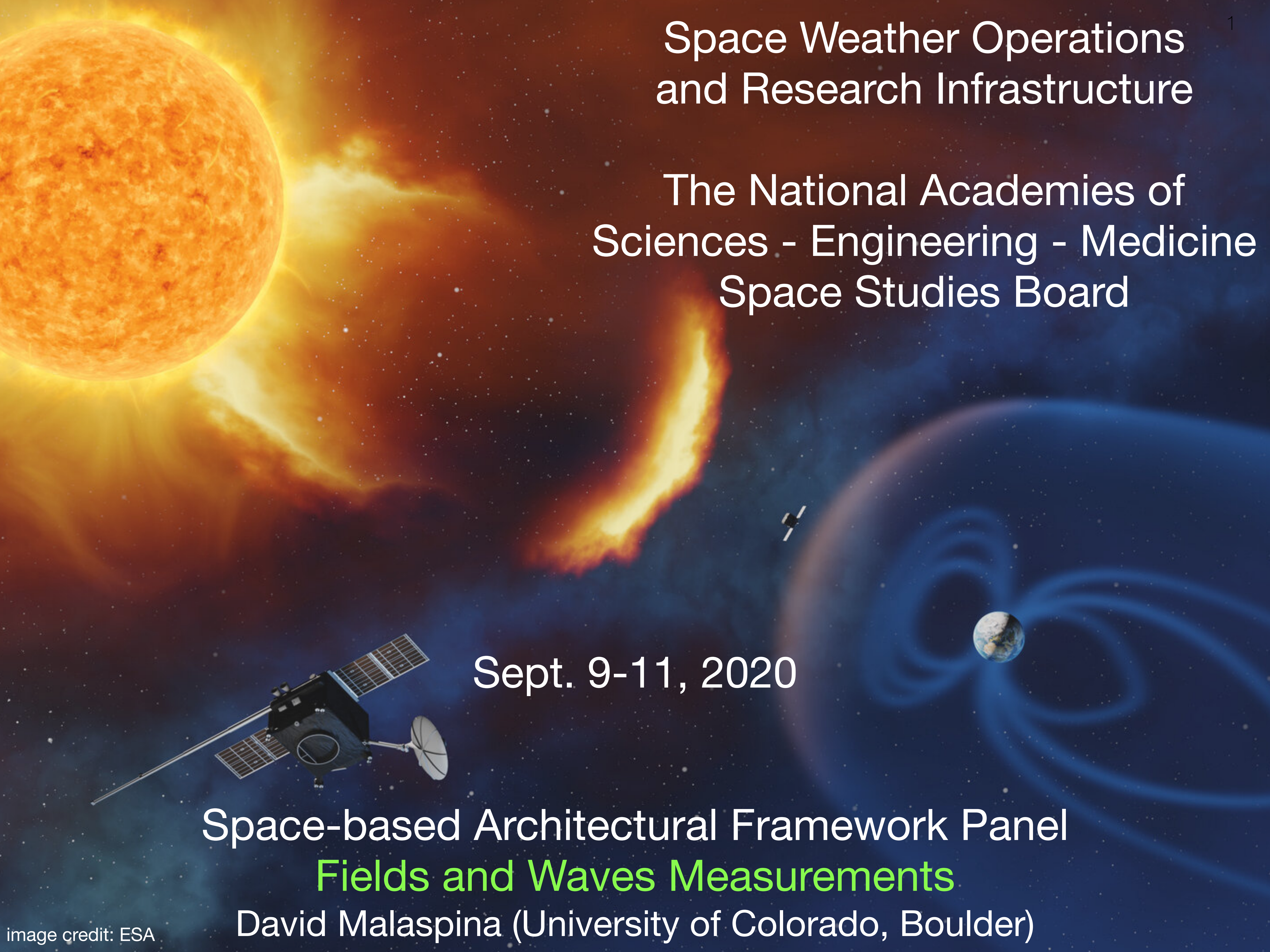
Space Weather Operations and Research Infrastructure

The National Academies of Sciences - Engineering - Medicine
Space Studies Board

Sept. 9-11, 2020



Space-based Architectural Framework Panel

Fields and Waves Measurements

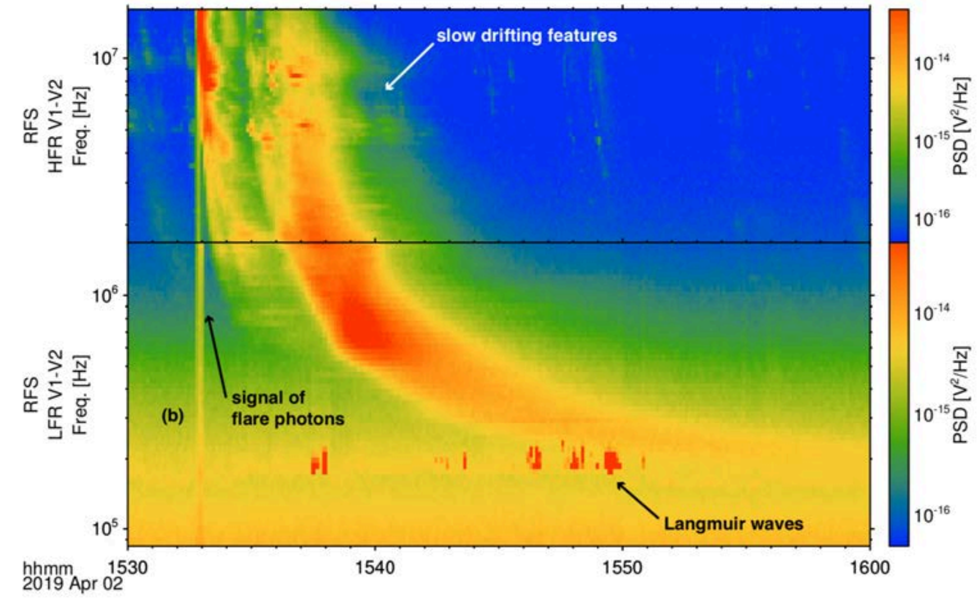
David Malaspina (University of Colorado, Boulder)

image credit: ESA

Overview

Fields and Waves

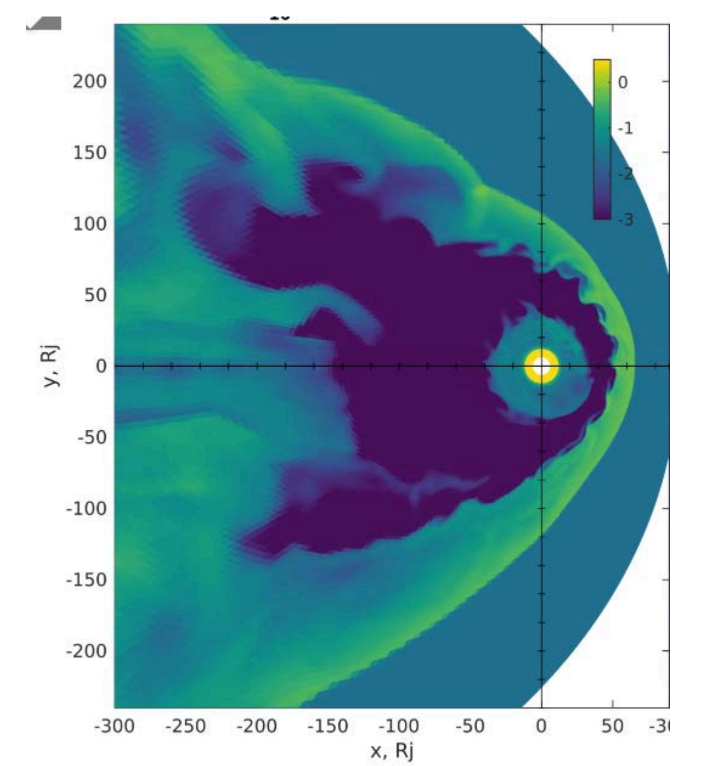
- In-situ measurement of electric and magnetic fields by spacecraft
  - DC magnetic fields (planetary, solar wind fields)
  - DC electric fields (plasma flows, low freq. waves)
  - plasma waves
  - radio waves (below ionospheric cutoff ~20 MHz)
  - dust impacts



Ref: 2a

Space Weather Utility

- Real-time Warnings
  - solar wind structures (e.g. Coronal mass ejections)
  - solar radio storms
  - solar energetic particle events
- Hazard Prediction / Modeling Geospace System Response
  - solar wind energy transfer efficiency (geoeffectivness)
  - radiation belt dynamics
  - particle precipitation into the atmosphere
  - geomagnetic dynamics
  - interplanetary dust impact hazard (“hail” of space weather)



Ref: 2b

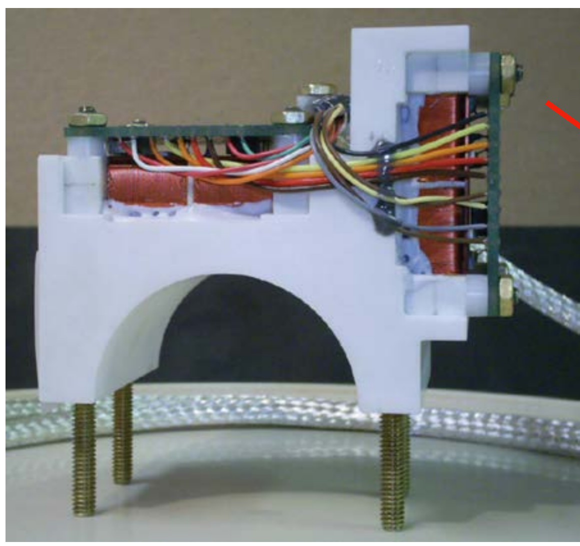
Goals of this Report

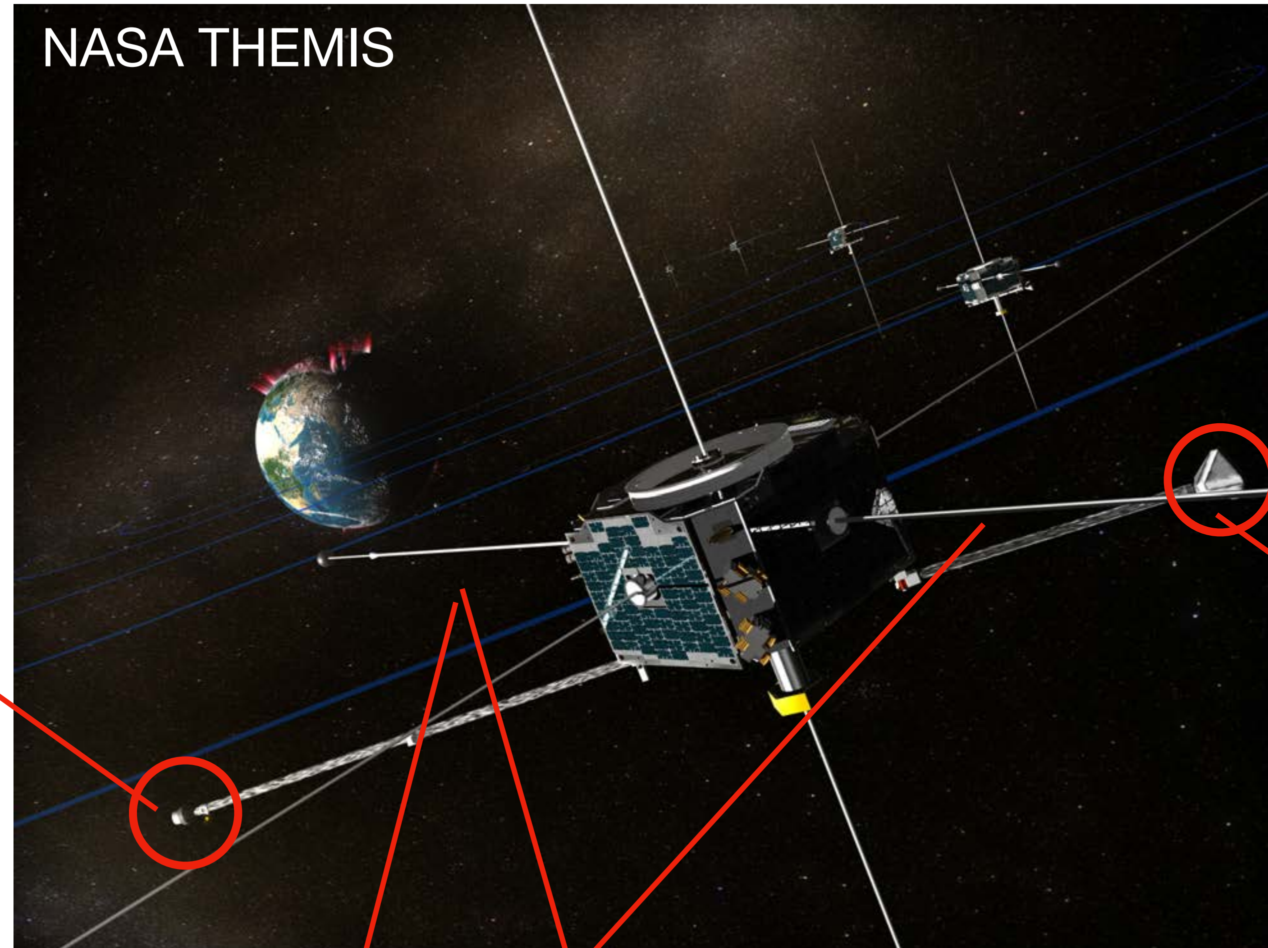
- Report utility of fields / waves observations for space weather applications
- List observation assets (current or future)
- Identify observation gaps (current or future)

Fields and Waves Instruments

DC Magnetic fields
(DC to ~20 Hz)

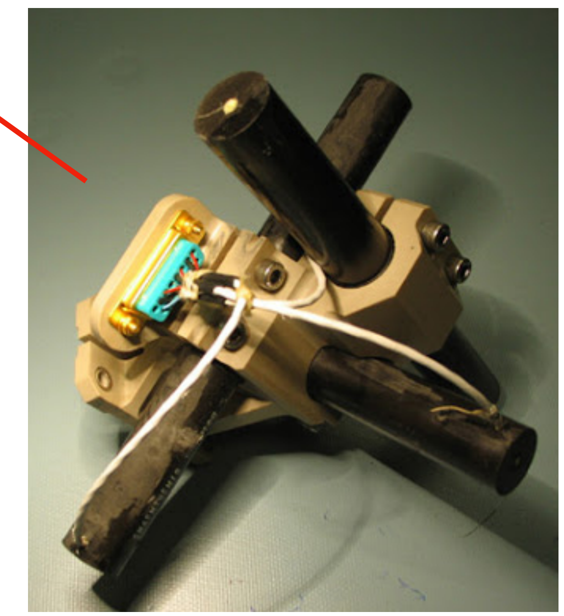
Fluxgate magnetometer
(few m boom)





AC Magnetic fields
(~20 Hz to ~100 kHz)

Search coil
magnetometer
(few m boom)

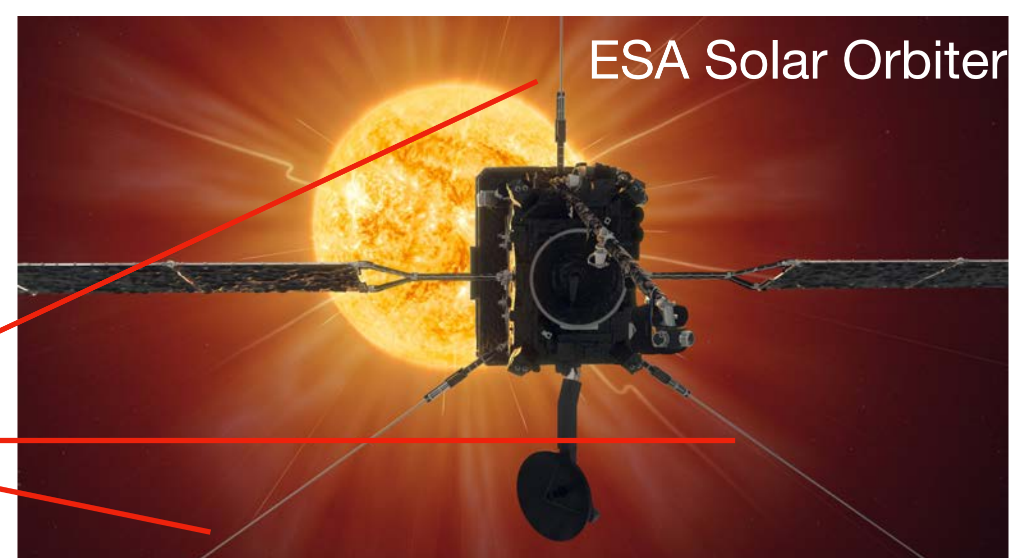


DC Electric fields
(DC to ~100 Hz)

Double Probes
(25 to 50 m booms)

AC Electric fields
(~100 Hz to ~20 MHz)

Antennas
(~few m to 50 m antennas)



DC Magnetic Fields - Low Earth Orbit

Utility for Space Weather (Real Time)

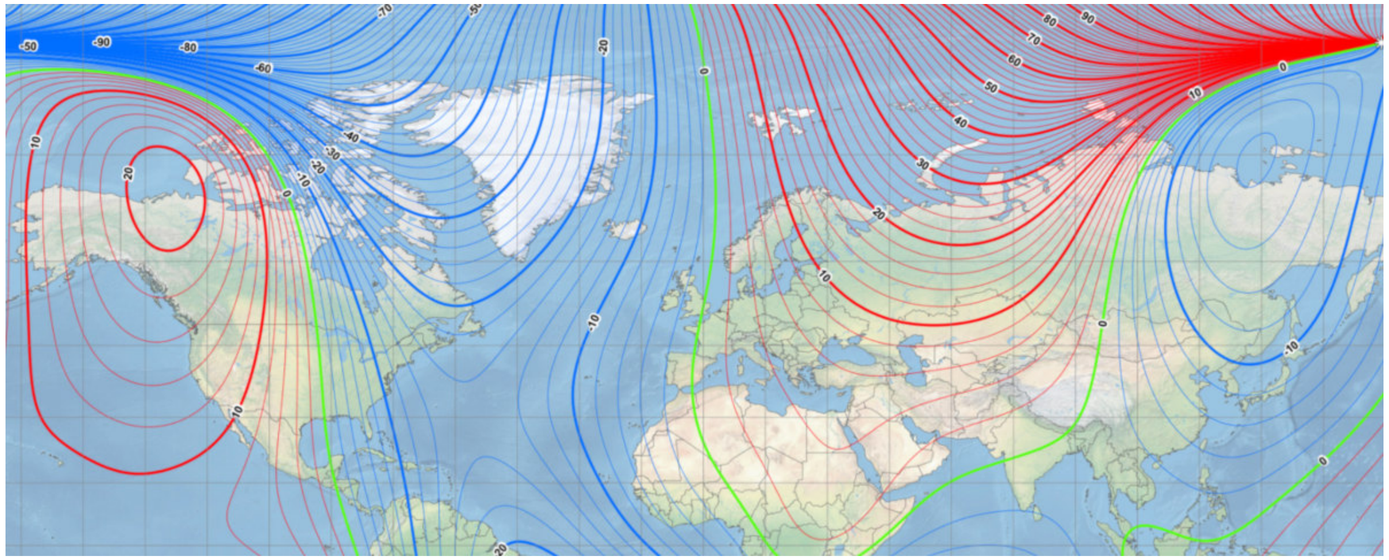
- Limited (ground magnetometers used instead)

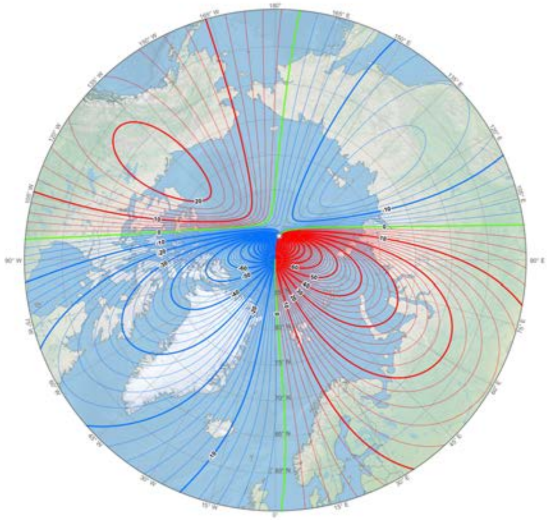
Utility for Space Weather (Prediction / Modeling / Impact Mitigation)

- Ionospheric current system dynamics (e.g. AMPERE [Ref: 4a, 4c, 4d])
- World magnetic model (WMM)

Example: World Magnetic Model [Ref: 4b]

- Enables magnetic navigation by GPS units when signal lost due to space weather events
- Earth main field model (space weather effects are perturbations on this)
  - see also: IGRF (International Geomagnetic Reference Field)
- Standard model used by U.S. Department of Defense, U.K. Ministry of Defence, NATO, and the International Hydrographic Organization (IHO), for navigation, attitude and heading referencing systems using the geomagnetic field.
- Also used widely in civilian navigation and heading systems
- Produced at 5-year intervals, current model expires on December 31, 2024





DC Magnetic Fields - Low Earth Orbit

Summary

Distributed vs. Single-point	Resiliency	Real-time to NOAA	Data Buy
Distributed	Good	-	AMPERE

Current

Agency	NASA	NOAA	USAF	ESA	JAXA	Commercial
Mission	ELFIN (cubesat)	-	DMSP	Swarm	-	AMPERE

Future

Agency	NASA	NOAA	NGA	ESA	JAXA	Commercial
Mission	GDC	-	MagQuest	-	-	AMPERE

Gaps

- No operational data for WMM after Swarm
  - Swarm launched in 2013, longer-term solution needed, MagQuest competition started

DC Magnetic Fields - Inner Magnetosphere

Utility for Space Weather (Real Time)

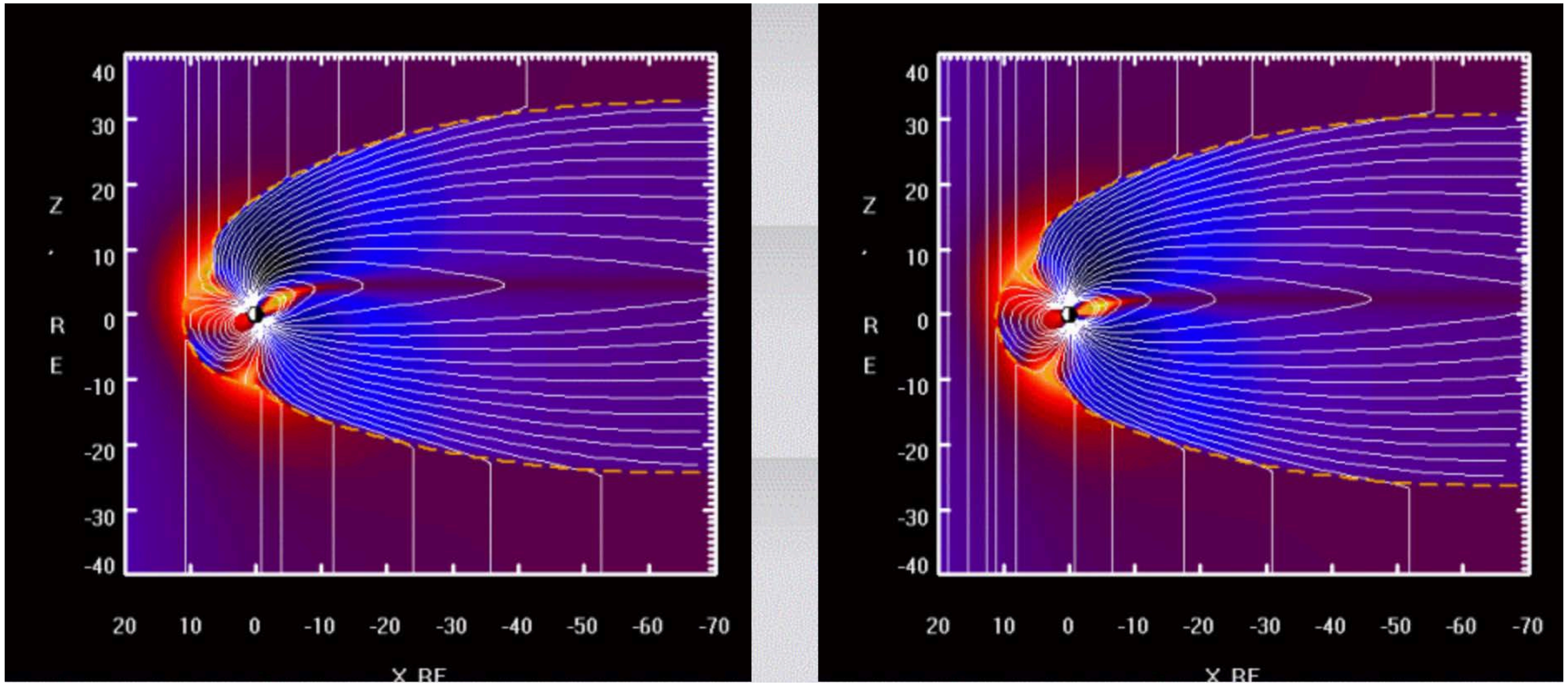
- Report sudden geomagnetic storm commencement (e.g. [Ref: 6c, 6d])

Utility for Space Weather (Prediction / Modeling)

- Empirical Models for geomagnetic field dynamics / response to events
  - key for monitoring radiation belt dynamics, particle precipitation (e.g. [Ref: 6e, 6f 6g])
  - key for modeling magnetosphere beyond LEO (e.g. [Ref: 6a])

Example: Tsyganenko Magnetic Field Model [Ref: 6b]

- Empirical model of Earth magnetic field beyond LEO
- Key for radiation belt dynamics models, solar energetic particle transport models, interplanetary shock impact models



DC Magnetic Fields - Inner Magnetosphere

Summary

Distributed vs. Single-point	Resiliency	Real-time to NOAA	Data Buy
Distributed	Good	GOES	-

Current

Agency	NASA	NOAA	USAF	ESA	JAXA	Commercial
Mission	THEMIS, MMS	GOES	DSX	Cluster	Arase	-

Future

Agency	NASA	NOAA	USAF	ESA	JAXA	Commercial
Mission	GTOSat (cubesat)	GOES	-	-	-	-

Gaps

- Few planned future missions
- Operational measurements have limited radial coverage (GOES is GEO only)
- Current operational measurements are difficult to calibrate (GOES systematic errors [Ref: 7a])
- Science missions have long revisit times
- Opportunity for commercial data buy
- No planned future missions for DC Electric fields
  - needed for Ultra Low Frequency (ULF) waves, used for radiation belt predictive modeling
    - e.g. [Ref: 10e, 10f, 10h]

DC Magnetic Fields - Beyond Earth

Utility for Space Weather (Real Time)

- CME Early warning (+/- Bz) (e.g. [Ref: 8a, 8b, 8c, 8d])
- Upstream solar wind monitor - feeds geomagnetic, radiation belt predictions [Ref: 8e, ref therein]

Utility for Space Weather (Prediction / Modeling)

- Upstream solar wind conditions used by many magnetospheric, geomagnetic models
- Event identification (CME, CIR, SIR) used by many geomagnetic models [Ref: 8e, ref therein]

Example: CME Bz determination

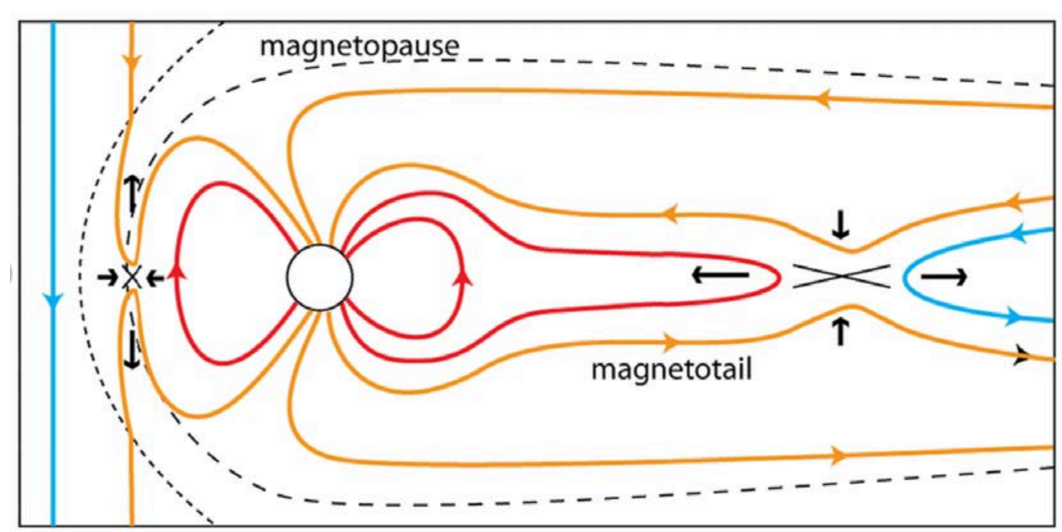
- Sign of Bz component of interplanetary magnetic field determines CME geoeffectiveness
  - Bz negative is anti-parallel to Earth's intrinsic northward B field
    - efficient energy transfer into geomagnetic system (enhanced magnetic reconnection)
  - Bz positive is parallel to Earth's intrinsic northward B field
    - inefficient energy transfer into geomagnetic system (suppressed magnetic reconnection)
- Existing physics-based models can only reproduce, not forecast, Bz [Ref: 8a]
- Potential remote Bz determination requires s/c out of the ecliptic [Ref: 8b]

Table 1

Tally of each 3h Kp event for the 25 CMEs used for skill scores for NOAA data and both Bz4Cast methods. Bz4Cast-L1 integrates the actual interplanetary data from the L1 location; Bz4Cast-E integrates the estimated solar wind parameters from the real-time runs of ENLIL simulations performed by the CCMC at NASA GSFC.

NOAA			Bz4Cast-L1			Bz4Cast-E		
Event forecast	*Event observed*		*Event forecast*	*Event observed*		*Event forecast*	*Event observed*	
	Yes	*No*		*Yes*	*No*		*Yes*	*No*
Yes	33	16	Yes	21	38	Yes	24	27
No	31	195	No	35	181	No	36	188

[Ref: 8c]



[Ref: 8d]

DC Magnetic Fields - Beyond Earth

Summary

Distributed vs. Single-point	Resiliency	Real-time to NOAA	Data Buy
Distributed	Good	DSCOVR / SWFO	-

Current

Agency	NASA	NOAA	USAF	ESA	Commercial
Mission	ACE, Wind, STEREO, PSP, ARTEMIS	DSCOVR	-	Solar Orbiter	-

Future

Agency	NASA	NOAA	USAF	ESA	Commercial
Mission	IMAP	SWFO	-	Lagrange L5, Bepi Columbo	-

Gaps

- No observatory at L4, L5 (to achieve > 45 min space weather event warning time)
  - (e.g. [Ref: 9a, 9b, 9c, 9d])
- Placement beyond Earth difficult, expensive, few opportunities
- Observatories < 1 AU do not have real-time data
- Observatories < 1 AU do not have continuous coverage of events reaching Earth
  - Would need something like Solar Sentinels [Ref: 9e]

VLF Plasma Wave Electric and Magnetic Fields - Inner Magnetosphere

Utility for Space Weather (Real Time)

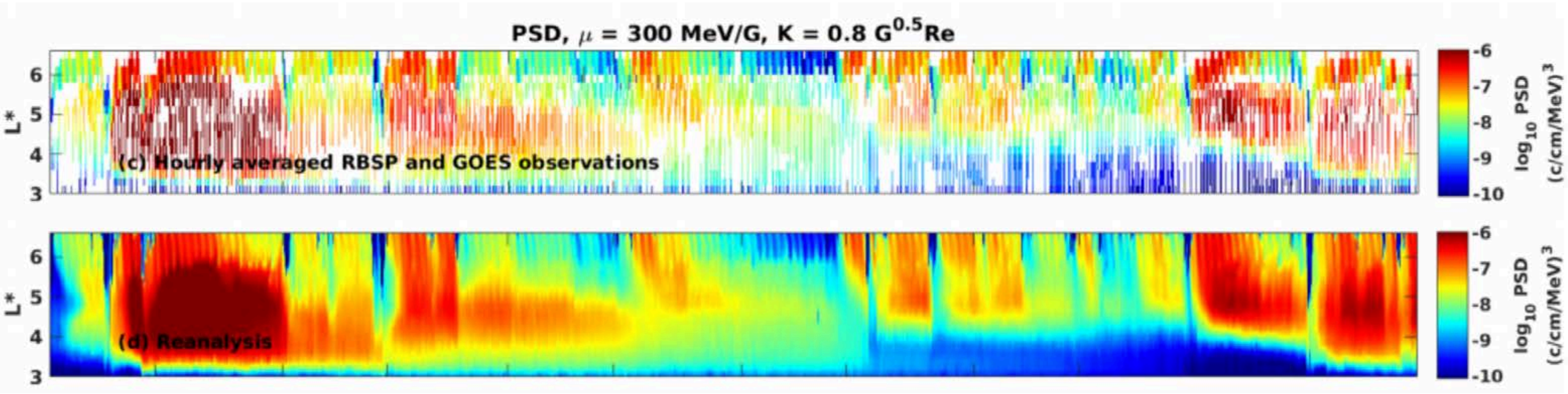
- Limited

Utility for Space Weather (Prediction / Modeling)

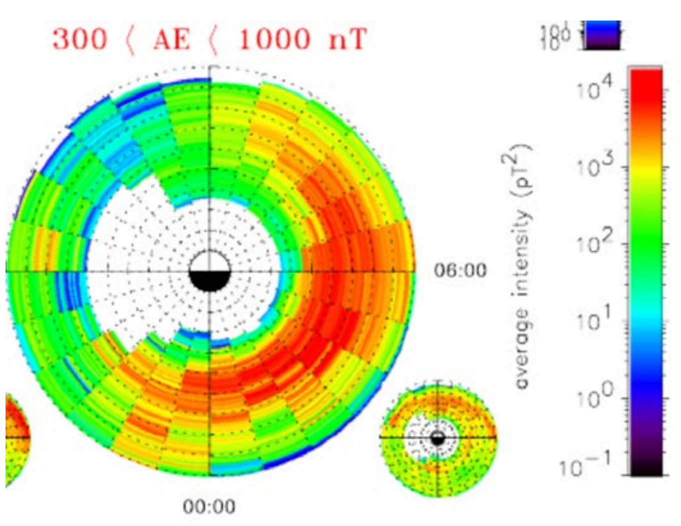
- Climatology of plasma waves vital to predicting radiation belts, particle precipitation
  - (e.g. [Ref: 10c, 10d, 10e, 10f, 10g, 10h])

Example: Radiation Belt Relativistic Electron Flux Prediction via VLF Wave Models

- Climatological wave observations key for radiation belt prediction
  - require years of data from many spacecraft (e.g. [Ref: 10b])
    - vary significantly with solar and geomagnetic conditions



[Ref: 10a]



[Ref: 10b]

VLF Plasma Wave Electric and Magnetic Fields - Inner Magnetosphere

Summary

Distributed vs. Single-point	Resiliency	Real-time to NOAA	Data Buy
Distributed	Moderate	-	-

Current

Agency	NASA	NOAA	USAF	ESA	JAXA	Commercial
Mission	THEMIS	-	DSX	Cluster	Arase	-

Future

Agency	NASA	NOAA	USAF	ESA	JAXA	Commercial
Mission	-	-	-	-	-	-

Gaps

- No planned future observations
  - critical gap as we enter new solar cycle territory [Ref: 11a]

Radio Frequency Electric Fields - Beyond Earth

Utility for Space Weather (Real Time)

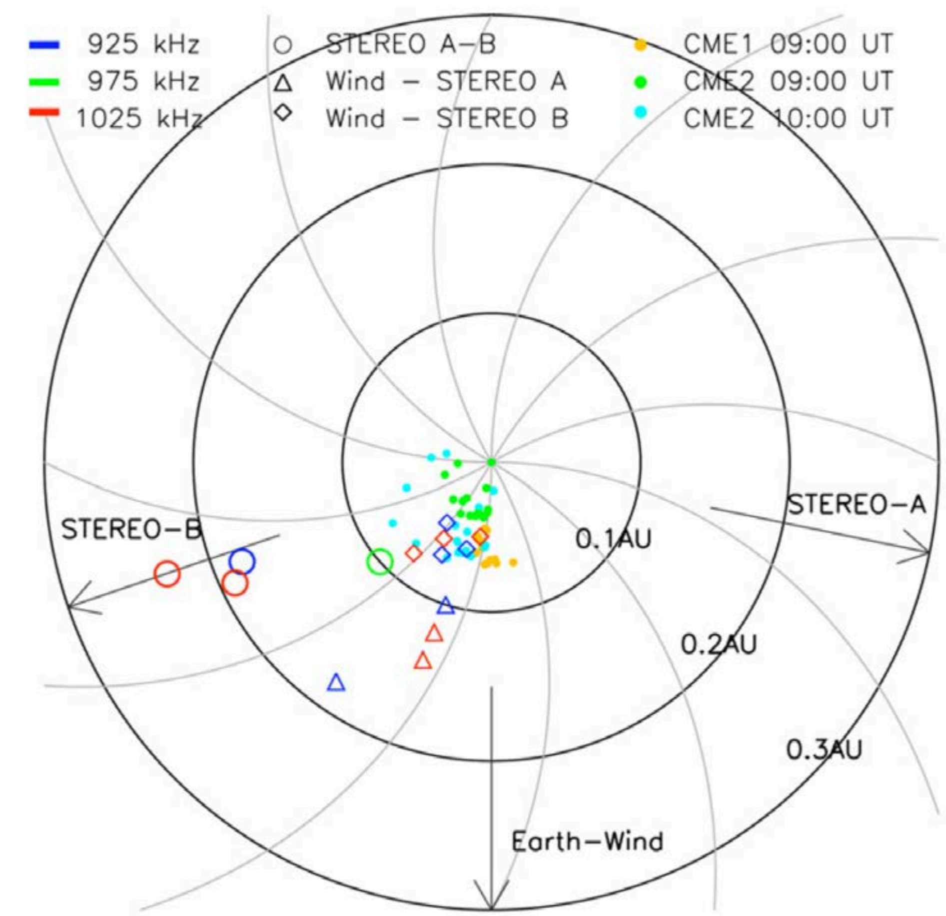
- Solar energetic particle (SEP) warnings (type III radio bursts) [Ref: 12a, 13a, 13b]
- Type II solar radio burst identification for CME shock front propagation [Ref: 12b]

Utility for Space Weather (Prediction / Modeling)

- Earth connectivity of particle beams
- Heliospheric density profile probe [Ref: 12c and ref therein]
  - important for CME propagation predictions
- CME propagation via type II solar radio emission

Example: Tracking CME shock front propagation

- CME shock fronts emit radio waves
  - Frequency depends on radial distance from Sun
  - Multiple s/c can triangulate source regions
    - follow shock fronts



[Ref: 12b]

Radio Frequency Electric Fields - Beyond Earth

Summary

Distributed vs. Single-point	Resiliency	Real-time to NOAA	Data Buy
Distributed	Moderate	-	-

Current

Agency	NASA	NOAA	USAF	ESA	Commercial
Mission	Wind, STEREO, PSP	-	-	Solar Orbiter	-

Future

Agency	NASA	NOAA	USAF	ESA	Commercial
Mission	CURIE (cubesat), SunRISE (cubesats)	-	-	-	-

Gaps

- No operational observations
  - No real-time data
  - No operational automated event detection
- No observatory at L4
  - ~30% of major SEPs affecting Earth/moon originate behind solar W limb [Ref: 13a]
    - important for travel from Earth to Mars [Ref: 13b]

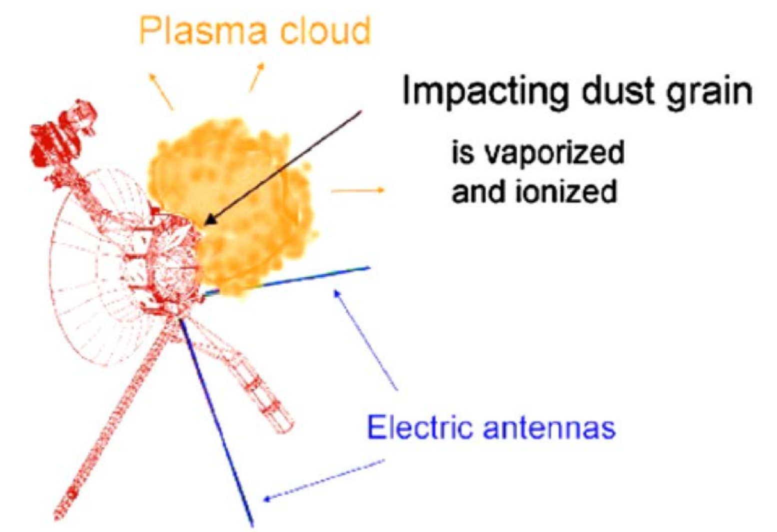
High frequency electric fields - dust impact detection - Beyond Earth

Utility for Space Weather (Real Time)

- Limited (failure root cause analysis)

Utility for Space Weather (Prediction / Modeling)

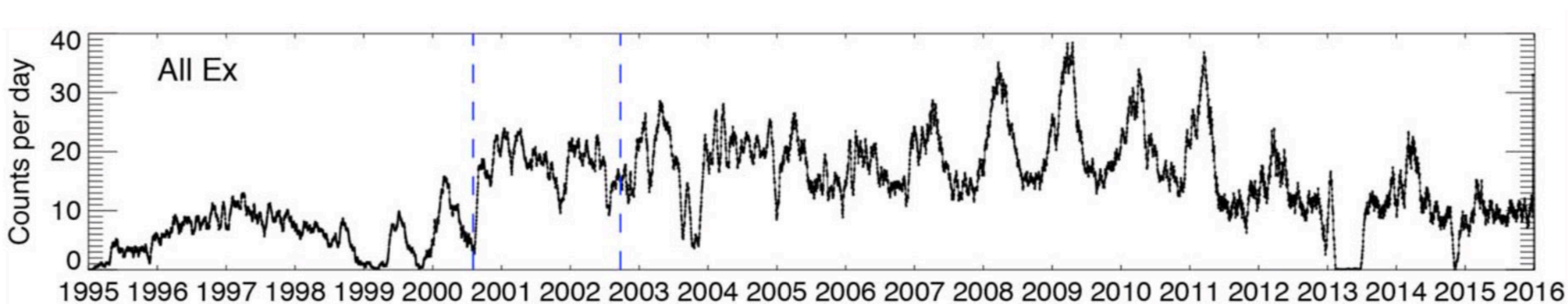
- Interplanetary dust hazard model input
- Important for long duration spaceflight risk assessment
  - e.g. travel to Mars



[Ref: 14d]

Example: Yearly, Solar Cycle Variation of Interplanetary Dust

- **Hypervelocity interplanetary dust impacts can damage spacecraft**
  - break extended structures, blind star cameras, destroy electronics
    - Mariner 4 [Ref 14a]
    - MMS, Wind, IMAGE [Ref: 14b]
    - Solar panel damage on Hubble, Sentinel 1A
- With electric field antennas, entire spacecraft surface becomes a detector [Ref: 14c, 14d, ref therein]
  - large collecting area = high enough fluxes for climatological measurements



[Ref: 14c]

Dust impacts on Wind spacecraft (1995 - 2015)

High frequency electric fields - dust impact detection - Beyond Earth

Summary

Distributed vs. Single-point	Resiliency	Real-time to NOAA	Data Buy
Single-point	Low	-	-

Current

Agency	NASA	NOAA	USAF	ESA	Commercial
Mission	Wind, STEREO, PSP	-	-	Solar Orbiter	-

Future

Agency	NASA	NOAA	USAF	ESA	Commercial
Mission	-	-	-	-	-

Gaps

- No planned future observations
- No other long-term monitor of interplanetary dust environment
- No dust size calibration w/ simultaneous dedicated dust detector observations
- No cross-calibration between missions

Space-Based Fields and Waves Measurements for Space Weather — Summary

Fields / Waves Measurement Type	Location	Primary Space Weather Application(s)	Platforms: Current	Platforms: Planned	Major Gap
DC Magnetic fields	Low Earth orbit	• World Magnetic Model maintenance • Ionospheric current system dynamics	Swarm, Ampere, DMSP	MagQuest, GDC, AMPERE	• No operational data for WMM
DC Magnetic fields	Inner magnetosphere	• Geomagnetic field dynamics, Modeling radiation belts, precipitation	GOES, DSX, MMS, Arase, THEMIS, Cluster	GTOsat	• Few planned future missions
DC Magnetic fields	Beyond Earth (L1, L5, L4, near Sun)	• CME early warning (+/- Bz) • Upstream solar wind monitor	ACE, Wind, DSCOVR, STEREO, Solar Orbiter, PSP, BepiColumbo	SWFO, Lagrange L5, IMAP	• No observatory at L4, L5
VLF plasma wave fields	Inner magnetosphere	• Climatology of plasma wave drivers of radiation belts, precipitation	Arase, THEMIS, DSX	?	• No planned future observations
Radio frequency electric fields	Beyond Earth (L1, L5, L4, Moon, near Sun)	• CME propagation • SEP event prediction • Radio blackout warnings	Wind, STEREO, PSP, Solar Orbiter	CURIE, SunRISE	• No operational observations
High frequency electric fields for dust impact detection	Beyond Earth (L1, L5, L4, Moon, near Sun)	• Climatology of interplanetary dust hazard	Wind, STEREO, Solar Orbiter, PSP	?	• No planned future observations

In-situ measurement of electric and magnetic fields by spacecraft:

- Used for real-time warnings
  - CMEs, SEPs, solar radio storms, geomagnetic storm severity
- Used for hazard prediction / geospace modeling
  - Upstream solar wind conditions, CME geoeffectiveness, radiation belt relativistic electron fluxes, atmospheric particle precipitation, interplanetary dust impact hazard
- Most current data are provide by scientific (not operational) spacecraft
  - Often require atypical orbits
  - Refresh often not a priority
  - Commercial data buys not viable beyond GEO (currently)
- Some regions well-covered by current and planned capability
  - LEO, L1
- Several observation classes have no / non-robust continuity plan
  - No plan : Dust, VLF waves
  - Non-robust plan: solar radio, inner magnetosphere B-field
- Expansion of current capability requires expansion to new regions of space
  - L4, L5, < 1 AU

References

Reference (Slide # / letter)	Author / Year	doi or URL
2a	Pulupa+ 2020	doi: 10.3847/1538-4365/ab5dc0
2b	JHU/APL GAMERA model output	https://civspace.jhuapl.edu/Science/tools.php?tool=gamera
4a	Waters+ 2020	10.1007/978-3-030-26732-2_7
4b	World Magnetic Model	https://www.ngdc.noaa.gov/geomag/WMM/
4c	Matsuo+ 2015	10.1002/2014JA020565
4d	McPherron+ 2018	10.1002/2017GL076741
6a	Andreeva and Tsyganenko 2017	10.1002/2017SW001684
6b	Tsyganenko magnetic field models	http://geo.phys.spbu.ru/~tsyganenko/modeling.html
6c	Joselyn 1985	10.1016/0273-1177(85)90137-1
6d	Molinski 2002	10.1016/S1364-6826(02)00126-8
6e	Cilden-Guler+ 2018	10.1016/j.asr.2017.10.041
6f	Cunningham 2016	10.1002/2015JA021981
6g	Boberg+ 2016	10.1016/j.asr.2015.10.027
7a	Loto'aniu+ 2019	10.1007/s11214-019-0600-3
8a	Vourlidas+ 2019	0.1098/rsta.2018.0096
8b	Gibson+ 2019	10.3389/fspas.2018.00032
8c	Austin and Savani, 2018	10.1002/wea.3076
8d	Eastwood+ 2017	10.1007/s11214-017-0399-8

References

Reference (Slide # / letter)	Author / Year	doi or URL
8e	Wind spacecraft senior review report	https://wind.nasa.gov/docs/Wind_SR2017_proposal.pdf
9a	Rodriguez+ 2020	doi.org/10.1029/2020SW002533
9b	Markos+ 2015	http://www.helas.gr/hipparchos/hipparchos_v2_12.pdf
9c	Akioka+ 2005	10.1016/j.asr.2004.09.014
9d	Owens+ 2019	10.1029/2019SW002204
9e	Solar Sentinels: Report of the Science and Technology Definition Team	http://www.predsci.com/~pete/research/tim/SentinelsExecSumm.pdf
10a	Cervantes+ 2019	10.1029/2019JA027514
10b	Meredith+ 2020	10.1029/2020GL087311
10c	Millan and Thorne, 2007	10.1016/j.jastp.2006.06.019
10d	Reeves+ 2016	10.1002/2015JA021569
10e	Fok+ 2011	10.1016/j.jastp.2010.09.033
10f	Horne+ 2013	10.1002/swe.20023
10g	Ripoll+ 2017	10.1002/2017JA024139
10h	Tu+ 2013	10.1002/jgra.50560
11a	Petrovay 2020	10.12942/lrsp-2010-6
12a	Laurenza+ 2009	10.1029/2007SW000379
12b	Martinez Oliveros+ 2010	10.1088/0004-637X/748/1/66

References

Reference (Slide # / letter)	Author / Year	doi or URL
12c	Krupar+ 2018	10.3847/1538-4357/aab60f
13a	Richardson+ 2014	10.1007/s11207-014-0524-8
13b	Posner and Strauss 2020	10.1029/2019SW002354
14a	Mariner 4 dust damage	https://www.nasa.gov/vision/universe/watchtheskies/meteor_cloud.html
14b	Williams+ 2016	10.2514/6.2016-5675
14c	Malaspina and Wilson 2016	10.1002/2016JA023209
14d	Mann+ 2011	10.1007/s11214-011-9762-3