NOAA Space Weather (SWX) Program: Solar and Heliospheric Requirements

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Community Meeting on NOAA Satellites

Informing the Future of NOAA Satellite Observations

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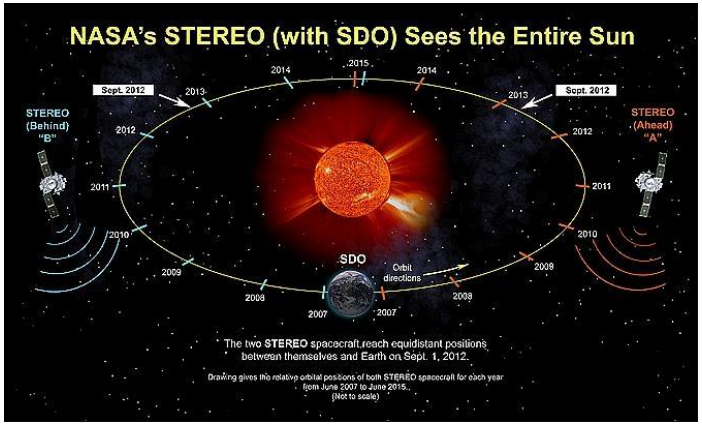
Outline

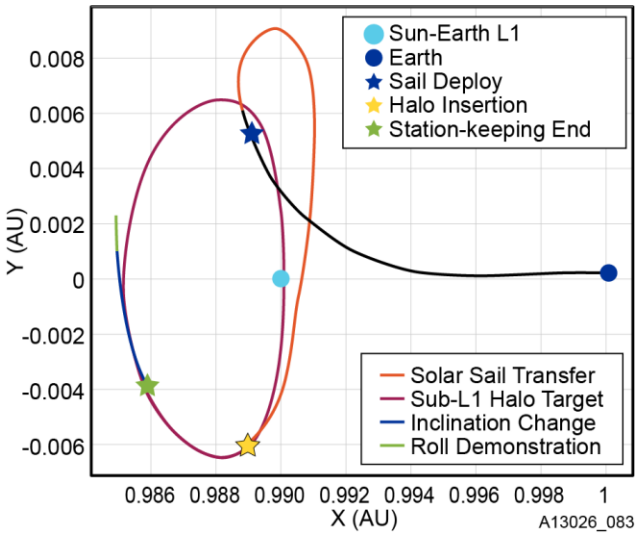
- Observational objectives from the Sun-Earth Line and other locations
- Trade space
- Assumptions
- Evaluation
- Recommendation and rationale

Introduction

- A number of solar and heliospheric (solar wind) requirements are contained in NOAA's Program of Record (POR) 2025 and in the NSOSA Space Platform Requirements Working Group (SPRWG) report.
- The Space Weather Program aims to continue the existing objectives and include several new ones.
- Two multi-part trade studies will be used to develop and explore the tradespace for a NOAA satellite constellation focusing on predicting space weather disturbances from observations taken on the Sun-Earth line (SEL) and off the SEL.
- The studies estimated benefits from solar/heliospheric satellite missions: improvements in data-product and model accuracy and availability.
- The results are included in the Analysis of Alternatives for SWP's MS1.



The STEREO mission demonstrated the usefulness of multiple solar/heliospheric vantage points for SpWx.



Solar sail technologies can enable observations below L1

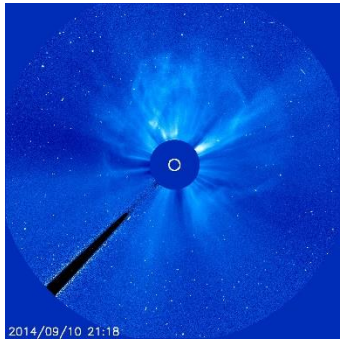
Trade Space: SEL Objectives

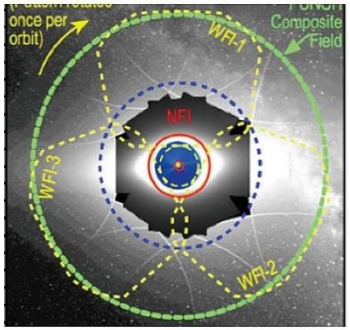
- A number of objectives were identified for observations from locations along the Sun-Earth Line (SEL):

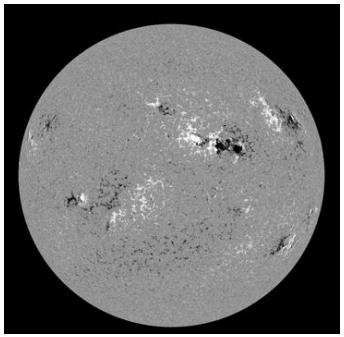
- Objectives (instrument)
  - Coronal imagery (coronagraph; optional polarization capabilities)
  - Coronal/heliospheric density (heliospheric imager; optional polarization capabilities)
  - Surface magnetic field (photospheric magnetograph; line-of-sight or vector)
  - In addition, in situ solar wind and IMF measurements and GEO UV and X-ray imaging are part of the POR 2025

- Locations
  - At L1. Legacy: SOHO and SWFO-L1
  - In GEO: GOES-U/CCOR
  - LEO: NASA's PUNCH mission
  - Ground: GONG array

- End product
  - Useful information for forecasting the upstream solar wind
  - Arrival time and amplitude of Coronal Mass Ejections (CMEs) and Corotational Interaction Regions (CIRs) traveling towards Earth
  - Synoptic maps of solar surface magnetic structure.







a.Coronagraph (LASCO/C3);
b.Heliospheric imager (WFI);
c.Magnetograph (HMI)

Trade Space: Key Performance Parameters and Measures of Effectiveness

- Key performance parameters (KPPs) for Sun-Earth Line (SEL) observations:
  1. Characterizing CMEs in the corona seen from L1
  2. Characterizing CMEs away from the Sun (HI1 FOV) seen from L1
  3. Characterizing CIRs away from the Sun (HI1 FOV) seen from L1
  4. Measuring solar surface magnetic field distribution on part of Sun visible from L1 for use in synoptic maps

- The measure of effectiveness (MOE) is a function of the accuracies of IP models (solar wind including transient structures):
  1. Improved 3D ambient field and flow model accuracy (improved WSA inputs)
  2. Improved CIR/CME model inputs and tracking to 0.5 AU
  3. Improved arrival times, strength of disturbance forecasts at Earth.

Trade Space: Prioritization

- An operational space weather user seeks one or more types of information:
  1. Data products (e.g., NOAA Level 3 and higher)
  2. Output of global models (Enlil, GeoSpace) for situational awareness
  3. Output of regional or tailored models (Kp/Dst, GEOMAG) if the models describe the user's system.

- Users of solar space weather information are divided in 5 categories:

User Category	Data Products	Global model	Regional/Tailored Models
#2. Satellite operators	(✓)	✓	✓
#4. Commercial aviation		✓	✓
#1. Electric power grid #5. Emergency managers		✓	✓
#3. GNSS operators	(✓)	✓	✓

SEL Objectives: Recommendation and Rationale

- Though awaiting full cost-benefit comparison (accuracy improvement of CME/CIR forecasts), the following option appears optimal at this point:

#	Instrument	Loc	WL	POL	FOV	comments
1	Coronagraph	L1	Y	Y	~ 3 -22 Rs	1, 2, 3, 7, 8
5	Heliospheric imager	L1	Y	Y	~ 20 Rs – 0.5 AU	1, 2, 3, 7

- Possible trade options are:

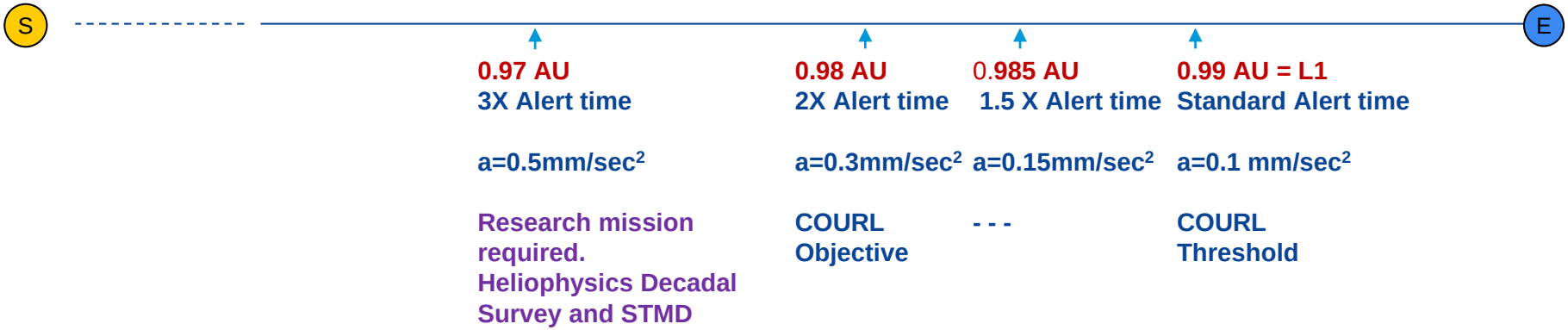
#	Instr	Loc	WL	POL	FOV	comments
3	Coronagraph	LEO/GEO	Y	Y	“	1, 2, 4, 5
7	Heliospheric imager	LEO/GEO	Y	Y	“	1, 2, 4, 5

- The following magnetograph option is viable only if an L5 drift is contemplated

#	Instrument	Loc	WL	POL	FOV	comments
9	Magnetograph	L1	n/a	n/a	Solar disk	6, 7

- Recommendation: #1 + #5 is best configuration for solar space weather data, but heliospheric imager not needed if separate L5 mission with HI implemented
- Rationale: Configuration 1+5 provides data for the solar SPRWG objectives and part of the SWORM 2.1 objectives while continuing and extending the POR 2025 capabilities. Descoped configurations are also provided.

Sub-Lagrange 1 Locations: Objectives



- Sub-L1 locations provide advanced lead times for solar wind and magnetic field arrival at Earth.

- Requirements for such locations are traced to standard sources

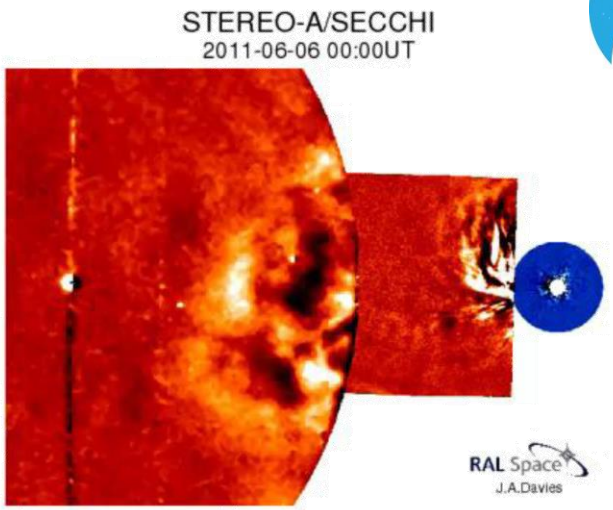
Sensor	Source	Product Improvement/ Model Use
Solar wind plasma	POR	Solar wind density, velocity, and temperature; geomagnetic storm onset time
Magnetic field	POR	Field strength and direction; geomagnetic storm intensity
Coronal imaging	POR	CME arrival time and storm onset time
Supra-thermal i+/e-	POR	Particle tracers; increased precision in CME arrival time
Heliospheric imaging	SPRWG	CME coasting; increased precision in CME arrival time

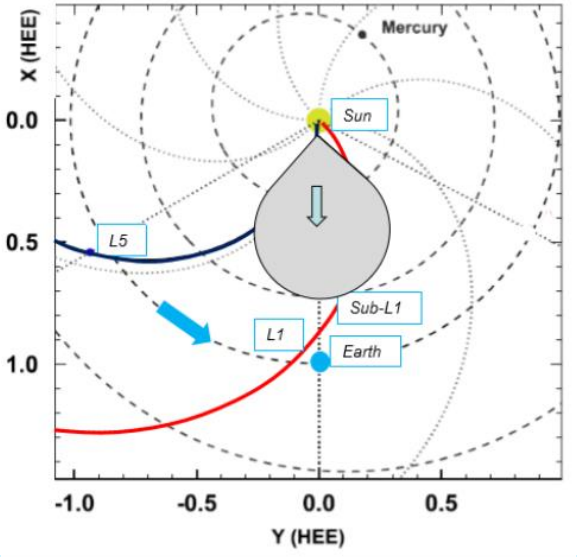
Off-SEL: Objectives

- Observations from Lagrange 5 and other off-SEL locations provide:

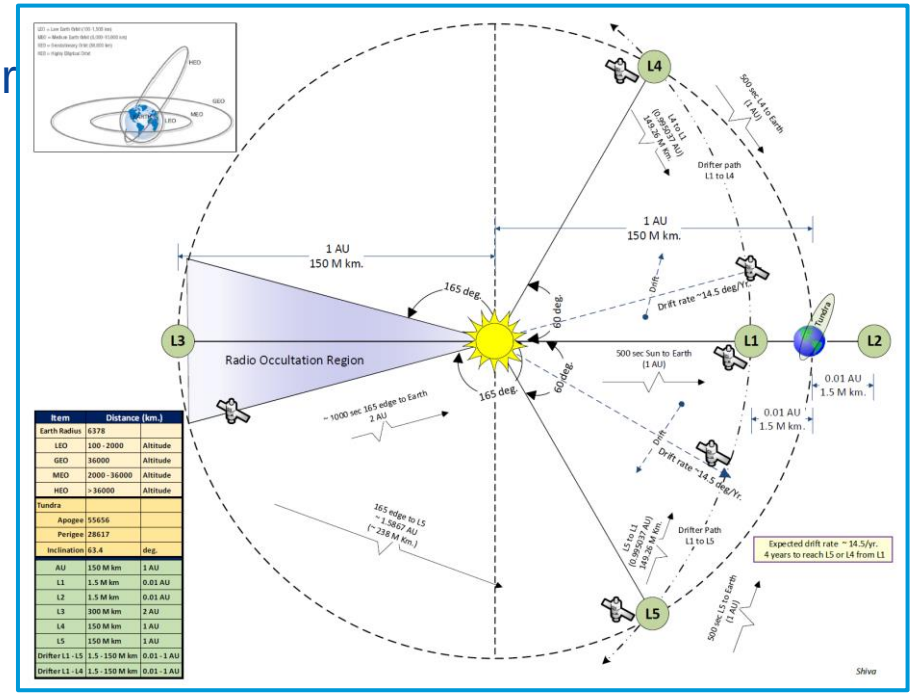
1. Stereoscopic views of CMEs and other structures (top right).
2. Warnings for impacting geoeffective structures before they rotated onto the SEL

- In addition to Earth's space weather, L5 and L4 are useful vantage points for lunar and martian weather (below).





Solar radiation storm analysis for Earth and Mars applications [Gibbs, 2020]



SWX Program: comms parameters for L1/L4/L5 missions

Off-SEL: Mission Options

- Basic scenarios considered for L5 (off-SEL):
  1. Two L1 and L5 dedicated missions
  2. L5 mission is second phase of L1 (incl. sub-L1)
- Comparisons:

Options	Cost	Schedule	Technical
1. Dedicated mission	HIGH – Large # of space elements [STEREO; Solar Cruiser]	2027 for both L1 and L5 missions	Comms to L5 due to path length; propellant volume for ESPA-size s/c
2. L1 mission with extension to L5	LOW – Smaller # of space elements	L5 delayed until 2030	Comms to L5 due to path length; propellant volume for ESPA-size s/c

-
  - Coronagraph
  - Magnetograph
  - Heliospheric imager
  - Energetic particle detector
- Other instruments include sensors for lower energy ions and electrons, and for solar X rays.

L5 and other Off-SEL objectives: Recommendations and Rationale

- **Orbit options**
  - Fly the phased service architecture: mission to L1 followed by drift to L5 at end of life.
  - Additional support may come from ESA's Lagrange 5 mission. Plans can include that mission after it has been fully finalized.
  - **Rationale** –
  - This option provides the best cost/benefit scenario due to the number of spacecraft needed and the complementarity of several objectives. The above preliminary results must be confirmed by further AoA studies
- **Instrument development**
  - Compact coronagraphs and heliospheric imagers exist and will soon be launched on operational or research missions (SWFO-L1 in 2024; PUNCH/NFI and WFI in 2023).
  - It is necessary to develop a low mass, wide-field, LOS or vector magnetograph such as CMag and increase the existing TRL. Legacy sensor is HMI.
  - **Rationale**
    - Several competing technologies have been recently demonstrated and reduction of SWaP and optics appears feasible.

Summary

- Solar and heliospheric requirements for the Space Weather Program prompted multi-part trade studies for instrument and orbit options with results included in the Program AoA.
- The first study focused on solar imaging from legacy Sun-Earth Line locations: L1, GEO, and LEO with a comparison to ground where useful.
- A second study focused on solar imaging and in situ measurements from sub-L1 and from L5 and other off-SEL locations. Off-SEL imaging has high priority due to stereoscopic and early-warning options.
- POR 2025 objectives (in situ L1 measurements and imagery from GEO) were not part of the trade study.
- An additional part of the studies reviewed solar sail technologies for sub-L1 and other orbits.
- In all studies mentioned above, solar/heliospheric requirements were ranked, and sensors were identified based on legacy operational and research missions.

Backup

Sun-Earth line: Considerations for Solar Observables Driving Space Weather

The main solar drivers of Space Weather along the S/E line (CIRs and CMEs) may be addressed by s/c observations in 3 ways from either Geo or L1 orbits:

1) Coronagraphs to observe the launch, structure, and propagation of CMEs within the range of 3-25 Rsun, as projected on the POS
2) Heliospheric imagers to extend observations of CMEs and CIRs out to at least 0.5 AU, as projected on the POS
3) Space-based magnetographs to observe the solar surface magnetic field distribution, with resolution similar to that achieved by the GONG network (and upcoming GONG2 system) – i.e., obviate the need for GONG

Sun-Earth line: Assumptions

L1

- Two s/c needed for reliability, one being held in reserve
- 4 dishes available in global network (size, band?)
- Dishes provided by NOAA for SWFO-L1 unlikely capable of handling multiple imager data rate at L1
- Bandwidth commensurate with anticipated data stream
- If magnetograph included, would exacerbate data rate issue

GEO, LEO, GS

- Weight/mass not an issue on s/c
- Adequate comm available
- 3 s/c to be provided, 2 because of eclipses and 1 for backup
- Proper background correction can be demonstrated

Sun-Earth line: Instrument Trades

1. Standard coronagraph
   - White-light or Polarized-light
   - FOV, Cadence
2. Heliospheric Imager
   - White-light or Polarized-light
   - FOV, Cadence
3. Solar surface magnetic field
   - LOS or Vector
4. Locations
   - L1 vs. GEO, LEO, GS
5. Significant missions:

- Operational: GONG (ground based)
- Research: SOHO, STEREO, SMEI, PUNCH, others.

Sun-Earth Line: Orbit Trades

Coronagraph and Heliospheric Imager

- Option: L1
  - Very significant advantage in terms of background corona subtraction
  - Important since CMEs very faint structures
  - Downlink may be an issue; may need s/c in storage for redundancy
- Option: LEO, GEO, GS
  - Some seasonal issues with coverage, two s/c required, with third in storage for redundancy
  - Quality of background subtraction serious issue, continually varying as s/c orbits Earth; NRL optimistic, evaluating for GOES-U CCOR
  - Not established how well this can be done, must PROVE to high degree of reliability; no clear answer until 6 mos after launch
  - ATM, SMM, SMEI illustrate peril of poor background subtraction

Magnetograph

- No orbit backgrounding issue, MDI, HMI heritage (solar brightness)
- If not L1, varying orientation becomes an issue, but tractable
- But need 2, for redundancy (vs GONG)

Evaluation (1/2): Key Alternatives

The following are key orbit configurations for measuring CIRs and CMEs

#	Instr	Loc	WL	POL	FOV	comments
1	Coronagraph	L1	Y	Y	~ 3-22 Rs	1, 2, 3, 7, 8
2			Y	N	“	“
3		LEO/GEO	Y	Y	“	1, 2, 4, 5
4			Y	N	“	“
5	Heliospheric imager	L1	Y	Y	~ 20 Rs – 0.5 AU	1, 2, 3, 7
6			Y	N	“	“
7		LEO/GEO	Y	Y	“	1, 2, 4, 5
8			Y	N	“	“
9	Magnetograph	L1	n/a	n/a	Solar disk	6, 7
10		LEO/GEO	n/a	n/a	“	“

1. WL only make little sense and only minor savings on cost and mass
2. Value of POL demonstrated by STEREO, is driving PUNCH mission
3. Stable s/c position enables extremely accurate background corrections
4. Continually moving s/c makes backgrounding risky and complicated
5. Need two instruments for year-round CME coverage
6. If no plan to move s/c w magnetograph to L5, makes no sense; use GONG
7. Assumes 4 dishes of adequate size for tracking
8. Goal is 3 Rs to 25-30 Rs

Evaluation (2/2): Risk Assessment

- Assuming a coronagraph only at L1 (with another on backup s/c), need to show there be little impact on CME forecasting if no heliospheric imager is included
  - Need to consider effect on forecasting if L1 coronagraph only, STEREO fails, and there is no L5 mission
- Need to determine which is more reliable and cost effective for magnetograph:
  - the GONG/GONG2 network with its ~6 stations
  - a s/c instrument at L1, with backup and plan in place to drift ”old” s/c toward L5

Off-SEL: Cost Elements

Option 1 (L1 and L5 Dedicated Missions): 1&2; Option 2 (L1 followed by L5 Mission): #3

	Option Elements		1	2	3
	Sensors	**Reference Sensor**	**SEL Dedicated**	**Off-SEL Dedicated**	**SEL/off-SEL phased**
Satellite					
	Coronagraph	SWFO-L1 CCOR	x	x	x
	Magnetograph	CMag		x	x
	Protons (High energy solar and galactic)	GOES SPGS		x	x
	Heliospheric Imager	PUNCH/WFI	**X***	x	x
	IP Magnet.	SWFO-L1 Mag	x	x	x
	IP Plasma	SWFO-L1 SWiPS	x	x	x
	X-ray Irradiance	GOES EXIS		x	x
	Supra-Thermal Ions	SWFO-L1 STIS	x	x	x
	Electrons 30-400 keV	GOES STIS	x	x	x

*included only if there were no off-SEL mission and no drifter