therefore, TROPICS missions that fall within the current scope of the program do not require a mission-specific EA. In order to confirm this conclusion, TROPICS managers will complete the provided environmental checklist to ensure that the missions are within the current scope of the program. SMD understands that this checklist only applies for payloads launched from the US.

If the mission is being launched from New Zealand, SMD understands that this will require compliance with US Executive Order 12114, *Environmental Effects Abroad of Major Federal Actions*, and will complete NASA's EO 12114 environmental checklist. This checklist serves to confirm that TROPICS will comply with applicable environmental rules and regulations of the host country, New Zealand. It will also serve to determine if the proposed launches have the potential to impact a non-participating nation, or the open ocean.

As discussed with SMD, no environmental studies will be required as long as potential impacts to non-participating nations and the open ocean can be avoided or mitigated. The TROPICS team is encouraged to work with New Zealand authorities during mission planning to ensure the project can be implemented without adverse environmental effects. SMD will be responsible to ensure that TROPICS mission launches meet all range safety requirements and planning contingencies in order to minimize potential environmental effects in the unlikely event of a launch mishap.

The Record of Environmental Consideration (REC) will be prepared in support of either the NRP or EO 12114 checklist, pending the launch location. The REC will also document the mission's commitment not to include any hazards on the payloads themselves. Specifically, the SVs are not expected to contain propellants, radioactive sources, biological material or release any chemicals. Any decision to include any of these will trigger additional NEPA analysis.

In the event that SMD "sells" any unused TROPICS Program launch capacity, SMD will ensure that potential customers purchasing excess launch capacity are conducting missions within the same scope as the TROPICS Program. Specifically, SMD will ensure that such missions do not involve the use of radioactive or biohazard material.

It is currently understood that this mission implementation is being planned without NASA-Center involvement. Therefore, no Center-specific Environmental Management Systems (EMS) requirements or permits are anticipated. The REC will therefore be prepared at NASA Headquarters. SMD is committed to comply with NEPA by Key Decision Point (KDP)-C per NASA `NPR 8580.1A`.

In addition to work being performed at MIT LL, other work will be performed by vendors under contract to MIT LL which will be compliant with Federal, State, and local law or requirements and Executive Orders.

3.13 Integrated Logistics Support Plan

The TROPICS project will implement logistic requirements consistent with NPD 7500.1, *Program and Project Life Cycle Logistics Support Policy*, for supply support, maintenance, test and support equipment, training, technical documentation, packaging, handling, and transportation.

The TROPICS project will provide planning and provisioning of logistics for the SV and ground support equipment shipments to the launch site and will comply with NASA NPR 6000.1H, *Requirements for Packaging, Handling and Transportation for Aeronautical and Space Systems, Equipment and Associated Components*, when handling and transporting hardware, documentation, software, and ground support equipment among various facilities.

Transportation of all TROPICS critical items will follow the MIT LL handling, movement, storage, and shipment requirements and the safety requirements referenced in the Mission Assurance Requirements document.

3.14 Science Data Management Plan

This section describes how the TROPICS project will manage the scientific data generated and how this data will be generated, processed, distributed, analyzed, and archived. This plan will become a standalone document that is baselined at Operational Readiness Review (ORR).

The satellite data will be downlinked to a ground network. After coordination with the MOC, data will be transferred to the TROPICS DPC at UW. All algorithms for Level 1 and 2 data processing will reside at the UW DPC. Data will be processed and delivered to a NASA DAAC for archival and dissemination to the user community.

The list of data products can be found in Table 1 in the PLRA with their units and ground latency. The TROPICS PLRA also has the data products requirements. The science team and instrument team will deliver science-grade algorithms to the TROPICS DPC. UW SSEC will integrate, test, and operationalize the science-grade code. SSEC will also develop and maintain the ground processing architecture and deliver data to a NASA DAAC. All processed products will be stored in HDF5 or netCDF format. The ground processing architecture will leverage the MicroMAS ground processing.

- **Level 0 Processing**
  This processing collects the raw TROPICS data packets from the downlink portal on a fixed schedule, segments the data in set of scans (granules), and performs quality assurance, time stamping, and engineering unit conversions.

- **Level 1 Processing**
  Raw counts are first calibrated and geolocated to produce Level 1A data, which then have an antenna pattern correction applied to produce a Level 1b (Lvl1b) Brightness Temperature (T_b). The Lvl1b data are produced at native resolution and grid spacing.

- **Level 2 Processing**
  Two additional T_b data products will be made available to provide uniform spatial resolution on a common grid. Lvl2a-UR is a T_b product mapped to a Unified Resolution (UR). A Level 2a High Resolution (Lvl2a-HR) product provides high-pass filtered brightness temperatures mapped to a higher spatial resolution (15 km at nadir) for cloud and precipitation studies. The Backus-Gilbert method,

used successfully in several prior missions, will be used to generate the Lvl2a products. This effort will be led by Prof. Bennartz and utilize the science team members' algorithms. The core TROPICS Level 2b product is the vertical temperature and moisture profiles and precipitation estimates. TC intensity uses the MSW and MSP data products.

Further details will be described in document TRPCS-PL-008, the *TROPICS Science Data Management Plan.*

3.15 Integration Plan

The TROPICS SV consists of two major sub-assemblies: the spacecraft bus and the payload.

The spacecraft bus assembly, integration, and test plan will be determined by the selected bus vendor, with oversight from MIT LL. MIT LL seeks to procure a bus that requires a minimum of NRE. This should allow the vendor to execute with minimal modifications to existing assembly, integration, and test plans.

The payload will be assembled and tested by MIT LL. The components will be procured from outside vendors and assembled at MIT LL. Each payload will be functionally tested and then calibrated in groups of three before integration to the spacecraft bus.

The baseline plan calls for the bus vendor to perform both payload integration and environmental testing; both bus vendors are capable of conducting the necessary tests, and have included SV testing in their preliminary schedules and budgets.

The project will procure a full qualification unit of the spacecraft bus and mate it to a qualification payload. The resulting complete SV will be known as the Qualification Unit (QU).

The QU will undergo environmental verification by subjecting the unit to qualification level loads. After the full environmental test is complete, a comprehensive functional test of the SV (bus & payload) will be repeated. In addition, re-measurement of the qualification unit spectrometer performance will also occur ; due to the specific expertise and required support hardware this will be performed by MIT LL at the laboratory, not by the bus vendor. The design will be considered qualified if the SV (bus & payload) performance matches the initial performance with allowable deviation.

The first flight unit will undergo a similar set of tests as the QU, but at the acceptance level. For subsequent units, the testing duration will be reduced to a more limited functional and environmental set of tests.

Detailed qualification and acceptance test descriptions for random vibration, shock, thermal, and thermal vacuum testing are provided in Section 12 of TRPCS-PL-003, *TROPICS Systems Engineering Management Plan.*

Figure 13 below describes the planned integration and test flow:

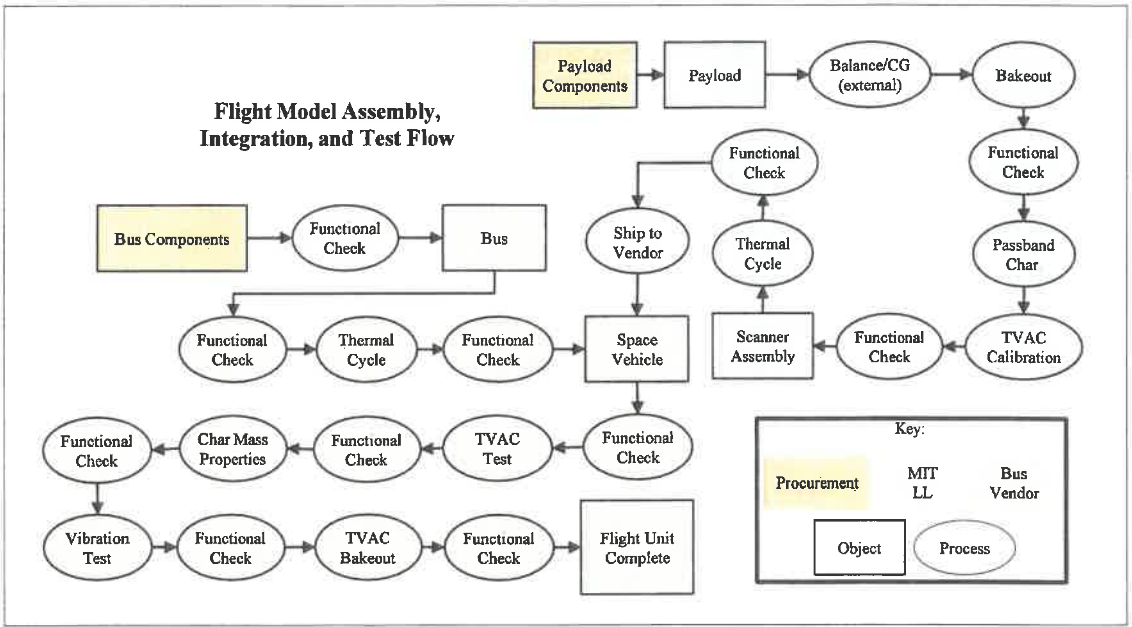

Figure 13: *Planned Assembly, Integration, & Test Flow*

Details of system integration will be spelled out in document `TRPLS-PL-014`, the *TROPICS Integration Plan.*

3.16 Configuration Management

The latest copy of the TROPICS contract deliverable, *TROPICS Configuration Management Plan*, document `TRPCS-PL-010`, fulfills the requirements of the configuration management plan. A summary is provided below.

Software for both the payload and the bus will be configuration controlled using the industry-standard "Git" version control system. The "Git" data repositories are access-controlled, and will be located on a server computer with redundant disks that undergoes regular backups to a separate storage system.

The same "Git" repository will be used for configuration control of documents, including those in the DRD agreed to with NASA (such as this document). Also included in the repository will be the Microsoft Excel spreadsheet used to track requirement flow-down, verification, and validation. Internal and external ICDs will be included as well.

All configuration management systems are located on an internal MIT LL-controlled network that is inaccessible from the outside world except via secure authentication methods on laboratory-owned and managed hardware. (See 3.7)

3.17 Security Plan

The MIT LL Security Services Department (SSD) provides the Laboratory's contractual requirements, restrictions, and safeguards to prevent unauthorized disclosure of classified and unclassified but sensitive information. The SSD focuses on protecting the confidentiality, integrity and availability of Laboratory information, whether in electronic, paper or other forms. MIT LL procedures and processes meet the requirements for DoD clearances. Laboratory personnel have a shared responsibility to ensure that safeguards are used to protect all information that has not been formally approved for public release.

Information security is discussed in section 3.7 and in TRPCS-PL-007, *TROPICS Software Management & Development Plan.*

3.18 PROJECT PROTECTION PLAN

Project protection in the context of this mission will consist largely of ensuring reliable and protected communications between the ground stations and each of the SVs. This involves taking steps to ensure that a malicious actor is not capable of either taking control of or damaging the satellite. Both up and down RF links will make use of standard encryption protocols to ensure data privacy.

Uplink commands to the SV will make use of a Vehicle Command Count (VCC) to ensure commands are received reliably from the desired ground station only. (A VCC ensures that malicious re-emission of RF commands are not able to spoof the satellite into repeating a set of actions).

Project protection is also inherent in the security plan, described in Section 3.17.

A full Project Projection Plan (PPP), document TRPCS-PL-009, is being filled out in conjunction with the Program Office at LaRC.

3.19 TECHNOLOGY TRANSFER CONTROL PLAN

All employees of MIT LL are United States citizens. As a Federally-Funded Research and Development Center (FFRDC) under the auspices of the United States Air Force MIT LL has significant infrastructure in place to ensure International Traffic in Arms Regulations (ITAR) compliance. In particular, the MIT LL Contracting Services Department has a process in place to ensure that all outside procurements and contracts are consistent with the Export Arms Regulations (EARs) of the United States Government. This existing process meets the intent of NASA NPR 2190.1.

3.20 KNOWLEDGE MANAGEMENT PLAN

As TROPICS represents the first science constellation of CubeSats for NASA, it is expected there will be a number of useful lessons learned that can be applied to future missions both at MIT LL and at NASA. The TROPICS program will provide summaries of lessons learned at appropriate major milestone reviews to capture the lessons in a timely matter and allow the information to be passed on to future programs.

The TROPICS project does not include a set of tasks or meetings with an explicit focus on lessons learned. However, information sharing and capturing of lessons learned are embedded into the structure and process of the project. For example:

- The TROPICS team conducts weekly meetings at which management, systems engineers, and unit engineers discuss progress and issues. This is an opportunity for engineers to share their experience across disciplines.
- The chief engineer role is held by a senior engineer with broad expertise who will provide technical oversight of the hardware build and design. This broad view will allow the chief engineer to share issues and lessons learned across mission subsystems.

- Calibration and test procedures for all flight hardware will be subject to MIT LL-internal peer review by a broad team of experts with prior flight-hardware experience. In addition, calibration and test procedures will first be executed against the qualification unit to ensure procedures are comprehensive and perform the intended function. Thus any "lessons learned" will be learned against the qualification unit and not flight hardware.
- The online TROPICS Wiki and issue tracking system applies to software, firmware, and hardware. This serves as a dynamic repository of lessons learned.

3.21 Human Ratings Certification Package

Not Applicable

3.22 Planetary Protection Plan

Not Applicable

3.23 Nuclear Safety Launch Approval Plan

Not Applicable

3.24 Range Flight Safety Risk Management Process Documentation

Not applicable since TROPICS is developing a payload to fly on an Expendable Launch Vehicle.

3.25 Expendable Launch Vehicle Payload Safety Process Deliverables

TROPICS will develop the payload safety process deliverables in accordance with `NPR 8715.7`, *Expendable Launch Vehicle Payload Safety Program.* The focus is on payload design, fabrication, testing, vehicle integration, launch processing, launch, and GSE used to support payload-related operations. `NASA-STD 8719.24` provides more details on payload processing for launch.

3.26 Education Plan

Not Applicable

3.27 Communications Plan

Communications both external to MIT LL (NASA) and within MIT LL are critical to the success of the TROPICS mission. TROPICS will ensure an integrated approach to communicate effectively with customers, stakeholders, and the public the importance and relevance of the TROPICS mission and how it integrates within and supports the NASA vision.

This integrated approach will endeavor to make a positive contribution to the state of knowledge, and reflect the high-professional standards under which MIT LL/NASA operates. TROPICS communications will be compliant with *Managing Agency Communications* (NPD 1380.1), and *Requirements for Documentation, Approval, and Dissemination of NASA Scientific and Technical Information* (NPR 2200.2).

4 System Trades

Table 8 summarizes the state of the trade studies as of April 2017. A selection of these are discussed below.

No.	Description	FAD	Completion Milestone
1	Bus vendor trade study	No	PDR
2	Power Optimization Trade	Yes	PDR
3	Channel Set Compliance Implementation Study	Yes	SRR/MDR
4	Weight/Risk Optimization Trade	Yes	SRR/MDR
5	Descope Flight Units Trade	Yes	PDR
6	Constellation Management Study	Yes	PDR
7	Geolocation Compliance and Star Tracker	Yes	SRR/MDR
8	Reliability Trade Analysis	Yes	PDR
9	Algorithm Refinement Study	Yes	PDR
10	Science Performance Analysis	Yes	PDR
11	W/F-Receiver Front End Trade	No	PDR

Table 8: *Current State of TROPICS Trade Studies*

4.1 Bus Vendor Trade

The TROPICS team is utilizing the rapidly advancing capabilities of the commercial CubeSat bus vendors. This section covers aspects of these trade studies: power optimization, geolocation compliance and star tracker, and reliability trade analysis.

The choice of bus vendor is critical to mission success, as the bus provides on-orbit mechanical structure, thermal management, power, and communications, and ADCS systems for the SV. The CubeSat industry has seen a significant increase in bus standardization, reliability, and capability since the original TROPICS proposal. MIT LL will leverage this commercial investment to procure a set of highly reliable and capable CubeSat buses.

Uncertainty in the quality and capability of potential bus vendors is an unavoidable byproduct of the rapidly-evolving industry. To reduce the risks associated with this procurement MIT LL has issued a RFP for a bus study to seven different commercial and government lab CubeSat bus providers. Of these seven vendors two have been identified as potentially having the desired execution capability and design maturity. Blue Canyon Technologies (BCT) and Tyvak have been tasked by MIT LL to conduct a 3-month study to evolve their existing bus design to meet the TROPICS mission requirements. This will give the TROPICS team time to evolve the bus requirements (e.g. provided payload power) as the payload design matures and also allow the team an in-depth look into the design, build, and test processes of each vendor as we work closely with them over the study period.

At the conclusion of the study MIT LL will select one of the two study vendors to execute the bus build. Criteria for the selection will include:

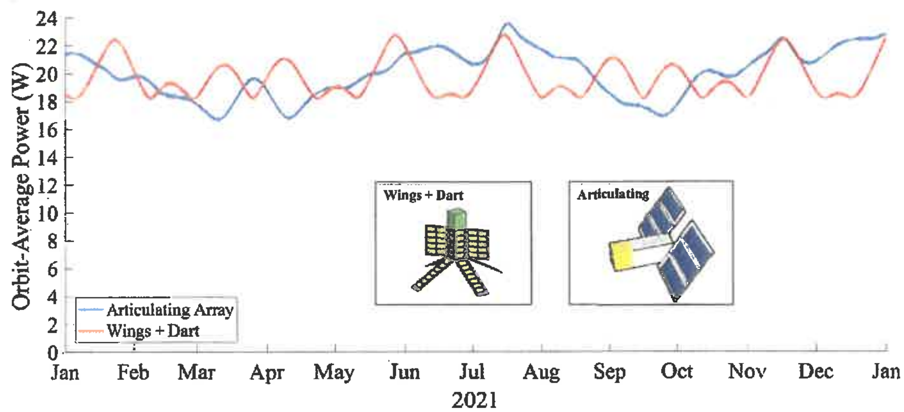

Figure 14: *Fixed & Articulating Panel Options*

- Cost and schedule
- Maturity of bus design and flight heritage
- Predicted bus performance with respect to requirements and goals
- Additional NRE required to complete bus design
- Demonstrated past performance of relevant hardware
- Vendor's Quality Control System
- Vendor's ability to execute
- Program Risk

4.2 Power Optimization Study

Related to the bus vendor study and down-select is the choice of solar panel, which will be provided by the bus vendor along with the delivered bus. The payload power draw with a 20% margin on the maximum expected value is 6.6 Watts. This is the requirement that has been shared with both potential bus vendors.

Potential bus vendors are investigating both articulated and fixed arrays. An articulated array will rotate about a fixed axis to maximize generated power by optimizing panel pointing relative to the sun. The articulated array has the complexity of requiring an additional motor to articulate the array and may induce some difficulties to the ADCS system due to the dynamic moment of inertia. This must be measured against the complexity of a fixed-panel array having a larger number of solar cell strings, more surface normals (and with them more peak-power trackers to maximize generation efficiency), and a potentially complicated panel deployment. In addition, if the fixed-panel option includes a deployed panel near the rotating payload head, a potentially complex set of analyses will need to take place in order to ensure that the panels do not enter the side-lobes of the rotating spectrometer antenna pattern and corrupt the science measurement.

MIT LL will work with both vendors during the study to determine which panel configuration offers the best combination of risk, complexity, cost, and power generation. Final panel configuration will be determined prior to issuing the FFP contract to the chosen bus vendor for the constellation bus.

4.3 Channel Set Compliance Implementation Study

The MicroMAS-2a (MM-2a) payload (presently under assembly, integration, and test) is the design heritage for the TROPICS payload, but it does not meet all of the TROPICS requirements. The objective of this study is to determine the implementation path to alter the MM-2a payload's design to meet TROPICS requirements. The first TROPICS requirement that is not being met is the number of F-band (i.e., 118-GHz) channels. MM-2a could only fit five channels in its allotted volume, while TROPICS requires seven. Second, the MM-2a 205-GHz G-band channel does not meet the threshold TROPICS noise figure (i.e., receiver temperature) requirement, which necessitates a partial redesign of the G-band receiver front end. Thirdly, radio frequency interference between the Intermediate Frequency Processors (IFPs) require the payload to have separate enclosures for each IFP. This trade will also evaluate the volume, mass, and power trade offs to ensure the TROPICS payload meets the baseline requirements.

4.4 Weight & Volume Trade

To reduce overall system risk MIT LL may leverage the flexibility provided by being the primary launch vehicle payload by designing to dispensers such as the CSD manufactured by the Planetary Systems Corporation that provide for mass and volume above the Poly Picosat Orbital Deployer (P-POD) standard.

The current payload design has a mass allocation with contingency of 1.8 kg. 11% margin brings this to 2 kg. The payload will be mated with a commercially-procured bus to produce the SV. The bus will not include significant mass growth allowance, as either potential bus vendor will use an existing and mature bus design.

MIT LL is invoking an 8 kg SV mass limit based upon the allowable loads on the CSD dispenser tab mechanisms. 2 kg of the 8 kg is allocated to the payload (see above), and 5 kg is allocated to the bus with an additional 1 kg held in reserve. The current Tyvak design has 95% margin against the 5 kg limit ; the BCT design with contingency has an 11% margin against the 5 kg mass limit.

The current payload design has a length of 1.9U. Both bus vendors can support the payload volume while remaining compliant with a standard deployment mechanism. The length margin is approximately 5% ; however, if necessary, MIT LL will modify the existing scanner/motor assembly design to recover approximately 2 cm of length.

4.5 Constellation Size Trade

The number of orbital planes and the number of satellites in each plane will influence the latitude-weighted median revisit rate, a critical metric for ensuring relevant timescales of TC evolution are captured and a driving mission requirement.

Budget constraints —*in particular the cost of the bus procurement, which includes payload integration and SV testing* —constrain the number of TROPICS satellites. Given cost estimates provided by both candidate bus vendors MIT LL plans to build and qualify a single qualification unit and then field a constellation of 6 satellites.

Figure 15 shows that 6 satellites separated into 3 orbital planes is sufficient to meet the baseline mission requirement of 60-minute latitude-weighted median revisits. This can be reduced to 5 satellites in two orbital planes while still meeting baseline mission requirements and reduced to 4 while still meeting threshold mission requirements. The values in the figure assume equal spacing of the orbital planes and random phasing of the satellites within an orbital plane. A Monte-Carlo analysis with 500 realizations of random intra-plane phasing is used to produce the results.

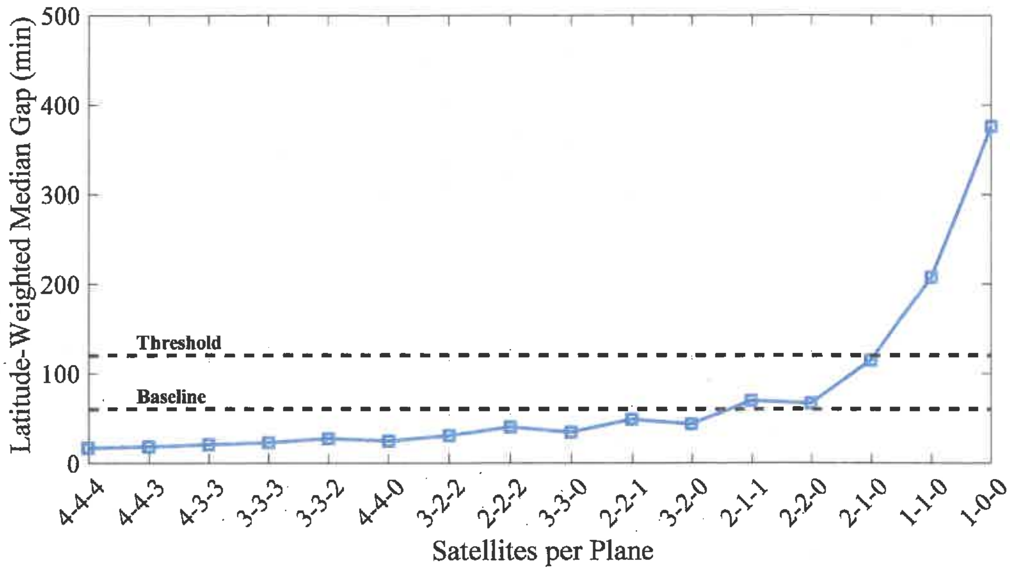

Figure 15: *Median Revisit Rate vs Constellation Size. Altitude = 500 km, Inclination = 30°*

4.6 Constellation Management Study

Part of the Constellation management study is determining the ground station network, which is discussed in this section. The project team will also discuss constellation management with the bus vendors during the studies. The baseline plan calls for use of the NASA NEN for communications. MIT LL will work with the chosen bus vendor to ensure that their chosen radio is compatible with the NEN and has sufficient power to support the necessary data rates. Candidate bus vendors already have systems in development that operate with the NEN, including radios that have demonstrated interoperability and a ground system interface that meets the NEN ICD. This should greatly simplify MIT LL oversight of the ground station development.

The bus vendor may recommend use of a different ground-station network. In particular, the "K-SAT" network of S-band ground stations may deliver sufficient data capacity at a low cost. Both potential bus vendors have systems that have already demonstrated interoperability with the "K-SAT" network.

MIT LL is also investigating the Mobile CubeSat Command & Control (MC3) ground station network. This network is relatively new and includes smaller dishes with correspondingly lower gain ; however, the ground station locations are well placed to interface with satellites in our desired orbit.

Network criteria that will inform decision include:

- Network loading and downlink capacity
- RF link budget & margin
- Cost
- Interface complexity
- Interoperability against desired radio
- Ease of testing
- Confidence in provider technical capability
- Prior experience with mission operator

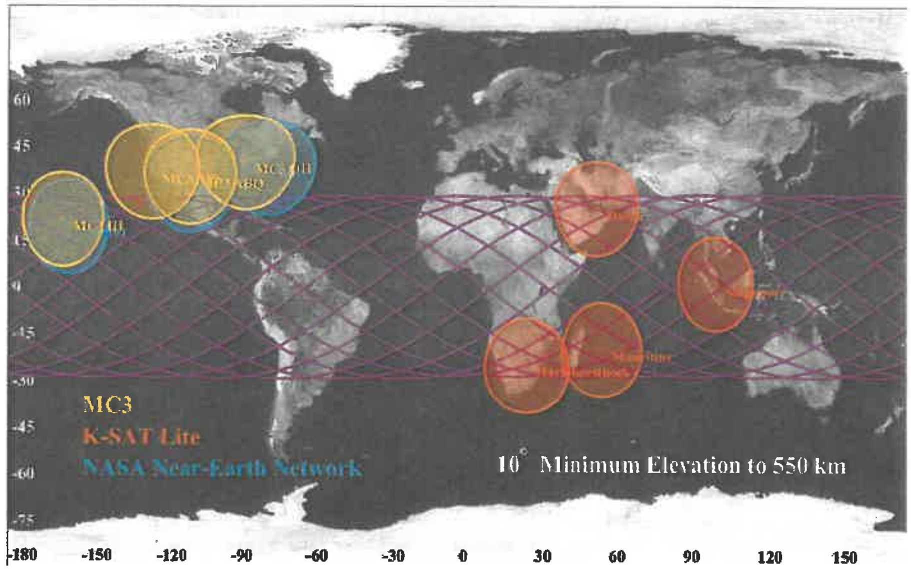

Figure 16: *Potential ground station networks & coverage area*

4.7 Geolocation Compliance & Star Tracker Study

The TROPICS mission will provide vertical temperature and moisture profiles and precipitation estimates in an Earth-centered coordinate frame. The measurements recorded by the radio spectrometer must be translated and rotated into this frame. Errors in SV position and radiometer orientation in the Earth-centered frame will translate to errors in geolocation. The geolocation errors should be a fraction of the system resolution. At the minimum constellation altitude of 500 km the smallest sampled area on the ground with nadir pointing has a resolution of 13 km. A 1-km geolocation error keeps the pointing knowledge to $<$ 10% of a resolution element.

MIT LL assumes for geolocation budgeting a star tracker pointing accuracy of 30 arcsec. This is twice roll accuracy (worst axis) predicted by BCT. With this value star tracker pointing is a minor term in the geolocation budget and a geolocation error of $<$ 500 m is expected.

Without the star tracker, MIT LL would consider using a combination of magnetometer and Earth-horizon sensor. This provides an accuracy of 1.5°. With this value inertial attitude sensing dominates the geolocation budget and a geolocation error of 14 km is expected. An additional drawback of this sensing mechanism is that the on-board magnetometer is susceptible to magnetic fields generated by the SV. This is particularly a concern given that the SV includes current loops such as those in the DC motors driving the reaction wheels and the payload. This performance degradation has not been included in the 1.5° accuracy number.

A potential regret of the star tracker is that it does not operate when pointed near the Earth, moon, or sun. However, this can be remedied by including two star trackers on the bus, each pointing in different directions. Both potential bus vendors include two star trackers on their bus as the default inertial attitude sensing mechanism.

A detailed pointing budget is beyond the scope of this document, but will be presented at the TROPICS Systems Requirements Review (SRR)/Mission Definition Review (MDR) as part of the geolocation TPM, TPM-008.

4.8 Reliability Trade Analysis

MIT LL will modify or replace parts as necessary from the original MicroMAS-2 payload design to ensure that the payload will reliably be able to operate in the space environment over the full mission lifetime. COTS parts are being replaced with space-qualified parts where a risk has been identified. MIT LL will conduct environmental testing for parts without sufficient flight heritage or space qualification and without suitable replacements. This includes radiation testing by MIT LL in an appropriate facility at the University of Massachusetts.

A candidate payload parts list as well as parts selected for additional environmental testing will be presented at SRR. Testing will be completed and parts selected as part of a preliminary design presented at PDR. Final payload design will be presented at CDR.

4.9 Algorithm Refinement Study

This study will be completed by the PDR, and covers refining the algorithm's methodology/technique of all the algorithms producing TROPICS data products (and therefore requires an Algorithm Theoretical Basis Document). These data products include:

- Level 1a: geolocated and calibrated antenna temperatures
- Level 1b: geolocated, calibrated, and inter-calibrated brightness temperature
- Level 2a: spatially re-sampled brightness temperatures to a unified resolution
- Level 2b: atmospheric vertical temperature profiles
- Level 2b: atmospheric vertical moisture profiles
- Level 2b: instantaneous surface rainfall rate
- Level 2b: maximum sustained wind speed
- Level 2b: mean sea-level pressure

4.10 Science Performance Analysis

This study, to be completed at PDR, consists of tracing the performance of the entire system from radiance to science data products. Using high-resolution hurricane simulations and radiosonde ensembles, radiances will be simulated using the characteristics of the TROPICS SV (e.g., payload and orbits). The system engineering team will utilize this testbed for requirement flowdown at SRR/MDR and releasing technical margin throughout the design phases. Figure 17 shows the flow of the data product generation and how the simulation testbed will be used to verify science performance.

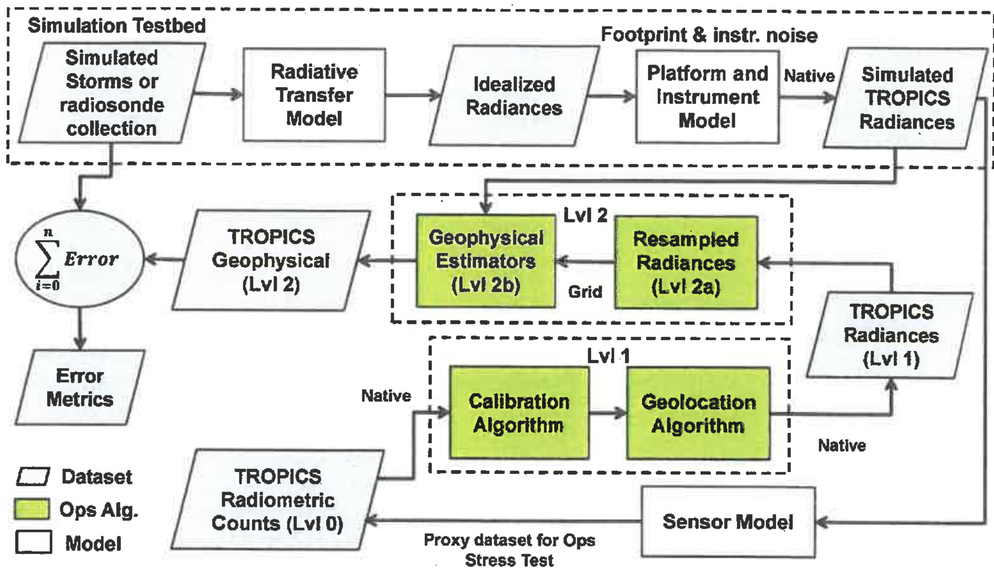

Figure 17: *Data product flow chart with simulation testbed*

4.11 W/F RFE

The W/F-band RFE module is on the critical path for the payload development. University of Massachusetts (UMASS) Amherst is providing the TROPICS W/F-RFE based on the design for MM-2a, and while the MM-2a met performance specifications, the units consist of a number of Monolithic Microwave Integrated Circuits (MMICs) laboriously assembled and tuned. To provide other options to mitigate schedule risk, two studies will be performed to determine the best path forward for the W/F-RFE. UMASS will investigate a Silicon-Germanium (SiGe) chip that incorporates a number of functions onto a single die, which should make manufacturing and tuning of the W/F-RFE much simpler, with more consistent performance, while reducing the schedule for the flight builds. At the same time, a study will be undertaken by Millitech to design a W/F-RFE that meets the same requirements. In both cases, the output is a design that can meet the specifications achieved by the original UMASS design. Once the studies are complete, MIT LL will select which of the three paths (i.e., UMASS original design, UMASS SiGe, and Millitech) to take. The path chosen will minimize cost and schedule risk, while maintaining the required performance.

Due to the long lead time (> 1 year) the study will conclude and the procurement process will begin prior to PDR.

The current budget and schedule assume the SiGe chip from UMASS.

5 Waivers or Deviations Log

Due to the nature of the project and its size, TROPICS will be heavily tailoring `NPR 7120.5`. The tailoring plan is described in the compliance matrix in Appendix B. There are currently no waivers or deviations from `NPR 7120.5E`.

6 Change Log

Revision table is included at the front of the document.

A Reference Documents

Document[†]	Description / Title
NPR 7123.1B	NASA Systems Engineering Processes and Requirements
NPR 7120.5E	NASA Space Flight Program and Project Management Requirements
PLRA	TROPICS Program-Level Requirements Appendix
TRPCS-PL-001	MIT LL TROPICS Program Management Plan
TRPCS-PL-002	MIT LL TROPICS Mission Assurance Plan
TRPCS-PL-003	MIT LL TROPICS Systems Engineering Management Plan
TRPCS-PL-004	MIT LL Work Breakdown Structure
TRPCS-PL-005	MIT LL Integrated Master Schedule
TRPCS-PL-007	MIT LL Software Management & Development Plan
TRPCS-PL-008	MIT LL Science Data Management Plan
TRPCS-PL-009	MIT LL Project Protection Plan Plan
TRPCS-PL-010	MIT LL Configuration Management Plan
TROPICS Proposal	TROPICS Proposal to NASA Earth Ventures Program
GSFC-STD-1000	Rules for the Design, Development, Verification, and Operation of Flight Systems
Margins & Contingency Module	Margins & Contingency Module. Exploration Systems Engineering, version 1.0
CDS Rev 13	CubeSat Design Specification, Revision 13
LSP-REQ-317.01	Launch Services Program Program Level Dispenser and CubeSat Requirements Document

[†]Use latest current revision as of release of this document when no revision is specified.

Table 10: *Reference Documents*

B Compliance Matrix

Compliance matrix with columns to indicate where tailoring has been applied is delivered as a separate Microsoft Excel workbook.

ACRONYMS

A/D Analog / Digital Converter. 28

ADCS Attitude Determination & Control System. 12, 39, 40

AMSU Advanced Microwave Sounding Unit. 8

API Application Programming Interface. 33

ATMS Advanced Technology Microwave Sounder. 8, 9, 30

BCT Blue Canyon Technologies. 39, 41, 43

CBE Current Best Estimate. 24, 25

CDR Critical Design Review. 15, 16, 44

CE Chief Engineer. 14–16, 25

CPOD CubeSat Proximity Operations Demonstration. 28

CSD Canisterized Satellite Dispenser. 12, 41

DAAC Distributed Active Archive Center. 13, 33, 34

DPC Data Processing Center. 33, 34

DPM Deputy Project Manager. 13–16

DRD Data Requirements Description. 20, 25, 30, 36

DRR Disposal Readiness Review. 31

DSP Data Security Plan. 29

EA Environmental Assessment. 33

EAR Export Arms Regulation. 37

EMS Environmental Management Systems. 33

EOSDIS Earth Observing System Data and Information System. 13, 33

ESD Earth Science Division. 7, 16

ESDS Earth Science Data Systems. 13, 33

ESSP Earth System Science Pathfinder. 7, 13, 15, 16, 30

FFP Firm Fixed-Price. 23, 24, 27, 40

FFRDC Federally-Funded Research and Development Center. 37

FPLOE Fixed-Price Level-of-Effort. 23

FW Firmware. 17

GSE Ground Support Equipment. 20, 38

ICD Interface Control Document. 12, 36, 42

IFP Intermediate Frequency Processor. 28

IMAPP International MODIS/AIRS Processing Package. 33

IMS Integrated Master Schedule. 19, 23, 24

IMU Inertial Measurement Unit. 28

IOC In-Orbit Checkout. 23

ITAR International Traffic in Arms Regulations. 37

KDP Key Decision Point. 33

KPM Key Performance Metric. 16, 25

LaRC Langley Research Center. 7, 13, 37

LEO Low Earth Orbit. 10

LLAN Lincoln Local-Area Network. 29

MAO Mission Assurance Office. 16

MC3 Mobile CubeSat Command & Control. 42

MDR Mission Definition Review. 43, 44

MIT LL MIT Lincoln Laboratory. 7, 11–13, 15–18, 22–25, 27–29, 31–46

MM Mission Manager. 16

MMIC Monolithic Microwave Integrated Circuit. 45

MOC Mission Operations Center. 32, 34

NEN Near-Earth Network. 32, 42

NEPA NASA National Environmental Policy Act. 33

NPR NASA Procedural Requirement. 7, 33

NRC National Research Council. 8

NRE Non-Recurring Engineering. 24, 27, 35, 40

NRP NASA Routine Payload. 33

OGC Office of General Counsel. 33

OPS Operations. 17

ORR Operational Readiness Review. 34

OSE Observing System Experiments. 9

P-POD Poly Picosat Orbital Deployer. 41

PATH Precipitation and All-weather Temperature and Humidity. 8

PDR Preliminary Design Review. 16, 17, 23, 24, 28, 29, 32, 44, 45

PE Program Executive. 16

PI Principal Investigator. 7, 10, 13–17, 24, 25, 30

PLRA Program-Level Requirements Appendix. 13, 17, 26, 28, 29, 34

PM Project Manager. 10, 13–17, 24, 25, 30

PMW Passive Microwave. 7–10

PPP Project Projection Plan. 37

PS Project Scientist. 13–15

PSE Project Systems Engineer. 13–17, 19, 24, 25

QMS Quality Management System. 16, 25

QU Qualification Unit. 35

REC Record of Environmental Consideration. 33

RF Radio Frequency. 11, 27, 37, 42

RFE Receiver Front End. 23, 28, 45

RFI Request for Information. 24

RFP Request for Proposal. 24, 39

SEMP Systems Engineering Management Plan. 28, 29

SiGe Silicon-Germanium. 45

SMD Science Mission Directorate. 7, 16, 33

SPOC Science & Payload Operations Center. 32

SQL Structured Query Language. 13

SRB Standing Review Board. 30, 31

SRR Systems Requirements Review. 43, 44

SSD Security Services Department. 36

SSEC Space Science & Engineering Center. 13, 33, 34

SSMIS Special Sensor Microwave Imager/Sounder. 8

SV Space Vehicle. 7, 10–13, 22, 23, 27–29, 32–35, 37, 39, 41, 43, 44

SW Software. 17

TA Technical Authority. 13

TC Tropical Cyclone. 7–10, 35, 41

TID Total Integrated Dose. 28

TPM Technical Performance Measure. 17, 24, 25, 43

TRL Technical Readiness Level. 28

TROPICS "Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats". 7–14, 16–19, 21, 24, 25, 27–41, 43–46

TVAC Thermal Vacuum. 28

UMASS University of Massachusetts. 45

UW University of Wisconsin. 13, 33, 34

VCC Vehicle Command Count. 37

WBS Work Breakdown Structure. 18, 24

NPR 7120.5E Compliance Matrix -- Project Product Requirements
Program or Project Name: TROPICS

Para #	NPR 7120.5 Requirement Statement	Require-ment Owner	Tailor	MD AA	CD	P M	Comply?	Justification & Guidelines	Approval
1.1.2	NASA Centers, Mission Directorates, and other organizations that have programs or projects shall develop appropriate documentation to implement the requirements of this NPR.	OCE	X	A			FC		
1.1.3	The Mission Directorate shall submit their plan for phased tailoring of the requirements of this NPR within 60 days of the effective date of this NPR.	OCE	X	A			FC		
2.1.1	Regardless of the structure of a program or project meeting the criteria of Section P.2, this NPR shall apply to the full scope of the program or project and all the activities under it.	OCE	X			A	FC		
2.1.4.1	Projects are Category 1, 2, or 3 and shall be assigned to a category based initially on: (1) the project life-cycle cost (LCC) estimate, the inclusion of significant radioactive material, and whether or not the system being developed is for human space flight; and (2) the priority level, which is the priority level, which is related to the importance of the activity to NASA, the extent of international participation (or joint effort with other government agencies), the degree of uncertainty surrounding the application of new or untested technologies, and spacecraft/payload development risk classification.	OCE	X	A			FC		
2.1.4.2	When projects are initiated, they are assigned to a NASA Center or implementing organization by the MDAA consistent with direction and guidance from the strategic planning process. They are either assigned directly to a Center by the Mission Directorate or are selected through a competitive process such as an Announcement of Opportunity (AO). For Category 1 projects, the assignment shall be with the concurrence of the NASA AA.	OCE	X	A			FC		

2.2.1	Programs and projects shall follow their appropriate life cycle, which includes life-cycle phases; life-cycle gates and major events, including KDPs; major life-cycle reviews (LCRs); principal documents that govern the conduct of each phase; and the process of recycling through Formulation when program changes warrant such action.	OCE				A	FC		
2.2.2	Programs and projects shall follow their appropriate life cycle, which includes life-cycle phases; life-cycle gates and major events, including KDPs; major life-cycle reviews (LCRs); principal documents that govern the conduct of each phase; and the process of recycling through Formulation when program changes warrant such action.	OCE				A	FC		
2.2.3	The documents shown on the life-cycle figures and described below shall be prepared in accordance with the templates in appendices D, E, F, G, and H.	OCE				A	FC		
2.2.4	Each program and project shall perform the LCRs identified in its respective figure in accordance with NPR 7123.1, applicable Center practices, and the requirements of this document.	OCE				A	FC		
2.2.5	The program or project and an independent Standing Review Board (SRB) shall conduct the SRR, SDR/MDR, PDR, CDR, SIR, ORR, and PIR LCRs in figures 2-2, 2-3, 2-4, and 2-5.	OCE	X			A	T	Not a Single Project Program so PIR is N/A	[initials] 6/20/19
2.2.5.1	The Conflict of Interest (COI) procedures detailed in the NASA Standing Review Board Handbook shall be strictly adhered to.	OCE	X	A	A	A	FC		
2.2.5.2	The portion of the LCR conducted by the SRB shall be convened by the Convening Authorities in accordance with Table 2-2.	OCE	X	A	A	A	FC		
2.2.5.3	The program or project manager, the SRB chair, and the Center Director (or designated Engineering Technical Authority representative) shall mutually assess the program's or project's expected readiness for the LCR and report any disagreements to the Decision Authority for final decision.	OCE	X		A	A	FC		
2.2.6	In preparation for these LCRs, the program or project shall generate the appropriate documentation per the Appendix I tables of this document, NPR 7123.1, and Center practices, as necessary, to demonstrate that the program's or project's definition and associated plans are sufficiently mature to execute the follow-on phase(s) with acceptable technical, safety, and programmatic risk.	OCE	X			A	FC		

	Table I-1 Uncoupled and Loosely Coupled Program Milestone Products and Control Plans Maturity Matrix						**N/A**	**Project is not an Uncoupled or Loosely coupled Program**	
	Table I-2 Tightly Coupled Program Milestone Products Maturity Matrix						**N/A**	**Project is not a Tightly Coupled Program**	
	Table I-3 Tightly Coupled Program Plan Control Plans Maturity Matrix						**NA**	**Project is not a Tightly Coupled Program**	
	Table I-4 Project Milestone Products Maturity Matrix								
	Headquarters and Program Products								
Table I-4	1. FAD [Baseline at MCR]	OCE		A		A	FC		
Table I-4	2. Program Plan [Baseline at MCR]	OCE		A		A	FC		
Table I-4	2.a. Applicable Agency strategic goals [Baseline at MCR]	OCE		A		A	FC		
Table I-4	2.b. Documentation of program-level requirements and constraints on the project (from the Program Plan) and stakeholder expectations, including mission objectives/goals and mission success criteria [Baseline at SRR]	OCE		A		A	FC		
Table I-4	2.c. Documentation of driving mission, technical, and programmatic ground rules and assumptions [Baseline at SDR/MDR]	OCE		A		A	FC		
Table I-4	3. Partnerships and Inter-agency and international agreements [Baseline U.S. partnerships and agreements at SDR/MDR; Baseline International agreements at PDR]	OCE		A		A	FC		
Table I-4	4. ASM minutes	OCE		A		A	N/A	No ASM required due to AO process	

Table I-4	5. NEPA compliance documentation per NPR 8580.1	EMD		A		A	FC		
Table I-4	6. Mishap Preparedness and Contingency Plan [Baseline at SMSR] [per NPR 8621.1]	OSMA		A		A	FC		
	Project Technical Products								
Table I-4	1. Concept Documentation [Approve at MCR]	OCE				A	T	Incorporated into Project Plan, & SRR package – no MCR held as AO selection mandated Phase A start	JB 6/30/19
Table I-4	2. Mission, Spacecraft, Ground, and Payload Architectures [Baseline mission and spacecraft architecture at SRR; Baseline ground and payload architectures at SDR/MDR]	OCE				A	T	Incorporated into SRR package – no SDR/MCR held as AO selection mandated Phase A start	JB 6/20/19
Table I-4	3. Project-Level, System and Subsystem Requirements [Baseline project-level and system-level requirements at SRR; Baseline subsystem requirements at PDR]	OCE				A	FC		
Table I-4	4. Design Documentation [Baseline preliminary design at PDR; Baseline detailed design at CDR; Baseline As-built hardware and software at MRR/FRR]	OCE				A	FC		
Table I-4	5. Operations Concept [Baseline at PDR]	OCE				A	FC		
Table I-4	6. Technology Readiness Assessment Documentation	OCE				A	FC		
Table I-4	7. Engineering Development Assessment Documentation	OCE				A	FC		
Table I-4	8. Heritage Assessment Documentation	OCE				A	FC		

Table I-4	9. Safety Data Packages [Baseline at CDR] [per NPRs 8715.3 & 8735.2]	OSMA				A	FC		
Table I-4	10. ELV Payload Safety Process Deliverables [Baseline at SIR] [per NPR 8715.7]	OSMA				A	FC		
Table I-4	11. Verification and Validation Report [Baseline at MRR/FRR]	OCE				A	T	Intent will be met using a spreadsheet with linked test report or other verification material	6/20/17
Table I-4	12. Operations Handbook [Baseline at ORR]	OCE				A	T	This activity will be procured and the intent of this requirement will be met but use of the documentation of the operator organization	6/20/17
Table I-4	13. Orbital Debris Assessment per NPR 8715.6 [Final ODAR at SMSR]	OSMA				A	T	Initial ODAR to be provided at PDR since AO selection mandated Phase A start	6/6/2017
Table I-4	14. End of Mission Plans per NPR 8715.6/NASA-STD 8719.14, App B [Baseline at SMSR]	OSMA				A	FC		
Table I-4	15. Mission Report	OCE				A	FC		
	Project Management, Planning, and Control Products								
Table I-4	1. Formulation Agreement [Baseline for Phase A at MCR; Baseline for Phase B at SDR/MDR]	OCE		A	A	A	T	Combined with Project Plan	6/20/17
Table I-4	2. Project Plan [Baseline at PDR]	OCE		A	A	A	FC		
Table I-4	3. Plans for work to be accomplished during next Implementation life cycle phase [Baseline for Phase C at PDR; Baseline for Phase D at SIR; Baseline for Phase E at MRR/FRR; Baseline for Phase F at DR]	OCE				A	FC		

Table I-4	4. Documentation of performance against Formulation Agreement (see #1 above) OR against plans for work to be accomplished during Implementation life cycle phase (see #3 above) including performance against baselines and status/closure of formal actions from previous KDP	OCE				A	FC		
Table I-4	5. Project Baselines [Baseline at PDR]	OCE				A	T	No independent IBR	JB 6/30/17
Table I-4	5.a. Top technical, cost, schedule and safety risks, risk mitigation plans, and associated resources	OCE				A	T	Incorporated into Project Plan as opposed to stand alone document	JB 6/30/17
Table I-4	5.b. Staffing requirements and plans	OCE				A	T	Incorporated into Project Plan, monthly reports, and review packages	JB 6/30/17
Table I-4	5.c. Infrastructure requirements and plans, business case analysis for infrastructure Alternative Future Use Questionnaire (NASA Form 1739), per NPR 9250.1 [Baseline for NF 1739 Section A at SDR/MDR; Baseline for NF 1739 Section B at PDR]	FED OCFO				A	N/A		
Table I-4	5.d. Schedule [Baseline Integrated Master Schedule at PDR]	OCE				A	FC		
Table I-4	5.e. Cost Estimate (Risk-Informed or Schedule-Adjusted Depending on Phase) [Baseline at PDR]	OCE				A	T	Cost estimate broken out by WBS	JB 6/30/17
Table I-4	5.f. Basis of Estimate (cost and schedule)	OCE				A	FC		
Table I-4	5.g. Baseline Joint Cost and Schedule Confidence Level(s) and supporting documentation	CAD	X			A	N/A	Not required for projects with an estimated life cycle cost less than $250M	23 May 17

Table I-4	5.h. External Cost and Schedule Commitments [Baseline at PDR]	OCE		A		A	N/A		
Table I-4	5.i. CADRe [Baseline at PDR]	CAD	X			A	T	Lagging CADRe performed	23May17
Table I-4	6. Decommissioning/Disposal Plan [Baseline at DR]	OCE				A	T	Merge with End-of-Mission plan as opposed to stand alone document	6/20/17
	Table I-5 Project Plan Control Plans Maturity Matrix								
Table I-5	1. Technical, Schedule, and Cost Control Plan [Baseline at SDR/MDR]	OCE				A	T	Incorporate in SRR - no SDR/MCR held as AO selection mandated Phase A start	6/20/17
Table I-5	2. Safety and Mission Assurance Plan [Baseline at SRR] [per NPDs 8730.5 & 8720.1, NPRs 8715.3, 8705.2, 8705.6 & 8735.2, and NASA Stds 8719.13 & 8739.8]	OSMA				A	FC		
Table I-5	3. Risk Management Plan [Baseline at SRR] [per NPR 8000.4]	OSMA				A	T	Incorporated into Project Plan as opposed to stand alone document	5/25/17
Table I-5	4. Acquisition Plan [Baseline at SRR]	OCE				A	T	Incorporated into Project Plan as opposed to stand alone document	6/20/17
Table I-5	5. Technology Development Plan (may be part of Formulation Agreement) [Baseline at MCR] [per NPD 7500.2 and NPR 7500.1]	OCT				A	T	Plan is provided in combined Formulation Agreement/Project Plan	5/30
Table I-5	6. Systems Engineering Management Plan [Baseline at SRR]	OCE				A	FC		
Table I-5	7. Information Technology Plan [Baseline at SDR/MDR] [NPDs 2200.1 & 1440.6 and NPRs 2200.2, 1441.1, 2800.1 & 2810.1]	OCIO				A	T	Project required to meet DoD requirements (ref. in Project Plan)	

Table I-5	8. Software Management Plan(s) [Baseline at SDR/MDR] [per NPR 7150.2 & NASA Std 8739.8]	OCE				A	T	Incorporate in SRR - no SDR/MCR held as AO selection mandated Phase A start	6/20/17
Table I-5	9. Verification and Validation Plan [Baseline at PDR]	OCE				A	T	Will use a spreadsheet and proj. plan section to capture V&V approach	6/20/17
Table I-5	10. Review Plan [Baseline at SRR]	OCE				A	T	Incorporated into Project Plan as opposed to a stand alone document	6/20/17
Table I-5	11. Mission Operations Plan [Baseline at ORR]	OCE				A	FC	Incorporated into Project Plan (stand-alone at ORR)	
Table I-5	12. Environmental Management Plan [Baseline at SDR/MDR] [per NPR 8580.1]	EMD				A	T	Incorporated into Project Plan as opposed to a stand alone document	26/5/17
Table I-5	13. Integrated Logistics Support Plan [Baseline at PDR] [per NPD 7500.1]	LMD				A	T	Incorporated into Project Plan as opposed to stand alone document	30 May 17
Table I-5	14. Science Data Management Plan [Baseline at ORR] [per NPD 2200.1 and NPRs 2200.2 & 1441.1]	SMD				A	FC		
Table I-5	15. Integration Plan [Baseline at PDR]	OCE				A	FC		
Table I-5	16. Configuration Management Plan [Baseline at SRR]	OCE				A	FC		
Table I-5	17. Security Plan [Baseline at PDR] [per NPD 1600.2 and NPRs 1600.1 & 1040.1]	OPS				A	T	Incorporated into Project Plan as opposed to stand alone document	23 May 17
Table I-5	18. Project Protection Plan [Baseline at PDR]	OCE				A	FC		

Table I-5	19. Technology Transfer (formerly Export) Control Plan [Baseline at PDR] [per NPR 2190.1]	OIIR				A	T	Incorporated into Project Plan, If launch(s) occur outside of US, technology transfer considerations will be reassessed	5/23/17
Table I-5	20. Lessons Learned Plan [Baseline at PDR] [per NPD 7120.4 and NPR 7120.6]	OCE				A	FC		
Table I-5	21. Human Rating Certification Package [Baseline at SDR/MDR] [per NPR 8705.2]	OSMA				A	N/A	Not a human rated mission	PWP 5/25/17
Table I-5	22. Planetary Protection Plan [Baseline at PDR] [per NPD 8020.7 and NPR 8020.12]	SMD				A	N/A	Not going to or bringing material from another planet	25 May 17
Table I-5	23. Nuclear Safety Launch Approval Plan [Baseline at SDR/MDR] [per NPR 8715.3]	OSMA				A	N/A	No radioactive material	PWP 5/25/17
Table I-5	24. Range Safety Risk Management Process Documentation [Baseline at SIR] [per NPR 8715.5]	OSMA				A	N/A	Not a launch or entry vehicle program	PWP 6/19/17
Table I-5	25. Education Plan [Baseline at PDR]	OE				A	N/A	No longer a SMD/agency requirement	5/25/17
Table I-5	26. Communications Plan [Baseline at PDR]	OComm				A	FC		
2.2.8	Projects in phases C and D (and programs at the discretion of the MDAA) with a life-cycle cost estimated to be greater than $20 million and Phase E project modifications, enhancements, or upgrades with an estimated development cost greater than $20 million shall perform earned value management (EVM) with an EVM system that complies with the guidelines in ANSI/EIA-748, Standard for Earned Value Management Systems.	OCE	X	A		A	T	EVM will be tailored to align with MIT/Lincoln Lab's approach and financial systems, while ensuring predictive performance reporting consistent with reporting provided under the AF contract used to implement the project	6/20/17
2.2.8.1	EVM system requirements shall be applied to appropriate suppliers, in accordance with the NASA Federal Acquisition Regulation (FAR)	OCE				A	FC		

	Supplement, and to in-house work elements.								
2.2.8.2	For projects requiring EVM, Mission Directorates shall conduct a pre-approval integrated baseline review as part of their preparations for KDP C to ensure that the project's work is properly linked with its cost, schedule, and risk and that the management processes are in place to conduct project-level EVM.	OCE		A		A	FC		
2.2.10	Each program and project shall complete and maintain a Compliance Matrix (see Appendix C) for this NPR and attach it to the Formulation Agreement for projects in Formulation and/or the Program or Project Plan. The program or project will use the Compliance Matrix to demonstrate how it is complying with the requirements of this document and verify the compliance of other responsible parties.	OCE	X			A	FC		
2.3.1	Each program and project shall have a Decision Authority who is the Agency's responsible individual who determines whether and how the program or project proceeds through the life cycle and the key program or project cost, schedule, and content parameters that govern the remaining life-cycle activities.	OCE	X	A			FC		
2.3.1.1	The NASA AA shall approve all Agency Baseline Commitments (ABCs) for programs requiring an ABC and projects with a life-cycle cost greater than $250 million.	OCE	X	A		A	N/A	Project LCC is less than $250M	
2.3.2	Each program and project shall have a governing PMC.	OCE	X	A			FC		
2.3.3	The Center Director (or designee) shall oversee programs and projects usually through the CMC, which monitors and evaluates all program and project work (regardless of category) executed at that Center.	OCE	X		A		FC		
2.3.4	Following each LCR, the independent SRB and the program or project shall brief the applicable management councils on the results of the LCR to support the councils' assessments.	OCE	X	A	A	A	FC		
2.4.1	After reviewing the supporting material and completing discussions with concerned parties, the Decision Authority determines whether and how the program or project proceeds into the next phase and approves any additional actions. These decisions shall be summarized and recorded in the Decision Memorandum signed at the conclusion of the governing PMC by all parties with supporting responsibilities, accepting their respective roles.	OCE	X	A			FC		

2.4.1.1	The Decision Memorandum shall describe the constraints and parameters within which the Agency, the program manager, and the project manager will operate; the extent to which changes in plans may be made without additional approval; any additional actions that came out of the KDP; and the supporting data (i.e., the cost and schedule datasheet) that provide further details.	OCE	X	A		A	FC		
2.4.1.2	A divergence from the Management Agreement that any party identifies as significant shall be accompanied by an amendment to the Decision Memorandum.	OCE	X	A		A	FC		
2.4.1.3	During Formulation, the Decision Memorandum shall establish a target life-cycle cost range (and schedule range, if applicable) as well as the Management Agreement addressing the schedule and resources required to complete Formulation.	OCE	X	A		A	FC		
2.4.1.5	All projects and single-project programs shall document the Agency's life-cycle cost estimate and other parameters in the Decision Memorandum for Implementation (KDP C), and this becomes the ABC.	OCE	X	A		A	FC		
2.4.1.6	Tightly coupled programs shall document their life-cycle cost estimate, in accordance with the life-cycle scope defined in the FAD or PCA, and other parameters in their Decision Memorandum and ABC at KDP I.	OCE	X	A		A	N/A	Project is not a Tightly Coupled Program	
2.4.1.7	Programs or projects shall be rebaselined when: (1) the estimated development cost exceeds the ABC development cost by 30 percent or more (for projects over $250 million, also that Congress has reauthorized the project); (2) the NASA AA judges that events external to the Agency make a rebaseline appropriate; or (3) the NASA AA judges that the program or project scope defined in the ABC has been changed or the tightly coupled program or project has been interrupted.	OCFO	X	A		A	FC		
2.4.2	All programs and projects develop cost estimates and planned schedules for the work to be performed in the current and following life-cycle phases (see Appendix I tables). As part of developing these estimates, the program or project shall document the basis of estimate (BOE) in retrievable program or project records.	OCE	X			A	FC		

2.4.3	Tightly coupled and single-project programs (regardless of life-cycle cost) and projects (with an estimated life-cycle cost greater than $250 million) shall develop probabilistic analyses of cost and schedule estimates to obtain a quantitative measure of the likelihood that the estimate will be met in accordance with the following requirements.	CAD	X			A	N/A	Project is not a Tightly Coupled or Single-Project Program	23 May 17
2.4.3.1	Tightly coupled and single-project programs (regardless of life-cycle cost) and projects (with an estimated life-cycle cost greater than $250 million) shall provide a range of cost and a range for schedule at KDP 0/KDP B, each range (with confidence levels identified for the low and high values of the range) established by a probabilistic analysis and based on identified resources and associated uncertainties by fiscal year.	CAD	X			A	N/A	Project is not a Tightly Coupled or Single-Project Program	23 May 17
2.4.3.2	At KDP I/KDP C, tightly coupled and single-project programs (regardless of life-cycle cost) and projects (with an estimated life-cycle cost greater than $250 million) shall develop a resource-loaded schedule and perform a risk-informed probabilistic analysis that produces a JCL.	CAD	X			A	N/A	Project is not a Tightly Coupled or Single-Project Program	23 May 17
2.4.4	Mission Directorates shall plan and budget tightly coupled and single-project programs (regardless of life-cycle cost) and projects (with an estimated life-cycle cost greater than $250 million) based on a 70 percent joint cost and schedule confidence level or as approved by the Decision Authority.	CAD	X	A			N/A	Project is not a Tightly Coupled or Single-Project Program	23 May 17
2.4.4.1	Any JCL approved by the Decision Authority at less than 70 percent shall be justified and documented.	CAD	X	A			FC		
2.4.4.2	Mission Directorates shall ensure funding for these projects is consistent with the Management Agreement and in no case less than the equivalent of a 50 percent JCL.	CAD	X	A			FC		
2.4.5	Loosely coupled and uncoupled programs are not required to develop program cost and schedule confidence levels. These programs shall provide analysis that provides a status of the program's risk posture that is presented to the governing PMC as each new project reaches KDP B and C or when a project's ABC is rebaselined.	OCE	X	A		A	N/A	Project is not a loosely coupled or uncoupled program	
3.3.1	Programs and projects shall follow the Technical Authority process established in Section 3.3 of this NPR.	OCE	X	A	A	A	FC		

3.4.1	Programs and projects shall follow the Dissenting Opinion process in this Section 3.4.	OCE	X	A	A	A	FC		
3.5.1	Programs and projects shall follow the tailoring process in this Section 3.5.	OCE	X	A	A	A	FC		
3.5.5	A request for a permanent change to a prescribed requirement in an Agency or Center document that is applicable to all programs and projects shall be submitted as a "change request" to the office responsible for the requirements policy document unless formally delegated elsewhere.	OCE	X	A	A	A	FC		
3.6.1	A Center negotiating reimbursable space flight work with another agency shall propose NPR 7120.5 as the basis by which it will perform the space flight work.	OCE	X		A	A	N/A	Project is not a reimbursable activity	
3.7.1	Each program and project shall perform and document an assessment to determine an approach that maximizes the use of SI.	OCE	X			A	FC		