High-Level 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 examined (but did not evaluate, as instructed) the current list of Strategic Science Area (SSA) goals and formulated a set of 12 Focused Mission Topics (FMTs) that together comprise a mission architecture that provides the scientific observations needed to make significant advancements on the 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 1). 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 (Figure 2). 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.

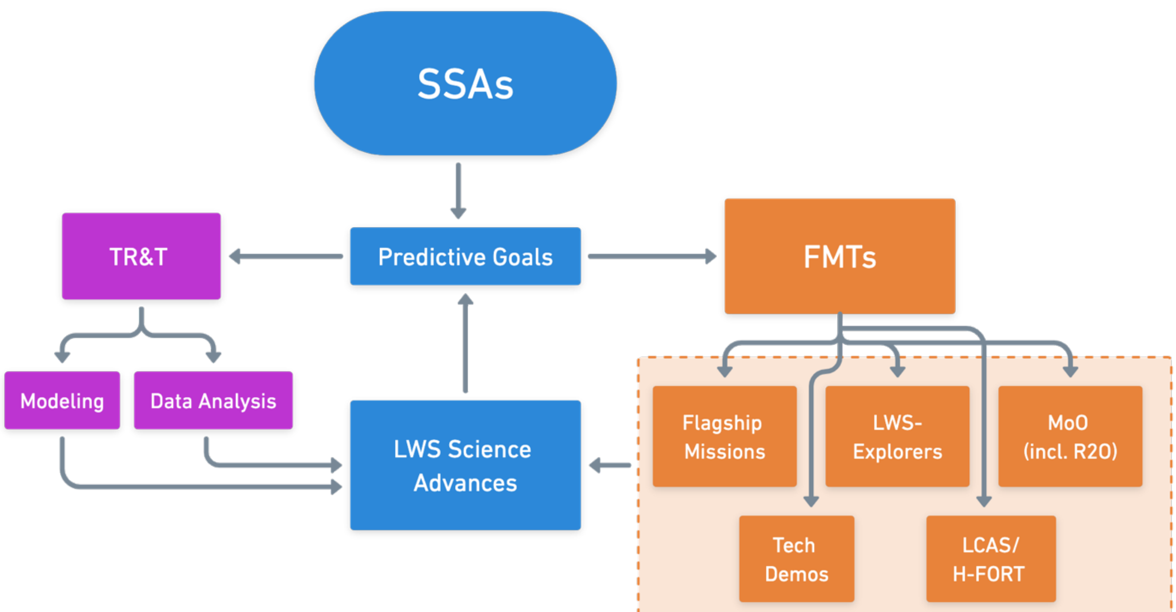

Figure 1. Flow chart illustrating the parallel relationship between the TR&T topics and FMTs. Both flow from the SSAs through the SSA Predictive Goals and subsequently flow down to modeling and analysis efforts (for TR&T) or specific mission designs (for FMTs). An FMT can be implemented within a variety 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.

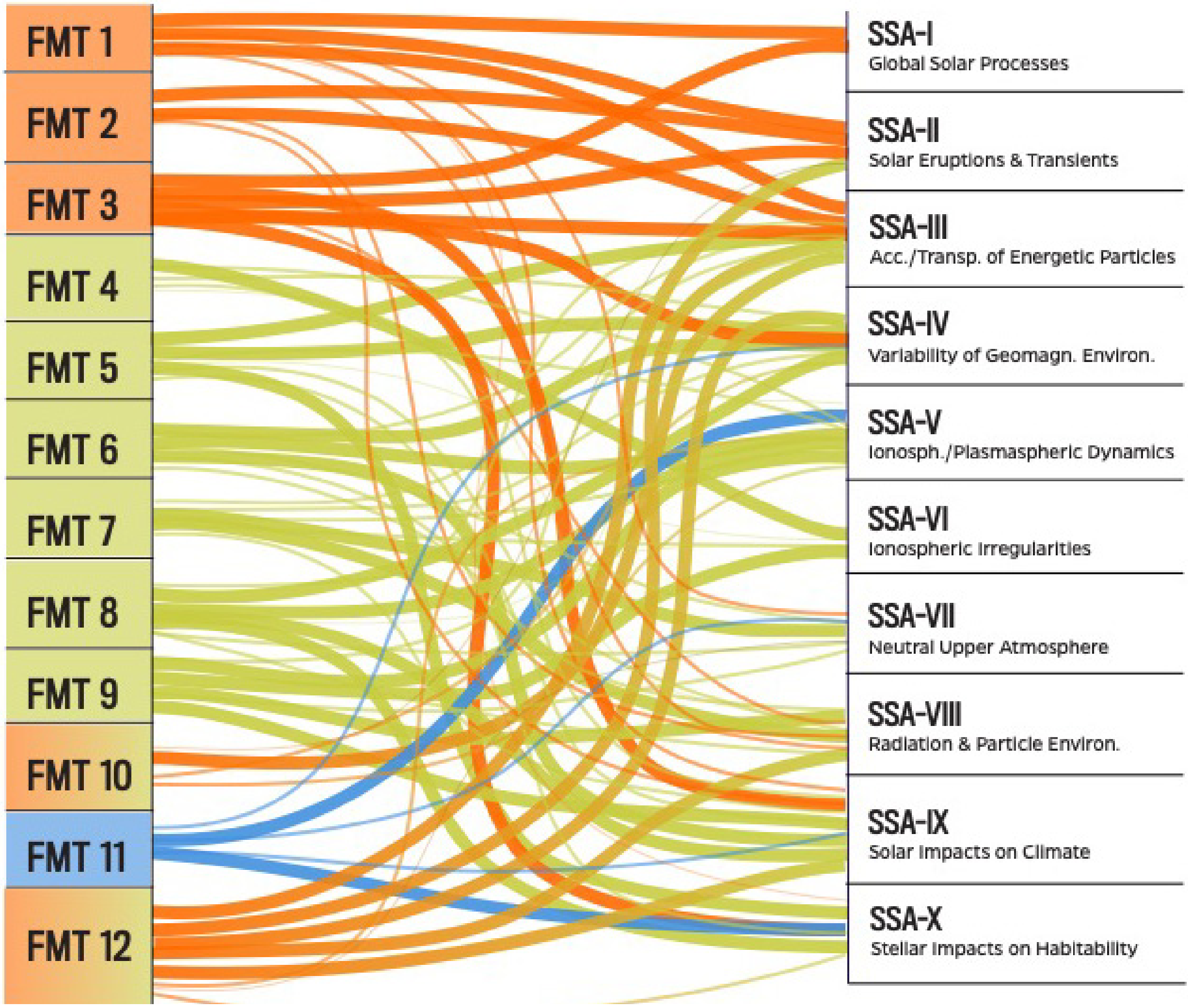

Figure 2. Mapping of the FMTs to the SSAs illustrates that most FMTs contribute to more than one SSA. Thick connection lines indicate direct contributions; thin lines indicate indirect contributions.

Given the numerous implementation options, the committee used the following criteria to compile the final list of 12 FMTs (as given in Table 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.

Table 1. List of FMTs.

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
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

HMCS, Heliophysics Mission Concept Studies

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 3). 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.

Example mission concepts for all the FMTs are summarized in Section 6 and described in more detail in Section 8 of the report. Seven 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. The seven design studies were done at the trade study level and

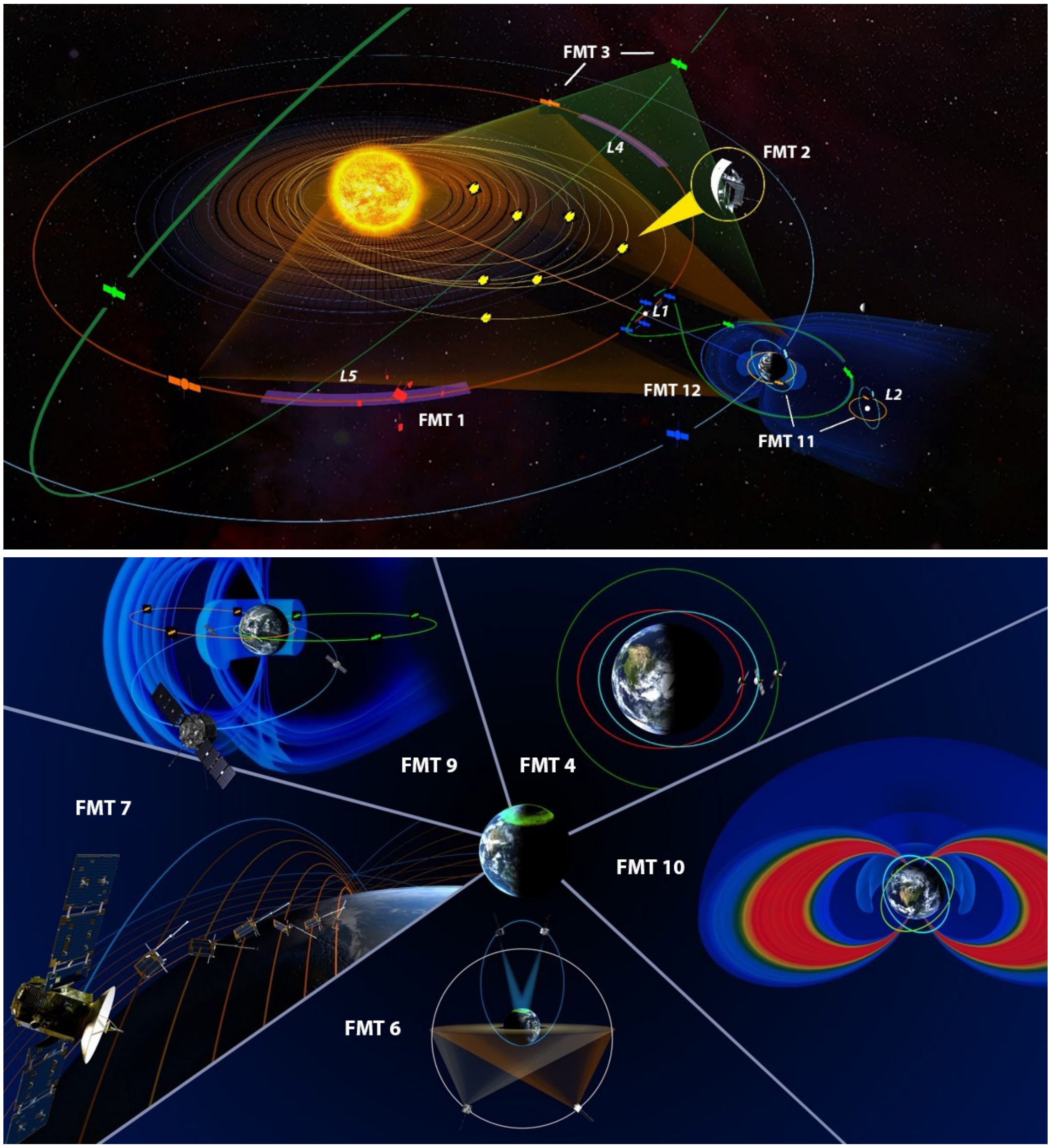

Figure 3. Graphical overview of the FMTs designed and studied for this report. (Top) Summary of the deep-space FMTs. (Bottom) Summary of the geospace FMTs.

thus require more detailed study if pursued as possible FMT implementations. 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.

There were several opportunities for the heliophysics community to provide feedback and comments to the committee during the process. These included a dedicated web-based forum, committee email, and multiple live presentations. Additionally, the committee accepted offered, and also solicited, input from experts in the community regarding specific science aspects related to the FMTs.

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. 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.

Specific recommendations for technology development are called out in the individual FMTs but also collected in Table 2. Among these needs are developments related to formation and coordinated flying; the data pipeline, both onboard and on the ground; inter-spacecraft and uplink/downlink communications; CubeSat/SmallSat capabilities in guidance, navigation, and control; and advanced propulsion technologies to enable non-Keplerian orbits and novel vantage points.

Table 2. Summary of recommended technology developments

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 radio frequency telemetry rates (Deep Space Network upgrades, CubeSat-Ka, etc.)

Instrumentation	Spacecraft Systems	Processes
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		

ENA, energetic neutral atom; TRL, technology readiness level.

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. 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.

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