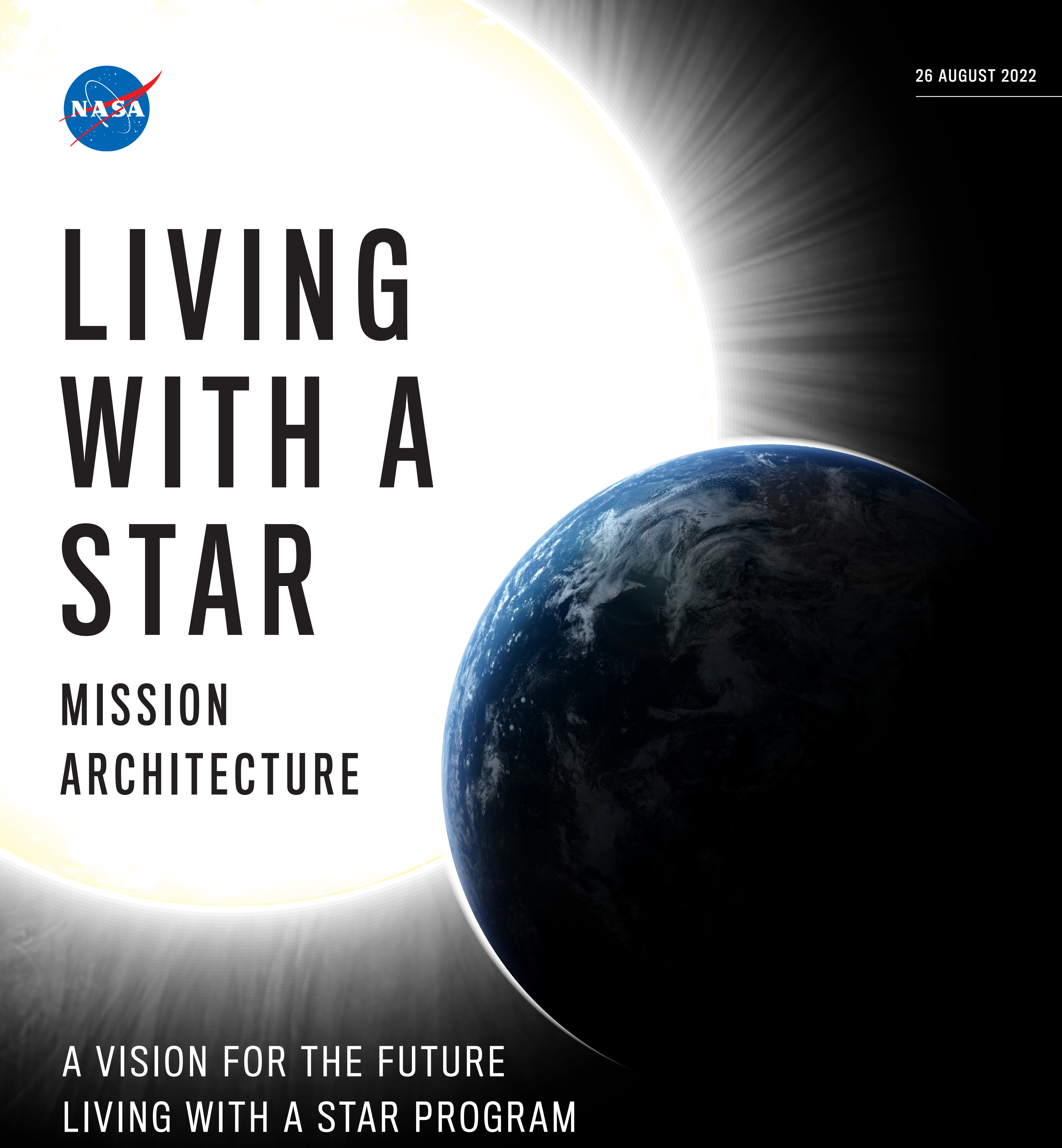
26 AUGUST 2022



LIVING WITH A STAR

MISSION ARCHITECTURE

A VISION FOR THE FUTURE LIVING WITH A STAR PROGRAM

LWS ARCHITECTURE COMMITTEE

C. M. S. Cohen, T. Berger, M. I. Desai, N. Duncan, G. C. Ho, N. Maruyama, T. Pulkkinen, A. Szabo, A. Vourlidas, E. Zesta, Y. Zhang

California Institute of Technology, University of Colorado, Southwest Research Institute, Ball Aerospace, Johns Hopkins Applied Physics Laboratory, University of Michigan, Goddard Space Flight Center

Living With a Star Architecture Committee Report for the NASA Heliophysics Division

An Architecture Recommendation for NASA's Living With a Star Program

26 August 2022

Table of Contents

List of Figures and Tables

List of Figures

List of Tables

1. Committee Roster and Acknowledgments

1.1. Committee Roster

George Ho
Program Manager
Johns Hopkins Applied Physics Laboratory

Christina Cohen
Chair
California Institute of Technology

Jeff Morrill
Ex Officio
NASA Headquarters

Elsayed Talaat
Ex Officio
NOAA/National Environmental Satellite Data and Information Service (NESDIS)

Simon Plunkett
Ex Officio
NASA Headquarters

Thomas Berger
University of Colorado

Mihir Desai
Southwest Research Institute

Nicole Duncan
Ball Aerospace

Naomi Maruyama
University of Colorado

Tuija Pulkkinen
University of Michigan

Adam Szabo
NASA Goddard Space Flight Center

Angelos Vourlidas
Johns Hopkins Applied Physics Laboratory

Eftyhia Zesta
NASA Goddard Space Flight Center

Yongliang Zhang
Johns Hopkins Applied Physics Laboratory

1.2. Acknowledgments

The committee thanks external experts and reviewers for their valuable input, significantly improving this report: Scott Bailey, Anthea Coster, Heather Elliott, Jerry Goldstein, Allison Jaynes, Jeff Klenzing, Noé Lugaz, Robert Marshall, Paul O’Brien, Robert Pfaff, Cora Randall, Sabrina Savage, Harlan Spence, and Drew Turner.

2. Executive Summary

The Living With a Star (LWS) Architecture Committee is a 10-member committee of experts from the broader heliophysics science community. It was formed at the request of NASA's Heliophysics Division to (1) assess the current LWS mission line and (2) recommend a future mission architecture to further the goals of the LWS program. The committee formulated a set of 12 Focused Mission Topics (FMTs) that together make up a mission architecture that provides the scientific observations needed to make significant advancements on the LWS Strategic Science Area (SSA) goals and related objectives.

FMTs are mission analogs to the Focused Science Topics (FSTs) used in the LWS Targeted Research and Technology (TR&T) program (Figure 3-2). As such, they should be periodically reviewed and realigned with any changes made to the SSAs. The current list of SSAs was finalized in 2019; since then, many aspects of space weather science have evolved rapidly and may not be adequately captured in the SSAs and, thus, may not be reflected in the FMTs. Similarly, not all of the results from the recent NASA Space Weather Gap Analysis are included. The committee strove to identify at least one FMT for each SSA, and many FMTs address components of more than one SSA. However, there are objectives of some SSAs that are not addressed by any FMT; in some cases, there are missions in formulation that target those aspects; in other cases, new observations are not required.

Given the numerous implementation options, the committee used the following criteria to compile the final list of 12 FMTs (Table 6-1):

- Cover as many orbit types as possible, from low Earth orbit (LEO) to deep space, without replicating past studies.
- Approach the SSAs as a system. Maximize the "SSA-to-FMT" ratio by choosing FMTs with relevance to multiple SSAs.
- Lean "forward" and consider implementations that drive technological developments while closing long-standing LWS knowledge gaps.
- Take into account commercial space, the rising availability of rideshares, and the miniaturization of spacecraft and instruments to create a "future-proof" architecture for LWS.

The committee solicited specific input from experts in the community regarding specific science aspects related to the FMTs, and there were several opportunities for the heliophysics community to provide feedback and comments to the committee during the process.

Because each FMT was developed somewhat independently (primarily flowing from the goals/objectives of the individual SSAs), during the process, the committee reviewed the combined set of FMTs to identify (and subsequently address) any significant architectural gaps. Taken as a whole, the final set of 12 FMTs describes a mission architecture that has a breadth of orbits and diversity of platforms that promise significant scientific return focused on LWS goals (Figure 6-1). The diversity of the architecture also provides NASA with the flexibility needed to adapt to the rapid changes occurring in space weather science priorities. To aid in this flexibility, the committee did not rank or prioritize the FMTs because selections/order should include timely consideration of a variety of factors such as launch opportunities, recent technological advancements, relative importance/priority of desired improvements in predictive capabilities, synergies with existing missions, and cooperative opportunities with other directorates and agencies.

Seven of the mission concepts were studied by the design centers at APL and GSFC (at the trade study level only), three were studied at a higher level (leaving spacecraft design and other details for future studies), and two were leveraged from concurrent Solar Terrestrial Probes (STP) mission studies. Which concepts were sent to the design centers was primarily driven by time constraints and suitability and should not be taken as an indication of priority. It is important to stress that these concepts are concrete examples but not the only means by which an FMT can be addressed. The committee envisions that a process similar to the FST announcement of opportunities would be used for the FMTs, where example implementations are given but the scientific community is free to propose their own visions.

Quad charts for each of the FMTs providing a summary of the mission concepts, which SSAs are addressed, and why it is an FMT are included in the report and can be downloaded/viewed here. Specific recommendations for technology development were identified for the individual FMTs but also collected in Table 7-1. All of the concepts involve constellations and are at the nominal Class C mission level. Although the committee did not a priori restrict concepts based on either size (e.g., flagship versus Explorer versus SmallSat/CubeSat) or type (e.g., single versus multiple spacecraft), the result suggests a “sweet spot” regarding cost versus science return, particularly for the type of system science identified in the SSA goals. Similarly, advancement in the understanding of the different aspects of the “system of systems” that comprises LWS science requires multipoint measurements that are best addressed by constellations. An additional benefit of constellations is the flexibility of deploying individual elements over time, allowing overlaps with existing missions to realize additional science and achieving effective long-term science with shorter-lifetime systems.

Finally, it was outside the scope of the committee to examine and include the architectural roles of data buys and data streams from non-NASA assets, including ground-based assets such as those managed by the National Science Foundation (NSF). However, it is clear that these would be useful (and in some cases critical) additions to the proposed architecture and should be considered where possible. Similarly, models were not addressed, because they fall under the purview of the TR&T and the other research and analysis programs, but should be viewed as a vital component of a “complete” science architecture. The committee would also like to stress that the science realized from any proposed architecture is only as good as the support given to the data analysis required to create scientifically useful data sets and to the infrastructure needed to make those products accessible to the broader scientific community.

3. The LWS Program and Charge to the Committee

The goal of the LWS program is to further scientific understanding of the complex Sun–Earth system and those aspects of it that affect life and society, in order to enable quantitative predictive capability for a variety of space weather phenomena. The 2015 LWS 10-year vision report (http://lwstrt.gsfc.nasa.gov/images/pdf/LWS_10YrVision_Oct2015_Final.pdf) lists four strategic goals:

1. Deliver the understanding and modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth, Moon, Mars and throughout the solar system.

2. Develop a fuller understanding of how and to what degree variations in the Sun's radiative and particulate outputs will in conjunction with other forcing factors affect regional and global climate in the present century.

3. Deliver the understanding and modeling required for effective forecasting specification of magnetospheric radiation and plasma environments.

4. Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below.

The program consists of a well-developed research program, Targeted Research and Technology (TR&T), and a mission line that "[obtains] the measurements needed to further understanding" (NASA, 2015 LWS 10-year vision report). In 2015, the LWS Steering Committee identified SSAs that focused on system science and provided a long-term vision for the research goals. The SSAs also created structure and focus for the more immediate research efforts. In 2017, the LWS Steering Committee was replaced with the Living With a Star Program Analysis Group (LPAG); this group reviewed, updated, and expanded the list of SSAs in 2019 to create the current list of 10 (Table 3-1).

Table 3-1. LWS Strategic Science Areas as of 2019.

SSA-I	Origins and Variability of Global Solar Processes
SSA-II	Solar Eruptive and Transient Heliospheric Phenomena
SSA-III	Acceleration and Transport of Energetic Particles in the Heliosphere
SSA-IV	Variability of the Geomagnetic Environment
SSA-V	Dynamics of the Global Ionosphere and Plasmasphere
SSA-VI	Ionospheric Irregularities
SSA-VII	Composition and Energetics of the Neutral Upper Atmosphere
SSA-VIII	Radiation and Particle Environment from Near Earth to Deep Space
SSA-IX	Solar Impacts on Climate
SSA-X	Stellar Impacts on Planetary Habitability

The scientific purview of the LWS program significantly overlaps and connects with other NASA Science Divisions (Planetary Science, Astrophysics, Earth Science), aspects of the Exploration Systems Development Mission Directorate, and Heliophysics' Space Weather and STP programs (Figure 3-1). While the SSAs provided clarity regarding the goals and objectives of the research portion of the LWS program, the mission line side remained more opaque. Many scientific measurements of the Sun–Earth system that are needed to advance space weather predictive capability are the same as those required for basic scientific study of the heliosphere, making a clean separation at the mission level between the LWS and STP programs particularly difficult.

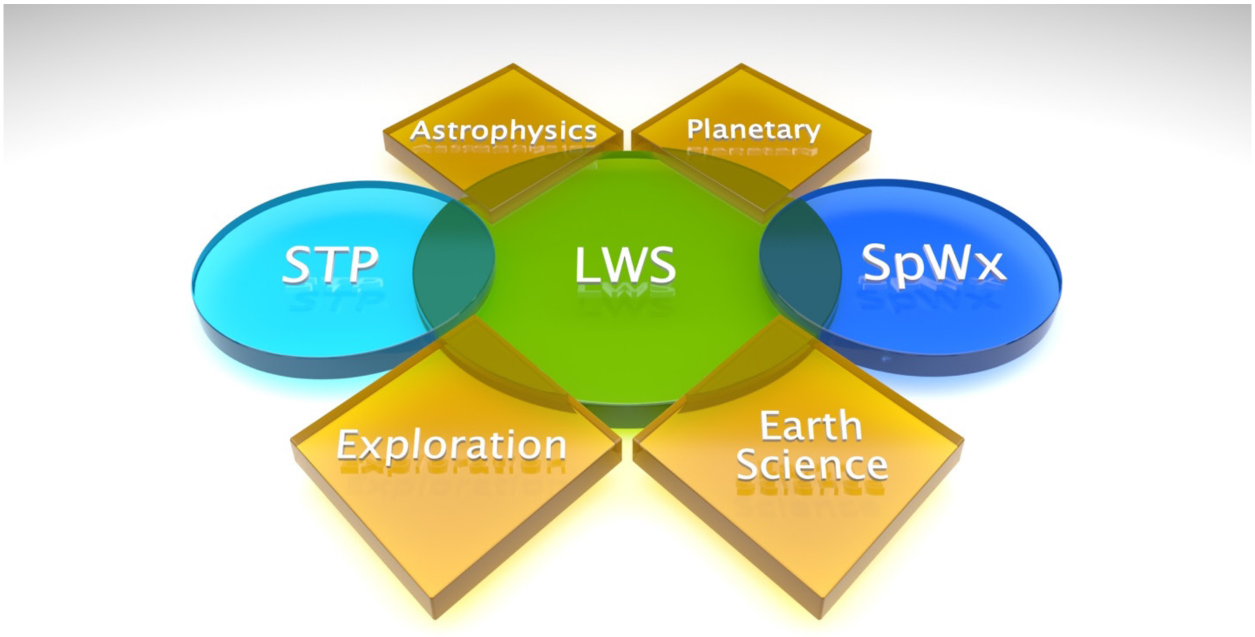


Figure 3-1. LWS science overlaps that of the STP and Space Weather Heliophysics' programs as well as intersecting with several NASA Science Divisions and the Exploration Systems Development Mission Directorate.

The 2013 Decadal Survey Midterm Assessment recommended that distinctions be made between the science goals and implementation strategies of the STP and LWS programs. In response, the Heliophysics Division (HPD) has examined the two programs and identified the following primary distinction: The STP program focuses on "broad-based advance of heliophysics" with "missions that address general knowledge gaps that inhibit advancement of the entire scientific field" (Leisner, 2020). The LWS program focuses on "specific knowledge gaps relevant to life and society" (Leisner, 2020) and a mission line that addresses knowledge gaps that fall within the defined SSAs.

A 10-member committee of experts taken from the broader heliophysics science community was formed to (1) assess the current LWS mission line and (2) recommend a future mission architecture designed to further the goals of the LWS program. The committee was instructed not to reevaluate the LWS science or the SSAs. With guidance from HPD, the committee used the SSAs to form FMTs. These are mission analogs to the FSTs that are routinely identified by the LPAG to focus modeling and data analysis efforts on specific topics that advance the SSA goals (Figure 3-2).

Similar to FSTs, the set of FMTs should be reviewed periodically (whether by LPAG or by a new LWS committee remains to be determined) to revise, expand, or reduce the set as appropriate to flow from the SSAs and their predictive goals. Just as the FSTs do not prescribe the form and type of research, leaving that to the scientific community responding to the announcement of opportunity, the FMTs describe mission topics that can be fulfilled via myriad mission/instrumentation concepts to be proposed by the scientific community. For each FMT, the committee constructed concrete example concepts (summarized in Section 6 and given in more detail in Section 8), but these are not the only, or perhaps even the best, way of addressing the FMTs.

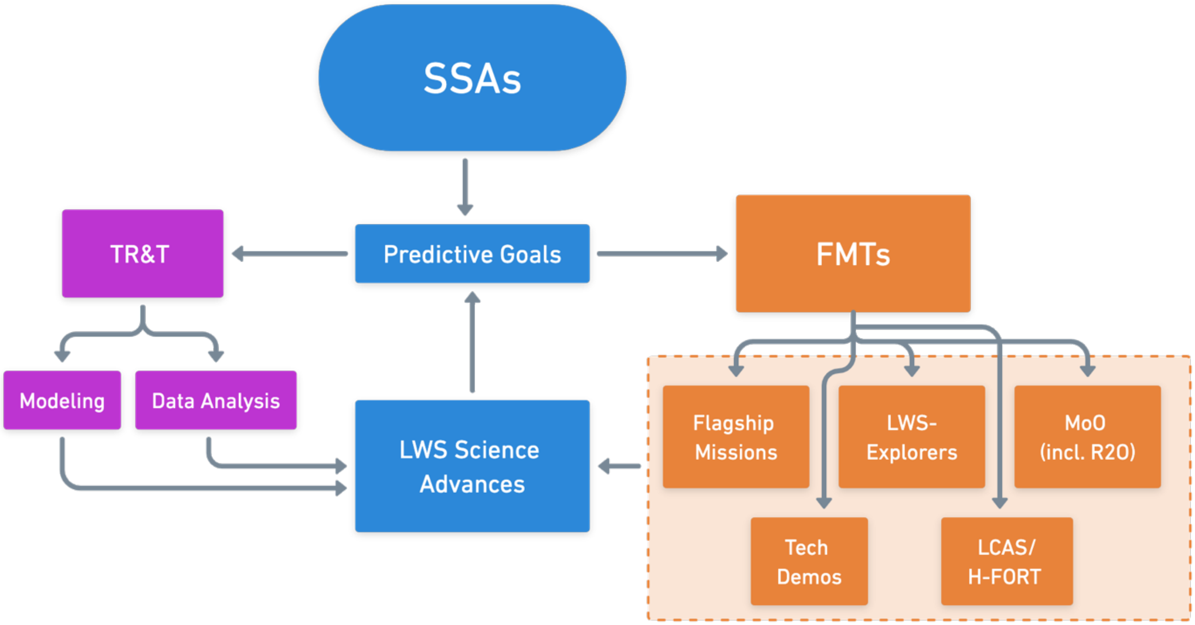


Figure 3-2. Flow chart illustrating the parallel relationship between the TR&T topics and FMTs. Both flow from the SSAs through the SSA Predictive Goals and subsequently flow down to modeling and analysis efforts (for TR&T) or specific mission designs (for FMTs). An FMT can be implemented within a variety of existing NASA programs, examples of which are indicated by the orange boxes. H-FORT, Heliophysics Flight Opportunities in Research and Technology; LCAS, Low Cost Access to Space; MoO, Mission of Opportunity.

4. The Process

The committee had a kickoff meeting on 25 February 2021 with HPD representatives. Because of travel restrictions, all meetings have been virtual, via Zoom, and occurred biweekly through July 2022. These meetings were recorded and shared with the committee as a record of the work and for those members who were unable to attend a given meeting. A shared folder on Google Drive was created to capture and share material.

The committee started with a review of the SSAs as described in the 2019 LPAG report. Committee members formed four subgroups (Solar/Heliosphere, Geospace, Energetic Particles, and Neutral Atmosphere), and each SSA was assigned to one of the four groups (Table 4-1). The subgroups created a spreadsheet for each SSA in which science objectives were identified from the SSA-stated goals and predictive goals. For each objective, a flow-down was created to specify Measures of Success, Measurement Strategy, Physical Parameters, Required Measurements, Envisioned Implementation, and Required Technology/Modeling Development. These were discussed and reviewed by the full committee before inviting comments/input from the general heliophysics community.

Table 4-1. SSA grouping and subcommittee assignments.

Group	SSA	Lead	Subcommittee
1. Solar/ Heliosphere	SSA-I: Origins and Variability of Global Solar Processes	Berger	Berger Vourlidas Szabo Duncan
	SSA-II: Solar Eruptive and Transient Heliospheric Phenomena	Szabo/ Vourlidas	
2. Geospace	SSA-IV: Variability of the Geomagnetic Environment	Pulkkinen/ Zesta	Zhang Maruyama Zesta Pulkkinen Duncan Berger (VI)
	SSA-V: Dynamics of the Global Ionosphere and Plasmasphere	Maruyama	
	SSA-VI: Ionospheric Irregularities	Zhang	
3. Energetic Particles	SSA-III: Acceleration and Transport of Energetic Particles in the Heliosphere	Cohen	Cohen Desai Ho Duncan Szabo
	SSA-VIII: Radiation and Particle Environment from Near Earth to Deep Space	Desai	
4. Neutral Atmosphere	SSA-VII: Composition and Energetics of the Neutral Upper Atmosphere	Zhang/Berger	Duncan Vourlidas Berger Zhang Maruyama Zesta (VII)
	SSA-IX: Solar Impacts on Climate	Vourlidas/ Maruyama	
	SSA-X: Stellar Impacts on Planetary Habitability	Zesta	

The community input was obtained through forms hosted on the LWS Architecture Committee website created by APL (https://lws-ac.jhuapl.edu). The website briefly describes the study and committee and presents the list of 10 SSAs, organized by group; a “contact us” email link is provided as well. During the period when community input was gathered, each SSA listing was an active link that took users to a form for comments. The forms presented a brief executive summary of the SSA and listed the predictive goals followed by the committee-created science objectives. For each objective, the measurement strategy, physical parameters, requirement measurements, and envisioned implementation were described, and the user was given the opportunity to comment on each piece. A space for additional comments was also provided at the end of the form. The user’s name and email address were captured in case clarification was desired later.

The webpage and forms were advertised in all the standard community newsletters (e.g., Space Physics and Aeronomy Section News associated with the American Geophysical Union; Solar, Heliosphere and INterplanetary Environment [SHINE]/Geospace Environment Modeling [GEM]/Coupling, Energetics, and Dynamics of Atmospheric Regions [CEDAR] associated with NSF) as well as presented at the Heliophysics 2050 and CEDAR workshops. Community input was accepted from 8 August to 1 September 2021. A total of 50 comments were collected over this period and discussed by the committee. In addition to the community comments, the committee discussed overlaps in measurement strategies and envisioned implementations. From these spreadsheets and related discussions, FMTs were created with specific science objectives and initial envisioned implementations. For those implementations that were not “straightforward” (i.e., orbits/constellations that have been used by NASA in the past), the FMT concepts were presented to the mission design centers (APL/APL Concurrent Engineering Lab. and GSFC/Mission Design Lab) that provided support to the committee for further study (the full reports with proprietary costing will be provided to NASA directly). The order in which the FMTs were studied was primarily determined by when an FMT was suitably scoped to be presented to the design center. Unfortunately, because of time limitations, not all the FMT concepts were studied by ACE Lab or MDL; however, no implied priority should be inferred from this.

On 19 January 2022, the current status of the committee’s work was presented at the LWS town hall (held virtually). Community input was accepted verbally and via “chat” during this event and could be submitted afterward via email. In addition, at various times during the formulation of the FMTs, community experts on particular scientific aspects were invited to present information to the committee and answer relevant questions or were queried via email.

After the initial set of FMTs was identified, the committee was again separated into subgroups. This was done by considering the intersection of orbits and study targets (see Table 4-2) and specific committee member expertise. The subgroups were then tasked with reviewing the FMTs that fell into their assigned orbit grouping to identify and quantify any existing scientific gaps. From that examination, a few additional FMTs were developed to ensure a more complete architecture. The full list of FMTs is given in Table 6-1, and each one is described in Section 6.

Table 4-2. Subcommittee assignments based on orbits and target objects.

	Target Object					
Orbits	**Sun**	**Solar Wind**	**Outer Magnetosphere**	**Inner Magnetosphere**	**IT System**	**Study Group (lead in bold)**
Heliosphere (not Earth-bound orbits)	yes	yes				Group 1: **Cohen**, Ho, Desai, Vourlidas, Szabo, Duncan, Pulkkinen (magnetosphere remote sensing)
Solar wind/outer magnetosphere (Earth-bound orbits)	yes	partly	partly			
Outer magnetosphere/ magnetotail orbits		partly	yes	partly		Group 2: **Pulkkinen, Zesta**, Berger (radiation belts), Szabo (solar wind), Duncan, Maruyama
Inner magnetosphere orbits				yes	partly	
Low-altitude orbits	yes		yes	yes	yes	Group 3: **Maruyama, Zhang**, Duncan, Vourlidas (solar), Berger (thermosphere), Zesta (precipitation)
Scientific expertise	Cohen, Ho, Desai, Vourlidas, Szabo, Berger, Duncan		Pulkkinen, Zesta (Berger)		Maruyama, Zhang (Duncan, Zesta)	

Although the committee made an effort to create an FMT for at least one portion of every SSA, some aspects of individual SSAs are not addressed by any FMT. In some cases, this was due to the SSA objectives being primarily addressed by a mission already in formulation. For example, Geospace Dynamics Constellation (GDC) will fly at 350–400 km near or above the ionospheric F-region peak to obtain simultaneous measurements of ions and neutrals to study the ion–neutral interaction processes. This addresses many of the ionospheric portions of the SSA-V goals, including those related to total electron content. The remaining goal of understanding the connection between the ionosphere and plasmasphere and the role of cold plasma is subsequently addressed within the formulated FMTs.

In other cases, progress on predictive capability largely relies on improved modeling efforts and use of existing data. For example, the portion of SSA-VIII related to characterizing/predicting the contribution of galactic cosmic rays (GCRs) to the radiation environment does not require a mission concept focused on GCR measurements but rather an investment in combining the existing spacecraft and ground-based measurements along with modeling of the particle propagation through the Earth's magnetosphere/atmosphere. Thus, the FMTs focus on other aspects of SSA-VIII.

Finally, this report does not address the role of ground-based facilities in the overall architecture. Naturally there are some SSA goals that would be either best addressed by or significantly augmented by such facilities, but because they are generally outside the purview of NASA, they are not included in the proposed architecture. Similarly, the role of monitoring missions was viewed to be primarily under NOAA's jurisdiction; therefore, such missions are not included. Whether some element of a given FMT could be used for monitoring is a consideration that fell outside the scope of this report but certainly should be considered by NASA (preferably with input from NOAA) when making mission selections. It should also be mentioned that realizing the full potential of any mission architecture requires data analysis and modeling efforts as well as the acquisition, storage, and dissemination of the observations. Although the report does not address these aspects, they should be considered part of a more complete "science architecture" and not be neglected in the financial planning for any mission.

5. Assessment of the Current State of the LWS Architecture

While the work of the LPAG has resulted in a set of SSAs that are well scoped, well defined and periodically revised, the LWS mission line appears less well planned. As indicated in the Decadal Survey Midterm Assessment, the distinction between LWS missions and STP missions has not been particularly successful. The original distinction between the two programs led to a tendency for LWS missions to be larger than those of STP; however, this imposes a limitation on the diversity of the LWS mission architecture that may unnecessarily constrain the mechanisms for obtaining LWS-related observations. To best serve the observational needs of the LWS program, a coherent vision of a complete architecture is needed—one that encompasses a variety of spacecraft sizes and configurations. While the current fleet of LWS missions is making significant advances in our understanding of energy and momentum flow from the Sun to the geospace system, significant gaps remain (as indicated by the SSAs) in our understanding of space weather. Solar Dynamics Observatory (SDO), Parker Solar Probe, and Solar Orbiter are providing new insights into the connection of the inner heliosphere and the solar corona; the observations of the Van Allan Probes led to new understanding of the formation and energization of the radiation belts; and GDC promises to reveal how energy and momentum are deposited into the ionosphere/thermosphere system. As the SSAs outline, after these first steps, a number of key science questions related to space weather could be answered with a properly constructed next generation of LWS missions. This report aims to identify possible mission concepts that would allow NASA to take these next steps.

6. Focused Mission Topic (FMT) Summaries

The FMTs represent a new mission architecture concept, first introduced in this report. The FMT definition and the role of FMTs within the LWS framework are discussed in Section 3. In this section, we present summaries of the 12 FMTs considered by the committee, highlighting the relevance to the LWS objectives and why it is an FMT, and ending with a discussion of the connections between FMTs and SSAs, demonstrating the cross-cutting nature and programmatic utility of FMTs.

6.1. Overview

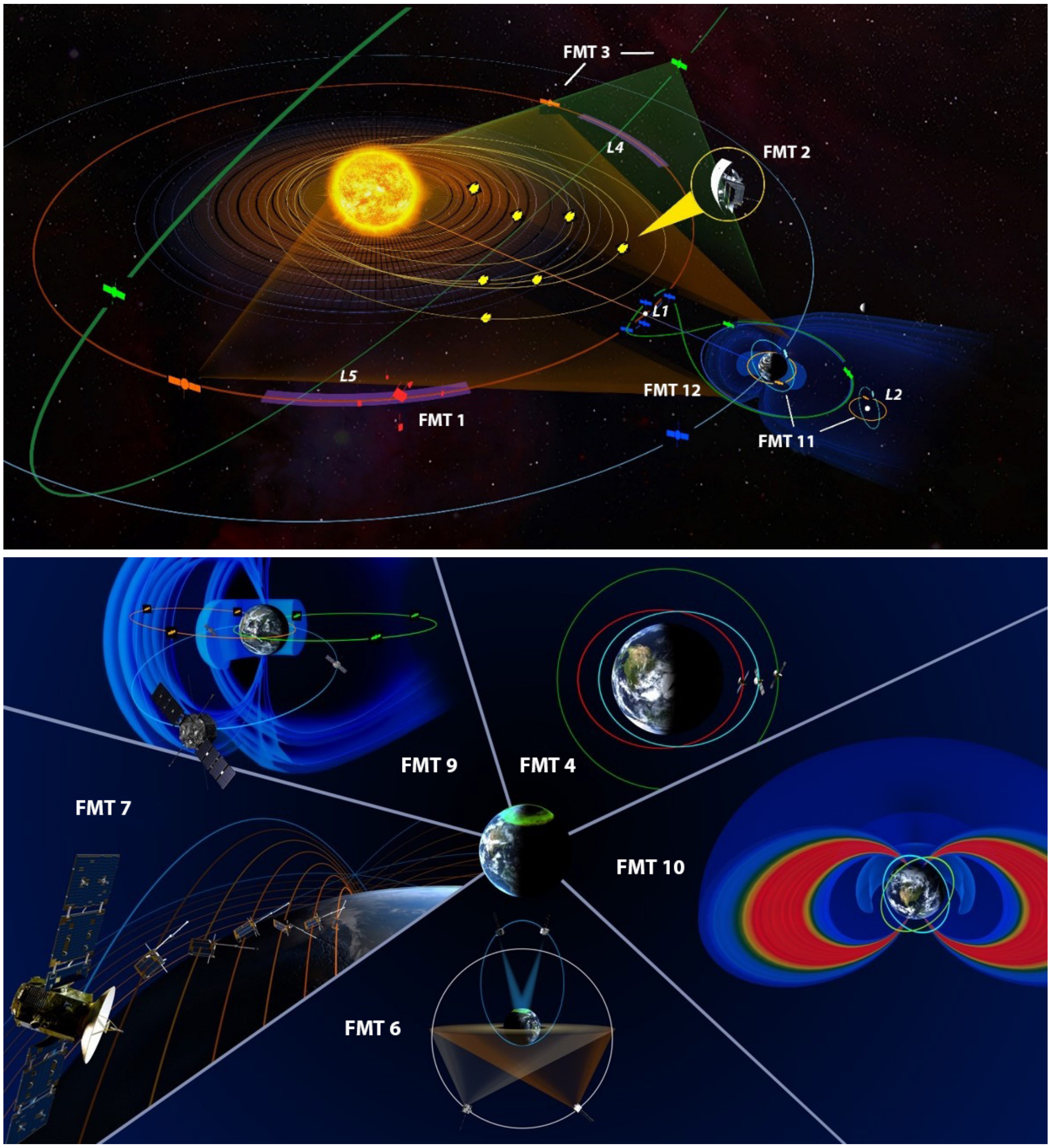


Figure 6-1. Graphical overview of the FMTs designed and studied for this report. (Top) Summary of the deep-space FMTs. (Bottom) Summary of the geospace FMTs. Each FMT is described in detail in the following sections.

The committee strove to define at least one FMT directly relevant to each SSA. However, because of organizational and time constraints, only seven concepts were studied in the GSFC/MDL and APL/ACE Lab mission design centers. Three concepts were formulated at a higher level, leaving spacecraft design and other details for possible future studies. The committee also leveraged the STP mission studies performed concurrently under the Heliophysics Mission Concept Studies (HMCS) program, for those concepts deemed particularly relevant to LWS objectives. The final list includes 12 FMTs, summarized in Table 6-1 and visually depicted in Figure 6-1.

Similar to the Astrophysics Decadal studies, the FMT mission design studies were constrained to Concept Maturity Level (CML) 3 (trade study level) and not the more common CML 4 (point design level) used for designing specific missions. Each FMT was formulated as a mission with top-level science objectives to define a flow-down to a payload and hence to bound the trade space for spacecraft size, operations, and other resources. The committee supplied key mission drivers, representative instrument parameters (size, weight, power, data), and architecture needs to the ACE and MDL teams to form the inputs for study. Engineers from the development teams refined the concept maturity of the FMTs based on additional discussion with LWS Architecture Committee members as part of the design process, as is typical for these labs. Although specifying nominal payloads/instrumentation was required for the studies, it is not the intent of this report to recommend payloads for the mission concepts. It is expected that the relevant payload discussions/considerations would be made after a particular FMT is selected for development.

The design centers required acronyms for the concepts being studied. Thus, for uniformity as well as ease and clarity of communication, each FMT mission concept has an associated acronym. It should be made clear that these names do not represent specific missions, nor are the detailed concepts presented in Section 8 the only ones that can fulfill the goals of the FMTs. They are presented as concrete examples to elucidate multiple aspects of the FMTs.

Table 6-1. Summary of the FMTs developed in this report.

FMT	Concept Name	Design Center	Primary Target
1	Sun-Earth Line Observing System	MDL	Solar-Heliospheric
2	Multi-Spacecraft System to Observe the Dynamics of the Inner Heliosphere	ACE Lab	Solar-Heliospheric
3	Origins of Space Weather	HMCS-based	Solar-Heliospheric
4	Geospace Observing System	MDL	Geospace
5	Magnetospheric Constellation	HMCS-based	Geospace
6	Magnetotail and Inner Magnetosphere Mission	MDL	Geospace
7	Low-Earth-Orbit Constellation for Ionosphere/Thermosphere/ Mesosphere System Observations	MDL	Geospace
8	The Cold Plasma Cycle	---	Geospace

FMT	Concept Name	Design Center	Primary Target
9	Inner Magnetosphere and Radiation Belts Mission	ACE Lab	Geospace
10	Solar Impacts on Climate	---	Solar-Geospace-Earth
11	Earth as an Exoplanet	---	Geospace-Astrophysics
12	PeriGeospace Observing System	ACE Lab orbit only	Solar-Heliospheric-Geospace

All the FMT concepts are nominally Class C at the mission level, with deviations to more stringent assurance requirements (e.g., Class C+) for longer or more complicated architectures. The recommended Class C/C+ designation was largely a result of the practical desire to leverage advancements in the launch industry to manifest multiple spacecraft on a single launch. This approach maintains the desire for missions of national priority and provides the opportunity to include more independent observatory elements by reducing the cost of their launch. For most architectures, the FMT specifies multiple flight elements on the same launch but intends for them to be the primary payloads and not secondary rideshares.

The FMT studies were not fully evaluated against Class C assurance requirements for their mission-unique elements under NPR 8105.4. This practice is typical for this phase of mission development, and consideration of these factors in the next phases of development can drive technical, schedule, and cost changes. The mission-unique elements that were deferred to later study but could be potential drivers include lifetimes >3 years, deep-space environments, radiation, constellation approach to sparing, CubeSat reliability, magnetic cleanliness, and environment requirements for ESPA (EELV [Evolved Expendable Launch Vehicle] Secondary Payload Adapter)-type launches. For the purposes of this report, it was assumed that a Class C constellation can be composed of individual observatories that meet Class D requirements.

FMTs that completed studies focused on either development toward a point solution or resolution of architecture trades, resulting in some differences between level of detail and development between reports. FMTs that went to the MDL (FMT-1, FMT-4, FMT-6, and FMT-7) focused on developing point solutions with greater technical detail in the flight dynamics and spacecraft. In these studies, architecture drivers were considered as frozen inputs and the FMT reports identify candidate architecture trades that should be considered in future development. Because the MDL was constrained to be conducted over a fixed 1-week period, constellation missions were simplified by considering development of a single observatory. This meant that for FMTs whose constellations consisted of different observational needs (and potentially different spacecraft), the driving requirements from each observatory were combined to create a general-purpose observatory that was baselined for each element. This resulted in efficiencies in the spacecraft costing and schedule for identical copies, but future studies should conduct a trade to determine whether this is the optimal solution given the needs of each different observatory and launch segment. FMTs that went to the ACE Lab (FMT-2, FMT-9, and FMT-12) focused on concept development and identified key architecture trades for detailed study. These studies resulted in FMTs that provide more detailed architecture trades but can be less detailed in the overall observatory solutions. Overall, the FMT studies provide excellent insights into the feasibility and cost of these architectures, while maintaining flexibility to tailor the architectures to numerous specific science cases in the next phases of development.

Given the numerous implementation options, the committee used the following criteria to compile the final FMT list:

- Cover as many orbit types as possible, from LEO to deep space, without replicating past studies.
- Approach the SSAs as a system. Maximize the “SSA-to-FMT” ratio by choosing FMTs with relevance to multiple SSAs (see Section 6.14 and Figure 6-2).
- Lean “forward” and consider implementations that drive technological developments while closing long-standing LWS knowledge gaps.
- Take into account commercial space, the rising availability of rideshares, and the miniaturization of spacecraft and instruments to create a “future-proof” architecture for LWS.

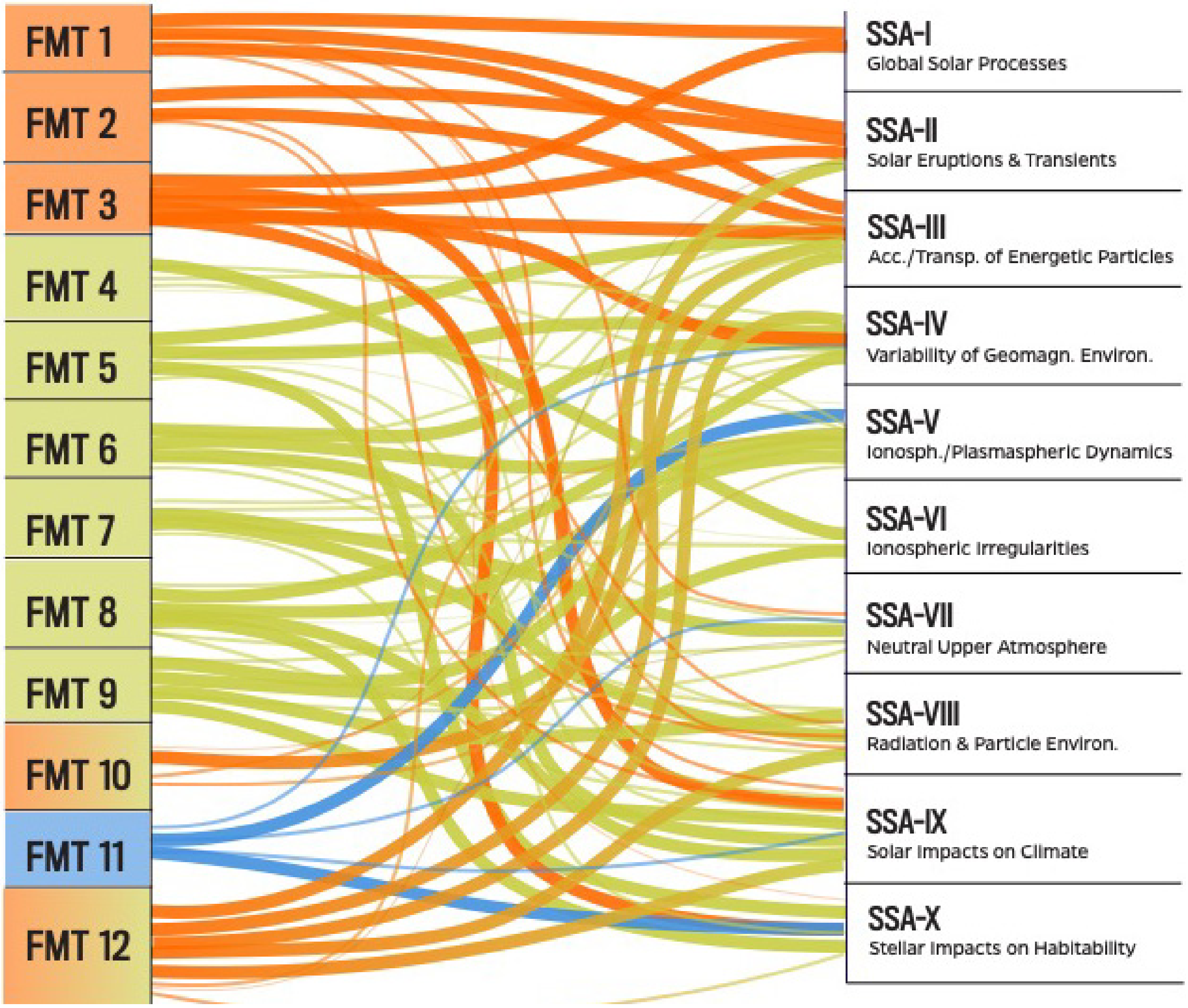


Figure 6-2. Mapping of the FMTs to the SSAs illustrates that most FMTs contribute to more than one SSA. Thick connection lines indicate direct contributions; thin lines indicate indirect contributions.

6.2. FMT-1: Sun-Earth Line Observing System

Study performed at GSFC Mission Design Laboratory

Concept Summary

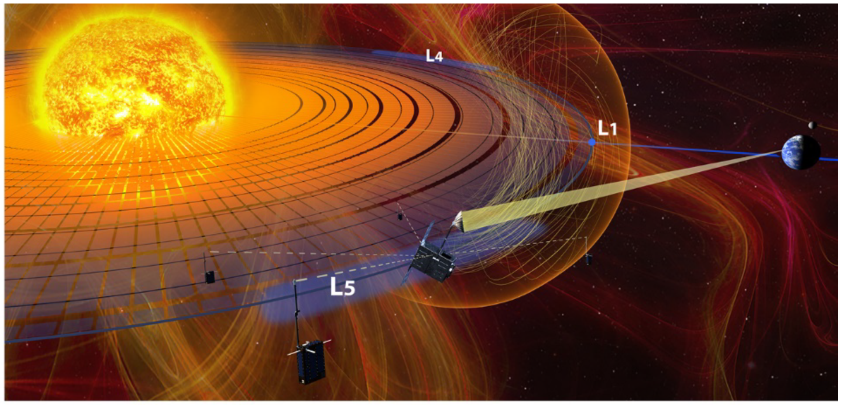
- **Science Objective:** To understand the life cycle of solar eruptive activity from initiation (magnetic field emergence) to formation (3D reconstruction of pre-eruptive coronal magnetic topology) to propagation (two-viewpoint imaging of transients > 0.5 AU to interaction (ambient heliosphere state)
- **Design Philosophy:** Cover activity over >180° of the solar surface and across more than two-thirds of the Sun–Earth Line with an adaptable rideshare-based mission architecture
- **Design Approach:** The mission employs a "hub–spoke" systems architecture
  - Two observatory nodes in orbits around the Sun–Earth L4 and L5 points
  - Each node is composed of an ESPA-class three-axis-stabilized spacecraft (hub) with up to four 8U CubeSats (spokes) spinning or three-axis stabilized, as required
  - Disaggregated design: remote sensing payloads reside on the hub, spokes carry in situ instrumentation; the hub acts as the "ground station" for the spokes. All uplinks/downlinks are executed via the hub.
  - 6-year mission; ESPA-compatible spacecraft; single rideshare launch; Class C+

LWS SSAs Addressed

- Directly: **SSA-I** (Origins and Variability of Global Solar Processes), **SSA-II** (Solar Eruptive and Transient Heliospheric Phenomena), **SSA-III** (Acceleration and Transport of Energetic Particles in the Heliosphere)
- Indirectly: **SSA-VII** (Composition and Energetics of the Neutral Upper Atmosphere), **SSA-IX** (Solar Impacts on Climate)

Required Technology Development

- Deep-space CubeSats (propulsion, guidance, subsystem reliability)
- Deep-space CubeSat delivery system
- Inter-spacecraft communication design/operations
- Onboard autonomy



Why Is It an FMT?

- Architecture concepts are relevant for a variety of missions. For example:
  - The "hub–spoke" architecture can be deployed in various locations in the heliosphere or peri-geospace, as either a single grid or multiple grids to satisfy different LWS science objectives.
  - The spoke deployment system can be used in a variety of spacecraft classes (ESPA and above) and environments (from low Earth orbit to deep space).
  - The ESPA-class design of the node enables a wide range of launch options.
  - The networked approach of the hub + spokes design drives a number of technology developments (e.g., inter-spacecraft communications, onboard autonomy).
  - The disaggregated approach offers programmatic flexibility and science/operations resiliency.
- Examples of mission variants based on the architecture:
  - String-of-pearls along 1-AU orbit to L4/5 point; a third node at L1 or at Mars L1; an L1 diamond with three to four nodes; drifter nodes toward the L4/5 point

The overarching science objective of FMT-1 is to understand the life cycle of solar eruptive activity, *from the energy buildup and initiation* (via measurements of magnetic field emergence in the photosphere and energy accumulation in the corona), *to energy release and formation of the ejecta* (via 3D reconstruction of pre-eruptive and eruptive coronal magnetic field topologies), *to propagation and ambient interactions in the corona and heliosphere* (via two-viewpoint imaging of solar transients [coronal mass ejections [CMEs], shocks, and stream interaction regions]) > 0.5 AU. The concept is summarized in Figure 6-3. Section 8.1.1 presents details from the MDL study.

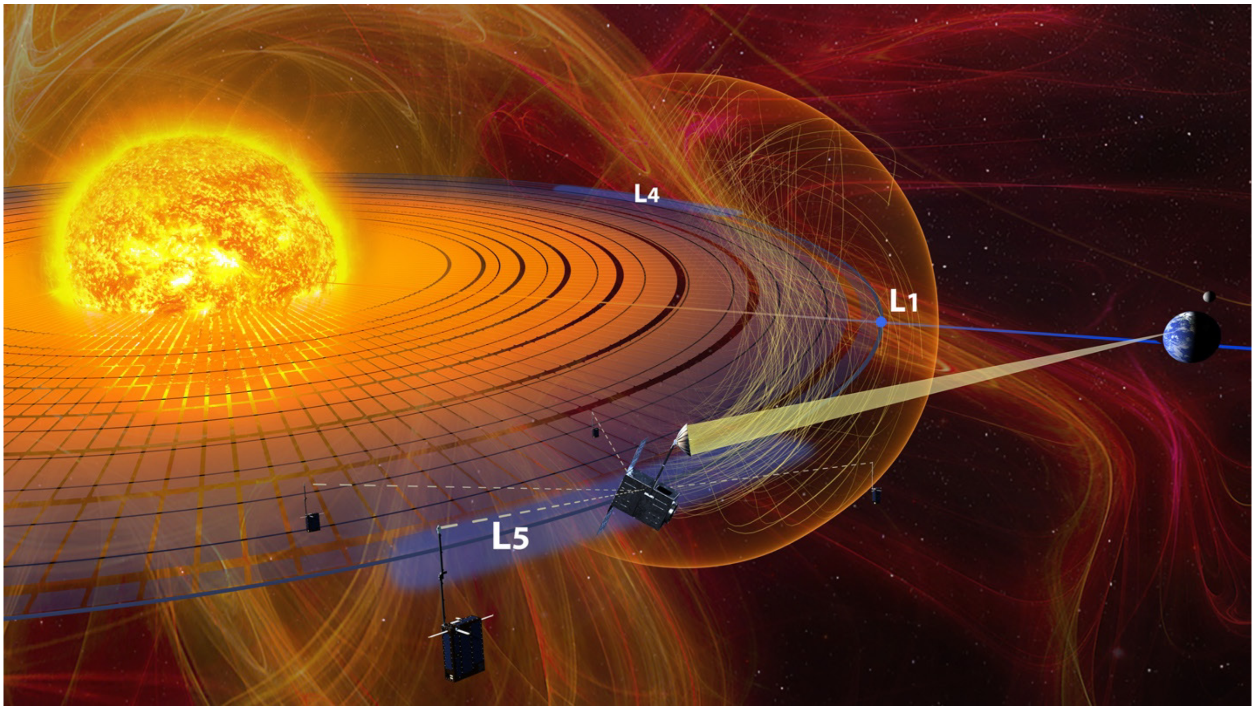


Figure 6-3. **The FMT-1 concept**. The objective is to achieve optimal coverage of activity over the solar surface and across the Sun–Earth line with a flexible and realistic mission architecture. The mission employs a "hub–spoke" system design approach. It comprises two observatory nodes in orbits around the Sun–Earth L4 and L5 Lagrangian points. Each node consists of an EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter (ESPA)-class spacecraft (**hub**) for up to four 8U CubeSats (**spokes**). The mission introduces a disaggregated design: Remote sensing payloads such as the coronograph-heliospheric imager (COR-HI); Extreme Ultraviolet Imager (EUV), and Solar Irradiance reside on the hub, while the spokes carry in situ instrumentation such as the solar wind plasma and magnetic field (particles and fields) and Solar Energetic Particle sensor (SEP) instruments. The hub acts as the "ground station" for the spokes. All uplinks/downlinks are executed via the hub.

6.2.1. Relevance to the LWS Architecture Committee Objectives

The FMT-1 design flows primarily from the predictive goals of SSA-I (Origins and Variability of Global Solar Processes) and SSA-II (Solar Eruptive and Transient Heliospheric Phenomena) and secondarily from SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere). As an FMT, the concept is flexible and, with the example payload discussed in Section 8.1.1, addresses objectives of additional SSAs. Figure 6-2 visualizes the LWS relevance of FMT-1. The traceability for each SSA is detailed in the respective spreadsheet. In a quantitative summary, FMT-1 addresses the following number of objectives for each relevant SSA: I (3 of 4), II (4 of 5), III (4 of 6), VII (1 of 3), and IX (2 of 5).

6.2.2. Why Is It an FMT?

FMT-1 was explored as a mission concept study called Sun-Earth Line Observing System (SELOS). The SELOS mission concept accomplishes the goals of FMT-1. We stress that the SELOS mission concept is not the only mission concept that could meet the objectives of this FMT; it is presented as a single example developed for the purpose of preliminary architecture and technology exploration, as well as mission cost estimation. In Section 8.1.1, we describe the SELOS mission concept study in some detail to illustrate some of the technical solutions addressed by the study.

This FMT represents a mission architecture because it can be adapted to different LWS science objectives via modification of the payload, orbit, or mission duration and because it contains architecture elements that can be used across numerous mission concepts, both in deep space and in geospace. To be more specific, SELOS is an FMT for the following reasons:

- It contains architecture concepts that are relevant for a variety of missions. For example:
    - The “hub–spoke” architecture can be deployed in various locations in the heliosphere or perigeospace, as either a single or multiple grids to satisfy different LWS science objectives.
    - The spoke deployment system can be used in a variety of spacecraft classes (ESPA and above) and environments (from LEO to deep space).
    - The ESPA-class design of the node enables a wide range of launch options, from rideshare to dedicated launches, depending on the number of nodes of a particular mission concept.
    - The networked approach of the hub + spokes design drives the development of a number of capabilities (e.g., inter-spacecraft communications, onboard autonomy).
    - The disaggregated approach to node and payload distributions provides programmatic flexibility and operational/scientific resiliency. For example, the nodes can be launched separately, the payload can be built by different institutions and/or agencies, and the science can be augmented incrementally with subsequent launches.
- The concept architecture can lead to several mission variants, such as:
    - String-of-pearls along 1 AU orbit to the L4/5 point, and beyond
    - A third node at L1 or at Mars L1
    - An L1 diamond with three to four nodes
    - Drifter nodes toward the L4/5 point

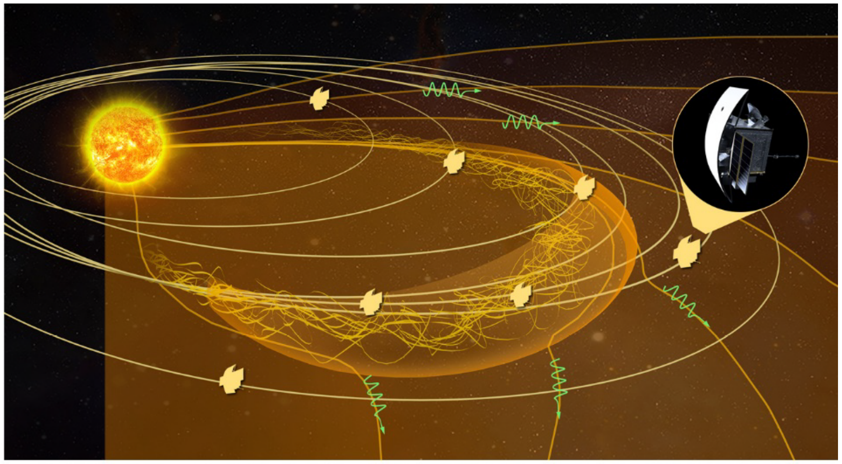
- The concept itself is adaptable and offers the possibility of several trade studies for adjusted cost, schedule, or scope to accommodate programmatic considerations. For example:
  - Insertion of additional spacecraft (or nodes) at different orbits around L4/L5
  - Bus options and trades from CubeSat to STEREO-bus
  - Scalability costs (particularly ground operations)

6.3. FMT-2: Heliospheric Explorers Multi-Spacecraft System to Observe the Dynamics of the Inner Heliosphere

Study performed at ACE Lab

Concept Summary

- **Science Objective:** To understand the dynamic changes in coronal mass ejections (distortion, deflection, and erosion) and other solar wind structures as they propagate from the Sun to 1 AU, as well as to understand the transport/diffusion of SEPs in the inner heliosphere
- **Design Approach:**
  - Seven to nine small spacecraft in 0.4 × 0.9 AU orbits maximizing constellations in 60–90° wedges
  - Primarily in situ observations with options for solar remote sensing



LWS SSAs Addressed

- **SSA-II:** Understand and forecast the occurrence and evolution of impulsive events (i.e., flares, coronal mass ejections, and corotating interaction regions) that originate either at the Sun or in the heliosphere
- **SSA-III:** Understand the acceleration and transport of energetic particles in the heliosphere

Required Technology Development

- Onboard autonomy
- Constellation operations

Why Is It an FMT?

- The constellation approach enables a variety of science objectives depending on the number of spacecraft.
- The ESPA compatibility provides programmatic flexibility and adaptation to changing science priorities and/or longer mission lifetimes.
- The payload per spacecraft can vary to address specific science objectives from, say, denser SEP sampling to CME 3D reconstructions and beyond.

The primary science objective of the FMT-2 is to understand (1) the dynamic evolution of solar wind transients (e.g., coronal mass ejections [CMEs], corotating interaction regions [CIRs]/stream interaction regions [SIRs], and the heliospheric current sheet [HCS]) as they propagate through the inner heliosphere and (2) the transport and diffusion of solar energetic particles before they reach 1 AU using a multi-spacecraft configuration and both in situ and remote sensing observations. The concept is summarized in Figure 6-4. Section 8.2.1 presents details from the MDL study.

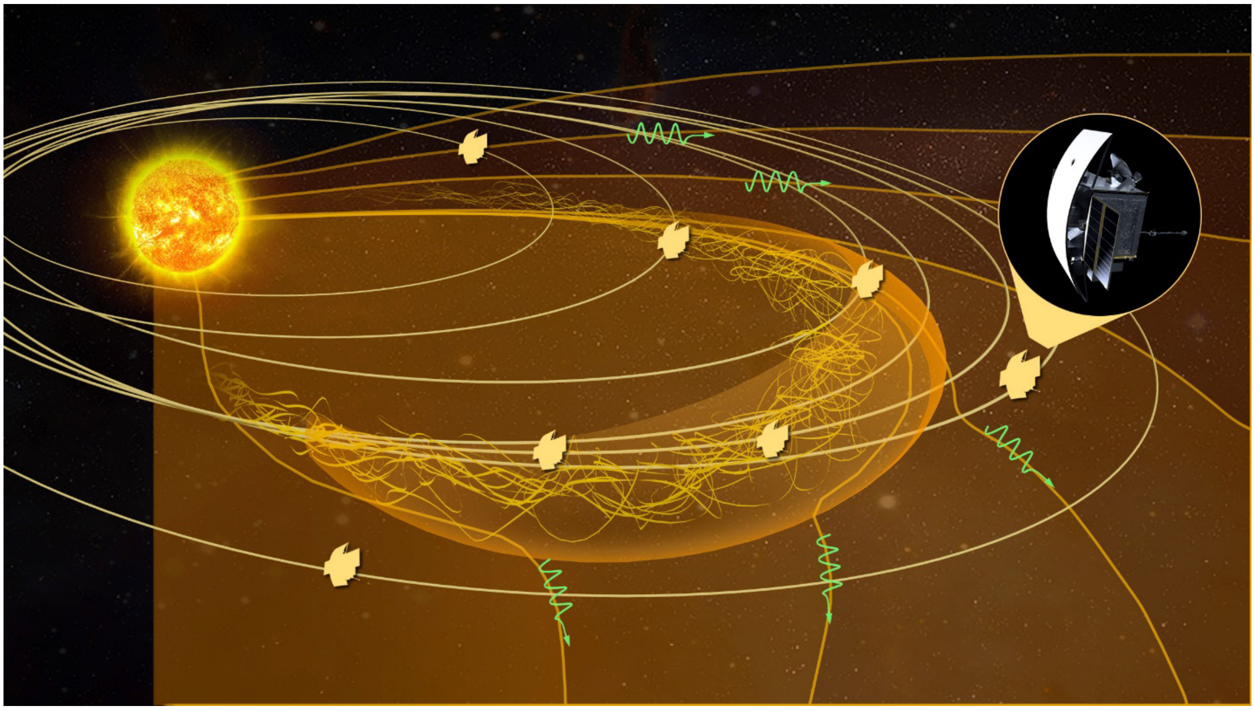


Figure 6-4. **The FMT-2 concept**. The objective is to achieve multi-spacecraft configurations in 60–90° ecliptic wedges to observe the same transients and solar energetic particle (SEP) events at different longitudinal and radial positions. The mission employs a single launch vehicle injecting seven to nine spacecraft into inner heliospheric orbits and Venus gravity assist maneuvers to distribute them into the desired configuration. Multiple instrument complements were studied that included both in situ and remote sensing instrumentation.

6.3.1. Relevance to the LWS Architecture Committee Objectives

The FMT-2 design flows primarily from the predictive goals of SSA-II (Solar Eruptive and Transient Heliospheric Phenomena) and SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere).

We visualize the wide LWS relevance of the FMT-2 concept in Table 6-4. The detailed traceability for each SSA can be found in the respective spreadsheet. In a quantitative summary, FMT-2 addresses the following number of objectives for each relevant SSA: II (4 of 5) and III (6 of 6).

6.3.2. Why Is It an FMT?

The FMT-2 concept (referred to as HELIX) was studied not as a point design but as a number of different trades that included different number of spacecraft, different instrumentation, and different orbits. This allows the later fine-tuning of this concept to reflect emerging scientific objectives and fiscal realities. The FMT-2 concept was identified and designed to fill observational gaps left by previous missions, and in particular to better connect solar remote observations of solar wind transients with heliospheric in situ measurements and with the geomagnetic response of these events. The study concluded that this concept is technologically feasible and would lead to quantifiable improvements in the forecasting of space weather phenomena. While SDO, Parker Solar Probe, and Solar Orbiter are designed to establish the possible sources of the slow solar wind, determining the dynamic evolution of solar wind transients intrinsically requires simultaneous multipoint observations. The following options were studied:

- A variable constellation with the number of spacecraft varied from four to ten. The desirability of a particular constellation was evaluated based on the fraction of mission time when three, four, or five spacecraft occupied a 60° or 90° wedge with maximum radial separation. It was established that beyond seven or eight spacecraft, the improvement was minimal (i.e., wedges with five spacecraft or more common with radial separations reaching between 0.25 and 0.3 AU) using a single Venus gravity assist maneuver.

- Three different instrument suites were evaluated: (1) a threshold configuration with the minimum number of instruments (all in situ) to address the highest-priority questions, (2) a baseline mission (all in situ instruments) that would be able to provide closure regarding the main science objectives, (3) and an aspirational mission that would add one of five remote solar sensing instruments—a different one for different spacecraft—to also address solar-heliospheric connections. All three configurations were fitted into a small volume-constrained spacecraft that can be attached to an ESPA Grande carrier. Thus, eight spacecraft could be launched with two ESPA Grande rings, and, in theory, a primary payload still could be added to the top of the stack, enabling a wide range of launch options.

6.4. FMT-3: Origins of Space Weather

No concept study performed

FMT based on Heliophysics Mission Concept Study (HMCS) called 4π-HeliOS

Concept Summary

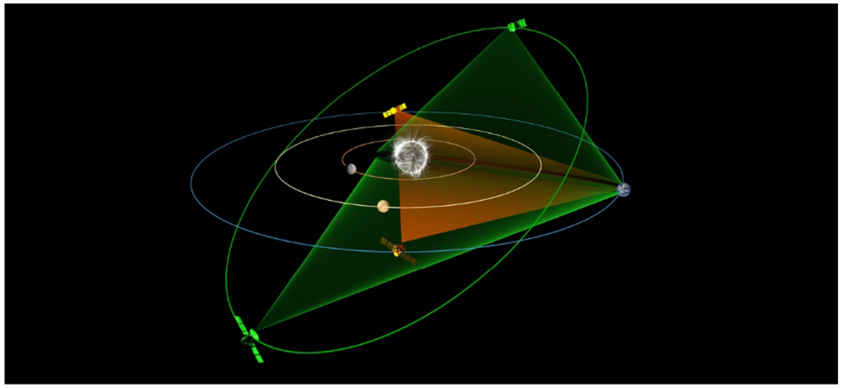
- **Science Objective:** To understand how the Sun creates the variable inner heliosphere by investigating solar activity and its impact on the inner planets across all longitudes and latitudes. FMT-3 will map the solar activity over the full Sun (4ϖ) from the surface (via photospheric magnetic field mapping) to the corona (via chromospheric-coronal imaging) to Earth (via imaging to ~1 AU).
- **Design Philosophy:** Cover activity simultaneously over the full solar surface and atmosphere and across the heliosphere in 3D via a spacecraft pair on different orbit planes
- **Design Approach:** The mission uses a modular systems architecture.
  - A spacecraft pair (“in-pair”) 180° apart, orbiting at 90° from Earth
  - A spacecraft pair (“out-pair”) 180° apart in a 45°–60° inclined orbit
  - Each spacecraft carries the same imaging payload (Doppler and magnetic fields, chrom-coronal-visible imaging). Additional payload per mission objective.
  - 10-year mission; Class C/D (in-pair); Class B (out-pair)

Addressed LWS SSA Predictive Goals

- Directly: **SSA-I** (Origins and Variability of Global Solar Processes), **SSA-II** (Solar Eruptive and Transient Heliospheric Phenomena), **SSA-III** (Acceleration and Transport of Energetic Particles in the Heliosphere), **SSA-IV** (Variability of the Geomagnetic Environment, **SSA-IX** (Solar Impacts on Climate), **SSA-X** (Stellar Impacts on Planetary Habitability)
- Indirectly: **SSA-VIII** (Radiation & Particle Environment from Near Earth to Deep Space)

Required Technology Development

- Deep-space optical communications
- High-performance ion engines



Why Is It an FMT?

- Highly modular architecture that adapts to a variety of programmatic scenarios.
  - The in-pair and out-pair can be launched independently, providing programmatic flexibility and/or collaboration opportunities with international partners.
- The FMT-3 architecture requires only payload changes to meet the remote sensing requirements of a wide-ranging set of objectives, from fundamental solar/stellar physics (e.g., dynamo) to Sun–planet interactions to space weather operations.
- It can serve as the framework for a long-term program equivalent to the EOS program for Earth studies.
- Examples of mission variants based on the 4π-HeliOS architecture include:
  - Out-pair (or even single spacecraft) in highly inclined orbits (>70°) to target solar dynamo studies
  - In-pair in Venus orbit for higher resolution, earlier measurements of solar transients

The overarching science objective of FMT-3 is to understand how the Sun creates the variable inner heliosphere by *investigating* solar activity and its impact on the inner planets across all longitudes and latitudes. In other words, FMT-3 will map the solar activity over the full Sun (coverage of “4π steradians,” abbreviated as “4π”) from below the surface (via helioseismology and photospheric magnetic field mapping) to the corona (via chromospheric and coronal imaging) to the boundary of the inner heliosphere (via coronagraphic imaging to ~20 Rs). The concept is depicted in Figure 6-5. Section 8.3.1 presents an example of a possible implementation.

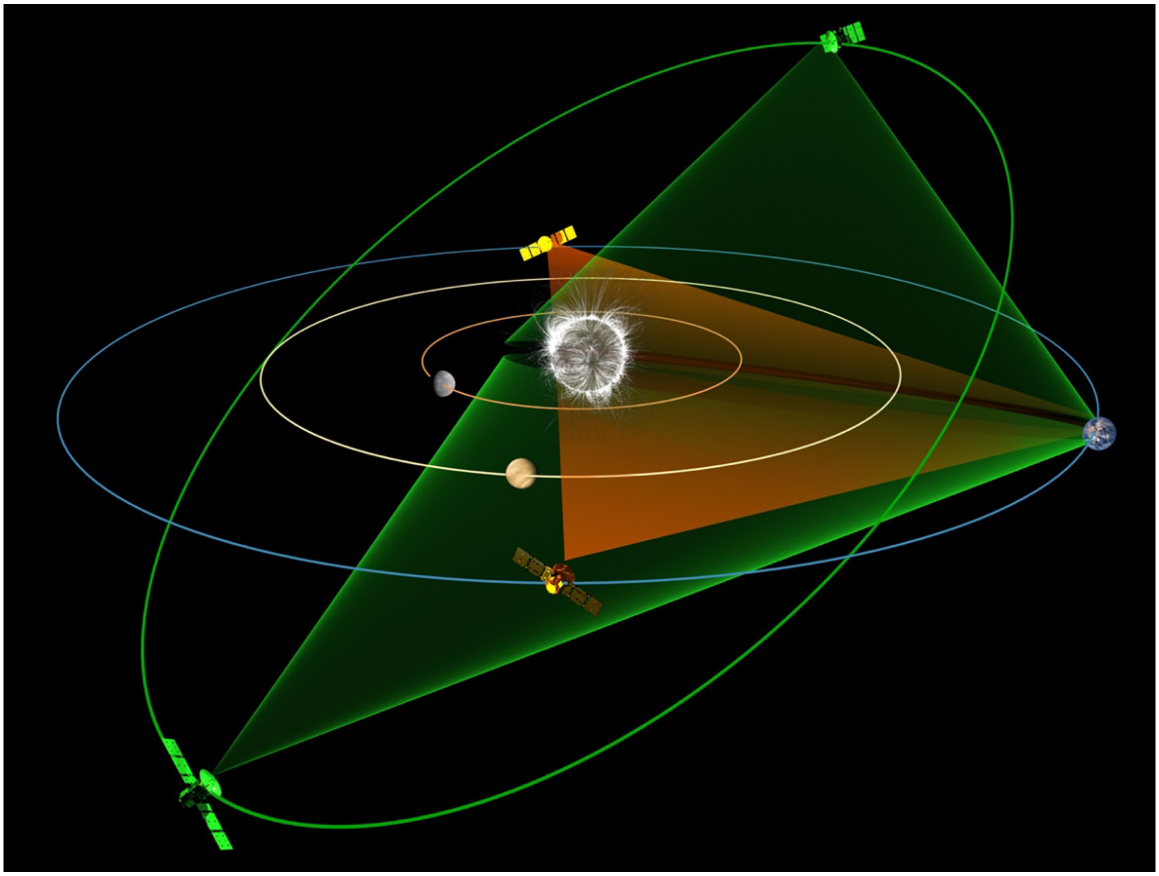


Figure 6-5. The FMT-3 architecture consists of spacecraft pairs launched in one of two 1-AU orbits: ecliptic orbits (“in-pair”) and/or highly inclined (45°–60°) orbits (“out-pair”). The “in-pairs” are stationed at 90° on either side of Earth, while the “out-pairs” use gravity assists at Jupiter (or Venus, when higher-performance ion engines become available) to rise above the ecliptic. All four spacecraft carry a core set of remote sensing instruments (magnetograph, imager, coronagraph). Other instrumentation can be added on each spacecraft, depending on the FMT focus (e.g., heliospheric imagers, spectrometers, in situ).

6.4.1. Relevance to the LWS Architecture Committee Objectives

As presented in the following, FMT-3 is a highly ambitious architecture that directly addresses half of the LWS Science program, namely, the predictive goals of SSA-I (Origins and Variability of Global Solar Processes), SSA-II (Solar Eruptive and Transient Heliospheric Phenomena), SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere), SSA-IV (Variability of the

Geomagnetic Environment), SSA-IX (Solar Impacts on Climate), and SSA-X (Stellar Impacts on Planetary Habitability). Figure 6-2 demonstrates the strong LWS relevance of FMT-3.

6.4.2. Why Is It an FMT?

The FMT-3 design is an adaptation for LWS of the 4π-HeliOS concept developed under the STP HMCS program. We retain the name here, but it should be understood that FMT-3 reflects the priorities of the LWS program and therefore it is not identical to the STP 4π-HeliOS study. The STP study will be delivered to NASA by the end of June 2022.

We note that the 4π-HeliOS concept may not be the only mission concept that could meet the overarching objectives of FMT-3, although the basic architecture (an observing system based on highly inclined plus ecliptic orbits) will likely remain unaltered.

This FMT represents a mission architecture because it can be adapted to different LWS science objectives via modification of the payload, orbit, or mission duration. To be more specific, 4π-HeliOS is an FMT for the following reasons:

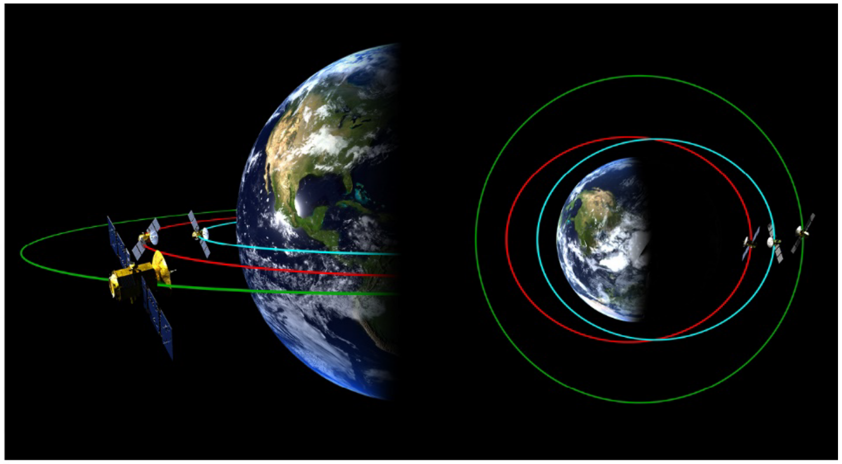
- It is a highly modular architecture that can be adapted to a variety of programmatic scenarios. For example:
    - The ecliptic spacecraft can be launched independently of the out-of-ecliptic ones, thus providing programmatic flexibility and creating a natural collaboration opportunity with international partners. For example, the spacecraft and/or the payload can be built by different institutions and/or agencies, and the science can be augmented incrementally with subsequent launches.
- The concept architecture can lead to several mission variants, such as:
    - Spacecraft pairs (or even single spacecraft) in highly inclined orbits (>70°) to target solar dynamo studies
    - Longer-duration missions (solar cycle scale) to achieve highly inclined circularized orbits inward of 1 AU to increase space weather relevance (faster orbits around the Sun, higher imaging resolution, etc.)
    - In-ecliptic component in Venus (instead of Earth) orbit for higher resolution, earlier detections/measurements of solar transients
- The FMT-3 architecture is so comprehensive that it requires only payload changes to meet the remote sensing requirements of a wide-ranging set of objectives, from fundamental solar/stellar physics (e.g., dynamo) to Sun–planet interactions to even space weather operations. It could serve as the framework of a long-term program equivalent to the Geostationary Operational Environmental Satellite (GOES) or Earth Observing System (EOS) programs for Earth studies. A long-term program can lead to the buildup of observing platforms, with complementary capabilities, around the Sun and inner heliosphere, to solve many fundamental astrophysics problems while providing space weather coverage commensurate with that for terrestrial weather.

6.5. FMT-4: Geospace Observing System

Study performed at GSFC Mission Design Laboratory

Concept Summary

- **Science Objective:** Understanding the formation, evolution, and dissipation of ionospheric irregularity
- **Design Approach:**
  - Three equatorial low-Earth-orbit satellites: one for remote sensing and two for in situ measurements
  - The remote sensing satellite is on a circular orbit at 800-km altitude and 15º inclination
  - The in situ satellites are at 600 × 250 km elliptical orbit with 15º inclination. They are out of phase by 180º.
  - They can be put in orbit by a single launch.



LWS SSAs Addressed

- Directly: **SSA-VI** (Ionospheric Irregularities)
- Indirectly: **SSA-VII** (Composition and Energetics of the Neutral Upper Atmosphere), **SSA-V** (Dynamics of the Global Ionosphere and Plasmasphere), **SSA-IX** (Solar Impacts on Climate), **SSA-X** (Stellar Impacts on Planetary Habitability)

Required Technology

- In situ instruments for electron, ion, and neutral density; ion and neutral composition; plasma drift and neutral wind; electric and magnetic field; and radio transceiver
- Remote sensing instruments for thermospheric neutral wind profile (e.g., O THz limb scanner [new]), electron density profile and plasma bubble imaging (far ultraviolet scanning spectrograph imager), neutral gravity wave (OH band imager [new])

Why Is It an FMT?

- This FMT contains architecture concepts relevant to a variety of missions. For example:
  - The ionospheric and neutral observation architecture can be used to address ionosphere and plasmasphere science objectives, where plasma and neutral measurements are also required.
  - The FMT is relevant to extrasolar science given that the plasma and neutral measurements can address atmospheric loss questions.
  - The design of simultaneous and coincident observations by multiple satellites with both in situ and remote sensing techniques could be used for other missions.

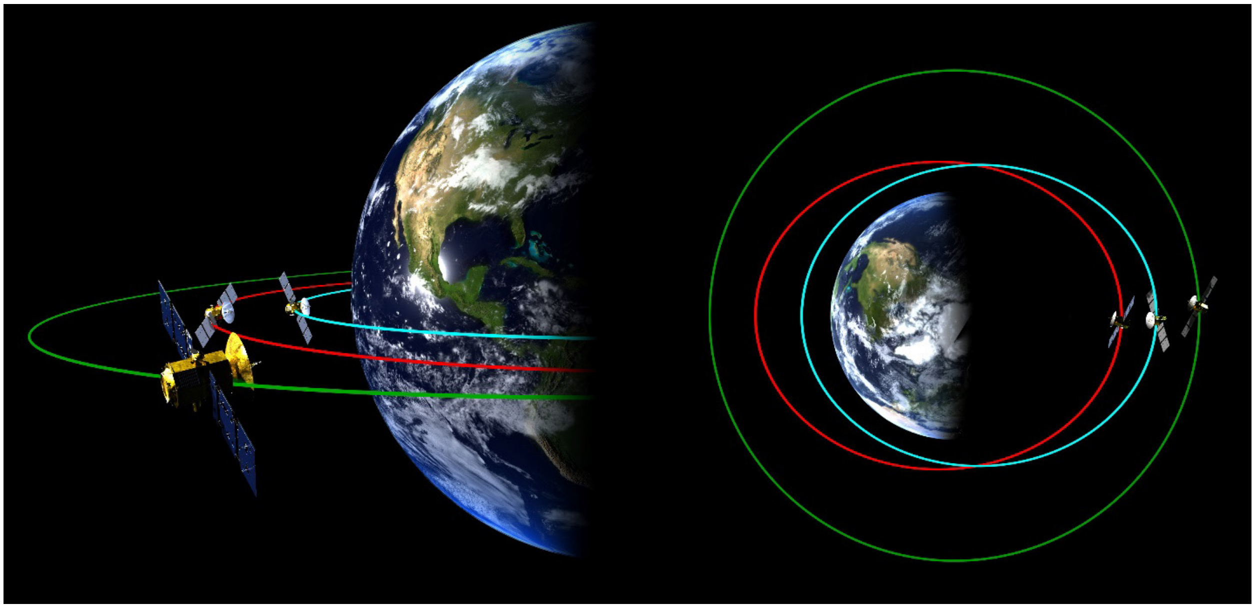


Figure 6-6. The FMT-4 concept for a Geospace Observing System.

FMT-4 is an architecture concept developed to address the science questions of SSA-VI on ionospheric irregularities. The quad chart on the previous page briefly summaries the major focal points, the orbit design of the three-satellite observation system, and required measurements and technology. This FMT takes advantage of coincident in situ and remote sensing observations by multiple satellites to determine 3D structures of ionospheric irregularities, their evolution, and associated ionosphere and thermosphere condition, and it also tests theories on drivers of the irregularity initiation and simultaneously measures frequency-dependent radio scintillation in the ionospheric irregularity region. These observations not only address the ionospheric irregularity–related science questions, which enables development of irregularity prediction, but also provide a way to mitigate the radio scintillation by recommending optimal operating radio frequencies.

6.5.1. Relevance to the LWS Architecture Committee Objectives

The science objective of the FMT-4 is to understand the formation, evolution, and dissipation of ionospheric irregularity; elucidate the physical mechanisms and plasma instabilities responsible for producing ionospheric irregularities as well as the causal chains that generate or suppress them; and provide a full description of how the irregularities interact with radio waves, leading to scintillation or signal absorption. FMT-4 will enable the development of a capability to predict ionospheric scintillation in the equatorial region and mitigate the effects of ionospheric irregularities on radio communication and navigation.

FMT-4 is designed to simultaneously observe the condition and structures of the ionosphere and thermosphere, mesosphere gravity wave, and frequency-dependent radio scintillation with in situ and remote sensing instruments on three LEO satellites. This unique new observation system directly addresses SSA-VI (Ionospheric Irregularities), which has four key focal points:

1. Understanding the formation, evolution, and dissipation of irregularity structuring

2. Ascertaining how radio signals are degraded by ionospheric irregularities
3. Predicting scintillation, equatorial spread F, and polar cap absorption
4. Mitigating the effects of ionospheric irregularities on radio communication and navigation

6.5.2. Why Is It an FMT?

The FMT-4 concept was studied as a mission (referred to as the Geospace Observing System [GOS]) to address the focal points specified in SSA-VI. FMT-4 takes advantage of recent technology development and previous architecture ideas to simultaneously observe the seeding or source (e.g., gravity waves), structures and variations of ionospheric irregularity, associated thermospheric conditions, and impact on radio scintillation with in situ and remote sensing instruments on multiple LEO satellites. The observations offer a new and unique data set to significantly advance our understanding of ionospheric irregularity–related physics and provide a way to mitigate or minimize radio scintillation by selecting or switching radio frequencies and/or using a relay to avoid ionospheric irregularity regions.

GOS is an FMT because it contains architecture concepts that are relevant for a variety of missions. For example:

- The ionospheric and neutral observation architecture can be used to address SSA-V (Dynamics of the Global Ionosphere and Plasmasphere), where plasma and neutral measurements are also required.
- GOS is also closely related to the architecture study of SSA-VII (Composition and Energetics of the Upper Neutral Atmosphere). GOS's architecture and instruments for neutral observations can be adopted or combined with the SAA-VII architecture design.
- The SSA-X (Stellar Impacts on Planetary Habitability) science focus areas include observational investigation of atmospheric loss in our solar system and its application to extrasolar systems. Measurements of both plasma and neutrals are required to address part of the SSA-X focus areas.
- SSA-IX (Solar Impacts on Climate) is also related to FMT-4. Understanding the influence of solar variability on Earth's climate requires knowledge of solar variability itself and climate changes due to the coupling among the upper, middle, and lower atmosphere. The coupling process requires neutral and plasma observations that FMT-4 can provide.
- Understanding the geomagnetic environment, especially geomagnetic storms, is part of the science questions that SSA-IV (Variability of the Geomagnetic Environment) addresses. Geomagnetic storms cause significant disturbances in the ionosphere and thermosphere. The disturbances also have a feedback effect on the geomagnetic storms. The architecture of FMT-4 observations can directly adopted to support the SSA-IV study.
- Finally, the design of simultaneous and coincident observations by multiple satellites with both in situ and remote sensing techniques could be used for other missions in the heliosphere and beyond.

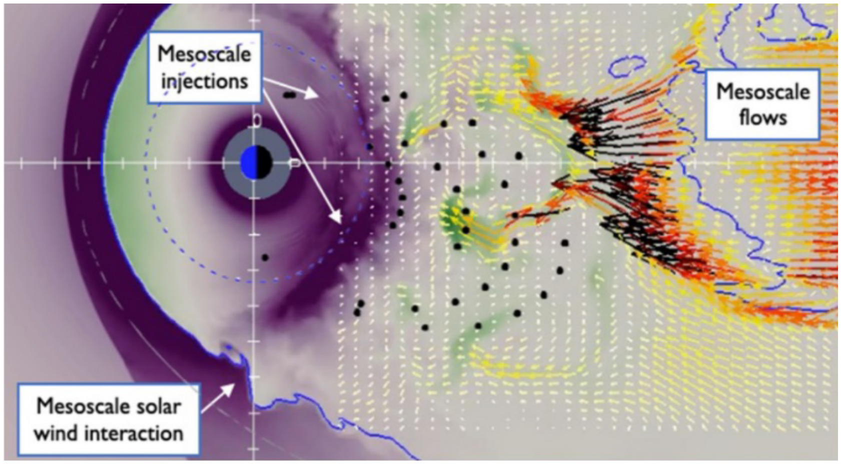
6.6. FMT-5: Magnetospheric Constellation

No concept study performed

FMT based on HMCS MagCon study at GSFC Mission Design Laboratory

Concept Summary

- **Science Objective:** Measure the mesoscale (1–3 R_E) flow of mass, momentum, and energy throughout the magnetosphere
- **Design Approach:** True multi-satellite mission (baseline 36 identical spacecraft with THEMIS-style instrumentation comprising a magnetometer, ESA, and energetic particle instruments)
  - 12 satellites on 8.24 R_E × 6,237-km low-inclination orbit
  - 12 satellites on 10.79 R_E × 3,725-km low-inclination orbit
  - 12 satellites on 15 R_E × 1,400-km low-inclination orbit
- 3-year lifetime, ESPA-Grande-compatible spacecraft; launch options to be studied further



LWS SSA Predictive Goals

- The MagCon strawman concept addresses the following SSAs:
  - Directly: **SSA-IV, SSA-V**
  - Indirectly: **SSA-III, SSA-VIII, SSA-IX, SSA-X**

LWS SSA Predictive Goals

- Spacecraft and instruments are available; mass manufacturing and cross-calibration preflight needs to be considered.
- Ground operations need to be streamlined with 36 spacecraft.

Why Is It an FMT?

- Modular/scalable architecture enables programmatic and science flexibility.
- Science-grade spacecraft enabled with existing SmallSat avionics and performance unavailable from industry. These designs can form the basis for cutting-edge, and affordable, scientific constellations.
- Novel mission design (staggered perigee) to keep spacecraft aligned in local time. The design can be exploited by several other mission concepts.
- Innovative approach to meet high-data-volume requirements via a combination of government (NASA) and private services (AWS) and/or a relay satellite.
- The FMT offers a viable basis for a cross-scale mission, adding MMS/Cluster-like constellations to the mesoscale backbone created by this FMT.

The overarching science objective of FMT-5 is to understand the mesoscale (1–3 R_E) flow of mass, momentum, and energy through Earth's magnetosphere, from mesoscale input on the dayside and flanks to mesoscale storage and release in the nightside plasma sheet and near-Earth transition region. To understand the processes leading to enhancements of the ring current and radiation belts, the auroral precipitation and field-aligned currents, and their associated space weather impacts to the level of being able to provide accurate and localized (shorter and longer term) predictions, it is necessary to understand the mesoscale processes that localize the energy and plasma transport in the magnetosphere.

FMT-5 particularly focuses on two large-scale areas of investigation: (1) the mesoscale energy input along the dayside magnetopause and flanks and (2) the mesoscale storage and release in the nightside plasma sheet and the near-Earth transition region (see Table 6-2). Monitoring Earth's nightside magnetosphere from geostationary orbit out to the magnetotail and the magnetospheric boundaries in the dayside with a multi-spacecraft mission with inter-spacecraft distances on the order of a few Earth radii can provide a comprehensive understanding of the spatial and temporal variability of the energy input at the boundaries as well as the mesoscale bursty bulk flows that account for the majority of plasma transport in the nightside.

The FMT-5 objectives can be achieved by a baseline configuration comprising 36 identical spacecraft, each carrying a magnetometer, an electrostatic analyzer, and a solid-state telescope or some other energetic particle instrument. The mission concept is summarized in Figure 6-7.

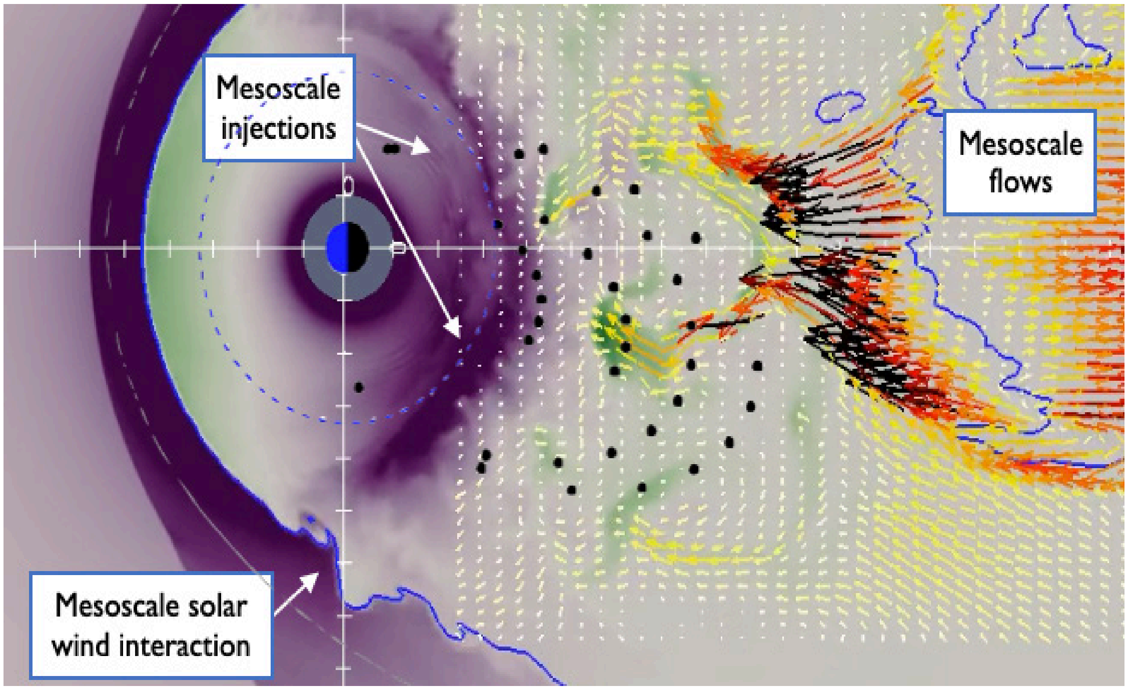


Figure 6-7. FMT-5 studies the flow of mass, momentum, and energy through geospace at mesoscale resolution. Mesoscales lie between the small (electron and ion)-scale microphysical processes and the global configuration that is established by the interaction of the solar wind with Earth's magnetic field. Between these two well-studied regimes, the mesoscales serve as "messengers" of dynamical processes at either end of the scale. Mesoscales are difficult to study observationally because of the need for multipoint measurements, but technology has advanced to the point that such studies are now within reach.

Table 6-2. FMT-5 areas of investigation for flow of mass, momentum, and energy through geospace.

1. Mesoscale energy input at the dayside magnetopause and flanks	2. Mesoscale storage and release in the nightside plasma sheet and near-Earth transition region
1a. Determine quantitatively the extent and temporal evolution of magnetopause reconnection as functions of solar wind and magnetosheath conditions and associated driving structures	2a. Determine how processes at different spatiotemporal scales contribute to transport of mass and energy during the different convection modes and in response to changing solar wind conditions
1b. Determine the instantaneous temporal and spatial (particularly longitudinal) extent of energy and mass transfer phenomena in response to solar wind and upstream structures and internal conditioning	2b. Reveal the coupling of the MI system at the transition region and determine the magnetospheric drivers of ionospheric mesospheric structures, such as auroral arcs
1c. Compare the total amount of input energy as a function of solar wind and internal conditions and determine the dominant mechanisms responsible for energy and mass transport	2c. Determine the source and energization mechanisms of particles injected into the inner magnetosphere

6.6.1. Relevance to the LWS Architecture Committee Objectives

This FMT flows from the following predictive goals:

1. SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere), with its multipoint observations of particle injections into the Earth's inner magnetosphere (in particular the azimuthal structuring of such injections) and transport of solar wind particles through the magnetopause via magnetic reconnection or through Kelvin–Helmholtz instability (KHI) at the flanks

2. SSA-IV (Variability of the Geomagnetic Environment), by comprehensively tracking the flow of mass and momentum during geomagnetic storms and substorms and, when combined with ground magnetometer measurements, measuring the mesoscale dynamics responsible for localized geomagnetically induced currents

3. SSA-VIII (Radiation and Particle Environment from Near Earth to Deep Space), by measuring the mesoscale structuring of plasma in Earth's plasma sheet, and by quantifying the input into the inner magnetosphere, a critical missing element needed for accurate modeling and understanding of ring current and radiation belt enhancements

6.6.2. Why Is It an FMT?

Earth’s magnetosphere and upper ionosphere have been probed by several multi-spacecraft missions: The four Cluster satellites had separations ranging from a few hundred kilometers to several Earth radii, the MMS five-spacecraft mission was a tight constellation with inter-spacecraft distances from a few tens of to a few hundred kilometers, and the five THEMIS spacecraft were placed in orbits that aligned along the magnetotail at apogee. Although these missions successfully addressed some of the fundamental plasma physical processes in Earth’s magnetosphere, they cannot resolve the structuring of the flows and transport processes in the mesoscales, which would require a dense network of satellites with separations in the range of a few Earth radii. This FMT focuses particularly on resolving the magnetospheric dynamics in those scales, which have been interpreted to be critical for the basic energy entry and transport processes.

The global magnetosphere–ionosphere system can be monitored using both in situ and remote sensing technologies. The extensive heritage of the in situ plasma measurements is used here, and the novelty of the concept comes from the large network of spacecraft that allows resolving the mesoscale processes. Novel imaging technologies now allow for imaging the tenuous space plasmas as well, and concepts such as those presented in FMT-6 and FMT-8 would be an excellent complement to the in situ measurements in this FMT.

Although common now throughout commercial industry, NASA has not yet developed large constellation missions, primarily because of cost concerns and perceived difficulty with calibration of so many instruments. Many of the LWS science objectives from low Earth orbit through the magnetosphere require multipoint measurements. The implementation in this FMT is modular and enables scaling up or down in terms of number of spacecraft. Some relevant key points are as follows:

- The baseline observatory leverages existing CubeSat/SmallSat avionics and flight software, currently set to fly on GTOSat into Earth’s radiation belts. These are spinning, magnetically clean spacecraft, which are not commonly available from industry partners. All magnetospheric in situ spacecraft require spinners, as do some ionosphere/thermosphere/mesosphere missions.
- FMT-5 is designed to be modular and scalable. The baseline mission consists of 36 spacecraft, with 12 spacecraft per propulsive ESPA. Each propulsive ESPA can drop off the complement of spacecraft at the desired orbit. The modular approach enables a scalable architecture, regardless of the final orbit design or science objectives, and is applicable to any magnetospheric constellation mission, including missions where the petal orbits have different local times (LTs).
- The requirement to adhere to NASA-STD-8719.14A requires the spacecraft to carry sufficient ΔV to deorbit after end of mission. Our baseline is ~400 m/s, which provides flexibility for other mission concepts.
- The FMT-5 orbits have a unique staggered perigee design, which forces the line of apsides for the different orbits to precess at the same angular rate and maintain LT alignment. The THEMIS mission did not have these staggered perigees, which caused the outer spacecraft (B and C) to rapidly lose their alignment.

- FMT-5 was able to close the downlink requirement via direct to Earth (DTE), through a combination of NASA government and Amazon Web Services (AWS) commercial services. An option of a relay satellite was also designed and costed. It was found that 36 nodes is about the limit where DTE is feasible; anything larger would greatly benefit from the designed (but not currently baselined) relay satellite.
- As currently designed, FMT-5 focuses on mesoscale (1–3 R_E) resolution over a large volume of space. It could also form the basis for a cross-scale-type mission with the addition of an MMS- or Cluster-type constellation embedded in the mesoscale/fluid backbone created by MagCon.

6.7. FMT-6: Magnetotail and Inner Magnetosphere Mission

Study performed at GSFC Mission Design Laboratory

Concept Summary

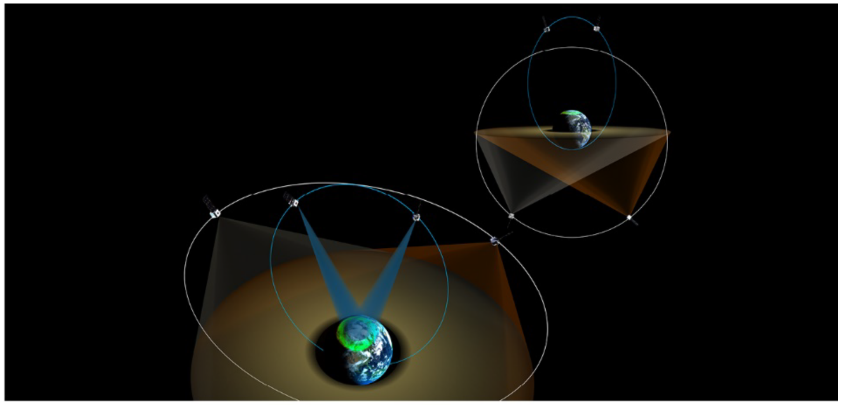
- **Science Objective:** To understand the response of Earth's near-space environment, magnetic field, and plasma populations to solar wind driving at global scales and mesoscales
- **Design Approach:** Two pairs of identical satellites on a single launch for continuous observations of the northern auroral oval and the inner magnetosphere plasma populations
  - Two satellites on Tundra-type orbits 180° apart provide 24/7 coverage of the northern auroral oval (perigee 1000 km, apogee 6.1 R_E, ~82° inclination, 12-hour orbital period)
  - Two satellites on circular high-inclination orbits 90° apart provide continuous imaging of the plasmasphere and ring current (circular orbit at 6.1 R_E, same inclination)
  - Three-year mission, ESPA-compatible spacecraft; single launch with ELV class (Falcon 9)
  - Strawman payload:
    - Elliptical: Far ultraviolet imager at two Lyman-α frequencies
    - Circular: Extreme ultraviolet He^+, O^+, energetic neutral atom (ENA) low, ENA mid/high energy
    - **Both pairs can accommodate basic in situ plasma and fields measurements**

LWS SSAs Addressed

- Directly: **SSA-IV, SSA-V**
- Indirectly: **SSA-III, SSA-VIII, SSA-IX, SSA-X**

Technology Development

- Instrument miniaturization
- ENA remote sensing of magnetotail mesoscale structure and fast flow at timescales ≤10 minutes



Why Is It an FMT?

- The remote sensing component meets the need for continuous global observations of the aurora and plasma populations that will support multiple mission concepts.
- The concept is scalable/adaptable to provide programmatic and science flexibility.
- The elliptical orbits can be used to monitor the ionosphere, but they also traverse the inner magnetosphere and upper atmosphere, allowing for frequent in situ measurements in key regions for space weather.
- The concept architecture can lead to several mission variants, such as:
  - Stand-alone auroral, inner magnetospheric monitoring
  - Comprehensive magnetospheric dynamics monitoring
  - Stand-alone, single-satellite global observations of both the solar wind drivers and key magnetospheric responses

The overarching science objective of FMT-6 is to understand the large-scale dynamic response of Earth's magnetotail and inner magnetosphere to major solar-origin disturbances. Global imaging enables understanding of the magnetosphere–ionosphere system evolution from the start of the geomagnetic storm to its recovery. Continuous observations of auroral dynamics reveal both outer magnetosphere drivers and magnetotail energy transport, and the energetic ring current and low-energy plasmaspheric populations in the inner magnetosphere manifest the energization and loss processes during a storm. The FMT-6 objectives will be accomplished by a four-spacecraft mission that will image the Earth with pairs of satellites from two different orbits: an elliptical orbit pair monitoring the auroral development and a circular orbit pair monitoring the inner magnetosphere and near-plasma-sheet populations. This concept is summarized in Figure 6-8 and assumes that the solar wind drivers and their impact on Earth's magnetopause are monitored by other missions of the Heliophysics Observatory.

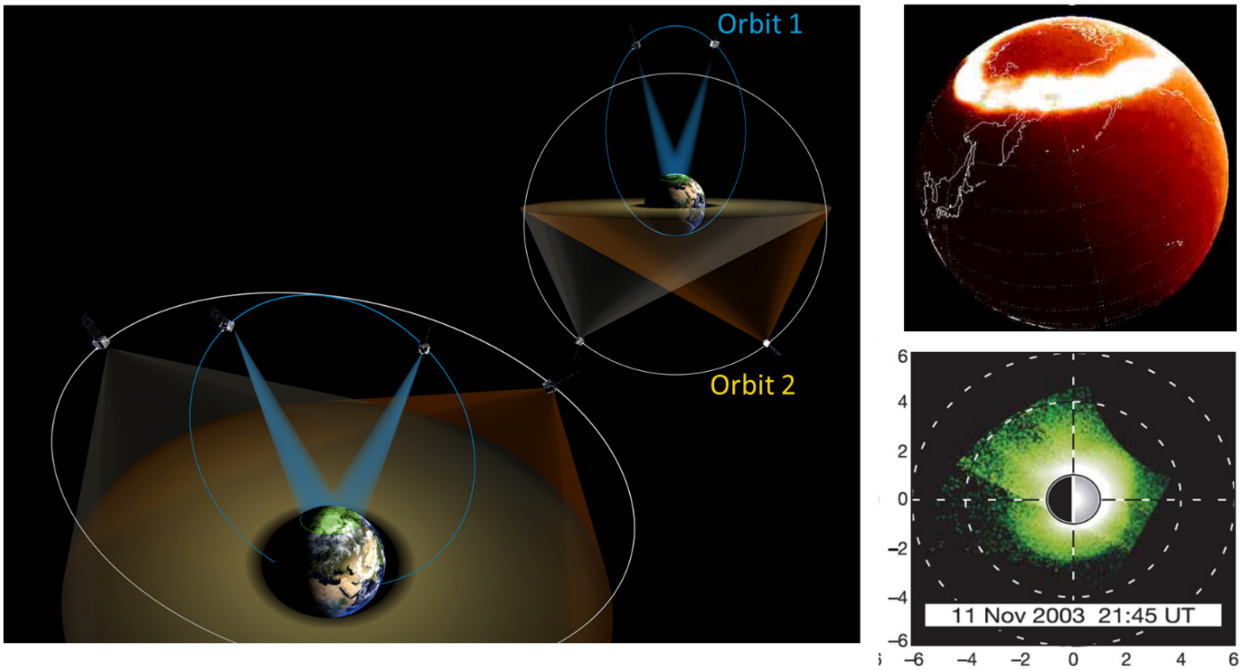


Figure 6-8. **The FMT-6 concept**. The objective is to achieve continuous coverage of activity within the auroral region by two spacecraft in elliptical orbits. At the same time, two spacecraft in circular orbit with 180° phase shift at the altitude of the elliptical orbit apogee can provide continuous imaging of the ring current and the plasmasphere in the inner magnetosphere. The four spacecraft can be launched with a single launch vehicle. While the mission concept design study focused solely on the imaging capabilities, both orbits are well suited for in situ measurements, adding to the understanding of the electromagnetic fields and particle environments in the inner magnetosphere.

Alternatively, a single satellite with global imaging from a select high-altitude orbit could provide observations from both drivers and responses, albeit not on a 24/7 basis, but with sufficient coverage to track full storm cycles. This is presented as an enhancement concept in Section 8.6.8.

Magnetospheric processes occurring at isolated locations on the subsolar magnetopause, in the nightside plasma sheet, or deep within Earth's ring current can affect the location and nature of the cusps, the particle populations precipitating into the auroral oval, or flux levels in the global radiation belt. Although isolated in situ measurements made by closely spaced clusters of spacecraft can provide hints as to the nature of the local processes, they cannot quantify the significance of the observed local process to the global system science of the solar wind–magnetosphere interaction.

Global observations are needed to obtain a systems science view of the solar wind–magnetosphere interaction. In the absence of measurements by cost-prohibitive fleets comprising tens or hundreds of spacecraft making in situ measurements, a single global imager can provide a cost-effective means of addressing the systems science of the magnetosphere with a higher density of observations than any potential multipoint mission. Here, systems science constitutes both in-depth studies of the processes occurring within individual regions, such as those in the vicinity of the magnetopause, the near-Earth magnetotail, and the ring current, as well as studies of their simultaneous interactions as a connected whole. In particular, global imaging can determine which of the many proposed solar wind–magnetosphere interaction processes and magnetospheric modes dominate as a function of solar wind and geomagnetic conditions, identify the fundamental process controlling these interactions and modes, verify and validate global space weather models, and track the end-to-end flow of solar wind energy through the magnetospheric system.

6.7.1. Relevance to the LWS Architecture Committee Objectives

The FMT-6 design flows primarily from the predictive goals of SSA-IV (Variability of the Geomagnetic Environment) and SSA-V (Dynamics of the Global Ionosphere and Plasmasphere) and secondarily from SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere) and SSA-VIII (Radiation and Particle Environment from Near Earth to Deep Space). However, the FMT-6 study, with the strawman payload summarized in Section 8.6.2, can also address questions related to SSA-IX (Solar Impacts on Climate) and SSA-X (Stellar Impacts on Planetary Habitability).

The strawman FMT-6 measurements map to a variety of predictive goals and measures of success of the SSAs (see Table 6-4). SSA-IV seeks to improve the ability to predict the geomagnetic field variability on the ground, but to do that, the measures of success need to include the capability to predict spatial and temporal dynamics of geomagnetic storms, substorms, and magnetotail field dipolarizations as well as the associated disturbances observable on the ground driving geomagnetically induced currents. Of particular interest is to improve on assessing the uncertainty of the estimates as well as the predictability of events.

6.7.2. Why Is It an FMT?

Earth’s magnetosphere and upper ionosphere are among the best-probed regions of space, simply because of their accessibility from Earth. However, many of the as-yet-unanswered questions are increasingly critical for the forecasting of conditions and impacts during significant space weather phenomena such as geomagnetic storms. Prior missions have focused on either the magnetosphere or the ionosphere, and to date there are no observations simultaneously covering the entire global system over the geomagnetic storm cycle. This fundamental limitation will be addressed by FMT-12.

The global magnetosphere–ionosphere system can be monitored by a variety of means, using both in situ and remote sensing technologies. Because of the extensive heritage and continuing significant scientific and technological interest, this FMT focused on a mission concept that is novel and has not recently been assessed by mission studies. Hence, it is to be noted that many other concepts that are not covered by an FMT in this study form critical pieces of our ability to fulfill the LWS objectives.

The only way to conclusively determine temporal and spatial variability within a very large region of space such as Earth's magnetosphere is through remote imaging. Although the tenuous plasmas and the vast spatial scales in the magnetosphere pose challenges for capturing the dynamics, new technologies allow for significantly improved temporal and spatial resolution over prior missions—the most recent of which was the IMAGE mission from the early 2000s.

The FMT-6 study focused on a mission architecture that would yield continuous imaging of key regions and an enhancement option concept that can provide global observation of both drivers and responses, albeit not continuously. The concept can be adapted to different combinations of LWS science objectives via modification of the payload, orbit, or mission duration. Specifically, the FMT-6 study accomplishes the following goals:

- While configured as a mission with four spacecraft on two distinct orbits, the concept can be modified for a variety of missions with highly diverse scientific objectives.
    - The elliptical orbits can be used to monitor the ionosphere, but they also traverse the inner magnetosphere and upper atmosphere, allowing for frequent in situ measurements in key regions for space weather.
    - The four-spacecraft, two-distinct-orbit configuration can be launched in a single launch, which may serve a variety of purposes with highly varying scientific objectives.
    - The four spacecraft are scoped to be composed of two sets of two identical spacecraft, but if resources allow or scientific objectives require, there is no inherent need to have identical spacecraft beyond the sets of imaging instruments.
- The concept architecture can lead to several mission variants, such as the following:
    - Stand-alone auroral monitoring mission (e.g., augmented with in situ and/or additional atmospheric remote sensing instrumentation);
    - Stand-alone inner magnetosphere monitoring mission (e.g., augmented with in situ monitoring of the radiation belt, ring current, and plasmasphere particle populations);
    - Comprehensive magnetospheric dynamics monitoring (e.g., augmented with multi-satellite in situ magnetospheric observations of the plasma characteristics; see FMT-5).
    - Stand-alone, single satellite global observations of both the solar wind drivers and key magnetospheric responses, see Section 8.6.8.

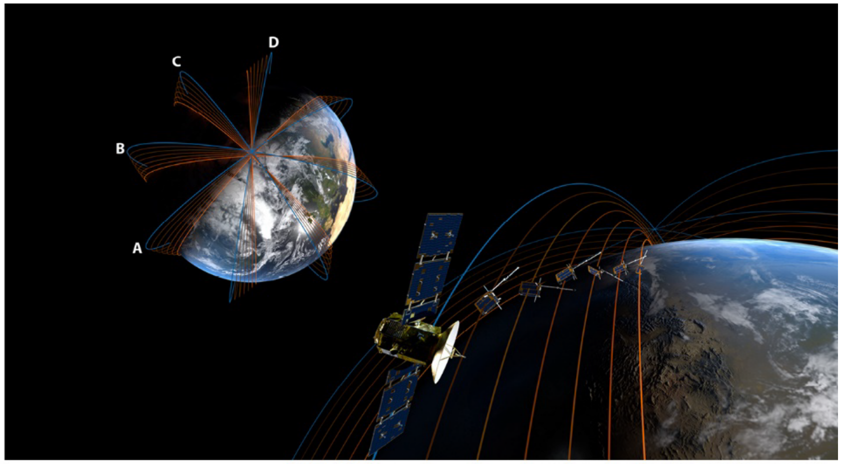
- The concept itself is adaptable and offers the possibility for several trade studies to adjust cost, schedule, or scope to accommodate programmatic considerations. Examples are as follows:
    - Number of spacecraft in elliptical orbit (four spacecraft with apogee at the Northern and Southern hemispheres would provide continuous coverage of both auroral oval regions, which would be scientifically highly relevant)
    - Number of spacecraft in circular orbits (adding spacecraft and/or instrumentation would allow for monitoring of the magnetospheric boundaries and/or the geomagnetic tail not included in the basic concept study)
    - Number of spacecraft in the 30 R_E circular orbit to accomplish continuous global observations of both solar wind drivers and responses (see end of Section 8.6.8, option of two satellites at 90° phase along the same orbit)
    - Bus options and trades from small satellites to major missions
    - Scalability costs (particularly ground operations)

6.8. FMT-7: Low-Earth-Orbit Constellation for Ionosphere/Thermosphere/Mesosphere (ITM) System Observations

Study performed at GSFC Mission Design Laboratory

Concept Summary

- **Science Objective:** Understanding the 4D (3D space, 1D time) dynamics and response of the thermosphere (density, composition, temperature, and wind) to drivers (heating, cooling, mass, and momentum transfer) from above and below, especially during geomagnetic storms
- **Design Approach:**
  - Four motherships, each carrying six CubeSats, are put in polar low-Earth-orbit (LEO) circular orbits (600 km) by a single launch. They drift to different local times over a year.
  - The motherships also carry remote sensing instruments and release CubeSats by dipping to 400 km.
  - The CubeSats will have in situ instruments only.



LWS SSAs Addressed

- Directly: **SSA-VII**
- Indirectly: **SSA-III, SSA-IV, SSA-V, SSA-VI, SSA-VIII, SSA-IX**

Required Technology

- In situ instruments for neutral density, composition, and wind; electric and magnetic field; and particle precipitation
- Remote sensing instruments for thermospheric neutral density, composition, and wind profiles (e.g., O THz limb scanner, far ultraviolet scanning spectrograph imager, and NO 5.3-µm limb imager)

Why Is It an FMT?

- The architectural element is flexible and offers the possibility of several trade studies for adjustment of cost, schedule, or scope. For example:
  - Addition of additional motherships at different LEO altitudes
  - Tailoring of instruments to each mothership, in contrast to the identical configuration shown in this study; note, however, that this may impact the redundancy of the constellation and require a mission assurance class change.
  - Scalability of costs, particularly in the process of mothership deployment (single dedicated launch or multiple rideshare launches), communications infrastructure (dedicated ground station passes for all elements or networked communications using new LEO commercial capabilities), and payload designs (existing versus new development instrument packages).

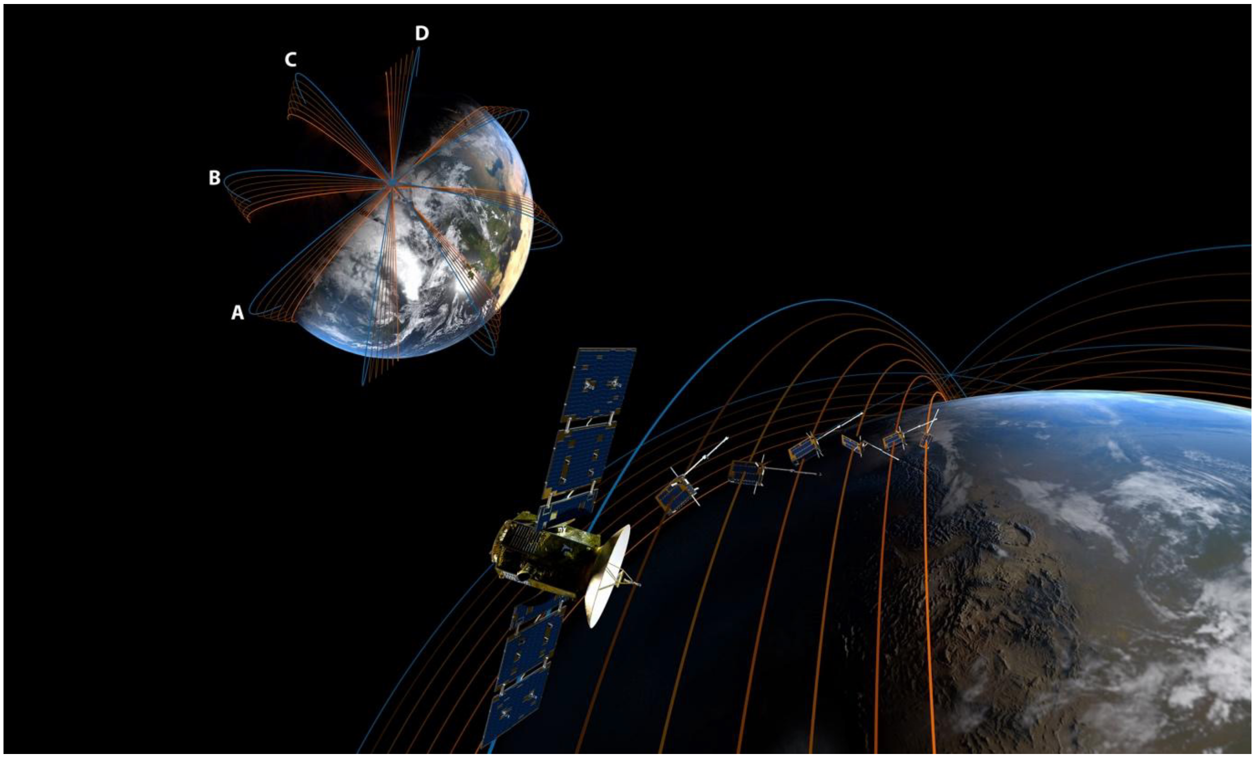


Figure 6-9. **The MAVRIC-D mission concept.** The primary objective of the mission is to obtain a simultaneous sampling of a large volume of the ITM system through the deployment of a constellation of "motherships," each of which deploys multiple CubeSat secondary probes. The four mothership platforms orbit in near-circular 600-km polar orbits with ~90° separation in longitude (upper left). Each mothership carries six probe spacecraft that are released at specific altitudes during the early mission phase. The probes separate in LT relative to the mothership and to each other because of orbital period variation, eventually covering a full range of LTs and altitudes from 350 to 600 km. The motherships continuously acquire remote sensing observations of chemistry, thermodynamics, and atmospheric dynamic drivers of the system.

The prime science objective of FMT-7 is to understand the neutral and ion composition of the ITM system and the primary drivers of neutral and ion density changes during geomagnetic storm conditions. In particular, the mechanisms by which neutral density increases during geomagnetic storms remain poorly understood; reliable predictions of thermospheric neutral density changes are not currently available, directly impacting satellite drag calculations that are the primary source of uncertainty in LEO satellite trajectory prediction. The recent loss of 40 Starlink satellites on 2 February 2022 because of excessive drag after their deployment in a 210-km perigee "staging orbit" during G1 geomagnetic storm conditions illustrates the strong variability in thermospheric neutral density, even during minor storms. SpaceX estimates that the neutral density at 210 km was 50% larger than what was experienced in prior launches during geomagnetically quiet conditions. Although a 50% density increase at 210 km is not surprising to ITM researchers, there are currently no empirical or physics-based models that can *accurately and reliably* forecast such changes, particularly for the stronger storms in the G3–G5 category. In particular, the physical links between magnetospheric field variations due to CMEs or solar wind driving, ionospheric preconditioning by solar EUV radiation, and ionospheric electrical currents that drive Joule heating and subsequent expansion of the neutral thermosphere remain unclear.

A primary reason for the lack of predictive models of thermospheric neutral density is that missions providing neutral atmosphere measurements have flown only at single altitudes while carrying only accelerometer instruments and Global Navigation Satellite System (GNSS) precise orbit determination (POD) antennas. Although accelerometer and POD measurements from missions such as CHAMP, GRACE, GOCE, and Swarm provide high-fidelity density inferences, they do so at fixed altitudes (typically above 450 km[1]), and these missions were not optimized to measure thermospheric density or ionospheric composition.

FMT-7 is specifically targeted at *simultaneously* measuring both neutral density variations and molecular and ion composition of the atmosphere at a range of altitudes from the mesosphere (80–200 km) to the middle thermosphere at 600 km. To overcome the spatial and temporal sampling limitations of past missions, FMT-7 requires a *constellation* of identical satellites deployed at multiple LT polar orbit planes as well as smaller "probe" satellites deployed to a range of altitudes in these LT orbital planes. This concept is very flexible and could be developed using a variety of main satellite and probe designs and mission assurance classes. For example, the main satellites could be large imaging platforms that deploy the probe satellites from their nominal altitudes, or the main and probe satellites could be deployed via separate launch operations. The concept is also very flexible as to how many LT orbital planes are occupied, the constellation deployment schedule, and the concept of operations of the constellation. However, a foundational characteristic of the concept is the use of identical satellites and instrumentation suites to ensure both redundancy and intercalibration of instruments and also to reduce cost.

The existence of a GDC-like mission is assumed in the development of this FMT, and we note that GDC will likely consist of four spacecraft deployed in a single orbital plane at two altitudes, at most. Thus, depending on the instrument suite chosen, the GDC mission may fill some of the LT/altitude slots that FMT-7 would otherwise need to fill. But we stress that synergy between GDC and FMT-7 is highly dependent both on GDC carrying high-fidelity neutral density diagnostic instruments and on GDC data being available and interoperable with any science studies associated with FMT-7.

6.8.1. Relevance to the LWS Architecture Committee Objectives

FMT-7 focuses primarily on SSA-VII (Composition and Energetics of the Neutral Upper Atmosphere) and includes charged-particle instrumentation to measure the LEO components of SSA-VIII (Radiation and Particle Environment from Near Earth to Deep Space). The orbital design and instrumentation also contribute observations relevant to SSA-III to SSA-VI as well as SSA-IX, making this FMT a truly wide-scope element in any future LWS mission architectural implementation.

Table 6-3 shows the relevant SSA observational goals that FMT-7 addresses. A more detailed science traceability matrix that was used to develop the MAVRIC-D mission concept is shown in the detailed spreadsheets.

---

[1] GOCE orbited at only 260 km but as a result had a particularly short 3.5-year measurement span from 2009 to 2013 (before the peak of Solar Cycle 24) and was optimized for gravimetric studies, not thermospheric neutral density variations during geomagnetic storms.

Table 6-3. Mapping of FMT-7 objectives to LWS SSA observational objectives.*

SSA	Observational Objectives Addressed by FMT-7
III	Megaelectronvolt charged-particle measurements in LEO
IV	Kiloelectronvolt charged-particle/plasma measurements in LEO
V	Infrared emissions of the upper atmosphere
VI	Neutral density, temperature, and composition of the thermosphere
VII	All of the observational goals of this primary SSA for FMT-7
VIII	Megaelectronvolt charged-particle measurements in LEO
IX	State and composition of the lower and middle atmosphere

*Note that SSA-VII (Composition and Energetics of the Neutral Upper Atmosphere) is the primary SSA to which FMT-7 is designed.

In a quantitative summary, FMT-7 addresses the following number of observational objectives for each relevant SSA: III (3 of 6), IV (1 of 3), V (8 of 12), VI (3 of 4), VII (5 of 6), VIII (2 of 4), and IX (4 of 5).

6.8.2. Why Is It an FMT?

FMT-7 brings together critical measurements at a range of LEO altitudes that have previously only been accomplished through disparate, single-altitude missions. It represents an LWS mission architecture element because it uniquely addresses a critical Sun–Earth system science goal, sampling a large volume of the complex ITM system using an adaptable constellation concept that can be easily modified to achieve other NASA Heliophysics or Earth Science division goals in LEO.

The architectural element is flexible and offers the possibility of several trade studies for adjustment of cost, schedule, or scope. Examples are as follows:

- Addition of additional motherships at different LEO altitudes
- Tailoring of instruments to each mothership, in contrast to the identical configuration shown in this study; note, however, that this may impact the redundancy of the constellation and require a mission assurance class change
- Scalability of costs, particularly in the process of mothership deployment (single dedicated launch or multiple rideshare launches), communications infrastructure (dedicated ground station passes for all elements or networked communications using new LEO commercial capabilities), and payload designs (existing versus new development instrument packages)

6.9. FMT-8: The Cold Plasma Cycle

No concept study performed

Concept Summary

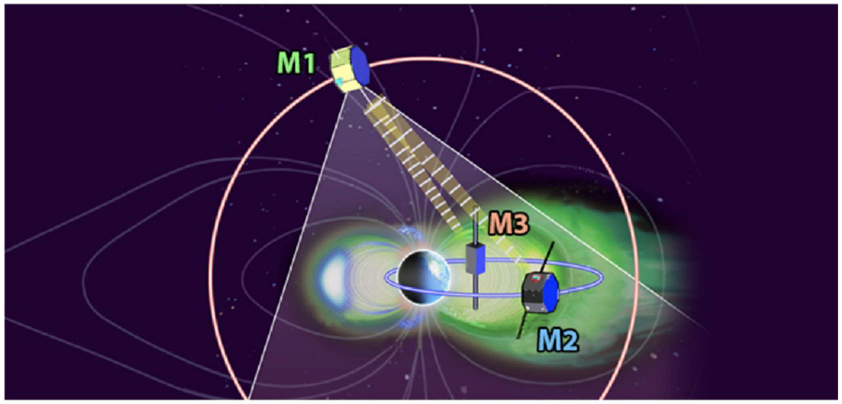
- **Science Objective:** Understand the circulation dynamics of magnetospheric cold plasma, from the ionosphere to magnetospheric circulation or loss, and its impact on the storm cycle of emptying and refilling of the plasmasphere, where most of the cold plasma resides
- **Design Approach:** Three-satellite mission
  - Imager (M1): High-inclination 20 R_E circular polar orbit; EUV global imaging of plasmasphere; radio receiver for total electron content (TEC) along lines of sight from M2 and M3
  - Plasma/Fields (M2): 11-hour equatorial GTO-like orbit (5.8 R_E × 1.1 R_E); in situ E-field, B-field, waves, cold plasma mass spectrometer; radio transmitter to M1 for TEC measurements
  - RadioSat (M3): Microsatellite on the same orbit with M2 with high-cadence radio transmitter to M1 for cross-scale plasma density measurements
- **Launch:** Single ESPA Grande; M1 has an upper stage into circular polar orbit
- **Lifetime:** 2–3 years

LWS SSA Predictive Goals

- The FMT-8 strawman concept addresses the following SSAs:
  - Directly: **SSA-IV, SSA-V**
  - Indirectly: **SSA-III, SSA-VIII, SSA-IX, SSA-X**

Technology Development

- Instruments are mature. All development should be focused on optimizing mission parameters:
  - Orbital acquisition and calculations of ΔV
  - Merging bus capabilities for common bus design
  - Single versus multiple launches



Why Is It an FMT?

- While the global imaging of the plasmasphere is covered in FMT-6 and the wave-particle interactions are covered in FMT-9, nowhere else is the complete cycle of the low-energy plasma studied, which represents a significant gap in our understanding.
- The concept is highly synergistic with other FMTs. It is scalable and adaptable and offers a variety of options that can be tailored to broader or narrower science goals, allowing for implementation flexibility.
- Additional trade studies include the following:
  - Number of M1 spacecraft needed for continuous/optimal coverage from polar orbit
  - Inclusion of additional RadioSat (M3) microsatellites
  - Altitude of the circular orbit versus spatial resolution of the global images

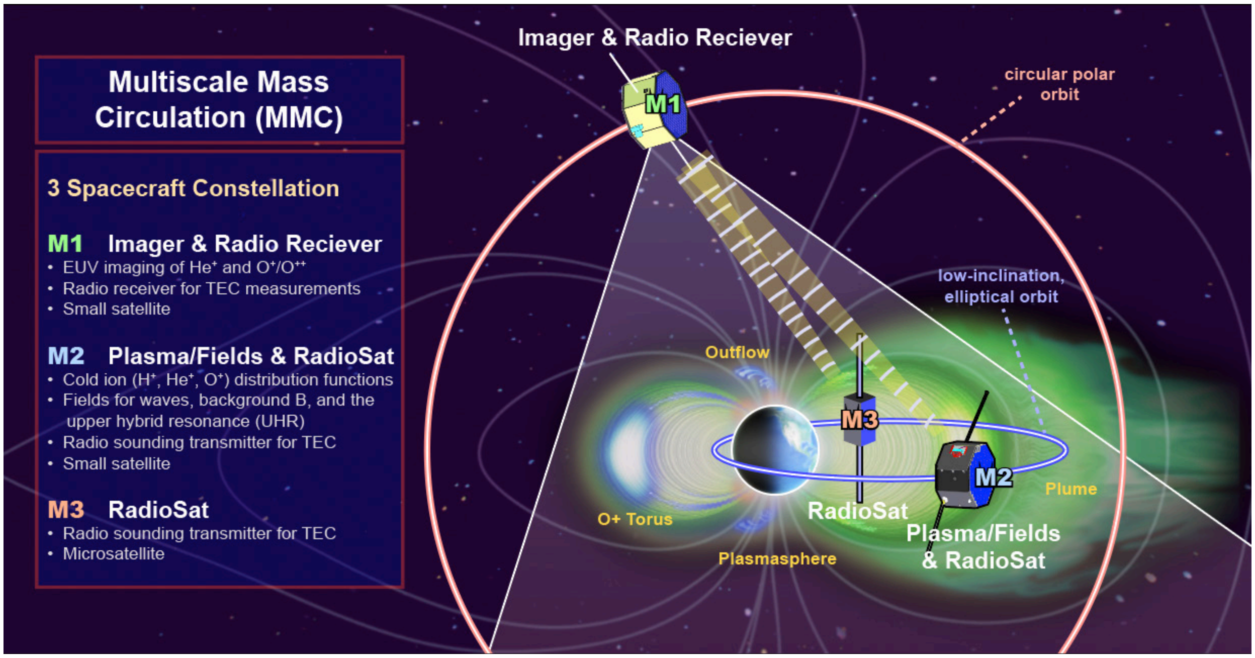


Figure 6-10. **The FMT-8 mission concept.** MMC is a three-spacecraft constellation that combines imaging, in situ measurement, and limited radio sounding to observe the life cycle of magnetospheric plasma mass across multiple spatial scales.

The goal of this FMT is to understand the life cycle of magnetospheric plasma mass and how it is supplied from the ionosphere and circulated throughout the magnetosphere. Cold plasma (0.1–100 eV) carries the vast majority of this plasma mass (hundreds of metric tons), and understanding its erosion and refilling is one of the biggest knowledge gaps in magnetospheric physics. The majority of the cold magnetospheric plasma resides within the plasmasphere, colocated with the energetic ring current ions and radiation belt electrons, the two plasma populations that carry most of the plasma pressure and energy, respectively. Significant attention and several missions (IMAGE, TWINS, Van Allen Probes, DSX) have been focused on the ring current and radiation belt populations because of their direct and detrimental impacts with satellite surface charging and single event effects. However, it is the underlying cold plasma population that controls the generation of waves that drive the loss and energization processes of the ring current and radiation belt particles. And it is the rapid depletion of the cold plasma during geomagnetic storms and slow refilling after storm recovery that drives ionospheric dynamics and associated space weather impacts in the mid- and low latitudes. It is in part because of the significant challenges inherent in measuring the lowest-energy ions that the life cycle of cold plasma remains the storm-time geospace phenomenon least constrained by observations.

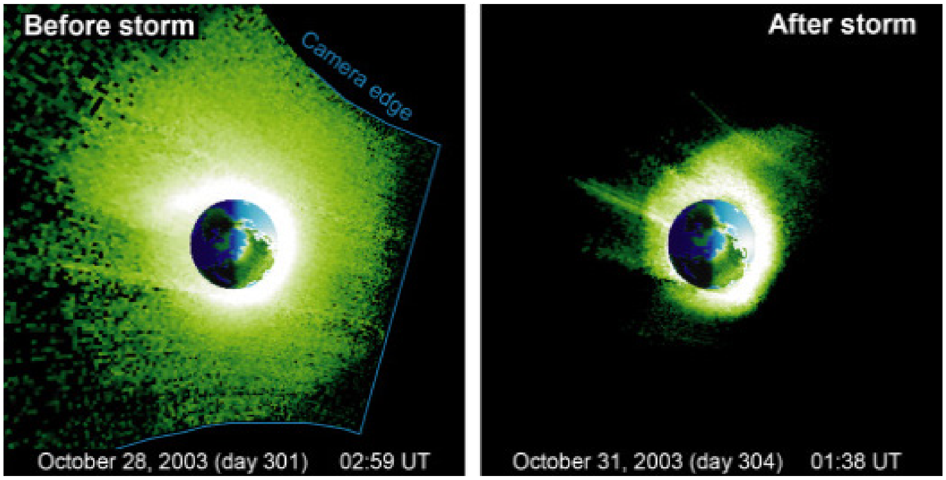


Figure 6-11. IMAGE satellite observations of the erosion of the plasmasphere during the Halloween storm of 28 October 2003. The two images show the before and after size of the plasmasphere. From Hudson et al. (2008).

6.9.1. Relevance to the LWS Architecture Committee Objectives

A mission focused on the cold plasma cycle is an integral, essential component of LWS science. It has a direct link to SSA-V (Dynamics of the Global Ionosphere and Plasmasphere) and to SSA-IV (Variability of the Geomagnetic Environment). It also flows indirectly from SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere), SSA-VII (Composition and Energetics of the Neutral Upper Atmosphere), and SSA-VIII (Radiation and Particle Environment from Near Earth to Deep Space) through the following relationships:

- **Ionospheric outflow.** Both plasmaspheric refilling and creation of the dense oxygen torus involve the supply of enormous masses of plasma from the ionosphere (SSA-V).
- **Coupling through Alfvén waves.** The hundreds of metric tons of plasma mass held by low-energy (<100 eV) ions exert major control over Alfvén waves, whose impacts include energy and information propagation as well as many magnetosphere–ionosphere coupling processes, and have a direct connection to geomagnetically induced current formation (SSA-IV).
- **Reconnection rate control.** The heavy ion mass within plasmaspheric plumes reaching the magnetopause slows dayside reconnection, while the escaping plasmaspheric mass loads the plasma sheet affecting the intensity of the substorm processes (SSA-IV).
- **Particle acceleration.** As the low-energy plasma propagates throughout geospace, it is heated to hundreds of electronvolts or even to kiloelectronvolt energies during its circulation, and can contribute up to 40% of the plasma in parts of the plasma sheet and ring current (SSA-IV).
- **Wave-particle interactions.** The dynamic mass distribution in the plasmasphere defines formation regions of the plasma waves that control acceleration and loss processes of the radiation belt electrons and ring current ions (SSA-III, SSA-VIII).

- **Exospheric interactions.** The high-density plasmasphere can boost the Coulomb collision rate with the low-energy ring current (SSA-IV) and regulate charge-exchange interactions that strongly influence the global escape rate of the neutral H exosphere (SSA-VII).

6.9.2. Why Is It an FMT?

This FMT focuses on the science of plasma mass circulation, which is not explicitly described elsewhere in LWS science. The inner magnetosphere hosts three distinct plasma regions—the plasmasphere, the ring current, and the radiation belts—which are all partially colocated and strongly interacting especially during geomagnetically active times. Understanding these interactions is critical for determining when, where, and how the ring current and radiation belts wax and wane, with implications for spacecraft safety, as well as how the magnetosphere–ionosphere coupling processes drive space weather impacts seen in the ionosphere and on the ground.

While the higher-energy populations have been studied previously, the complexity of measuring low-energy plasmas has often resulted in the exclusion of such instrumentation from inner magnetosphere missions. This FMT study focuses exclusively on the cold plasma and its processes, using a multitude of instrumentation, which would significantly increase our understanding of the ionosphere as a plasma source, and the circulation of mass within the magnetosphere.

This FMT study can be adapted to different LWS science objectives and SSAs, and a similar mission architecture can be used as part of numerous other mission concepts. The FMT-8 concept is scalable and adaptable, offering the possibility of several variants that can be tailored to accomplish broader or narrower science goals. For example:

- Inclusion of a second imager spacecraft provides continuous stereo imaging. This option optimizes the ability to image the 3D distribution of plasma mass, by obtaining simultaneous equatorial and meridional views.

- Inclusion of additional RadioSat microsatellites will increase the number of total electron content (TEC) lines of sight (LOSs), better constraining the plasma density distributions determined from EUV image inversions. Up to four RadioSats can be mounted on a single ESPA port (see below).

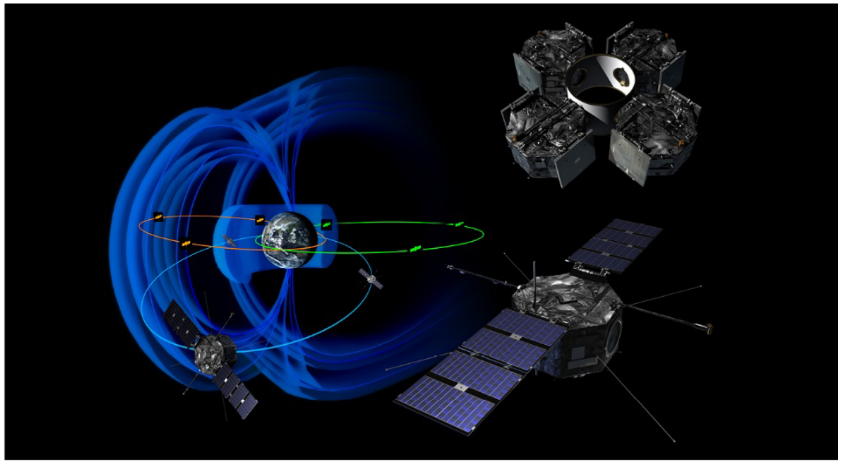
- Lowering of the imager circular polar orbit radius to 10 R_E or 8 R_E will increase the spatial resolution of global images.

6.10. FMT-9: Inner Magnetosphere and Radiation Belts Mission

Study performed at APL ACE Lab

Concept Summary

- **Science Objective:** Understand the response of the near-Earth space environment to solar and geomagnetic disturbances affecting energetic charged particles in the radiation belts and inner magnetosphere
- **Design Approach:**
  - Identical copies of a spin-stabilized spacecraft in multiple geosynchronous transfer orbit (GTO)-like orbits covering a range of magnetic local times (MLTs), 1.2 ≤ L-shell ≤ 7.0, and low magnetic latitudes
  - Each GTO-like orbit precesses to cover the entire MLT range over a period of <0.5 years with the full constellation
  - Near-real-time communications enabling nowcasting capabilities as well as data-assimilative inputs for ring current and radiation belt forecasting models



LWS SSAs Addressed

- **SSA-VIII** (Radiation and Particle Environment from Near Earth to Deep Space)
- **SSA-IV** (Variability of the Geomagnetic Environment)
- **SSA-V** (Dynamics of the Global Ionosphere and Plasmasphere)

Required Technology

- In situ instruments for energetic electron and ion measurements covering the energy range from cold plasma to ring currents (1 keV to 1 MeV) to relativistic particles in the inner and outer radiation belts (1–10 MeV e– and up to 1 GeV/nuc ions)
- Direct current (DC) magnetic field instrumentation
- Alternating current (AC) electric and magnetic field instrumentation
- Spacecraft charging instrumentation

Why Is It an FMT?

- The energetic particle environment in near-Earth space affects critical orbital technology. Spacecraft charging remains poorly understood but is a source of many anomalies. Single event upsets due to relativistic particle impacts are another major source of orbital anomalies.
- The response of the radiation belts and ring current systems to solar wind and geomagnetic storm inputs remains poorly understood and is largely unpredictable.
- The Van Allen Probes mission demonstrated that many of the remaining questions can only be addressed with multiple simultaneous measurements at a range of MLTs, rapid (<2-hour) L-shell revisit times, and overlap between measurements in GTO and geosynchronous Earth orbit regions.

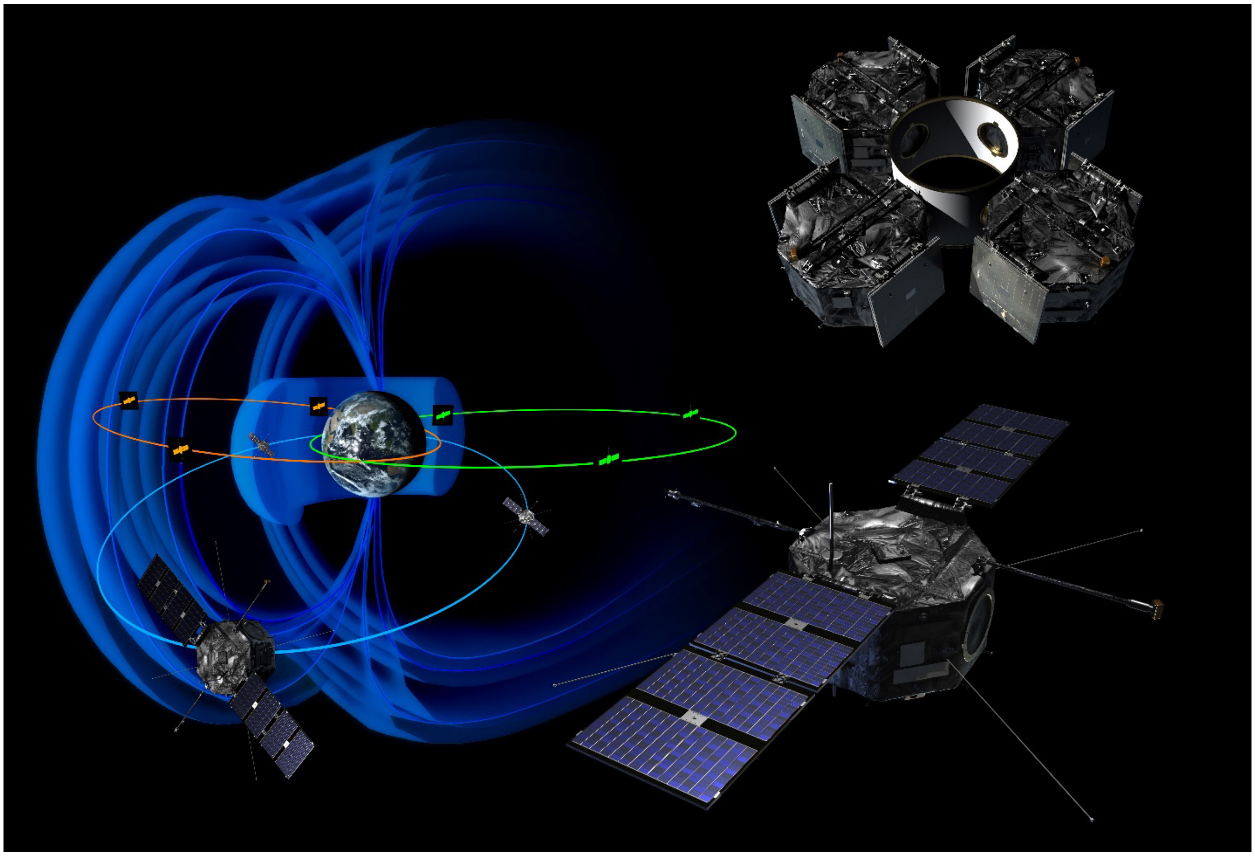


Figure 6-12. The FMT-9 concept that explores the near-Earth environment.

The prime science objective of FMT-9 is the measurement of the energetic charged particle (ECP) radiation environment of the inner magnetosphere and near-Earth space. This FMT primarily addresses the SSA-VIII, (Radiation and Particle Environment from Near Earth to Deep Space), but it also provides data that can be used to address several other SSAs, including SSA-IV (Variability of the Geomagnetic Environment), SSA-V (Dynamics of the Global Ionosphere and Plasmasphere), and SSA-VI (Ionospheric Irregularities). FMT-9 will also address new and outstanding science questions identified and remaining following the Van Allen Probes termination of mission in October 2019. Mission designs for FMT-9 that are cognizant of the requirements for operational space weather forecasting and nowcasting may also provide critical data for improving operational space weather services, including prompt reporting of radiation hazards to spacecraft in all geospace orbits as well as to astronauts in near-Earth geospace.

The near-Earth radiation environment is highly dynamic and results from a complex interplay between cold and warm plasmas, several key plasma wave modes, and energetic particles in the ring current and radiation belts. From Van Allen Probes, we understand the critical roles of wave-particle interactions in dictating the response of Earth’s radiation belt electrons to geomagnetic activity:

- Chorus waves and acceleration mechanisms
- Hiss and electromagnetic ion cyclotron (EMIC) waves and loss-cone scattering mechanisms

- Ultralow frequency (ULF) waves and acceleration and radial transport/redistribution mechanisms

Radiation belt electrons are also important energy inputs to Earth's ionosphere and atmosphere (mesosphere, stratosphere) systems. However, from Van Allen Probes, we also know that the wave environments that determine the radiation belt electron population dynamics are strongly dependent on radial distance (L-shell), magnetic local time (MLT), and geomagnetic activity level as well. Without *simultaneous* observations of the wave environment spanning the relevant range of L-shell and MLT, it is not possible to accurately predict how the radiation belt electrons will respond to particular geomagnetic conditions on timescales relevant to space weather predictive studies.

There are many key unanswered questions regarding how the plasmasphere and radiation belts respond to geomagnetic storm conditions triggered by solar wind CIRs and CMEs—the primary drivers of major space weather events in geospace. In particular, the exact mechanism of ring current energization and whether or how it differs for solar wind or CME drivers remains unclear. Substorm impacts on radiation belt structure and spacecraft charging events, driven by magnetotail reconnection and "dipolarization," also remain poorly understood: Current maps of radiation belt dynamics during geomagnetic storming are based on the single-orbit Van Allen Probes mission and invariably show oversimplified longitudinal MLT symmetry.

Observations from the LEO environment alone are too different and remote to offer sufficient accurate predictive/forecast capabilities. Observations from the GEO environment alone are too different from the core/heart of the outer and inner electron radiation belts to offer sufficient observations for accurate predictive/forecast capabilities. There is wide agreement in the space physics community that while the magnetic equatorial geosynchronous transfer orbit (GTO) Van Allen Probes mission revolutionized our understanding of radiation belt physics, particularly in regard to wave-particle energy exchange across the L-shell domain, it also established the clear need for simultaneous multi-MLT measurements of key radiation belt and plasmasphere characteristics in order to understand the non-axisymmetric structure and dynamics of the radiation belts and plasmasphere. This can only be accomplished by a constellation of spacecraft in appropriate orbital configurations that enable these measurements. Thus FMT-9, like many other LWS architecture elements, aims to establish a multi-spacecraft constellation spanning orbital regimes from LEO out to and beyond GEO.

In addition to addressing key science questions concerning cross-species and cross-energy coupling critical to radiation belt physics, properly designed FMT-9 concepts can also offer radiation nowcast and forecast capabilities enabled by multi-satellite constellation designs optimized to provide the time, L-shell, and MLT resolution necessary for resolving the dynamic, storm-time geospace radiation environment.

6.10.1. Relevance to the LWS Architecture Committee Objectives

The primary objectives of FMT-9 are as follows:

- Develop science-based predictions of the dynamic radiation environment and spacecraft charging environment from the troposphere through geosynchronous Earth orbit (GEO) and out into interplanetary space.

- Develop predictions of their relevance to hazardous upper-atmosphere and spaceflight conditions.

The specific predictive goals of FMT-9 are as follows:

- Improve the prediction of the radiation environment from the troposphere to interplanetary space, and within planetary magnetospheres—particularly for high-radiation disturbed periods such as during solar proton events and geomagnetic storms.
- Develop predictions of hazardous upper-atmosphere (e.g., polar airline route) and orbital spaceflight conditions, particularly in LEO where commercial spaceflight and space stations are developing.

FMT-9 measurements can also contribute to addressing other SSAs in the LWS science architecture, specifically:

- **SSA-IV: Variability of the Geomagnetic Environment.** FMT-9 measurements of the ECP environment in geospace will record the incoming, accelerated particles from the magnetotail, thus contributing to understanding the plasma and energy flow relevant to science investigations related to SSA-IV.
- **SSA-V: Dynamics of the Global Ionosphere and Plasmasphere.** FMT-9 measurements of the ECP environment in geospace will record the accelerated populations by local wave-particle interactions, thus contributing to science investigations relevant to SSA-V.
- **SSA-VI: Ionospheric Irregularities.** FMT-9 measurements of the ECP environment in geospace will contribute energetic particle distribution data to science investigations relevant to SSA-VI.

Table 6-4 details the FMT-9 mapping to several SSA observational objectives. Note that SSA-VIII (Radiation and Particle Environment from Near Earth to Deep Space) is the primary SSA to which FMT-9 is designed.

6.10.2. Why Is It an FMT?

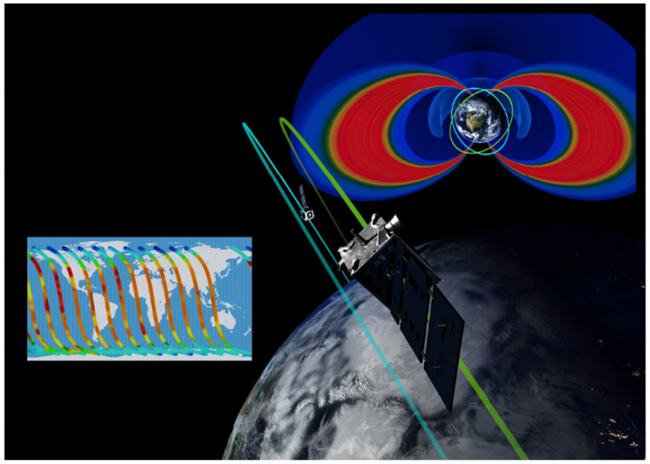
FMT-9 fills a critical gap in our observational capabilities relating to the formation, structure, and dynamics of Earth's radiation belts. It represents an LWS mission architecture element because it uniquely addresses a critical Sun–Earth system science goal, sampling a large volume of the complex inner magnetosphere system using an adaptable constellation concept that can be easily modified to achieve a range of Heliophysics or Earth Science division goals related to planetary magnetospheric environments and the linkages to ionospheric and atmospheric environments.

6.11. FMT-10: Solar Impacts on Climate

No concept study performed

Concept Summary

- **Science Objective:** Understand and predict how solar activity, both electromagnetic and particulate, impacts the climate of a planet with an established atmosphere, in particular focusing on nitric oxide (NOx) life cycle throughout a solar cycle
    1. How does solar spectral irradiance (SSI) variability affect the circulation between the upper (thermosphere), middle (mesosphere), and lower (stratosphere) atmosphere?
    2. How do geomagnetic storms impact the circulation throughout the whole (upper, middle, and lower) atmosphere?
    3. What is the effect of energetic particle precipitation (EPP) on the chemistry and subsequent transport throughout the whole atmosphere?
- **Design Approach:** ESPA-compatible, >2 constellations to monitor broader horizontal coverage in the polar region; coverage altitude 60–150 km; >5-year mission lifetime; low Earth orbit 98° inclination (Sun-synchronous)



LWS SSAs Addressed

- Directly: **SSA-IX, SSA-III, SSA-VII**
- Indirectly: **SSA-IV, SSA-V**

Technology Developments

- Inter-spacecraft communication design/operations
- Continuous measurements of NOx between 60- and 150-km altitude
- Simultaneous measurements of energy input to the upper atmosphere and the impacted atmospheric compositions, wind, and temperature

Why Is It an FMT?

- First mission concept to directly address SSA-IX goals
    - The SSA goals lie in the “no man’s land” between Heliophysics Division and Earth Science Division regimes
    - Concept could act a trailblazer
- Architecture concept for “solar cycle”-scale missions
    - Evaluate high reliability versus multiple launches
- Adaptable to several missions targeting stratosphere–mesosphere interface chemistry

The overarching science objective of the FMT-10 FMT is to understand and predict how solar activity, both electromagnetic and particulate, impacts the climate of a planet with an established atmosphere, in particular, focusing on nitric oxide (NOx) life cycle throughout a solar cycle. The specific science questions to be addressed are as follows:

4. How does solar spectral irradiance (SSI) variability affect the circulation between the upper (thermosphere), middle (mesosphere), and lower (stratosphere) atmosphere?
5. How do geomagnetic storms impact the circulation throughout the whole (upper, middle, and lower) atmosphere?
6. What is the effect of energetic particle precipitation (EPP) on the chemistry and subsequent transport throughout the whole atmosphere?

The concept is summarized in Figure 6-13. Section 8.10.1 presents details of the mission concept.

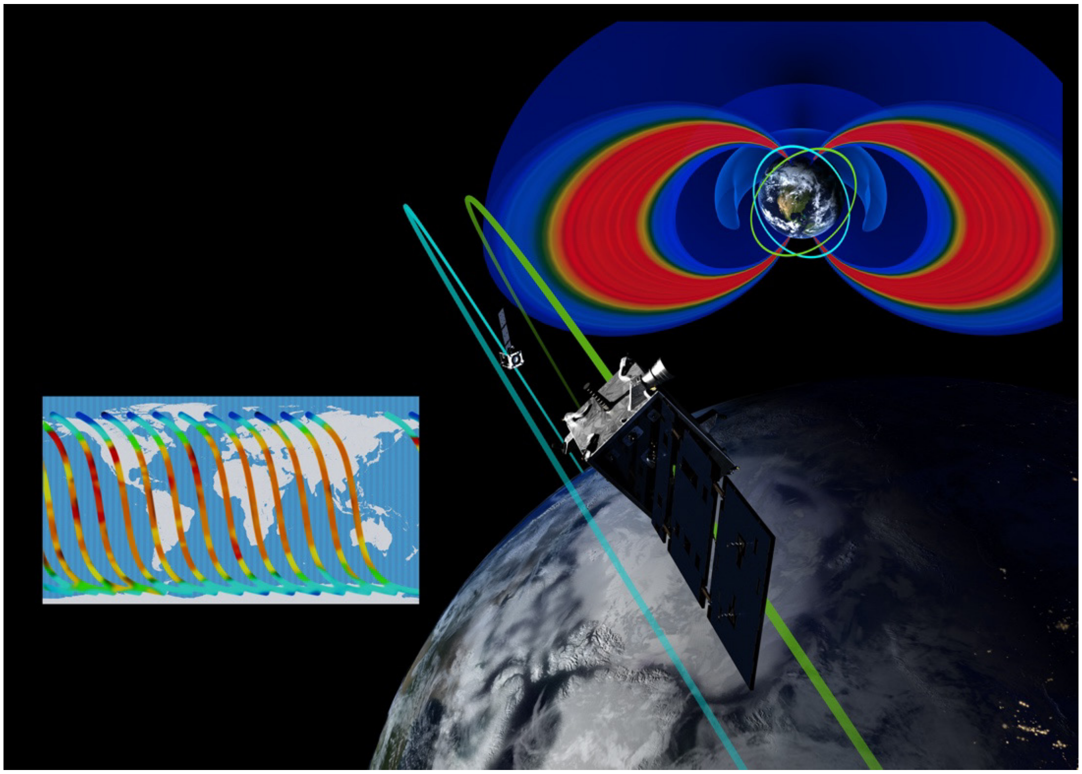


Figure 6-13. **The FMT-10 concept.** It uses a constellation (2+ spacecraft) to obtain atmospheric chemistry measurements through the space-troposphere interface. The goal of missions within this concept is to decipher the impact of solar activity on Earth on climatological timescales.

6.11.1. Relevance to the LWS Architecture Committee Objectives

This FMT design flows primarily from the predictive goals of SSA-IX (Solar Impacts on Climate), SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere), and SSA-VII (Composition and Energetics of the Neutral Upper Atmosphere), and secondarily from SSA-IV (Variability of the Geomagnetic Environment), SSA-V (Dynamics of the Global Ionosphere and

Plasmasphere), and SSA-VIII (Radiation and Particle Environment from Near Earth to Deep Space). However, FMT-10, because of its interdisciplinary nature of the science topic as summarized in Section 8.10.1, addresses objectives of additional SSAs as well.

We demonstrate the interdisciplinary LWS relevance of the FMT-10 concept in Figure 6-2. The detailed traceability for each SSA can be found in the respective spreadsheet.

6.11.2. Why Is It an FMT?

The FMT-10 concept did not undergo a mission design study because of time constraints. Therefore, the implementation details, such as payload size, orbit parameters, and the concept of operations, may require some changes as a result of a study. However, our emphasis is on the larger architecture-level design elements. Many of these elements are common to the other geospace studies, and thus we are confident that FMT-10 represents a viable FMT. Specifically, it is an FMT for the following reasons:

- The SSA-IX goals extend across the “no man’s land” between NASA’s Heliophysics Division (HPD) and Earth Science Division (ESD) programmatic areas of authority, which leads to piecemeal and overall disconnected approaches to understanding the effect of space processes on the terrestrial atmosphere. FMT-10 is designed as an *interdivisional* mission concept that bridges this gap by envisioning a “whole atmosphere observing system.” This is a trailblazing concept that can spawn several focused mission concepts to attack specific issues in the space-atmosphere coupling (e.g., a mission targeting the stratosphere/mesosphere interface chemistry and dynamics). The Space Weather Gap Analysis identifies measuring EPP into E- and D-regions as a high priority. Although the important role played by NO (generated by EPP) in regulating thermospheric temperature in recovery of geomagnetic storms is recognized, another role of NOx in connecting the geospace to the lower atmosphere is not accounted for very well in the report).

- In addition, FMT-10 is promoting an architecture for “solar cycle”-length *research* missions. Long-term missions are usually the purview of operational agencies, focused on monitoring rather than active research. NASA HPD missions tend to be designed with short life cycles to reduce cost and complexity, although they often survive many times their design lifetime (e.g., SOHO, TIMED, STEREO). This experience indicates that long-term missions can be achieved within the mission assurance requirements of typical 2- to 5-year operational life cycles using a multiple-launch approach instead of single, high-reliability spacecraft. FMT-10-like missions could be the first types of this “hybrid” approach to mission design.

- FMT-10 addresses the challenges of temporal and spatial cross-scale coupling and complex coupling between chemistry and dynamics involving multiple atmospheric layers; for example, EPP tends to occur in short temporal (approximately minutes to approximately hours) and spatial scales, while the subsequent impact on the atmospheric chemistry and dynamics (transport) tends to occur in longer temporal scales (approximately a few months) over a broader spatial regime.

6.12. FMT-11: Earth as an Exoplanet

No concept study performed

Concept Summary

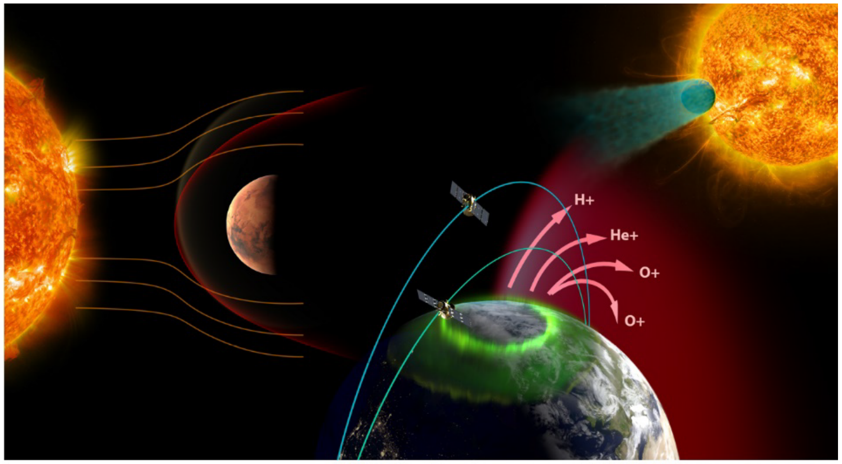
- **Science Objective:** (1) Assess how stellar activity (flares, EUV radiation, SEP events, CMEs) may impact planetary habitability through atmospheric loss; (2) Assess the role of planetary/exoplanetary magnetic fields on atmospheric loss and on shielding the planet from solar/stellar activity
- **Design Philosophy:** Measure *simultaneously* the solar drivers as well as the target system (geocorona or thermosphere) and its reaction (ion/neutral escape).
- **Design Approach:** The mission employs a three-component systems architecture.
  - Solar driver: Earth-impacting solar wind/flux properties (plasma, magnetic field, EUV, etc.)
  - Target: EUV measurements of major species of upper thermosphere and geocorona and plasma properties at the acceleration region (in situ)
  - Reaction: Mass-resolved ion fluxes at the far tail (down to a few electronvolts)
  - All spacecraft should be ESPA-compatible
  - To measure truly escaping ions, measurement should be made as far as possible along the magnetotail (e.g., at L_2)
  - 5-year mission; ESPA-compatible spacecraft; Class C; single/multiple launches (requires detailed study)

Addressed LWS SSA Predictive Goals

- Directly: **SSA-X** (Stellar Impacts on Planetary Habitability)
- Indirectly: **SSA-IV** (Variability of the Geomagnetic Environment), **SSA-V** (Dynamics of the Global Ionosphere and Plasmasphere), **SSA-VII** (Composition and Energetics of the Neutral Upper Atmosphere), **SSA-IX** (Solar Impacts on Climate)

Required Technology Development

- Active potential control of the spacecraft
- Cold plasma measurement techniques



Why Is It an FMT?

- It represents a holistic measurement approach where all three aspects of the problem—the drivers (solar inputs), the target system (geocorona or thermosphere), and the reaction to the driver (ion/neutral escape)—are addressed simultaneously to answer a multidivisional question: “Do planetary magnetospheres affect the habitability of a planet?” The specific measurements can be achieved with different payload and orbital configurations.
- The concept’s orbital requirements and measurement types neatly complement the designs of other FMTs: magnetospheric imaging (FMT-6), plasmasphere (FMT-8), solar climate (FMT-10), and perigeospace (FMT-12). The goals of SSA-X can be achieved via dedicated missions or as components of/additions to other FMTs.

The goal of this FMT is to synthesize current information and ideas about exploring Earth as a prototype for exoplanets to understand and assess their potential for habitability. This FMT addresses SSA-X, which seeks to understand and predict how stellar activity and the space environment near a planet and its moons can impact the planet's habitability. It is a novel research realm inspired by the more than 4000 exoplanets that have already been discovered. Because no specific mission can yet make definitive observations on exoplanet habitability, this FMT focuses on how Earth can be used to understand the mechanisms of atmospheric loss and how solar activity and the planetary environment can impact it.

The FMT is built around two overarching science objectives:

1. Assess how stellar activity (flares, EUV radiation, SEP events, CMEs) may impact planetary habitability through atmospheric loss

2. Assess the role of planetary/exoplanetary magnetic fields on atmospheric loss and on shielding the planet from solar/stellar activity

These objectives can be achieved by leveraging data from multiple missions throughout our own solar system and by applying state-of-the-art models that the heliophysics community has developed, with an eye toward the expanding field of exoplanetary research and the key factors that control planetary habitability. Additionally, the aim of these investigations is, in turn, to feed back on and improve studies of the heliosphere by testing heliospheric models under different conditions.

6.12.1. Relevance to the LWS Architecture Committee Objectives

FMT-11 follows directly from the predictive goals of SSA-X (Stellar Impacts on Planetary Habitability). It also flows from SSA-IV, SSA-V, SSA-VII, and SSA-IX.

Understanding atmospheric loss in Earth's atmosphere leads to the study of energy input to the polar caps from the magnetosphere during active periods (SSA-IV, SSA-V), ionization of neutrals and energization of ions to escape energies (SSA-V, SSA-VII), and global imaging of the response of a planetary environment to solar activity (SSA-V). The mapping of the strawman FMT-11 to the SSAs is shown in Figure 6-2.

6.12.2. Why Is It an FMT?

In SSA-X, habitability of a planet within the habitability zone of its star is linked to its chemistry and atmospheric loss. There are two parameters that impact atmospheric loss: (1) stellar activity (more active stars strip planetary atmospheres more easily, as in Figure 6-14) and (2) the planet's magnetic field, which could shield the planet from both harmful stellar radiation and wind or, depending on its strength, help strip more atmosphere. These are big questions for which research is still in its infancy.

The 4000+ exoplanets identified so far are rocky planets, close-in to their stars and often within the habitable zone. They are typically in systems of K or M dwarves and are "self-selected" by the observational method of discovery, namely stellar variation due to the planetary transit. Ground telescope observations, as well as observation by the TESS mission, have shown that these exoplanets suffer flares and stellar activity much higher than those seen on Earth (Hu et al., 2022). Such activity is likened to our young active Sun in our solar system (Airapetian et al. 2019) with NOx chemistry identified as favorable to habitability.

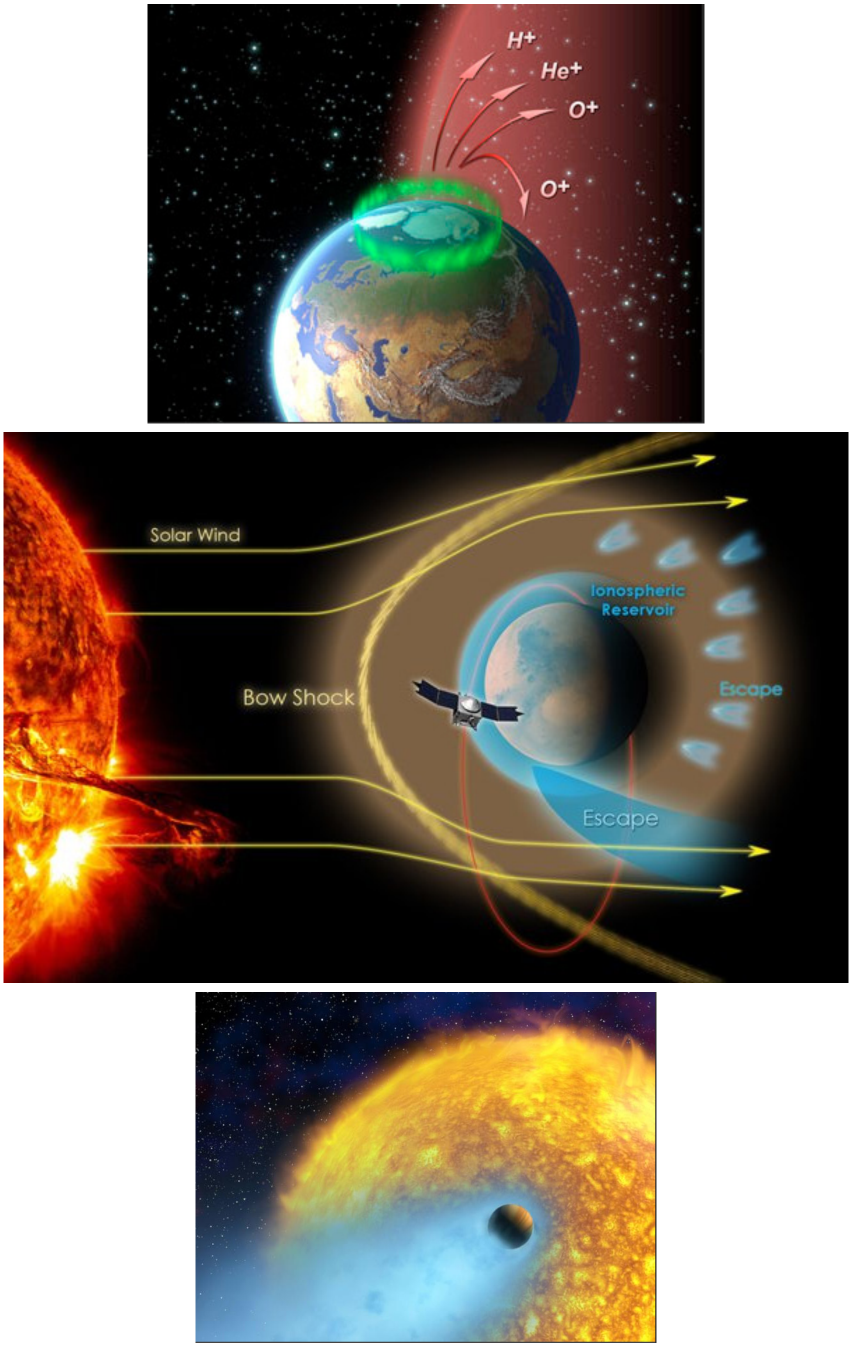


Figure 6-14. (Top) Plasma escape from Earth's ionosphere. (Middle) Atmospheric escape from Mars' atmosphere as observed by MAVEN. (Bottom) An artist's conception of HD 209458 b, an exoplanet whose atmosphere is being torn off at more than 35,000 km/hour by the radiation of its nearby parent star. This hot Jupiter was the first alien world discovered via the transit method as well as the first planet to have its atmosphere studied. [Image credit for bottom panel: NASA/European Space Agency/Alfred Vidal-Madjar (Institut d'Astrophysique de Paris, Centre National de la Recherche Scientifique).]

The MAVEN mission has yielded significant results on Mars's atmospheric evolution but has not found a definitive relationship between solar activity and atmospheric loss, opposite to what was found on Earth from the Polar mission (Moore et al., 1999). Understanding the relationship between ion outflow and exospheric variability with strong solar activity and observing the NOx chemistry cycle with intense solar activity are the required first steps in filling this gap.

It is significant that the best-known habitable planet, Earth, has not to date had a mission dedicated to filling this gap and understanding the impact of solar activity on ionospheric and atmospheric escape. FMT-11 fills that gap. It provides two architecture variants, both of which are highly synergistic with other FMTs and address multiple SSA needs. The path forward is to use such missions to study atmospheric escape on Earth, advance our understanding of the physical processes, advance first-principles models, and then apply those models to exoplanets.

This FMT did not undergo a mission design study because of time constraints. Therefore, we turned to previous mission concepts, proposed in various venues, and extracted the larger architecture-style elements common to all. Many of these elements were studied in the other FMTs or rely on well-understood orbit designs. Specifically, FMT-11 is an FMT for the following reasons:

- It represents a holistic measurement approach where all three aspects of the problem—namely, the solar inputs (drivers), the target system (geocorona or thermosphere), and the reaction to the driver (ion/neutral escape)—are addressed simultaneously to answer a multidivisional question: "Do planetary magnetospheres affect the habitability of a planet?" Although the approach is generic, the specific measurements can be achieved with different payload and orbital configurations.
- The concept's orbital requirements and measurement types neatly complement the designs of the following FMTs: magnetospheric imaging (FMT-6), plasmasphere (FMT-8), solar climate (FMT-10), and perigeospace (FMT-12). This means the goals of SSA-X can be achieved either via dedicated missions (i.e., along the lines of the example concepts discussed later) or as components of/additions to other FMTs, resulting in considerable programmatic and scientific flexibility for the LWS program.

6.13. FMT-12: PeriGeospace Observing System

Only orbit study performed

Concept Summary

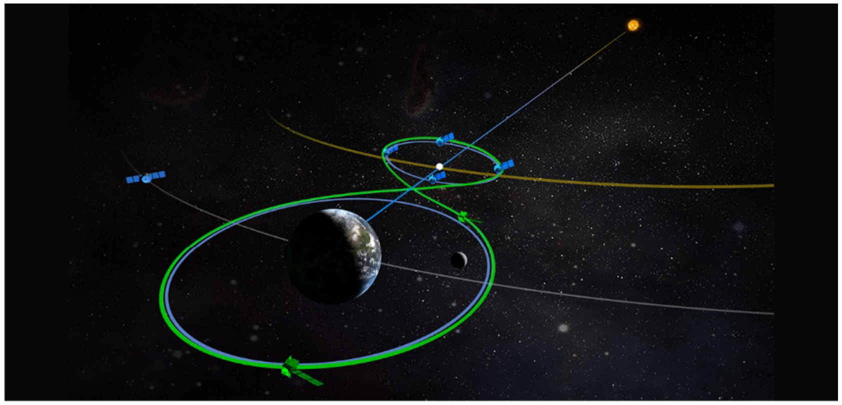
- **Science Objective:** To understand the physical coupling of the solar wind to geospace by measuring and imaging the "last mile" evolution of solar wind structures from L1 to their impact on the magnetosphere in 3D
- **Design Philosophy:** Use a systems approach to capture the state of the solar wind between L1 and the magnetosphere (perigeospace) with distributed in situ spacecraft and multi-viewpoint remote sensing with an adaptable rideshare-based mission architecture
- **Design Approach:** The FMT is built as a system of observing grids
  - **L1-Diamond Grid:** Two to four spacecraft in halo orbits around the Sun–Earth Lagrange point; each spacecraft carries plasma, magnetic field, and intra-grid plasma probing with radio transceivers
  - **L1-Earth Cyclers Grid:** 1+ spacecraft with plasma/field measurements cycling between L1 and Earth; can be combined with L1 grid
  - **PeriGeo Imaging:** Imaging of structures impacting the magnetosphere from an Earth-trailing location; augmentations: imaging of plasmasphere/ionosphere; extreme ultraviolet stereoscopy of Earth-facing eruption sources
  - 2+-year mission; ESPA-compatible spacecraft; multiple rideshare launch; Class D or C

LWS SSAs Addressed

- Directly: **SSA-II** (Solar Eruptive and Transient Heliospheric Phenomena), **SSA-III** (Acceleration and Transport of Energetic Particles in the Heliosphere), **SSA-IV** (Variability of the Geomagnetic Environment), **SSA-VIII** (Radiation and Particle Environment from Near Earth to Deep Space)
- Indirectly: **SSA-VII** (Composition and Energetics of the Neutral Upper Atmosphere), **SSA-IX** (Solar Impacts on Climate), **SSA-X** (Stellar Impacts on Planetary Habitability)

Required Technology Development

- Inter-spacecraft communication design/operations
- Large dynamic range imaging systems



Why Is It an FMT?

- Architecture approach conducive to a variety of missions. For example:
  - The L1-Earth cycler orbits can be adapted to focus on cislunar or Earth polar objectives
  - Can be deployed as a single or multiple grids to satisfy different LWS science objectives
  - The ESPA-class design of the node enables a wide range of launch options
  - The disaggregated approach offers programmatic flexibility and science/operations resiliency
  - The intra-grid radio probing can be adapted to other geospace or heliospheric locations.
- Examples of mission variants based on the PeriGEON architecture:
  - Cislunar grid; upstream-L1 cyclers; Venus L2 cyclers

The overarching science objective of FMT-12 is to understand the physical coupling of the solar wind to geospace by mapping in 3D and imaging the “last mile” evolution of solar wind structures from L1 to their impact on the magnetosphere. The following is an example set of specific science objectives that could be addressed with this FMT:

- What is the mesoscale plasma and magnetic structure (<70 R_E) of solar transients (CMEs, SIRs/CIRs, shocks, and SEPs) in the near-Earth space?
- How does the solar wind interact with the magnetosphere from the magnetopause to the magnetotail?
- What is the relative contribution of external (solar) versus internal (geospace) drivers to space weather?
- How does the solar wind drive regional space weather?

The concept is summarized in Figure 6-15. Section 8.12.1 presents details of the mission concept.

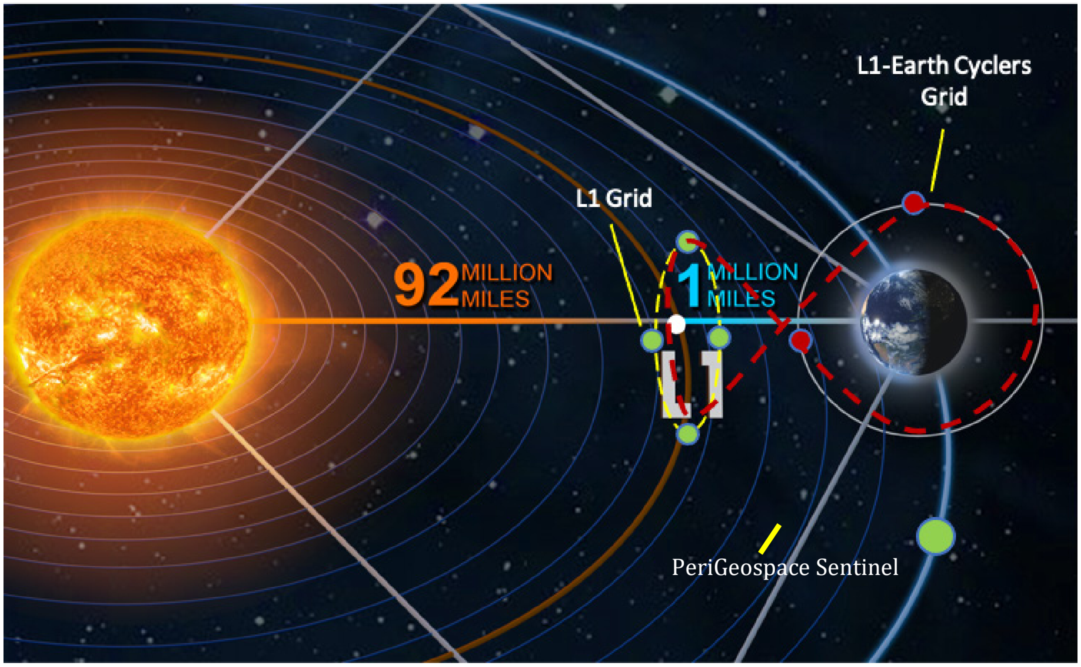


Figure 6-15. **The FMT-12 concept** comprises a three-part system of spacecraft to cover the near-Earth space (or PeriGeospace). Six+ spacecraft orbit between L1 and Earth in Lyapunov orbits so that, at any given time, four of them form a diamond around L1 (“L1 Grid”) to measure incoming solar wind, while 2+ spacecraft orbit between L1 and Earth (and around Earth) (“L1-Earth Cyclers Grid”). The third component is a spacecraft in trailing Earth orbit to image plasma flow through the L1–Moon–Earth system at high signal-to-noise ratio (“PeriGeospace Sentinel”).

6.13.1. Relevance to the LWS Architecture Committee Objectives

We define as FMT-12 “PeriGeospace” the region of space between roughly the Sun–Earth Lagrange L1 point and the magnetopause. From a space weather perspective, PeriGeospace represents the “last mile” of the evolution of solar structures before their impact on the terrestrial environment and is, thus, crucial for understanding the genesis of space weather. PeriGeospace research has been identified as one of the critical gaps in the latest NASA Space Weather Gap Analysis. This region also represents the transition from solar and inner heliospheric (SH) research to geospace (Geo) research and is, therefore, an ideal target for developing cross-cutting mission concepts that could unify the two pillars of heliophysics.

FMT-12 represents an attempt to design exactly such a cross-cutting mission concept. The mission design flows directly from the predictive goals of (1) two SH SSAs: SSA-II (Solar Eruptive and Transient Heliospheric Phenomena) and SSA-III (Acceleration and Transport of Energetic Particles in the Heliosphere) and (2) two Geo SSAs: SSA-IV (Variability of the Geomagnetic Environment) and SSA-VIII (Radiation and Particle Environment from Near Earth to Deep Space). It also addresses predictive goals from SSA-VII (Composition and Energetics of the Neutral Upper Atmosphere), SSA-IX (Solar Impacts on Climate), and SSA-X (Stellar Impacts on Planetary Habitability). Depending on the details of the specific mission implementation, the FMT could support also SSA-V (Dynamics of the Global Ionosphere and Plasmasphere). In other words, this cross-cutting concept can directly impact 8 of the 10 SSAs of the LWS program.

We demonstrate the interdisciplinary LWS relevance of the FMT-12 concept in Figure 6-2. The detailed traceability for each SSA can be found in the respective spreadsheet.

In a quantitative summary, FMT-12 addresses the following number of objectives for each relevant SSA: II (3 of 5), III (6 of 6), IV (3 of 4), and VIII (7 of 8).

6.13.2. Why Is It an FMT?

For reference and clarity purposes, we refer to FMT-12 as the PeriGeospace Environment Observing Network (PeriGEON) from this point forward. The concept did not undergo a mission design study because of time constraints. Therefore, the implementation details, such as payload type and size or the concept of operations, may require changes after such a study. In any case, PeriGEON is not the only interdisciplinary concept. It is presented as an example. However, our emphasis is on the larger, architecture-level design elements. Many of these elements are common to the other FMTs, for both SH and Geo objectives. Specifically, this concept is an FMT for the following reasons:

- It represents a unique SH/Geo mission concept that attacks research gaps in both areas within a unifying architecture. PeriGEON is designed as a true heliophysics mission concept that bridges the SH and Geo communities by envisioning a modular “near-Earth observing network.” The systems approach can spawn several focused mission concepts to attack specific issues in the Sun–Earth coupling, from basic research (e.g., energy flow into the magnetosphere) to R2O (e.g., improved predictions of the 3D interplanetary magnetic field time series).
- PeriGEON promotes an adaptive constellation mission architecture where the members of the constellation vary their concept of operation depending on their location. For

example, the same spacecraft will undertake solar wind observations at L1 and magnetopause observations around Earth, or a Lyman-α imager would observe the plasmasphere near Earth and map the solar Lyman-α variability from L1, etc.

- The concept is modular, with additional spacecraft carrying improved or different instrumentation joining the constellations as rideshare and programmatic opportunities arise. The spacecraft can be provided by U.S. or foreign providers, thus leveraging national and international collaborations.

6.14. FMT-SSA Mapping and Synergies

As discussed in Section 4, the committee developed multiple science objectives for all 10 SSA areas (Table 6-4). These science objectives are more focused than the general SSAs, thus allowing the derivation of measurement requirements for each question. The measurement requirements are necessary to design FMTs and associated mission concepts.

The FMTs, described above, have been developed to target a few of the science objectives but also consider providing measurements that would be critically important for other science objectives. Each science question had at least one FMT targeting it, and often multiple FMTs would provide measurements that would fully address the science objective. This is illustrated in Table 6-4, where an FMT that fully addresses a science question is listed in bold (red for solar/helio and blue for geospace missions). FMTs that contribute significant supporting measurements but that would not fully address the science objective are in regular font (orange for solar/helio and green for geospace missions). The table makes it evident that there is significant overlap and synergy between the various FMTs. This reflects the desire to provide multiple possible approaches to addressing the science objectives.

The color scheme in Table 6-4 also reveals that there is a good balance between solar/helio and geospace FMTs and that often there is a critical synergy between solar/helio and geospace missions, each providing critical measurements. For example, FMT-1, FMT-2, and FMT-3 provide critical solar and solar wind inputs for the geospace FMTs. Reading Table 6-4 from right to left further demonstrates that the selected FMTs were carefully designed to have broad impact. Many FMTs fully address five or more individual science objectives and support half a dozen more.

Although it was not the role of this committee to prioritize or recommend an ordering to the implementation of the FMTs, it is worth noting that advanced planning may result in additional scientific return because of these identified synergies.

Table 6-4. **Relationship between SSA objectives and FMTs.**

SSA	Science Objective	FMT
SSA-I: Origins and Variability of Global Solar Processes	Determine the characteristics of convective flows and meridional circulation at all latitudes and depths down to the tachocline, determine the location and strength of the toroidal magnetic flux belts, and characterize the strength, structure, and evolution of the polar fields to enable predictive models of solar cycle magnitudes and phases.	FMT-3
	Determine the signatures of imminent active region emergence in surface and subsurface flow and magnetic field structures. Understand the origin of active region formation in terms of subsurface flows as a function of depth. Determine the global coronal connectivity of active regions and the mechanisms that lead to their eventual decay.	FMT-1 FMT-3

SSA	Science Objective	FMT
	Determine how chromospheric and coronal magnetic field dynamics and energy inputs from the convection zone/photosphere create solar wind variations on global scales to create "fast" and "slow" solar wind. Understand the mechanisms leading to solar wind stream interactions in the heliosphere, both within and out of the ecliptic plane.	**FMT-1** FMT-2 **FMT-3**
	Understand global solar spectral and total irradiance variation as a function of magnetic field activity at a level sufficient to enable predictive models of planetary atmospheric responses to active region evolution. Enable the transition from empirical characterizations via indices (e.g., F10.7) to measured solar spectral irradiance inputs driving advanced physics-based models of planetary atmospheres.	**FMT-1**
SSA-II: Solar Eruptive and Transient Heliospheric Phenomena	Understand what triggers flares.	**FMT-1** **FMT-3**
	Determine the impact of flares on Earth's atmosphere.	**FMT-4** FMT-7
	Determine what conditions lead to CME initiation and determine the process of CME release from the Sun.	**FMT-1** **FMT-2** **FMT-3**
	Determine the propagation and evolution of interplanetary CMEs in interplanetary space.	FMT-1 **FMT-2** **FMT-3** FMT-12
	Determine the formation and evolution of stream interfaces (CIRs, SIRs, HCS) and mesoscale structures.	FMT-1 **FMT-2** FMT-3
SSA-III: Acceleration and Transport of Energetic Particles in the Heliosphere	Determine what properties of shocks, and at what scales, control the SEP variations in composition, spectra, and time profiles.	FMT-1 **FMT-2** FMT-3 FMT-12
	Determine what properties of the background medium, and at what scales, affect the shock acceleration process.	FMT-1 **FMT-2** FMT-3
	Determine the role of suprathermal ions, over what energy range, in SEP acceleration.	**FMT-2**
	Determine what the source(s), distribution, and properties (e.g., composition, spectrum) of suprathermal ions are and how they vary.	**FMT-2**

SSA	Science Objective	FMT
	Determine how particles are transported in 3D space and over what spatial and temporal scales.	FMT-1 **FMT-2** FMT-3 FMT-5 FMT-6 FMT-7 FMT-10 FMT-12
	Determine what properties (including transient structures) of the background medium affect/control the particle transport.	FMT-1 **FMT-2** FMT-3
SSA-IV: Variability of the Geomagnetic Environment	Determine how the solar wind drives the state of the magnetosphere globally and in mesoscale (few R_E spatial scale) and how the magnetosphere and the solar wind together determine the dynamics of how the ionosphere drives the geomagnetically induced current.	FMT-2 FMT-4 **FMT-5** **FMT-6** FMT-7 **FMT-8** FMT-9 FMT-10 **FMT-12**
	Determine how energy stored in the magnetosphere during storms and substorms is released to the high-latitude upper atmosphere and the magnetosphere–ionosphere coupling processes that drive the strength, location, and dynamics of the generated auroral currents, along with which ionospheric dynamic processes give rise to the geoelectric fields that drive the geomagnetically induced current.	**FMT-4** **FMT-5** **FMT-6** **FMT-7** **FMT-8**
	Determine what solar wind and/or magnetospheric information is needed to develop (physics-based or machine learning) models to predict the geomagnetically induced current occurrence in space and time and also determine the factors that contribute to the spatial location/distribution of the peak geomagnetically induced current.	FMT-2 **FMT-5** FMT-6 FMT-8
	Determine which solar wind, magnetospheric, or ionospheric processes and conditions cause extreme geomagnetically induced current events and whether there is a correlation between the magnitude of the ground disturbance (ΔB or AL [Auroral electrojet low]) and the peak geomagnetically induced current (dB/dt).	FMT-2 FMT-4 **FMT-5** FMT-6 FMT-7 **FMT-8** FMT-12

SSA	Science Objective	FMT
SSA-V: Dynamics of the Global Ionosphere and Plasmasphere	Understand the fundamental processes that govern the flow of mass and energy of cold plasma (hidden population in the magnetosphere) between the ionosphere and magnetosphere.	FMT-6 FMT-7 FMT-8 FMT-9 FMT-10
	Characterize ionospheric variability and determine the different sizes of the temporal and spatial scales of these variabilities depending on latitudes and altitudes, and how the different scales couple with each other.	FMT-6 FMT-7 FMT-8 FMT-10
SSA-VI: Ionospheric Irregularities	Determine the complete set of plasma instabilities for generating or suppressing ionospheric irregularities.	FMT-4 FMT-7 FMT-9
	Determine the interaction between radio waves and ionospheric irregularities for scintillation and absorption.	FMT-4
SSA-VII: Composition and Energetics of the Neutral Upper Atmosphere	Understand and quantify the thermospheric response (variations in density, composition, and temperature) to the energy input from the magnetosphere, variation in solar radiation, radiative cooling, and impact from the lower atmosphere.	FMT-1 FMT-4 FMT-7 FMT-8 FMT-10
SSA-VIII: Radiation and Particle Environment from Near Earth to Deep Space	Understand the physical processes that cause the spatiotemporal variability of galactic cosmic rays.	FMT-2 FMT-5 FMT-6 FMT-7 FMT-8 FMT-9 FMT-10 FMT-12
SSA-IX: Solar Impacts on Climate	Determine how Earth's whole neutral atmosphere responds to solar irradiance variations over the solar cycle through dynamical and/or chemical processes and how solar variability impacts energetics of the atmosphere (including CO_2) along with the temporal and spatial scales of those mechanisms.	FMT-1 FMT-4 FMT-7 FMT-10
	Determine how the lower and middle atmosphere are coupled through dynamics and how this dynamical coupling depends on solar variability along with how galactic cosmic ray modulation by the solar magnetic cycle influences lower atmospheric dynamics (e.g., cloud formation) and/or chemistry.	FMT-4 FMT-6 FMT-10 FMT-12
	Determine how the lower and middle atmosphere respond to solar irradiance variability in timescales of hours to years.	FMT-1 FMT-4 FMT-6 FMT-10
	Determine how NO evolves during storms and determine its timescales and solar cycle dependence.	FMT-7 FMT-10

SSA	Science Objective	FMT
	Determine the mechanisms by which energetic particle precipitation impacts the ozone layer and how solar proton events impact middle atmospheric chemistry along with their spatial and temporal scales.	**FMT-10**
SSA-X: Stellar Impacts on Planetary Habitability	Understand the processes that drive neutral and ion escape from an Earth-like magnetized planet and determine their contribution to the total planetary atmospheric loss.	FMT-4 FMT-6 **FMT-11** FMT-12
	Determine the role the planetary magnetic field plays in modulating atmospheric loss.	FMT-4 FMT-6 **FMT-11** FMT-12
	Determine the mechanisms and relative importance of solar wind/CME, solar EUV radiation, and SEP mediation of atmospheric loss for an Earth-like magnetized planet.	FMT-4 FMT-6 **FMT-11** FMT-12
	Determine the long-term effects of atmospheric loss on habitability.	FMT-4 FMT-6 **FMT-11** FMT-12

7. Summary and Additional Comments

7.1. Technological Development

The FMT reports contain specific recommendations on technology developments needed to support the suggested architectures. An overview is provided in Table 7-1, and additional aspects are discussed in more detail below.

Table 7-1. Summary of the technology developments identified during the creation of the FMTs.

Instrumentation	Spacecraft Systems	Processes
Novel instrumentation: ▪ THz limb scanner (thermospheric neutral wind profile) ▪ OH imager (neutral gravity wave) ▪ ENA imaging at mesoscales and below <10 min ▪ Cold plasma measurements with an energy threshold of <1 eV ▪ TRL-9 multiband GPS receiver that can operate at GEO ▪ Continuous measurements of NOx between 60- and 150-km altitude ▪ Simultaneous measurements of energy input to the upper atmosphere and the impacted atmospheric compositions, wind, and temperature ▪ Dual-purpose (solar/geospace) imaging systems (e.g., large dynamic range)	▪ Deep-space CubeSats (propulsion, guidance, subsystem reliability) ▪ Deep-space CubeSat delivery system ▪ Inter-spacecraft communication design/operations ▪ Onboard autonomy ▪ Deep-space communications ▪ High-performance ion engines ▪ Advanced, highly automated LEO communications relay network ▪ Active potential control of the spacecraft	▪ Inter-spacecraft communication design/operations ▪ Transfer/adopt commercial mass production processes for science payloads ▪ Create efficient ground operations for managing scientific constellations ▪ Increased RF telemetry rates (DSN upgrades, CubeSat-Ka, etc.)
Instrument miniaturization ▪ CubeSat-qualified mass spectrometer instruments ▪ CubeSat-qualified high-accuracy (nano-g) accelerometer instruments ▪ CubeSat-qualified atomic oxygen measurement systems ▪ Compact, low size/mass/power particle instruments		
Onboard processing capabilities for E- and B-field wave measurements		

DSN, Deep Space Network; RF, radio frequency; TRL, technology readiness level.

7.1.1. Constellation Management and Formation Flying

Constellation architectures will enable the multipoint measurements that are needed to make progress on many of the SSAs. Constellations can be broadly divided into two primary concepts of operations: (1) formation flying, wherein the observatories autonomously react to measurements from other observatories in the constellation, and (2) coordinated flying, wherein the observatory operations are planned by the ground. Both types of constellations could benefit from technology development. Formation flying will require development in autonomous decision-making through onboard algorithms, increased processing capabilities to support decision-making, and inter-spacecraft communications. Formation flying in LEO and GEO will be complicated by space traffic management considerations, because dynamically reallocating orbits could cause an increased threat of conjunctions. Coordinated flying can benefit from technology development for tools on the ground to automate constellation planning and management to reduce human-in-the-loop staffing needs.

NASA has flown several constellations for Heliophysics; however, the overall expectations for constellation architectures are not well understood by the development community. To enable the missions outlined in this report, the committee suggests that NASA provide updated guidance for constellation development. This guidance should include mission assurance expectations at constellation and element levels, testing/workmanship requirements for first and subsequent units as a function of mission class, sparing approach, and requirements for onboard artificial intelligence/machine learning TRL maturation and qualification. For the purposes of this report, it was assumed that Class C/C+ constellations can be composed of individual observatories that meet Class D requirements without a requirement for an in-flight spare. It was also assumed that maximum cost and schedule benefit from identical observatories was realized, which included minimal testing for n+1 units and procurement of all observatories at the same time.

Although the constellations outlined in this report assume concurrent build/deployment, there are programmatic advantages to deploying constellations over time that the committee encourages NASA to consider. The strategy of replacing shorter-lifetime systems every few years could address long-term science goals without requiring the development of long-life space systems. The benefits of this approach include measurement resiliency with older constellation elements, opportunity to address additional science goals by including secondary measurement from different vantage points or with different instrument suites, options for instrument evolution, encouraging workforce development by providing regular opportunities for instrument procurement/development, and the potential for increased rideshare utilization. For cost-effectiveness of deploying constellations over time, the agencies should consider refreshing contracting and procurement mechanisms to support this new way of fielding space systems. Best practices from across the space sector include issuing competitions/contracts for multiple units, funding all procurements with the first unit build, and minimizing time between builds. From a technical perspective, deployment over time is best implemented by standardization of interfaces and instrument requirements/resources (size, weight, power, data) to minimize the impacts of instrument evolution between unit builds.

7.1.2. Autonomy

Many deep-space missions do not require continuous downlinking of data to Earth. However, current operations typically require weekly orbit determination operations. The operational cost of these missions could be significantly reduced if spacecraft autonomy capabilities were developed that would enable monthlong independent operation by spacecraft. This would include self-determination of orbit and attitude along with smart recovery from various failure modes.

7.1.3. Increased Telemetry Rates

As instrument and mission capabilities evolve, the amount of data to downlink is steadily increasing. Simultaneously, downlink capabilities are being restricted by the miniaturization of spacecraft (limiting dish sizes and power), constellations (which can compete for aperture time), the desire for low cost (descoping booms and gimbals), and the fact that farther vantage points are being sought (requiring increased deep-space aperture time and stronger links). Technology development across the data pipeline is needed to enable the compact, data-rich mission architectures envisioned in this report. Investments in onboard data processing hardware and software could be used to make intelligent decisions about what data to downlink, significantly reducing telecommunications hardware requirements both on board and on the ground. The practice of selectively downlinking data is already being used by science operations teams; decision-making is typically implemented through quick-look data products on the ground. Implementing decision-making through onboard algorithms represents a paradigm shift that will require updated guidance to address development risk and TRL maturation for automation through artificial intelligence/machine learning.

Industry-wide demand for high-throughput data links is driving continuous improvements in onboard telecommunications hardware, inter-spacecraft communication, optical communications, and data-relay networks in LEO/medium Earth orbit (MEO)/GEO. The missions outlined in this report could benefit from these advancements in satellite communications across the commercial sector. Several architectures include inter-spacecraft communications links to uplink/downlink between different members of the SmallSat and CubeSat constellations. These inter-spacecraft links were assumed to exist but require further concept development to determine whether additional investment is needed to provide the envisioned capabilities. Leveraging advancements from in-space commercial communications networks is a compelling way to increase bandwidth and reduce onboard hardware. The committee encourages NASA to continue exploring options to purchase services from commercial data networks. Extending the data-relay model to deep space would enable compact deep-space missions that can leverage rideshares to increase access to vantage points throughout the solar system at reduced cost. A deep-space relay network (RN) would provide the opportunity to trade telecommunications resources for increased mission capability, such as propulsion, instrumentation, rideshare utilization, and mass/cost savings. The committee recommends that the Heliophysics Division investigate potential partnerships with the Planetary Science Division and the Exploration Systems Development Mission Directorate to discuss commercial and/or agency-developed deep-space communications relays. The architectures outlined in this report could benefit from enhanced communications infrastructures in LEO/MEO/GEO and deep space but were developed for compliance with the current downlink capabilities of the Near Earth Network (NEN) and Deep Space Network (DSN).

7.1.4. Subsatellite Management

Several FMTs are hybrid SmallSat/CubeSat constellations. For the FMTs for which mission design studies were conducted, it was assumed that CubeSat capabilities existed that could support each mission architecture, and representative CubeSat parameters were used in mission development. The Wallops Mission Planning Lab (MPL) was consulted on the state of the art for CubeSat technologies; however, their recommendations for technology developments to support FMT needs were not received in time to be included in this report. Several hybrid FMT architectures use a primary SmallSat to carry and deploy CubeSats into their science orbits. The required CubeSat deployment mechanisms for low altitude and deep space were assumed to exist but could require technology development to meet deployment requirements in these environments. Overall, the aspiration to use CubeSats as Class D constellation elements for FMTs in challenging environments will require technical development to provide longer lifetimes; increased ΔV; and tighter guidance, navigation, and control capabilities.

7.1.5. Propulsion

Continued investment in advanced propulsion technologies will provide NASA with greater flexibility in developing the LWS architecture to address the need for novel vantage points and increased observations. Solar sails provide the opportunity for sustained observations from non-Keplerian orbits. This capability could simplify FMT architectures by replacing the need for complicated operations scenarios, high ΔV systems, and/or multiple cycling spacecraft to achieve persistent, high-availability observations. This is particularly relevant to FMTs that include sustained observations from non-Lagrange points (inside Earth–Sun L1, between Earth–Sun L1 and the Earth, off the Earth–Sun line, and elsewhere in interplanetary space), the Earth's bow shock and magnetotail, high solar latitudes (i.e., solar polar), and high Earth latitudes (i.e., auroral observations). The committee encourages NASA to fund continued development of solar sails, and consider their use in future FMT concept development.

7.2. Diversity of Proposed Architecture

The proposed LWS mission architecture has several distinct advantages over the current collection of LWS missions. Most obviously, it is planned/created to ensure a wide range of orbital coverage supporting key LWS science goals. Additionally, it is diverse, involving not only more "traditional" spacecraft (e.g., MIDEX [Medium-Class Explorer]) but also SmallSats and CubeSats. Within the FMTs, there are concepts that involve constellations of identical spacecraft, distinct spacecraft, and "motherships" plus CubeSats. Most of the FMTs described in this report are compatible with ESPA rings, and many can be accomplished with a single launch (although trade studies involving multiple launches were also examined for some concepts and may be appropriate for others). Finally, several FMTs are composed of components that can be disaggregated, allowing for flexibility in launch schedules and the number/type of institutions involved in building/designing the spacecraft and payloads.

It is worth mentioning that although the committee did not restrict concept considerations to a particular size or "type" (e.g., single spacecraft versus constellations), all the concepts fall within the C-class range or below, and all are constellations. This natural selection appears to be the result of a "sweet spot" in terms of cost versus science, combined with the desire to make progress on interconnected, system-related objectives (as described by the SSAs). Because the FMTs address complex science questions, often over a range of scales, they generally required mission concepts larger than a single CubeSat/SmallSat as well as spatially separated observations. The distinct cost advantage of rideshares and ESPA-type launches also influenced the class of the resulting architecture elements.

7.3. Summary

This report details a proposed mission architecture for the LWS program that is significant in its breadth of orbits, diversity, and promise of scientific return related to LWS goals. The 12 identified FMTs describe observational platforms where scientific measurements will contribute to substantial progress on the SSA goals as described in the 2019 LPAG report. The committee believes the diversity of the architecture provides NASA with the flexibility to respond to the changing priorities and needs of advancing space weather science. It is important to recognize that the proposed set of FMTs is based on the current identified SSAs and should be revisited as those SSAs (and their derived goals) are altered in the future (Figure 3-2). There are several aspects of space weather science that have evolved rapidly since 2019 (and continue to do so) and potentially are not fully captured by the current set of SSAs (e.g., space situational awareness).

The committee did not prioritize the FMTs (or the individual components of suggested implementations) for a number of reasons. We did not have the necessary budgetary or larger NASA-mission context required to do so, but we also were not prepared to recommend the related prioritization of the SSA goals. NASA should be afforded the flexibility to select/order the FMTs with the consideration of a multitude of factors such as launch opportunities, recent technological advancements, relative importance/priority of desired improvements in predictive capabilities, synergies with existing missions, and cooperative opportunities with other directorates and agencies.

The mission concepts studied provide concrete examples of a way to address the FMTs, but they are not the only possible implementations. Because most of them were only examined to the “trade study level,” actual implementations will require more detailed/complete studies. Additionally, the role of data buys and data streams from non-NASA assets was not examined by the committee, but these should be considered as useful additions to the architecture where possible. Lastly, the science realized from any proposed architecture is only as good as the support given to the data analysis required to create scientifically useful data sets and to the infrastructure needed to make those products accessible to the broader scientific community.

8. Mission Concept Designs

8.1. FMT-1 Mission Concept Design Summary: Sun-Earth Line Observing System

8.1.1. Mission Design

Table 8-1. FMT-1 key driving requirements.

Mission Class	C+
Lifetime	6 years (3 on station); goal: 5 years (on station)
Launcher Class	ELV-class (Falcon, Vulcan, New Glenn, etc.)
Spacecraft Class	ESPA-compatible
Concept of Operations	Instruments are always on
Assumptions	▪ Technology thrusts are important for enabling mission ▪ Inter-satellite communications ▪ Children carry in situ instruments and are required to be <~10 Mm ▪ One L-orbit’s worth of data has to be stored ▪ Beacon capability for low-latency SWx data ▪ Onboard autonomy ▪ Instruments participate in spacecraft pointing control

ELV, expendable launch vehicle; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; SWx, space weather.

Table 8-2. FMT-1 significant trades and decisions.

Trade	Outcome
Dual manifest versus ESPA/primary	Baselined ESPA Grande
Transit time versus payload mass	2.5 years to L4
±30 orbits versus ΔV	Bias to 30 achieved for L4, L5 can be optimized
Gimballed HGA (and cost) versus slewing parentcraft	Two-axis gimballed HGA

ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; HGA, high-gain antenna.

8.1.2. Mission Implementation

Table 8-3. FMT-1 spacecraft and payload architecture.

Spacecraft Properties	▪ 2× ESPA-compatible spacecraft (hub), three-axis stabilized ▪ <5 arcs/s (jitter), 60 arcs (knowledge) ▪ ~200 W, ~70-kg payload, 5–10 Gbit/day downlink via Ka-band
Payload Architecture	▪ Each hub carries up to four 6U CubeSats (spokes); in situ instruments are mounted on CubeSats; remote sensing instruments are on hub ▪ Each CubeSat carries one (or two, depending on SWaP) in situ instrument: plasma (FC), magnetometer (MAG), particle detector (SEP); fourth CubeSat is a backup magnetometer ▪ All CubeSats are spinners; MAG/SEP rotation axis is normal to the ecliptic; FC rotation axis is along the Sun–spacecraft vector
Hub–Spoke Architecture	▪ Spokes use patch X-band antennas or omnis to send data to the hub ▪ Telemetry budget: 5–10 kbps for spoke–hub communications

ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; FC, Faraday cup; SWaP, size, weight, and power.

8.1.3. Orbit Design

L-0: Launch
L+1 day: Midcourse Correction 1 (MCC1)
L+4 days: SELOS-L4 Departure Maneuver
L+100 days: SELOS-L5 Departure Maneuver
L+2.0 years: SELOS-L5 Orbit Shaping Maneuver
L+2.7 years: SELOS-L4 Capture Maneuver
L+3.7 years: SELOS-L5 Capture Maneuver

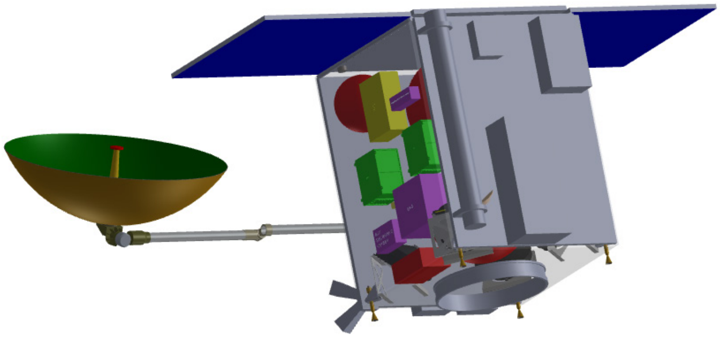
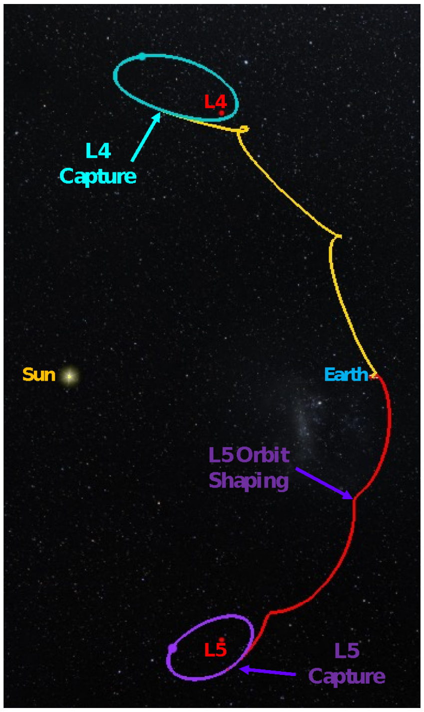


Figure 8-1. Deployed SELOS hub.



8.1.4. Concept of Operations

- Each hub carries three or four spokes and releases them on-station in loose formation around the hub (10^3- to 10^4-km spacing).
- Spokes communicate/downlink data to the hub via X-band, and from the hub to Earth via Ka-band.

Table 8-4. FMT-1 concept of operations.

Hub Concept of Operations	Spoke Concept of Operations (to be refined)
▪ **Launch/Early Orbit** ▪ **Cruise Phase** – Drift to L4/L5 and place in wide elliptical orbit (~±30° to be resolved) around L-point – Hub instruments on, childcraft off ▪ **Deploy Childcraft** – Released on-station in loose formation around the hub (10^3- to 10^4-km spacing) ▪ Science mode ▪ Instruments operate 24/7 ▪ Receive data from childcraft and transmit to ground ▪ Disposal ▪ Passivate and slow drift	▪ **Launch/Early Orbit** – Minimal aliveness tests ▪ **Cruise Phase** – Childcraft off ▪ **Science Phase** – Released on-station in loose formation around the hub (10^3- to 10^4-km spacing) – Science mode – Instruments operate 24/7 autonomously – Send data to hub, receive commanding from hub (for operations plans changes) ▪ Disposal ▪ Passivate and slow drift

8.1.5. Technology Development

During the study, we identified four areas where further technology development may be needed:

- **Deep-space CubeSats (propulsion, guidance, subsystem reliability).** Only a couple of CubeSats (Mars Cube One [MArCO]) have been deployed and operated in deep space so far. Although they propagated a bit further than the SELOS spokes (1.5 AU), their 6-month lifetime is much shorter than SELOS. Therefore, a detailed study for the design of a deep-space CubeSat is needed to define a practical parameter space for reliability, propulsion, guidance, and communications.

- **Deep-space CubeSat delivery system.** Ejection of multiple CubeSats from a carrier spacecraft (particularly an ESPA-compatible one) is a novel idea with different requirements than existing delivery systems from the International Space Station. Issues such as reliability in deep space as well as the communications concept of operation during cruise phase may require the development of a specialized delivery system.

- **Inter-spacecraft communication design/operations.** The MDL study found that the communication architecture between the hub and spokes requires additional work. Issues such as communication protocol (e.g., frequencies for transmitting and receiving, scanning versus fixed antennas) and low size, weight, and power radios and antennas are likely to require further technology development before such hub–spoke systems can be deployed in space.

Onboard autonomy. The large number of spacecraft in the FMT-1 concept (up to 10, potentially) would place a significant burden on the complexity and staffing of the ground operations system, *if* operations were to be contacted in the standard fashion (communicate with each spacecraft individually). Therefore, it is imperative that interaction with ground stations be minimized, including with the science operations teams. For that reason, investment in increasing the onboard autonomy of the spacecraft, from executing observing schedules, to selective data downlink and onboard processing, to higher data levels, to—possibly—recovery from critical events, is required.

8.2. FMT-2 Mission Concept Design Summary: Heliospheric Explorers Multi-Spacecraft System to Observe the Dynamics of the Inner Heliosphere

8.2.1. Mission Design

Table 8-5. FMT-2 key driving requirements.

Mission Class	C+
Lifetime	3 years; goal: 5 years
Launcher Class	ELV-class (Falcon, Vulcan, New Glenn, etc.)
Spacecraft Class	ESPA-compatible
Concept of Operations	Instruments are always on
Assumptions	▪ Technology thrusts are important for enabling mission ▪ Beacon capability for low-latency SWx data ▪ Onboard autonomy ▪ Constellation operations

ELV, expendable launch vehicle; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; SWx, space weather.

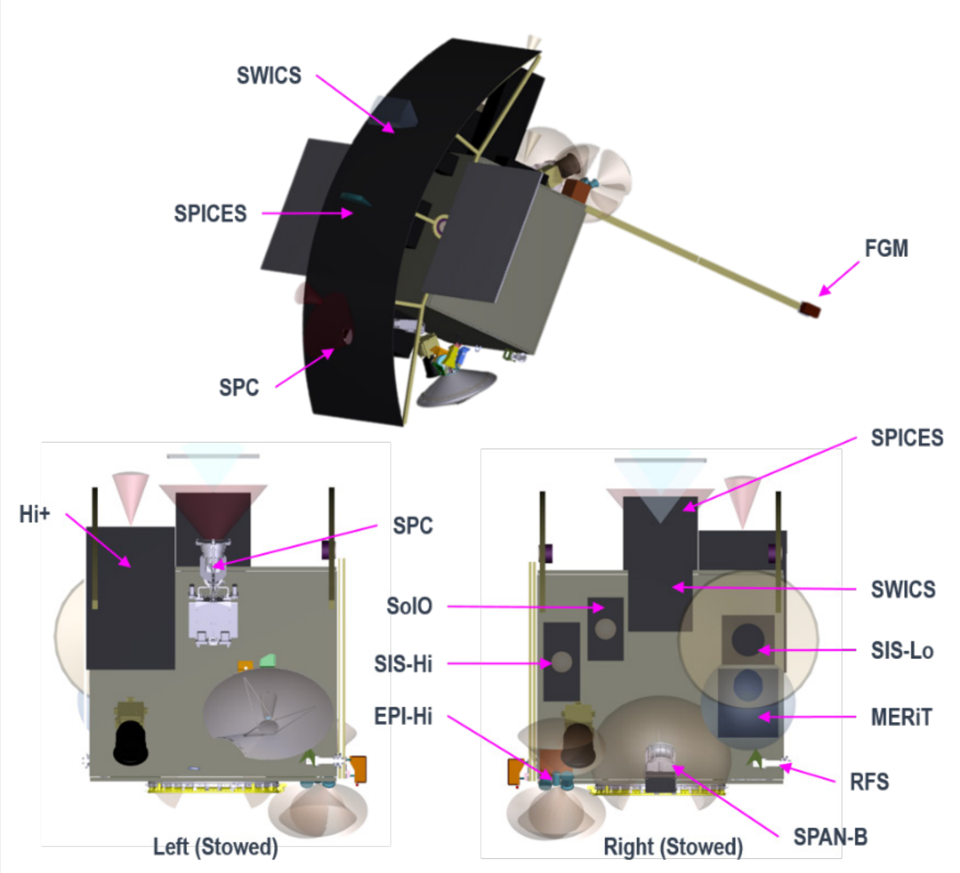
Table 8-6. FMT-2 significant trades and decisions.

Trade	Outcome
Primary or secondary payload	Baselined ESPA Grande primary mission
Number of VGAs	Only a single VGA was evaluated
Concept of operations	Can store data for a week requiring autonomy

ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; VGA, Venus gravity assist.

8.2.2. Mission Implementation

Table 8-7. FMT-2 spacecraft and payload architecture.

Spacecraft Properties	▪ 4–8× ESPA-attached spacecraft, three-axis stabilized ▪ 380 W, 313/438/485 kg dry mass per spacecraft ▪ 43/68/122 Mbit/day downlink via Ka-band
Launch Configuration	▪ Individual spacecraft attached to ports of an ESPA Grande ring ▪ With two rings nine spacecraft could be launched with one on the top
Payload Options	▪ Threshold mission: MAG, FC, SW Comp., suprathermal ions, SEPs ▪ Baseline: threshold + radio waves, SW electrons, upgraded SW composition, suprathermals, and SEPs ▪ Aspirational: baseline + each spacecraft carries one of the following: coronagraph, vector magnetograph, EUVI, X-ray spectrometer, or heliospheric imager 

ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; EUVI, extreme ultraviolet imager; MAG, magnetometer; FC, Faraday cup; SW Comp., solar wind composition; SEPs, solar energetic particle sensor; SW electrons, solar wind electrons.

8.2.3. Orbit Design

The FMT-2 constellation injects into heliocentric orbit via a single launch, with a ~7.5-month orbit periodicity (1:1 resonance with Venus). A Venus encounter occurs after ~0.5 revolution about the Sun (roughly 3.7–5.7 months). An alternative 2:1 resonance could be employed to provide an extended launch period, with launch occurring several months earlier than the 1:1 option, and encountering Venus after ~1.5 revolutions, or roughly 22.5 months postlaunch. A launch in 2032–2033 is assumed with C3 of ≤15 km²/s².

Upon arrival at Venus, each spacecraft experiences a Venus gravity assist (VGA) that disperses the constellation into distinct science orbits. A single deterministic Venus spacing maneuver (VSM) is performed for most spacecraft 10–80 days after launch (optimal timing depends on the Venus transfer geometry) to enable a minimum time-spacing between each sequential Venus encounter. A "central" spacecraft in the constellation encounters Venus at the nominal epoch with no VSM required, while the other spacecraft are spaced away from the central spacecraft (e.g., for a seven-spacecraft constellation with a minimum spacing of one flyby per 8 hours).

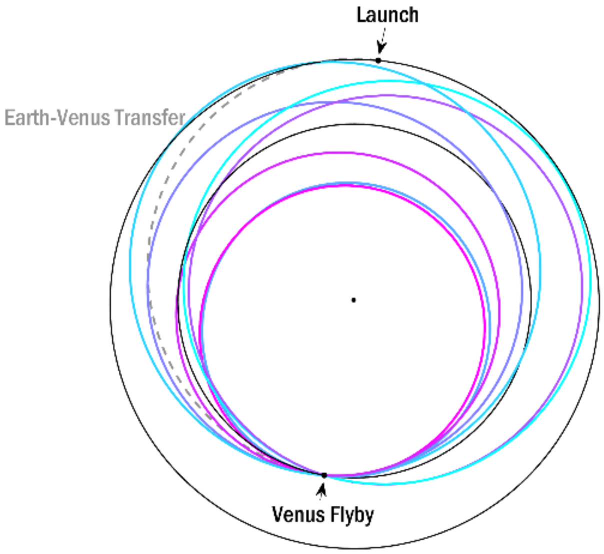


Figure 8-2. Globally optimal seven-spacecraft orbit.

8.2.4. Concept of Operations

- Launch/early orbit
- Cruise phase
    - Orbit to Venus encounter
    - All spacecraft in proximity to each other
    - All instruments on
- VGA (L + 3–22 months depending on type of orbit)
    - Individual VGAs typically 8 hours apart
- Science mode
    - Instruments operate 24/7
    - Store data, transmit up to 7 days

- Disposal
    - Passivate and slow drift

8.2.5. Technology Development

During the study, we identified only one technology development that may be needed.

- **Spacecraft autonomy.** The telemetry requirements of each spacecraft are very modest, and with new onboard storage technology, a week's worth of science data can be easily stored. This significantly reduces the DSN requirements of the mission, but it also introduces a number of challenges, such as orbit determination and maintenance as well as autonomous recovery from some failure modes. A beacon ping probably would have to be implemented on X-band and sent on the low-gain antenna to provide simple health updates.

8.3. FMT-3 Mission Concept Design Summary: Origins of Space Weather

The following sections discuss only the LWS adaptations and other summarizing information from the STP 4π-HeliOS study. The details of that study will be provided to NASA through the HMCS report.

8.3.1. Mission Design

Table 8-8. FMT-3 4π-HELIOS key driving requirements.

Mission Class	C ("in-pair"), B ("out-pair")
Lifetime	10+ years (including a 5-to 6-year cruise phase for "out-pair")
Launcher Class	ELV-class (Falcon, Vulcan, New Glenn, etc.); Falcon-9H for "out-pair"
Spacecraft Class	Dedicated launches
Concept of Operations	Instruments are always on during science phase
Assumptions	▪ Beacon capability for low-latency SWx data ▪ Onboard autonomy ▪ Instruments participate in spacecraft pointing control

ELV, expendable launch vehicle; SWx, space weather.

Table 8-9. Significant changes from STP concept.

STP Concept	LWS Concept
Out-of-ecliptic orbits (>60°)	45°–60° inclination
Helioseismology (driving requirement)	Optional

STP Concept	LWS Concept
Out-of-ecliptic heliospheric imaging (optional)	Required
“In-pair” parking location (>120°)	90° (Earth quadrature)

8.3.2. Mission Implementation

Table 8-10. FMT-3 spacecraft and payload architecture.

Spacecraft Properties	Same as in the STP version
Payload Architecture	▪ Common payload: vector magnetograph, chrom/coronal imager, coronagraph, heliospheric imager ▪ In-pair: particles and fields (augmentation for “out-pair”)

8.3.3. Orbit Design

The LWS concept uses variations of the orbits studied during the ACE run for the STP version. Detailed analysis, and particularly the spacecraft configuration for a VGA, will require a separate mission design run.

8.3.4. Concept of Operations

- The “in-pair” is launched separately and begins science operations as soon as possible after the lunar gravity assists (follows the STEREO concept of operations).
- The “out-pair” begins science operations once it returns to within 2 AU, about 5 years after its launch toward Jupiter. The length of the cruise phase will depend on the orbit inclination and spacecraft mass.

8.3.5. Technology Development

During the study, we identified four areas where further technology development may be needed:

- **Deep-space optical communications.** While Ka-band is adequate for the “in-pair” because of its fixed angular location relative to Earth, traditional radio communications become cumbersome and mission-constraining for the “out-pair.” The variable Sun–spacecraft–Earth angle necessitates (1) the use of gimbal mechanisms for either the antenna or the Sun-pointing payload and (2) relatively large antenna sizes that severely constrain the placement of the instruments to monitor the Sun–Earth line. Developing and maturing optical communications technologies for deep-space missions will significantly reduce the complexity and cost of out-of-ecliptic observations.
- **High-performance ion engines.** Current ion engines impose a significant mass penalty for the out-pair, thus restricting the available resources for the science payloads. Higher and lighter ion engines will help increase the types of instruments that can be included and bring the circularization of the out-of-ecliptic orbits within realistic timescales.

8.4. FMT-4 Mission Concept Design Summary: Geospace Observing System

The following sections present the results of a mission concept design study named the Geospace Observing System (GOS) performed at the NASA/GSFC MDL.

8.4.1. Mission Design

Table 8-11. FMT-4 key driving requirements.

Observatory Constellation	Two Astra-based in situ satellites at 600 × 250 km elliptical orbit with 180° offset in phase. One remote sensing satellite at 800-km circular orbit. The three satellites are at 15° inclination orbits to take coincident measurements in the low-latitude and equatorial regions at different local times periodically. All are launched from the same launch vehicle (Falcon, Vulcan, New Glenn, etc.). ASTRE has been studied before. The current study focuses on the remote sensing satellite.
Launch Readiness Date	26 February 2029
Mission Class	C
Lifetime	3 years; goal: 5 years
Spacecraft Class	ESPA-compatible
Concept of Operations	▪ Gravity wave imager has night/day modes; all others run 24/7 ▪ Communication architecture: S-band helical antenna (six ground stations) ▪ Communication passes: two to three times per orbit (101-min orbit period) ▪ Four reaction wheels for finer control authority (redundancy benefit) ▪ Momentum unloads every ~8 days ▪ 180° yaw flip in 30 min (“seasonally” or about five to seven times per year) ▪ Controlled reentry recommended
Trades and Decisions	▪ Single primary mission configuration versus traditional ESPA primary configuration ▪ DSN versus NSN + commercial ground stations ▪ Inclination versus mission mass (15° baseline)

NSN, Near Space Network.

8.4.2. Mission Implementation

The GOS study focuses in detail on the remote sensing satellite element of FMT-4. Table 8-12 summarizes the properties of the FMT-4 satellites and instruments. The diagrams provided in Figure 8-3 depict stowed and deployed views of the remote sensing satellite.

Table 8-12. Properties of FMT-4 satellites and instruments.

Remote Sensing Spacecraft Properties	▪ One Class C spacecraft, three-axis-stabilized with 8 thrusters, 12 Sun sensors, 4 reaction wheels, and 2 star trackers; mass, 266.8 kg ▪ Pointing accuracy ± 0.1° (3-sigma); pointing knowledge: ±0.03° (3-sigma) ▪ ~1250 W, ~85-kg payload, 2.9 Mbps, downlink via S-band transponder
Remote Sensing Payload Architecture	▪ Far ultraviolet spectrograph imager: 10 kg, 24 W ▪ Gravity wave imager: 58.9 kg, 4 W ▪ THz neutral wind sensor: 16 kg, 40 W ▪ GPS receiver for total electron content
In Situ Spacecraft Properties	Body-mounted solar panel to minimize the interference with in situ measurements
In Situ Payload Architecture	▪ Electric and magnetic field sensor ▪ Ion and neutral mass spectrometer ▪ Ion drift and neutral wind sensor ▪ Radio transceiver (moved from remote sensing satellite)

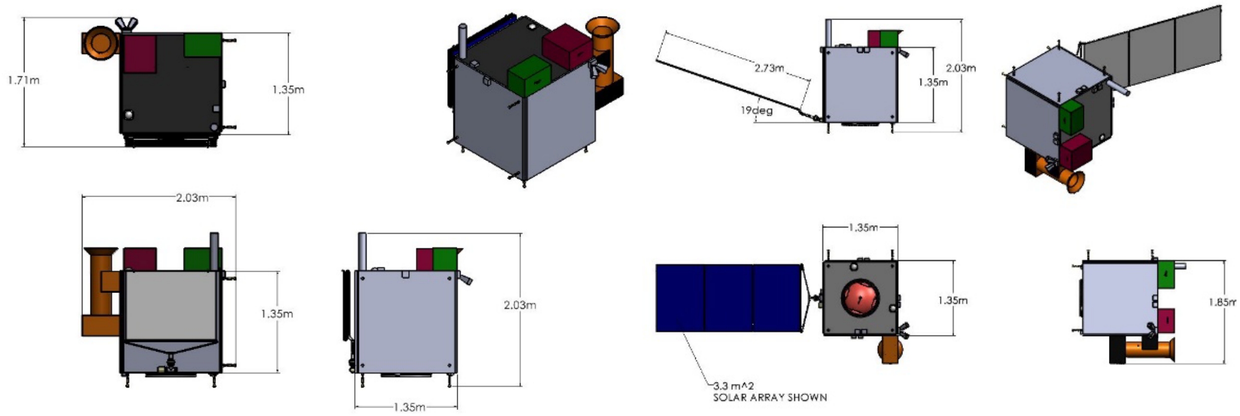


Figure 8-3. Stowed view (left four diagrams) and deployed view (right four diagrams) of the GOS remote sensing satellite.

8.4.3. Orbit Design

The mission concept includes three LEO satellites for simultaneous in situ and remote sensing measurements of ionosphere and thermosphere at different altitudes with a spatial coverage in the equatorial region. To optimize the conjunction among the three satellites, the remote sensing satellite is placed at an 800-km circular orbit with an inclination of 15° (see green line in Figure 8-4). Both red and cyan lines are for satellites with in situ measurements with apogee/perigee of 600 and 250 km. But they are 180° from each other (mirrored) and at 15° inclination angle. The right panel in Figure 8-5 shows the orbit configuration 135 days after launch. The orbit design aims to maximize the coincident observations of low latitude and equatorial plasma bubbles, associated the neutral and plasma conditions and impact on radio scintillation at different frequencies (Figure 8-6).

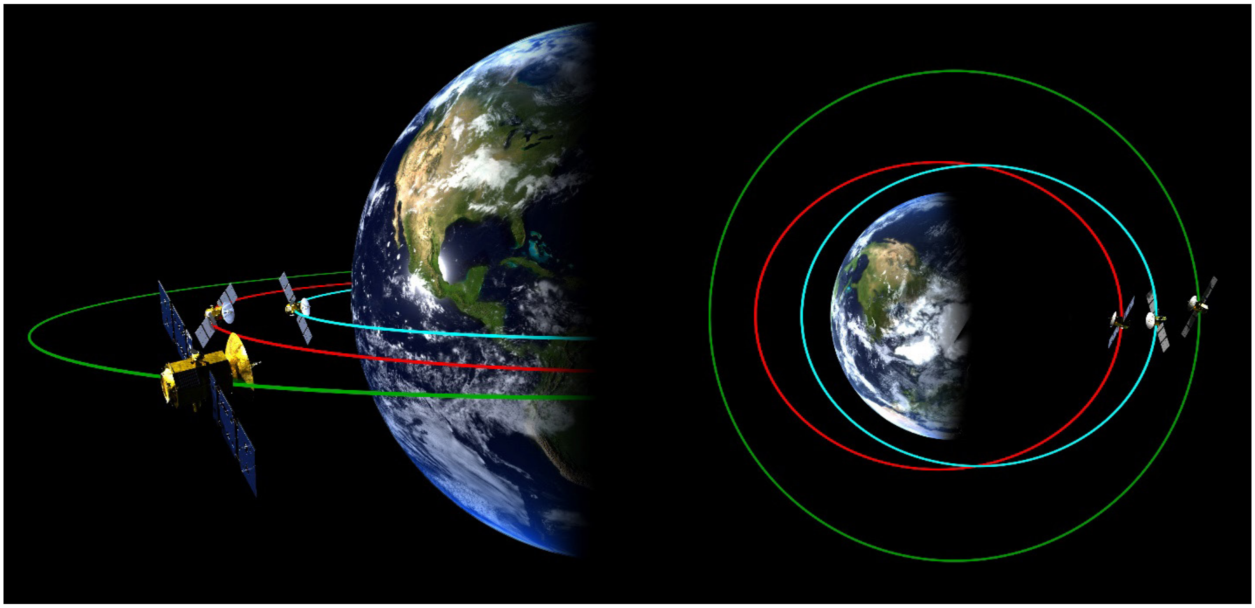


Figure 8-4. A depiction of the three-LEO-satellite observation system in the equatorial region.

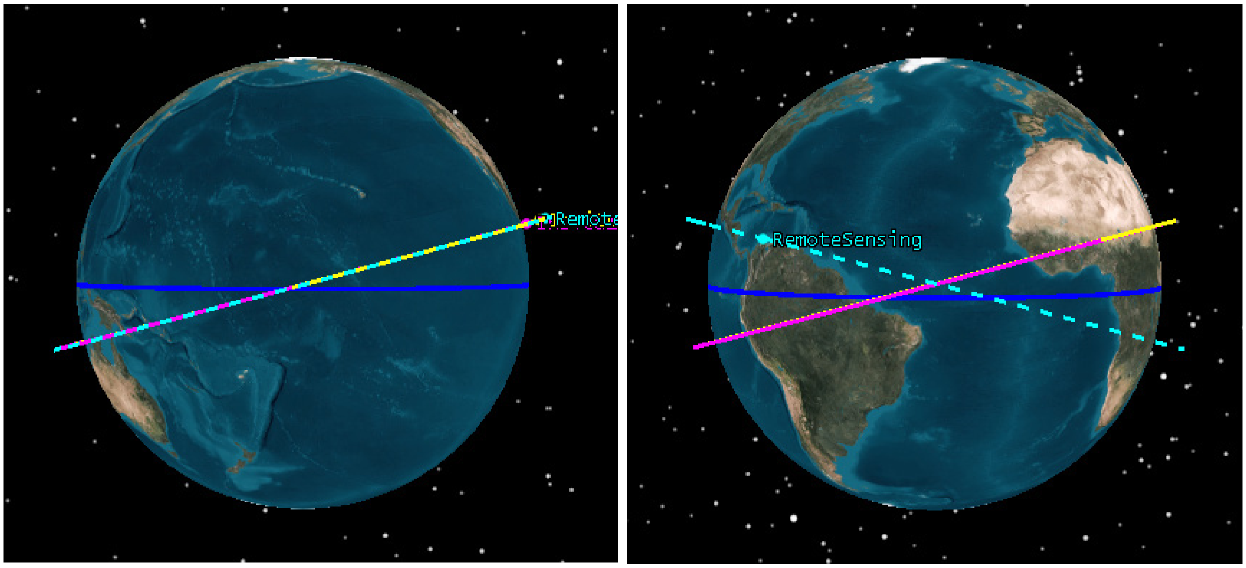


Figure 8-5. (Left) Initial orbit of the three LEO satellites from a single launch to an orbit with 15° inclination. The dark blue line indicates the equator. (Right) Orbits after 135 days of nodal drift. The cyan dashed line indicates the remote sensing satellite. Note: The color coding is different from that used in Figure 8-4.

8.4.4. Operation Concept

8.4.4.1. Schedule

The launch readiness date is 26 February 2029 for a 3-year operation (with a goal of 5 years of operation). All three GOS satellites will be launched to the same 600-km orbit. Within 3 months after launch, the remote sensing satellite will be moved to 800-km circular orbit while the in situ satellites are changed to 600 × 250 km elliptical orbits with 180° phase shift. Except for the gravity wave imager, all other instruments on the three GOS satellites run continuously. Figure 8-7 summaries the launch, 3-year operation, 2-year extended operation, and final controlled reentry.

8.4.4.2. Operation Plan

It is recommended that the GOS mission operations center (MOC) use the cloud-based virtual multi-mission operations center (vMMOC) services and shared infrastructure, including network

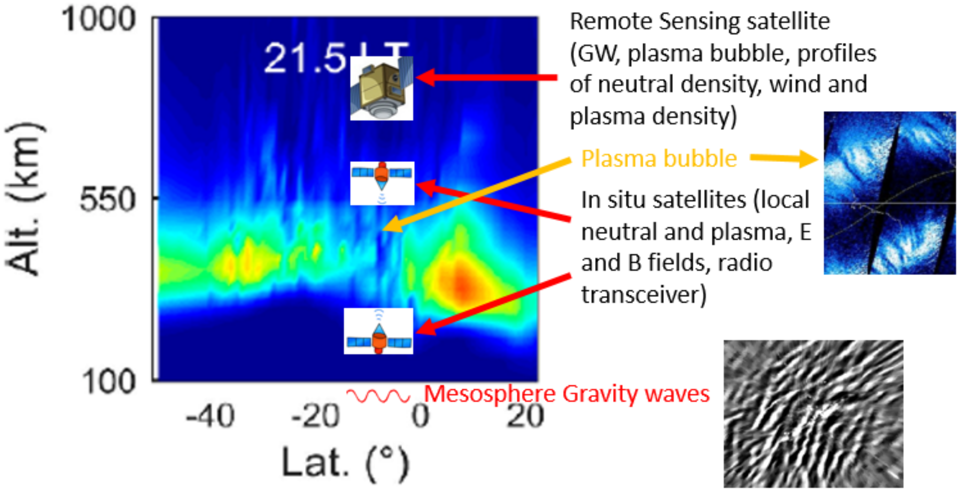


Figure 8-6. An overview of coincident observations of mesospheric gravity waves (GWs), plasma bubbles, profiles of neutral wind, neutral density, plasma density and drift, electric and magnetic fields, as well as frequency-dependent radio scintillation.

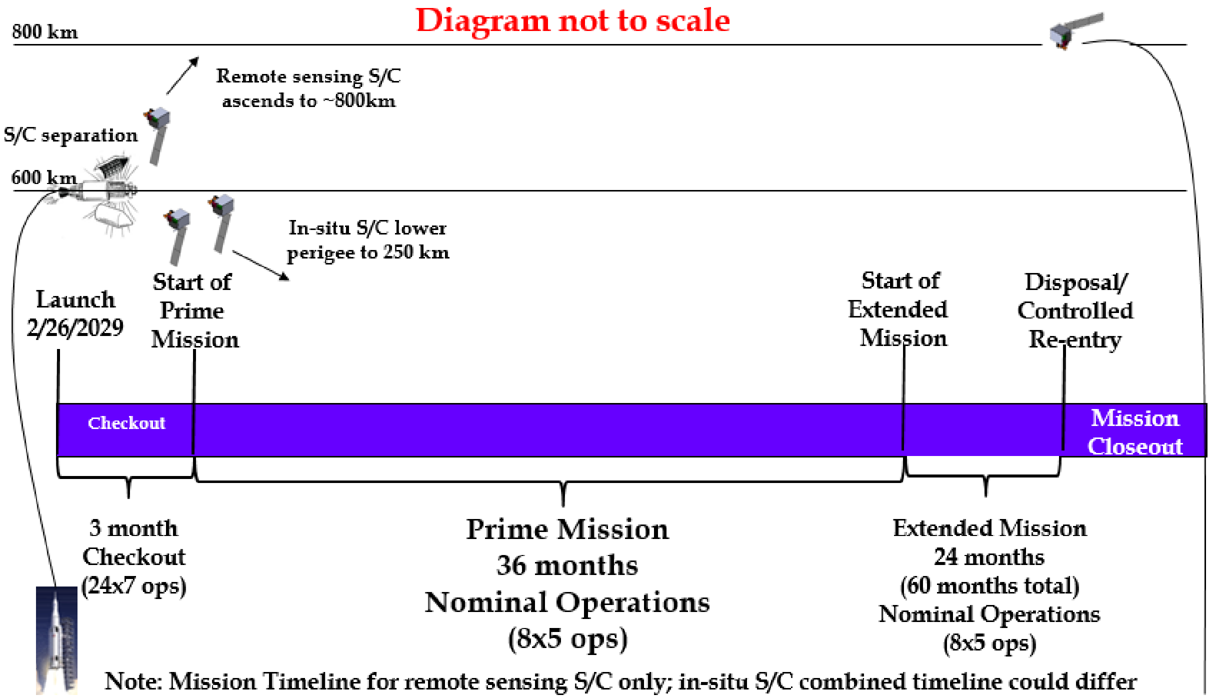


Figure 8-7. A schedule of FMT-4 operation from launch to disposal. S/C, spacecraft.

interfaces to NASA and partner agency resources and physical control center space at GSFC as needed/desired. The vMMOC would provide standard services: flight operations, mission planning and contact scheduling, telemetry, navigation, level-zero processing and products (time-ordered, quality annotated data sets), and communications between the MOC and science data stream (SDS).

8.4.4.3. Communication

GOS is an equatorial ionospheric irregularity mission that includes two nadir-pointing satellites with apogees 180° apart and a third nadir-pointing instrumented satellite at 15° inclination. The third satellite will be at 800-km circular orbit.

Radio-frequency communication for the three satellites will be S-band telemetry, tracking, and command (TT&C) via Omni and/or a directional antenna to the Near Space Network (NSN), DTE (and possible RN, previous Space Network [SN]). GPS will be used for orbit determination, with possible backup by the NEN and SN. S-band through the U.S. Tracking and Data Relay Satellite System (TDRSS) will be used for launch and LEO critical events if the NEN is not available.

8.4.4.4. Orbital Debris Removal

The orbital debris requirements for LEO missions are outlined in NASA-STD-8719.14B.

The baseline disposal plan is controlled reentry with risk to human life on the ground below the 0.01 limit. Potential other risks: Data on the instrument's internal component are limited. There may be unidentified components made of temperature-resistant materials (titanium, stainless steel, beryllium) that have not been analyzed for reentry and can potentially increase the DCA (debris casualty area).

8.4.4.5. Issues and Risks

Equatorial low-elevation stations are scarce, and FMT-4 may be competing with other spacecraft for antenna time. Figure 8-8 show the potential ground station coverage for 15° inclination orbits. There is a risk of collision after insertion and then ascent/descent into operational orbits. Ascent from 600 km to 800 km must be planned carefully because the GOS remote sensing spacecraft may have to ascend past several known constellations of satellites (A-Train, Iridium, SpaceMobile, and others). There is also a mega-constellation plan to operate thousands of spacecraft (Starlink, Kuiper) in orbits near or between GOS insertion and final orbit location.

8.4.5. Technology Development

There are a few areas for technology development:

- Engine placement (plume) on the remote sensing satellite may become nonideal for unrealized science requirements.
- There are limited ground stations near the equator.
- More detailed analysis of remote sensing versus in situ alignment is needed.

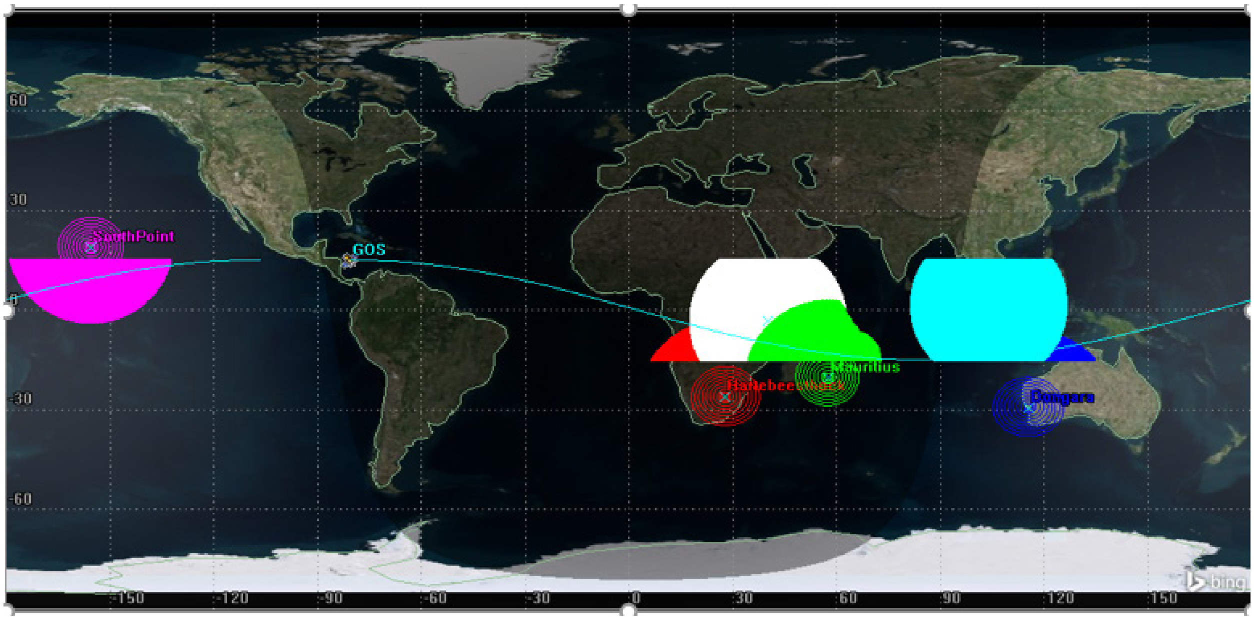


Figure 8-8. Ground station coverage for 15° inclination orbit and Near Space Network (NSN) with 5° minimum elevation angle.

- The launch vehicle adapter needs to be developed for the remote sensing and in situ satellites.

8.4.6. Assumption of Existing Measurements/Missions

GOS is designed to be self-sufficient with regard to addressing the science focal points. However, measurements from other existing missions, such as TIMED, GOLD, ICON, and DMSP, are helpful for providing information about the ionosphere and thermosphere as well as auroral conditions to gain a better understanding of ionospheric irregularity initiation, development, and dissipation.

8.5. FMT-5 Mission Concept Design Summary: Magnetospheric Constellation

8.5.1. Mission Design

MagCon strategy is to use relatively simple instrumentation, consisting of a standard fluxgate magnetometer, an electrostatic analyzer (ESA), and a solid-state telescope (SST) or some other energetic particle detector, and place the spacecraft into three separate orbits, each with different apogee/perigee combinations (Table 8-16).

Considerations for the mission strategy are as follows:

- There is an orbit trade where perigee is low (altitude of a few hundred kilometers to 1000 km) versus perigee above geosynchronous (i.e., a more Geotail-like orbit). The low perigee, which is the approach chosen here, offers good downlink rates and inner magnetospheric science. However, it does require the spacecraft to deorbit within

25 years of end of life, in accordance with NASA-STD-8719.14A. Higher perigees have no such requirement, other than to remain above the geosynchronous belt for 100 years, but come with the cost of downlink requiring either significantly more transmit power in the satellites to be able to close the link budget, or a relay satellite. In addition, the higher-perigee option would require a different orbit-insertion scenario. A further advantage of the high-perigee option is that the ΔV requirements would be in the meters-per-second range, which could be accomplished with a small cold gas system, thereby significantly reducing the size of the spacecraft.

- The staggered perigee orbit design is a key feature because it keeps the constellation synchronized in LT throughout the mission.
- Keeping the mass of the observatories as low as possible is critical to the constellation. In the studied concept, the spacecraft are smaller in volume and mass than THEMIS (by about 40 kg), having taken advantage of a reduction in the size of subsystems (electrical power system, command and data handling, communications) and not accommodating an electric field instrument. Although the design closes as is, there is likely room to reduce the mass further, because the current design is rather stiff with a thick honeycomb structure.

8.5.2. Mission Design

Table 8-13. MagCon key driving requirements.

Mission Class	▪ Constellation Class C ▪ Spacecraft could be Class D ▪ Overall Class C mission assurance comes from constellation architecture
Lifetime	▪ 3-year baseline, 5-year objective ▪ Fuel is only limitation, but station-keeping ΔV requirement is fairly small
Launcher Class	EELV
Concept of Operations	Instruments always on
Assumptions	▪ Baseline is simple, THEMIS-style instrumentation, which is sufficient to close on science ▪ Assume observatories and deployer ESPA must adhere to NASA-STD-8719.14A ▪ If waiver is available, it drastically alters the amount of hydrazine that is required

EELV, Evolved Expendable Launch Vehicle; ESPA, EELV Secondary Payload Adapter.

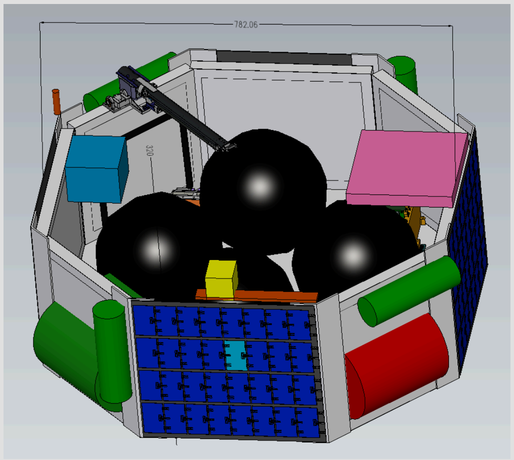
Table 8-14. FMT-5 significant trades and decisions.

Trade	Outcome
Hydrazine versus green propulsion	Although green propulsion was initially desired (because of simplicity of integration and safety concerns), the current high-TRL green propulsion solution requires 30 min of ~70-W input power to heat the catbed. This was a significant issue for deployment. In addition, the high-TRL green propulsion tanks drove a wider spacecraft than desired.
High versus low perigee	Low perigee was chosen to close the downlink.
Commercial versus in-house ESPA	This trade is still under study. It is unclear whether commercial options exist that can accommodate the spacecraft.
DTE versus relay communications	DTE is significantly less expensive and simplifies the deployer design (because the deployer is turned into a relay satellite after deployment).

DTE, direct to Earth; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; TRL, technology readiness level.

8.5.3. Mission Implementation

Table 8-15. Mission implementation.

Spacecraft Properties	▪ ESPA Grande–compatible spacecraft, two per port held by ST-5-style “Frisbee” dispenser ▪ Spin-stabilized, with spin axis roughly perpendicular to ecliptic ▪ <5° spin axis control <1° knowledge ▪ 300 MB/day data ▪ 85.6 kg ▪ 24.1-W science mode ▪ 30.7 W available at end of life	
Payload Architecture	▪ Each spacecraft carries a magnetometer (0.1-nT accuracy), an ESA, and an energetic particle instrument ▪ Antenna is similar to MMS “garden weasel”	

ESA, electrostatic analyzer; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter.

8.5.4. Orbit Design

Baseline design is to have three elliptical orbits, each monitoring different apogee distances that cover both the nightside transition region (10–16 R_E) and the dayside magnetopause and flanks (12–15 R_E). Perigees are staggered to provide equal precession rates for all petals. Perigees can be lowered depending on the highest perigee desired. Perigees can be raised as needed, although the orbit-insertion scenario and orbit perturbations due to lunar interactions would need to be considered further.

8.5.5. Concept of Operations

Each ESPA carries 12 spacecraft. The launch vehicle upper stage performs all orbit burns and drops off ESPAs into desired orbits. Each ESPA then deploys all 12 spacecraft in pairs, one ahead and one behind, over the course of several hours to allow for spacing. Spacecraft come out spin-stabilized with the spin axis roughly perpendicular to the ecliptic plane. Once the spacecraft checkout is complete, small ΔV is applied to separate spacecraft along the orbit, then thrusters fire again to lock relative positions. Once an ESPA has deployed all its childcraft, it performs a deorbit burn.

Table 8-16. Baseline orbits and ΔV required to deorbit. Ongoing trade to lower perigees by a factor of 2, which will reduce ΔV by factor of 2 as well. Design currently closes as is.

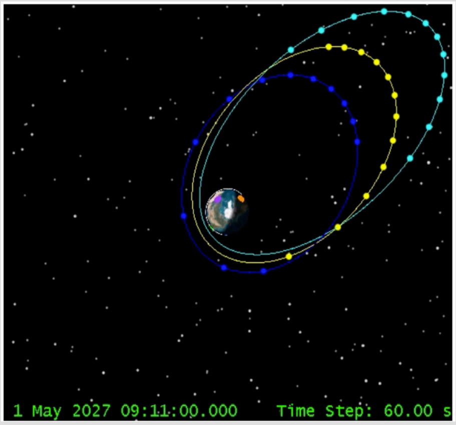
Orbit	Apogee (R_E)	Perigee (km)	Period (hours)	Deorbit (m/s)	
A (blue)	8.24	6237	16.26	422	
B (yellow)	10.79	3725	21.67	239	
C (cyan)	15.00	1400	32.52	99	

Table 8-17. MagCon concept of operations.

	ESPA	Childcraft
Launch/Early Orbit	Deploys childcraft	Turn on and enter safe mode
Cruise	Deorbits	▪ Commission spacecraft; turn on and cross-calibrate instruments ▪ Perform small burns to separate spacecraft along orbit

	ESPA	Childcraft
Science Mode	–	▪ Instruments on 24/7, unless required to be off because of low-perigee considerations ▪ Downlink data DTE at perigee
End of Mission	–	Perform burn to deorbit

DTE, direct to Earth; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter.

8.5.6. Technology Development

This FMT includes no identified technology needs; the spacecraft and instruments are available today. Mass manufacturing and preflight calibration of instruments is a consideration; lessons have been learned from MMS and from recent design change considerations to ESAs to make them more amenable to mass production. To speed development and reduce cost, more observatory-level testing versus component- or subsystem-level testing should be considered. Finally, with 36 spacecraft, ground operations would need to be streamlined. Commercial services such as AWS (which we have demonstrated closes the link) could be leveraged here.

8.6. FMT-6 Mission Concept Design Summary: Magnetotail and Inner Magnetosphere Mission

The following sections present the results of a mission concept design study named Whole Earth B-field Exploration and Reconnaissance (WEBER) performed at the NASA/GSFC MDL.

8.6.1. Observational Needs

Past estimates of the flow of energy through the magnetosphere (shown in Figure 8-9) can serve as a guide to the observational requirements for a global imaging mission. Only a small fraction of the solar wind's kinetic energy enters the magnetosphere through the magnetopause. The bulk of the energy entering the magnetosphere is stored as open magnetic flux within Earth's magnetotail, released in the form of Joule heating of the ionosphere, precipitating particles that also heat the ionosphere, and enhancements in the strength of the ring current. Ring current loss processes include charge exchange with neutrals, magnetopause outflow, and ring current ion precipitation. Table 8-18 summarizes the observations needed to identify dominant interaction modes and track energy flow through the magnetosphere.

8.6.1.1. Solar Wind Input

Monitors at L1 are not sufficient to identify the time of arrival of the solar wind discontinuities proposed to trigger bursty reconnection at the dayside magnetopause or substorm onset in the nightside magnetotail. For these purposes, near-Earth measurements of interplanetary magnetic field and solar wind plasma energy input and triggers are essential.

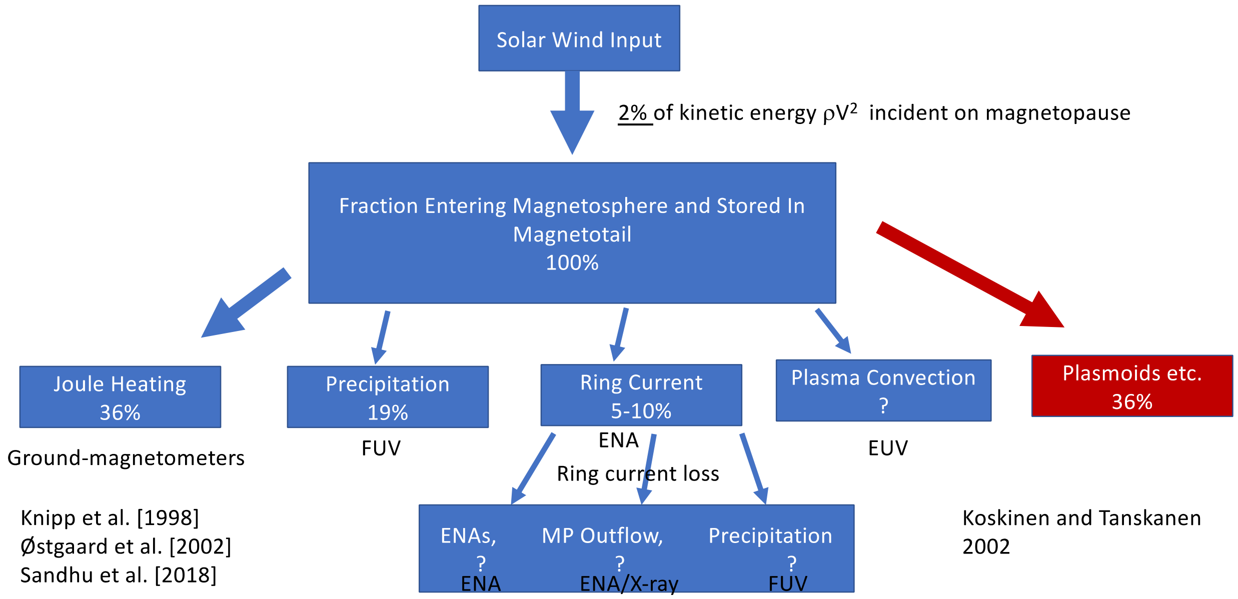


Figure 8-9. Energy flow through Earth's magnetosphere. A small fraction of the solar wind kinetic energy gains access to Earth's magnetosphere; releases fast Earthward flows in the magnetotail; is later dissipated in the ionosphere by Joule heating and particle precipitation in the ring current through collisions, charge exchange, and wave-particle interactions; and is ejected back to the solar wind via plasmoids and tailward transport of plasma. These processes can be monitored by energetic neutral atom (ENA), extreme ultraviolet (EUV) and X-ray imaging of the inner magnetosphere and outer magnetosphere and magnetopause, and far ultraviolet (FUV) imaging of the auroral region. MP, magnetopause.

8.6.1.2. Magnetopause

Magnetic reconnection at the magnetopause driven by periods of southward interplanetary magnetic field causes the dayside auroral oval to move equatorward and enables magnetosheath particles to enter the magnetosphere and flow downward to form both the high- and low-altitude cusps. Such spatiotemporal dynamics of the magnetopause can be quantified with a soft X-ray imager that can image the whole boundary with sufficient spatial and temporal resolution to discriminate between the different modes of interaction.

The rate and locations at which the magnetopause erodes inward, the dayside auroral oval moves equatorward, and particles precipitate through the cusps into the polar ionosphere distinguish between steady and unsteady reconnection rates, patchy and local or global and extended reconnection extents, and the locations predicted by, for example, component, antiparallel, or maximum shear models. In conjunction with nightside auroral observations (see below), these dayside observations can identify intervals of steady magnetospheric convection in which the magnetopause location remains nearly stationary because nightside reconnection returns magnetic flux at the same rate as it is being removed by dayside reconnection.

8.6.1.3. Auroral Oval

Global images of the auroral oval can be used to determine whether the dayside oval is expanding in response to enhanced reconnection, contracting in response to the return of magnetic flux to the dayside from the nightside magnetosphere, or stationary during steady-state conditions when flux eroded balances flux returned. Further, the location and temporal variation of the proton aurora provide important clues concerning where, when, and how steadily reconnection occurs on the dayside magnetopause.

Magnetopause reconnection consumes magnetospheric magnetic flux and imposes a dawn-to-dusk electric field on the dayside magnetosphere. This electric field causes the plasmapause to move outward, generating plasma plumes that stretch out sunward to the magnetopause, where reconnection is occurring. The rate at which they move is a direct measure of the electric field applied to the magnetosphere and can be quantified with an extreme ultraviolet (EUV) imager.

8.6.1.4. Magnetotail

The energy stored in the tail lobes can be monitored by the size of the open polar cap in the ionosphere. Energy release may come in the form of patchy, localized reconnection that produces a single azimuthal localized bursty bulk flow, a rapid sequence of such bursts that sums to a widespread release, episodic bursts that occur during steady magnetospheric convection events, a single global release, a series of global releases known as sawtooth substorms, or a sequence of releases during geomagnetic storms with properties different from those of isolated substorms during quiet times. Whereas global images are needed to track the dimensions of the entire auroral oval, high spatial and temporal resolution observations from ground-based all-sky imagers are needed to track auroral streamers that correspond in a one-to-one manner to bursty bulk flows within the Earth’s magnetotail.

Magnetotail reconnection sends streams of charged particles and field-aligned currents into the nightside ionosphere that cause the aurora to brighten, thereby providing an opportunity for auroral imagers to diagnose the corresponding dimensions and cadences of reconnection in the magnetotail. The extent and time dependence of these brightenings provide information concerning the spatiotemporal nature of reconnection within the magnetotail. The corresponding poleward motions of the nightside auroral define the quantity of magnetic flux closed, the energy transferred, and the significance of individual nightside reconnection modes.

Magnetotail reconnection imposes dawn-to-dusk electric fields on the nightside inner magnetosphere, causing the nightside plasmapause to erode earthward. The rate at which the plasmapause erodes is yet another measure of the strength of the electric fields and significance of each proposed individual or sequence of individual nightside interaction mechanisms.

8.6.1.5. Inner Magnetosphere

Magnetotail reconnection injects clouds of ions into the ring current, whose penetration depths, spatial extents, and intensities again depend on those of the proposed reconnection mode. Steady or intermittent injections of energized plasma sheet plasma enhance the ion energy stored within the ring current. The rate at which the content of ions within the ring current increases defines the rate of energy transfer to this region of space and the significance of each interaction mode; such dynamics can be observed with an energetic neutral atom (ENA) camera.

Three proposed loss mechanisms prevent ring current ion intensities from increasing indefinitely: charge exchange with exospheric neutrals, precipitation into the atmosphere, and magnetospheric outflow through the dusk-side magnetopause. Observations of ENAs can diagnose charge exchange, observations of the auroral emissions produced by precipitating protons diagnose their loss to the atmosphere, while observations of the dayside magnetopause location and dawn/dusk asymmetry in ring current ions diagnose loss via magnetopause outflow and shadowing.

8.6.1.6. Exosphere

Charge exchange of single-charged hydrogen and oxygen with exospheric neutrals produces the ENA signatures that diagnose the ring current and inner plasma sheet conditions, whereas charge exchange of multiply charged heavier atoms in the solar wind with exospheric neutrals produces the soft X-ray signals that diagnose the locations of the magnetopause and high-altitude cusps. While the relative importance of the various processes occurring at the magnetopause and in the ring current can be discerned from ENA and soft X-ray observations, information concerning the exospheric neutral densities along their LOSs can be obtained from a Lyman-α imager to determine the distributions of plasma ions along these same LOSs.

Table 8-18. Traceability matrix for globally imaging the magnetosphere.

Objective	Target	Instrument	Comment
Solar wind input	Interplanetary magnetic field	Magnetometer	Cadence sufficient to resolve discontinuity orientation by minimum variance algorithms
	Plasma	Plasma instrument	Cadence similar to those of imagers
Dayside reconnection	Magnetopause, cusps	Soft X-ray imager	Cadence faster than 8–10 min to distinguish steady from bursty reconnection
	Dayside oval, cusps	FUV imager	▪ Proton and electron lines ▪ Cadence similar to that of XRI imager
	Dayside electric fields	EUV plasmapause imager	Cadence ~minutes sufficient to track plasmapause motion
Nightside reconnection	Global nightside oval	FUV auroral imager	Electron lines, cadence similar to above
	Auroral mesoscale and transients	ASI array	▪ Red, green, blue lines for energy flux ▪ Cadence of ~10 s
	Injections	ENA imager	>3 keV, cadence of 10 min to identify injections
	Nightside electric field	EUV plasmapause imager	Cadence similar to above
Ring current loss	Ring current	ENA imager	>20 keV, cadence similar to above
	Precipitation	FUV imager	Proton lines, cadence similar to above

Objective	Target	Instrument	Comment
	Magnetopause outflow	XRI imager	Cadence similar to above
Determining neutral densities	Exosphere	Lyman-α imager	10-min cadences suffice

ASI, all-sky imager; ENA, energetic neutral atom; EUV, extreme ultraviolet; FUV; far ultraviolet; XRI, X-ray imager.

8.6.2. Mission Design

Table 8-19. WEBER mission concept design study key driving requirements.

Launch	LRD September 2032
Mission Class	C+
Lifetime	3 years
Launcher Class	Single launch with ELV-class (Falcon, Vulcan, New Glenn, etc.)
Spacecraft Class	ESPA-compatible
Concept of Operations	▪ Elliptical orbit: imagers on when spacecraft is at greater than ~45–50° latitude and the northern auroral oval is in view; imagers off during perigee and lower latitudes ▪ Circular orbit: instruments are on all times except during calibration modes
Data Rate/Latency	▪ Full data at 60-min latency ▪ 5% quick-look data at 30-min latency ▪ Quick-look data processing on board spacecraft
ACS	▪ Three-axis stabilized, Earth pointing ▪ Pointing requirements driven by elliptical orbit auroral imager: – Accuracy: 0.5° at 3-sigma – Knowledge: 0.25° 3-sigma – Jitter: 0.07°/1 min 3-sigma
Timing	<4 ms absolute timing for best synchronization between four observatories
Assumptions	▪ Propulsion ▪ Instruments handle their own thermal constraints ▪ Two pairs of identical spacecraft on different orbits with the same apogee and polar inclination; one spacecraft pair is on a highly elliptical orbit phased 180°, and the other spacecraft pair is on a circular orbit, phased 90° apart

ACS, attitude control system; ELV, expendable launch vehicle; ESPA, expendable secondary payload adapter; LRD, launch readiness date.

Table 8-20. FMT-6 significant trades and decisions.

Trade	Outcome
Single versus dual launch	Single launch with ELV-type launch vehicle from VSFB; Falcon 9 baselined
Orbit parameters (apogee and inclination) for a single launch and for continuous observations of the auroral oval and the inner magnetosphere	Constellation of four observatories: ▪ Two spacecraft at 6.17 R_E (39,352 km) altitude circular, 82° inclination, 90° true anomaly orbit; these two spacecraft will provide continuous observation of the inner magnetosphere ▪ Two spacecraft at 6.17 R_E (39,352 km) altitude apogee, 1000-km perigee elliptical, 82° inclination, 180° true anomaly orbit; these two spacecraft will provide continuous monitoring of the northern auroral oval
Spacecraft design: two separate designs for the two different orbits or common design	▪ Single bus design ▪ Design the circular orbit that includes the larger volume payload and larger propulsion capability; final cost table includes accommodation for propulsion savings for the elliptical orbit satellites ▪ Option for additional payload buy into available volume
Communications architecture: considered a variety of options to meet downlink requirement for four spacecraft	▪ 60-min downlink of full science data ▪ 2-kbps continuous "open broadcast" of quick-look data ▪ X-band used for data download; S-band omni option enables the broadcast of continuous quick-look data
Radiation requirements: considered orbit apogee trade with radiation impact	▪ TID of circular orbit is 122 krad (Si) for 100 Mil Al ▪ TID of elliptical orbit is 695 krad (Si) for 100 Mil Al ▪ Spacecraft structure will protect most bus components but not exposed instruments; a follow-on study will identify specific shielding needs, particularly in elliptical orbit ▪ In elliptical orbit, instruments are off during perigee and within the radiation belts

ELV, expendable launch vehicle; TID, total ionizing dose; VSFB, Vandenberg Space Force Base.

8.6.3. Mission Implementation

The WEBER study created a single design for all four spacecraft. The design envelope is defined by the most demanding requirement of either orbit objective as follows:

- Mass, volume, and structure are defined by the circular orbit payload.
- Radiation needs are defined by the elliptical orbit bus and instruments.
- Attitude control and knowledge are defined by the far ultraviolet (FUV) imager of the elliptical orbit.

- Propulsion is defined by the needs of the circular orbit, and propulsion tanks drive mass and volume of the bus design.

Table 8-21. Spacecraft specifications.

Spacecraft Properties	▪ Bus is three-axis stabilized, ram and nadir (earthward) pointing ▪ Mass: 633 kg ▪ Volume stowed: 5.25 m^3 ▪ Dimensions stowed: 2.29 m × 1.75 m × 1.44 m (including component extensions beyond the bus structure)
Solar Array	▪ One three-panel gimballed solar array is the only bus deployable ▪ Dimensions: 1 × 2.72 m ▪ Effective area: 2.55 m^2 ▪ Two single-axis SADAs (Moog Type 2) located on the array boom allow for tracking the Sun
Propulsion	▪ Two propellant tanks: PN 80340-1 ▪ Two helium tanks: PN 80202 ▪ Four thrusters ▪ Support/mounting structure, tubes, valves ▪ Note: Elliptical orbit requires smaller tanks; the support structure will be fitted to accommodate the smaller tanks
Communications	▪ Assume science data volume of 350 kbps; 2 kbps continuous transmission of quick-look data, 60-min latency of full science data download: – S-band radio with two omni antennae: • 2 kbps for command and housekeeping telemetry • 2 kbps for science quick-look on open broadcast mode and on different frequency than command transmission – X-band radio: 10 Mbps for full science data ▪ Orbital analysis shows no interruption of ground station coverage from the NEN
Launch Vehicle Accommodation	▪ All four spacecraft are mounted on a single adapter plate with a 24-inch Mark II Planetary Lightband attach and deploy band (see Figure 8-10) ▪ Vehicle fairing dimensions are according to the NSSL specifications ▪ Matching vehicles could be Falcon 9 and Heavy, Vulcan, New Glenn

Payload Architecture Circular Orbit	▪ Observations of the ring current, through ENA imaging – ENA mid and high energy; nadir FOV; wide FOV; one per spacecraft, cadence <2 min ▪ Observations of the plasmasphere, through EUV imaging – O^+ EUV; nadir FOV; wide FOV; one per spacecraft, cadence <2 min – H^+ EUV; nadir FOV; wide FOV; one per spacecraft, cadence <2 min ▪ Observations of the plasma sheet, through ENA imaging – ENA low energy; zenith FOV, optimum observations during equatorial pass on the nightside, FOV wide in azimuth, narrow in latitude; one per spacecraft, cadence <10 min ▪ Additional payload buys into available volume and resources (e.g., in situ electromagnetic field, plasma and neutral particle measurements)
Payload Architecture Elliptical Orbit	▪ Observations of the global northern auroral oval, through FUV imaging – FUV imager; nadir FOV; FOV encompasses the whole auroral oval; spatial resolution $\leq$20 km; cadence <2 min; at least two different wavelengths; one system per spacecraft – Additional payload buys into available volume and resources (e.g., in situ measurements)

ENA, energetic neutral atom; EUV, extreme ultraviolet; FOV, field of view; FUV, far ultraviolet; NEN, Near Earth Network; NSSL, National Security Space Launch; SADA, solar array drive assembly.

Figure 8-10 shows the overall bus design, coordinate system, and payload fields of view (FOVs), while Figure 8-11 shows the detailed configuration of all bus components. Component locations are driven by the need to optimize heat dissipation as well as to accommodate the required FOVs (instruments, antenna, solar array). Figure 8-11 also shows the launch vehicle accommodation of all four spacecraft.

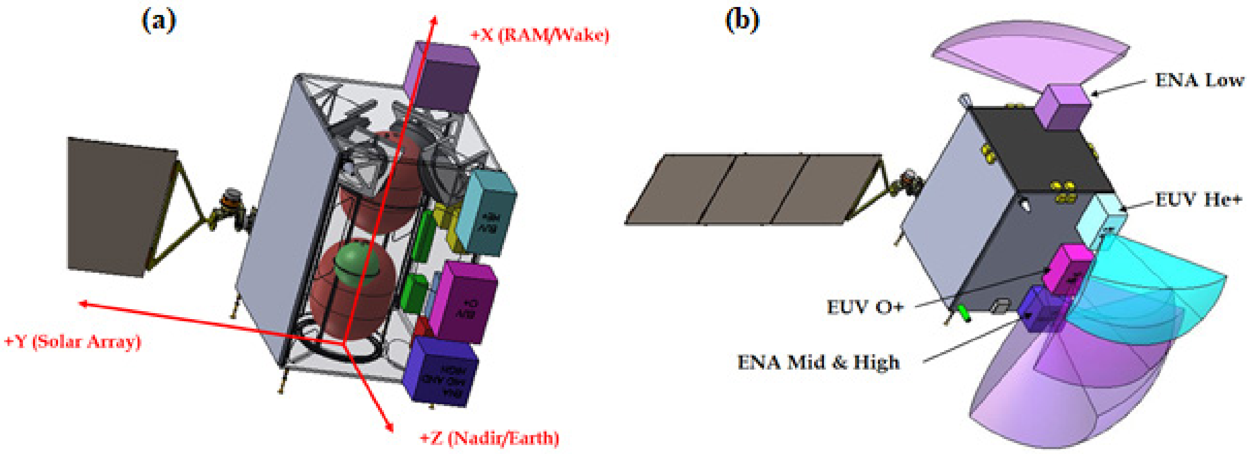


Figure 8-10. (a) The circular orbit bus and its key payload. The bus coordinate system has X pointing to RAM, Z pointing nadir/earthward, and Y along the solar arrays. (b) The FOVs of the nominal payload imagers.

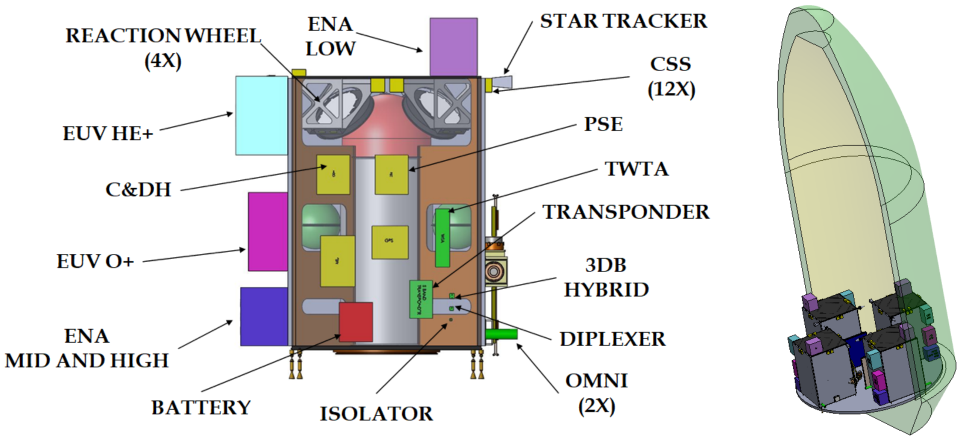


Figure 8-11. (Left) The FMT-6 bus components. (Right) The four-spacecraft accommodation inside the launch vehicle. C&DH, command and data handling; CSS, coarse sun sensors; EUV, extreme ultraviolet; PSE, power system electronics; TWTA, traveling-wave tube amplifier.

8.6.4. Orbit Design

Orbital design analysis focused on optimizing the orbit altitude to avoid radiation belts for the circular orbit and on optimizing the inclination and period of the elliptical orbit to maximize coverage of the full northern auroral oval. For the elliptical orbit, both Molniya (period 0.5 day) and Tundra (period 1 day) were considered but ultimately rejected because of their lower inclination (63.4°) that was not optimal for auroral oval coverage. The selected higher-inclination (82°) orbit will revisit the same geographic area over the northern high latitude every other orbit, and the slow precession can be corrected with propulsion. This will allow auroral studies over North America with conjugate ground coverage at a spatial resolution much higher (sub-kilometer) than provided by the satellite FUV imager.

However, maintaining satellite conjugacy with the same ground location requires a 10 m/s weekly propulsion correction, as opposed to a Molniya orbit that requires minimal station-keeping of the order of 0.7 m/s. Future work will have to revisit this issue for ultimate optimization.

Orbit acquisition after launch will be done in the following order:

- All four spacecraft will separate simultaneously from the launch vehicle into a 39,352-km-altitude (apogee) × 185-km-altitude (perigee) elliptical orbit.
- All four spacecraft will raise perigee to 1000-km altitude to reduce drag effects.
    - 78–108 m/s is required to raise perigee (depending on timing).
- One spacecraft will perform maneuvers (of ~25 m/s total) to achieve the 180° separation in the elliptical orbit over a number of days.
- Two spacecraft will perform maneuvers to raise perigees to circularize the orbits.
    - 1.3 km/s in total is required to raise perigee to 39,352 km (a.k.a. circularize).

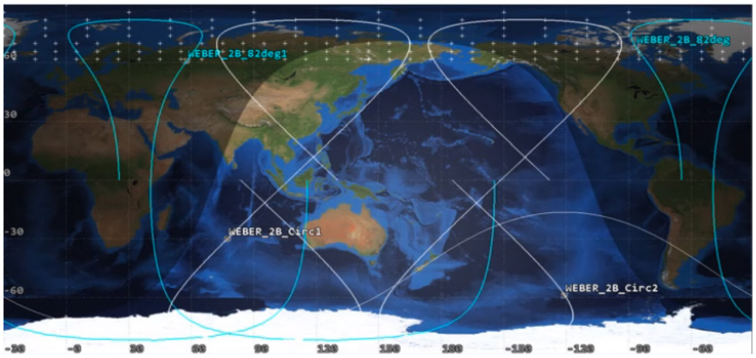
  - One circular spacecraft will delay its circularization maneuver to time itself into a 90° phase from its counterpart (may require an additional 25 m/s to achieve correct phasing).

Two Spacecraft in Highly Elliptical Synodic Orbits

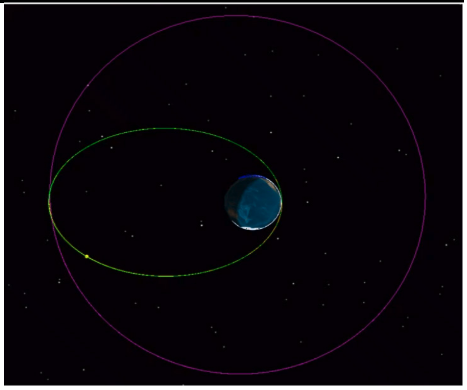
- Apogee altitude: 39,352.3 km
- Perigee altitude: 1000 km
- Period: 0.5 sidereal day (~11.95 hours)
- Phased 180° apart to maintain nearly 24/7 coverage of the auroral oval

Two Spacecraft in Circular Orbit

- Share apogee with the elliptical orbits
- 39,352 × 39,352 km orbit
- ~3500 km above geosynchronous Earth orbit radius
- Phased 90° apart to maintain continuous coverage of the inner magnetosphere above the equator



WEBER FMT-6 orbit ground track. The white curves are the tracks of the circular orbits, and the light blue curves are the tracks of the elliptical orbit.



FMT-6WEBER orbit configuration.

The selected elliptical orbit has the same period as a Molniya orbit (~12 hours) but higher inclination (82° versus 63.4°) to maximize coverage of the full northern auroral oval.

Orbital modeling demonstrated coverage of the full nominal auroral oval (region between 60° and 90° latitude) of more than 90% of the mission lifetime.

Figure 8-12. WEBER mission concept of operations.

8.6.5. Concept of Operations and Mission Timeline

Figure 8-13 shows the mission timeline. Immediately after launch, all four spacecraft separate together and follow the orbit-acquisition maneuvers described in the previous section. During the 3-month commissioning, operations coverage is 24/7.

At the end of the 3-month commissioning period, the mission enters the 3-year (36-month) prime mission phase. For the first 6 months of the prime mission, nominal operations of science data taking and downlinking are established and operations are 12/7. During these first 6 months of the prime mission, all automation procedures are established, and for the remaining 30 months of the prime mission, operations are reduced to 8/5. This analysis did not include an extended mission phase, and mission closeout and reentry activities are initiated after the end of the prime mission.

Each spacecraft is assumed to operate and communicate with ground stations independently. Station-keeping needed for the elliptical orbits requires ΔV of 10 m/s.

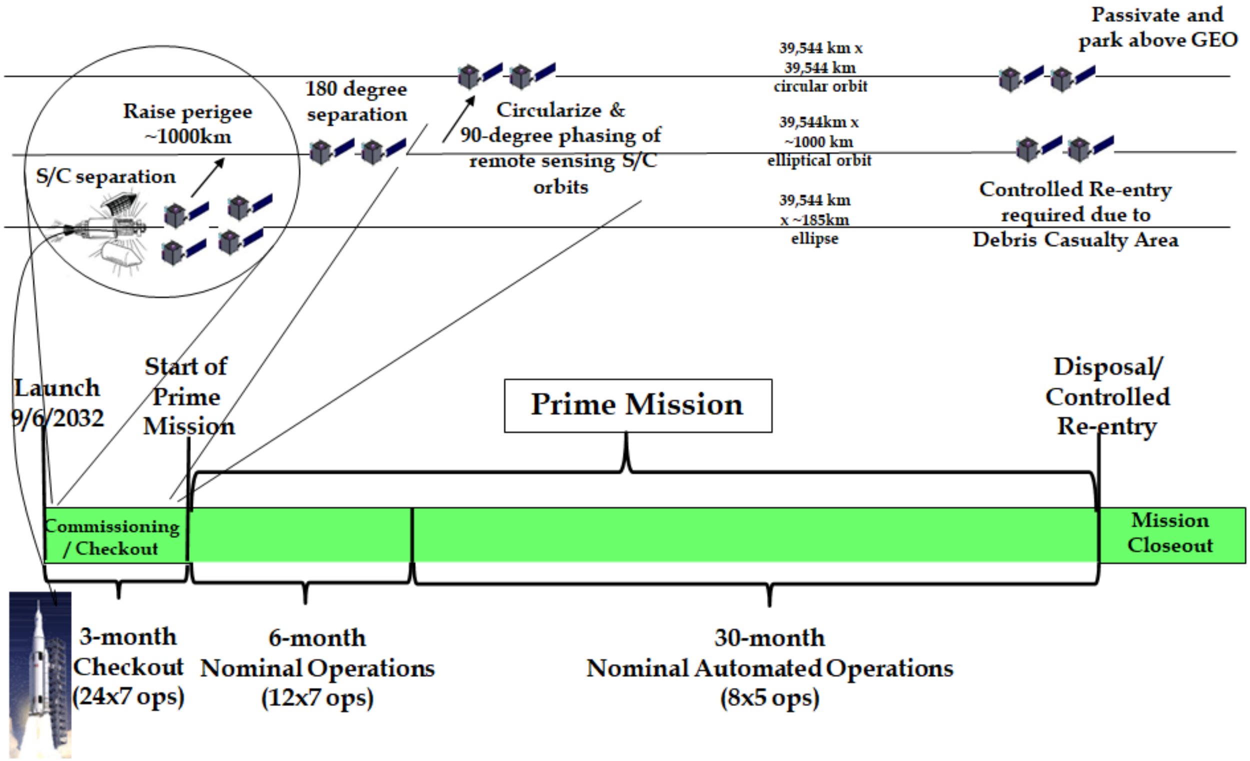


Figure 8-13. FMT-6 mission timeline. S/C, spacecraft.

Table 8-22. Summary of instrument operations.

Elliptical Synodic Orbits	Circular Orbits
Launch/Early Orbit ▪ Perigee raised to 1000 km ▪ Instrument turn-on and health checks ▪ Instrument on-orbit calibration **Science Phase** ▪ Instruments operate 24/7 ▪ Both continuous real-time summary data broadcast and full data dumps ▪ Exclusion zones are Sun-pointing ▪ Allow for on-orbit instrument calibration maneuvers **Deactivate for Reentry**	**Launch/Early Orbit** ▪ Circularization of orbit ▪ Instrument turn-on and health checks ▪ Instrument on-orbit calibration **Science Phase** ▪ Instruments operate 24/7 ▪ Both continuous real-time summary data broadcast and full data dumps ▪ Exclusion zones are Sun-pointing ▪ Allow for on-orbit instrument calibration maneuvers **Deactivate for Reentry**

8.6.6. Technology Development and Further Studies

We address technology development both in terms of mission areas that need to be further studied when an actual mission is being considered for implementation and in terms of technology development that will enable new, groundbreaking observations.

A key technology development area is the need for remote monitoring of the structure of Earth's magnetotail and plasma sheet. Such global measurements have been impossible to date because of the very cold and tenuous plasma within Earth's magnetotail and plasma sheet. A further difficulty is posed by the rapid mesoscale dynamics of the magnetotail, requiring the imaging cadence to be on the order of 10 min or less. While monitoring of the transition region at the inner edge of the plasma sheet by in situ measurements is the focus of FMT-5, using constellations to monitor the global dynamics in the magnetotail is as yet unrealistic. Therefore, global imaging would be ideal, particularly if it could be done from different vantage points (i.e., from within and above the plasma sheet).

This FMT focused on low-energy ENA imaging of the plasma sheet, and simulations show that this method holds promise for ENA energies of ~5 keV. Viewing the plasma sheet from the equatorial inner magnetosphere would produce ENA intensity on a projected cross-section of the magnetotail, thus identifying mesoscale structures such as fast flow channels in a cadence of 10 min.

Further out-of-the-box studies are needed to develop techniques that enable the 3D imaging of the whole magnetotail.

The study identified several needs for further analysis:

Orbit Analysis

- Continue investigating other orbit inclinations to determine what inclination/phasing combination provides maximum coverage
  - By switching to a Molniya orbit, it is possible to achieve the same coverage as the 82° orbit if the sensor can be rolled (the rolling required is only 2°).
- Perform analysis of the station-keeping required for different orbit inclinations
  - 82° may require substantially more ΔV to maintain argument of periapsis/right ascension of the ascending node versus the Molniya.
- Reentry
  - Do more analysis on how to optimize controlled reentry ΔV.

Communications

- Explore using TDRSS as a primary or backup for the 2-kbps broadcast mode
- Explore options for lower latency than 60 min for full data

Payload Accommodation

- Trade study between thermal, radiation, and FOV requirements for optimum placement of instruments
- Optimization of imager mounting angles to maximize science return

Navigation Analysis

- Perform orbit determination analysis for all maneuvers to ensure they can be planned and calibrated
- Orbit determination performance may play into maneuver cadence
- Redo any contact analysis if orbit changes

Radiation

- Circular orbit: 122 krad(Si) total ionizing dose (worst case, 95% confidence) for 3-year mission, 100 mil Al
- Elliptical orbit: 695 krad(Si) total ionizing dose (worst case, 95% confidence) for 3-year mission, 100 mil Al
- Spacecraft components can take advantage of bus structure for natural shielding, but instruments cannot; do full component radiation modeling to identify any special shielding needs

Navigation Control

- Attitude control system (ACS) simulations should be done with gimballed solar array
- Trade study on GPS system for radiation reason
- Detailed study of coarse sun sensor placement
- Explore the option to reorient or bias the reaction wheel assembly pyramid to increase capacity

8.6.7. Assumption of Existing Capabilities

Assumptions of available measurements and missions are as follows:

- **Solar monitoring.** It is assumed that images of solar activity (flares, CMEs) are available to provide context and linkage between solar and magnetospheric activity.
- **Solar wind and interplanetary magnetic field measurements.** It is assumed that an L1 monitor is available to provide information about the solar wind and interplanetary magnetic field configuration.

- **Ground magnetic field measurements.** It is assumed that geomagnetic indices (Dst, AL) are available to provide context and an estimate of the general level of activity. It is assumed that individual magnetometer recordings close to key infrastructures are available to assess the geomagnetically induced currents and their relation to the magnetospheric activity.

Beneficial additional capabilities are as follows:

- **Magnetospheric in -situ measurements.** Processes in the auroral ionosphere and most processes in the inner magnetosphere are driven by dynamics taking place within Earth's magnetotail. Having (multipoint) measurements of the plasma, energetic particle, and electromagnetic field environment would be highly beneficial.
- **Inner magnetosphere in situ measurements.** Although imaging technologies have taken major steps forward, in situ observations from the inner magnetosphere can provide validation and verification of the imaging instruments.

8.6.8. Implementation, Descopes, and Enhancements

Global observations of all key magnetospheric regions as well as the impacting solar wind are possible from a single satellite in a high-altitude circular orbit from 30 R_E. With the aid of a single lunar gravitational assist, observations from locations throughout a highly inclined polar orbit with a radius of 30 R_E are feasible. As the orbit precesses, these observations can be made from all possible vantage points. With a period of 9.65 days, this orbit enables continual end-to-end observations of entire phases of geomagnetic storms, including the subsolar magnetopause, the auroral oval, the plasmapause, and the ring current in conjunction with simultaneous observations of the solar wind input, making the mission entirely self-standing. Observations of all targets except the full auroral oval continue even when the spacecraft is located at low latitudes, and the ring current observations are non-global from low latitudes. The single satellite at 30 R_E option is identical to a previously studied Medium Explorer mission concept: STORM (Principal Investigator: David Sibeck/GSFC). No advances beyond existing instrument or spacecraft technology are required for this mission.

Table 8-23. Payload and descope or synergistic options.

Region	Payload	Descoping/Synergy Option
Solar wind	In situ magnetometer and solar wind plasma instrument	Rely on L1 solar wind observations (not a desirable descope)
Magnetopause	Soft X-ray imager	
Auroral oval	Far UV imager	WEBER elliptical orbit option
Plasmapause	EUV imager	WEBER circular orbit option
Ring current	ENA imager	WEBER circular orbit option
Exosphere	Lyman-α imager	Rely on exospheric models

There are two variations in the single-satellite STORM-type mission:

1. Two spacecraft allow tomography of the 3D structure of the ring current and plasmasphere, and continual observations of the auroral ovals and the global ring current become possible. In this scenario, the two spacecraft might be separated by 90° (or 9.65/4 days) along their circular orbits. One of the two polar caps would always be within view of one or the other of the two spacecraft, and the orthogonal views of the soft X-ray, ENA, and Lyman-α imagers would immediately offer the possibility of reconstructing the time-dependent distributions of magnetosheath plasma, ring current ion, and exospheric neutral densities.

2. A single spacecraft with the X-ray and Lyman-α imagers as well as the in situ instruments in a 30 R_E circular orbit for global views of the magnetopause and solar wind input. The inner magnetosphere observations can be accomplished with auroral imagers (ENA, EUV, and FUV) placed into the existing WEBER architecture.

8.7. FMT-7 Mission Concept Design Summary: Low-Earth-Orbit Constellation for Ionosphere/Thermosphere/Mesosphere (ITM) System Observations

8.7.1. Mission Design Overview

For this study, FMT-7 was developed into a mission concept study called the Multi-Altitude Volumetric Reconstruction of Ionosphere/thermosphere Composition and Drivers (MAVRIC-D) performed at the NASA/GSFC MDL. The MAVRIC-D mission concept accomplishes the goals of FMT-7 through remote sensing measurements from a constellation of four “motherships”' orbiting at 600 km, each of which deploys six CubeSat-class probes to various altitudes for in situ measurements of the ITM system. We stress that the MAVRIC-D mission concept is not the only mission concept that could meet the objectives of this FMT; it is only a single example developed for the purpose of preliminary technology exploration and mission cost estimation. The MAVRIC-D mission concept was developed to CML 3 by GSFC/MDL.

Figure 6-9 shows a graphical representation of the MAVRIC-D mission as developed by the MDL team.

MAVRIC-D satisfies the objectives of FMT-7 by:

- Establishing a long lifetime, multi-spacecraft constellation in LEO from a single launch operation
  - The mothership constellation can easily be adapted to accommodate a range of Earth and space science payloads.
  - The mothership spacecraft are built to Class D mission assurance levels because the redundancy of the constellation allows a higher risk posture for any individual element of the constellation.

  - The mothership spacecraft are small enough to enable launches to any LEO altitude with current launch systems and, with an appropriate re-specification of launch vehicle, could potentially be deployed to medium Earth or geosynchronous Earth orbits as well.

- Using deployable probe spacecraft on each mothership, enabling a wide range of mission profiles and science applications

  - The concept shown in this report of probe deployment via mothership altitude changes can be adapted to other deployment scenarios such as ejection from a single altitude.

  - The number, type, and size of the probe spacecraft can be easily adapted to other science mission goals; for example, a larger number of 3U CubeSats could be accommodated on the mothership spacecraft developed in this study.

  - The communication between motherships, probes, and ground stations can be adapted to, for example, enable optical communication to LEO transport layers envisioned by commercial and Department of Defense operators.

- Combining remote sensing and in situ sampling on a three-axis-stabilized mothership platform

  - The motherships can accommodate a range of in situ instrumentation, including energetic particle detectors to provide data for studies of the plasmasphere, ring current, and precipitating particles in the polar high L-shell regions of the orbits.

  - A wide variety of remote sensing instruments can be accommodated on the platforms, allowing for similar constellation deployments to achieve other FMTs in later architecture studies.

Table 8-24 summarizes the MAVRIC-D mission characteristics, including the major assumptions used in the design study.

Table 8-24. MAVRIC-D key driving requirements.

Mission Class	D
Lifetime	Motherships: 6-year prime mission, deployable probes: <1 to 5 years depending on deployment altitude
Launcher Class	NSSL-qualified launcher (e.g., Falcon 9 RTLS)
Spacecraft Class	MIDEX-class motherships, 6U CubeSat probes
Concept of Operations	6U CubeSat probes deployed on command; data transmitted from probes until reentry

Assumptions	▪ Single launch deploys four motherships at a fixed LT polar orbit plane (600 km, 91° inclination), and they are separated into four equally spaced LT orbits ▪ All motherships and probes carry identical instrument payloads ▪ Altitude coverage by deployed probes from mothership altitude down through reentry ▪ S-band uplink/X-band downlink for motherships

MIDEX, Medium-Class Explorer; NSSL, National Security Space Launch; RTLS, Return to Launch Site.

Mission class was specified as D because of the redundancy in mothership and probe capabilities. Loss of up to two motherships and/or 12 probes before main mission termination was not considered a mission-failure condition; scientific return with the remaining instruments and deployments would still represent a major advance over past, current, and planned ionosphere–thermosphere missions because of the multiple orbits and altitudes measured. Table 8-25 summarizes the major trades made in the design study along with the outcomes of the trade studies.

Table 8-25. Trade study elements in the MAVRIC-D concept development and the final outcomes.

Trade	Outcome
Number of deployed probes: 4–6	Six deployed probes per mothership
Launch vehicle packaging: plate mounted or stacked	Stacked
Single or multiple launches	Single launch
Probe deployment plan: deploy during launch or after mothership orbit establishment	After mothership orbit establishment: dip down to 400 km, deploy three probes, raise back to 600-km deploying probes at 50-km intervals.
Probes communicate with motherships or ground antennas	Probes communicate DTE via KSAT Lite or other commercial ground stations

DTE, direct to Earth; KSAT, Kongsberg Satellite Services.

8.7.2. Mission Implementation

8.7.2.1. Observables and Payloads

- Energy input in high latitudes (particle precipitation and Joule heating rate)
- Energy loss rate through infrared radiation from NO, CO_2, and other radiative sources in the thermosphere
- Profiles of global neutral density, atomic and molecular composition, temperature, and wind from 60 to 1000 km

- FUV spectrograph imager, O THz neutral wind sensor, infrared sensor (SABER II), kiloelectronvolt particle sensor, neutral wind and mass spectrometer, ion velocity meter, megaelectronvolt particle sensor, and direct current (DC) fluxgate magnetometer

Table 8-26 shows the key instrument parameters of the MAVRIC-D mission concept.

Table 8-26. MAVRIC-D key instrument parameters.

Instrument	Type	Qty.	Unit Mass [kg, CBE]	Unit Orbit Average Power [W, CBE]	Unit Orbit Average Data [bits]	Pointing
FUV spectrograph	Optical	1	10	24	360 kbps	1°, 0.02°
O THz wind sensor	Optical/ radio	1	13	25	5 kbps	1°, 0.02°
Infrared SABER II	Optical	1	35	35	4 kbps	0.1°, 0.1°
Kiloelectronvolt particle sensor (0.03–30 keV)	In situ	1	7	10?	~1 kbps	1, 1?
Temperature and wind mass spectrometer (TWMS)	In situ	1	7.1	19.5	~1 kbps	
Ion velocity meter (IVM)	In situ	1	2.5	3.3	~1 kbps	
Megaelectronvolt particle sensor	In situ	1	0.268	0.368	~1 kbps	
DC fluxgate magnetometer (Mag)	In situ	1	1	2	3 kbps	3-m boom

CBE, current best estimate.

8.7.2.2. Spacecraft Design and Mass Budget

- CubeSat: three-axis stabilized, 6U (3 ×2 × 1), 12 kg, 15-kbps data rate
- Mothership instrument total mass: 84.1 kg
- Mission launch mass: 3209 kg (including four motherships and their CubeSats)

8.7.2.3. Spacecraft Power

- Solar array (4.1 m^2, two-axis gimballed), 66-Ah lithium-ion battery
- Payloads on each mothership (excluding the CubeSats): 139.2 W (orbit average)

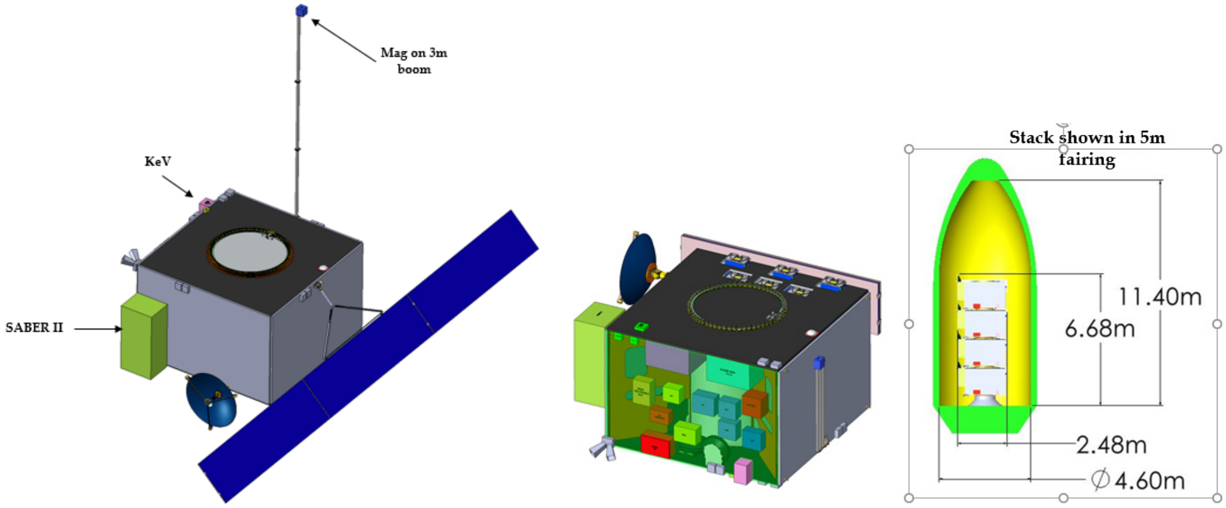


Figure 8-14. (Left) Depiction of a mothership. (Center) A transparent view of a mothership. (Right) Depiction of four motherships stacked in the launch vehicle.

8.7.2.4. Communications

- Total orbital average data rate for each mothership (including one CubeSat): 535 kbps
- Downlink (mothership): X-band system with Earth phased-array antenna (50 Mbps)
- Uplink (mothership): S-band
- Cross-link between mothership and CubeSat: a custom parabolic antenna (~1 Mbps) on the mothership and a helical S-band antenna on the CubeSat

8.7.3. Orbit Design

The MAVRIC-D mission concept relies on orbiting four identical satellite motherships in polar orbits with ~45° RAAN separation between orbital planes, as shown in Figure 6-9. The motherships are labeled A, B, C, and D, and their orbit design was subject to the following constraints and considerations:

- Four spacecraft (motherships) in four different orbit planes for a 6-year mission duration
- Launch on one launch vehicle (SpaceX Falcon 9)
- Each mothership carries six CubeSats
    - Each CubeSat will be dropped off in an altitude ranging from 400 km to 550 km
- Orbit considerations
    - Inclination
    - Different inclination values provide different plane precession rates

  - Altitude: 600-km circular altitude (chosen by the science team as optimal for science considerations)
  - Maneuvers
    - Spacecraft are responsible for inclination correction to operational orbit, altitude raising/lowering to CubeSat altitude deployment, and station-keeping and decommissioning to achieve/maintain/leave their orbits
- Navigation considerations
  - Orbit determination
    - GPS-based navigation to achieve position/velocity accuracies needed for maneuver planning and science
    - Antenna/receiver combo required to maintain POD-level accuracy per requirement

8.7.4. Mothership Orbit Design

The following requirements were applied to the design of the mothership orbits.

- Launch vehicle requirements
  - The launch vehicle shall deliver all four spacecraft to a 600-km-altitude circular orbit with a <94° inclination.
- Orbit requirements
  - Mothership operational orbit shall be at 600-km altitude with a 94° inclination, with each plane spaced 45° apart.
  - The motherships shall deploy CubeSats to their operational altitudes of 550–300 km.
  - The motherships shall perform an end-of-life reentry burn (controlled).
- ΔV requirements
  - All four spacecraft will carry consumables to meet the 6-year mission duration goal.

These requirements led to the following orbit characteristics for the mothership spacecraft:

- Nominal 600-km-altitude circular orbit
  - Near Sun-synchronous
- Launch into low inclination (−2.5° below operational inclination)

  - This causes the plane to precess (relative to the operational plane)

- Over the course of 1-year maneuver, the motherships will raise inclination to “lock” into the operational plane
  - Operational requirement to have mothership planes walk 90° every 6 months (to be determined)
  - Final operational planes spread 45° apart
- As required maneuver to/from deployment altitudes
  - Baseline six child satellites per mothership
  - Deployment altitude for children: 400 (2), 450, 500, 550 km
  - CubeSats deployed at lower altitudes will use differential drag and their own propulsion systems to lower below 400 km
- Some of the larger burns (i.e., plane change) may need to be divided into multiple smaller burns in a campaign
- Small amount of station-keeping required to maintain 600-km Sun-synchronous orbit
  - To-be-determined ΔV required on the child satellites to maintain their altitudes
- Reentry ΔV maneuver required in one orbit revolution
- GPS Tri-G receiver and GNSS patch-excited cup antenna
  - Used in GRACE follow-on mission
  - Meets POD science accuracy needs

Figure 8-15 shows the nominal mothership orbits with the deployed probe CubeSats shown in the same orbital plane (i.e., just after deployment and before LT dispersion of the lower-altitude probes).

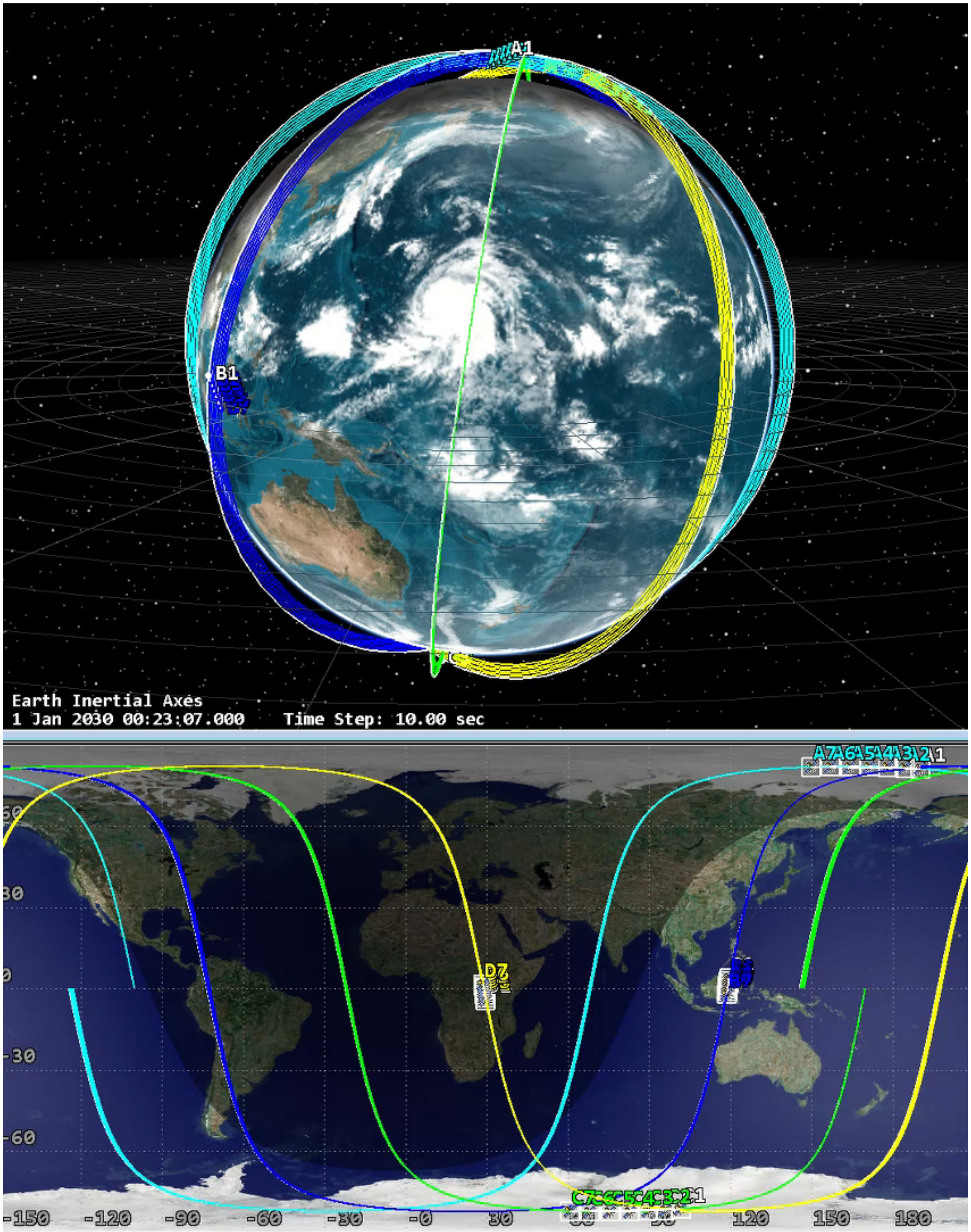


Figure 8-15. MAVRIC-D mothership orbital design. Satellites A1, B1, C1, and D1 are the motherships in 600-km circular polar orbits; satellites A2, A3, ... A7 and B2, B3, ... B7, etc., are the CubeSat probes released from the corresponding mothership.

The β-angle of the motherships and the eclipse durations over the course of the 6-year mission are shown in Figure 8-16.

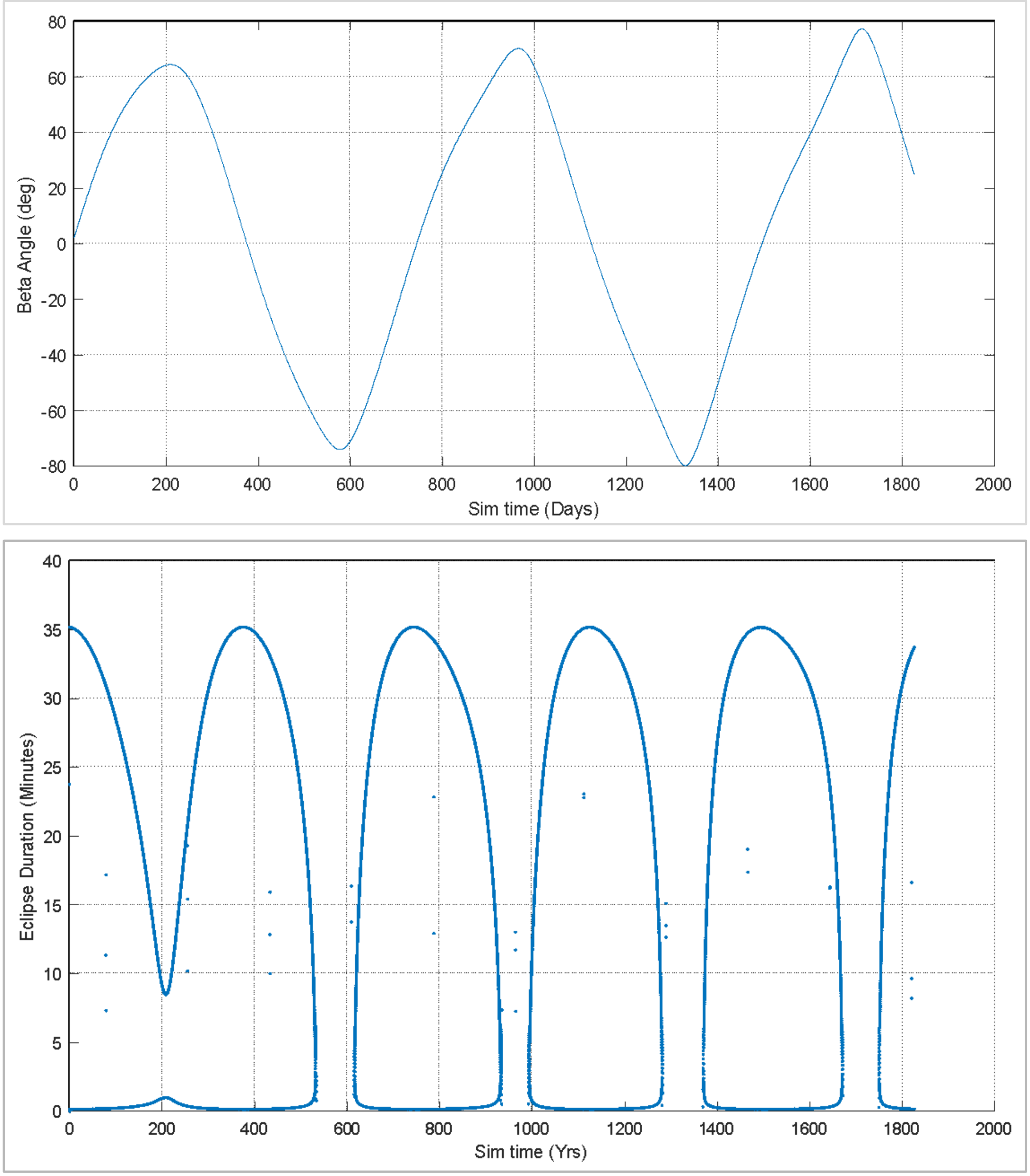


Figure 8-16. β-angle (top) and eclipse durations in minutes (bottom) for the 600-km circular polar orbits of the motherships.

The required velocity change magnitudes (ΔV) for the mothership spacecraft over the course of the 6-year mission are shown in Table 8-27.

Table 8-27. Orbital velocity change ΔV budget for the mothership spacecraft over the 6-year mission lifetime of the MAVRIC-D concept.

Mothership ΔV	Budget (m/s)
Sun-Synchronous Plane Change	130
Probe Deploy Transfers (down to 400 km)	110
Drag Makeup	45 (7.5 per year)
Deorbit	150

The CubeSat probe orbits were not analyzed in detail for this study. However, estimates were made for the drag makeup ΔV for the range of altitudes considered for the probes (550–350 km). The result was a range of ΔV from 15 to 255 m/s per year.

8.7.5. Concept of Operations

The MAVRIC-D concept of operations is complex because of the need to schedule the deployment of probe spacecraft and to communicate with the motherships and deployed probes throughout the mission. Figure 8-17 shows a diagram of the MAVRIC-D mission timeline.

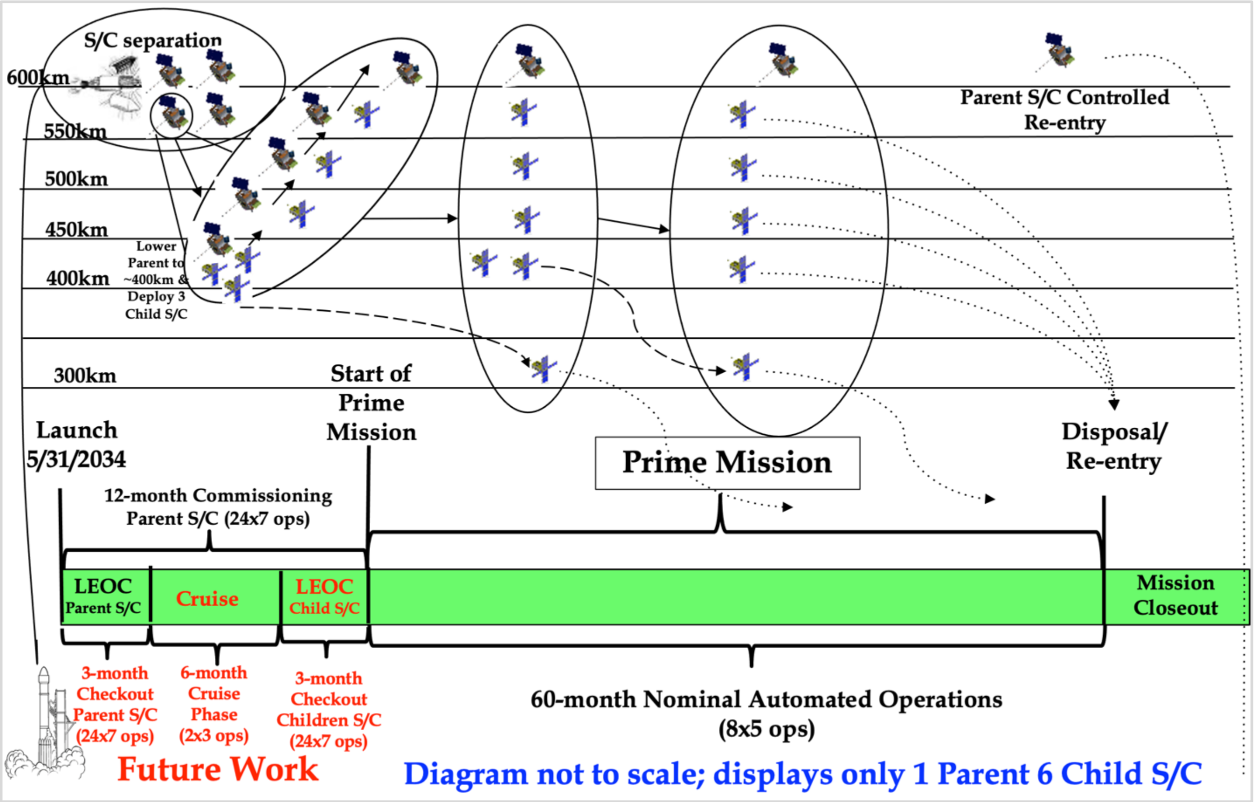


Figure 8-17. MAVRIC-D mission concept of operations timeline. Note that the altitude lowering and probe deployment are shown for a single mothership only. However, all four motherships execute the same maneuver simultaneously. LEOC, low-Earth-orbit communication; S/C, spacecraft.

The mission launch phase assumes that all four motherships are launched into a high-inclination 97.8° polar orbit at the same time on a common launch vehicle that the study assumed was a SpaceX Falcon 9 Return to Launch Site (RTLS) vehicle. From this initial launch plane, three of the four motherships would execute RAAN modifying maneuvers to achieve the final 45° separation of orbital planes. The maximum required RAAN increase is 135°. These maneuvers would require a to-be-determined amount of time to accomplish and a 130 m/s change in velocity (Table 8-27).

After achieving the 45° orbital plane separation, each mothership executes an orbital altitude change from 600 km down to 400 km. At the 400-km altitude, three probe CubeSats are deployed. The mothership then raises its orbit to 450 km, deploys one CubeSat probe, raises to 500 km, deploys another CubeSat, raises to 550 km, and deploys a final CubeSat. The end result is three CubeSat probes orbiting at 400 km and one each at 450, 500, and 550 km, respectively. Two of the probes at 400 km are intentionally re-entered during major geomagnetic storm conditions, taking and downlinking data until the lowest possible altitude prior to reentry and burn-up. After the two sacrificial probes are re-entered during major geomagnetic storms, there is one remaining probe at 400 km that will remain at that altitude for the remainder of the prime mission. At the end of the mission, all remaining CubeSat probes will be directed to reenter in sequence, starting with the lowest probe, each one timed to reenter during major geomagnetic storm conditions.

Figure 8-18 shows the orbital velocity changes required for the mothership deployment maneuver, modeled as a Hohmann transfer. The total required ΔV is approximately 110 m/s per mothership.

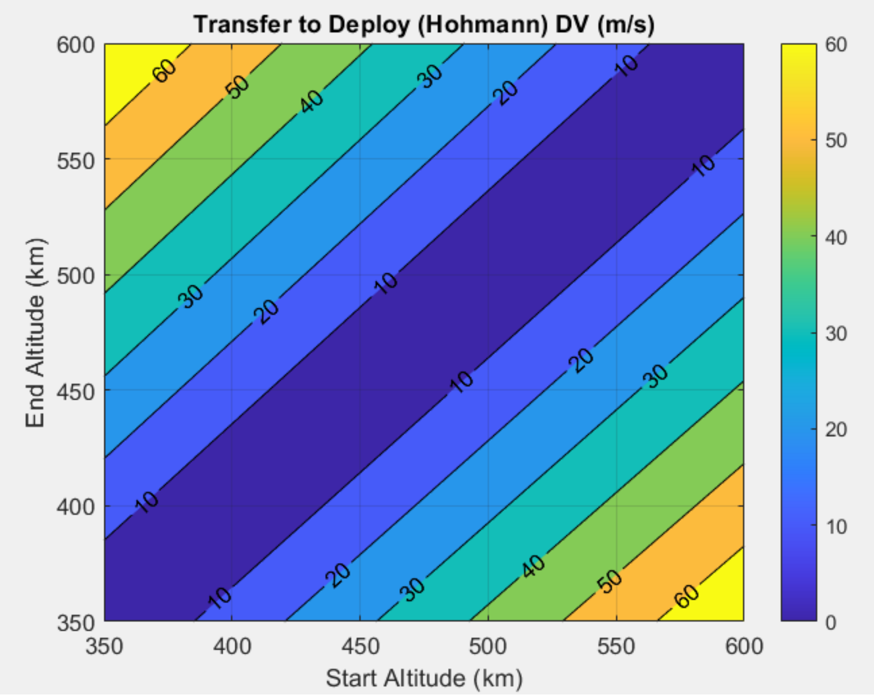


Figure 8-18. ΔV (DV) requirements to raise the motherships following CubeSat probe deployment.

All of the CubeSat probes deployed to lower altitudes will experience RAAN precession of their orbital planes relative to the motherships. Figure 8-19 shows the RAAN precession per year for the probes as a function of altitude and incremental inclination difference from the nominal 97.8° launch inclination. The estimated precession of RAAN for the deployed CubeSats is ~10° per year per 50 km of altitude below the nominal 600-km mothership orbit. Thus, the probe deployed to 550 km will precess 10° per year relative to the mothership from which it was deployed, and the probe deployed to 400 km will precess 40° in RAAN per year relative to the mothership from which it was deployed. Two years after the deployment of the CubeSat probes, the probes will cover nearly the full range of RAAN values of the mothership constellation and achieve the goal of a "volumetric sampling" of the ITM system at a variety of altitudes and LTs.

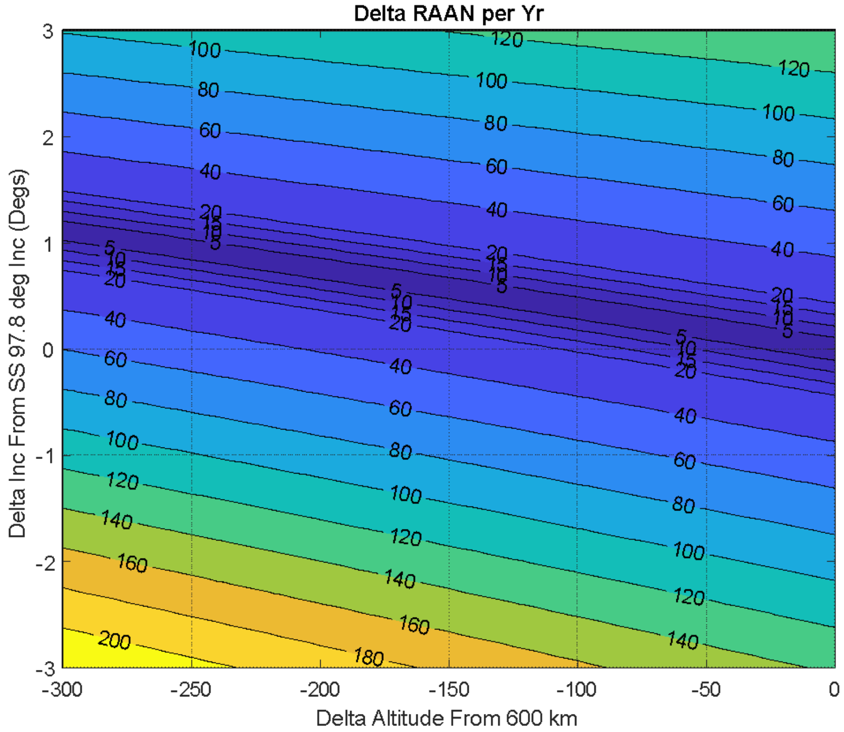


Figure 8-19. RAAN changes per year for a variety of altitudes starting from 600 km.

A challenge of the MAVRIC-D constellation concept is communicating to and from the large number of CubeSat probes. The MDL study considered only individual ground contacts with the CubeSat probes, which would put a large burden of tens to hundreds of scheduled contacts per day on any dedicated ground station network. The possibility of using commercial ground stations was considered but not investigated in detail. A more technically challenging but perhaps much more productive alternative is to have the CubeSat probes communicate only with the mothership constellation and then have the motherships relay all the data down during a much smaller number of ground contacts. As discussed above, after deployment of the probes, the RAAN precession over less than 2 years results in spacecraft dispersed across 360° of longitude so that a probe deployed from one mothership will eventually be in closer proximity to each of the other motherships as its orbit evolves. Having an optical inter-satellite communication system that can link any of the probes to any of the motherships at any given time would be enabling for this mission concept. Taking this concept further, the CubeSat probes could potentially use optical communication technology to communicate with planned and in-development commercial optical communication networks in LEO. Future implementations of FMT-7 will benefit from investigating both intra-constellation and commercial optical communication networks for maximum data return without the complexity of ground station scheduling.

8.7.6. Technology Development

For the motherships, there are no required technology development issues: The spacecraft bus, propulsion, thermal control, avionics, command and data handling, and communications systems are all based on existing standards for LEO satellite systems. For the 6U CubeSat probes, we identified several technologies for potential development:

- **CubeSat-qualified mass spectrometer instruments.** Current mass spectrometer instrumentation has been deployed on traditional large NASA research spacecraft. Development of an accurate mass spectrometer that could make measurements of H, He, N_2, N, O_2, O, and trace elements in the range of altitudes from 300 to 1000 km would be a significant enabling technology for FMT-7.

- **CubeSat-qualified high-accuracy (nano-g) accelerometer instruments.** Current accelerometer instruments have been deployed on dedicated large gravimetric satellites such as Swarm, GOCE, GRACE, and CHAMP. The development of an accurate nano-g precision accelerometer for a 6U CubeSat deployment would be enabling for FMT-7.

- **CubeSat optical communication network systems.** While the traditional radio-frequency communications described above are adequate for realization of FMT-7, the use of upcoming optical communications RNs in LEO would significantly increase the science return of any mission concept that addresses the goals of FMT-7.

- **CubeSat-qualified atomic oxygen measurement systems.** We note that the FIPEX instrument on the SWARM-EX CubeSat constellation that is due to launch in 2024 will likely satisfy this technology development milestone.

- **CubeSat storage and separation process.** The CubeSat probes will be stored in the motherships for up to a year after launch while the motherships maneuver to adjust their orbital planes to the final constellation positions. During this time, they will need to be monitored for instrument and systems health. The deployment mechanism for 6U-format CubeSats from a compact main spacecraft platform will also require some technical development.

- Balance out large gravity gradient torque (e.g., adding second boom)

8.8. FMT-8 Mission Concept Design Summary: The Cold Plasma Cycle

FMT-8 did not undergo a detailed mission concept design study. Study of the cold plasma cycle requires a combination of in situ and remote measurements. Aspects of plasmaspheric and ionospheric plasma studies are incorporated in other FMTs in a synergistic way: FMT-11 calls for global imaging of the magnetospheric key plasma regions, including EUV imaging of the plasmasphere. FMT-4 proposes making in situ and remote observations of ionospheric density through storms. FMT-10 calls for the remote monitoring of neutral and plasma density structure of the ionosphere. All these mission synergies can contribute to the goals of this FMT.

We provide below a dedicated mission example termed Multiscale Mass Circulation (MMC) that encompasses all elements in terms of observational needs, types of instruments, and number of satellite and orbit configurations in order to independently fully address the objectives of FMT-8.

8.8.1. Mission Design

The FMT mission concept is summarized in Figure 6-10. MMC is a three-spacecraft constellation that combines imaging, in situ measurements, and limited radio sounding to observe the life cycle of magnetospheric plasma mass across multiple spatial scales. The **Imager** spacecraft uses EUV cameras to observe the global and regional distribution of He^+ and O^+/O^{++} and uses a radio receiver as one part of a TEC measurement. The **Plasma/Fields** spacecraft measures full distribution functions of cold H^+, He^+, and O^+ ions, down to 0 eV using spacecraft potential control. The Plasma/Fields spacecraft also measures the background magnetic and electric fields and waves, including the upper hybrid resonance that allows determination of the in situ total electron density. The **RadioSat** spacecraft is a microsatellite with a radio transmitter that enables TEC measurements along the dynamically changing LOS to the Imager spacecraft radio receiver. A second transmitter on board the Plasma/Fields spacecraft operates with reduced duty cycle (one sub-second pulse every ~10 min). This combination of mutually supporting measurements (imaging + in situ + sounding) provides a cross-scale view of the majority of the plasma mass contained in the magnetosphere.

The Imager spacecraft is located on a circular polar orbit at 20 Earth radii (R_E), an ideal vantage point from which to perform continuous imaging of either the equatorial (L versus MLT) or meridional (L versus latitude) distributions of He^+ and O^+. The Plasma/Fields spacecraft is positioned on a low-inclination elliptical (GTO-like) orbit. This orbit covers detailed plasma and field measurements across a wide range of L-shells, with long dwell times in the outer plasmasphere and oxygen torus, where most plasma mass dynamics (erosion and refilling) occur. In situ data provide a vital single-point constraint from within the imaging field of view that greatly enhances the fidelity of global inversions of the EUV images. Each LOS measurement of TEC (from radio sounding) provides a point within each EUV image where the total LOS plasma density is definitively known. This knowledge enables determination of the fractional mass density carried by He^+ and O^+ along that LOS, a unique and important constraint on global EUV inversions.

8.8.2. Mission Implementation and Orbit Design

The baseline FMT-8 mission includes three spacecraft, as summarized in Table 8-28:

- **M1 Imager** is in a high-inclination 20-R_E circular orbit (5.25-day period), performs continuous dual-spectral EUV imaging, and receives radio signals from **M2** and **M3**.
- **M2 Plasma/Fields** is in an 11-hour GTO-like low-inclination eccentric orbit (5.8 R_E × 1.1 R_E, very similar to that of the Van Allen Probes), provides in situ sampling versus L-shell, and sends radio signals to **M1** once every 10 minutes.
- **M3 RadioSat** shares an orbit with **M2** and sends radio signals to **M1** to measure the TEC along the LOS between the two spacecraft. It uses onboard propulsion to optimize separation from **M2**, reaching the ideal configuration when one transmitter is near apogee simultaneously with the other being close to perigee.

To reach their orbits, all three spacecraft are launched on three ports of an ESPA Grande adapter ring on a launch vehicle that initially achieves GTO. After separating M2 and M3, the launch vehicle restarts its upper-stage motor to boost apogee to 20 R_E, separates M1, and performs a final burn to put the launch vehicle upper stage into a disposal orbit. Onboard spacecraft propulsion raises the M1 apogee to the lunar orbit; a lunar swing-by raises the M1 perigee to 20 R_E and its inclination to >70°. M1 then lowers its apogee to 20 R_E, circularizing the orbit. Meanwhile, M2 and M3 lower their inclinations to ≤10° and lower their apogees to 5.8-R_E radius.

Table 8-28. MMC spacecraft and orbits.

Spacecraft	Orbit	Description
M1 Imager & Radio Receiver ***Nadir-pointing***	Circular polar (e.g., 20 R_E)	▪ Provides global-to-regional imaging of the refilling, evolution, erosion, and circulation pathways of cold ions in the plasmasphere and dense O^+ torus ▪ Three-axis stabilized (nadir-pointing) ▪ Also on board: radio receiver enables TEC measurements coordinated with M3 RadioSat or M2 Plasma/Fields transmitters ▪ Onboard propulsion to achieve orbit
M2 Plasma/Fields & Radio Transmitter ***Spinning***	1.1 R_E × 5.8 R_E low inclination	▪ Measures cold ion refilling, heating, composition, and transport in the plasmasphere, oxygen torus, and trough, 12-s spin period, spin axis toward Sun ▪ Onboard propulsion to optimize separation from RadioSat ▪ Radio transmissions at reduced duty cycle (10-min cadence) to prevent interference with 12-s in situ particle and fields measurements
M3 RadioSat ***Three-axis stabilized***	1.1 R_E × 5.8 R_E low inclination	▪ Onboard radio transmitter to enable TEC measurement along LOS between RadioSat and Imager ▪ Microsatellite (smaller/cheaper) ▪ Onboard propulsion to optimize separation from Plasma/Fields in shared GTO

Table 8-29. MMC instrument payloads.

S/C	Instrument	Data (kbps)	Power (W)	Mass (kg)	Pointing	Description
M1	**EUV-He***	90	9	10	0.1°	

S/C	Instrument	Data (kbps)	Power (W)	Mass (kg)	Pointing	Description
	EUV-O*	12	9	10	0.1°	**Extreme Ultraviolet** imagers: EUV-He measures 30.4 nm light from He$^+$ ions, with sensitivity 2.98 (R s pix)$^{-1}$ sufficient to capture 50-mR signal at 60-s cadence. EUV-O measures 83.4 nm light from O$^+$/O^{++} ions, with sensitivity 0.69 (R s pix)$^{-1}$ to capture 10-mR signal at 24-min cadence. EUV-He/O are mechanically and electrically identical. Each bandpass is determined by choice of filter and multilayer mirror coating. EUV has 40° FOV and 0.45° resolution, sufficient (from 20 R$_E$) to capture regions <7.3 R$_E$ with spatial resolution Δr = 0.16 R$_E$. Heritage is IMAGE (camera) and Juno (electronics).
	RT: RF only†	5	10	7	10°	See **M3** entry below.
M2	**HOPE**	40	29	21	4.5°	**Helium Oxygen Proton Experiment**: in situ determination of species-resolved (H$^+$, He$^+$, O$^+$) ion spectra and PADs (0 eV to 50 keV, $\Delta E/E$ = 16%). To access ≥0-eV ions, HOPE uses a **Sensor-Panel-Bias (SPB)** system in which the instrument and adjacent S/C panel are biased negative (on-orbit programmable voltage steps) relative to S/C ground. Heritage is Van Allen Probes (minor changes to accommodate SPB). HOPE is heavily shielded and designed to survive >50-krad TID. S/C spin samples full ion distribution every 12 s.
M2	**Fields Suite**		11	15		**Fields**: measures E- and B-fields/ waves. Heritage is mostly Van Allen Probes EMFISIS except e-POP (MAG) and booms (THEMIS).

S/C	Instrument	Data (kbps)	Power (W)	Mass (kg)	Pointing	Description
	Fields: MAG	5	3	3	0.1°	Fluxgate **Magnetometer**: quasi-static (DC) background B-field vector (for ion pitch angles), DC–50-Hz waves, ±65,535 nT, accurate to 1 nT
	Fields: BWa	3	1	4	1°	**B-Waves**: measures plasma waves 5 Hz to 12 kHz, Δt = 6 s, 90 dB, triaxial search-coil assembly
	Fields: EWa	3	1	1	1°	**E-Waves**: higher-frequency plasma waves including the UHR line: 5 Hz to 12 kHz (WFR), 10 kHz to 1 MHz (HFR), Δt = 6 s, 90 dB. Uses two orthogonal double probes (shared with ELF)
	Fields: ELF	6	2	8	1°	**Electric Low Frequency**: quasi-static (DC) E-field, low-frequency waves (<32 Hz), spacecraft potential. Δt = 6 s, 90 kB, ±15 V, ±0.5 μV. ELF-ANT (antennas): two pairs of orthogonal spin-plane double probes, 100 m tip-to-tip, deployment maintains 12-s spin period
	RT[†]	5	13	10	10°	See **M3** entry below.
M3	**RT**[†]	5	13	10	10°	**Radio Tomography/Relaxation Sounder**: Its two subsystems, Radio Frequency (RF) and Active and Passive Plasma Sounder (APPS), share a dipole pair of axially deployed 1.5-m stacer antennas for transmitting and receiving signals. RF transmits dual-frequency radio signals to a remote RF receiver that measures their relative phase delay to determine the TEC along the LOS between spacecraft. Heritage is MAVEN/LPW (sounder).

[*][†]Instruments requiring technology development to raise the technology readiness level from [*]5 to 6 or [†]4 to 6.

DC, direct current; FOV, field of view; HFR, high-Frequency receiver; RF, radio frequency; S/C, spacecraft; TID, total ionizing dose; UHR, upper hybrid resonance; WFR, waveform receiver.

Table 8-30. MMC spacecraft design and implementation.

Spacecraft		Parameter	Requirement
M1 Imager & Radio Receiver ***Nadir-pointing***	Mission	ΔV to achieve science orbit	ΔV ≤ 700 m/s
		Orbit inclination	≥70°
		Orbit radius (circular)	20 ± 1 R_E
		Mission duration	≥3 years of science observations
	Spacecraft and Operations	Spacecraft total ΔV capability	>700 m/s
		Pointing (three-axis, to nadir)	<0.07° know, <0.15° control
		Instrument payload	EUV-He, EUV-O, RT-RF receiver only
		Payload mass, power	<37 kg, <36 W
		D/L: Ka-band, DSN 34-m ground station	>20 Mbps
		Ephemeris knowledge	≤22 km (three-axis, 3-sigma)
		Launch vehicle accommodation	ESPA Grande (one port)
M2 Plasma/Fields & Radio Transmitter ***Spinning***	Mission	ΔV to achieve science orbit	ΔV ≤ 710 m/s
		Orbit inclination	≤10°
		Perigee × apogee (altitude)	≥400 km × 4.8 ± 1 R_E
		Mission duration	≥3 years of science observations
	Spacecraft and Operations	Spacecraft total ΔV capability	>710 m/s
		Spin-stabilized	3–10 rpm
		Spin vector	Sun-pointed within 5°
		Attitude knowledge	Better than 0.1° (three-axis)
		Instrument payload	HOPE, Fields Suite, RT
		Payload mass, power	<80 kg, <70 W
		Magnetic cleanliness	<0.1 nT at end of mag boom
		D/L: S-band, DSN 34-m ground station	>1 Mbps
		Ephemeris knowledge	±100-km accuracy
		Launch vehicle accommodation	ESPA Grande (one port)

Spacecraft		Parameter	Requirement
M3 RadioSat ***Three-axis stabilized***	Mission	ΔV to achieve science orbit	ΔV ≤ 710 m/s
		Orbit inclination	≤10°
		Perigee × apogee (altitude)	≥400k m × 4.8 ± 1 R_E
		Mission duration	≥3 years of science observations
	Spacecraft and Operations	Instrument payload	RT
		Payload Mass, Power	<13 kg, <18 W
		D/L: X-band, DSN 34- ground station	>0.25 Mbps
		Ephemeris knowledge	≤100 km
		Launch vehicle accommodation	ESPA Grande (≤4 RadioSats per port)

8.8.3. Technology Development and Further Studies

There are no significant technological developments identified for this FMT, other than maturing the technology readiness level (TRL) of key instrument components. We do identify mission areas that need to be further studied when an actual mission is being considered for implementation.

A key technology development area is the orbital acquisition and calculations of ΔV to accomplish the desired orbits. The three spacecraft need to be placed on distinct orbits, and using a single launch vehicle as proposed in the FMT may or may not be the most economical way to accomplish that.

The FMT study specifies three unique spacecraft, each requiring individual design. A further study would address opportunities for merging bus capabilities between the spacecraft.

A further study of observational coverage is needed, to determine the percentage of time that all three spacecraft are in locations that allow the combined measurements, as well as how much of the orbit allows independent observations by each spacecraft. This study is intimately tied to the question of how the orbital periods of M1, M2, and M3 relate to one another, and how often and where the apogee conjunctions occur.

8.9. FMT-9 Mission Concept Design Summary: Inner Magnetosphere and Radiation Belts Mission

8.9.1. Mission Design Overview

FMT-9 was developed into an example mission concept named Charging and Radiation Environment Observatories (CREO). CREO was developed to Concept Maturity Level (CML) 3 design by the APL ACE Lab. The top-level CREO design goal was to provide measurements of the thermal plasma, waves, and energetic particle environments throughout near-equatorial geospace via a multi-MLT distributed constellation of identical spacecraft.

The primary CREO measurements and associated science goals are as follows:

- Measure pitch-angle and radial distributions of intensities and derived phase space density to determine active sources and losses of radiation belt electrons.
- Determine event-specific diffusion coefficients for predictive models of radiation belt electrons.
- Resolve wave growth regions, wave amplitudes and key quantities, and full extents of active regions for ULF, magnetosonic, EMIC, chorus, and hiss waves.
- Resolve ion distributions corresponding to EMIC, magnetosonic, and ULF waves.
- Resolve electron distributions corresponding to chorus and hiss waves.
- Resolve development and evolution of the partial and full ring current during each phase of a geomagnetic storm.
- Resolve plasmaspheric erosion, plume development, and refilling during each phase of a geomagnetic storm.
- Resolve energetic particle injection fronts' spatial extent, penetration depth (minima in L-shell), and impacts on the inner magnetosphere.
- Test hypotheses of energetic particle injection fronts' spatial extent, penetration depth (minima in L-shell), and impacts on the inner magnetosphere.
- Test hypotheses of hiss wave generation and relationship to whistler-mode chorus.
- Test hypotheses of the criticality of the plasmapause boundary in shaping and constraining critical inner magnetospheric processes.

To achieve the above science and monitoring capabilities, CREO must consist of a constellation of observatories. The primary objectives of the mission design study for CREO are to help inform trades on the number of launches and number of spacecraft required to meet the science requirements, as well as to determine the propellant requirements for the CREO spacecraft. Scenarios with both dedicated and rideshare launches are considered for CREO. In the following discussion, let N_{DL} represent the number of dedicated launches, N_{RL} represent the number of rideshare launches, n_{SC} be the number of CREO spacecraft co-manifested per launch, and N_{SC} be equal to the total number of CREO spacecraft in operation.

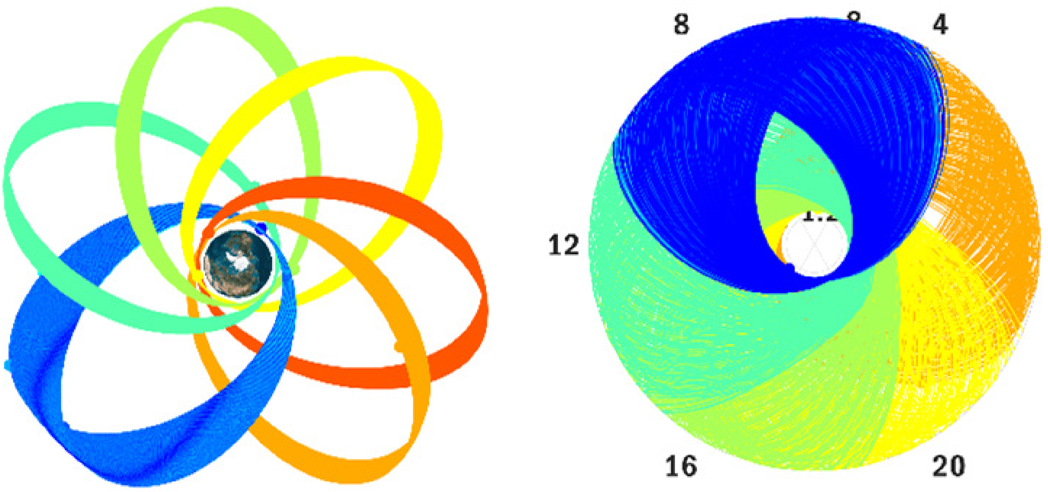


Figure 8-20. (Left) CREO Scenario 4 orbits in inertial space for 100 days of simulation time. Blue trajectories include four spacecraft from a dedicated launch, while the other colors show one spacecraft each delivered to orbit via rideshare using the ESPA-Grande-compatible CREO satellite design. (Right) CREO Scenario 4 orbits in L-shell versus MLT space for 100 days of simulation time. L-shell corresponds to radial dimension and ranges from 1.2 to 8 as shown here. MLT hours are listed every 4 hours in azimuth.

Four launch scenarios were studied in detail here:

- Multiple dedicated launches, no rideshare launches
    - Scenario 1: $N_{DL} = 2$ with $n_{SC} = 4$ ($N_{SC} = 8$)
    - Scenario 2: $N_{DL} = 3$ with $n_{SC} = 3$ ($N_{SC} = 9$)
    - Scenario 3: $N_{DL} = 3$ with $n_{SC} = 4$ ($N_{SC} = 12$)
- Single dedicated launch with multiple rideshares to supplement
    - Scenario 4: $N_{DL} = 1$ with $n_{SC} = 4$, $N_{RL} = 5$ with $n_{SC} = 1$ ($N_{SC} = 9$)

8.9.2. Mission Design Requirements

CREO subject-matter experts developed a series of science objectives and corresponding orbital coverage requirements to ensure that the CREO constellation had sufficient resolution in universal time, L-shell (approximately radial distance in Earth radii in the magnetic equatorial plane), and MLT to sufficiently resolve the relevant plasma, wave, and energetic particle environments in near-Earth geospace during geomagnetic storms and substorms (large-scale dynamic evolution over timescales of ≤ ~2 hours).

For the purpose of this architecture study, equatorial geospace was gridded into a series of L-shell and MLT sectors, the latter of which are referred to here as “MLT wedges.” The set of MLT wedges is defined by each of the MLT sectors, 4 hours in width, lying within [0, 24] hours. The distinct wedges begin at [0, 4, 8, ..., 20] hours MLT. The set of L-shell bands is defined for the purposes of CREO as each of the bands, 0.1 R_E in width, lying within [1.2, 8.0] R_E. Here, R_E = 6378.14 km represents the radius of Earth. A schematic depicting the MLT and L-shell bands is provided in Figure 8-21a, where the Sun direction aligns with 12 hours MLT.

Table 8-31 details three mission design criteria that the CREO mission design must satisfy in order to address the threshold of the science goal and subset of drivers listed above.

Table 8-31. Constraints associated with threshold science objectives.

Objective Name	Description
MLT_R	**MLT resolution:** Enable simultaneous observations of all MLT wedges a. ≥1 spacecraft inside each 4-h MLT wedge (LFWF, HFWF) b. MLT wedges at intervals of ΔMLT = 4 h over full range from $0 \leq MLT < 24$ h
LS_R	**L-shell revisit time:** Revisit each L-shell at a cadence of ≤2-h UT a. L-shells defined at intervals of ΔL = 0.1 R_E over full range from 1.2 $R_E \leq L \leq$ 7 R_E b. Optional coverage over [7, 8] R_E c. No associated MLT requirement
ML	**Magnetic latitude (ML):** Maintain spacecraft within [−30°, +30°] of magnetic equator

HFWF, high-frequency wave field; LFWF, low-frequency wave field.

In addition to the threshold objectives, a number of secondary objectives are defined to target diverse science goals that complete the list of science drivers. These fall into two categories of MLT conjunctions (MLT_C), and L-shell conjunctions (LS_C), as provided in Table 8-32.

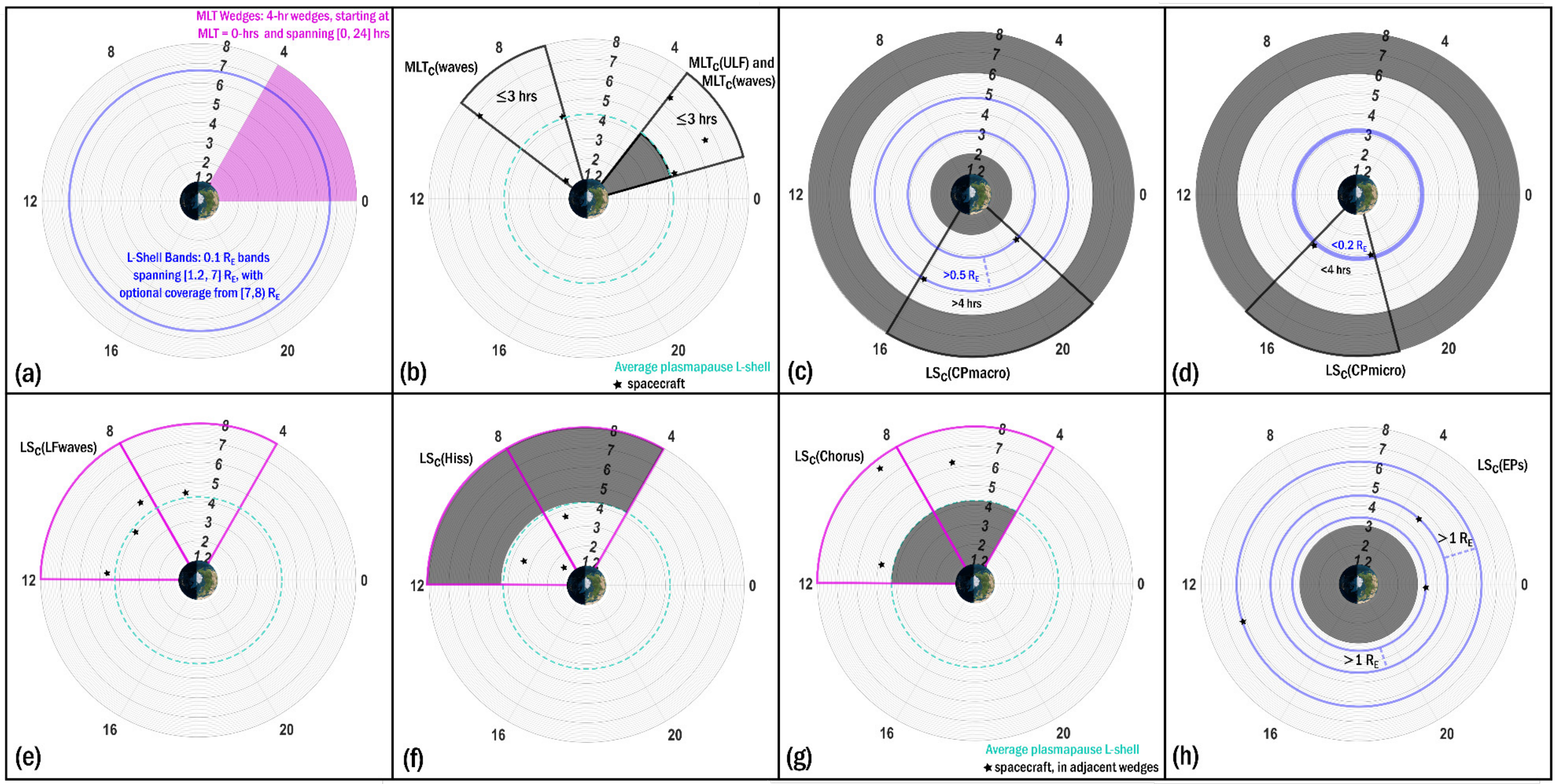


Figure 8-21. Schematics depicting examples of configurations satisfying various requirements: (a) MLT_R and LS_R, (b) MLT_C(ULF) and MLT_C(waves), (c) LS_C(CPmacro), (d) LS_C(CPmicro), (e) LS_C(LFwaves), (f) LS_C(Hiss), (g) LS_C(Chorus), (h) LS_C(EPs).

Table 8-32. Constraints associated with secondary science objectives.

Objective Name	Description	
MLT$_C$(ULF)	**MLT conjunction:** ≥3 spacecraft all within $0 \leq \Delta MLT \leq 3$ h a. ≥1 per week b. ≥15-min UT duration	c. L > 4.25 R$_E$ (outside plasmapause)
MLT$_C$(waves)		c. No L-shell requirement
LS$_C$(CPmacro)	**L-shell conjunction:** ≥2 spacecraft, each separated by ΔL>0.5 R$_E$ a. ≥2 L-shell conjunctions per 24 h UT b. ≥15-min UT duration c. $2 \leq L \leq 6$ R$_E$ ΔMLT > 4 h	
LS$_C$(CPmicro)	**L-shell conjunction:** ≥2 spacecraft all within a ΔL < 0.2 R$_E$ slice a. ≥2 L-shell conjunctions per 24 h UT b. ≥15-min UT duration c. L < 6 R$_E$ All within ΔMLT < 4 h (can be different wedges)	
LS$_C$(LFwaves)	**L-shell conjunction:** ≥3 spacecraft all within a ΔL ≤ 2 R$_E$ slice a. ≥1 per week b. ≥15-min UT duration c. From two adjacent MLT wedges	d. $3.25 \leq L \leq 6.25$ (in vicinity of plasmapause)
LS$_C$(Hiss)		d. L ≤ 4.25 R$_E$ (inside plasmapause)
LS$_C$(Chorus)		d. L ≥ 4.25 R$_E$ (outside plasmapause)
LS$_C$(EPs)	**L-shell conjunction:** ≥3 spacecraft, each separated by ΔL > 1 R$_E$ a. Every 2 h UT b. ≥15-min UT duration c. $3 \leq L < 8$ R$_E$ d. No MLT requirement	

8.9.3. Mission Implementation

8.9.3.1. Observables and Payload

CREO observables include the following:

- Magnetic fields, DC to low frequency (to ≥50 Hz)
- Magnetic field waves (10 Hz to 10 kHz)
- Electric field waves (10 Hz to 1 MHz)
- Cold (~0–100 eV) to thermal/suprathermal (0.1–10 keV) plasma
- Suprathermal to medium-energy particles (<10 keV to >1 MeV)
- Energetic particles (0.5 to ≥10 MeV)

Note: Not all observables may be required on each CREO spacecraft. A detailed optimization study should be conducted to minimize the total number of payloads required for CREO science.

Several types of instruments that meet the measurement requirements defined by the science goals were identified during the study. Fluxgate magnetometers (FGMs) provide the means to detect magnetic fields in the DC to ULF range, while a three-axis search-coil magnetometer (SCM) extends this to higher frequencies (10 kHz). E-field double probes (EDPs), similar to those used on the Van Allen Probes mission, are used to observe electric field measurements between 10 Hz and 1 MHz. In support of the study of ring current ions and electrons, plasma in the thermal to suprathermal range can be measured with the use of an electrostatic analyzer; an electron/ion spectrometer extends this coverage to the medium-energy range (>1 MeV). Lastly, radiation belt electrons and ions in the high-energy range can be detected using a relativistic electron and energetic proton telescope. Three payload designs using variations of each of these instruments were evaluated and provide a range of options to inform the eventual point design of the spacecraft.

The *threshold* payload is designed to meet all primary science objectives of the mission while minimizing its size, mass, and power at the expense of overall performance. For magnetic field observations, it uses a combination of FGM and SCM instruments similarly employed by the MMS mission. Electric fields are measured using a Van Allen Probes–heritage EDP configured with six 8-m spacer antennas. The threshold payload also borrows from Van Allen Probes' use of an electrostatic analyzer (Van Allen Probes/HOPE) for low-energy particle observations, while a single electron/ion spectrometer and three size/mass/power-friendly AC10-heritage electron-proton telescopes cover the medium- and high-range spectra (10 keV to 3 MeV).

The *baseline* design diverges from the threshold design with an EDP that leverages the use of four significantly longer stacer antennas (25 m) coupled with a pair of 7-m axial antennas that provide enhanced resolution of the electric field measurements. This design also doubles the number of spectrometers and replaces the three-telescope configuration with a single instrument (Van Allen Probes/REPT).

The *aspirational* payload affords the highest level of science data return for the mission in terms of both quality and quantity. The design leverages two FGM instruments and the Van Allen Probes–flown SCM to enable magnetic field gradiometry, an extended frequency range (up to 20 kHz), and enhanced processing and tuning capabilities. It supplements the EDP, electrostatic analyzer, and spectrometer configurations of the baseline design with an additional spectrometer instrument (IMAP/CoDICE) that offers improved measurements of protons and extends the lower range of electron energies. Lastly, the aspirational design would combine the AC10 three-telescope configuration with an additional telescope similar to the one used on the CIRBE mission (REPTile-2) for additional detectors and extended proton and electron ranges (>30 MeV and >10 MeV, respectively). A list of the instruments mapped to the three payload designs is provided in Table 8-33, along with information regarding measurement type, TRL, and heritage.

Table 8-33. Instrument designation for the threshold, baseline, and aspirational CREO science payloads.

Instrument	Measurement Type (Range)	Threshold	Baseline	Aspirational	TRL	Reference/Heritage
Fluxgate Magnetometer	Mag field: DC to low (≥50 Hz)	X	X	X (×2)	9	MMS/DFGM
Search-Coil Magnetometer	Mag field: low to high (10 Hz to 10 kHz)	X	X		9	MMS/SCM
				X	9	Van Allen Probes/SCM
E-Field Double Probes (EDP)	Electric Fields: low to high (10 Hz to 1 MHz)	X			6+	Van Allen Probes/EFW+EMFISIS: threshold build
			X	X	6+	Van Allen Probes/EFW+EMFISIS: baseline build
Electrostatic Analyzer	Plasma: thermal to suprathermal (0–100 eV, 0.1–10 keV)	X	X	X	9	Van Allen Probes/HOPE
Electron/Ion Spectrometer	Suprathermal to medium-energy particles (<10 keV to 1 MeV <)	X	X (x2)	X (x2)	6	GTOSat/REMS
				X	6	IMAP/CoDICE
Electron/ Proton Telescope	High-energy particles (1–10 MeV ≤)	X (x3)		X (x3)	9	AC10/mCPT
			X		9	Van Allen Probes/REPT
				X	6	CIRBE/REPTile-2

Additionally, some custom space weather effects experiments might be carried on board the CREO spacecraft, including materials experiments for surface/subsurface charging, charge–discharge monitors, and total radiation dose monitors. Those experiments may be custom-tailored for each CREO observatory to maximize science and engineering data return.

8.9.3.2. Spacecraft Design and Mass

Estimates for the spacecraft mass corresponding to each payload design were calculated parametrically by establishing the percentage of the total spacecraft mass attributed to the payload and deriving representative allocations of the remaining system mass for each subsystem. As a point of reference, the dry mass of the Van Allen Probe-A spacecraft's payload

(133.81 kg) accounted for 23% of the spacecraft's total dry mass. Other recent APL missions (IMAP, DART, Parker Solar Probe) yielded an average payload mass allocation of 17%.

For the purposes of this analysis, it is assumed that the baseline payload dry mass (58 kg) accounts for 20% of the entire baseline spacecraft dry mass, resulting in a total spacecraft dry mass of 290 kg for this particular concept design. Allocations for the various subsystems were based on inputs from subsystem leads involved with the study, known mass budgets of the aforementioned APL missions, and subsystem budget allocations estimated for similar space missions as outlined in the textbook *Space Mission Engineering: The New SMAD* (Wertz et al., 2011). The percentages attributed to the mechanical subsystems for the threshold and aspirational spacecraft were adjusted by −10% and +5%, respectively, to characterize notional structural changes required to support their respective payloads. This strategy enabled us to estimate the total dry mass for each of the three spacecraft without deviating from the baseline payload as the singular reference.

With the mechanical adjustments factored in and the contributing masses of each payload configuration, the current best estimate (CBE) total spacecraft dry masses for the three concepts are 272 kg for the threshold, 290 kg for the baseline, and 299 kg for the aspirational. The subsystem allocation percentages used for the baseline concept for the CREO spacecraft are provided in Table 8-34.

Table 8-34. CREO baseline parametric mass allocations.

CREO Baseline Subsystem	Mass (kg)	% of Total Mass
Payload	58	20%
Structures	75	26%
Thermal	9	3%
Power	87	30%
Telecommunications	9	3%
Command and Data Handling	9	3%
Guidance and Control	6	2%
Propulsion	15	5%
Harness	23	8%
Total spacecraft dry mass	**291**	**100%**

Contingency factors representative of each subsystem's estimated TRL yield the maximum expected values (MEVs) for each subsystem across the three designs and are used to calculate the allocated margins (11–12%). The maximum possible value (MPV) dry mass for the study was designed as 30% above the CBE mass to coincide with the equivalent total dry mass margin (30%) and an acceptable unallocated margin (MPV − MEV) of >16% in accordance with Quality Management System (QMS) guidelines (SD-QP-600). Summaries of all three master equipment lists (MELs) were compiled for CREO.

The propulsion subsystem lead provided a notional 200 m/s ΔV requirement for the LWS CREO mission. APL design requirements specified that a 10% ΔV margin should be factored into the calculation of required propellant mass. Using the aspirational spacecraft MPV dry mass (389 kg), the notional ΔV plus margin, and an I_{sp} (specific impulse) of 200, the rocket equation estimates a propellant mass of 40 kg of hydrazine for the mission. This study uses the Falcon 9 launch vehicle as the baseline launch provider and verified that the CAD model for the conceptual spacecraft would be able to fit within the allowable physical volume for rideshare spacecraft using the Falcon 9 24-inch ESPA payload adapter. Each spacecraft design's "top down" flight system MPV wet mass should also be below the maximum limit of 825 kg for the 24-inch adapter as defined in the *SpaceX Rideshare Payload User's Guide* (dated November 2020). The spacecraft wet mass can also be used to determine the viability of rideshare options in future launch vehicle trade studies. A more thorough analysis of the mass budget is expected for the point design of the selected concept.

The CREO observatories have been designed for compatibility with an ESPA Grande launch interface. Figure 8-22 shows the observatory design.

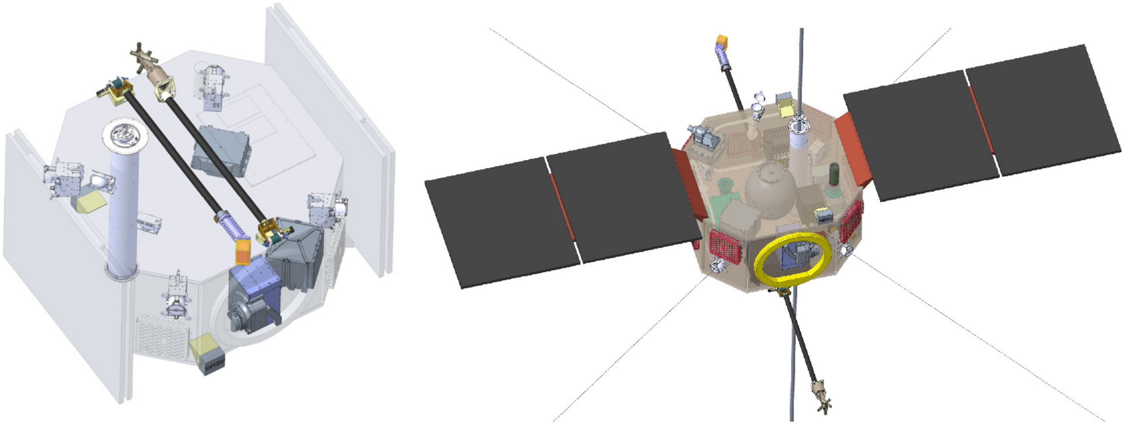


Figure 8-22. (Left) CREO observatory in the stowed configuration for launch. Spacecraft subsystems and structure are transparent and translucent, respectively, to highlight the science payloads. Note: This spacecraft design and stowed volume are compatible with the interface requirements for the ESPA Grande. (Right) CREO observatory in deployed configuration for science operations. Note: The yellow ring on the side of the spacecraft in this view is the interface to the 24-inch mounting port on an ESPA Grande.

8.9.3.3. Spacecraft Power

- Solar panels sized based on Van Allen Probes subsystems, CREO payload estimates, and state-of-the-art solar cell efficiencies (designed to 80% of Van Allen Probes array sizing)
- Considerations must include the following:
  - Radiation dose
  - Dielectric discharge mitigation

  - Surface charging mitigation
  - Eclipse duration
  - Magnetic cleanliness
  - Spacecraft grounding
  - Battery capacity and power electronics capabilities
- Assuming that the satellites will launch unpowered

8.9.3.4. Communications

- Maximum latency on the real-time beacon data from measurement time to MOC should be ≤5 min; this is a key driving requirement
- Beacon data rate is ~10 kbps, 770 Mbit/day (15% of total science data rate), and beacon communication is downlink only
- Limited to opposing low-gain antennas on spin-axis faces and assuming omnidirectional coverage
- Communications network assets could be ground stations, RN, or a combination of both
- Regular high-rate contacts used for primary science data telemetry downlink; must return 5.45 Gbit/day; this is well within traditional satellite communications paradigms
- Should beacon be considered a completely separate subsystem?
- Either multiband or wideband tunable approaches may be necessary
  - Try to share frequency use between space-to-ground and space-to-space allocations
- Dynamic and flexible network management will be necessary:
  - High amount of handover between network assets (similar to terrestrial LTE [long-term evolution])
  - Multiple access when a ground station or relay satellite has multiple LWS CREO satellites in view
- Consider service providers:
  - Government networks: NASA NSN, TDRS
  - Commercial ground station networks: NSN, Swedish Space Corporation, Kongsberg Satellite Services (KSAT), AWS
  - Commercial relay services: Inmarsat, SES O3b, Starlink, Globalstar, OneWeb

  - Dedicated ground stations built specifically for this mission

- S-band works well for beacon telemetry RNs; possibly also very high frequency/ultrahigh frequency

- Ka-band: may work for high rate, although reliance on spot beams complicates the communications architecture; X-band might also work well for this

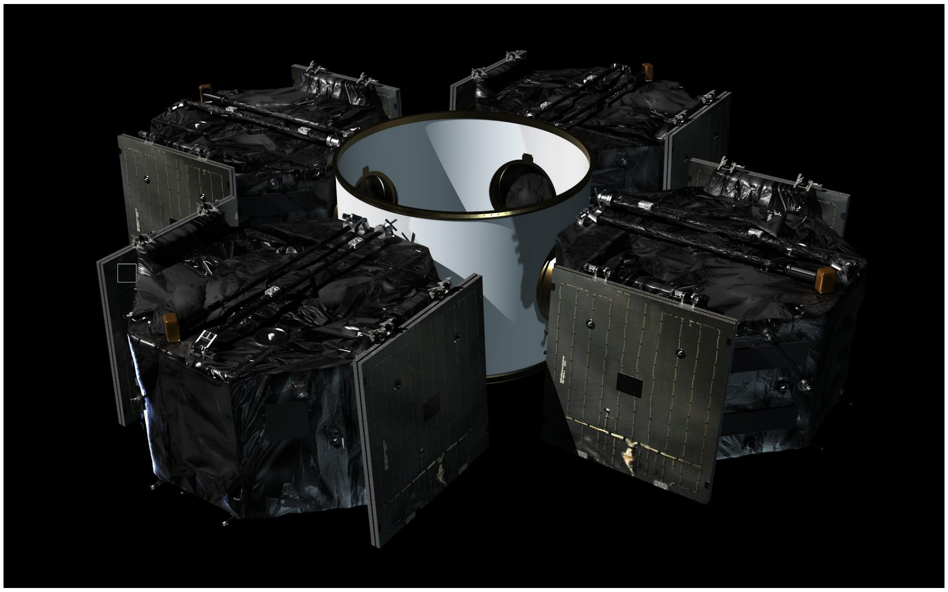


Figure 8-23. Rendering of four CREO spacecraft mounted on an ESPA Grande ring. The total span of all mounted spacecraft fits within a 4-m fairing.

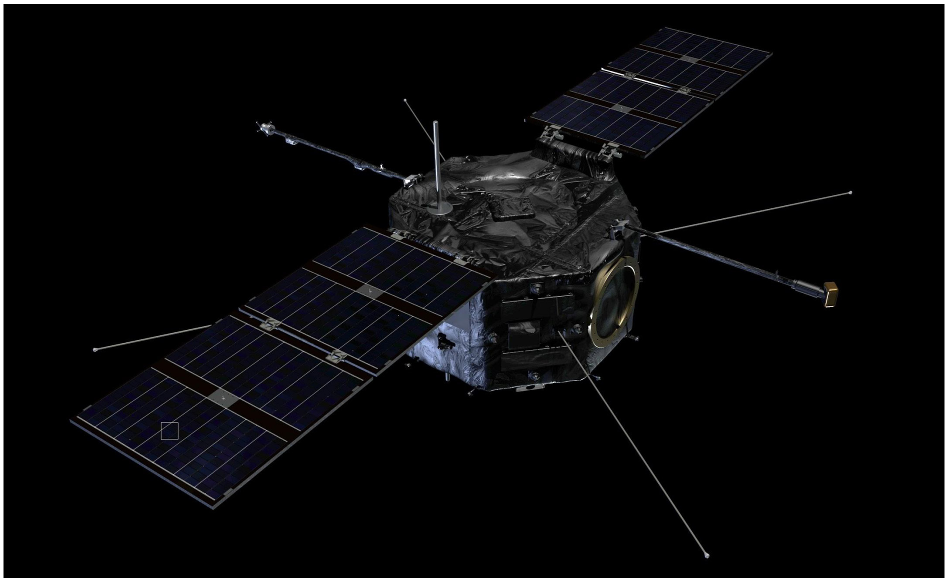


Figure 8-24. Rendering of a deployed CREO spacecraft. The Sun-pointed spin axis is perpendicular to, and centered in, the top octagonal deck.

8.9.4. Orbit Design

8.9.4.1. Orbit Design Overview

For both dedicated and rideshare launch, the final orbit dimensions are assumed to be the same. The orbital inclination is selected for dedicated launches to satisfy magnetic latitude (ML) bounds and reduce L-shell bound violations. Note that while slightly higher inclinations are likely feasible, they may lead to increased delays in L-shell revisit time. For rideshares, a conservative value of inclination is selected; however, many rideshare opportunities will have lower inclinations than that assumed here, as demonstrated in Figure 8-26 (data obtained via queries of post-2000 launch data, obtained through https://www.space-track.org/). For both dedicated and rideshare launches, the initial value of right ascension of the ascending node is enabled as a control variable to optimize science performance. Although there is no control over the value of Ω_0 in practice for rideshare launches, treating Ω_0 as a control variable allows for the determination of best *possible* performance. The initial argument of perigee is also assumed as a control variable for dedicated launch scenarios; however, it is constrained to expected values for rideshare opportunities. Finally, because very little propellant is required to shift the spacecraft true anomaly by an arbitrary amount, full control over the initial value of true anomaly is assumed.

For CREO, orbits with dimensions comparable to GTOs are ideal candidates to optimize the science objectives, particularly objective LS_R (see definitions below). A summary of the orbital elements assumed for the final science orbits in this study is provided in Table 8-35, with a schematic orbit representation presented in Figure 8-20. Here, “final” means that all spacecraft have launched and have maneuvered into their optimized configurations for science operations.

Table 8-35. Orbital element assumptions for science orbits (all angles referenced from Earth J2000 frame).

	Dedicated Launch	**Rideshare Launch**
Perigee radius r_p	1.2 R_E (7653.6 km)	
Apogee radius r_a	7.5 R_E (47835.0 km)	
Period	12.8 hours	
Inclination i	10°	28.5°
Right ascension of ascending node Ω_0	Initial value varied to optimize science	Initial value varied to optimize science
Argument of perigee ω_0	Initial value varied to optimize science	0° or 180°
True anomaly θ_0	Initial value varied to optimize science	Initial value varied to optimize science

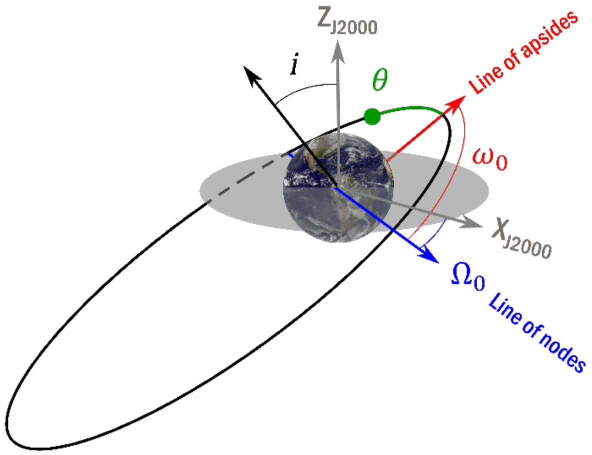


Figure 8-25. Schematic of orbital elements.

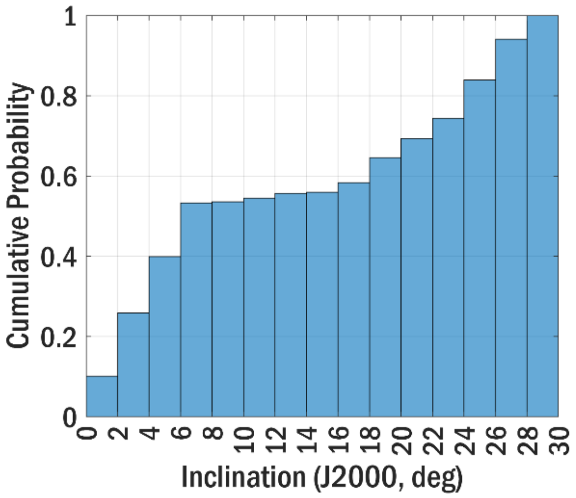


Figure 8-26. Inclination distribution for U.S.-launched GTOs.

8.9.4.2. Orbit Optimization Overview

For each of the launch scenarios previously identified, the mission design strategy focuses on optimizing science return for the threshold science over a 100-day span (or ~53 revolutions of the science orbit). Candidate orbits are evaluated using a genetic algorithm that controls the initial orbital parameters identified in Table 8-35 for each simulated spacecraft. Within the simulation, orbits are propagated in a medium-fidelity dynamical model that includes lunisolar and J2-4 aspherical gravity perturbations. The resulting trajectories are evaluated at 400-second time intervals to compute updates to the LS_R and MLT_R objectives for L-shell return-time and MLT spacing constraints. The perturbations present in the dynamical model evolve the science orbits over time, causing performance to deviate from a simplified two-body model, thus motivating the duration of the simulations performed here.

The genetic algorithm searches over the feasible space of orbit parameters to identify combinations that minimize an objective function representing the CREO threshold science objectives. This objective function seeks to maximize the time for which the desired MLT spacing of MLT_R is achieved, while minimizing a penalty accrued by L-shell return-time violations, as defined by LS_R. The objective function is defined as

$$= -100 \cdot \frac{\sum \quad t_{MLT}}{T} + 10 \cdot P_{LS} \,,$$

$$P_{LS} = \frac{|\epsilon_{LS}|}{1 + \; e^{-100 \cdot \epsilon_{LS}}}.$$

Here, T represents the mission simulation duration, and t_{MLT} represents the time steps for which the MLT spacing requirement is satisfied. In the penalty term P_{LS}, the L-shell error ϵ_{LS} represents the largest L-shell return-time violation across all L-shell bands, which is assessed once at the end of the simulation. Expressing P_{LS} as a logistic function ensures that no penalty is applied when the largest L-shell return-time is within the range defined by LS_R.

An improvement in science performance is observed by running the optimization over short durations and using the results to seed a longer-duration simulation. Simulations of 1, 5, 10, 20, 50, and 100 days are run, and the optimization results for each serve as the initial guess for the next duration in the sequence.

8.9.4.3. Orbit Optimization Results

Results of the optimization for each of the launch scenarios are provided in the upcoming sections. All results "begin" when *all* spacecraft are online and are in their desired final orbit configuration. That is, there is no quantification of the time required to perform multiple launches, or to perform the necessary phasing in true anomaly to achieve an optimal spacecraft configuration.

For reference, an example time history showing the first day of a Scenario 4 simulation is presented in Figure 8-27. Here, the time evolution of both the orbits and the associated MLT, L-shell, and ML values are shown. In the upcoming sections, summaries of the science performance are presented for each of the four launch scenarios.

Scenario 1: (N_{DL} = 2 with n_{SC} = 4; total: 8 observatories)

For two dedicated launches, with four spacecraft per launch, the spacecraft arrive in two distinct orbits. True anomaly phasing is performed to disperse the spacecraft to enable objective MLT_R. The final orbits appear in Figure 8-28a,b, with the spacecraft initial positions shown by the dot markers. From this initial configuration, a 100-day simulation is performed to optimize performance for objectives LS_R and MLT_R. Figure 8-28c shows the minimum, maximum, and average L-shell revisit time for each L-shell band of objective LS_R as well as the time evolution of the fraction of the mission duration for which objective MLT_R is satisfied. While LS_R is violated at least once for all L-shell bands, the average revisit time generally falls under the requirement. Objective MLT_R is satisfied for only ~55% of the simulation.

Recalling that the performance for the secondary science objectives is not included as a contribution toward the optimization objective function, the assessment of performance for these objectives occurs as post-processing of the simulation results. For those epochs for which each secondary objective is satisfied, the time to next conjunction is computed and presented in Figure 8-29. The requirement for each objective is indicated by a red dashed line. Any blue markers that appear above the red dashed lines indicate a violation of the conjunction return-time requirement for that secondary objective. Vacant regions of the plot indicate periods for which no valid spacecraft configurations exist.

For several of the secondary objectives, namely MLT_C(waves), LS_C(CPmacro), LS_C(Chorus), and LS_C(EPs), the requirements are satisfied for >80% of the simulation for Scenario 1. Objective MLT_C(ULF) is met for ~50% of the mission, and the remaining objectives are in violation of the requirements for most or all of the mission. Note that for LS_C(CPmicro), a significant number of valid configurations are separated by ~13 hours, just over the 12-hour requirement. If these configurations are counted as valid (i.e., the requirement is raised to 13 hours), the fraction of the mission satisfied increases from ~2% to 12%.

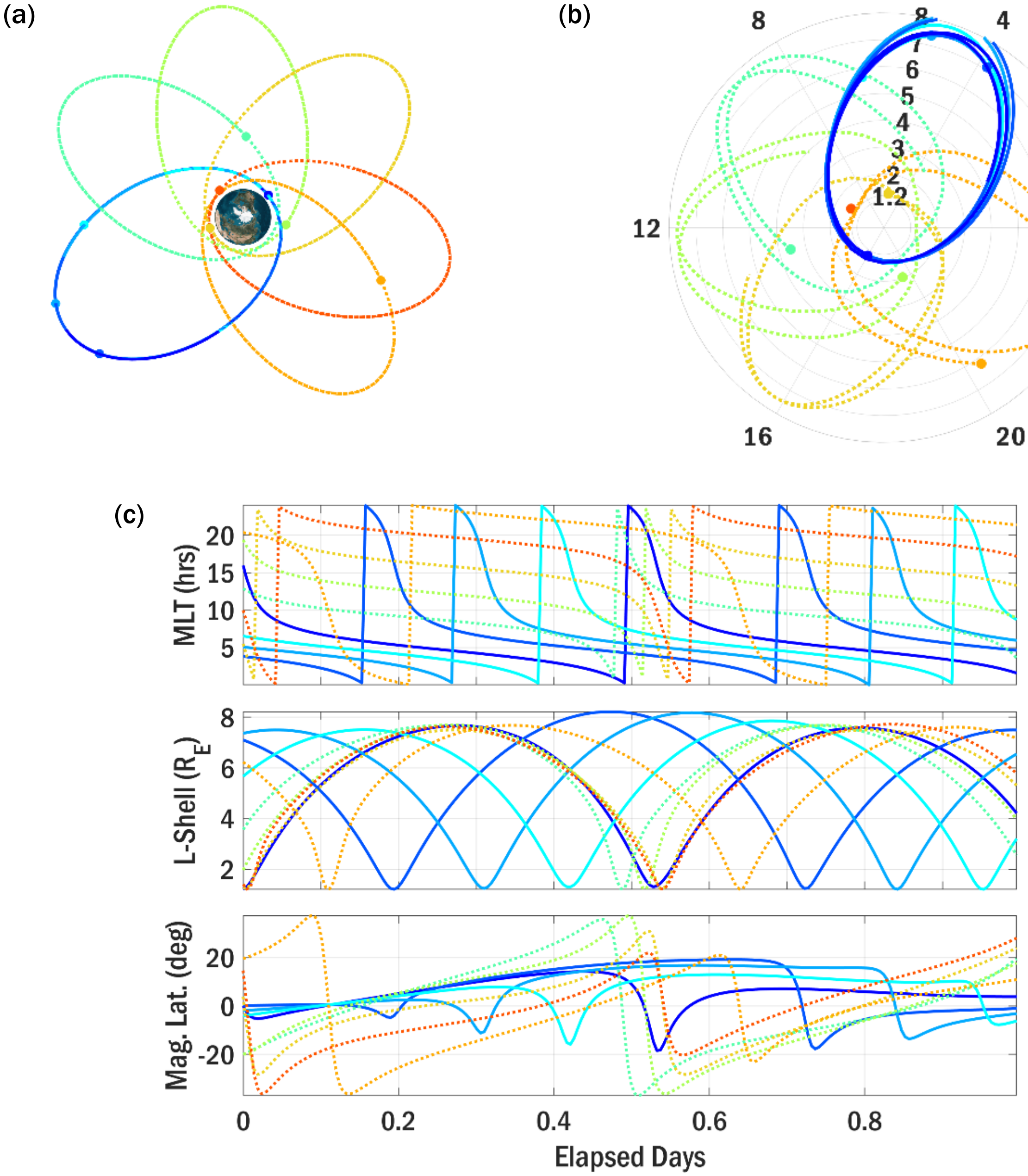


Figure 8-27. Example 1-day time history for Scenario 4 showing orbit evolution and associated MLT, L-shell, and MLs; evolution of one dedicated launch with four spacecraft is shown as solid lines, and four rideshares of one spacecraft each are shown as dotted lines. (a) **Inertial orbit view.** (b) Orbits in MLT frame. (c) Time history of MLT, L-shell, and ML evolution (note that dedicated launches respect the constraints of objective ML; however, the rideshare launches reach latitudes of 37°).

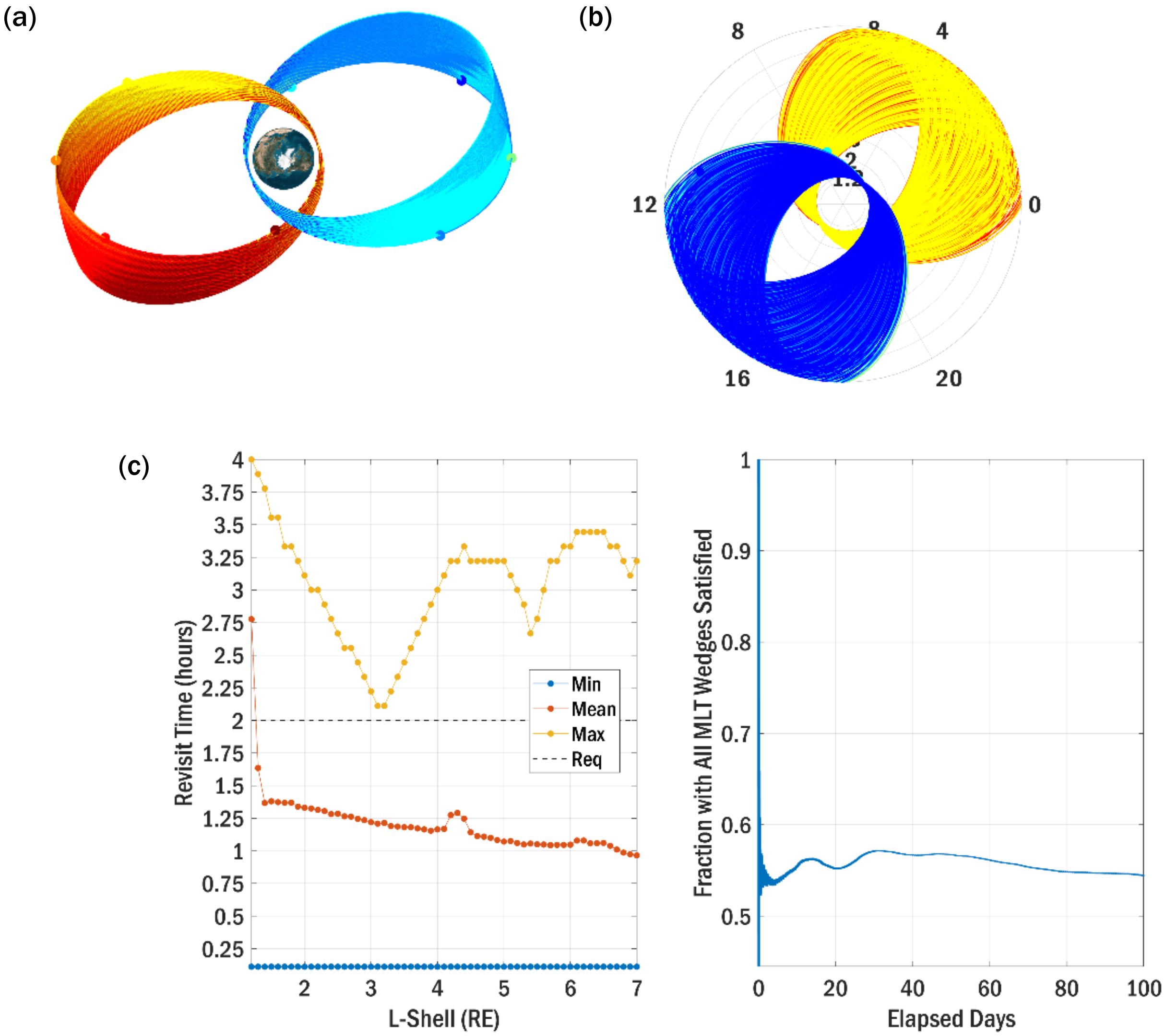


Figure 8-28. Scenario 1: L-shell revisit time has violations for all L-shell bands; however, average revisit time generally satisfies the requirement; MLT wedges satisfied ~55% of the simulation. (a) Inertial orbit view. (b) Orbits in MLT frame. (c) Left: L-shell revisit time (minimum, mean, maximum) for each L-shell band to assess LS_R objective; right: fraction of mission duration for which the MLT_R objective is satisfied.

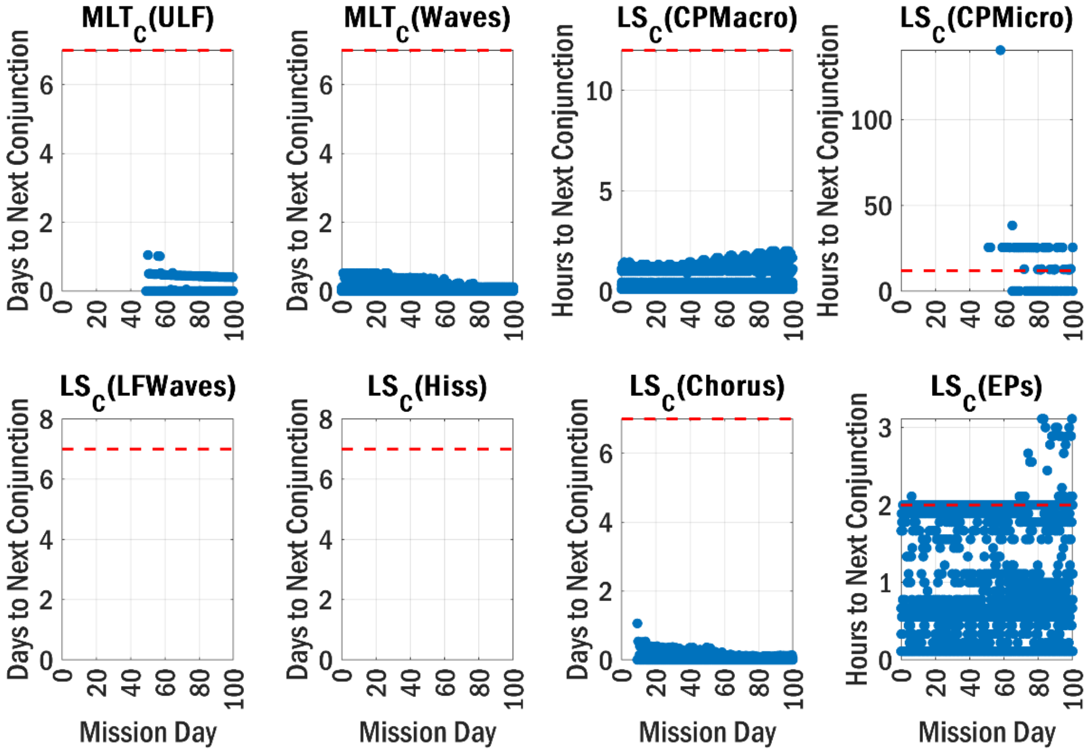


Figure 8-29. Scenario 1: Secondary objective time to next conjunction (requirement is indicated by a red dashed line).

Scenario 2: (N_{DL} = 3 with n_{SC} = 3; total: 9 observatories)

For three dedicated launches, with three spacecraft per launch, the spacecraft arrive in three distinct orbits, at which point true anomaly phasing is performed. The final orbits appear in Figure 8-30a,b, with performance for objectives LS_R and MLT_R summarized in Figure 8-30c. LS_R is satisfied for all L-shell bands for the full simulation, except for a few minor violations that fall very close to the requirement, and MLT_R is satisfied for ~91.5% of the simulation.

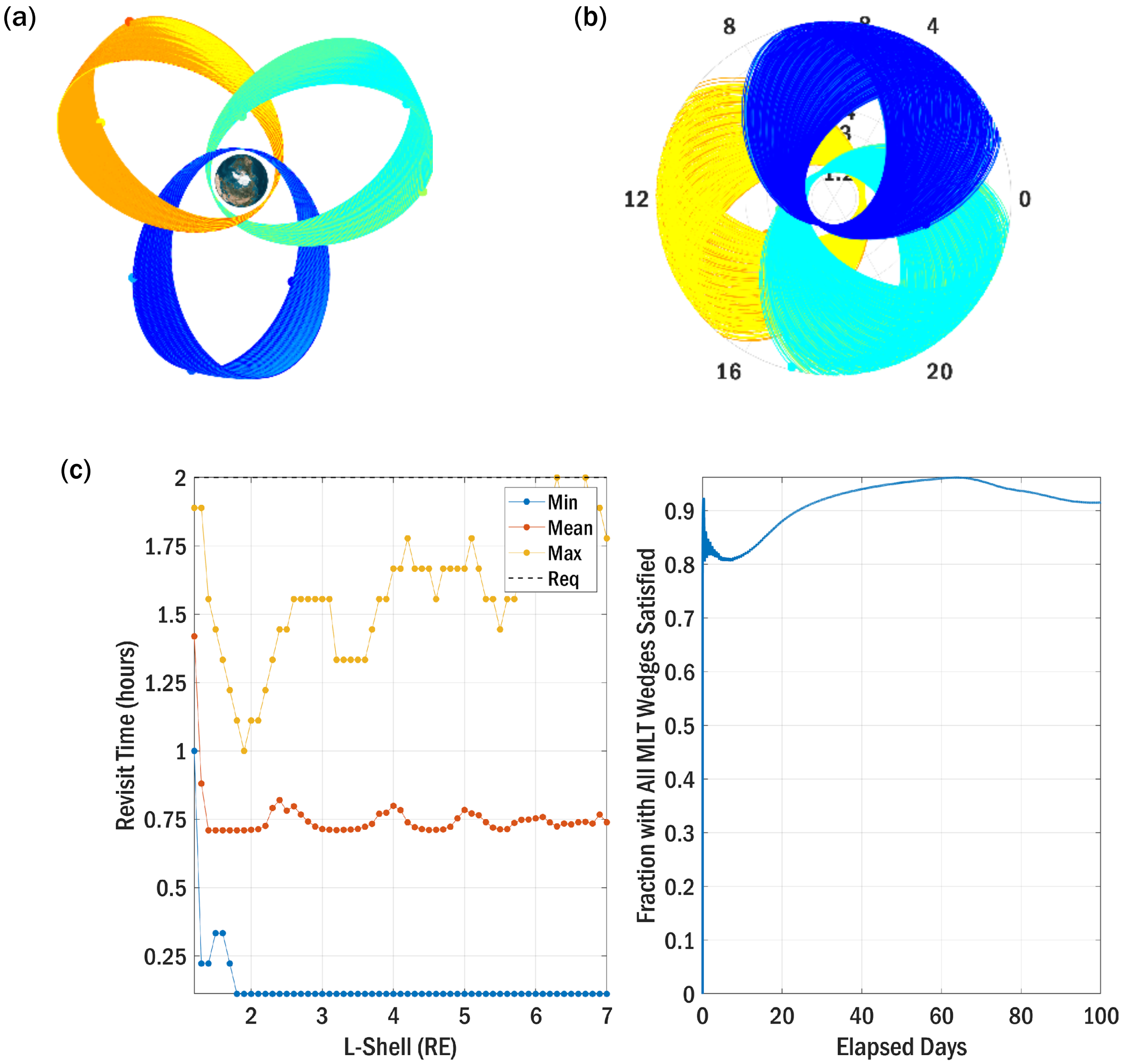


Figure 8-30. Scenario 2: L-shell revisit time satisfied for nearly the full duration, with minor violations just fractionally over the revisit requirement of 2 hours; MLT wedges satisfied >90% of the simulation. (a) Inertial orbit view. (b) Orbits in MLT frame. (c) Left: L-shell revisit time (minimum, mean, maximum) for each L-shell band to assess LS_R objective; right: fraction of mission duration for which the MLT_R objective is satisfied.

Secondary science objective performance is shown in Figure 8-31. For five of the eight secondary requirements, Scenario 2 achieves valid configurations for nearly the entire simulation. For the remaining three requirements, no valid spacecraft configurations are observed.

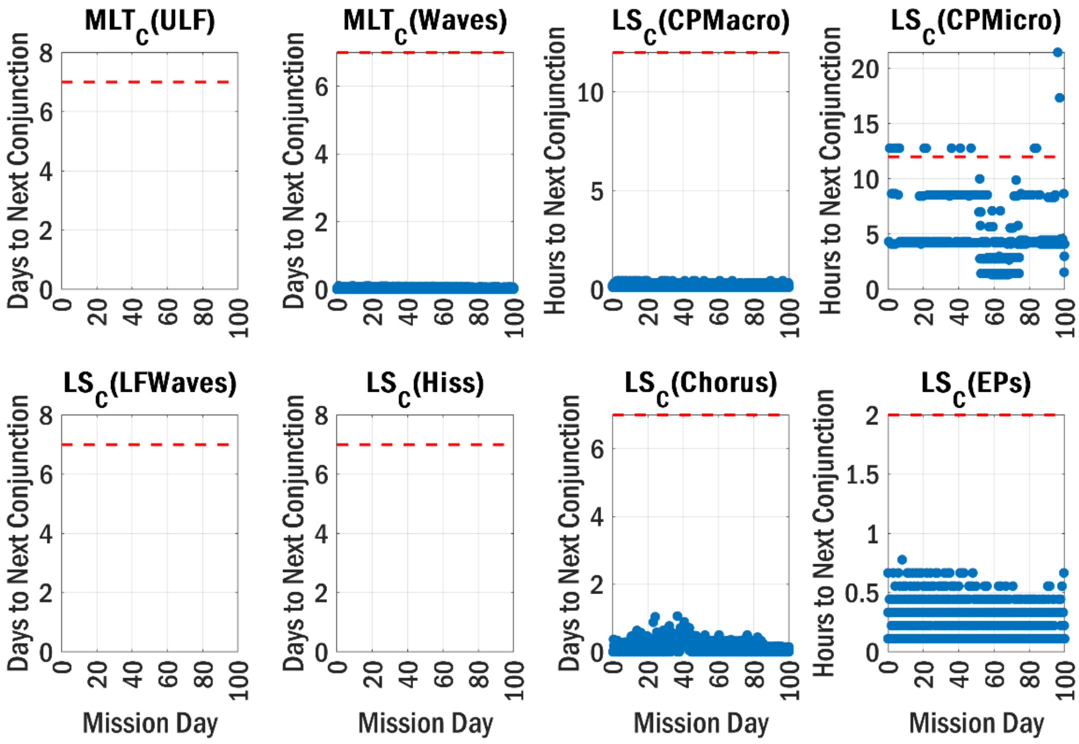


Figure 8-31. Scenario 2: Secondary objective time to next conjunction (requirement is indicated by a red dashed line).

Scenario 3: (N_{DL} **= 3 with** n_{SC} **= 4; total: 12 observatories)**

Here, an additional spacecraft is added to each launch from Scenario 2. The spacecraft arrive in three distinct orbits, pictured in Figure 8-32a,b. As shown in Figure 8-32c, LS_R is effectively satisfied for all L-shell bands for the full simulation, and MLT_R is also satisfied for essentially the full mission.

Science performance for the secondary science objectives is provided in Figure 8-33 for Scenario 3. Six of the eight secondary objectives have requirements met for the full mission simulation. LS_C(LFWaves) is satisfied for ~80% of the mission, while LS_C(Hiss) is satisfied for ~15%.

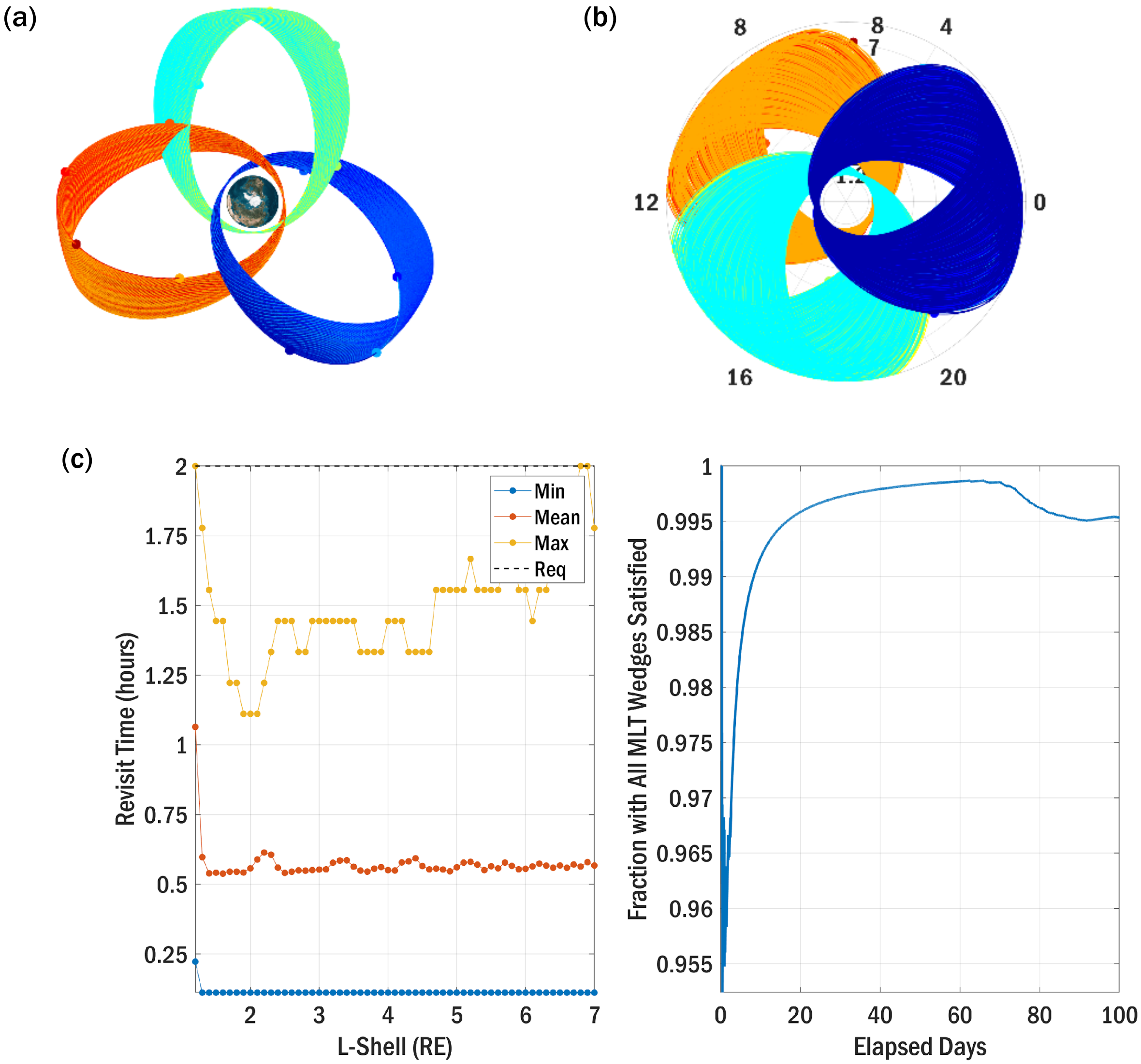


Figure 8-32. Scenario 3: L-shell revisit time satisfied for nearly the full duration, with minor violations just fractionally over the revisit requirement of 2 hours; MLT wedges satisfied >99.5% of the simulation. (a) Inertial orbit view. (b) Orbits in MLT frame. (c) Left: L-shell revisit time (minimum, mean, maximum) for each L-shell band to assess LS_R objective; right: fraction of mission duration for which the MLT_R objective is satisfied.

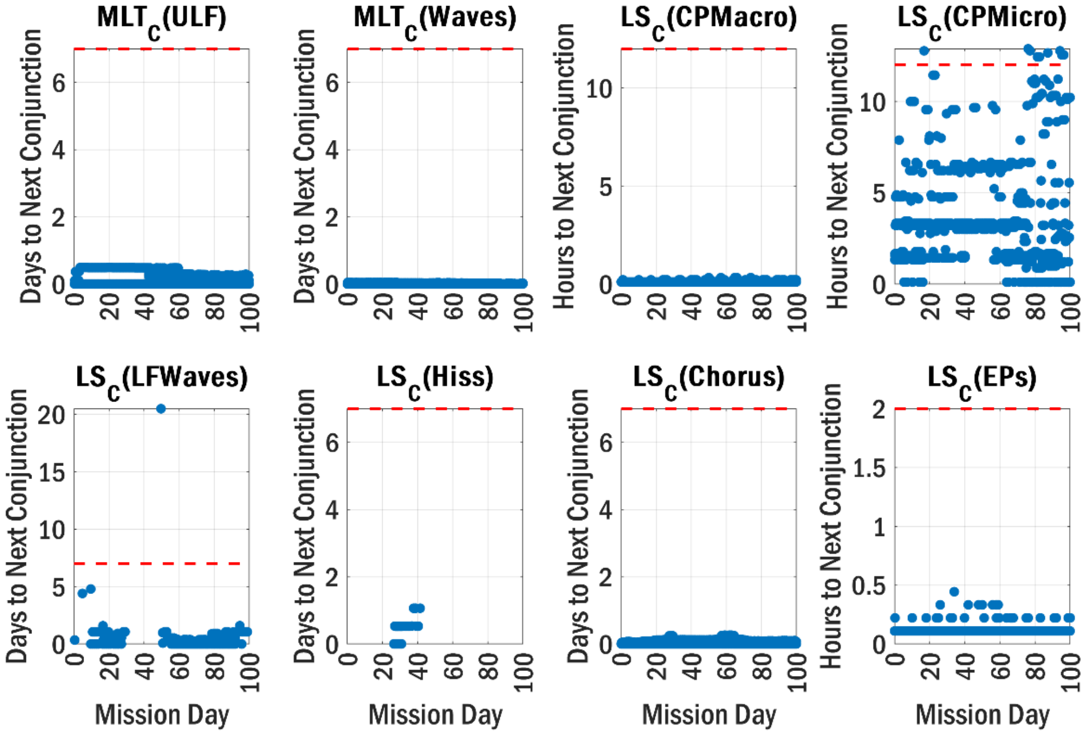


Figure 8-33. Scenario 3: Secondary objective time to next conjunction (requirement is indicated by a red dashed line).

Scenario 4: (N_{DL} = 1 with n_{SC} = 4, N_{RL} = 5 with n_{SC} = 1; Total: 9 observatories)

For a single dedicated launch with four spacecraft per launch, and five rideshare launches of a single spacecraft, the spacecraft arrive in six distinct orbits. One of the six distinct orbits has four spacecraft that are phased in true anomaly. Recall that, although in practice, no control over the relative spacing of the orbits in right ascension of the ascending node is possible for the rideshare launches, Ω is treated as a variable in this study to determine the best *possible* performance. Randomizing Ω will generally lead to a decrease in performance compared with the results presented here. Because of the inclination assumptions for the rideshare-launched orbits, periods of ML violations will occur. However, the contributions from these periods are still included in the assessment of science performance.

The final orbits for Scenario 4 appear in Figure 8-34a,b, with the summary of performance for LS_R and MLT_R appearing in Figure 8-34c. LS_R is violated at least once for most of the L-shell bands; however, the average revisit time falls under the requirement for all bands. Objective MLT_R performance is comparable to that of Scenario 2 and is satisfied for ~91.7% of the simulation.

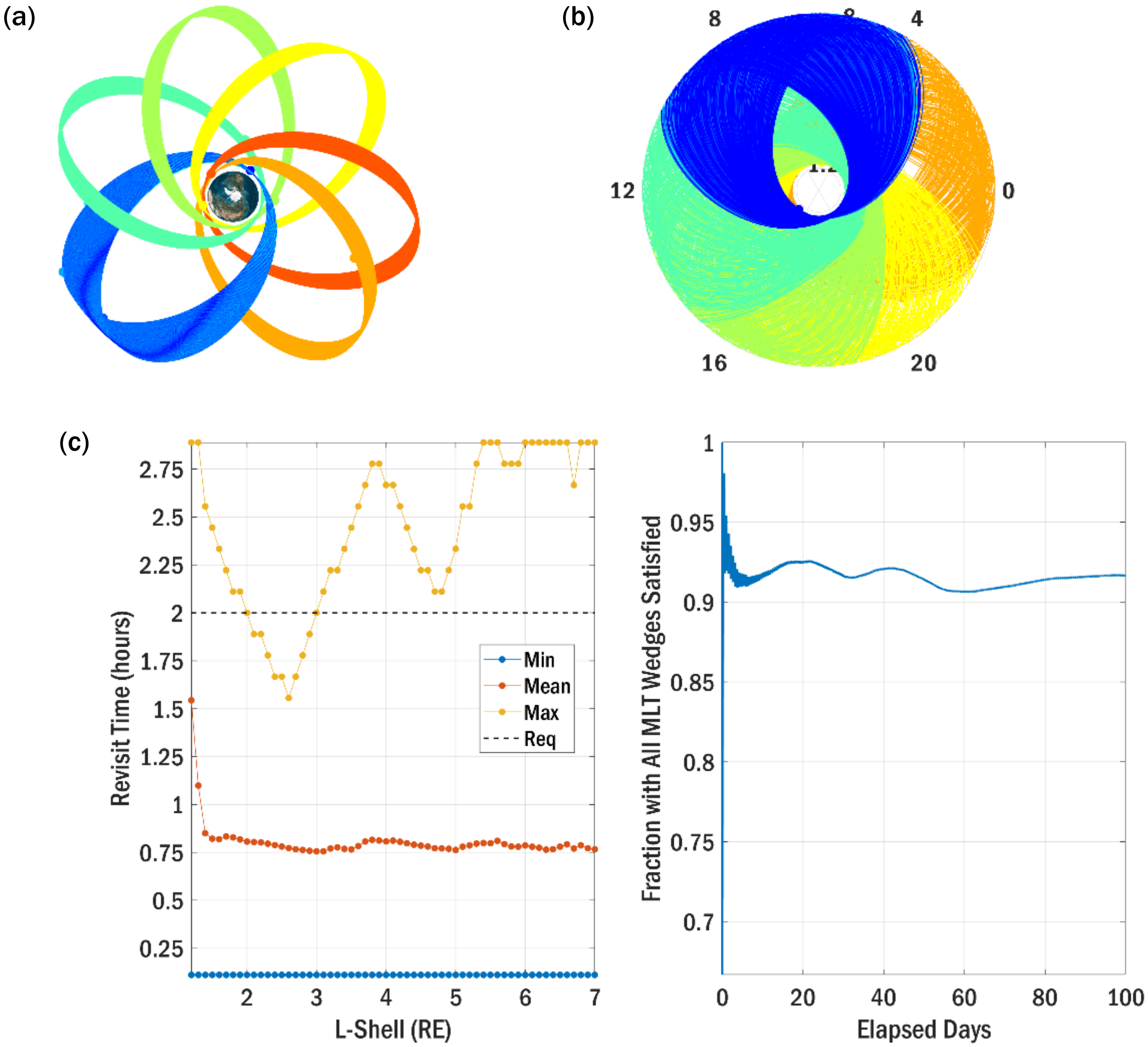


Figure 8-34. Scenario 4: L-shell revisit time has violations for all L-shell bands; however, average revisit time satisfies the requirement; MLT wedges satisfied >90% of the simulation. (a) **Inertial orbit view.** (b) **Orbits in MLT frame.** (c) **Left: L-shell revisit time (minimum, mean, maximum) for each L-shell band to assess LS_R objective; right: fraction of mission duration for which the MLT_R objective is satisfied.**

While the performance of the threshold objectives is slightly degraded when compared with Scenario 3, the secondary objectives have very strong performance for Scenario 4, as indicated in Figure 8-35. Seven of the eight requirements are satisfied over 100% of the mission, and the eighth requirement is satisfied for 84.6% of the simulation.

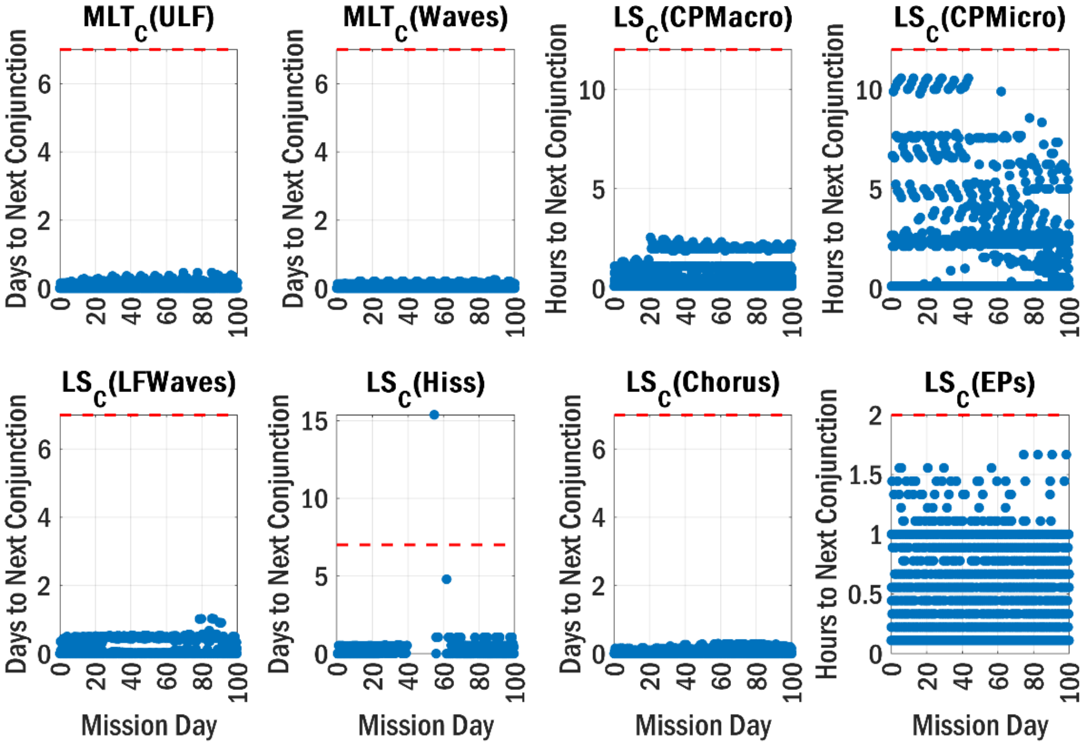


Figure 8-35. Scenario 4: Secondary objective time to next conjunction (requirement is indicated by a red dashed line).

8.9.4.4. Comparing Performance from Different Scenarios

A comparison of performance between launch scenarios is provided in Figure 8-36 and Figure 8-37. In Figure 8-36, the fraction of the L-shell bands that do not experience any requirement violations for the full mission duration is plotted for each scenario, in addition to the average fraction of the mission duration for which objective MLT_R is satisfied. The average is taken across the values appearing in Figure 8-27, Figure 8-29, Figure 8-31, and Figure 8-33. In Figure 8-37, the fraction of the mission duration for which each of the secondary objective requirements is satisfied appears. A few observations are summarized below.

8.9.4.4.1. Threshold Objectives

- Performance of objective LS_R is multidimensional because it must be assessed across 59 L-shell bins. For this study, each L-shell bin is presented rather than averaging across the bins. For Scenarios 1 and 4, maximum revisit times approach two times the required value and are expected to have degraded performance for this objective when compared with Scenarios 2 and 3. Violations for Scenarios 2 and 3 are very small, and likely negligible. Although the values for these scenarios in Figure 8-32 are slightly less than 1, in practice the small revisit time violations would be treated as negligible.

- Scenario 3 performs the best across both threshold objectives LS_R and MLT_R and is also associated with the maximum total number of spacecraft across all the scenarios, with $N_{SC} = 12$.

- Scenarios 3 and 4 each correspond to $N_{SC} = 9$ and have similar performance for MLT_R.
- Although more L-shell bands experience violations of the 2-hour revisit requirement for Scenario 4, the *average* revisit time is comparable to those of Scenarios 2 and 3.

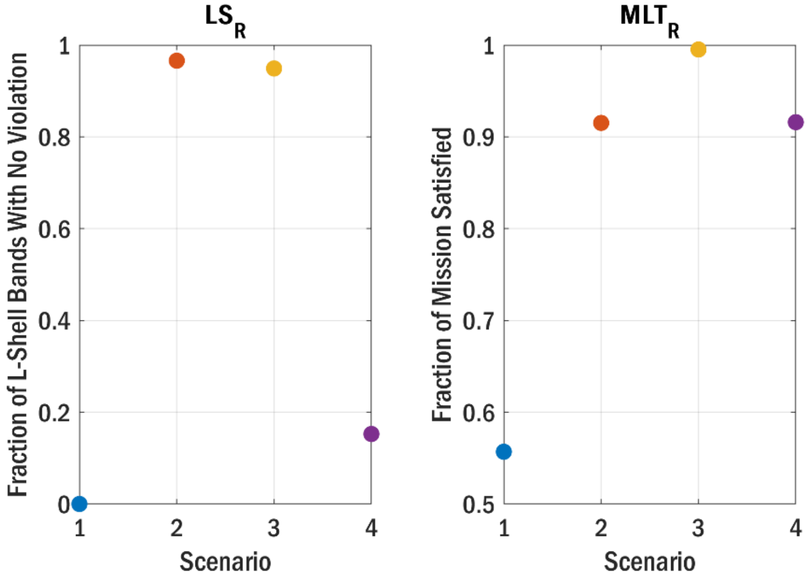


Figure 8-36. Comparison of performance for threshold science objectives for Scenarios 1–4.

8.9.4.4.2. Secondary Objectives

- For Scenario 1, for LS_C(CPmicro), a significant number of valid configurations are separated by ~13 hours, just over the 12-hour requirement. If these configurations are counted as valid (i.e., the requirement is raised to 13 hours), the fraction of the mission satisfied increases from ~2% to 12%. Similar sensitivity studies to the conjunction-time requirement boundaries would lead to adjusted values for secondary objective performance across most of the scenarios.
- For Scenario 3, by swapping the requirement implementation for LS_C(LFWaves) and LS_C(Hiss) from “adjacent wedges” to a similar parameter of $\Delta MLT < 8$ hours, many more valid periods are registered. In fact, an increase in performance from 80% for LS_C(LFWaves) and 20% for LS_C(Hiss) to 100% for both is achieved. Again, sensitivity studies across all the scenarios and objectives may prove useful to capture uncertainties in expected performance values for the multidimensional science objective space.
- Performance for MLT_C(ULF) decreases for Scenario 2 when compared with Scenario 1, despite having one additional spacecraft in the simulation. For MLT_C(ULF), at least three spacecraft must be within 3 hours MLT of each other, while located outside the plasmapause toward the orbit apogee. For Scenario 2, this would require that all three spacecraft from a single launch become roughly colocated, which would cause an increase (reduced optimality) in the objective function value J. The significant increase in performance for threshold objective MLT_R between Scenarios 1 and 2 likely leads to the

decrease in performance for MLT$_C$(ULF), because these two objectives are in direct competition with one another.

- Scenario 4 performs very strongly for all the secondary objectives, likely because of the increase in the number of distinct orbits in terms of right ascension of the ascending node, Ω. Again, although in practice the mission would have little control over the value of Ω for rideshare opportunities, this scenario demonstrates the distinction between the contributions of dedicated and rideshare launches toward the secondary objectives.

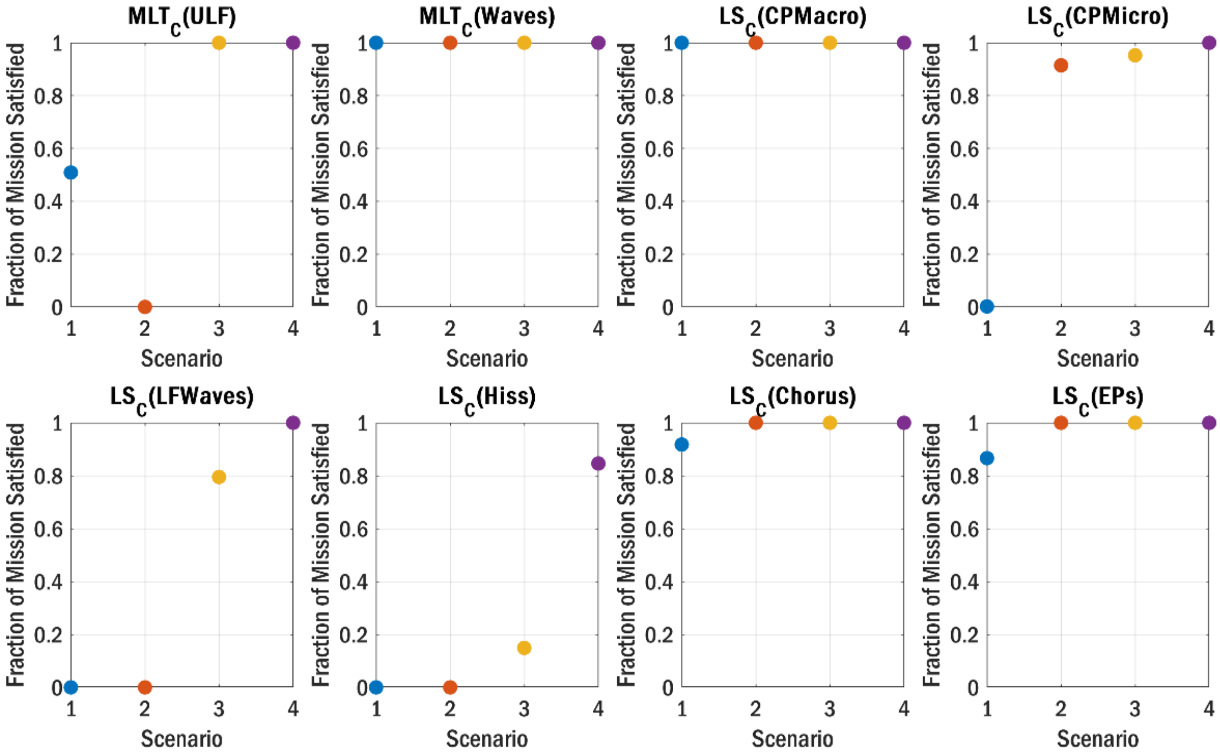


Figure 8-37. Comparison of performance for secondary objectives for Scenarios 1–4.

8.9.4.4.3. Summary of Results

Scenario 4—consisting of nine CREO spacecraft (four deployed via a dedicated Falcon-9 launch and five deployed via subsequent rideshare opportunities)—enables maximum CREO science (as defined above) for the minimum number of observatories. Note that because of the use of rideshare to complete the CREO constellation, the constellation may be built up over time after the dedicated launch of the first four spacecraft.

8.9.4.5. ΔV Requirements

Depending on the class of GTO, the range of ΔV required to adjust the orbit to the desired dimensions for a rideshare launch varies. The “Atlas V Launch Services User’s Guide” provided by United Launch Alliance serves as a useful reference for information on the various classes of GTOs (https://www.ulalaunch.com/docs/default-source/rockets/atlasvusersguide2010.pdf). Of U.S.-launched GTOs (as queried via https://www.space-track.org/), roughly 52% are short-coast transfers, 26% are extended-coast transfers, 10% are sub-synchronous transfers (spacecraft is too massive for the launch vehicle to inject into a standard GTO), and 12% are super-synchronous (spacecraft mass is less than launch vehicle capability for GTO). Estimated cost to adjust the orbit properties for a range of GTO dimensions is shown in Figure 8-38. Historical launch data for launches after the year 2000 are overlaid for reference. The CREO spacecraft design enables up to 200 m/s ΔV for the mission lifetime. Most of the short-coast rideshares, and a portion of the extended-coast and super-synchronous GTO rideshare options, could be accommodated by CREO.

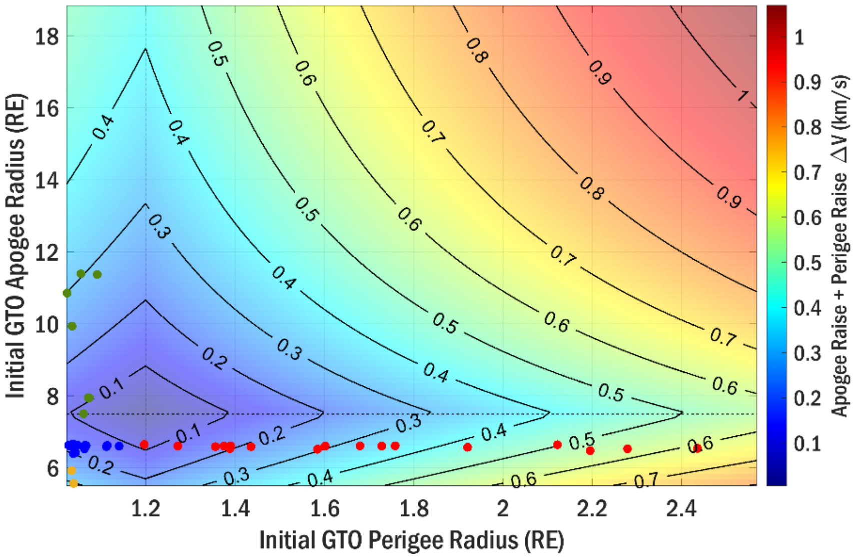


Figure 8-38. ΔV required to adjust orbit dimensions to those specified in Table 8-35 for a range of GTO options, with historical launch data overlaid for U.S.-launched sub-synchronous (gold points), short-coast (blue points), extended-coast (red points), and super-synchronous (green points); note that only a portion of the historical sub-synchronous data are shown because of the figure axis limits.

Assuming the desired science orbit dimensions have been achieved, the cost to adjust the true anomaly (θ) phasing can be assessed. The ΔV required to shift θ for a given spacecraft is a function of the magnitude of the shift and the time allowed to achieve that shift. An example demonstrating the ΔV required to shift θ by 0–180° within up to 10 days is provided in Figure 8-39. For <10 m/s, most the of the true anomaly space is accessible for this maximum phasing duration; however, by increasing the time allowed to achieve the shift, any true anomaly shift is achievable for trivial ΔV.

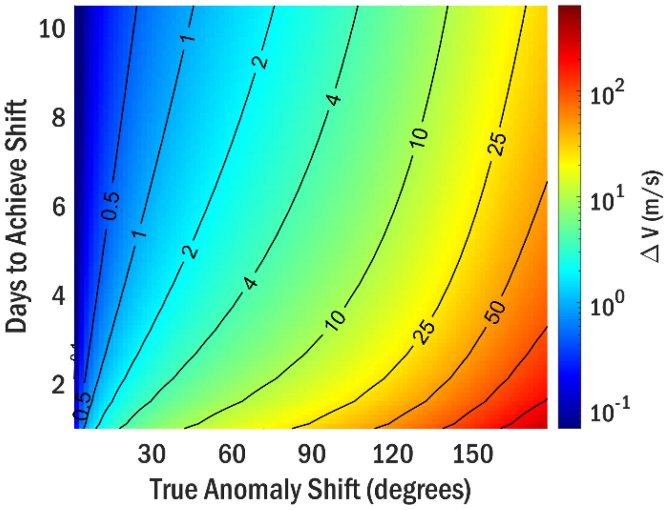


Figure 8-39. ΔV required to shift orbit true anomaly for a given spacecraft is a function of the desired shift as well as the time allotted to achieve that shift. This example demonstrates up to 10 days to shift true anomaly; however, any shift is achievable for trivial ΔV by extending the duration.

8.9.5. Concept of Operations

The CREO spacecraft are Sun-pointed spinning platforms like the Van Allen Probes mission spacecraft. Spinning platforms are required to sample energetic particle pitch angles through their full distribution, and Sun-pointing is required to obtain electric and magnetic field measurements in the GSM (geocentric solar magnetospheric) coordinate system. Specifications for the spin characteristics are as follows:

- The rotation rate is 3–4 revolutions per minute.
- Spin axis shall be orthogonal to Earth's rotation axis and aligned closely to Sun line of sight (not directly Sun-pointing).
- Spin-axis pointing and rate will be maintained autonomously; no rapid reorientations will be required; angular rates and accelerations are slow.

Deployable equipment and instruments on CREO include the following:

- Solar panels with solar panel normals parallel to the spin axis
- Magnetometer booms (×2)
- Electric field stacers/antennas (×6)

Onboard propulsion (up to 200 m/s ΔV over the course of the mission) enables some orbit tuning capability and adjustment of phasing for multiple spacecraft along a common orbital trajectory. A monopropellant propulsion system will be used on each spacecraft for achieving/maintaining spin rate and spin-axis orientation and for trajectory correction maneuvers.

Each spacecraft shall have dual-channel GPS receivers for ephemerides, precision timing, and acquisition of POD data that can be used during the LEO perigee periods for atmospheric density diagnostics.

The CREO mission operations are relatively simple. Once each spacecraft is established in its nominal GTO trajectory, the instruments are turned on and data are recorded and transmitted to ground stations. The standard science data products will have a nominal data rate of ~70 kbps. All data will be telemetered to the ground via traditional radio-frequency encoding with a dedicated ground station or commercial ground station network (to be determined in refined mission operations studies).

CREO will collect and transmit critical space weather nowcasting data products, including a continuous 10-kbps real-time “beacon” data stream to the ground via a commercial or Department of Defense LEO communications RN to ensure L0 data availability at the MOC within 10 min of actual observation time.

8.9.6. Critical Technology Development

The CREO mission requires relatively few technology developments to enable spacecraft and instrument deployment. The following are viewed as technology enhancements that would improve the data return and/or quality:

- An advanced, highly automated LEO communications RN, in partnership with commercial communications networks (e.g., SES O3b; SpaceX Starlink) or the Department of Defense’s Transport Layer. The use of commercial ground station networks is also viewed as enhancing.
- A TRL-9 multiband GPS receiver that can operate at GEO would enhance orbital trajectory and timing data beyond MEO range.
- Onboard processing capabilities for E- and B-field wave measurements: onboard monitoring of wave subpacket structures, onboard calculation and recording of wavefield statistics (beyond just average power), and onboard tracking and capture of the upper hybrid frequency.
- Compact, low size/mass/power particle instruments enabling extended angular coverage (corresponding to faster temporal resolution for all-sky distribution data), broader range of energies, and multiple species with high mass resolution (e.g., resolving carbon from nitrogen from oxygen).
- Cold plasma measurements with an energy threshold of <1 eV. Requires development of active electric potential control on at least part of the spacecraft around the plasma instrument.

8.10. FMT-10 Mission Concept Design Summary: Solar Impacts on Climate

FMT-10 did not undergo a detailed mission concept design study. In the following, we refer to a potential mission design as the Solar Impacts on CLimate Explorer (SICLEx) for brevity. The name is not meant to imply that this is a mission to be developed within the NASA Explorer program.

8.10.1. Mission/Measurement Strategy

The following measurement strategies are required to address the science objectives:

- Simultaneous measurements of SSI and particle precipitation, variations in NOx, atmospheric parameters (wind, temperature, composition including CO_2), and the stratospheric ozone over solar cycle.

- Measurements near sub-auroral and auroral latitude regions, with high spatial and temporal coverage with the pitch-angle distribution with high spatiotemporal resolution. For that purpose, coordination of ground-based measurements would be critical (such as the THEMIS All-Sky Imager, Canadian riometers, Japanese PWING, etc.) from the beginning of the mission planning stage.

8.10.2. Special Considerations for Mission Design

- Simultaneous measurements of energy input to the upper atmosphere and the impacted atmospheric compositions, wind, and temperature.

    - **Energetic particle precipitation.** The pitch-angle distribution must be observed with better spectral resolution than NOAA MEPED (Medium Energy Proton and Electron Detector).

    - **Atmospheric composition.** We must make continuous global observations of NOx and tracers (~60- to 150-km altitude in particular), including during polar night (NASA TIMED/SABER did not have NOx).

        - Stellar occultation is one of the demonstrated techniques for measuring NOx in the polar night, which would require Sun-synchronous orbit (so that the relevant stars will not be so clustered in right ascension). If the LT is fixed, there would be no parts of the cycle where no stellar occultation could be made.

        - Furthermore, it is important to include the capability to distinguish between NO and NO_2. Keeping the LT fixed would make it easier to determine whether NO versus NO_2 is dominating NOx if one uses techniques that cannot measure both constituents at the same altitude.

    - **Atmospheric dynamics.** We must synthesize disparate observations of gravity waves to characterize their sources, evolution, and impacts. We need wind observations in the mesosphere and thermosphere.

- Close collaborations with state-of-the-art (whole) atmosphere modeling development:

    (i) There are still large uncertainties in D-region chemistry (reactions/rates). What measurements are needed to validate them?

    (ii) We must simulate the full energy range of precipitating electrons.

    (iii) We must improve the treatment of sub-grid-scale waves.

- To enable solar cycle mission duration, a new approach is required. For example, NOAA's approach is to build and launch two spacecraft while keeping one in hibernation, or to launch every 5 years.

8.10.3. Mission Design

Table 8-36. SICLEx key driving requirements.

Mission Class	Modified C or D
Mission Duration	10+ years
Design Lifetime	2–5 years (per spacecraft)
Launcher Class	Standard expendable launch vehicle
Spacecraft Class	ESPA-compatible
Concept of Operations	Instruments are always on
Assumptions	▪ >2 spacecraft to monitor broader horizontal coverage in the polar region ▪ Coverage altitude of 60–150 km ▪ Identical instrumentation (optional) ▪ Orbital altitude: low Earth orbit (~600 km) circular ▪ 98° inclination (Sun-synchronous)

ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter.

Table 8-37. FMT-10 significant trades and decisions.

Trade	Outcome
Spacecraft replacement versus high-reliability single spacecraft	Requires design study
Number of spacecraft for optimal MLT coverage	Requires design study
Joint HPD–ESD funding approach	Requires programmatic coordination

ESD, Earth Science Division; HPD, Heliophysics Division; MLT, magnetic local time.

8.10.4. Envisioned Implementation

Table 8-38. FMT-10 spacecraft and payload architecture.

Spacecraft Properties	▪ ESPA-compatible ▪ Baseline: two spacecraft with identical instrumentation. Total number of spacecraft for optimal MLT coverage to be determined from dedicated mission study

Payload Architecture	▪ Spectrometers and photometers to measure full solar spectral irradiance (0.1–300 nm) with <20% accuracy ▪ Electron and ion precipitating particle spectrometer (30 keV—2 MeV) ▪ NOx: NO can be measured by a submillimeter radiometer for both day and night. It consists of a 1.1-m-diameter telescope with four tunable heterodyne receivers covering the ranges 486–504 GHz and 541–581 GHz as well as one receiver fixed at 118.75 GHz together with back ends that provide spectral resolution from 150 kHz to 1 MHz. On the other hand, during daytime, the NO density can be determined by measuring the fluorescent scattering of solar radiation at 215 and 237 nm in the (1.0) and (0.1) gamma bands using limb scanning. ▪ Doppler interferometer for remote sensing measurements of the vector wind and temperature profiles ▪ Temperature and composition including ozone: Microwave Limb Sounder for upper troposphere, stratosphere, and mesosphere ▪ Broadband infrared limb emission measurement to derive vertical profiles of CO_2 volume mixing ratio from approximately 70 km to 120 km ▪ Identical instrumentation ▪ Remote-sensing-only payload
	▪ 24/7 monitoring ▪ Innovative approach of long-term measurements (i.e., wind, temperature, composition) combined with a capability to trigger high-cadence particle measurement during storms ▪ Large storage buffers to hold event data; selective download via user input

ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; MLT, magnetic local time.

8.10.5. Orbit Design

- Initial two-spacecraft constellation. The spacecraft are inserted in the same orbit but separated by 90° planes. Capability to incrementally expand the constellation by inserting spacecraft at additional planes to increase MLT coverage.

- Near-polar 98°-inclination (Sun-synchronous) orbit at ~600-km altitude (to be defined via dedicated mission study).

8.10.6. Concept of Operations

The FMT-10 SICLEx adopts a straightforward concept of operations:

- The SICLEx FMT-10 instruments are always on, acquiring data at synoptic steady cadences.

- Capability to use external trigger (e.g., flare detection above a predefined threshold by the spectral irradiance instrument) to initiate rapid cadence for particle measurements or other storm-specific data acquisition.

- Coordinate measurements during storms with the ground-based component.

8.10.7. Technology Development

We identified three areas where further technology development may be needed:

- **Technologies and/or procedures to achieve in-space calibration and cross-calibration to ~1–2% accuracy.** This level of accuracy will ensure the reliability and science value of long-term observations from the chain of FMT-10 spacecraft over the 10+-year baseline science operations phase. Typical calibration levels for remote sensing instruments are to 10% levels—better for spectral irradiance monitoring, but combing time series from different instruments and missions has always been difficult.

- **Onboard autonomy.** As an example, high-precision particle precipitation measurements and other storm-specific data acquisition can be initiated by an external trigger (i.e., by using flare detection above a predefined threshold by the spectral irradiance instrument or by using ground-based commands). Algorithms, timing chains, and decision flow-downs are not currently mature enough for time-critical autonomous (or even semiautonomous) operations.

- **NOx high-sensitivity imaging for extended altitude coverage (60–150 km).** Such imaging has not yet been demonstrated. For example, while NASA's Student Nitric Oxide Explorer (SNOE) observes fluorescent scattering[2] of solar radiation during the day, no such measurements are made during polar night. In contrast, submillimeter radiometers provide NO measurements during both daytime and nighttime. The instruments are limb scanners, observing NO thermal emission lines in a band centered around 551.7 GHz (Sheese et al., 2013; Frisk et al., 2003). Encouraging the further development of similar or different measurement approaches to map NOx 24/7 would be invaluable in achieving the science objectives of a SICLEx-type mission.

8.11. FMT-11 Mission Concept Design Summary: Earth as an Exoplanet

No mission studies were done for this FMT, so we are proposing two possible architectures for measuring atmospheric escape during solar activity and using models to extrapolate knowledge gained from Earth's environment to exoplanetary environments.

8.11.1. Ion Outflow Mission

Much of atmospheric escape on Earth happens via ion outflow, particularly the escape that is highly correlated with solar activity (Moore et al., 1999). Magnetospheric and solar wind energy input comes down the two polar caps during active times along magnetic field lines. Alfvén waves easily stream down to the upper atmosphere, where at the right transition altitude, the exobase transition energizes the thermal ionospheric ions, providing them with the necessary energy to escape Earth's gravity. High solar and geomagnetic activity provides both high ionization rates of the neutral atmosphere and the waves and mechanisms that will accelerate the newly created ions to escape the atmosphere, as shown below in Figure 8-40 and Figure 8-42. The latter shows the MEMEX mission concept (Moore et al., 2017; Parsay et al., 2021).

---

[2] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2003JA010199, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2003JA010227

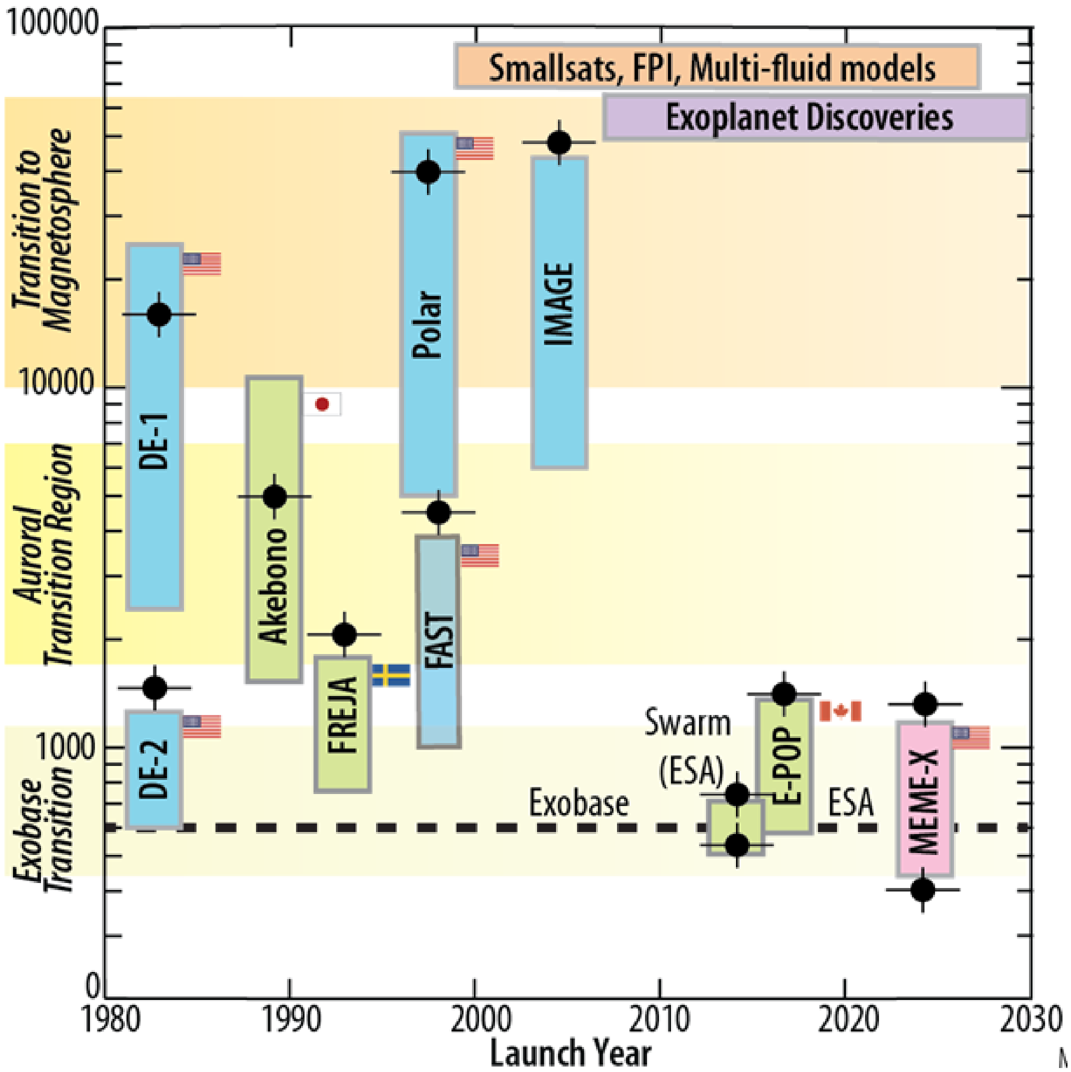


Figure 8-40. Altitudinal distribution of key magnetosphere–ionosphere–atmosphere interaction processes and the missions that have historically studied them. The MEMEX-type mission will be the first to address the acceleration processes at the exobase transition region that during active times push ions outward, out of Earth's gravity.

8.11.1.1. Mission Concept Like MEMEX

MEMEX is a constellation of altitudinally separated satellites in the acceleration regions (300–800 km).

8.11.1.1.1. Measurement Strategy

MEMEX is a constellation of a minimum of two identical satellites. It measures the energy inputs (E-fields, B-fields, precipitating particles), the local wave properties and intensity and frequency (E-field probes, SCM), and the complete plasma and neutral state parameters (plasma density, drift, temperature, and composition; neutral density, wind, temperature, and composition), as well as their altitudinal and azimuthal gradients, to ascertain which acceleration processes successfully lead to ion escape and under what driving conditions.

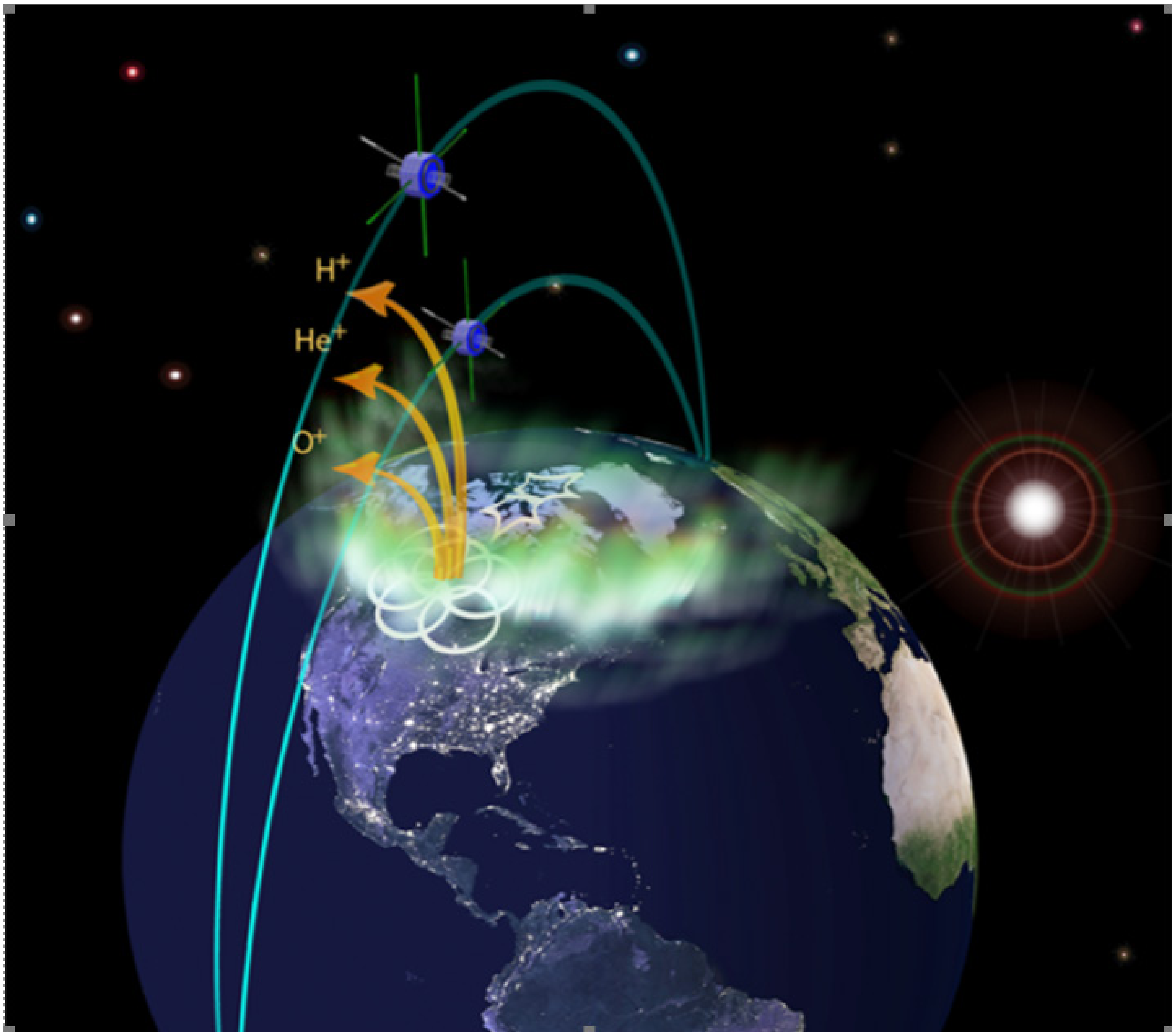


Figure 8-41. The MEMEX mission concept (originally as MISTE in the 2012 Heliophysics Decadal Survey) is a prime example of a mission that aims to understand the ion outflow and escape from Earth's gravity.

8.11.1.1.2. Orbit Configuration

Figure 8-42 provides an overview of the measurement strategy and orbit configuration. The mission consists of spacecraft in two identical LEO, elliptical (300 × 1200 km) orbits, off phase to accomplish either high-latitude magnetic conjunctions altitudinally separated (left side) or high-latitude rapid revisits at the same altitude (right side) for separating spatial and temporal structure of the acceleration processes.

Satellites are launched with single ELV launch and use propulsion to acquire final orbit configuration and for station-keeping. Several other FMT studies have explored such release processes.

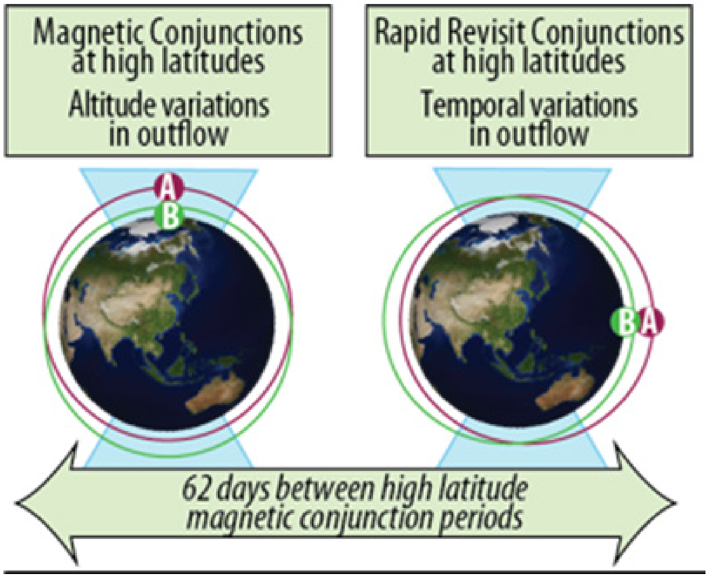


Figure 8-42. The MEMEX orbit configuration offers an example for the FMT-11 spacecraft component tasked with capturing the plasma properties at the acceleration region.

8.11.1.1.3. Future Trade Studies

- Number of satellites required for optimum altitudinal separation and revisit times
- Communication issues as the number of satellites increases

8.11.2. Total Atmospheric Escape from L2

This architecture aims to understand how the magnetic field shields our atmosphere from the variable solar drivers by obtaining simultaneous measurements across the system: from the upstream solar wind to the geocorona to ion escape past the L2 Lagrangian point. The concept envisions two sets of spacecraft: one pair in highly elliptical orbit to measure the solar wind upstream conditions (the solar forcing) and the state of the geocorona, and another pair at the Sun–Earth L2 Lagrange point to measure the fluxes of escaping ions in the distant magnetotail.

8.11.3. Mission Strategy

8.11.3.1. Measurement Strategy

The following measurements are required to address the science objectives:

- Mass-resolved ion fluxes at the far tail (down to a few electron volts) (can be achieved with active spacecraft potential control, or by measuring electric fields)
- EUV measurements of major species of upper thermosphere and geocorona
- Upstream solar wind conditions, including proton fluxes, interplanetary magnetic field, extreme ultraviolet (EUV) measurements from the Sun, and imaging of transients (e.g., CMEs, streams) impacting Earth

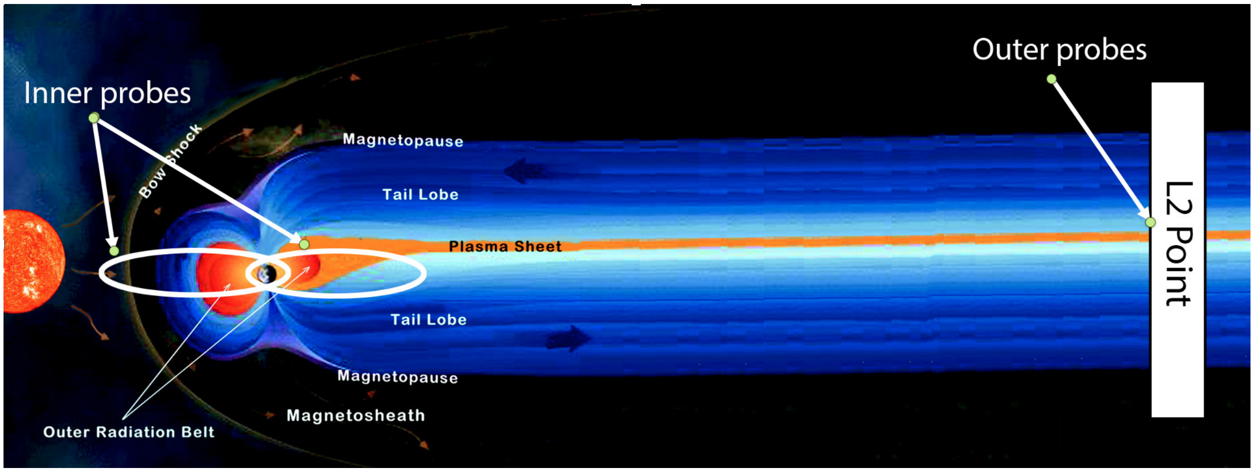


Figure 8-43. Top-level mission architecture for the atmospheric escape mission concept) (adapted from Lyon, 2000).

8.11.3.2. Special Considerations for Mission Design

- All spacecraft should be ESPA-compatible.
- To measure truly escaping ions, measurement needs to be made as far as possible along the magnetotail.
- Certain measurements could be provided by other assets (i.e., solar EUV irradiance, transient imaging), but a detailed mission study is required to establish the resource limits for the payloads.

8.11.4. Mission Design

Table 8-39. FMT-11 key driving requirements.

Mission Class	C
Mission Duration	5 years (preferably during rising or declining solar cycle phase)
Design Lifetime	2–5 years (per spacecraft)
Launcher Class	Standard ELV
Spacecraft Class	ESPA-compatible
Concept of Operations	Instruments are always on.
Assumptions	▪ 4+ spacecraft in two orbits (L2 and HEO) ▪ Active potential control for the L2 spacecraft is needed to reach low energies

ELV, expendable launch vehicle; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; HEO, high Earth orbit.

Table 8-40. FMT-11 significant trades and decisions.

Trade	Outcome
Instrument complement beyond core package	Requires design study
Number of spacecraft for optimal far-tail and geospace coverage	Requires design study

8.11.5. Envisioned Implementation

Table 8-41. FMT-11 spacecraft and payload architecture.

Spacecraft Properties	ESPA-compatible Some spacecraft could be spinners (depending on instrumentation)
Payload Architecture (inner probes)	Magnetic fields: 0–200 ±1 nT SW ions: 100 eV to 5 keV Density: 1–200 cc EUV geocorona imagers: (Lyman-α, N, O) EUV solar irradiance
Payload Architecture (L2 probes)	Ion composition: 1–60 keV/q (particularly O and N) Magnetic fields: 0–200 ±1 nT

ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; SW, solar wind.

8.11.6. Orbit Design

- Two spacecraft in highly elliptical orbits (LEO to 15 Re, roughly), 180° apart (inner probes). Capability to expand the constellation by inserting spacecraft at other planes to increase coverage of the geocorona.
- Two spacecraft in halo orbits around L2 (outer probes). Orbit amplitude and number of spacecraft for optimal measurements of escaping ions requires a dedicated mission study.

8.11.7. Concept of Operations

This concept adopts a straightforward concept of operations.

- The instruments are always on and acquire data at synoptic modes.
- It will be possible to switch to event mode (e.g., higher cadence) when a solar transient impact is imminent (via ground uplink).
- The data acquisition modes are synchronized across the inner and outer probes.

8.11.8. Technology Development

We have identified two areas where technology development may be required:

- **Active potential control of the spacecraft.** Although this capability has been implemented in the past, it is not a common approach. Hence, it is considered a costly and complex requirement for spacecraft builds. Feasibility studies to identify better engineering procedures and, hopefully, low-cost implementations should be encouraged because this capability will enable the in situ measurements of low-energy plasmas that are otherwise currently unfeasible.

- **Cold plasma measurement techniques.** As discussed earlier, the measurements of electronvolt-level energies are complicated because of the influence of the spacecraft potential. As a result, little information exists on cold plasmas in the near-Earth space. Engineering approaches and/or new measurement techniques to improve the situation should be encouraged.

8.11.9. Assumption of Existing Capabilities

We assume the following existing measurements:

- Solar activity and state
- Solar wind impacting the Earth
- Ground observations of ionospheric convection through radar facilities
- GLIDE mission observations of exosphere and its dynamics

8.11.10. Leveraging Other Planetary Missions

Being able to observe Earth in the same manner that we observe exoplanets, through UV or X-ray irradiation (XIR) observations, will be invaluable. The Planetary Decadal Survey was just released and announced a flagship mission to Uranus. Heliophysics should leverage this and all other deep-space missions to fly UV and XIR imagers that can look back at Earth during its Sun transits to identify all chemistry and other characteristics that will guide future exoplanet observations.

Leverage FTM-10 for the comprehensive global study of NO and OH emissions from Earth and their dependence on solar activity. Leverage FMT-12 for the large-scale imaging of geospace and comprehensive measurements of the ambient solar wind between L1 and the magnetosphere. In fact, FMT-10, FMT-11, and FMT-12 are highly complementary and can form the basis for a comprehensive system for the study of stellar–planetary interactions using Sun–Earth as the basis.

8.12. FMT-12 Mission Concept Design Summary: PeriGeospace Observing System

8.12.1. Mission Strategy

8.12.1.1. Measurement Strategy

The following measurement strategies are required to address the science objectives:

- In situ measurements of fields and particles, including SEPs and plasma/particle composition
- Remote sensing of the plasmasphere, magnetosphere (including energetic neutral atoms, soft X-rays, visible light), and solar wind (away from Sun–Earth line)

8.12.1.2. Special Considerations for Mission Design

- All spacecraft carry a core of identical instrumentation consisting of the basic solar wind measurements (field, density, temperature). Other instrument types can be added depending on specific mission objectives (precise number requires mission study).
- All spacecraft should be ESPA-compatible.
- All spacecraft carry a space weather beacon capability (i.e., continuous data transmission to Earth through a low-telemetry pipe).
- Instrument designs should account for both SH and Geo targets.
- The PeriGeospace Sentinel is primarily a remote sensing platform. The determination of the angular distance from Earth requires mission study.

8.12.2. Mission Design

Table 8-42. FMT-12 key driving requirements.

Mission Class	Modified C or D
Mission Duration	5 years
Design Lifetime	2–5 years (per spacecraft)
Launcher Class	Standard ELV
Spacecraft Class	ESPA-compatible
Concept of Operations	▪ Instruments are always on ▪ Target and/or measurement range depends on location in orbit
Assumptions	▪ 6+ spacecraft to cover the L1-Earth space ▪ Deep-space platforms and communications ▪ Identical instrumentation ▪ Out-of-ecliptic inclination (to be determined with mission study)

ELV, expendable launch vehicle; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter.

Table 8-43. FMT-12 significant trades and decisions.

Trade	Outcome
Instrument complement beyond core package	Requires design study
Number of spacecraft for optimal PeriGeospace coverage	Requires design study
Inter-satellite plasma probing (via Faraday rotation)	Ultrahigh frequency or C- or X-band
Orbit design for PeriGeospace Sentinel	Requires programmatic coordination

8.12.3. Envisioned Implementation

Table 8-44. FMT-12 spacecraft and payload architecture.

Spacecraft Properties	▪ ESPA-compatible ▪ Some spacecraft could be spinners (depending on instrumentation)
Payload Architecture (core package)	▪ Magnetic fields: 0–200 ± 1 nT ▪ SW ions: 100 eV – 5 keV; 10% energy resolution ▪ Density: 1–200 cc ▪ Suprathermal electrons: 20 eV – 10 keV ▪ Ion composition: 100 eV – 30 keV ▪ Energetic ions: 0.5–30 MeV
Payload Architecture	▪ Imager options: Lyman-α, ENA, SXR, VIS ▪ High signal-to-noise ratio heliospheric imager on PeriGeospace Sentinel ▪ Plasma probing: C- or X-band transceiver at each spacecraft ▪ 24/7 beacon mode ▪ X or Ka downlink ▪ Onboard autonomy for event detection and high-cadence observing programs

ENA, energetic neutral atom; ESPA, EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter; SXR, soft X-ray; VIS, visible.

8.12.4. Orbit Design

Because of time constraints, only an orbit analysis was pursued with the APL ACE team. To focus the analysis, we explored three orbit scenarios:

- L1 to L2-Moon and L1 to Earth cyclers (to cover PeriGeospace)
- L1 to Venus-L2 cyclers (to extend coverage beyond L1 to meet the space weather forecasting requirement of 24 hours for Bz; see the Space Weather Gap Analysis)
- Upstream L1 orbits using low-thrust conventional propulsion (to evaluate the extent of upstream coverage using conventional approaches)

The results are summarized below.

8.12.4.1. L1 to L2-Moon and L1 to Earth Cyclers

Guided by the science objectives, the initial requirements for the orbit design were (1) the ability to place spacecraft within 2° of the Sun–Earth line around Sun–Earth L1, (2) the ability to stay at L1 for >6 months before an Earth loop, (3) the ability to place spacecraft in an Earth–Moon halo L2 orbit, and (4) ballistic or minimal propulsion solutions. These requirements are largely met by 30°–70° (Sun–Earth–spacecraft angle) libration point orbits with trivial ΔV constraints and some station-keeping. Figure 8-44 shows an example of a 70° Sun–Earth L1 quasi-halo orbit (within 1.6° from the Sun–Earth line). The relative out-of-plane amplitudes (<700,00 km) are induced to maintain ΔV ~ 0, but they are also favorable for science because they improve the 3D sampling around the L1 region beyond the original Space Weather Diamond configuration of four spacecraft in a halo L1 orbit. Similar orbits can be designed for L1-Moon transfers and for different orbit amplitudes around Earth. (The example shown in Figure 8-44 has a perigee of 0.6 million kilometers.)

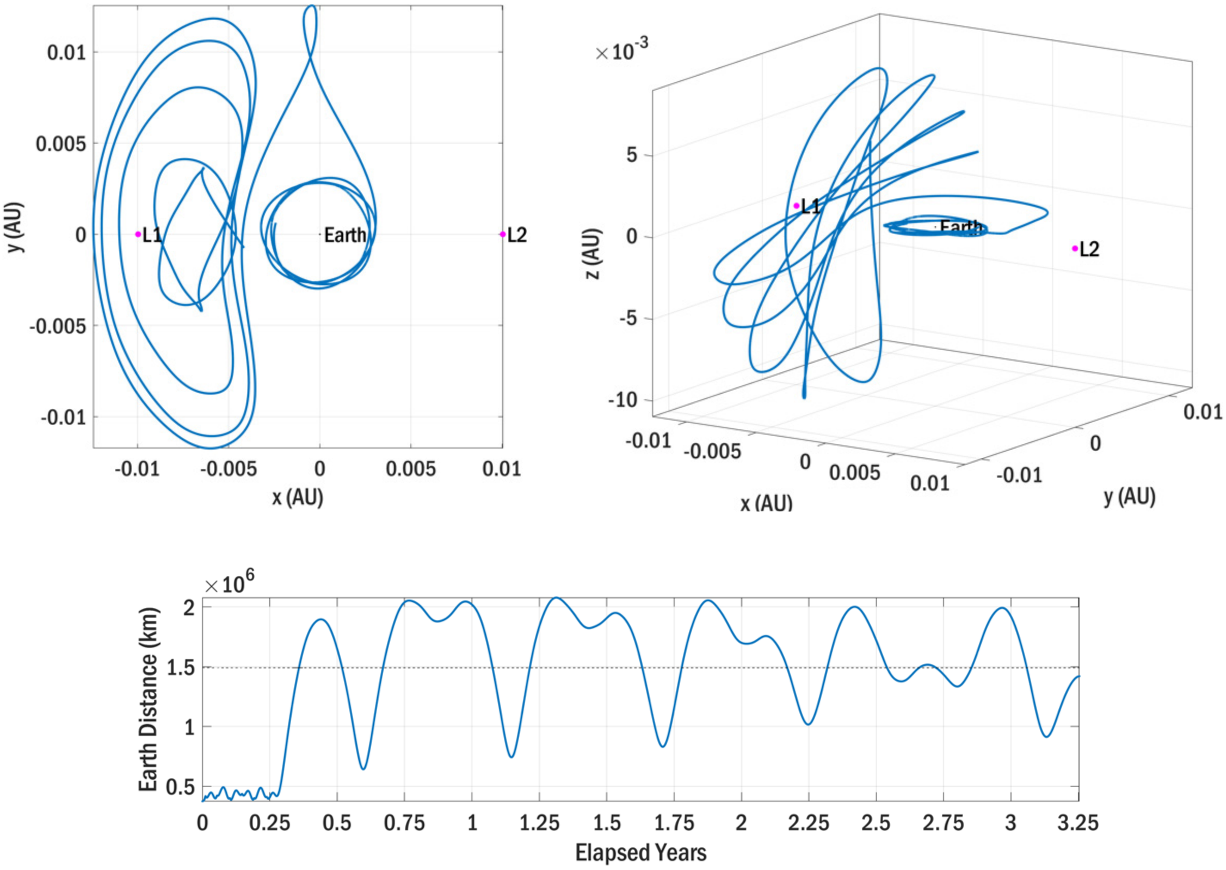


Figure 8-44. Example L1-Earth Cycler orbit. It represents a 70° Lyapunov orbit with ΔV ~ 0. The top panels show the orbit on the ecliptic (top left) and out of the ecliptic (top right) in the Sun–Earth rotating frame. The bottom panel shows the spacecraft–Earth distance as a function of time. In this scenario, the spacecraft spends about one-quarter of the year at the L1 vicinity between each Earth flyby.

8.12.4.2. L1 to Venus-L2 Cyclers

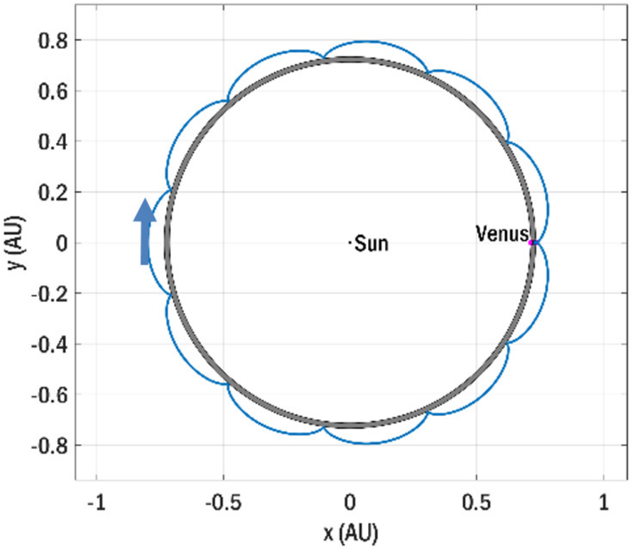


Figure 8-45. “Exterior” homoclinic orbit relative to Venus-L2.

- Low-cost transfers between Sun–Earth and Sun–Venus libration point orbits are unavailable. Because the two systems do not naturally connect, the ΔV is large, ~3.7 km/s (Topputo et al., 2005). Cyclers are likely not feasible without low thrust. Even this case, however, would require a detailed orbital analysis to check feasibility.
- Because cyclers between Sun–Earth and Sun–Venus systems will be very expensive, exterior homoclinic transfers may be an attractive alternative for covering the Venus–Earth space and thus enabling large-scale studies and longer forecasting horizons for several key transient parameters (e.g., Bz, momentum, speeds). In an exterior homoclinic orbit, the spacecraft traverses around the Sun externally to Venus’ orbit, both departing and returning to a Sun–Venus L2 orbit. Figure 8-46 shows an example of this orbit. Options that fall near resonance with Venus should be available. This orbit has obvious advantages for improving studies and space weather research in support of Mars exploration activities.

8.12.4.3. Upstream L1 Orbits Using Low Thrust

In this scenario, we exploit low thrust to shift the location of a spacecraft at L1 toward the Sun using conventional propulsion. We used a first-order dynamical model where the Sun and Earth are modeled as point masses, the Earth is assumed on circular orbit about the Sun, and all other gravitational forces are ignored.

Starting with a stationary spacecraft at L1, Figure 8-46 (left panel) shows that a thrust of just 0.3 mm/s^2 could shift the spacecraft to 2× the L1 distance (~3–10^6 km), thereby doubling the current forecasting horizon for solar transient impacts. The right panel of Figure 8-46 visualizes the trade space between thrust and spacecraft mass to achieve the required accelerations. In our example, a 500-kg spacecraft (i.e., similar to the STEREO spacecraft) requires only ~150 mN of thrust to reach 0.3 mm/s^2. Our architecture baselines rideshare-size spacecraft, (i.e., less than 300 kg). Therefore, such spacecraft could easily achieve orbits 2+ times further than L1 with minimal propulsion. If they carry adequate fuel, they may even be capable of cycler-type trajectories upstream of L1. The feasibility of this scenario requires a more detailed study.

8.12.5. Concept of Operations

FMT-12 adopts a straightforward concept of operations:

- The PeriGEON instruments are always on, acquiring data at synoptic steady cadences.

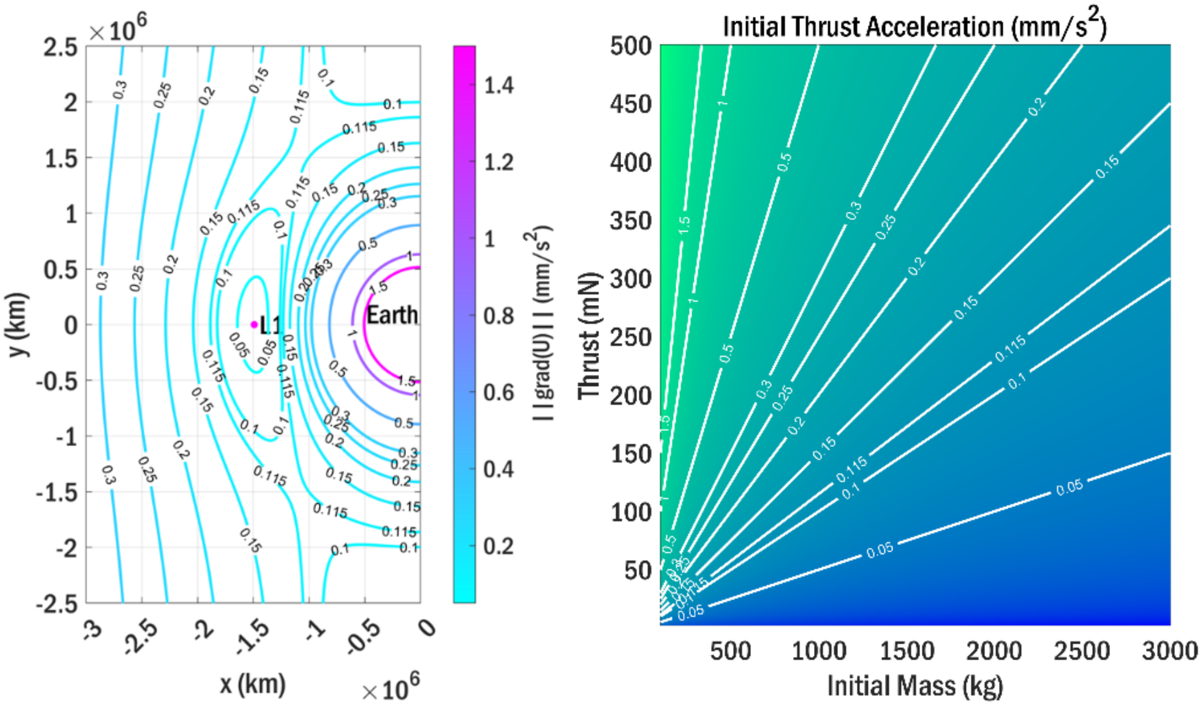


Figure 8-46. (Left) Contours of acceleration levels required to shift a spacecraft from L1. It takes only 0.3 mm/s² to reach twice as far from L1 (3–10⁶ km). (Right) Thrust versus spacecraft mass trade space to reach the required accelerations. A 500-kg spacecraft requires ~150 mN of thrust to reach 2× upstream of L1.

- Capability to use external trigger (e.g., flare detection above a predefined threshold by the spectral irradiance instrument) to initiate rapid cadence for particle measurements or other storm-specific data acquisition.
- Coordinate measurements during storms with the ground-based component.

8.12.6. Technology Development

We identified three areas where further technology development may be needed:

- **Adaptable instrument designs to meet both deep-space and geospace imaging requirements.** Adaptation may involve variable geometric factors, detectors with variable gains, adaptable data acquisition strategies and camera electronics, and other concerns.
- **Large dynamic range imaging systems.** Imaging of the solar wind and the magnetosphere from PeriGeospace vantage points will likely require optical systems capable of sensitivities beyond the current 14-bit capabilities. Twenty-bit images are available from the STEREO/SECCHI heliospheric imagers (requiring hours of exposures), but they are insufficient for imaging solar wind structures with sufficient fidelity around Earth because of the high albedo of the planet. Similar concerns arise for other imaging methods.
- **Onboard autonomy.** Mission operations of the FMT-12 constellation will likely be complex given the large number of spacecraft (6+) and the large expanse of space they cover. The

ability of the spacecraft to adapt their observing programs to the ambient conditions (e.g., switch to burst mode when an s shock or CME is crossing over them) will greatly simplify mission operations. If plasma probing via intra-satellite radio communications is implemented, then additional autonomy operations will be required to process the radio signals into higher-level products (e.g., Bz or density time series) before downlink to Earth.

Appendix A. List of Acronyms and Abbreviations

3DP	Three-Dimensional Plasma and Energetic Particle Investigation
AC10	AeroCube-10
ACE	APL Concurrent Engineering (Laboratory)
ACS	Attitude Control System
APL	Johns Hopkins Applied Physics Laboratory
APPS	Active and Passive Plasma Sounder
ASI	All-Sky Imager
AWS	Amazon Web Services
C&DH	Command and Data Handling
CAD	Computer-Aided Design
CBE	Current Best Estimate
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CHAMP	Challenging Minisatellite Payload
CIRBE	Colorado Inner Radiation Belt Experiment
CME	Coronal Mass Ejection
CoDICE	Compact Dual Ion Composition Experiment (IMAP instrument)
COR-HI	Coronograph-Heliospheric Imager
CREO	Charging and Radiation Environment Observatories
CSS	Coarse Sun Sensor
DC	Direct Current
DCA	Debris Casualty Area
DFGM	Digital Fluxgate Magnetometer (MMS instrument)
DMSP	Defense Meteorological Satellite Program
DSN	Deep Space Network
DTE	Direct to Earth
ECP	Energetic Charged Particle
EDP	E-field Double Probe
EELV	Evolved Expendable Launch Vehicle

EFW	Electric Fields and Waves (Van Allen Probes instrument)
ELV	Expendable Launch Vehicle
EMFISIS	Electric and Magnetic Field Instrument Suite and Integrated Science (Van Allen Probes instrument)
EMIC	Electromagnetic Ion Cyclotron
ENA	Energetic Neutral Atom
EOS	Earth Observing System
EPP	Energetic Particle Precipitation
ESA	Electrostatic Analyzer
ESD	Earth Science Division
ESPA	EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter
EUV	Extreme Ultraviolet
EUVI	Extreme Ultraviolet Imager
FC	Faraday cup
FGM	Fluxgate Magnetometer
FIPEX	Flux-Φ-Probe-Experiment
FMT	Focused Mission Topic
FOV	Field of View
FST	Focused Science Topic
FUV	Far Ultraviolet
GCR	Galactic Cosmic Rays
GDC	Geospace Dynamics Constellation
GEO	Geosynchronous Earth Orbit
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GOS	Geospace Observing System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
GSM	Geocentric Solar Magnetospheric

GTO	Geosynchronous Transfer Orbit
GTOSat	Geostationary Transfer Orbit Satellite
GW	Gravity Wave
HEO	High Earth Orbit
H-FORT	Heliophysics Flight Opportunities in Research and Technology
HFR	High-Frequency Receiver
HFWF	High-Frequency Wave Field
HGA	High-Gain Antenna
HMCS	Heliophysics Mission Concept Studies
HOPE	Helium Oxygen Proton Electron (Van Allen Probes instrument)
HPD	Heliophysics Division (NASA)
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMAP	Interstellar Mapping and Acceleration Probe
ITM	Ionosphere/Thermosphere/Mesosphere
KHI	Kelvin–Helmholtz Instability
KSAT	Kongsberg Satellite Services
LCAS	Low Cost Access to Space
LEO	Low Earth Orbit
LEOC	Low-Earth-Orbit Communication
LFWF	Low-Frequency Wave Field
LOS	Line of Sight
LPAG	Living With a Star Program Analysis Group
LRD	Launch Readiness Date
LSC	L-Shell Conjunction
LT	Local Time
LTE	Long-Term Evolution
LWS	Living With a Star
MAG	Magnetometer
MAVEN	Mars Atmosphere and Volatile EvolutioN

MCC	Midcourse Correction
MDL	Mission Design Laboratory
MEO	Medium Earth Orbit
MEV	Maximum Expected Value
ML	Magnetic Latitude
MLT	Magnetic Local Time
MLTC	MLT (Magnetic Local Time) Conjunction
MMC	Multiscale Mass Circulation
MMS	Magnetospheric Multiscale
MOC	Mission Operations Center
MoO	Mission of Opportunity
MP	Magnetopause
MPL	Mission Planning Lab
MPV	Maximum Possible Value
NASA	National Aeronautics and Space Administration
NEN	Near Earth Network
NESDIS	National Environmental Satellite Data and Information Service
NSF	National Science Foundation
NSN	Near Space Network
NSSL	National Security Space Launch
PAD	Pitch-Angle Distribution
PeriGEON	PeriGeospace Environment Observing Network
POD	Precise Orbit Determination
PSE	Power System Electronics
QMS	Quality Management System
RAAN	Right Ascension of the Ascending Node
REMS	Relativistic Electron Magnetic Spectrometer (GTOSat instrument)
REPT	Relativistic Electron-Proton Telescope (Van Allen Probes instrument)
RF	Radio Frequency

RN	Relay Network
RTLS	Return to Launch Site
SADA	Solar Array Drive Assembly
SCM	Search-Coil Magnetometer
SDO	Solar Dynamics Observatory
SDS	Science Data Stream
SELOS	Sun-Earth Line Observing System
SEP	Solar Energetic Particle
SH	Solar and Inner Heliospheric
SNOE	Student Nitric Oxide Explorer
SpaceX	Space Exploration Technologies Corp.
SPB	Sensor-Panel-Bias
SSA	Strategic Science Area
SSI	Solar Spectral Irradiance
SST	Solid-State Telescope
STEREO	Solar Terrestrial Relations Observatory
STORM	Solar-Terrestrial Observer for the Response of the Magnetosphere
STP	Solar Terrestrial Probes
SW	Solar Wind
SWaP	Size, Weight, and Power
SWARM-EX	Space Weather Atmospheric Reconfigurable Multiscale Experiment
SWx	Space Weather
SXR	Soft X-Ray
TDRSS	Tracking and Data Relay Satellite System
TEC	Total Electron Content
TESS	Transiting Exoplanet Survey Satellite
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TID	Total Ionizing Dose
TR&T	Targeted Research and Technology

TRL	Technology Readiness Level
TT&C	Telemetry, Tracking, and Command
TWTA	Traveling-Wave Tube Amplifier
UHR	Upper Hybrid Resonance
ULF	Ultralow Frequency
UV	Ultraviolet
VGA	Venus Gravity Assist
VIS	Visible
VSFB	Vandenberg Space Force Base
VSM	Venus Spacing Maneuver
WEBER	Whole Earth B-field Exploration and Reconnaissance
WFR	Waveform Receiver
XIR	X-Ray Irradiation
XRI	X-Ray Imager

Appendix B. Bibliography

Airapetian, V. S., V. Adibekyan, M. Ansdell, D. Alexander, T. Bastian, et al. “Reconstructing Extreme Space Weather from Planet Hosting Stars.” *Bull. AAS* 51, no. 3 (2019). https://baas.aas.org/pub/2020n3i564.

Barth, C. A., K. D. Mankoff, S. M. Bailey, and S. C. Solomon. “Global Observations of Nitric Oxide in the Thermosphere.” *J. Geophys. Res.* 108, no. A1 (2003): 1027. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2002JA009458.

Defense Meteorological Satellite Program (DMSP). SSJ4 webpage. https://dmsp.bc.edu/html2/ssj4inst.html.

Frisk, U., M. Hagström, J. Ala-Laurinaho, S. Andersson, J.-C. Berges, et al. “The Odin Satellite: I. Radiometer Design and Test.” *Astron. Astrophys.* 402 (2003): L27–L34. https://doi.org/10.1051/0004-6361:20030335.

Hu, J., V. S. Airapetian, G. Li, G. Zank, and M. Jin. “Extreme Energetic Particle Events by Superflare-Associated CMEs from Solar-Like Stars.” *Science Adv.* 8, no. 12 (2022). https://www.science.org/doi/10.1126/sciadv.abi9743.

Hudson, M. K., B. T. Kress, H.-R. Mueller, J. A. Zastrow, and J. B. Blake. “Relationship of the Van Allen Radiation Belts to Solar Wind Drivers.” *J. Atmos. Sol.-Terr. Phys.* 70, no. 5 (2008): 708–729. https://doi.org/10.1016/j.jastp.2007.11.003.

Knipp, D. J., B. A. Emery, M. Engebretson, X. Li, A. H. McAllister, et al. “An Overview of the Early November 1993 Geomagnetic Storm.” *J. Geophys. Res.* 103, no. 26 (1998): 26197–26220. https://doi.org/10.1029/98JA00762.

Koskinen, H. E. J., and E. I. Tanskanen. “Magnetospheric Energy Budget and the Epsilon Parameter. *J. Geophys. Res.* 107, no. A11 (2002): 1415. https://doi.org/10.1029/2002JA009283.

Leisner, J. “Explore Science: Distinguishing Solar Terrestrial Probes and Living With a Star Programs.” October 2020. https://www.nationalacademies.org/documents/embed/link/LF2255DA3DD1C41C0A42D3BEF0989ACAECE3053A6A9B/file/DC6C5A036F0D2838264493B2409CF1B03B5E79F064A1.

Living With a Star Program Analysis Group (LPAG). “Executive Committee (EC) Report.” December 31, 2019. https://lwstrt.gsfc.nasa.gov/assets/docs/lpag/LPAG_EC_report_2019_12_31.pdf.

Lyon, J. G. “The Solar Wind-Magnetosphere-Ionosphere System.” *Science* 288, no. 5473 (2000): 1987–1991. https://www.science.org/doi/10.1126/science.288.5473.1987.

Mertens, C. J., J. M. Russell III, M. G. Mlynczak, C.-Y. She, F. J. Schmidlin, et al. “Kinetic Temperature and Carbon Dioxide from Broadband Infrared Limb Emission Measurements Taken from the TIMED/SABER Instrument.” *Adv. Space Res.* 43, No. 1 (2009): 15–27. https://www.sciencedirect.com/science/article/pii/S0273117708002883?via%3Dihub.

Moore, T. E., K. S. Brenneman, C. R. Chappell, J. H. Clemmons, G. A. Collinson, et al. "Future Atmosphere-Ionosphere-Magnetosphere Coupling Study Requirements." In *Magnetosphere-Ionosphere Coupling in the Solar System*, AGU Monograph #222, Edited by C. R. Chappell, R. W. Schunk, P. M. Banks, J. L. Burch, and R. M. Thorne. Hoboken, NJ: John Wiley and Sons, 2017, p. 357.

Moore, T. E., W. K. Peterson, C. T. Russell, M. O. Chandler, M. R. Collier, et al. "Ionospheric Mass Ejection in Response to a CME." *Geophys. Res. Lett.* 26, no. 15 (1999): 2339–2342. https://doi.org/10.1029/1999GL900456.

Østgaard, N., G. Germany, J. Stadsnes, and R. R. Vondrak. "Energy Analysis of Substorms Based on Remote Sensing Techniques, Solar Wind Measurements, and Geomagnetic Indices." *J. Geophys. Res.* 107, no. A9 (2002): 1233. https://doi.org/10.1029/2001JA002002.

National Academies of Sciences, Engineering, and Medicine. *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment.* Washington, DC: The National Academies Press, 2020. https://doi.org/10.17226/25668.

National Aeronautics and Space Administration. "Heliophysics Living With a Star Program. Enabling Science, Technology, and Exploration to Advance Society: 10-Year Vision Beyond 2015." https://lwstrt.gsfc.nasa.gov/images/pdf/LWS_10YrVision_Oct2015_Final.pdf.

Parsay, K., K. Yienger, D. Rowland, T. Moore, A. Glocer, et al. "On Formation Flying in Low Earth Mirrored Orbits -- A Case Study. *Acta Astronaut.* 184 (2021): 142–149. https://doi.org/10.1016/j.actaastro.2021.04.005.

Sandhu, J. K., I. J. Rae, M. P. Freeman, C. Forsyth, M. Gkioulidou, et al. "Energization of the Ring Current by Substorms." *J. Geophys. Res. Space Phys.* 123, no. 10 (2018): 8131–8148. https://doi.org/10.1029/2018JA025766.

Sheese, P.E., K. Strong, R. L. Gattinger, E. J. Llewellyn, J. Urban, et al. "Odin Observations of Antarctic Nighttime NO Densities in the Mesosphere–Lower Thermosphere and Observations of a Lower NO Layer." *J. Geophys. Res. Atmos.* 118, no. 13 (2013): 7414–7425. https://doi.org/10.1002/jgrd.50563.

Space Exploration Technologies Corp. (SpaceX). "Rideshare Payload User's Guide." November 2020.

Wessen, R., C. S. Borden, J. K. Ziemer, R. C. Moeller, J. Ervin, and J. Lang. "Space Mission Concept Development Using Concept Maturity Levels." AIAA SPACE 2013 Conference and Exposition, September 10–12, 2013, San Diego, CA. https://doi.org/10.2514/6.2013-5454.

"Space Weather Science and Observation Gap Analysis for the National Aeronautics and Space Administration (NASA)." https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf.

Topputo, F., M. Vasile, and F. Bernelli-Zazzera. "Low Energy Interplanetary Transfers Exploiting Invariant Manifolds of the Restricted Three-Body Problem." *J. Astronaut. Sci.* 53, No. 4 (2005): 353–372. https://doi.org/10.1007/BF03546358.

United Launch Alliance. “Atlas V Launch Services User’s Guide.” March 2010. https://www.ulalaunch.com/docs/default-source/rockets/atlasvusersguide2010.pdf.

Waters, J. W., L. Froidevaux, R. S. Harwood, R. F. Jarnot, H. M. Pickett, et al. “The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura Satellite.” *IEEE Trans. Geosci. Remote Sens.* 44, No. 5 (2006): 1075–1092. https://trs.jpl.nasa.gov/bitstream/handle/2014/40951/05-0617.pdf?sequence=1.

Wertz, J. R., D. F. Everett, and J. J. Puschell, eds. *Space Mission Engineering: The New SMAD*. Microcosm Press, 2011.