An Autonomous Space Weather Constellation

A white paper submitted to the Heliophysics 2050 Workshop

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1. Executive Summary

This white paper presents the science case, concept of operations, and technological capabilities needed for an Autonomous Space Weather Constellation. The constellation will observe the Sun from multiple vantage points and sample solar-wind conditions from multiple locations. It aims to fill the gaps in our observational capabilities in order to facilitate validated, near-real time, data-driven models of the Sun's global corona, heliosphere, and associated space weather effects to safeguard human and robotic exploration throughout the solar system.

2. Background

The mission concept presented here is an outgrowth of the Heliophysics Design Reference Missions (DRMs) discussed in the Report from the 2018 Workshop on Autonomy for Future NASA Science Missions (Tan et al. 2019). One of the DRMs discussed in the report[1] is the Autonomous Space Weather Constellation. Here we summarize the science rationale, the concept of operations, and the enabling technologies needed to enable this mission. These topics will be discussed in further detail in the Heliophysics 2050 Workshop paper.

3. Scientific Rationale

The current Heliophysics System Observatory (HSO) has provided unprecedented coverage of the Sun and its impact on Earth, the planets, and other small bodies (e.g., comets) in the solar system. However, the research community and NOAA cannot yet provide the following types of predictions with high accuracy and confidence:

- Predict (not after the fact) whether a sunspot region will spawn coronal mass ejections (CMEs), solar flares, and energetic particle events in the next hours to days
- Predict the arrival time and physical properties of the solar wind and transient events (such as CME) to better than about ½ a day

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[1] The workshop report is intended to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

- Predict the geoeffectiveness (in terms of geomagnetic storm strength, e.g. *Kp* index or *Dst*) of CMEs, whether they are directed toward Earth or slightly away from Earth, with more than 1 hour lead time
- Provide an "all clear" prediction for inclement space weather activity over next month

While there are isolated instances of success, none of the aforementioned predictions can be provided with reliability over a broad spectrum of solar conditions. **One major reason for the lack of reliable space weather predictions is the sparse coverage of measurements in interplanetary space at scales of 1 AU.** Specifically:

- A lack of 4π steradian coverage of the Sun's photospheric/chromospheric fields introduces systematic errors in global field models
- Magnetic fields at the Sun's polar regions are not well-constrained
- Sparse in-situ sampling of the heliosphere limits the learning capability of solar wind and CME models.

The Autonomous Space Weather Constellation is a DRM aimed at filling the gap in our observational capabilities in order to facilitate validated, near real-time, data-driven models of the Sun's global corona, heliosphere, and associated space weather effects. The next section outlines the concept of operations for this DRM, and how it drives the need for specific autonomy capabilities.

4. Concept of Operations

To capture a broad range of solar conditions (from solar minimum to maximum, and back to minimum), the DRM has a nominal mission length of 10 years.

The DRM will consist of a constellation of spacecraft **S** = $\{S_0, S_1, \ldots, S_n\}$ offering a simultaneous $4\boldsymbol{\pi}$ steradian view of the solar surface. With a full suite of instruments onboard each spacecraft, the rate of data flowing into the onboard computer can easily be on the order of 100s of MB/s. A tiered storage/downlink concept will be employed to cull the data so the required telemetry is a factor of 1000 lower. This reduction cannot be accomplished using conventional compression techniques alone. Various approaches are required to achieve this data rate reduction including the following:

A. Onboard data processing to convert observables to higher-level, science-quality data products (e.g., converting 24 Stokes polarization images to six atmospheric measurements by performing onboard inversions, cf. use of an FPGA on Solar Orbiter's Polarimetric Magnetic Imager, or acceleration by deep neural networks)
B. Data culling (data cutouts, subsampling, onboard averaging): requires onboard inference to categorize datasets
C. Compressed sensing: i.e., designing detectors so that they capture the signal in terms of specially chosen basis functions, and downlinking those sparse coefficients for reconstruction on Earth
D. Conventional lossy data compression

A potential concept for downlinking data from the constellation is peer-to-peer relay communication. This approach may be necessary to increase effective mission-wide bandwidth, maximize temporal coverage, and minimize latency. For instance, consider a spacecraft at 1 AU behind the Sun. It is not possible to directly downlink data from the satellite to a ground station on Earth. To avoid a delay of several months to send the data, this satellite can send data to a peer in the constellation. The receiving peer, with a direct line-of-sight to the ground station, can then relay the data to Earth.

5. Constellation-enabling Technologies and Scientific Investigations

Autonomous capabilities are needed for the following purposes:

- Onboard decision making to effectively utilize resources (power, observing capabilities, onboard storage, telemetry)
- Onboard machine learning (inference) for local space situation awareness and to provide space weather alerts
- Collection of multi-vantage point data needed for a continuously driven model of the Sun and heliosphere
- Global imagers to autonomously identify 'interesting' regions, and direct more detailed telescopes

In the full workshop paper, we will map these required capabilities to nomenclature used in NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document.

A **constellation simulation testbed** is needed to optimize the scientific value and operational benefit of the constellation. The testbed needs the following components:

- Physics-based magnetohydrodynamic (MHD) solver(s) driven by remotely sensed and in situ observations
- Modules for synthesizing observables measured by instruments in the constellation, including instrument characteristics (e.g., telescope point spread function, particle hits on detectors, noise, etc.)
- Modules for simulating onboard processing, including inference
- Module for the creation, sending, and receiving of peer-to-peer messages
- Module for autonomous decision making by members of the constellation

6. Summary

The Autonomous Space Weather Constellation aims to enhance our ability to understand and accurately forecast space weather events. It can be considered the deep space counterpart to the Geospace Dynamics Constellation (GDC; Jayes, Ridley et al. 2019). Whereas the GDC aims to monitor and understand space weather manifestations in geospace, the constellation presented here is focused on identifying the solar/heliospheric drivers of inclement space weather. It thus ideally complements the goals of GDC.

7. References

Jaynes, A., Ridley, A. et al, 2019, *Final Report of the Geospace Dynamics Constellation Science & Technology Definition Team*

Tan, F. et al., *2018 Workshop on Autonomy for Future NASA Science Missions: Outputs & Results*