Space Weather Operations and Research Future Infrastructure Workshop

This activity, the first of two workshops requested by NASA, NOAA, and the NSF, considers options for continuity and future enhancements of the U.S. space weather operational and research infrastructure. The workshop was held virtually in two parts: on July 16-17 & September 9-11, 2020.

Planning the Future of Space Weather Operations and Research Infrastructure

COMMITTEE FOR THE SPACE WEATHER OPERATIONS AND RESEARCH INFRASTRUCTURE WORKSHOP

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- **TUIJA I. PULKKINEN, NAS,[2] University of Michigan**
- **PETE RILEY, Predictive Science, Inc.**
- **RONALD E. TURNER, ANSER, Inc.**

Space Weather Operations and Research Infrastructure Workshop Phase 1

Project website:

https://www.nationalacademies.org/our-work/space-weather-operations-and-research-infrastructure-workshop

June 16-17, 2020 workshop (including presentations)

https://www.nationalacademies.org/event/06-16-2020/space-weather-operations-and-research-infrastructure-workshop-part-1

Sept. 9-11,2020 workshop (including presentations)

https://www.nationalacademies.org/event/09-09-2020/space-weather-operations-and-research-infrastructure-workshop-part-2

Space Weather Operations and Research Infrastructure Workshop Statement of Task:

Phase 1

The National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee to organize a workshop that will consider options for continuity and future enhancements of the U.S. space weather operational and research infrastructure. A report of the workshop proceedings will follow. The workshop will:

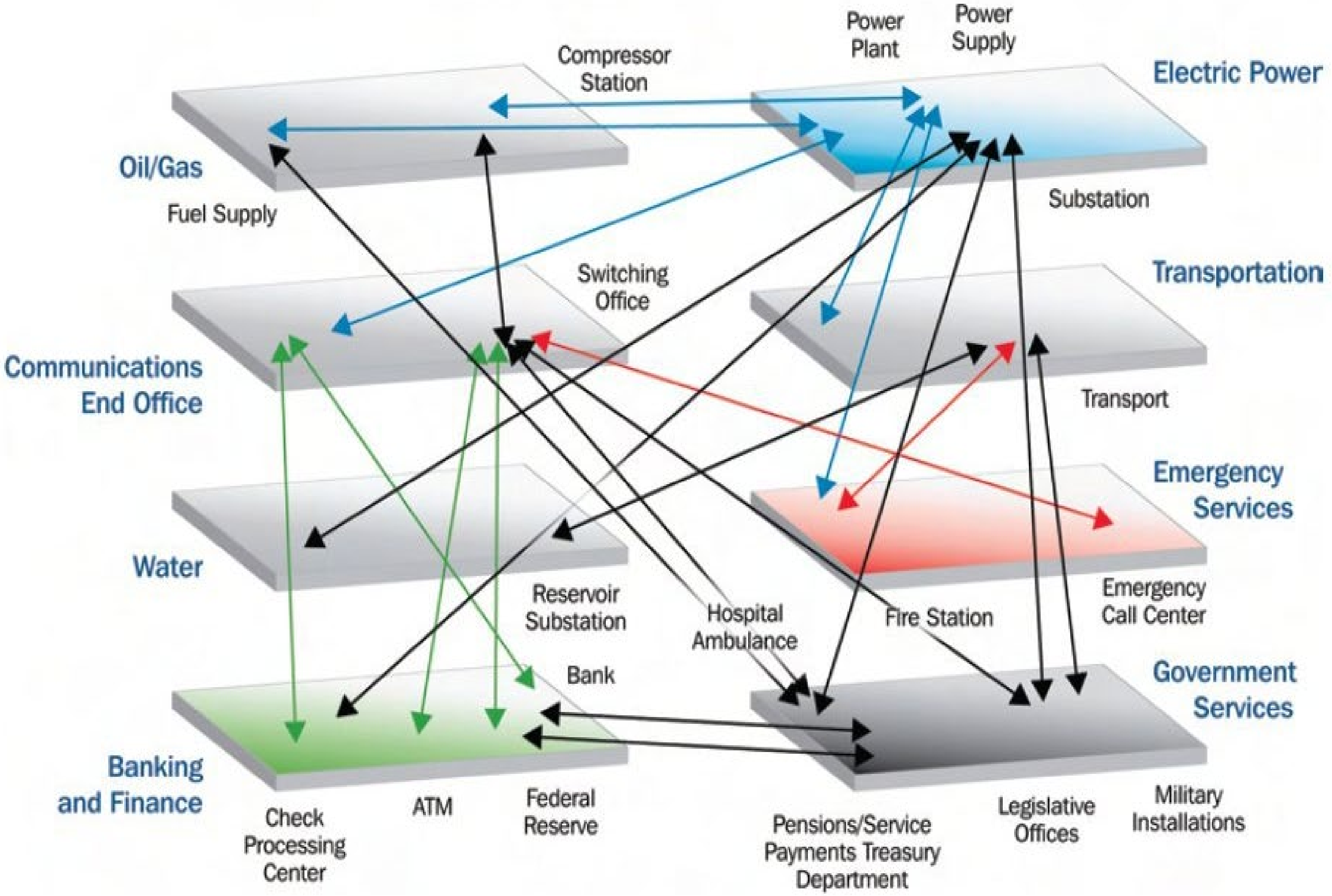
1. Review current and planned U.S. and international space weather-related observational capabilities;
2. Discuss baseline space weather observational needs;
3. Identify programmatic and technological options to ensure continuity of the baseline, giving particular attention to options to extend the Space Weather Follow On (SWFO) program; and
4. Consider options for technology, instrument, and mission development to support in situ and remote sensing space weather observations from either ground- or space-based vantage points, the latter including L-1, L-5, L-4, GEO, and LEO.

Phase II Workshop-Context

- While the Phase I workshop was oriented towards the identification of observations needed to advance space weather forecasts (“operational needs”), the Phase II workshop will be more focused on the research agenda and observations needed to improve understanding of the Sun-Earth system that generates space weather consequences.
- In addition to revisiting items from the Phase I workshop in need of further exploration, Phase II would, at the highest level – and taking into account the results of NASA’s space weather current science gap analysis and other relevant studies – seek to identify the key elements needed to establish a robust “research” infrastructure.

Executive Summary - Introduction

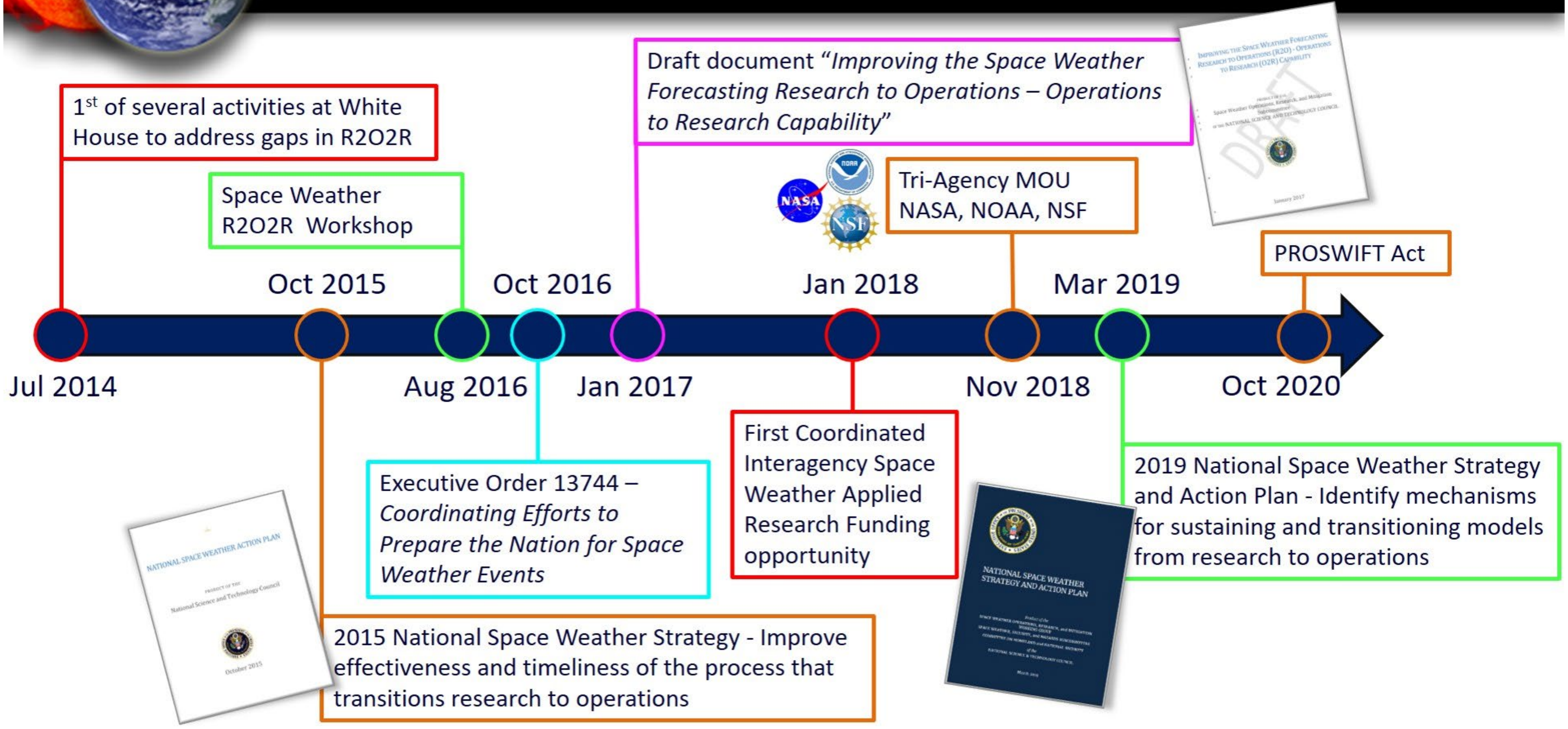
Connections and interdependencies across the economy



Severe Space Weather Events: Understanding Societal and Economic Impacts: A Workshop Report. Washington, DC: The National Academies Press. https://doi.org/10.17226/12507

National Priorities and the Development of a National Strategy for Space Weather, Tamara Dickenson, Chair

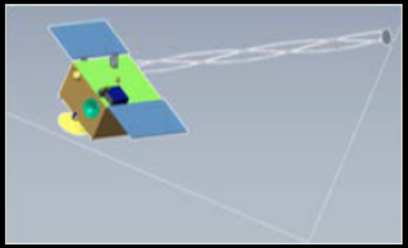
Policy Drivers for Space Weather Research-to-Operations-to-Research (R2O2R)



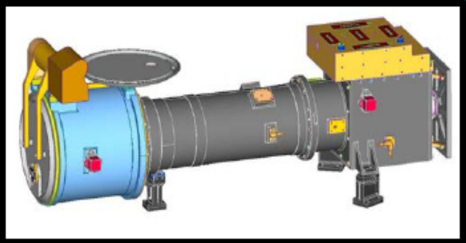
Agency Presentations: NOAA, Elsayed Talaat and Steve Voltz

SWFO Program Key Technical Components

3-Axis Stabilized ESPA Class Spacecraft

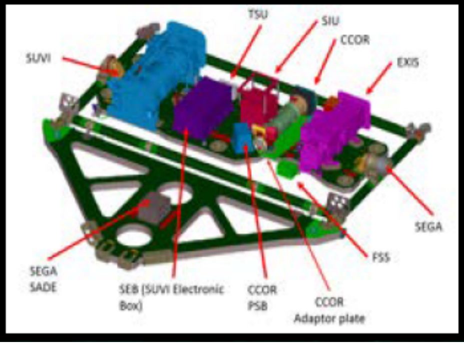


Compact Coronagraph (CCOR)



GOES-U Solar Pointing Platform (SPP)

CCOR + SUVI + EXIS



SWFO-L1 Mission Overview

- Space Weather Operational Observation at Earth-Sun Lagrange Point 1
- IAA with NASA to procure an ESPA Grande compatible spacecraft
- SWIS (Solar Wind Instrument Suite) awards nearly complete, CCOR in Phase D
- NOAA ground services
- Rideshare with NASA IMAP
- Nominal launch: 2024
- Potential ESA contributed instrument (X-Ray flux monitor)

Coronagraph Project

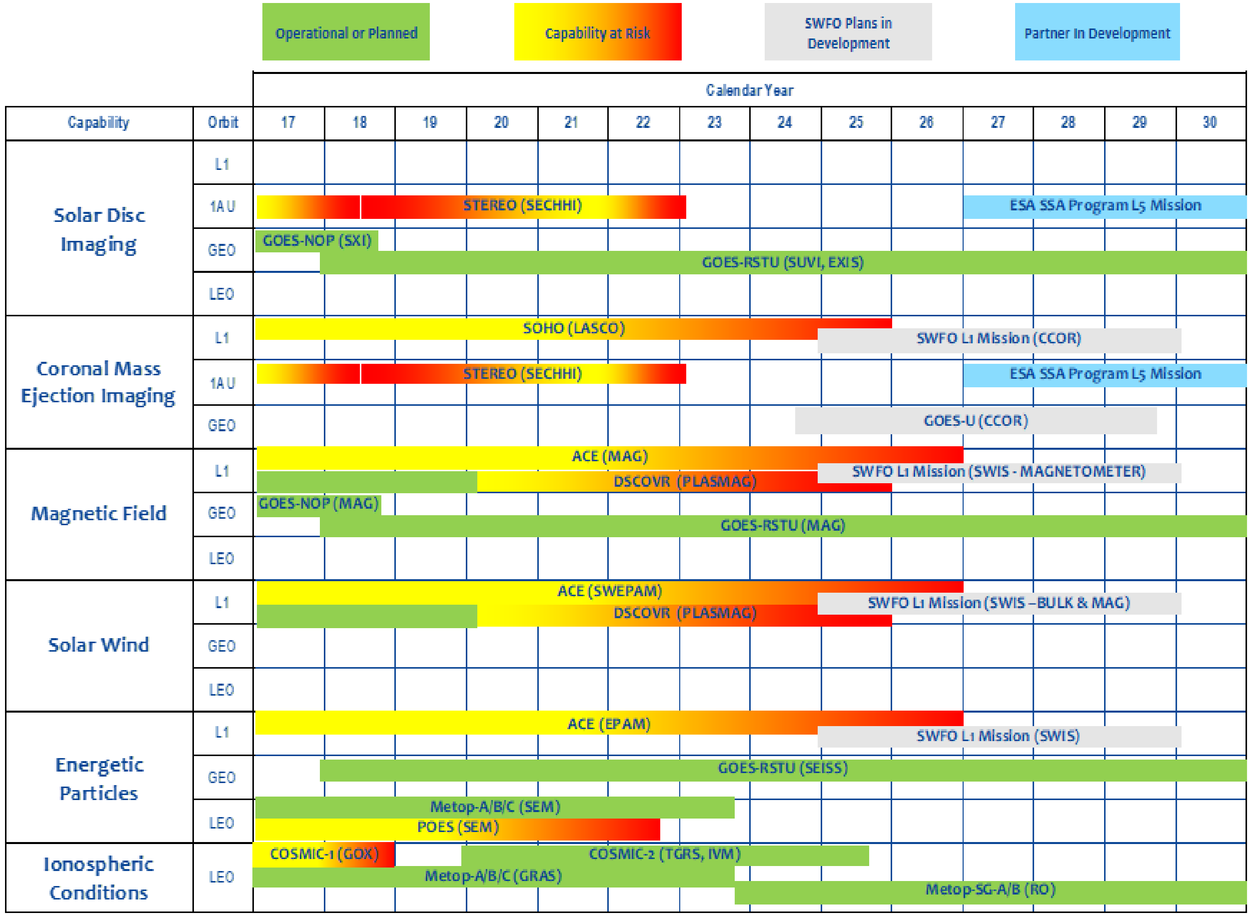
- Compact Coronagraphs under development by NRL via an IAA
- CCOR for SWFO-L1 Satellite, deliver 2022
- CCOR for GOES-U, deliver 2021
- Potential CCOR for ESA-L5 Satellite, deliver 2023

Coronagraph Accommodation on GOES-U

CME imaging from geostationary orbit
CCOR Integrated onto GOES-U SPP
Commanding and data flow through GOES-R ground services
Nominal launch: 2024

National Environmental Satellite, Data, and Information Service

Planning for Operational Space Weather (SWx)



Current "constellation" is a mix of research and operational space and ground assets.

NOAA, working with partners, is leading the transition to an operational SWx constellation.

Future system will continue to feature research (NASA, ESA, USAF, ISRO) and operational (NOAA, EUMETSAT, USAF, others) assets.

Current and planned constellation is mix of multi-agency research and operational assets: Dr. Stephen Voltz, NOAA

NASA Space Weather Strategy

Vision: Advance the science of space weather to empower a technological society safely thriving on Earth and expanding into space.

Mission: Establish a preeminent space weather capability that supports robotic and human space exploration and meets national, international, and societal needs by advancing measurement and analysis techniques, and by expanding knowledge and understanding for transitioning into improved operational space weather forecasts and nowcasts.

NASA is in the process of developing an implementation plan.

Presentation by Jim Spann

1. Observe
- Advance observation techniques, technology, and capability

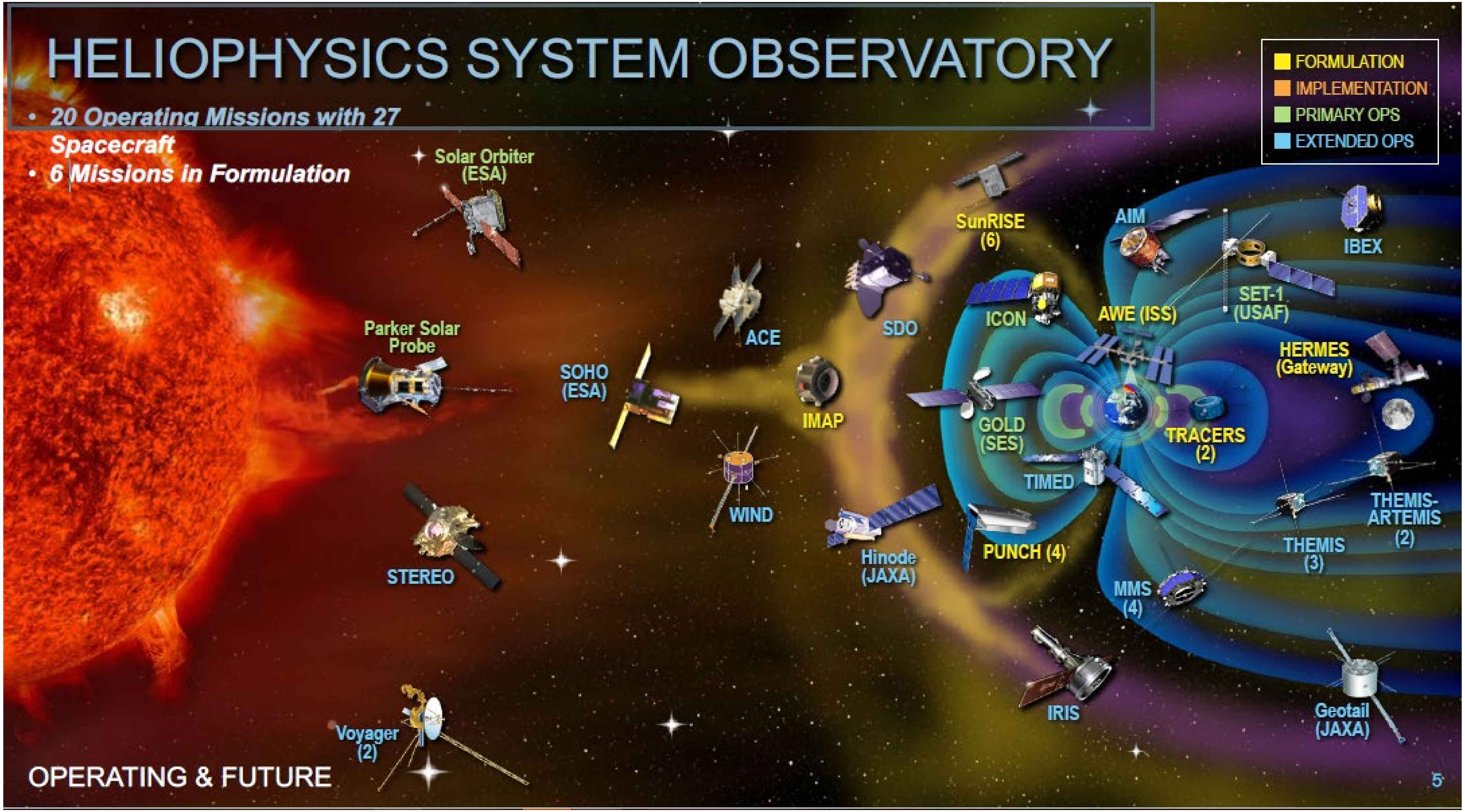
2. Analyze
- Advance research, analysis and modeling capability

3. Predict
- Improve space weather forecast and nowcast capabilities

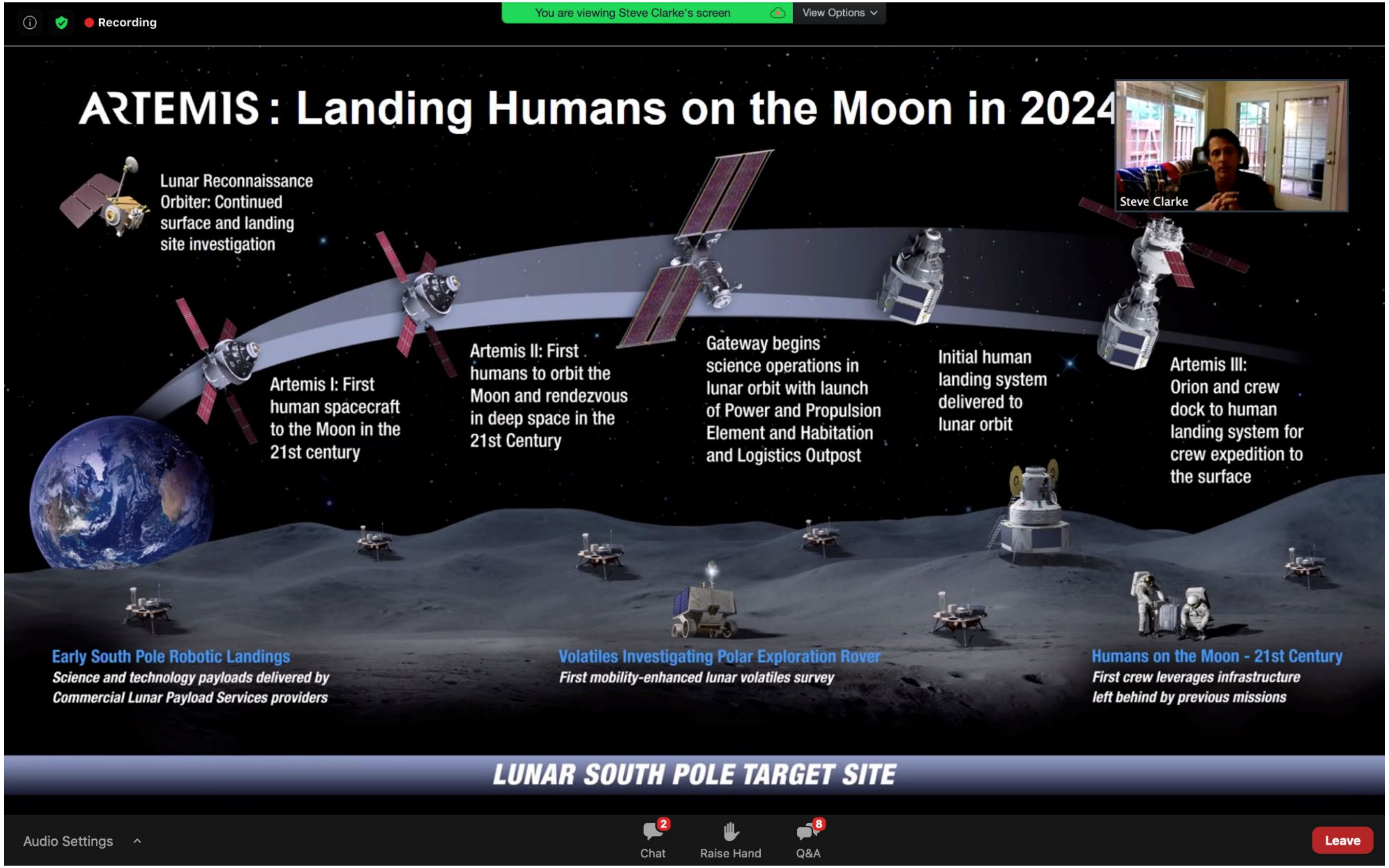
4. Transition
- Transition capabilities to operational environments

5. Support
- Support Robotic and Human Exploration

6. Partner
- Meet National, International, and societal needs consistent with Government directives


HELIOPHYSICS SYSTEM OBSERVATORY
• 20 Operating Missions with 27 Spacecraft
• 6 Missions in Formulation
FORMULATION
IMPLEMENTATION
PRIMARY OPS
EXTENDED OPS
Solar Orbiter (ESA)
Parker Solar Probe
STEREO
Voyager (2)
SOHO (ESA)
ACE
WIND
IMAP
SDO
Hinode (JAXA)
SunRISE (6)
ICON
GOLD (SES)
TIMED
PUNCH (4)
IRIS
AIM
AWE (ISS)
SET-1 (USAF)
IBEX
HERMES (Gateway)
TRACERS (2)
THEMIS-ARTEMIS (2)
THEMIS (3)
MMS (4)
Geotail (JAXA)
OPERATING & FUTURE
5

National Priorities for Human Spaceflight, John Allen, NASA Human Exploration



NSF Space Weather Research – Mike Wiltberger AGS

Supports investigators using observations, modeling, and theory to advance fundamental understanding of space weather and related processes

DKIST

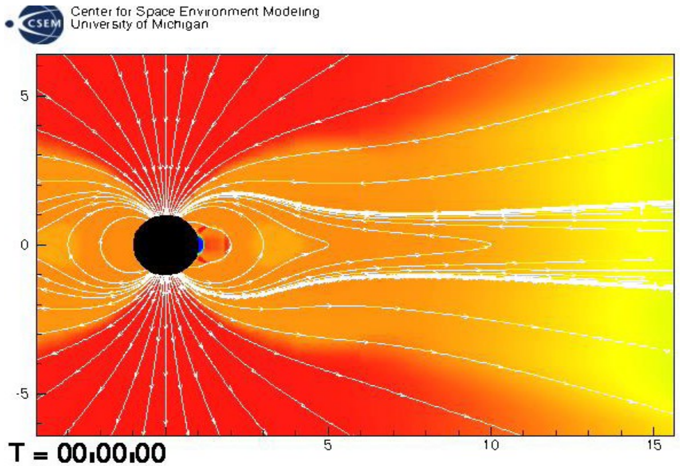
Incoherent Scatter Radars
AMISR, Arecibo
Jicamarca, Millstone Hill

Ground based monitoring
- **Magnetometers**
- **Neutron Monitors**

Superdarn Coherent Radar Network

New CubeSats: SWARM-EX constellation for studies of iono-thermosphere
VISOR-3 CubeSats to study coronal heating

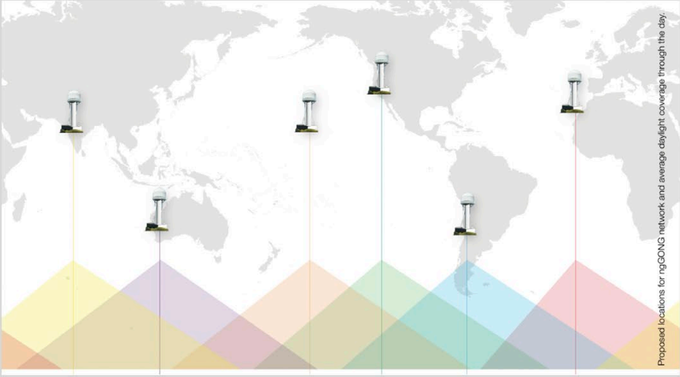
AMPERE – Uses magnetometers from Iridium satellite phone/data constellation to compute J in/out ionosphere



Modeling including NOAA-NASA-NSF R2O2R Partnership

Global Oscillations Network Group (GONG)
- 6 Instruments deployed across the globe
- Originally designed for solar interior studies
- MOU between NSF and NOAA supports data input to operational forecast system of solar B-field

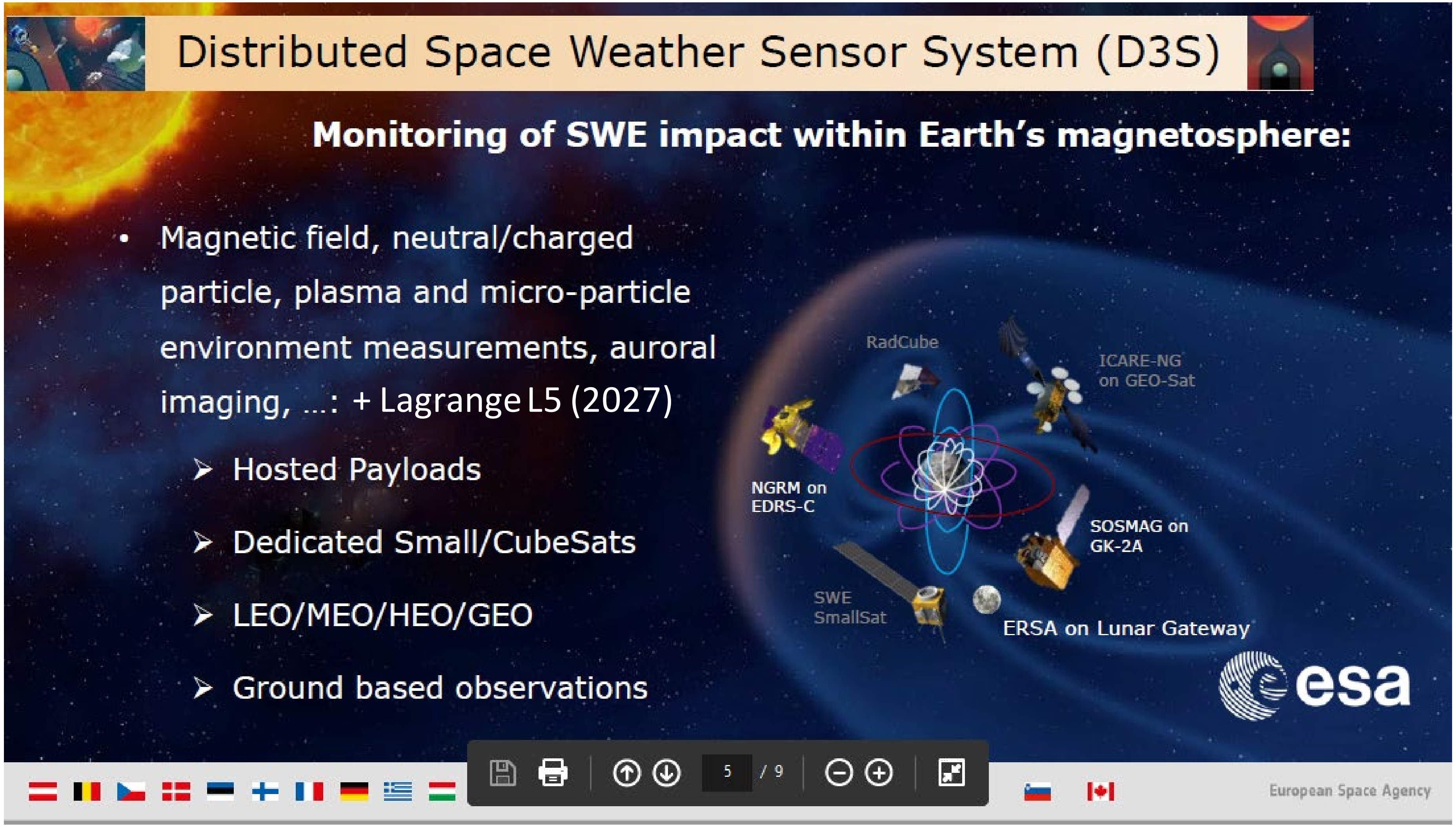
ngGONG Definition


Proposed locations for ngGONG network and average daylight coverage through the day.

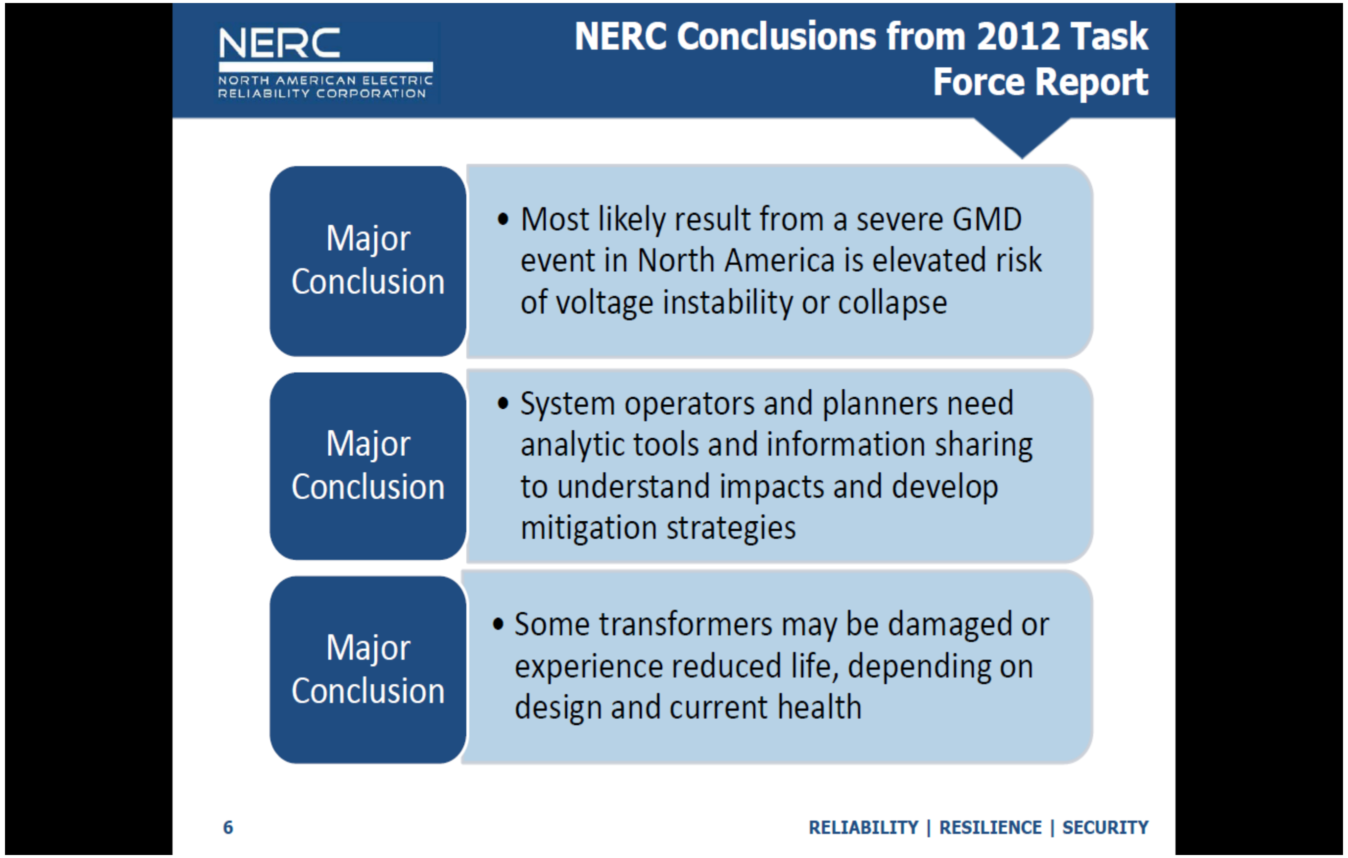
- ngGONG includes Space Weather considerations and requirements
- Provides the initial conditions to propagate **magnetic** CMEs & halo CMEs (from the ground)
- 24/7 boundary data for models that predict solar-wind & B_z. Requires bigger telescopes (**50 cm**)
- Requires constant, homogeneous image quality similar to space (**GLAO**). High transparency skies.
- Continues decades long observation of the solar interior & **far-side**
- Builds on **GONG** success: identical stations, autonomous operations

Complimentary and Collaborative International Activities

Representatives from JAXA, ESA, Canada: Mamoru Ishi, Juha-Pekka Luntama, David Boteler

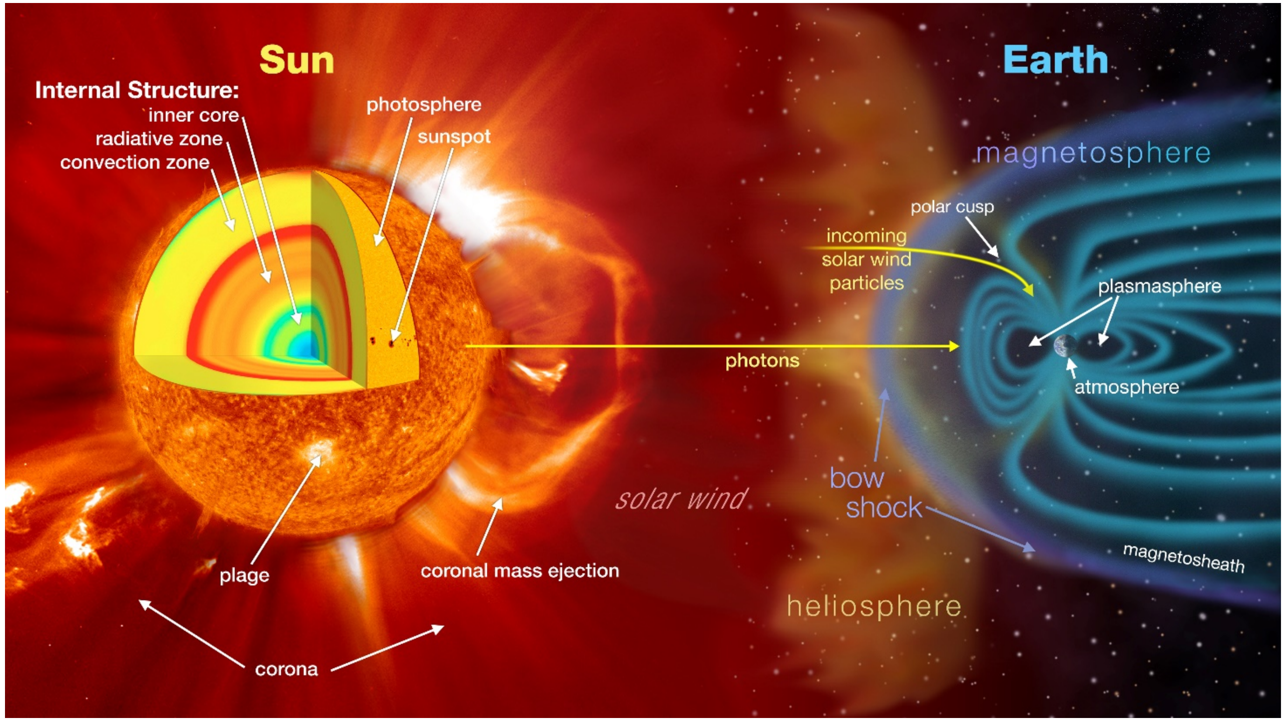


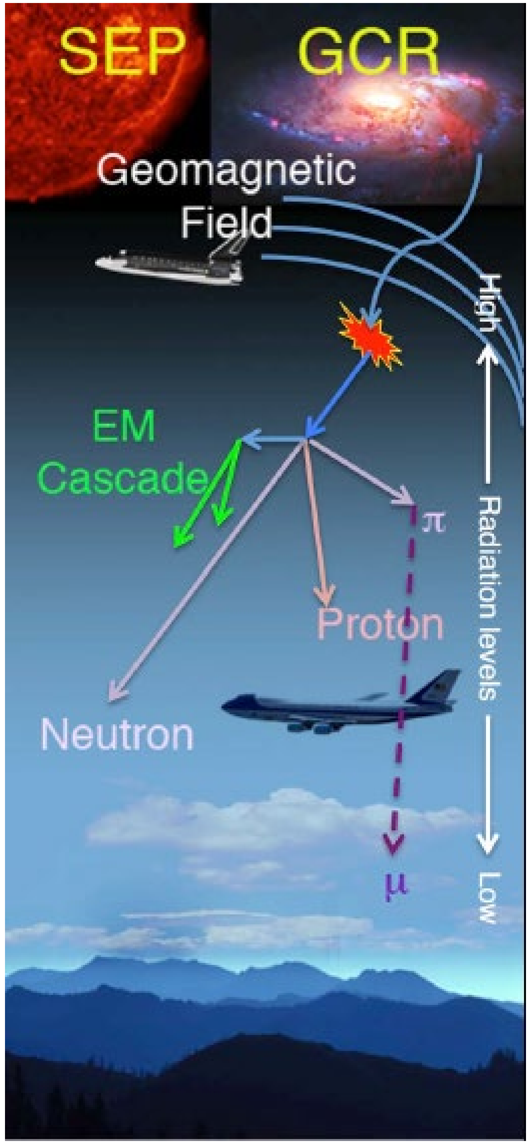
Space Weather User Community Needs, Conrad Lautenbaucher, Chair



Electric Power Industry, Aviation, Position-Navigation-Timing (GPS) users, Space Traffic Management

Sun/Heliosphere Knowledge Gaps, Janet Luhmann, Chair





- Sun/Heliosphere Knowledge gaps affect our Space Weather forecast capability on many fronts, including radiation effects on aviation and Humans in space, and both space-based and ground-based technologies and systems. The potential for long-lead forecasts depends on filling these gaps.

Samples of Useful Continuous Solar/Heliosphere Measurements

Global Solar Remote Sensing Measurements

1) Solar full-disk magnetograms obtained from a sufficient number of viewpoints to create updating (daily or better) global solar magnetic field maps.
2) Coronal white light, EUV and X-ray images obtained from a sufficient number of viewpoints, to determine both the locations and magnitudes of flares, and the sizes, shapes, directions and speeds of coronal eruptions (CMEs).
3) More spatially focused, higher resolution and higher cadence magnetograms and EUV images
4) Sufficient reconnaissance observations from both the farside and high heliolatitudes to ensure correct interpretation of 1) and 2)

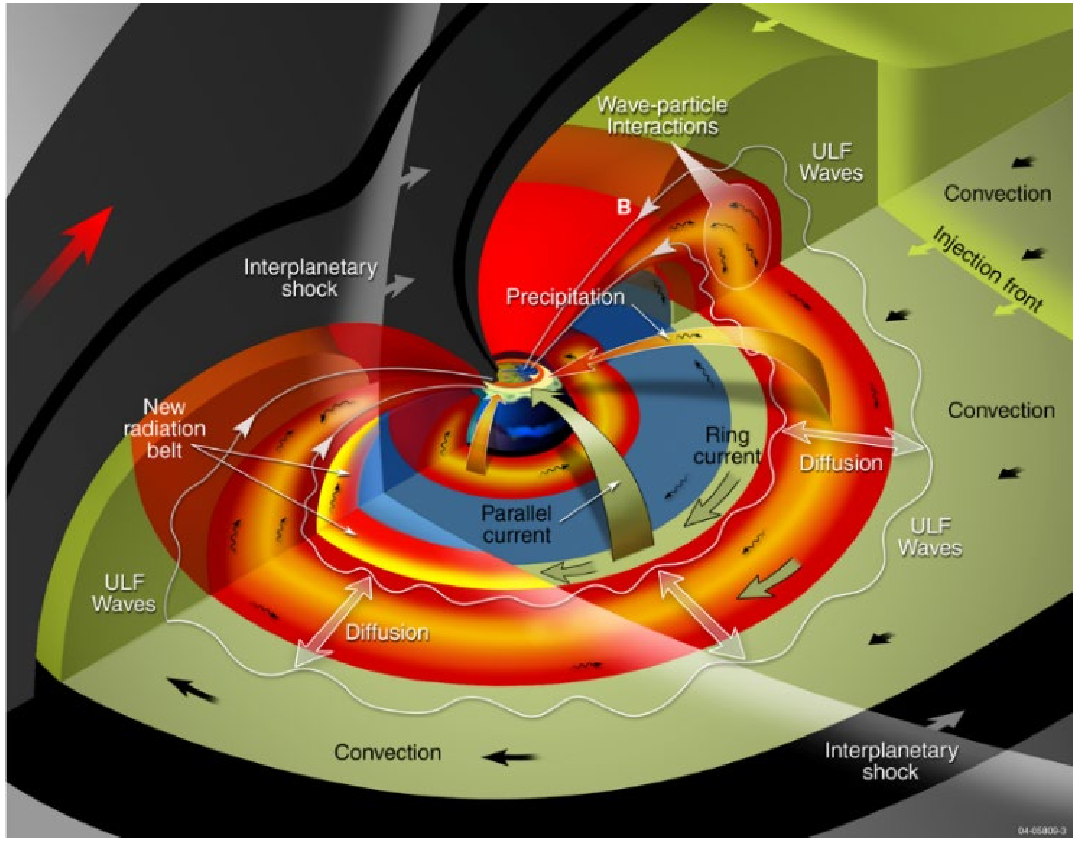
Multipoint, real-time in-situ measurements on and off the Sun-Earth-Line

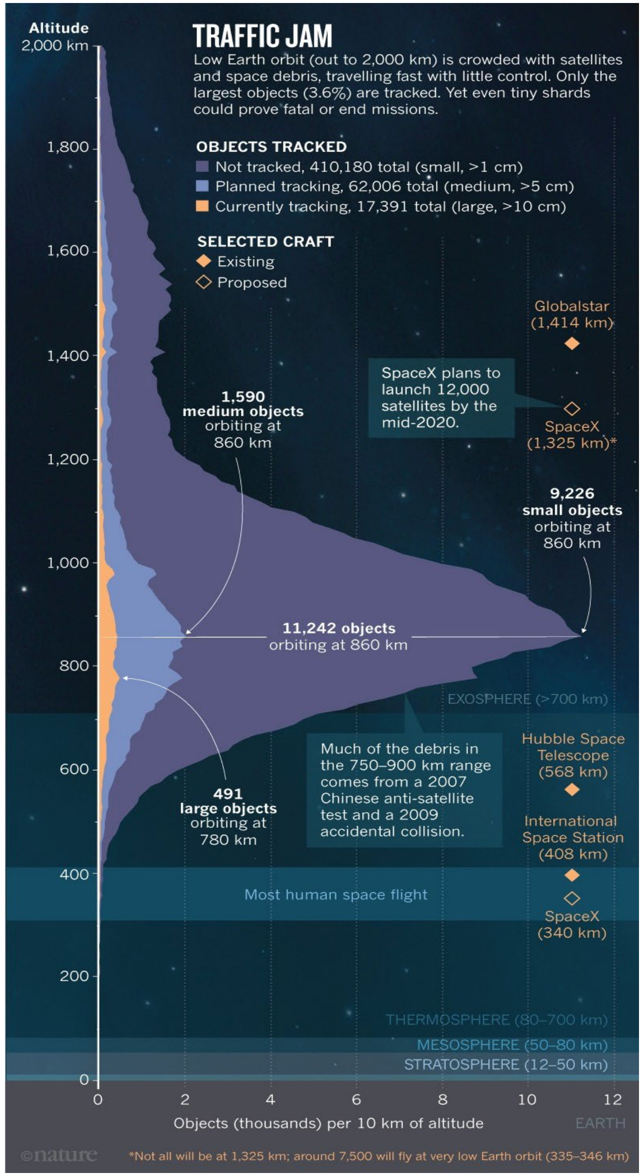
1) Regular solar wind plasma, vector magnetic field, and solar energetic particle (SEP) measurements at time resolutions from minutes to hours.

Research programs to Develop and Transition Solar/Helio Models with Forecast Potential

1) Realistic data-driven (and data-validated) models of the corona and solar wind, including the initiation and interplanetary results of coronal eruptions
2) Long term data- solar imaging and in-situ data sets
3) Applied machine learning analysis

Geospace Gaps, Mary Hudson, Chair





- Geospace knowledge gaps affect space weather forecasts – ICME arrival (left)
- Example: atmospheric density affects satellite drag & orbits
  Starlink deoribit following minor geomagnetic storm 38/49 s/c lost 3 Feb 2022;
- Cumulative space debris (right) may lead to collisional losses

Sample Continuous Geospace Measurements

Radiation belt electron, proton, ring current and plasmaspheric populations, in situ waves and fields measurements (1) near equatorial plane and (2) LEO polar orbits including Solar Energetic Particle access to high latitudes.

Plasmasphere, ring current, auroral imaging

Low-cost spacecraft charging/discharge monitors on every spacecraft.

Ground-induced currents	Regional and global magnetometer networks linked in real time.
Global ionospheric convection	SuperDARN coherent radar network.
Global B-field aligned current systems	Iridium satellite constellation for global phone/data (AMPERE)

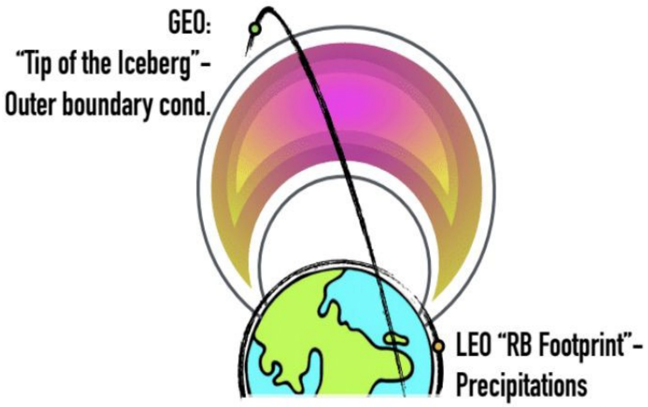
Global measurement of ionospheric irregularities:

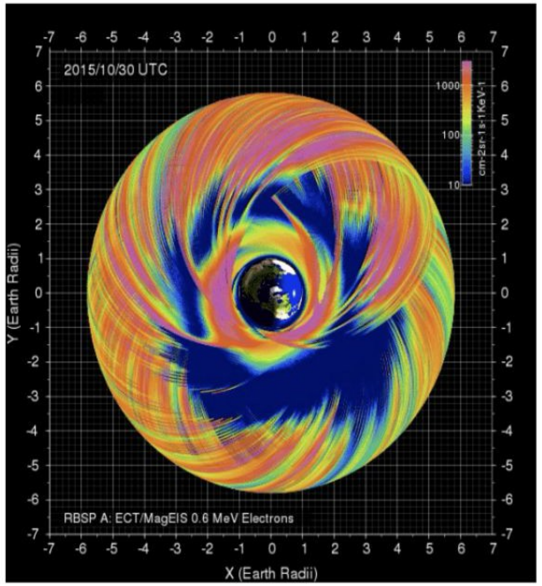
TEC measurement using GNSS satellites and ground/buoy receivers combined with radio occultation measurements

Global measurement of thermospheric neutral density, plasma drift, neutral composition, neutral dynamics,

Poynting flux from the magnetosphere and solar radiation (EUV flux) measurement

Other Infrastructure Issues: Space-based Architecture, Harlan Spence, Chair





Number of Small Sats by Sector

- Most commercial SmallSats are for remote sensing or broadband services

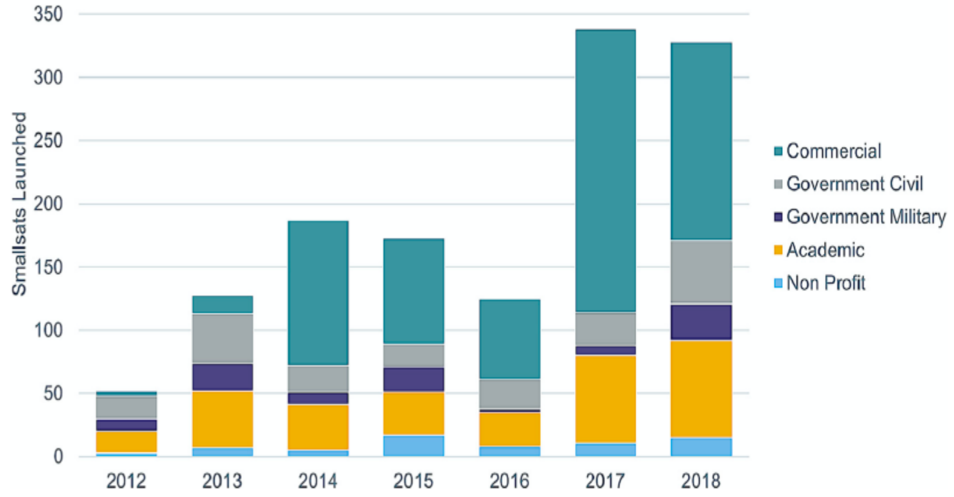


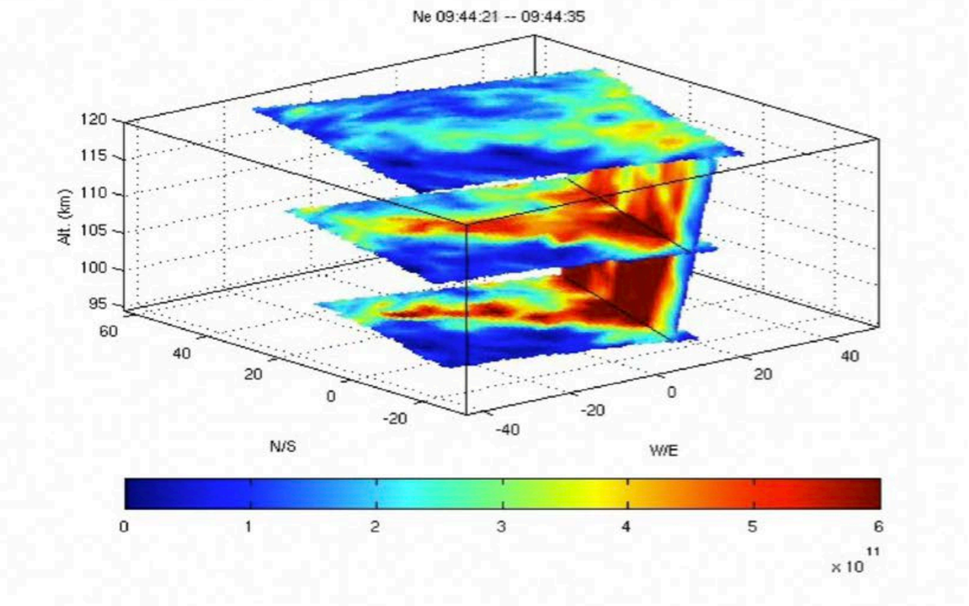
Image Credit: Bryce Space and Technology (https://brycetech.com/reports.html)

A constellation of small satellites at geo-transfer orbit can provide comprehensive radiation belt monitoring

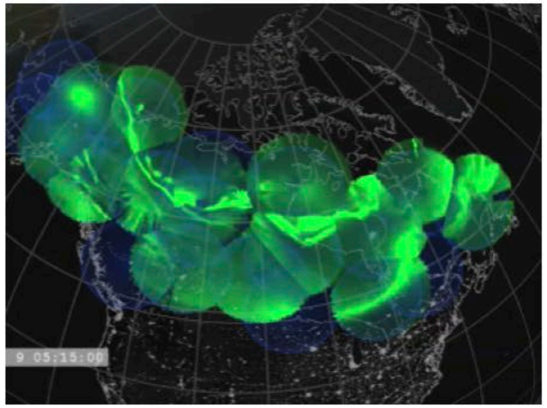
Ground-based Architecture, Anthea Coster, Chair

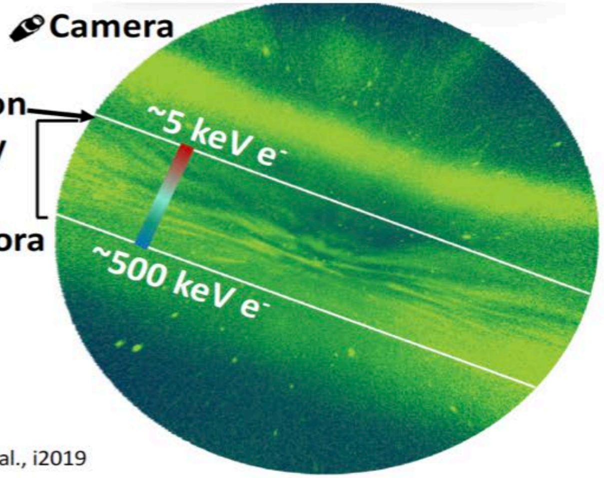
Atmosphere as particle detector

3D Image of the ionospheric response to a geomagnetic substsorm, captured with the electronically steerable ISR at Poker Flat, AK



ISR provides high quality localize 'ground truth' for developing space weather monitoring techniques



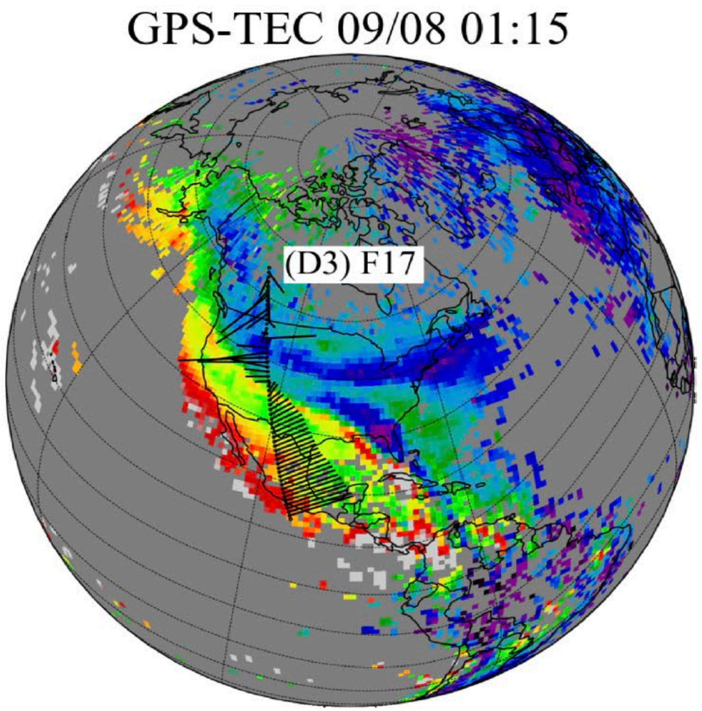


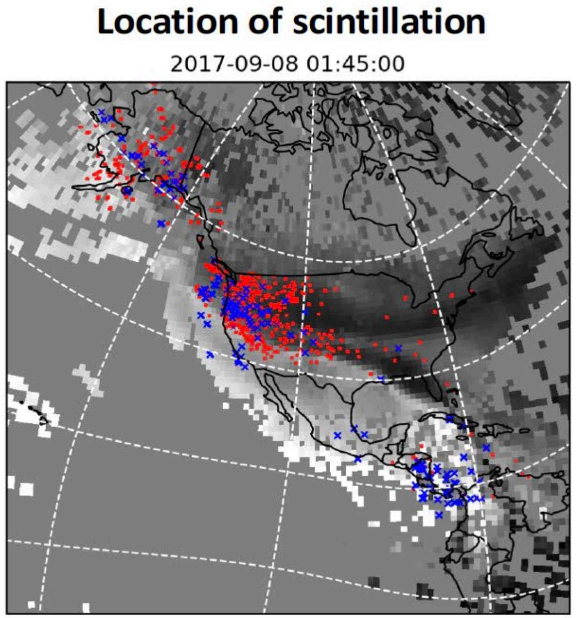
Sivadas et al., i2019

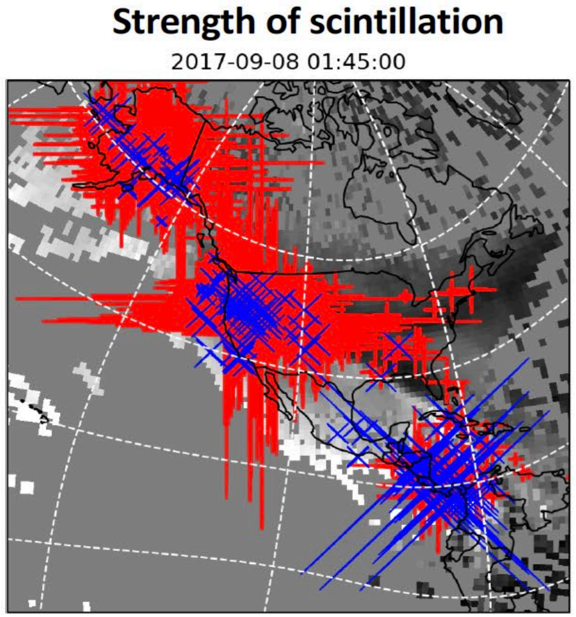
GPS scintillation over the continental U.S.

Tasks: 1) Construct an image of the ionosphere using ~40,0000 observations (5000 receivers x 8 satellites.
2) Compare with direct measurements of ionospheric flows by DMSP.

Result: A single diagnostic provides a map of the operational impact and the physical conditions that caused it.



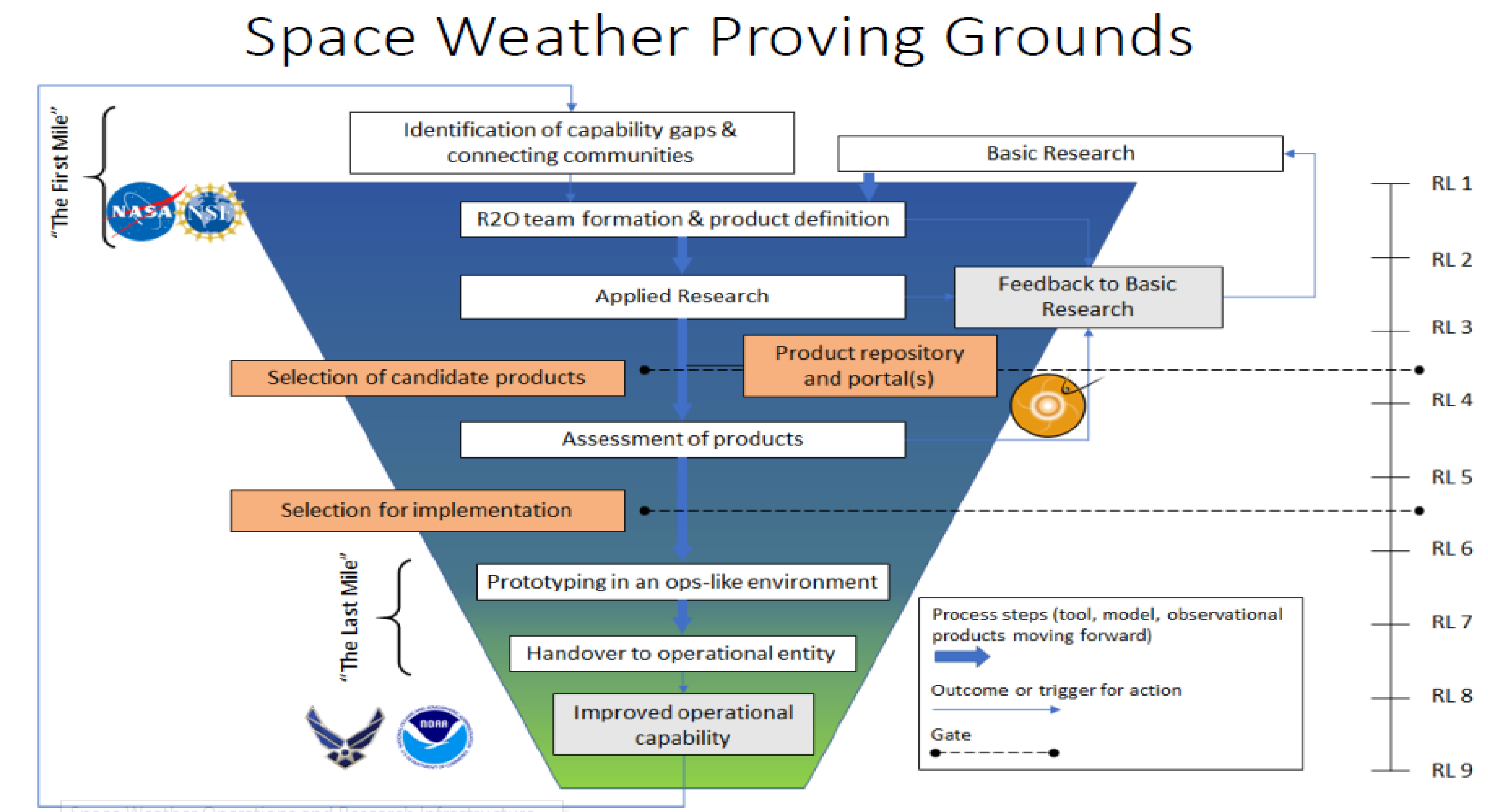




Red = phase scintillation Blue = amplitude scintillation

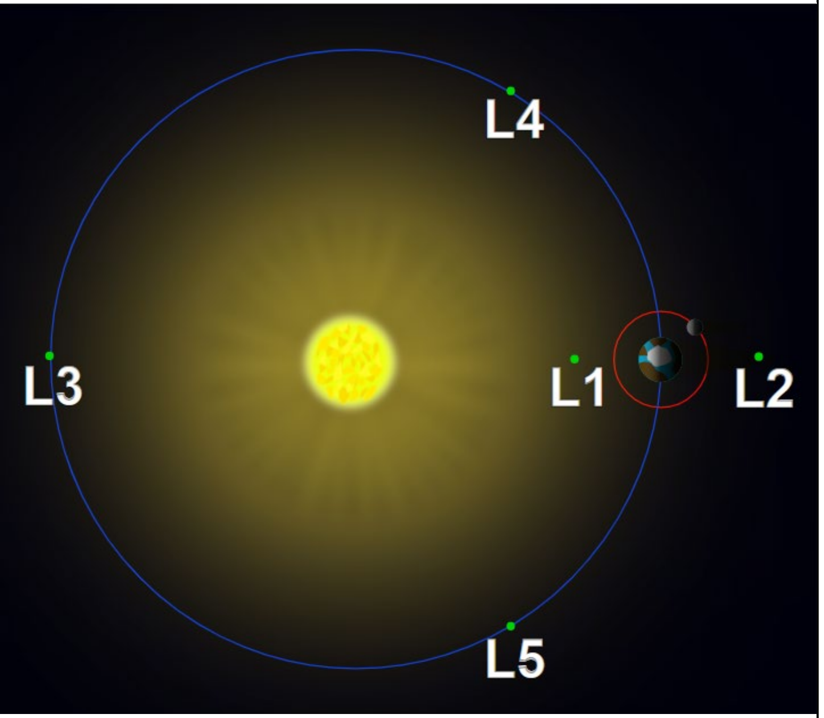
Mrak et al., in review

Supporting Research Architecture, Pete Riley Chair



Gabor Toth, model transition SWPC experience From: M. Leila May, "Model Validation and R2O at CCMC"

Summary of Report



- National Academies via an appointed ad hoc committee conducted a workshop that considered options for continuity and future enhancements of the space weather operational infrastructure. Example report chapters include:
  - Review current and planned U.S. and international space weather-related observational capabilities;
  - Review space weather observational needs;
  - Identify programmatic and technological options to ensure continuity of the baseline, the future Program of Record (POR), giving particular attention to options to extend the NOAA Space Weather (SWX) Program; and
  - Consider options for technology, instrument, and mission development to support in situ and remote sensing space weather observations from either ground- or space-based vantage points, the latter including L-1, L-5, L-4, 1Au coverage, sub-L1, GEO, GEOtransfer, and LEO among others.

Extra Slides

Project Context and Issues

- Objective II of the March 2019 National Space Weather Strategy and Action Plan: “Develop and Disseminate Accurate and Timely Space Weather Characterization and Forecasts.”
  - Requires the U.S. government to identify and ensure baseline observational capabilities, as well as to improve observations, research and modeling for characterizing and forecasting space weather events.
- The sponsors of the workshop are requesting a review of the current space weather capabilities in order to identify gaps and future needs for space weather products and services.
- The workshop's lead sponsor, NOAA, has asked that the workshop include a thorough examination of its Space Weather Follow On program (SWFO). This program seeks to establish the continuity of operational space weather observations beyond the currently operating DSCOVR mission and the joint ESA/NASA Solar and Heliophysics Observatory (SOHO) mission.
- NOAA and other workshop sponsors have requested an examination of potential improvements beyond the baseline capabilities SWFO is expected to provide, as well as an examination of future ground-based instruments relevant to space weather.
- The sponsors are also interested in examining emerging opportunities offered by smaller and more capable small satellites and smallsat constellations, as well as emerging capabilities in the commercial sector.

Phase 2 Workshop- SOT

• The National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee to organize a workshop that will focus on the research agenda and observations needed to improve the understanding of the Sun-Earth system that generates space weather consequences. Specifically, the Phase II workshop will:

• Examine trends in available and anticipated observations, including the use of constellations of small satellites, hosted payloads, ground-based systems, international collaborations and data buys, that are likely to drive future space
weather architectures; review existing and developing technologies for both research and observations;

• Consider the adequacy and uses of existing relevant programs across the agencies, including NASA's Living With a Star (LWS) program and its Space Weather Science Application initiative, NSF's Geospace research programs, and
NOAA's Research to Operations (R2O) and Operations to Research (O2R)programs for reaching the goals described above;

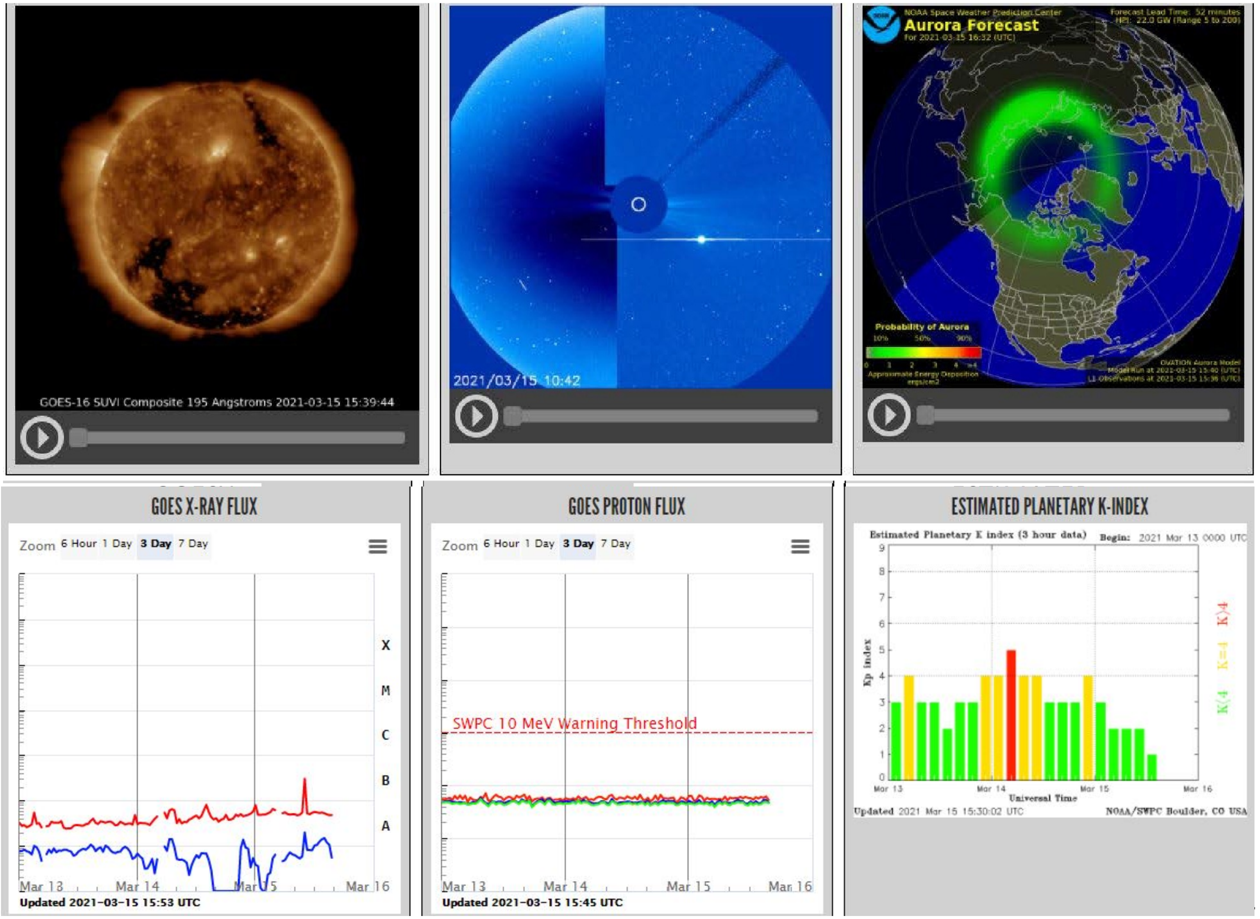
• Consider needs, gaps, and opportunities in space weather modeling and validation, including a review of the status of data assimilation and ensemble approaches;

• Consider how to incorporate data from NASA missions that are “one-off” or otherwise non-operational into operational environments, and assess the value and need for real-time data (for example, by providing “beacons” on NASA research missions) to improve forecasting models; and

• Take into account the results of studies, including NASA's space weather science gap analysis (part of the NASA Heliophysics Division's Space Weather Science Application program) and the NSF Investments in Critical Capabilities for Geospace Science (2016), to identify the key elements needed to establish a robust research infrastructure.

A proceedings summarizing the presentations and discussions at the workshop
will be prepared by the committee in accordance with institutional guidelines.

SWPC Home Page with Current Space Weather Conditions



Alerts, Watches and Warnings issued to customers and top of Homepage

https://www.swpc.noaa.gov/

LEO Satellite Operations

With LEO becoming more congested and collisions more likely, improved accuracy of trajectory forecasting is necessary:

- With current capabilities, error ellipses for satellite orbits grow quickly with forward propagation, resulting in:
  - Tracking & monitoring challenges
  - Excessive conjunction warnings

- With increasing traffic in LEO, the challenge will only increase, becoming a large burden for all operators, and possibly beyond the capabilities of small operators

- Increased traffic holds the opportunity for additional measurements, and corresponding improvements in thermosphere modeling and forecasting