Solving the Space Weather Problem: A 15+ Year Roadmap to Revolutionize Space Weather Research, Protect NASA Space Assets, and Enable Robust Operations

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Abstract

We propose a 'system-of-systems'—an integrated web of SpWx stations and state-of-the-art modeling facilities to enable a transformative advance in Space Weather nowcasting and forecasting. The Space Weather Aggregated Network of Systems (SWANS) will enable space situational awareness for end-users invested in spaceflight operations, infrastructure risk mitigation, and future human endeavors in space exploration while profoundly transforming Heliophysics research by 2050 or earlier.

Solving the Space Weather Problem:
A 15+ Year Roadmap to Revolutionize Space Weather Research, Protect NASA Space Assets, and Enable Robust Operations

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This document outlines a roadmap for addressing the Space Weather (SpWx) problem. It presents a strategic vision of how a community-wide effort could be organized and implemented to enable transformative advancement in SpWx research and ultimately, in applications.

We envision a ***'system-of-systems'—an integrated web of SpWx stations and state-of-the-art modeling facilities to enable a transformative advance in SpWx nowcasting and forecasting (Fig. 1)***. The **Space Weather Aggregated Network of Systems (SWANS)** will enable space situational awareness for end-users invested in spaceflight operations, infrastructure risk mitigation, and future human endeavors in space exploration while profoundly transforming Heliophysics research.

We approach the problem by identifying user (NASA or otherwise) requirements and tracing them through *science-measurement-performance* requirements to provide closure to a particular SpWx concern. We consider this a blueprint for a wider SpWx infrastructure plan that incorporates operational infrastructure to meet the needs of the Federal Government and SpWx users and taking full advantage of the current scientific understanding of SpWx.

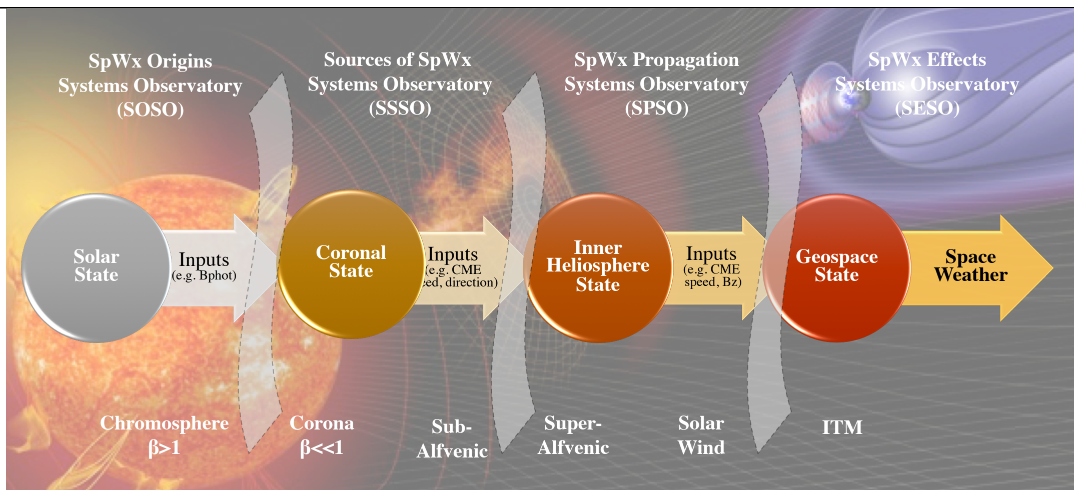

Figure 1 ***Conceptual strategy for developing a SpWx research plan. We treat SpWx as a chain of physical systems from the Sun to Earth, each with its own requirements, 'chokepoints', and infrastructure plan.***

Solar/Heliospheric/ITM Systems Observatories (SxSOs)*: A coordinated space fleet of research and monitoring sensors deployed in key locations within the inner heliosphere and geospace, from LEO to lunar to Sun-Earth Lagrangian points and beyond. Dedicated Data Centers, optimized for the operational and other idiosyncrasies of their Systems Observatory, archive and process the data into higher-level products. The Centers serve as research facilities and training centers for the next generation of researchers and SpWx operators.*

SWANS Modeling Centers*: Aggregate all in-situ and remote sensing data from the SxSOs and feed them into a comprehensive system of data-ingestive models for basic and applications-oriented research, such as nowcasting and forecasting of critical space weather risks and hazards. Depending on Agency-level agreements, the Center serves as an R2O transitioning and training facility.*

Building SWANS (in approximate timeline order)

- **Driving Requirements** from NASA and SpWx end-users (e.g. collision avoidance)
- **Strategic Knowledge Gaps** based on (1) the driving requirements and (2) a thorough assessment of the current status of SpWx prediction performance for various SpWx concerns (e.g. CME occurrence or regional forecast of ionospheric disturbances) and (3) the identification of '*chokepoints*' in observational or modeling capabilities that create the Gaps
- **Science Investigation Strategy:** Faced with a complex and highly nonlinear system, our strategy is to approach SpWx as a 'system-of-systems'. This allows us to treat the SpWx problem as a chain of smaller interconnected systems and then develop a research infrastructure plan around each one of them (SxSOs in Fig. 1)

Table 1 Example Traceability Matrix for defining a SOSO development plan

SpWx Req.	Chokepoint	Key Measurement	Benefit	Measurement Approach		
				Now	Next	Closure
Long-term forecasting (3+ days)	limited info on fa- side magnetic activity	Increase B_{phot} coverage: over East limb (now) to full 360° (next)	higher fidelity MHD corona-helio models → accurate CME/SW propagation modeling	B_{phot} from L5	B_{phot} from L5/ L4	4π coverage
Storm Intensity Dst (1+ day)	Unknown CME Bz magnitude and duration	Measure CME Magnetic Field	Increase Bz prediction accuracy	Exploit PSP, SO, Bepi	Upstream (~0.3au) B, meas	B_{COR}@ source, up-stream B grid.

- **Science Investigation Plan:** The components for each SxSO are derived by identifying the research 'chokepoints' at each physical regime with respect to particular SpWx requirements and tracing them to measurements, instruments and finally mission concepts. The resulting traceability matrices provide the foundation for designing roadmaps to build SxSO's, in accordance to the HPD resource strategy and constraints. In addition, the traceability matrices reveal gaps in technology or modeling tools and hence help identify areas for investment and/or collaborations with other Divisions, Agencies, Industry, both domestic and foreign.
- **SWANS Enabling infrastructure:** The success of the SWANS strategy depends not only on the ability to deploy the SxSOs but crucially in the ability to receive/process the observations, ingest them into models and provide concrete advances to meet SpWx users' needs. Any infrastructure implementation plan needs to include investments in the areas of **technology development**, **modeling tools/approaches**, and particularly**, targeted research programs**.
- **Near-Term Opportunities (aka 'low-hanging fruit'):** The full SWANS concept requires a substantial augmentation of the HPD budget over several years. There are, however, opportunities to advance the SxSA goals in the meantime. The strategy should identify these 'low-hanging fruits' such as, domestic/foreign rideshare opportunities, existing, but unexplored observations/databases, algorithmic developments that require minimal investments, etc. Leveraging of existing programs (Explorers, MoO, Balloons, etc.) should also be considered**.**
- **Mission/Instrument Concepts Archive:** A collection of relevant decadal missions and other concepts (similar to the Helio Roadmap but focused on SpWx)

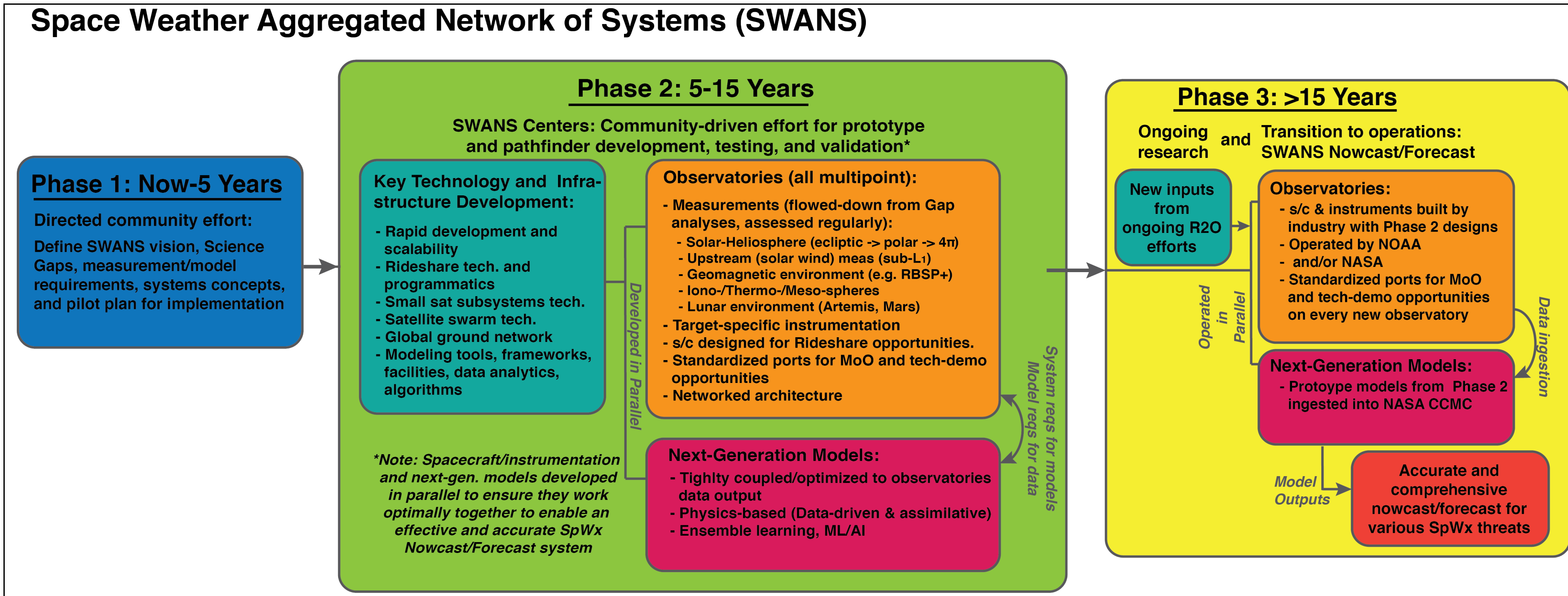

Figure 2 The organization and implementation strategy of SWANS.

Symbiosis with NASA Heliophysics: SWANS observatories expand the HSO and complement the Decadal Survey vision for future concepts (L5, Solar Polar, MagCon, etc.), as well as the DRIVE initiative. E.g. tech-demo and hosted payload opportunities on SWANS observatory platforms can be used to populate the geospace and inner heliosphere with instruments and data-coverage. DRIVE was recommended in part to enable transformative advances in the physical understanding of SpWx-relevant systems.

Data analytics component: SOC and operational/scientific data products from a massive constellation of simultaneous remote and in situ measurements (i.e., big data) will leverage state-of-the art algorithms of data-assimilative modeling, machine learning, and data-mining while maximizing the use of the HSO.

Strong modeling component: Global operational products for forecasting and nowcasting and anomaly analysis of SpWx hazards will leverage data-augment physics-based and data-driven and -assimilative models developed via SWANS. These models will provide share-holders and end-users with a series of user-friendly outputs for system nowcasting, forecasting, and space situational awareness applications.

Rapid development/scalability: SWANS can be developed modularly and continuously in an orchestrated effort and implemented over years in an ad hoc manner to meet the ever-growing needs of spaceflight operations and mitigating the risks of space weather. Individual SWANS observatories can be deployed separately or in groups based on the availability of resources and launch opportunities.

Community-wide participation: After preliminary prototype observatories and payloads are developed and flight proven, the "standard" SWANS payloads should be licensed to and mass-produced by industry. Each observatory in the network can be supplemented by NASA-funded low-cost MoO (HTIDES, TDO, etc.) programs, hence opening it to the entire community, enabling an additional program for high-end instrument development and testing in relevant environments. This will be enabled by developing a standard for SWANS spacecraft–instrument interfaces.

Simple, streamlined bus designs and operations: Each SWANS spacecraft could be a small sat built to a standard design for a desired orbit and delivered by ESPA-class, ride-share launch opportunities, for flexibility and versatility and required high-frequency of launches to populate the system of observatories.