Interplanetary Mesoscale Observatory (InterMeso): A Solar Terrestrial Probes mission concept to untangle dynamic mesoscale structures throughout the heliosphere

A White Paper to the Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033

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Synopsis:

Mesoscale dynamics are fundamental throughout space physics, but fall within an observational gap of current and planned missions. Measurements at the mesoscales in the solar wind (100's R_E to a few degrees heliographic longitude at 1 au) are crucial for understanding the connection between the corona and an observer anywhere within the heliosphere. Mesoscale dynamics may also be key to finally revealing the currently unresolved physics governing particle acceleration and transport, magnetic field topology, and the causes of variability in the composition and acceleration of solar wind plasma. Studies using single-point observations do not allow for investigations into mesoscale solar wind dynamics and plasma variability, nor do they allow for the exploration of the sub-structuring of large-scale solar wind structures like coronal mass ejections (CMEs), co-rotating/stream interaction regions (CIR/SIRs), and the heliospheric plasma sheet.

To address this fundamental gap in our knowledge of the heliosphere at these scales, the *Interplanetary Mesoscale Observatory* (InterMeso) concept employs a multi-point approach using four identical spacecraft in Earth-trailing orbits near 1 au. Varying drift speeds of the InterMeso spacecraft enable the mission to span a range of mesoscale separations in the solar wind, achieving significant and innovative science return. Simultaneous, longitudinally-separated measurements of structures co-rotating over the spacecraft also allow for disambiguation of spatiotemporal variability, tracking of the evolution of solar wind structures, and determination of how the transport of energetic particles is impacted by these variabilities.

The Need for Mesoscale Investigations

The mesoscale solar wind (100's R_E to a few degrees heliographic longitude at 1 au) remains elusive in our observations, modeling frameworks, and understanding. In order to finally close this fundamental gap in our knowledge of the solar wind, new multi-point missions are required with mesoscale separations (see *Allen et al.*, 2022a,b).

To address the overarching science objective of *Investigating the fundamental mesoscale nature of the variable solar wind and its impacts on particle acceleration, evolution, and transport*, the Heliophysics community requires a Solar Terrestrial Probes (STP) mission to: (1) Explore and identify the origin of the mesoscale variability of the background solar wind and transient solar wind structures and (2) Understand and characterize the impact of these mesoscale variations on particle acceleration and transport. The InterMeso mission concept provides one such solution for addressing the unresolved physics of mesoscale structure of the solar wind and transients.

STP Objectives[1]	InterMeso
STP #1: "Understand the fundamental physical processes of the complex space environment throughout our solar system, which includes the flow of energy and charged material, known as plasma, as well as a dynamic system of magnetic and electric fields."	InterMeso will untangle the dynamic mesoscale structuring of the solar wind enabling a new vantage point onto the fundamental physical processes structuring the solar wind and impacting particle populations.
STP #2: "Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields."	InterMeso probes the mesoscale variability of the solar wind, which can have wide-ranging impacts on radiation environments within interplanetary space and how the solar wind impacts planetary systems.
STP #3: "Develop the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers."	InterMeso, through a novel measurement of mesoscale variability and effects on particle populations, will allow for a determination of the drivers of solar wind variability, a critical missing link in our ability to predict conditions in space environments.

[1] https://science.nasa.gov/heliophysics/programs/solar-terrestrial-probes

InterMeso Science Traceability

The overarching science goals of InterMeso flow into eight targeted science questions, shown in the Science Traceability Matrix (STM) provided in **Table 1**. Addressing these questions requires simultaneous, multi-point observations with inter-spacecraft separations ranging from ~0.5 Mkm to 10's Mkm (i.e., 100's R_E to a few degrees in heliographic longitude at 1 au). Maintaining the constellation at a near-1 au heliocentric distance enables observations of both well-formed and still-steepening shocks of CMEs and SIR/CIRs.

All InterMeso spacecraft require measurements of the low-energy, bulk solar wind plasma to provide base information of the solar wind stream observed at each spacecraft. This includes sub-minute cadence observations of the bulk proton population for speeds ranging from 250 – 1000 km/s and densities from 1 – 100 cm^{-3}. This range of measurements with necessary accuracy can be accomplished with modern Faraday Cup instrumentation (e.g., *Case et al.*, 2020). Thermal ion (1-10's keV/*e*) composition measurements on a less-than-few-minute cadence will be critical to disambiguate changes in flux tube composition. This will require the ability to distinguish between various species and charge states including H, He^{2+}, $C^{5\text{-}6+}$, $N^{5\text{-}6+}$, $O^{6\text{-}7+}$, and $Fe^{6\text{-}12+}$ and can be satisfied by modern iterations of the Ulysses & ACE Solar Wind Ion Composition Spectrometer (SWICS) instrument design (*Gloeckler et al.*, 1992). Low-energy electron observations spanning from a few eV to tens keV (i.e., the core, halo, and strahl populations), are also needed and be achieved with the inclusion of a Parker Solar Probe (PSP) Solar Probe Analyzers-Electrons (SPAN-E)-type instrument (*Kasper et al.*, 2016).

Additionally, suprathermal and energetic ion/electron measurements are required to explore anisotropies and, importantly, differentiate various ion species for investigating mass-per-charge-dependent processes of particle acceleration and transport. Suprathermal ion (5 – 100 keV/nuc) and energetic ion (0.1 – 10 MeV/nuc) measurements with mass determination (i.e., H, ^{3}He, ^{4}He, C, N, O, Fe) are required on a cadence of several minutes and tens of minutes, respectively, which is within the capabilities of current generation versions of the Solar Orbiter Suprathermal Ion Spectrograph (SIS; *Rodríguez-Pacheco et al.*, 2020; *Wimmer-Schweingruber et al.*, 2021) instrument. Energetic electron observations (few tens keV to few MeV) are needed with capabilities of determining first-order anisotropy on a few second cadence to characterize mesoscale variations in SEP events, which can be achieved with Solar Orbiter Energetic Particle Telescope (EPT)-like instrumentation (*Rodríguez-Pacheco et al.*, 2020; *Wimmer-Schweingruber et al.*, 2021).

To probe mesoscale magnetic structuring and impacts of plasma waves and turbulence on particle transport, observations of the magnetic field and radio emissions released from flare events and shock acceleration are required. Vector magnetic field measurements must have a full-scale range of at least $\pm$100 nT with 0.1 nT or better resolution at cadences of 16 – 64 vectors/sec, obtainable by current fluxgate instrumentation (e.g., PSP/FIELDS; *Bale et al.*, 2016). Radio wave observations ranging from $10^{-18} – 10^{-12}$ $V^2/m^2/Hz$ over the frequency range of 0.1 kHz to 20 MHz, achievable with STEREO-SWAVES (*Bougeret et al.*, 2008) or Solar Orbiter Radio Plasma Waves (RPW; *Maksimovic et al.*, 2020)-type instrumentation, are also needed. Accurate timing and characterization of electron acceleration near the solar surface necessitates observations of hard X-rays with an indirect imager (e.g., *Krucker et al*., 2020) along with radio wave observations to determine both the source location and electron characteristics (for more discussion on the utility of such measurements, see *Allen et al.* 2022a,b). The X-ray instrument must measure hard X-ray spectra, images, and time series with an energy range between 5 – 100 keV, and is achievable with Solar Orbiter Spectrometer Telescope for Imaging X-rays (STIX)-type instrumentation (*Krucker et al*., 2020).

As such, the baseline payload for this mission requires each spacecraft of the constellation to be outfitted with: ***(1)*** bulk solar wind instrument, ***(2)*** thermal ion composition instrument, ***(3)*** suprathermal ion composition telescope, ***(4)*** energetic ion composition telescope, ***(5)*** low energy electron instrumentation, ***(6)*** energetic electron telescopes, ***(7)*** DC vector magnetic field sensor, and ***(8)*** high-frequency electric field radio wave instrumentation. Additionally, only one of the spacecraft must be equipped with ***(9)*** a hard X-ray indirect imager due to the relatively close separation needed for the InterMeso spacecraft to span the mesoscale regime.

Closure of the science objectives given in **Table 1** requires simultaneous multipoint observations with longitudinal separations that span the range of mesoscale dynamics in the solar wind at 1 au. As demonstrated in **Figure 1**, increasing the number of spacecraft increases the ability to discern characteristic longitudinal profiles relevant to structures in the solar wind, particularly Gaussian-type distributions (i.e., the spread of energetic particles from an acceleration region) and sigmoidal-type variations (i.e., current sheets or changes in topology across flux tubes). Distinguishing more complex topological variabilities, such as "ripples" in a large-scale shock structure (e.g., *Bale et al.*, 1999), or better constraining the non-planarity and radius of curvature

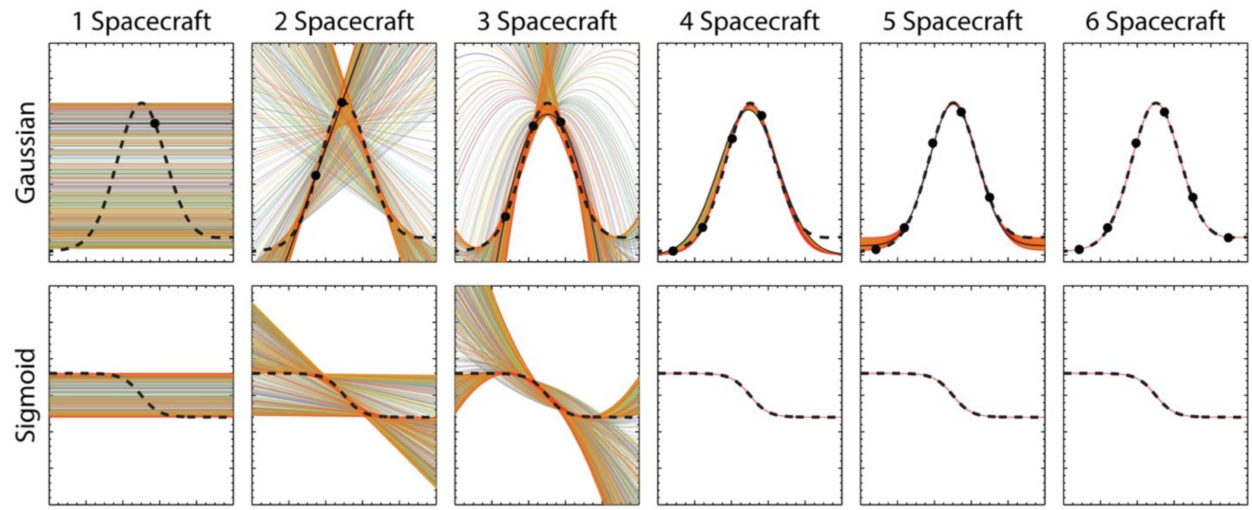

Figure 1: Randomized placement of single and multi-point spacecraft constellations throughout structures with Gaussian (top row) and sigmoidal (bottom row) longitudinal profiles (dashed curves) allow for assessment of required number of spacecraft for InterMeso. Filled in circles in the top row are examples of 1000 random placements of spacecraft constellations, resulting in the shown colored fits. The solid black curve on the top row is the corresponding fit from the shown example placements (black circles). From *Allen et al.* (2022b). *Four spacecraft are the optimal benefit-to-cost configuration for mesoscale variations.*

of interplanetary shocks (e.g., *Neugebauer & Giacalone*, 2005), also benefit from increasing numbers of longitudinally-separated observations.

While additional spacecraft can increase the science return of InterMeso, four points of measurement within relevant scales provide the highest benefit-to-cost for expected variability of mesoscale phenomena with features manifesting as either a Gaussian or sigmoidal distribution (shown in **Figure 1**). With fewer than four spacecraft, the ability to reconstruct the distribution becomes significantly deteriorated. However, the added value, particularly when including available mission resources and cost, diminishes with additional spacecraft. As such, the InterMeso mission architecture targets four spacecraft as a baseline to determine spatiotemporal variations and elucidate mesoscale structure.

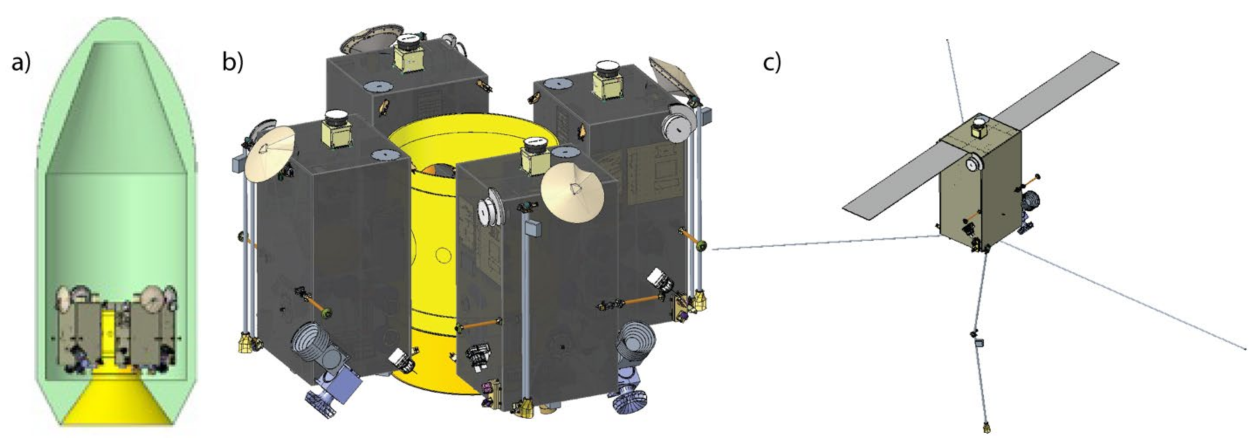

Figure 2: Four "strawman" InterMeso spacecraft in a stowed configuration mounted on an ESPA-Grande equivalent viewed inside a 5-meter faring (a) and viewed without the faring (b). (c) A "strawman" InterMeso spacecraft in the deployed configuration.

InterMeso Instrumentation

For this study, a slate of representative candidate instruments was selected to achieve the measurement requirements noted in the STM, and are further discussed in detail in the accompanying full report. All of these candidate instruments are at or above TRL 6, or will be prior to the Heliophysics Decadal Survey release, without any additional technology development. All assumed instruments have flight software equivalents that do not need significant code development. **Table 2** summarizes all instrument mass and power.

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
(1) Faraday Cup	5.90	15	6.79	5.00	15	5.75
(2) Thermal Ion Composition (SPICES)	13.14	15	15.11	24.17	15	27.79
(3) Suprathermal Ion Composition (SIS-Lo)	3.70	15	4.26	0.80	15	0.92
(4) Energetic Ion Composition (SIS-Hi)	2.40	15	2.76	0.40	15	0.46
(5) Lower Energy Electron Distribution (SPAN-E)	4.80	15	5.52	4.40	15	5.06
(6) Energetic Electron Distribution (MEPS)	4.80	15	5.52	10.00	15	11.50
(7) Fluxgate Magnetometers, Boom, Electronics Box	13.86	15	1.71	4.97	15	5.72
(8) Electric Field (AC Only)	7.53	15	8.66	10.54	15	12.12
(9) Indirect Hard X-Ray Telescope (Only on one spacecraft)	7.00	15	8.05	8.00	15	9.20
Total Payload Mass	**69.40**	**15**	**79.81**	**68.28**	**15**	**78.52**

Table 2: Payload Mass & Power Table.

InterMeso Spacecraft, Orbit, and Separation Scales

Key to the science of InterMeso, the mission requires multiple, longitudinally-separated spacecraft in the solar wind near 1 au with varying inter-spacecraft separations over the course of the mission. In family with spacecraft missions in development and in prime operations, the prime mission phase of InterMeso is designed to last three years in order to sufficiently sample inter-spacecraft separations needed from **Table 1**, but with systems that can remain operational likely for several years of extended mission operation. The flexible mission design of InterMeso currently targets a 2033 launch to coincide with the ascending phase of the solar cycle but is adjustable via daily launch opportunities throughout the decade.

A design of the InterMeso constellation is shown in **Figure 2**. To reduce cost and complexity in launch, the four InterMeso spacecraft can fit on a single ESPA-Grande equivalent and within a standard 5m fairing (shown in both the stowed and deployed configuration in **Figure 2**). All four spacecraft are launched together into heliocentric, Earth-trailing orbit, with each spacecraft independently communicating with Earth. The spacecraft will all have the same initial drift rate before maneuvers separate the spacecraft. **Figure 3a** shows the initial drift rate set by the launch vehicle (green line) as well as the drift rates of each InterMeso spacecraft throughout the mission.

These drift rates allow the spacecraft to slowly separate and allow sampling of the solar wind at inter-spacecraft separations spanning the full range of mesoscale dynamics. **Figure 3b** illustrates the cumulative combined days at various inter-spacecraft separations for both the three-year prime mission (black line) and for the inclusion of a two-year extended mission (red-dotted line). The inclusion of the 2-year extended mission phase, especially, provides additional opportunity for sampling mesoscale structuring near the transition from the inertial to the injection range; however, this additional sampling is not required for addressing the primary science goals.

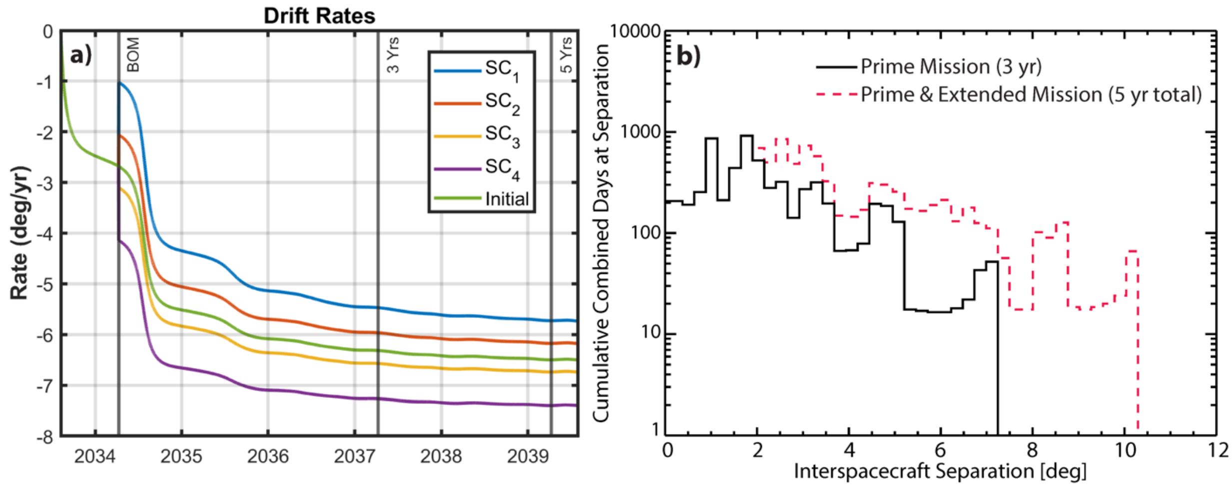

Figure 3: (a) Change in Earth-relative drift rate over the course of the mission. The "initial" line represents the drift rate targeted by the launch vehicle. (b) Cumulative combined days the InterMeso spacecraft spend at different inter-spacecraft separations over the prime mission (black) plus extended mission (red). Cumulative combined days is the sum of the number of days spent at each separation for each spacecraft pair (i.e., spacecraft 1&2, 1&3, 1&4, 2&3, 2&4, and 3&4).

Cost and Schedule

The InterMeso development schedule draws heavily from previous mission schedules, notably STEREO, and recent concept development efforts in the same class. Instrument schedules were benchmarked using comparable instrument schedules from STEREO, Parker Solar Probe, Solar Orbiter, Europa Clipper, and direct input from instrument teams. *It should be noted that no pre-formulation work is required before the start of Phase A.*

A high-level notional mission schedule, presented in **Figure 4**, baselines a launch in 2033 and includes ample margin. The mission architecture allows for daily launch opportunities across a multi-year launch window providing substantial flexibility in Phase A start dates. For this study launch, a 2033 launch was assumed to coincide with the ascending phase of solar cycle 26. However, the prime science of InterMeso will have data sufficiency for any launch occurring during the ascending phase, likely ranging from 2033 to 2037.

Phase D is projected to take about 3.5 years with the spacecraft integrated and tested in pairs. This 'buddy system' approach constrains the throughput expected from the harness and ground system equipment suppliers to production levels achieved on the Van Allen Probe and STEREO missions.

As shown in **Figure 5**, the Phase A-D cost of InterMeso is comparable to recent STP-class solar wind and/or multi-point missions. The total estimated cost of the baseline InterMeso mission (Phases A-E) with fees and unallocated cost reserves is $1,137 million in FY22 dollars. This estimate, shown in **Table 3**, includes $200.7 million for Launch Vehicle and Services (LV&S) – specifically, an Option-2 launch vehicle with 5-meter fairing and launch vehicle adapter.

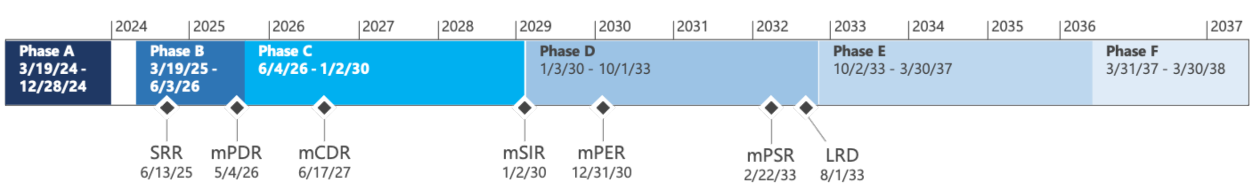

Figure 4: InterMeso Phase and Review Date Summary

Unallocated cost reserves are calculated as 50 percent of estimated Phase B-D costs excluding the price of LV&S, and 25 percent of estimated Phase E costs. DSN charges, while not included in the mission cost, are estimated to be $12.9 million through the end of Phase E. InterMeso is ready for immediate implementation with no pre-Phase-A funding or technology development required, allowing for immediate science return within this Decadal Survey period.

WBS ID	Description	Cost ($M FY22)	Basis, Comments
Ph A	Phase A	$ 6.0	Assumption based on previous missions
01, 02, 03	PMSEMA	$ 68.7	A-D wrap up based on recent STP missions
04	Science	$ 22.8	Estimated from recent STP missions
05	Payloads	$ 149.3	
06	Spacecraft	$ 205.1	
07	Mission Ops (B-D)	$ 24.1	Based on STEREO, scaled for 4 spacecraft
08	Launch Vehicle & Services (LV&S)	$ 200.7	Option 2 LV&S, including Launch Vehicle Adapter
09	Ground Data Systems	$ 14.9	InterMeso specific estimate from GDS lead
10	I&T	$61.8	Includes testbeds
A-D BASE	**Baseline (w/out reserves)**	**$ 753.4**	**Including Option 2 LV&S price**
A-D RES	Unallocated Cost Reserves	$ 273.3	50% of Phase B-D Baseline costs, excluding $200.7m Option 2 LV&S price
Ph A-D	**Phase A-D with Reserves**	**$ 1026.7**	
E	**Phase E Baseline**	**$ 88.3**	**Including all costs except DSN charges**
E RES	**Phase E Cost Reserves**	**$ 22.1**	**25% of Phase E Baseline**
A-E BASE	**Phases A-E**	**$ 841.7**	**Baseline, excludes Cost Reserves**

Table 3: Estimated InterMeso Phase A-E Costs (in millions of FY22 dollars) by WBS element.

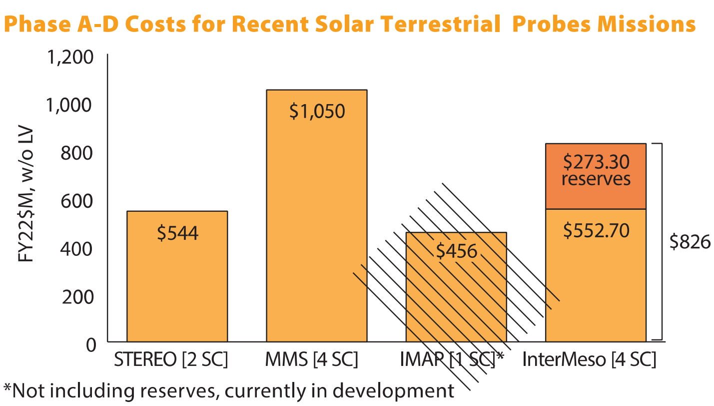

Figure 5: Phase A-D cost of InterMeso with 50% reserves compared to the previous three STP-class missions. *InterMeso is well within the family of costs for the STP program.*

Significance, Impact, and Timeliness

The goal of InterMeso, to resolve the critical physics and consequences of the mesoscale solar wind and transients, is particularly timely for the next decade. With the continued operation of ground-based solar observatories (e.g., DKIST) and solar/heliographic imaging satellite missions, InterMeso measurements will have complementary remote sensing observations of the solar footpoints of the spacecraft. The upcoming discoveries from PUNCH will enable a better understanding of the initial mesoscale structuring of the coronal young solar wind, and so will feed directly into the interpretations of mesoscale variability at 1 au from InterMeso, furthering our insight into the evolution of this mesoscale variability between the solar source and Earth at 1 au. Understanding of the transition from the inertial to dissipation range of plasma turbulence from HelioSwarm, coupled with understanding of the injection to inertial range from InterMeso, would for the first time provide a broad picture of plasma variability in the mesoscale solar wind. Additionally, the ESA Vigil mission to L5, in partnership with the NOAA, is planned to launch in 2027 and will include a heliospheric imager that can provide broader context for the in situ observations of the InterMeso mission. The potential synergies between InterMeso and upcoming missions (e.g., HelioSwarm, PUNCH, and Vigil) motivate such an architecture within the next decade.

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