Heliospheric Distributed In-Situ Constellation (HelioDISC)

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Executive Summary. HelioDISC will delve into the fundamental mysteries of the mesoscale solar wind and transient structures and the subsequent impacts on particle acceleration and transport. The mission will consist of four spacecraft in Earth-trailing orbits with inner spacecraft separations between 100s R_E and a few degrees in heliographic longitude at 1 au. Each spacecraft will measure the thermal to energetic ion (with composition) and electron populations, magnetic field, and hard X-rays from solar flares. Electric field observations will be studied for inclusion in the concept, as well as details of spacecraft separations and variable drifts, subsystems, and mission lifetime. This combination of measurements from multiple spacecraft with mesoscale separations will allow for unprecedented insight into the structuring of the solar wind and its effects on energetic particle populations throughout the heliosphere.

Science Motivation, Goals, and Objectives. Cross-scale and mesoscale dynamics are a fundamental science priority in space physics, but fall within an observational gap of current and planned missions. Particularly in the solar wind, the mesoscale (spatial scales of around 0.5 Mkm to 10's Mkm) is crucial for understanding the connection of the corona to an observer anywhere within the heliosphere, as well as for revealing the currently unresolved physics regulating particle acceleration and transport, magnetic field topology, and the causes for variability in composition and acceleration of solar wind plasma. Multi-point measurements with mesoscale separations are required to address this fundamental gap in our understanding, as studies using single-point observations generally do not allow for investigations into cross-scale and mesoscale solar wind dynamics and plasma variability, nor do they allow for the exploration of sub-structuring of large-scale solar wind structures such as coronal mass ejections (CMEs) and co-rotating interaction regions (CIRs).

The Heliospheric Distributed In-Situ Constellation (HelioDISC) mission seeks to:

1. Understand the origin, variability, and cross-scale structure of the solar wind and transients
2. Determine the impacts of the 3D structure and sub-structure of the solar wind and transients on particle acceleration
3. Determine the effects of this cross-scale structure on suprathermal and energetic particle transport and propagation

In order to address these goals, the community needs simultaneous multi-point observations with inter-spacecraft separation covering this critical scale length. The total span encompassed by the HelioDISC constellation will then be less than 10° in heliographic longitude during a nominal mission lifetime. Such a constellation would be located near 1 au, where the spacecraft are at large enough heliographic radial distances to observe well-formed shocks at CMEs and CIRs.

HelioDISC will require sub-second cadence observations of the bulk proton population, as well as sub-minute resolution thermal composition determination to probe the fundamental mesoscale plasma dynamics of the solar wind and transients. The objectives also require full 3D velocity distribution functions to disentangle local versus remote energization mechanisms and

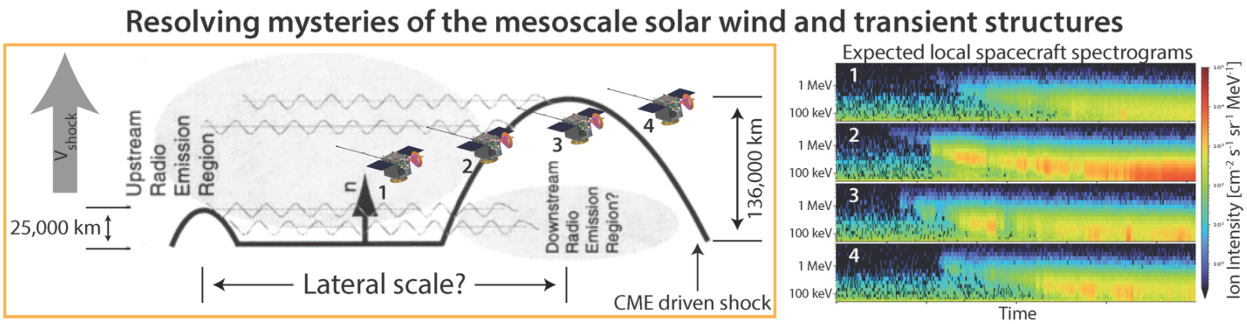

Figure 1. Mesoscale structuring of a CME shock inferred from radio wave observations with potential observations from four HelioDISC spacecraft (adapted from Bale et al., 1999). ***Mesoscale solar wind structuring and effects on particle acceleration are poorly understood and cannot be addressed by previous, current, or planned missions. HelioDISC closes on this critical gap in Heliophysics.***

enable robust calibration for high-quality solar wind plasma measurements. Additionally, suprathermal and energetic ion measurements are also required that can explore anisotropies and, importantly, differentiate various ion species for investigating mass-per-charge-dependent processes for particle acceleration and transport.

In order to probe the magnetic structuring and impacts of waves and turbulence on particle transport, observations of the magnetic field and electrons including the core, halo, and strahl populations, as well as the energetic electrons released from flare events and accelerated at shocks, are required. In general, closure of most of the objectives requires characterization of the magnetic field from DC background fields along with the wave/turbulence spectrum. Accurate timing and characterization of electron acceleration necessitates also observations of hard X-rays. Many of the science objectives would also benefit from electric field measurements. The HelioDISC concept study will investigate the trades between science benefit and additional cost due to electromagnetic interference and accommodation requirements placed on the spacecraft and other instruments with the inclusion of electric field instrumentation.

Mission Architecture Study. Closure of the HelioDISC science objectives necessitates simultaneous multipoint observations. Preliminary study has indicated that at least four spacecraft will be required as a baseline to determine spatiotemporal variations and elucidate general mesoscale structuring. Additional investigations into the expected science benefits of additional spacecraft will be conducted, along with study of the effects to cost, launch options, and operation constraints.

The baseline HelioDISC mission requires a constellation in Earth-trailing orbits near 1 au with inter-spacecraft separations varying from 100s R_E (0.5 Mkm) early in the mission to few degrees in heliographic longitude (10's Mkm) late in the mission. A robust investigation of the number of events (e.g., CME observations) needed at various separations, along with relative occurrence of events as a function of solar cycle, is required to finalize the optimal relative drift rates of the spacecraft for different launch dates throughout the solar cycle. This will also be needed to finalize an estimate of the mission lifetime. While the baseline mission will use two lunar gravity assists, similar to the orbital insertion of STEREO-B, precise orbital analysis is needed for providing the determined separation speeds. Telemetry options, including trade spaces between the use of a dish versus fan beam communications, as well as DSN requirements and tradeoffs of Ka-band versus X-band, need to be finalized. Finally, the optimal bus options and launch vehicles expected to be available over the next decade need to be established.

Notional candidate instruments have been identified, and final recommendations of notional payloads will be established during the design run to determine the optimal payload, with cost considerations, to address HelioDISC science. Notably, no enabling technologies are required for this mission architecture, as all instruments and subsystems are at a minimum of TRL 5.

The baseline HelioDISC payload includes: **(1)** Faraday Cup for bulk solar wind moments, **(2)** thermal to suprathermal ion composition instrument with high time resolution, **(3)** suprathermal to energetic ion composition instrument, **(4)** energetic ion composition sensor, **(5)** thermal electron instrument resolving 3D distributions, **(6)** energetic electron sensor, **(7)** magnetometers (DC vector), and **(8)** hard X-ray spectrometer. Additionally, electric field probes (both AC and DC) and AC magnetic field instrumentation will be investigated for inclusion in the payload.

Relevance to the Solar Terrestrial Probes Program. Despite being in line with the key science goals (SG) of the previous decadal survey, the science goals of HelioDISC have remained elusive, highlighting the need for a new mission architecture to solve these still open questions of heliospheric processes. Specifically, HelioDISC goals are directly related to SG4 “Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe”, SG3 “Determine the interaction of the Sun with the solar system…”, and SG1 “Determine the origins of the Sun’s activity and predict the variations in the space environment”. Additionally, HelioDISC directly addresses the decadal science challenge SHP-3 “Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere”. HelioDISC goals are also relevant to NASA roadmap focus areas F2, H1, W1, W2, and W3.

Fundamentally understanding the mesoscale structuring of the solar wind and transients and the subsequent effects on particle acceleration and transport will be paradigm shifting in our vantage point and insight into the heliosphere, as mesoscale dynamics are critical for resolving long-standing questions of the community. HelioDISC will fill an observational gap in the current Heliophysics Systems Observatory (HSO) as mesoscale solar wind structure and dynamics falls between the large-scales studied by the in situ instrumentation on STEREO and occasional opportune conjunctions within the HSO and the micro-scales unlocked by MMS, Cluster, and the potential HelioSwarm mission. As such, a new mission with an enabling, multi-point architecture is essential to address these objectives.

The goal of HelioDISC to resolve the critical physics and consequences of the mesoscale solar wind and transients is also particularly timely for the next decade. With the continued operation of solar observatories on Earth and within the near-Earth space environment, such a mission will have complementary remote sensing observations of the solar footpoints of the spacecraft. Additionally, the European Space Agency (ESA) Lagrange mission to L5, in partnership with the National Oceanic and Atmospheric Administration, is planned to launch in 2027 and will include a heliospheric imager that can provide broader context to the in situ observations of the HelioDISC concept to be studied here.

Cost Estimate. The rough order of magnitude (ROM) cost estimate of HelioDISC is $577M in FY21 dollars, including 30% reserves. This baseline estimate, which will be revisited after various trade spaces have been performed during the mission concept design run, is based on the real costs of the STEREO Phase B-D science, mission operations, and ground data systems. Additionally, estimates for system I&T, spacecraft, management, engineering, and mission assurance are from historical baselines at APL. Instrument costs were estimated using a parametric estimate and assuming instrument cost to copy cost of 40% with concurrent development effort.