2023 HEliophysics Strategic Technology Office (HESTO) Gap and Trend Analysis

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HESTO

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Preface

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Change History Log

Revision	Effective Date	Description of Changes
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1.0 Introduction

The HEliophysics Strategic Technology Office (HESTO) is tasked with guiding future investments in technologies relevant to Heliophysics to enable breakthrough science. To understand the future needs of the Heliophysics community, HESTO shall provide a regular report on technology gaps and trends. This is the first such report. It was developed over a period of six months by considering publicly available documents and summarizing their findings. The authors hope this report will be useful to the Heliophysics Technology Program and reflects the current needs of the community. Future reports will be further enhanced by soliciting community input.

1.1 Approach and Statement of Task

The following statement of task was developed to guide this report.

New discoveries in the field of Heliophysics require new measurements which depend on the ability to produce novel and transformative technologies, capabilities, and mission concepts. The Heliophysics Division (HPD) has formed an integrated technology program to strategically manage investments in instrument and mission technology development, to maximizing the return on investment and ensuring future capabilities meet Heliophysics science goals defined by the decadal surveys. NASA science missions are engines of innovation, leveraging innovative technologies to solve scientific problems. These technologies enable and advance space missions of the future, and yield benefits to the broader space business and consumer economy (e.g. Space Weather prediction). A yearly gap and trend analysis of technology development needs will enable strategic and targeted technology funding.

1.1.1 Scope

A Heliophysics gap analysis working group shall be composed of experts representing NASA, academia, and the commercial sector. The working groups analysis will include the tasks listed below.

- Assessment of the current state of NASA's measurement capabilities to address the science needs of the Heliophysics Division.
- Identification of high-priority measurements that are at risk of becoming unavailable or not currently available but are required to significantly advance the science of Heliophysics.
- The outcome of this working group shall be a report of no greater than 20 pages, listing at most ten high-priority measurement and platform technologies that require investments to enable breakthrough science results in Heliophysics.

It must be noted that the working group for this report is solely composed of representatives from NASA's Goddard Space Flight Center. This was due to the timing of funding availability which made it difficult to fund non-NASA working group members. This issue will be addressed by the next report.

1.1.2 Work Plan

The working group shall meet at least weekly to discuss progress and coordinate work. Coordination and recurrent communications during the study with the HPD are expected. The report may be publicly released after consultation and coordination with the HPD.

1.1.3 References

The following references shall be used to inform the gap and tend analysis as directed by HPD.

- Space Weather Science and Observation Gap Analysis for NASA

- Decadal LWS Architecture studies and documentation
- Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033 white papers
- Heliophysics 2050 Workshop: Measurement Techniques and Technologies white papers
- Heliophysics Mission Concept Studies (HMCS) ROSES projects and associated Goddard concepts MagCon and CMO

1.2 Report Organization

The structure of this report is as follows. It begins by summarizing the scope and findings of the reference documents. The following section then describes how the findings for all reports were prioritized. Finally the list of prioritized technology gaps is provided including platform technologies which are provided as their own section.

2.0 Summary of Reference Documents

The panel considered the reference documents listed in Section 1.1.3 References when performing this gap analysis. No other sources were considered. This section provides a short summary and description for each source as well as a summary of the technology gaps identified by the source authors.

2.1 Helio2050 Measurement Techniques and Technologies Workshop (Helio2050MT&T)

The Heliophysics 2050 Measurement Techniques and Technologies workshop (Helio2050MT&T) took place between February 23–25, 2022. This follow-on from the Heliophysics 2050 Workshop focused on Heliophysics science goals and objectives. The objective of the Helio2050MT&T workshop was to determine what technological advancements are needed to enable the scientific vision discussed in the Heliophysics 2050 workshop to enable transformative science. Organizers aimed to inform the community, NASA, and the Solar and Space Physics Decadal Survey by:

- Identifying experimentation and technology gaps that must be closed to achieve the scientific vision laid out in the Heliophysics 2050 workshop
- Identifying essential and missing measurement technologies necessary for significant advancements in solar and space physics
- Developing strategies to create an efficient pipeline of technology investment to benefit long-term research goals.

The workshop made publicly available one page summary white papers as well as e-posters. The workshop received 59 white papers from 44 authors representing 17 institutions. The panel read each white paper and categorized them into the following

- Mission Platform (Space-based, ground-based, sub-orbital, or other)
- Science Area (ITM, Solar Science, Magnetosphere, Heliosphere)

Papers were allowed to fall into multiple categories. Most white papers could be identified with ITM (49%), Solar (39%), Magnetospheric (37%), Heliospheric (27%), and Space Weather (7%) science. Most white papers targeted space-based measurements (73%) with a smaller sub-set associated with ground-based technologies (17%) or sub-orbital capabilities (7%). The panel also summarized the measurement type described in the white paper and whether the author(s) identified a clear technology maturation need. Approximately half of the papers identified technology needs. A number of mission platform technology needs were also identified.

2.2 Space Weather Science and Measurement Gap Analysis for NASA

The Space Weather Science Application Program within NASA's Heliophysics Division commissioned The Space Weather Science and Observation Gap Analysis report in response to the 2013 National Academies of Science, Engineering and Medicine Decadal Survey for Solar and Space Physics and the actions delineated in the 2019 National Space Weather Strategy and Action Plan. Johns Hopkins University Applied Physics Laboratory (JHU/APL) compiled the report between September 2020 and April 2021. The technical leads on the report were Angelos Vourlidas and Drew Turner, both of JHU/APL. These leads also chaired the report committee consisting of space weather experts from academia, the commercial sector, and the space weather operational and end-user community.

The committee's analysis was confined to the following two tasks:

- Assessing the current state of NASA's observational capability to address the science of space weather and NASA's capacity to provide data input that significantly advances forecasting and nowcasting capability
- Identifying high-priority observations that are at risk or not currently available that are required to significantly advance forecasting and nowcasting capability

The report follows the standard plan of a gap analysis (i.e., focus area, current state, desired state, gap, plan of action). They identified the scope of the analysis: NASA observing capability to advance space weather (SWx) forecasting/nowcasting and the set of specific SWx hazards for which improved fore/now/hindcasting (*-casting, hereafter) are desired. They also summarized the SWx users' needs regarding the degree of *-casting accuracy for the various SWx hazards and used this information to aid in identifying and prioritizing gaps.

The report's main conclusion is that space weather understanding, awareness, and predictions can primarily be advanced by using existing measurement technologies on an expanded network of space weather observatories, in various strategic orbits around the Earth and Sun [SPWGA-pg130], primarily in deep space.

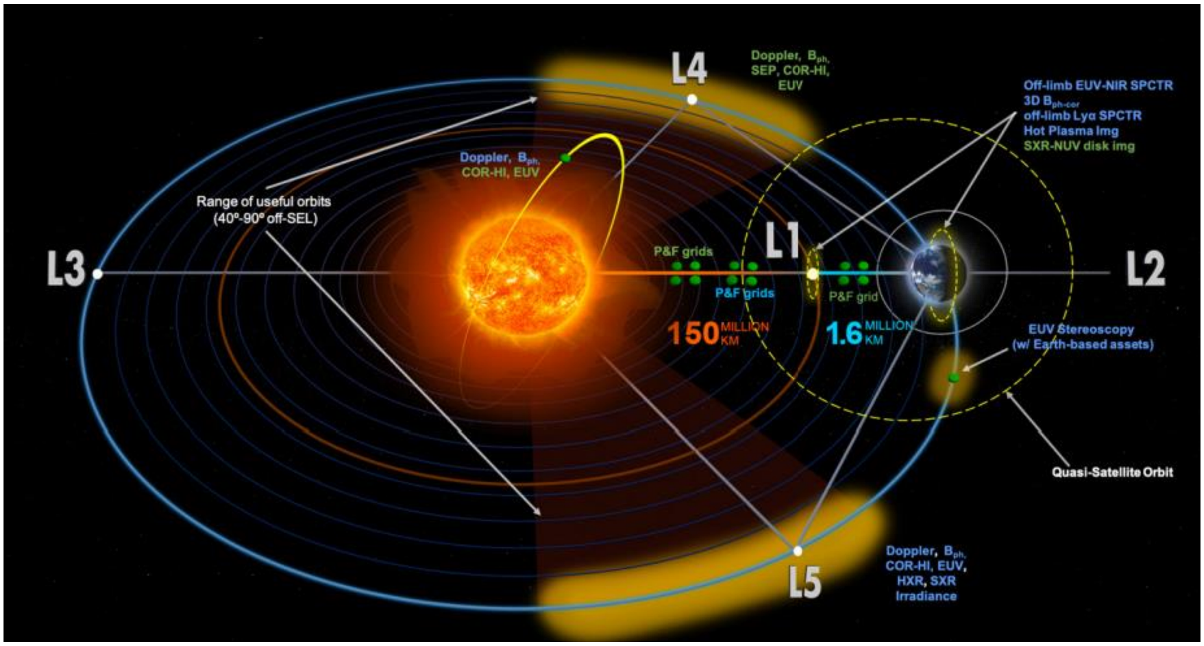

Figure 1: Visual representation of the locations and types of measurements required to lead to closure for several SWx research and forecasting issues.

The report does not define specific mission concepts which would combine all required measurements on platforms in specific orbits.

In addition, the report uncovered a few areas where novel measurement approaches could potentially lead to leaps in *-casting. They are listed in Table 6-5 with blue text and reproduced below. The report characterized these approaches with three priorities from most to least consequential (Close, Advance, Improve). Note that some acronyms were expanded in this version to make it more readable. A technology gap assessment from this panel is also provided in the right-most column.

id	Measurement	New Technology Assessment
Improve		
I3	Multipoint (grid) in-situ particles & fields, upstream of L1 (within 0.9 AU) *Direct impact to SWx forecasting accuracy; critical for model validation; novel science capability for transients*	Implies propulsion technology to achieve and maintain orbit and sensor miniaturization if on small satellites.
I12	EUV on-disk solar stereoscopy (2° to 10°angular separation) *Pre-eruption magnetic topology; flare/CME prediction*	Propulsion technology to maintain Earth-trailing orbit. Existing EUV imagers are sufficient.
Advance		
A2	Radially distributed (0.7 to 1 AU) in-situ particle and fields in the heliosphere *Combined I4, I2, I3 variant, focused on IP transport*	Implies propulsion technology to maintain orbit and sensor miniaturization if on smallsats.
A6	High Signal to Noise (SNR) Off-limb Ly-alpha spectroscopy for remote sensing of "seed" solar particles (for high-energy SEPs)	Proof of concept measurement described in J. Martin Laming et al 2013 ApJ

	Remote sensing of "seed" particles; potentially important for space exploration	770 73, DOI 10.1088/0004-637X/770/1/73. Instrument development required (current TRL-2 or TRL-3)
Close		
C1	4π coverage of vector magnetic field in the photosphere + Doppler + EUV disk + Visible light imaging > 20 Rsun *Closes most critical gaps on solar drive inputs for geospace and space exploration*	Implies propulsion technology to achieve and maintain orbit. No new sensor technologies needed.
C2	3 off-Sun-Earth-Line (120 deg apart) visible light imaging > 20 Rsun + off-ecliptic visible light imaging to > 80 Rsun + 67% coverage of LOS Bphot + strategically distributed in-situ particles and fields *C1 variant focused on IP and SEP propagation and space exploration*	Implies propulsion technology to achieve and maintain orbit. No new sensor technologies needed.
C3	Multi-height solar vector magnetic field measurements *Possible closure on eruption energetics and hence eruption prediction (hours to minutes); critical for space exploration*	Multiple approaches and technologies possible and needed
C4	Full-spectrum Solar Spectrum Irradiance (0.1 to 200 nm at 0.1 nm resolution) with good accuracy (< 20%) over solar-cycle time scales. *Near closure for solar irradiance input to atmospheric models*	May benefit from self-calibrating detectors

Table 1: Measurement gaps identified in the Space Weather Science and Measurement Gap Analysis for NASA

2.3 Living With a Star Architecture Committee Report

The Living With a Star (LWS) Architecture Committee included 10 expert members 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 providing the scientific observations needed to make significant advances toward the LWS Strategic Science Area (SSA) goals and related objectives.

Seven of the mission concepts were studied by the design centers at JHU/APL and Goddard (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. For each FMT the Report provides a complete set of science objectives, a possible implementation, and necessary technology developments for the mission to become implementable. The missions and their technology needs are listed in Table 2.

2.4 STP HMCS Reports

The following sections summarize the reports of STP mission concepts that were made available by HPD to the working group.

2.4.1 STP-Magnetospheric Constellation (MagCON)

The magnetopause is the entry point for solar wind energy into Earth's magnetic field. This energy leads to many forms of space weather, including aurora, geomagnetic storms, and energization of the Van

Allen radiation belts. However, the amount of solar wind energy, its disposition within the magnetosphere, and its coupling to the ionosphere are not well quantified. Single-point or tightly clustered in-situ measurements are insufficient for unraveling the multiscale dynamics that are central to solar wind driving the magnetospheric response. The next step in understanding magnetospheric dynamics is to explore the mesoscales, the intermediate scale in between the kinetic and global. This fundamental size scale of mass, momentum, and energy transport, is the weakest link in our chain of understanding.

The Magnetospheric Constellation Mission is a constellation mission of spinning in-situ spacecraft with particles and magnetic field instrumentation. Note that this is the same mission concept as studied by the LWS panel known as FMT-7. The science objectives are met with a constellation of 36 spacecraft collecting data from ~5Re to ~18 Re with azimuthal separation at apogee of <1 Re.

Technology Needs

The STP report does not provide any self-assessed technology needs. The instrumentation for each spacecraft is already available. The LWS study does mention two technology needs (1) Mass manufacturing and cross-calibration and (2) Streamlining ground operations to handle 36 spacecraft.

2.4.2 STP-Firefly (formerly known as 4π-Helios)

Magnetism is the fundamental driver to most solar and stellar physics phenomena and how stars interact with planetary environments. The Sun's magnetic field is generated by dynamo processes in the interior and at the surface. They generate space weather activity that is crucial to understanding planetary habitability. A single viewpoint of observations from the Sun-Earth line is a severe limitation to observational coverage of the solar magnetic surface, including the solar poles which are critical for understanding the solar dynamo. Firefly is a mission concept designed to provide both remote sensing and in situ observations of the Sun and heliosphere from a full 4π-steradian field of view. The overarching goal of this mission concept is to understand the global structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona as it creates the heliosphere.

The Firefly concept consists of four inner heliospheric spacecraft with both solar remote sensing and in-situ instrumentations. Two spacecraft will be parked at the Sun-Earth L4 and L5 Lagrange points, and the other pair will orbit the Sun 70° out of the ecliptic. This approach will provide simultaneous observations from multiple vantage points, enabling a continual and global 4π-steradian coverage of the Sun over much of a solar cycle.

Technology needs

The STP report does not provide any self-assessed technology needs and states that all instrument designs are already high TRL. The report does mention areas that would benefit in investment which would increase the capabilities of the mission. Firefly would benefit from high-performance communication systems, which allow more science data return and smoother operations. The mission would also benefit from technology development of the propulsion system, which would shorten the time for circularizing the orbits of the polar spacecraft.

2.4.3 STP-Coronal Microscale Mission (CMO)

The question of why the Sun has a tenuous upper atmosphere some 1000 times hotter than the photosphere remains fundamental in space plasma physics despite decades of study. Current instrumentation cannot resolve the structure or make out the mechanism(s) of heating in the solar corona. One theory is that coronal heating is confined to narrow current sheets with a characteristic width of 100 km in which energy is dissipated despite the low resistivity of the coronal plasma. The solar wind also originates in energization events in the solar corona. The consensus view is that many types of solar wind exhibit different plasma characteristics which encode how those types of solar wind likely formed. Different types of solar wind result from the time-history of solar wind formation, how it was heated in the low corona, how it was released into the heliosphere, and how it continues to be accelerated and heated through the middle and high corona. High resolution imaging in the solar corona would enable two important science goals, (1) What are the basic properties of primary heating events in the solar corona? (2) What is the role of primary heating events in the formation of the solar wind?

The Coronal Microscale Observatory (CMO) consists of three spacecraft flying in a precise formation. The first and last spacecraft are separated by 200 m, with a spacecraft in between them. This configuration allows for a multiband EUV telescope with a 100 m focal length providing resolution down to 16 milli-arcsec using novel photon sieves. The middle spacecraft carries a full-disk occultor in addition to the EUV detectors with the coronagraph being hosted on the last spacecraft. The requirements for knowledge of inter-spacecraft separation (±15 mm) and transverse alignment (±0.5 mm) are met with a precision 3D laser ranger and astrometric alignment system. CMO will be located in a large-amplitude quasi-halo orbit around the Sun-Earth L1 point, to provide an uninterrupted view of the Sun and a low-gravity environment conducive to formation flying.

Technology needs

The authors identify the following needs:

- Precise formation flying with 100 km separation and knowledge of spacecraft separation +/-15mm and transverse alignment of +/-0.5 mm
- Refinement of photon sieve technology. A single photon sieve is due to fly on VISORS in 2024.

2.4.4 STP-InterMeso

The InterMeso concept is a multi-spacecraft mission to untangle dynamic mesoscale structures (0.5 Mkm to tens of Mkm) and dynamics throughout the heliosphere, which have not been adequately observed to date. These scales are crucial for understanding the connections between the solar corona and the heliosphere, and for understanding particle acceleration, evolving magnetic-field structure, and inhomogeneities in composition and acceleration of solar wind plasma. InterMeso's science goals are to (1) Characterize and identify the origins of the mesoscale variability of the background and transient solar wind and (2) Characterize and understand the impact of these mesoscale variations on particle acceleration and transport.

InterMeso is a constellation of four spacecraft in Earth-trailing heliocentric orbits near 1 AU, using high-heritage (at or above TRL 6) architectures and instrumentation. Because the spacecraft will automatically drift apart with time, measurements will span the range from microscale to macroscale properties. The instrumentation on each spacecraft consists of a Faraday cup (plasma density, velocity, and temperature), SPICES (thermal ion composition), SIS-Lo (suprathermal ion composition), SIS-Hi (energetic ion composition), 2 SPAN-E (low-energy electron distribution function), MEPS (energetic electron distribution function), 2 fluxgate magnetometers on a boom (vector magnetic fields), SWAVES (AC electric fields and radio), STIX (hard X-ray imaging, on one spacecraft only).

Technology needs

The authors identified only one technology development need. SPICES is below TRL6 due to its high voltage power consumption, but development is currently funded though not complete. It's science goals are to (1) identify and quantify the key processes that govern mass and energy exchange between the ionosphere and magnetosphere (2) discover the pathways and processes governing cold plasma mass transport though and out of the inner magnetosphere and (3) determine how, where, and when cold plasma acts most efficiently to regulate coupling between magnetospheric regions and between plasma populations.

2.4.5 STP-Plasma Imaging Local and Tomographic experiment (PILOT)

The PILOT concept is a multi-spacecraft mission to provide multi-scale measurements of the magnetosphere to answer open questions about the mass and energy flow processes. Cold plasma (< 1 eV to 100 eV) carries the majority of the mass yet understanding its flow is lacking and key to understanding of Earth's magnetospheric dynamics. PILOT's science objectives are to (1) identify and quantify the key processes that govern mass and energy exchange between the ionosphere and the magnetosphere (2) Discover the pathways and processes governing cold plasma mass transport through and out of the inner magnetosphere (3) Determine how, where, and when cold plasma mass acts most efficiently to regulate coupling between magnetospheric regions and between plasma populations. PILOT achieves these objectives by using radio tomography and EUV imaging supported by in-situ measurements of cold ions and electromagnetic fields.

PILOT consists of 3 sets of spacecraft with different instrument suites for a total of 34 spacecrafts. A set of 30 identical (small) spacecraft in two near-equatorial highly elliptical orbits perform radio tomography to determine the total electron content. They transmit dual frequency radio signals from each satellite to the other satellites. The relative phase delay determines the total electron content along the line of sight between the spacecraft. They also measure in-situ magnetic fields, total density and energetic electron flux. The remaining 4 spacecraft (2 inner, 2 outer) spin to sample in-situ electromagnetic fields, ion and electron distributions, cold ion distribution functions and composition, and total density. The 2 spacecraft carry EUV cameras to image He+ and O+ ions.

Technology needs

The authors identified two instruments that require maturation. The radio tomography/relaxation sounder is self-assessed as TRL 4. This technique has been used in ionosphere for GPS signals but has not yet been demonstrated in the plasmaphere at the required frequencies. Current spaceflight-compatible chip scale atomic clocks do not currently have the accuracy and stability ($\sim 10{-}12$ s) to support PILOT. The primary issue is to deliver sufficient power to the antennas during transmission over the mission lifetime.

The EUV camera system which images He+ at 30.4nm (EUV-He) and O+/O++ at 83.4nm (EUV-O) is self-assessed at TRL 5 and requires development efforts to qualify the partial-aperture filters, and the mirror coatings applied to flat SiO2 substrates.

2.4.6 STP-Magnetosphere-Ionosphere Observatory (MIO)

MIO addresses unsolved scientific questions about the physics of energy flow and cause and effect within the interconnected magnetosphere-ionosphere system. MIO will determine the coupling between these two systems by directly sending electron beams down the magnetic lines to be measured on the ground using ground-based optical network. The four specific science goals of MIO are to: (1) determine to what regions in the magnetosphere the various auroral forms and the various ionospheric phenomena map (2) determine to where in the ionosphere magnetospheric regions, boundaries, and events map (3) determine what in the magnetosphere produces the various auroral forms and ionospheric phenomena and (4) determine in what ways the magnetosphere drives field-aligned currents.

The MIO mission concept is to fly a relativistic-electron accelerator on a primary spacecraft in the equatorial nightside magnetosphere. The accelerated electron beam can fired into the atmospheric loss cone to deposit electrons in the atmosphere to optically illuminate the magnetic footpoint. Besides the accelerator, the primary MIO spacecraft also hosts a plasma contactor to offset charging impacts of firing the accelerator, an electron drift instrument, a fluxgate magnetometer, and electric field waves instrument to understand the environment that the electrons are being accelerated in. The 4 daughter craft are spin-stabilized spacecraft hosting a magnetometer and electrostatic analyzer on each.

Technology needs

The authors identify the electron accelerator as being TRL 4 and therefore needing maturation. They identified some major areas of tech development needed for the accelerator. This includes the RF cavity design and thermal management. During operation, the RF copper cavities will heat and expand shifting the resonance which would lead to loss of energy gain. The electron injector design must be able to supply 300 W of peak power at 10 to 15 kV. Maturation of High electron mobility transistors (HEMTs) is also needed. Finally, beam transport design and tuning approaches are also required.

2.5 Summary

The following table provides a summary of the mission concepts described above as well as the technology needs identified by those studies.

Mission Concept name	Number of spacecraft	Orbit	Self-assessed technology need
FMT-1	10 (2 ESPA-class hub spacecraft with up to 4 8U spokes)	L4 and L5	• Deep-space cubesats (propulsion, guidance, subsystem reliability), • Deep-space cubesat delivery system, Inter-satellite communications/operations, • Onboard autonomy
FMT-2	7-9	0.4 x 0.9 AU orbits	• Onboard autonomy, Constellation operations
FMT-3 or STP-Firefly	4 (2 pairs)	1 pair 180° apart orbiting at 90°from Earth, 1 pair out of ecliptic	• Deep-space optical communications • High-performance ion engines
FMT-4	3	Earth-orbiting 800 km and 15° inclination, 600 x 250 km with 15° inclination	• In-situ instruments for electron, ions, and neutral density, ion and neutral composition, plasma drift and neutral wind, electric and magnetic field, and radio transceiver • Remote sensing instruments for neutral wind profile (e.g. O THz scanner), electron density profile and plasma bubble imaging (far ultra-violet

			scanning spectrograph imager), neutral gravity wave (OH band imager)
FMT-5 or STP-MagCon	36	Earth-orbiting 12 at 8.24 Re, 12 at 10.79 Re, 12 at 15 Re - all low inclination	• Mass manufacturing and cross-calibration • Ground operations need to be streamlined with 36 spacecraft
FMT-6	4 (2 pairs)	1 pair at 6.1 Re 1000 km apogee 82° inclination, 1 pair at 6.1 Re 82° inclination	• Instrument miniaturization • ENA remote sensing of magnetotail mesoscale structure and fast flow at timescale <=10 minutes
FMT-7	28 (4 motherships with 6 cubesats each)	LEO 600 km	• 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 profile (e.g. O Thz scanner, far ultra-violet scanning spectrograph imager and NO 5.3 µm limb scanner)
FMT-8	3	1 at High-inclination 20 Re orbit, and 2 in 11-hour equatorial GTO-lioke orbit (5.8 Re x 1.1 Re)	• Orbital acquisition and calculations of delta v • Merging bus capabilities for common bus design • Single vs multiple launches
FMT-9	2	GTO-like geosynchronous transfer orbits	• In-situ instruments for energetic electron and ion measurements from cold plasma to ring current (1 keV to 1 MeV) to relativist particles in the inner and outer radiation belts (1-10 MeV and up to 1 GeV/nuc ions) • DC magnetic field instrumentation • AC electric field and magnetic field instrumentation • Spacecraft charging instrumentation
FMT-10	2+	LEO 98 deg inclination	• Inter-spacecraft communication design/operations • Continuous measurement of NOx between 60 to 150 km • Simultaneous measurement of energy input to the upper atmosphere and the impacted atmospheric composition, wind, and temperature
FMT-11	2+ or 4+ - Two concepts	LEO	• Active potential control of the spacecraft • Cold plasma measurement technique
FMT-12	9+	2 to 4 at L1, 1 or more spacecraft orbiting between L1 and Earth	• Inter-spacecraft communications design/operations • Large dynamic range imaging systems

STP-InterMeso	4 (identical)	Earth-trailing heliocentric orbits near 1 AU	• High voltage power supply
STP-CMO	3	large-amplitude quasi-halo orbit around the Sun-Earth L1 point.	• Precision formation flying • Improvement of photon sieves
STP-Firefly	4	1 pair 180° apart orbiting at 90°from Earth, 1 pair out of ecliptic	• High Performance deep space communication systems. • Propulsion system improvements
STP-PILOT	34 (30 smallsats + 4 spacecraft)	18 outer orbit, 16 inner orbit Inner: 1.52 RE × 4.25 RE and Outer: 1.10 RE × 6.25 RE	• Radio Tomography (TRL 4) • EUV Camera (TRL 5)
STP-MIO	5 (1 primary spacecraft and 4 daughter craft)	4.3 x 9 Re, 24 hour orbit with < 5 degree inclination	• Electron accelerator (TRL 4) ○ RF cavity design and thermal management ○ Electron injector (gun) design and operation including high peak power high voltage power supply ○ All-solid-state RF system ○ Beam transport design

Table 2: Mission summaries for both LWS and STP concepts and technology needs identified

3.0 Technology Priorities

The goal of this report is to identify the top sensor and platform (or spacecraft) priorities. This section describes the priorities identified by the authors. Sensor and platform technologies are prioritized separately. Section 4 describes how prioritization was performed. In short, higher priority was given to technologies that have wide applicability or a large science impact, or both.

3.1 Sensor Technologies Priorities

High Priority –

- **Remote sensing of coronal magnetic fields** – Enables new understanding of solar – heliospheric – magnetospheric connections. Promises to enable more accurate space weather predictions and provide new understanding of solar wind acceleration and eruption initiation.

Medium Priority –

- **Remote Sensing of Neutral Winds in the Upper Atmosphere**
  - **Lidar** – Allows the measurement of neutral winds. Opens up significant new science.
  - **NO Sensor** – Currently unavailable technology with the promise of significant scientific return, but limited to a narrow, focused subject area. Possible space weather implications.
  - **THz imager** – improve size, weight, power, and cost needed.

- **High voltage power supply** – Enables sensor miniaturization across many in-situ sensor types including charged particle detectors and solar ENA detectors. Miniaturization of in-situ sensors is a major gap which, if available, would enable many of the missions identified here.

No low priority sensor gaps were identified in this study.

3.2 Platform Technology Priorities

High Priority –

1. **Spinning Platforms** – Many science objectives in Heliophysics require in-situ measurements over all angles with respect to the solar wind. The loss of this capability by industry partners would significantly impact the Heliophysics community.
2. **Technologies that enable deep space missions** – Many new mission concepts require spacecraft in deep space (non-low-Earth orbits). Technology maturation is required in a variety of areas to enable these mission concepts.

Medium Priority –

3. **Spacecraft Autonomy** – As missions concepts trend toward larger constellations combined with missions operating far away from Earth, for spacecraft need to be able to operate without constant ground contacts, which may be expensive and too frequent.

3.3 Sensor Technologies

3.3.1 High Priority

Remote Magnetic Field Measurements of the Corona

Science Areas: Solar Science, Space Weather

The low pressure of the corona means that the magnetic field constrains the structure of plasma in the inner corona (below 1.5 Rsun). Measuring magnetic field direction and strength is thus critical for understanding the fundamental physical processes of energy build up, storage, and release throughout the solar corona. The coronal field can be estimated by extrapolation from the photospheric field, which has been routinely measured from the ground and space for decades but usually only the line-of-sight component. For best results, the full vector photospheric field is needed. For the Solar Dynamics Observatory Helioseismic and Magnetic Imager, good measurements are usually only possible for active regions. For large-scale structures relevant to CMEs and the solar wind, accurate extrapolation requires fields measured over more than the visible face of the Sun: at least the region beyond the Sun's east limb (SWx Report 5.1.1.2) for potentially geoeffective structures, and preferably the entire 4π surface (HMT-4060).

A more accurate method for extrapolating the magnetic field is to combine photospheric field measurements with those from the chromosphere. The complex coronal magnetic field within active regions is particularly important for predicting the southward component of CME magnetic fields, which affects space weather impacts (SWx report, 5.1.1.7). It is also needed for assessing pre-flare and pre-eruption magnetic topology (SWx report, 5.1.2.1) and measuring coronal currents that are factors for flare prediction (SWx report, 5.1.2.2). Chromospheric magnetic field measurements have been attempted with the CLASP sounding rocket experiment, and orbiting instruments would allow routine mapping of the chromospheric magnetic field (HMT-4051). Such a mission will enable additional science, including the measurement of the Alfven wave flux through the chromosphere, the braiding of magnetic field lines, and propagation and mode conversion of waves. A mission with two vantage points, such as L4 and L5, would be critical for diagnosing the complex magnetic topology of the chromosphere.

Magnetic field strengths in the corona are estimated to be in the 10-100 G regime and are difficult to measure directly. The Zeeman effect can yield line-of-sight magnetic field measurements for coronal lines in the infrared observed above the limb and is expected to be exploited with DKIST. Oscillations of coronal infrared lines can also be used to infer the off-limb coronal magnetic field, as has been performed using Coronal Multi-channel Polarimeter (CoMP) data. An approach that has not been attempted yet is to measure the magnetic field using the Hanle effect applied to hydrogen Ly-alpha above the limb [HMT-4053]. Unlike the Zeeman effect, this method yields both the magnitude and direction of the magnetic field, and it is sensitive to typical field strengths of 10-100 G. An advantage over the Zeeman effect technique is that a relatively small telescope collecting area is required. Multiple vantage points potentially allow measurement of the full vector magnetic field in the corona [HMT-4058].

The magnetic field strength and direction in CMEs are perhaps the most important parameters for assessing the space weather impacts of CMEs [SWx report, 5.1.1.7], and would provide the most robust improvement for "all clear" space weather forecasts [SWx report, 5.1.1.1]. These parameters can be measured close to the Sun by the methods outlined above. Due to the large-scale structure of CMEs, multiple vantage points are preferable for accurately measuring the coronal field [HMT-4058, 4060]. Note also that the magnetic field of the ambient solar wind that the CME travels through is extrapolated from the photospheric magnetic field. For improved modeling of the CME, photospheric fields beyond the east limb are required (SWx Report, 5.1.1.3, 5.1.1.4).

The LWS FMT-3 is related to this topic and is also called out explicitly as SWx-C3. This is classified as high priority because of its fundamental importance combined with the fact that it is represented in many of the reference documents.

3.1.2 Medium Priority

Remote Sensing of Neutral Winds in the Upper Atmosphere

Science Areas: ITM, Space Weather

Earth's global wind system contributes significantly to the composition, morphology and variability of the ionosphere. Thermospheric neutral winds in the 90-140 km layer ("E region") blow ionospheric plasma across the magnetic field, resulting in charge separation, and the generation of an east-west electric field (E) that drives a vertical E x B drift of F-region plasma at the equator. This so-called E-region dynamo is one of the most important processes controlling the large-scale distribution of ionospheric plasma. One of the largest impediments to understanding spatiotemporal variability of the quiet-time ionosphere is a lack of knowledge of the winds that drive the E- and F-region electrodynamics.

Global thermospheric winds have been measured using interferometry techniques that detect Doppler shifts of faint green (557 nm) and red (630 nm) line emissions from oxygen atoms in motion. These measurements have been successfully made from space since 1981. However, interferometers are very sensitive to stray light, require large platforms for stability, and must have hardware/operational redundancy (e. g., multiple telescopes or viewing angles) in order to provide vector winds. Moreover, green light measurements (spanning 110-200 km) can only be made in sunlight conditions. The following two emerging technologies for thermospheric wind sensing overcome large size (and cost) requirements, and deliver wind measurements even during night-time.

THz Limb Scanner (Thermospheric Neutral Wind Profile)

THz limb scanning (TLS) [HMT-4036] measures the spectral radiances of OI emissions at 2.06 THz (147 µm) and 4.7 THz (63 µm) at the limb in the thermosphere (above 100 km). The technology is enabled by a "Schottky" (gallium) diode that mixes incoming signal from 2.06 THz down to an intermediate frequency band to measure O emissions. The line shapes and intensities provide simultaneous wind, temperature, and atomic oxygen density profiles in the IT region from an LEO platform. Unlike other commonly used Doppler-shift instruments, the TLS measurement capability is not affected by the background lighting conditions and inhomogeneity of the emission sources along the viewing line-of-sight. Thus, TLS provides global measurements of neutral winds, temperature, and O density at all local times, in the altitude and latitude regions where ion-neutral coupling is important.

This technology enables LWS-FMT4, LWS-FMT-7, and LWS-FMT-10.

Lidars (Light Detection and Ranging) for Atmospheric Composition

Resonance fluorescence lidars employ resonant backscattering from the atomic mesosphere-lower thermosphere (MLT) metal layers (i.e., Na, Fe, K, Ca, and Li, created by meteor ablation), and from the hydroxyl (OH) layer (formed by chemical processes). These layers are usually found between 70–110 km altitude, though recent observations have revealed events where Fe extends to 155 km.

A typical resonance lidar system employs a tunable laser capable of high average power (10–100 W), narrow linewidth (<1 MHz), and small beam divergence (<1 mrad), accompanied by a telescope one to several meters in diameter, and a low-noise, photon counting receiver. Wind and temperature profiles are derived from the center frequency, and the width of the backscattered metal spectrum. To measure all three wind components, it is necessary to scan the lidar sequentially along zenith and off-zenith directions using a steerable telescope. Because the laser pulses used are on resonance with the atomic line of a certain species, the scattering cross-section is enhanced by a factor of 10^{14} for that species. Metal-fluorescence lidar can provide measurements in the mesopause region with temporal resolution as short as 2 minutes when meter-diameter class telescopes are used. Development of resonance lidar systems has therefore for the most part been driven by the goal of investigating waves and instabilities in the upper mesosphere and lower thermosphere.

Drajic [HMT-4030] proposed metastable helium (He) produced in the thermosphere and exosphere as a target for an ISS-based 1083 nm resonance fluorescence lidar to measure helium density, T, and neutral winds between 300-700 km. Technology gaps exist in two critical areas for this concept: power-scaled CW lasers and large pulse energy, low repetition frequency pulsed lasers.

Clemmons and Swenson [HMT-4043] propose an orbiting atomic oxygen lidar to measure neutral density, temperature, and winds globally between 80-500 km. To advance this concept beyond the idea stage requires maturation of a solid-state, high-intensity ultraviolet pulsed laser capable of operating in the orbital environment, and a large, space-deployable aperture capable of gathering light in a non-imaging format. The concept for this measurement is based on a two-photon laser-induced fluorescence principle that has been successfully used to detect species such as atomic oxygen and atomic nitrogen in the laboratory.

This technology enables LWS-FMT4, LWS-FMT-7, and LWS-FMT-10.

Nitric Oxide Sensors

Nitric oxide (NO) plays an important role in Earth's radiation budget, and in coupling the lower atmosphere to geospace. NO is produced by ionization and dissociation of N_2 during energetic particle precipitation events. Absent sunlight, NO has a long chemical lifetime, and thus attains high concentrations in the mesospheric polar night vortex. Subsequently, NO descends to stratospheric altitudes through vertical transport or diffusion where it catalytically destroys ozone. Ozone loss leads to higher UV irradiance at Earth's surface, and changes to stratospheric temperatures and large-scale circulation.

Despite its importance to Earth, NO abundance is not well-quantified in the MLT. Several techniques have been developed to measure mesospheric NO in night-time conditions, but they require independent retrieval of atomic oxygen, and are limited in their altitude resolution and peak height retrievals. Thus, a direct and independent method of observing NO in the polar night MLT is currently needed.

Stellar occultation allows observation of the attenuation of light from a star by NO absorption. An advantage of this technique is high vertical resolution, although large apertures are required. [HMT-4016]. Recently, a UV spectrograph was deployed on a sounding rocket that successfully measured NO via stellar occultation of the g (1,0) band near 215 nm. (Bailey et al., 2022). The instrument deployed for Bailey's proof of concept was cylindrical, with a length of about 2m, diameter of 0.4m, and mass ~50 kg. The methodology can be further miniaturized via technologies ranging from TRL 4-7. Developmental needs are highest for narrow-band filters near the optimal wavelength of 215 nm (TRL 4), low noise detectors (TRL 5), and segmented, foldable mirrors to reduce the light collection area (TRL 5).

This technology enables LWS-FMT7 and LWS-FMT-10.

Ultra-High Voltage Power Supplies

Science Areas: ITM, Heliospheric, Magnetospheric, Space Weather

Many particle sensor architectures make use of electric fields to move charged particles (e.g. protons, electrons, ions), separate them, and position them on a sensor. The electric fields are provided by high voltage power supplies, which usually operate at thousands of volts. Higher voltage (50 to 100 kV) space-qualified power supplies are needed to enable size reduction of charged particle detectors especially for heavier elements. For example, FMT-1, 2, and 3 along with STP-FireFly and STP-InterMeso require the determination of heavy ion abundancies on a 1-minute time cadence or better. This is more than an order of magnitude greater than currently available. Using currently available high voltage power supplies such an instrument would be over 1 meter in size. A 50-100 keV power supply would enable these instruments to remain in the ~20 cm scale, thus allowing them to be included in the small spacecraft buses called for by these mission concepts.

3.4 Platform Technologies

The following section describes technology gaps associated with platform or spacecraft technologies. These technologies support our missions and should also be considered for investment.

3.4.1 Spinning Platforms

Science Areas: All

Spinning spacecraft have been one of the key technologies that historically enabled Heliophysics missions. The primary purpose of a spinning platform is to enable individual in-situ sensors to sample all angles with respect to the solar wind magnetic field, both upstream and downstream. The faster the spin, the less the measurements suffer from time aliasing. High-energy solar remote sensing missions also make use of Sun-pointed spinners (e.g., RHESSI). The availability of spinning spacecraft (especially SmallSats) provided by industry or universities has significantly decreased, because the commercialization of space has increased the market for standardized 3-axis stabilized spacecraft instead. The following technologies are associated with enabling spinning spacecraft:

- Fast attitude sensors – measuring the attitude of a spinner is not possible using standard star trackers since they require relatively long integration times
- Spin-stabilized Attitude Control Systems – the algorithms required to precisely control the attitude
- Antenna technologies – for deep space missions, de-spun antennas may be required or belly band phased arrays.
- Propulsion stabilization, typically precisely timed pulsed thrusters.
- Re-spin technologies

The following missions are currently baselining spinning spacecrafts; STP-InterMeso, STP-MagCon, FMT-1 may include spinning spacecraft, FMT-5 or STP-MagCon, FMT-8 , FMT-9, FMT-12, 4 of the spacecraft of STP-PILOT, and the 4 daughter-craft of STP-MIO

Spinning instrument platforms combined with a de-spun, 3-axis stabilized spacecraft may be another approach to support Heliophysics missions. HMT-4004 discusses the need for consistent and accurate E-field measurements and how a rotating instrument platform could solve this problem. HMT-4025 discusses the needs for the Interstellar Probe mission concept. The spacecraft spin axis is fixed by communications requirements to point toward Earth. Spinning is particularly important for an IMAP-Hi-style, single-pixel instrument.

3.4.2 Technologies to enable deep space missions

Science Areas: Solar, Heliospheric, Space Weather

Deep space missions are defined as those that go beyond the protection of Earth's magnetosphere. For Heliophysics, this will include missions placed at the Sun-Earth Lagrange points (principally L1, L4 and L5), and missions that go out of the ecliptic or close to the Sun. Spacecraft placed on the Moon or in a lunar orbit, or in highly elliptical Earth orbits are also considered deep space missions. Deep space solar missions may be needed to obtain more complete coverage of the Sun's photospheric magnetic field and corona, particularly in the polar regions. They will also be needed to provide supporting space weather data for the Artemis program.

The reference documentation identifies several missions that would operate in deep space, including the STP-Firefly, STP-InterMeso, [FMT-1], and [FMT-2] mission concepts. Deep space missions also enable goals SWGA-C1 and SWGA-C2 of the Space Weather Gap Analysis.

The two primary missing technologies that would enable deep space missions are

- Long-distance high-bandwidth downlink capabilities
- Interplanetary propulsion technologies such as electric propulsion or solar sails

Satellite uplinks and downlinks have always been done at radio frequencies, and the Ka-band is now standard for NASA, giving rates of around 100 Mbps. However, the Ka-band requires a large high-gain antenna (HGA) that is gimballed. This is a problem for SmallSats and CubeSats that have mass and size limitations [LWS report, 7.1.3]. In addition, stacking spacecraft in the launch vehicle limits the sizes of the HGAs. Constellations may benefit from relay spacecraft that receive signals from the constellation and downlink them to Earth [LWS report, 7.1.3]. Heliophysics will benefit from extending the relay technology to deep space missions.

Optical (laser) communication offers transmission rates of 100’s of Gbps and will be tested with NASA’s TBIRD CubeSat in 2023. A much smaller antenna is required for optical communication, but the narrow beam makes it a challenge to track the spacecraft. Optical communication promises to reduce the complexity and cost for out-of-ecliptic missions [LWS report 8.3.5]. Commercial optical communications networks in LEO may be an option for communicating with spacecraft constellations in a range of Earth orbits [LWS report 8.7.1].

Advances in propulsion technology can enable deep space missions can be enabled. Solar sail spacecraft generate momentum from the Sun’s light using large reflective sails, and will be valuable for persistent, high-availability observations from non-Keplerian orbits. Particular uses include missions measuring the solar wind at sub-L1 locations or delivering spacecraft to high solar latitudes or away from the Earth-Sun line, or missions to study Earth’s bow shock or magnetopause [LWS report, 7.1.5].

Ion engines are attractive for deep space missions due to lower propellant-mass requirements compared to traditional propulsion methods. These engines have been tested with the NASA Deep Space 1 and DART missions. However, significant improvements in efficiency are needed for tasks such as circularizing out-of-the ecliptic or inner Heliospheric orbits within realistic timescales [LWS report 8.3.5]. Other missions that could benefit from this are [FMT-1], [FMT-2] which are deep space missions, as well as [FMT-3] and [FMT-12].

3.4.3 Mission Autonomy

Science Areas: All

Mission autonomy is defined as the ability of a spacecraft to operate itself over a long period of time (months) without regular contacts with the ground. Without ground commanding, the spacecraft must be able to make its own decisions regarding its operations and be able to react to unforeseen circumstances. Autonomy may be required for some mission concepts important to Heliophysics [HMT-4055], for example, large constellations where it is impractical to command individual spacecraft at a weekly cadence. Deep space missions are another mission type which would greatly benefit from autonomy, as it is costly to maintain constant communications. Heliophysics or solar mission concepts that operate from the far side of the Sun would have limited communications. Most deep space missions have either simple, always-on science data collection mode, or advanced algorithms that enable unsupervised science operations that last for months. The data then can be compressed and sent efficiently to Earth using a small number of contact times. However, current deep space operations call for contacting spacecraft at least once every two weeks to update spacecraft scripts and perform orbit determination. Advances in spacecraft autonomy could include self-orbit determination using star trackers following the inner planets, advanced self-diagnoses, and self-correcting algorithms. The following missions identified onboard autonomy as a requirement: [FMT-1], [FMT-2], [FMT-5] or [STP-MagCon] and [STP-Firefly].

4.0 Prioritization Approach

Prioritization was performed by considering each identified gap individually and considering whether they were high, medium, or low priority.

- **High** – A Heliophysics-enabling capability, needed by many mission concepts, critically important to HPD science goals
- **Medium** – A new capability applicable to one or two Heliophysics subject areas. May only be applicable to one subject area but significantly improves science return
- **Low** - A new capability that improves upon past approaches. Applicable to only one Heliophysics subject area. The capability may reduce size, weight, and power needs, marginally improve performance, and does not necessarily enable new science questions to be addressed.

After each gap was placed in one of the above priorities, they were compared to others within the same category and further prioritized.

5.0 Summary and Conclusions

This report considered publicly available resources to determine the sensor and platform technology needs identified by the Heliophysics community to enable breakthrough science missions.

The following table summarizes the technology gaps and associated mission concepts they enable. In this table, only LWS and STP mission concepts are listed.

Name	Technology Type	Priority	Description	Missions Enabled	Science Area Enabled
Spinning Platforms	Platform	High	Many science objectives in Heliophysics require in-situ measurements over all angles with respect to the solar wind. The following technologies are associated with enabling spinning spacecraft: • Fast attitude sensors – measuring the attitude of a spinner is not possible using standard star trackers since they require relatively long integration times • Spin-stabilized Attitude Control Systems – the algorithms required to precisely control the attitude • Antenna technologies – for deep space missions, de-spun antennas may be required or belly band phased arrays. • Propulsion stabilization, typically precisely timed pulsed thrusters. • Re-spin technologies Independently spinning instrument platforms are another potential approach.	STP-InterMeso, STP-MagCon, FMT-1 may include spinning spacecraft, FMT-5 aka STP-MagCon, FMT-8 , FMT-9, FMT-12	All
Deep Space-enabling Technologies	Platform	High	Many mission concepts require spacecraft in deep space (non-low-Earth orbits). The two primary missing technologies that would enable deep space missions are • Long-distance high-bandwidth downlink capabilities • Interplanetary propulsion technologies such as electric propulsion or solar sails	STP-Firefly, STP-InterMeso, aka FMT-1, FMT-2, FMT-3, FMT-12. Deep space missions also enable goals SWGA-C1 and SWGA-C2 of the Space Weather Gap Analysis.	Solar, Heliospheric, Space Weather

Spacecraft Autononmy	Platform	Medium	As missions concepts trend toward larger constellations combined with operating far from Earth, spacecraft need to be able to operate independently without constant ground contacts, which may be expensive and too frequent.	FMT-1, FMT-2, FMT-5 aka STP-MagCon, STP-Firefly.	All
Remote Sensing of coronal magnetic fields	Instrument	High	Enables new understanding of solar – heliospheric – magnetospheric connections. Promises to enable more accurate space weather predictions and provide new understanding of solar wind acceleration and eruption initiation.	FMT-3	Solar Science, Space Weather
Remote Sensing of Neutral Winds in the Upper Atmosphere	Instrument	Medium	• **Lidar** – Allows the measurement of neutral winds. Opens up significant new science. • **NO Sensor** – Currently unavailable technology with the promise of significant scientific return, but limited to a narrow, focused subject area. Possible space weather implications. • **THz imager** – improve size, weight, power, and cost needed.	THZ Imager (FMT-4, FMT-7, FMT-10), Lidar (FMT-4, FMT-7, FMT-10), NO Sensor (FMT-7, FMT-10)	ITM, Space Weather
High Voltage Power Supply	Instrument	Medium	Enables sensor miniaturization across many in-situ sensor types including charged particle detectors and solar ENA detectors. Miniaturization of in-situ sensors is a major gap which, if available, would enable many of the missions identified here.	FMT-1, FMT-2, FMT-3, STP-Firefly, STP-InterMeso	ITM, Heliospheric, Magnetospheric, Space Weather

Table 3: A summary of the association between mission concepts and the priorities associated with this report.

6.0 References

The following section describes the references for each data source set individually.

6.1 Heliophysics 2050 Measurements and Technologies Workshop (February 23–25, 2022)

Helio2050 Measurement Techniques White Papers (from https://www.hou.usra.edu/meetings/heliotech2022/pdf/heliotech2022_program.htm)

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- [HMT-4027] Paxton, L., Ion Outflow Measurements via Optical Techniques, pdf

- [HMT-4028] Saint-Hilaire, P., Precise Formation Flying (PFF) in Trans-lunar Space, pdf
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- [HMT-4033] Nikoukar, R., Next Generation of Ionosphere Radio Imaging Sensors, pdf
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- [HMT-4036] Yee, J., Satellite Remote Sensing of Thermospheric Dynamics Using the Terahertz OI Fine Structure Emissions, pdf
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- [HMT-4060] West, M. J., A Strategy for A Coherent And Comprehensive Basis For Understanding The Middle Corona, pdf

6.2 Space Weather Science and Observation Gap Analysis for the National Aeronautics and Space Administration (NASA), Apr 2021

References to this document are defined with the following notation [SWGA-page##].

The study defined the following mission architectures, each of which is associated with a specific strategic science area.

- [FMT-1] Sun-Earth Line Observing System, Solar-Heliospheric
- [FMT-2] Multi-Spacecraft System to Observe the Dynamics of the Inner Heliosphere, Solar-Heliospheric
- [FMT-3] Origins of Space Weather, Solar-Heliospheric, same as [STP-4π-HeliOS]
- [FMT-4] Geospace Observing System, Geospace
- [FMT-5] Magnetospheric Constellation, Geospace, same as [STP-MagCon]
- [FMT-6] Magnetotail and Inner Magnetosphere Mission, Geospace
- [FMT-7] Low-Earth-Orbit Constellation for Ionosphere/Thermosphere/ Mesosphere System Observations, Geospace
- [FMT-8] The Cold Plasma Cycle, Geospace
- [FMT-9] Inner Magnetosphere and Radiation Belts Mission, Geospace
- [FMT-10] Solar Impacts on Climate, Solar-Geospace-Earth
- [FMT-11] Earth as an Exoplanet, Geospace-Astrophysics
- [FMT-12] PeriGeospace Observing System, Solar-Heliospheric-Geospace

6.3 Living With a Star Architecture Committee Report for the NASA Heliophysics Division, Aug, 2022

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6.4 STP Study Reports

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- [STP-MIO] Borovsky, J. Magnetosphere-Ionosphere Observatory
- [STP-4PI HELIOS] Raouafi, N., 4PI-Helios - Exploring the Heliosphere from the Solar Interior to the Solar Wind
- [STP-FIREFLY] Raouafi, N., Firefly - Exploring the Heliosphere from the Solar Interior to the Solar Wind
- [STP-MagCon] Kepko, L., Magnetospheric Constellation (MagCon)
- [STP-CMO] Rabin, D., Coronal Microscale Mission (CMO)

Appendix A: Summary Mission Table

Mission Designation	**Mission Name** Science Area	**Number of Spacecraft**	**Orbit**	**Associated Platform Technology Gap**	**Associated Instrument Technology Gap**
FMT-1	**Sun-Earth Line Observing System** Solar-Heliospheric	10 (2 ESPA-class hub spacecraft with up to 4 8U spokes)	L4 and L5	Mission Autonomy, Spinning Platform (optional), Deep space	None
FMT-2	**Multi-Spacecraft System to Observe the Dynamics of the Inner Heliosphere** Solar-Heliospheric	7 to 9	0.4 x 0.9 AU orbits	Mission Autonomy Deep Space	None
FMT-3, [STP-Firefly, formerly known as STP-4π-HeliOS]	**Origins of Space Weather** Solar-Heliospheric	4 (2 pairs)	1 pair 180° apart orbiting at 90°from Earth, 1 pair out of ecliptic	Deep Space	None
FMT-4	**Geospace Observing System** Geospace	3	Earth-orbiting 800 km and 15° inclination, 600 x 250 km with 15° inclination	None	THz limb scanner, OH band imager
FMT-5, [STP-MagCon]	**Magnetospheric Constellation** Geospace	36	Earth-orbiting 12 at 8.24 Re, 12 at 10.79 Re, 12 at 15 Re - all low inclination	Mission Autonomy, Spinning Platform	ENA remote sensing
FMT-6	**Magnetotail and Inner Magnetosphere Mission** Geospace	4 (2 pairs)	1 pair at 6.1 Re 1000 km apogee 82° inclination, 1 pair at 6.1 Re 82° inclination	None	None
FMT-7	**Low-Earth-Orbit Constellation for Ionosphere/Thermosphere/ Mesosphere System Observations** Geospace	28 (4 motherships with 6 cubesats each)	LEO 600 km	None	THz limb scanner, NO limb scanner

FMT-8	**The Cold Plasma Cycle** Geospace	3	1 at High-inclination 20 Re orbit, and 2 in 11-hour equatorial GTO-lioke orbit (5.8 Re x 1.1 Re)	Spinning Platform	None
FMT-9	**Inner Magnetosphere and Radiation Belts Mission** Geospace	3	GTO-like geosynchronous transfer orbits	Spinning Platform	None
FMT-10	**Solar Impacts on Climate** Solar-Geospace-Earth	2+	LEO 98 deg inclination		None
FMT-11	**Earth as an Exoplanet** Geospace-Astrophysics	2+ or 4+ - Two concepts	LEO		None
FMT-12	**PeriGeospace Observing System** Solar-Heliospheric-Geospace	9+	2 to 4 at L1, 1 or more spacecraft orbiting between L1 and Earth	Spinning Platform , Deep space	None
STP-INTERMESO	**InterMeso** Solar-Heliosphere	4 (identical)	Earth-trailing heliocentric orbits near 1 AU	Deep space	None
STP-CMO	**Coronal Microscale Observatory** Solar	3	large-amplitude quasi-halo orbit around the Sun-Earth L1 point.		None
STP-PILOT	**Plasma Imaging LOcal and Tomographic experiment** Geospace	34 (30 smallsats + 4 spacecraft)	18 outer orbit, 16 inner orbit Inner: 1.52 RE × 4.25 RE and Outer: 1.10 RE × 6.25 RE	Spinning Platform	None
STP-MIO	**Magnetosphere-Ionosphere Observatoray** Geospace	5 (1 primary spacecraft and 4 daughter craft)	4.3 x 9 Re, 24 hour orbit with < 5 degree inclination	Spinning Platform	None

Note that