National Aeronautics and Space Administration

Effects of space weather on technological systems and society

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Agenda for the two sessions

- NASA Goddard Space Flight Center (GSFC).
- Overview of space weather effects.
- *Geomagnetically induced currents (GICs).*
- *Orbital/atmospheric drag.*
- *Radiation effects on humans, including NASA Artemis Program shielding/mitigation approach.*
- Gannon Super Storm of May 2024.

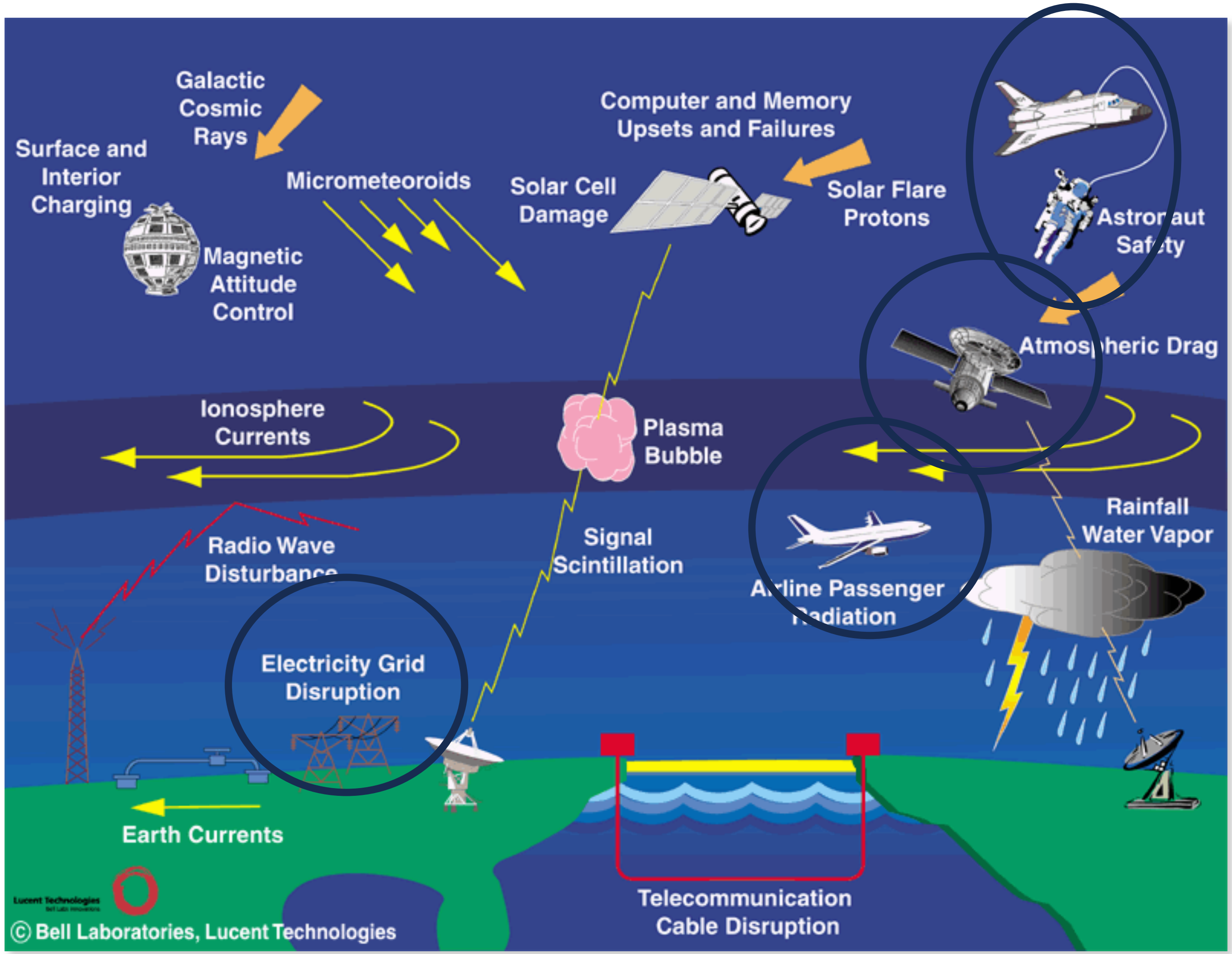
NASA GSFC

NASA Goddard Space Flight Center (GSFC), Greenbelt, MD:

- 10,000 folks out of which 3,000 are “feds” and 7,000 contractors.
- Robotic mission design, integration, launch, operations.
- The largest NASA science center.

NASA GSFC Heliophysics Science Division

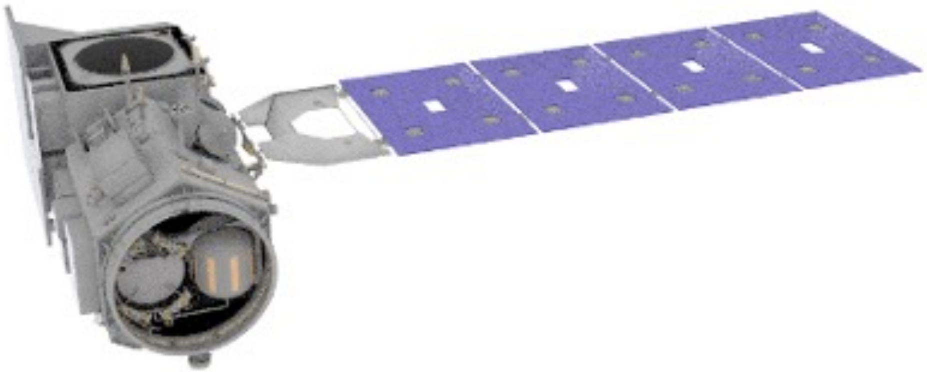
Space weather effects overview



Space weather impacts (credit: L. Lanzerotti)

Space weather effects overview

- Spacecraft can be impacted in a number of different ways depending on the orbit of the vehicle.

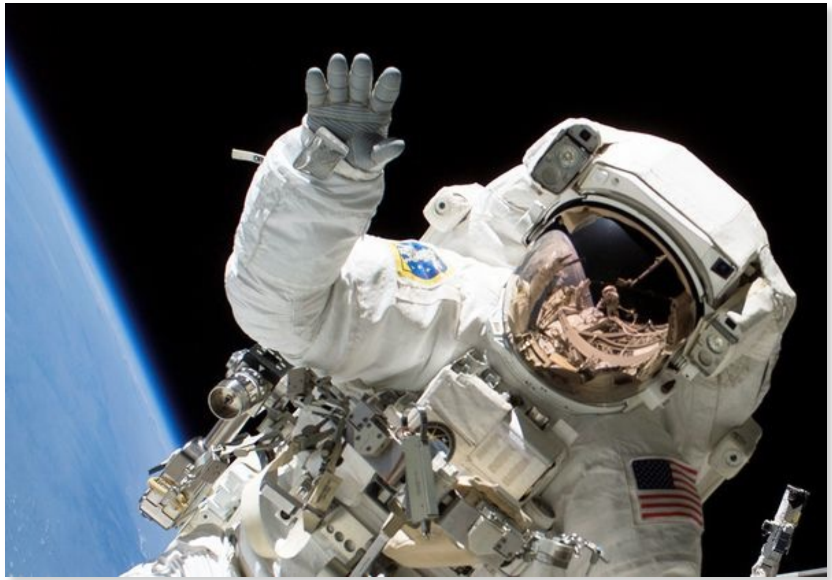


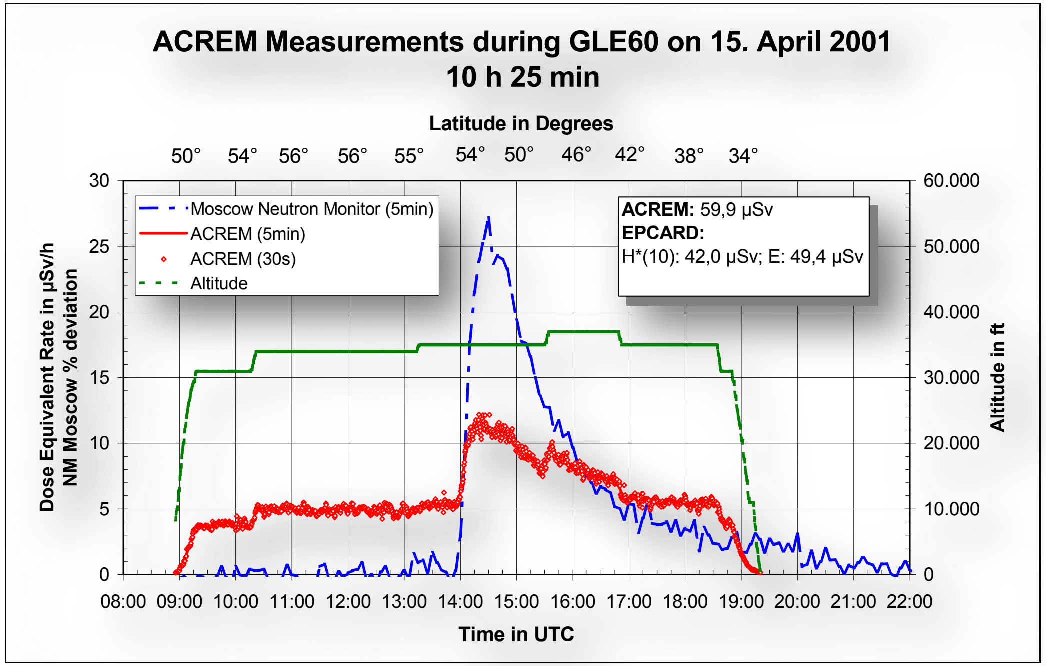
NASA's ICESat-2 spacecraft

- Surface (auroral and ring current electrons) and deep internal charging (radiation belt electrons).
- Single event upsets (GCRs, SEPs, inner radiation belt protons).
- Drag effects (upper atmospheric expansion).
- Total dose effect (cumulative radiation in any environment).
- Effects on the attitude control systems (magnetic field fluctuations and SEPs).

Space weather effects overview

- Energetic charged particle radiation is a hazard for humans in space and at airline altitudes. Especially less predictable SEPs are a concern.

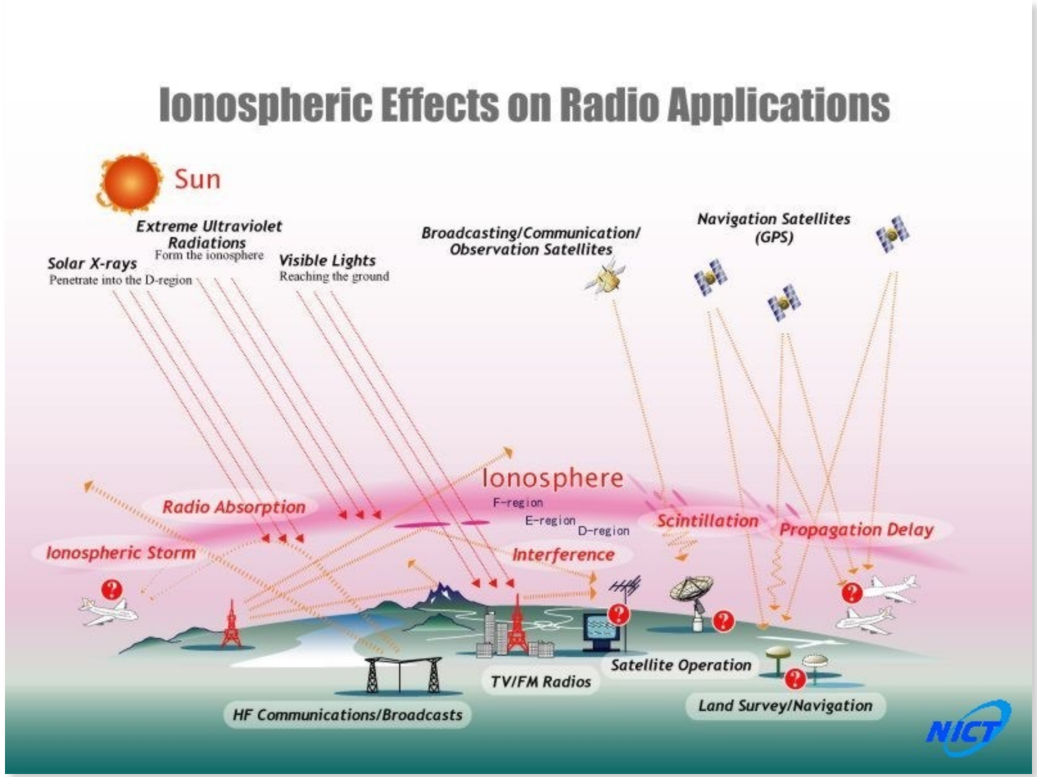




Dose observations from a commercial flight (Credit: Bartlett et al., 2002)

Space weather effects overview

- Signals using ionosphere or “just” passing through ionosphere are affected by space weather.



Credit: NICT

- Global navigation satellite systems such as GPS (e.g., EUV, X-rays, SEPs, magnetospheric activity)
- High-frequency (HF) radio communications (e.g., EUV, X-rays, SEPs, magnetospheric activity)
- Other GHz range comms such as cell phones (solar radio noise)

Space weather effects overview

- Geomagnetic field fluctuations drive geomagnetically induced currents (GIC) that can be a hazard to long conductor systems on the ground.

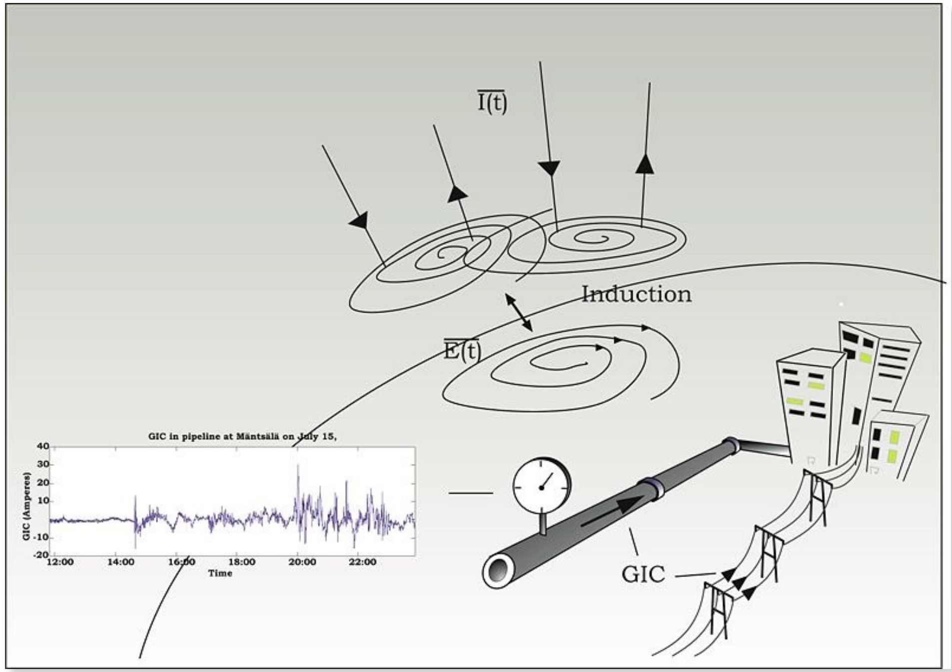
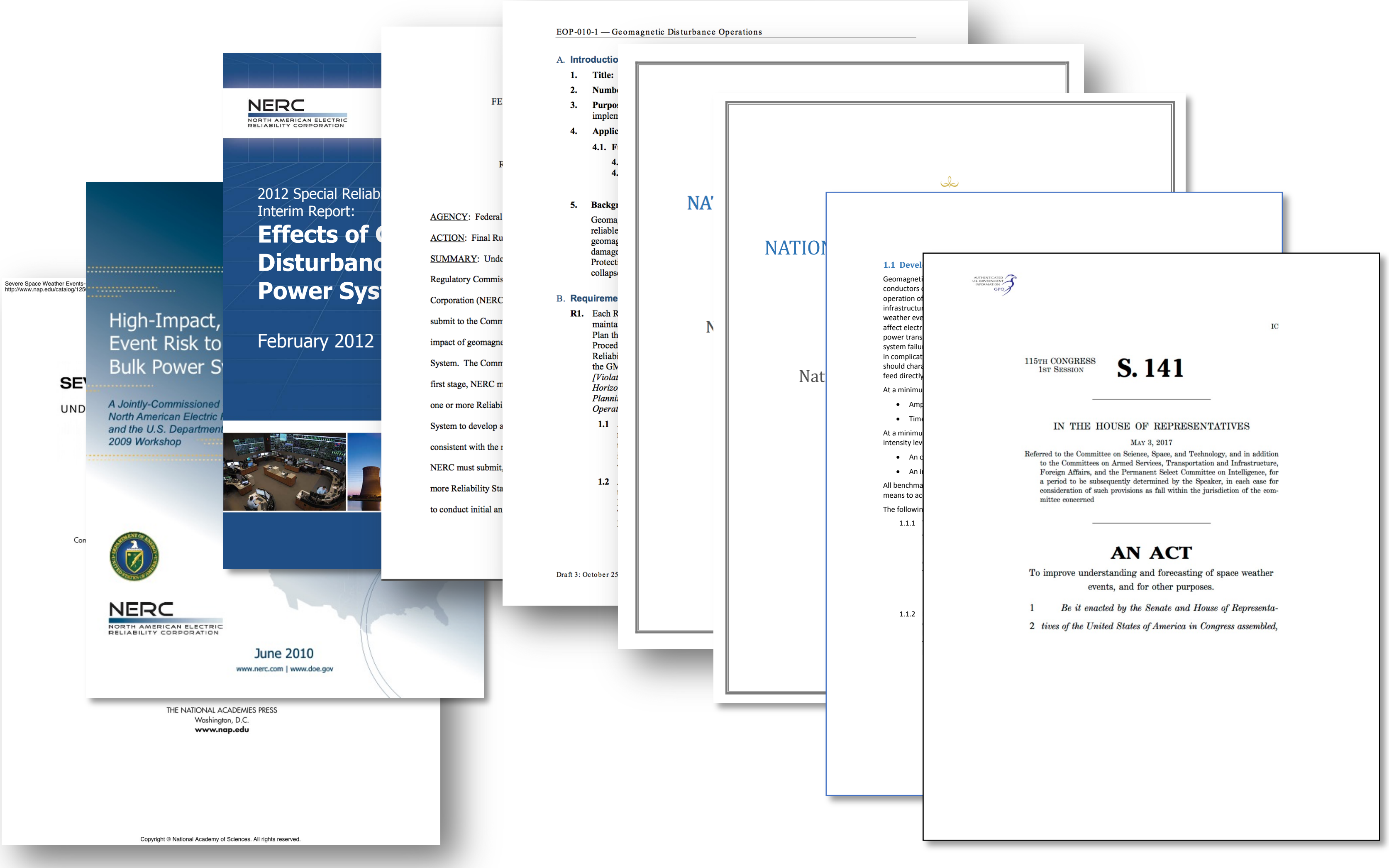


Illustration of mechanism for generating GIC

Transformer damage in South Africa

Credit: Gaunt and Coetzee (2007)

Brief history of the high-level US interest in GICs



Severe Space Weather Events-

SEV

UND

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www.nap.edu

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High-Impact,
Event Risk to
Bulk Power S

A Jointly-Commissioned
North American Electric
and the U.S. Department
2009 Workshop

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

June 2010

www.nerc.com | www.doe.gov

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

2012 Special Reliab
Interim Report:
Effects of
Disturbanc
Power Sys

February 2012

AGENCY: Federal

ACTION: Final Ru

SUMMARY: Unde

EOP-010-1 — Geomagnetic Disturbance Operations

A. Introductio

B. Requireme

Draft 3: October 25

NATION

115TH CONGRESS
1ST SESSION

S. 141

IN THE HOUSE OF REPRESENTATIVES

MAY 3, 2017

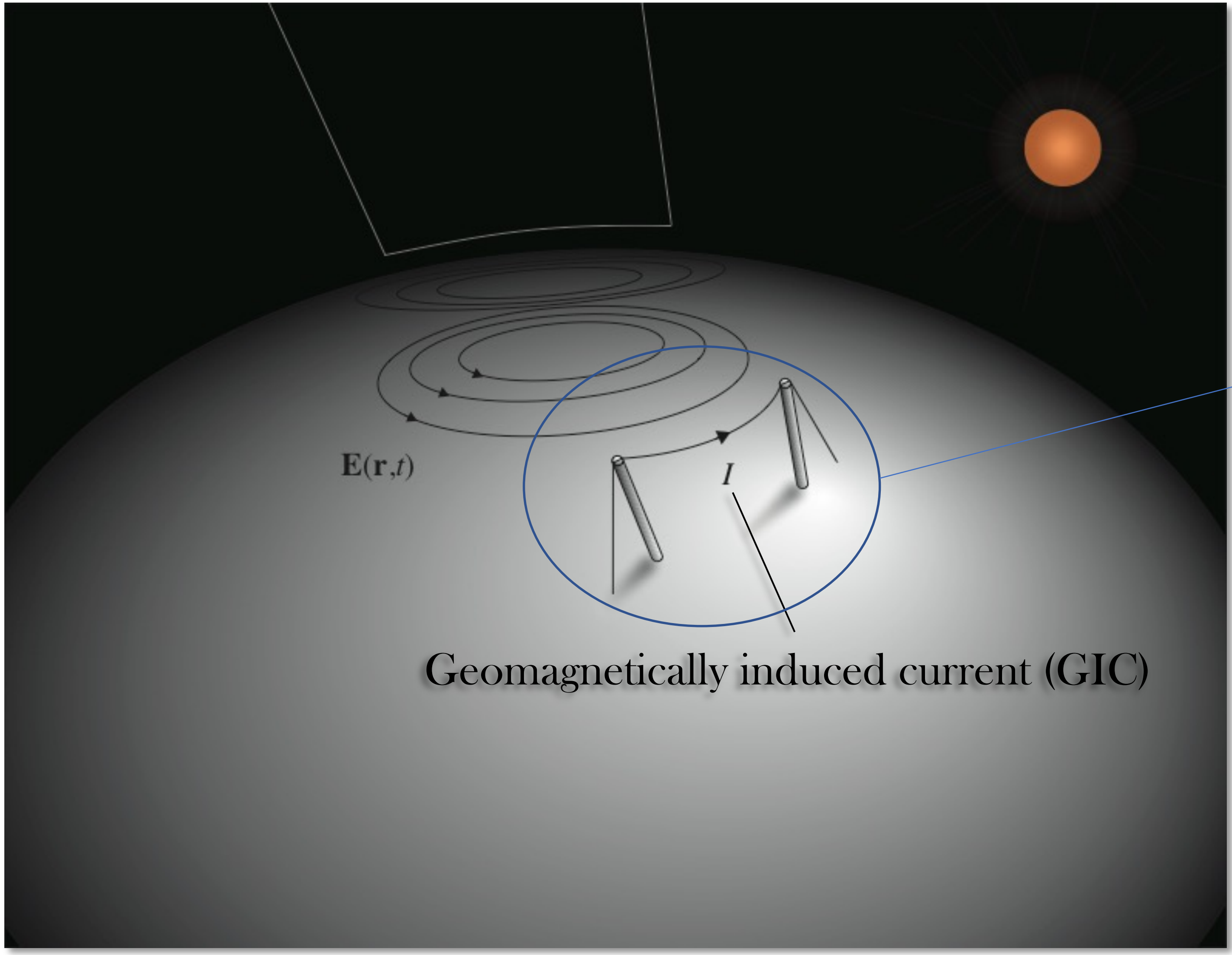
Referred to the Committee on Science, Space, and Technology, and in addition to the Committees on Armed Services, Transportation and Infrastructure, Foreign Affairs, and the Permanent Select Committee on Intelligence, for a period to be subsequently determined by the Speaker, in each case for consideration of such provisions as fall within the jurisdiction of the committee concerned

AN ACT

To improve understanding and forecasting of space weather events, and for other purposes.

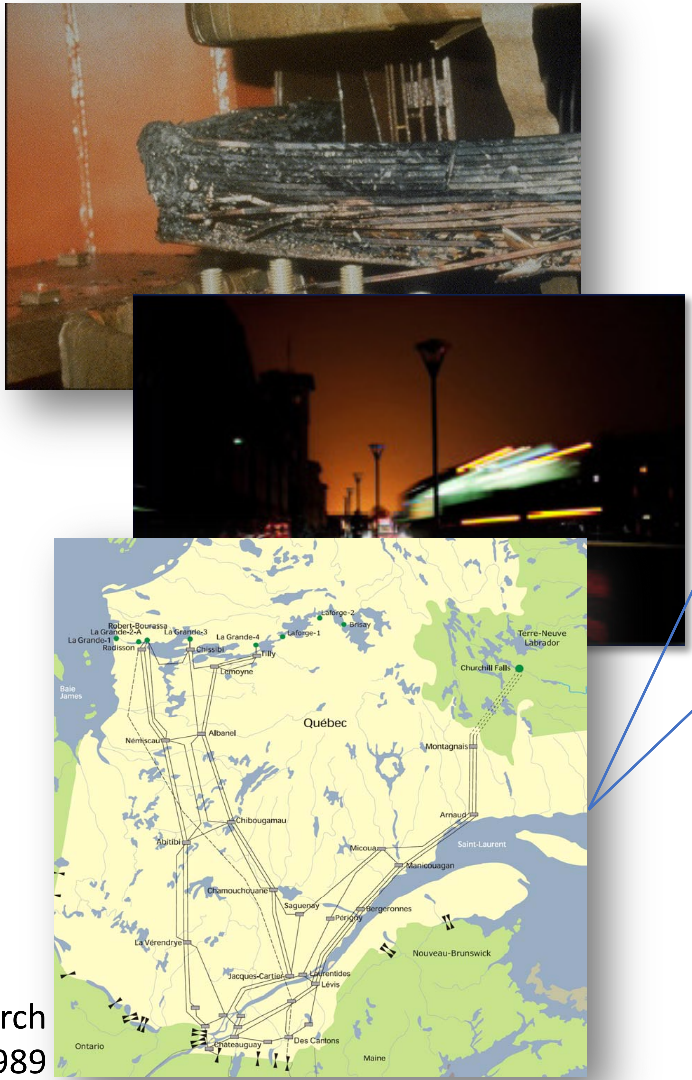
1 *Be it enacted by the Senate and House of Representa-*
2 *tives of the United States of America in Congress assembled,*

Why do we care?



GIC is related to the line integral of E(r,t)

Why do we care?

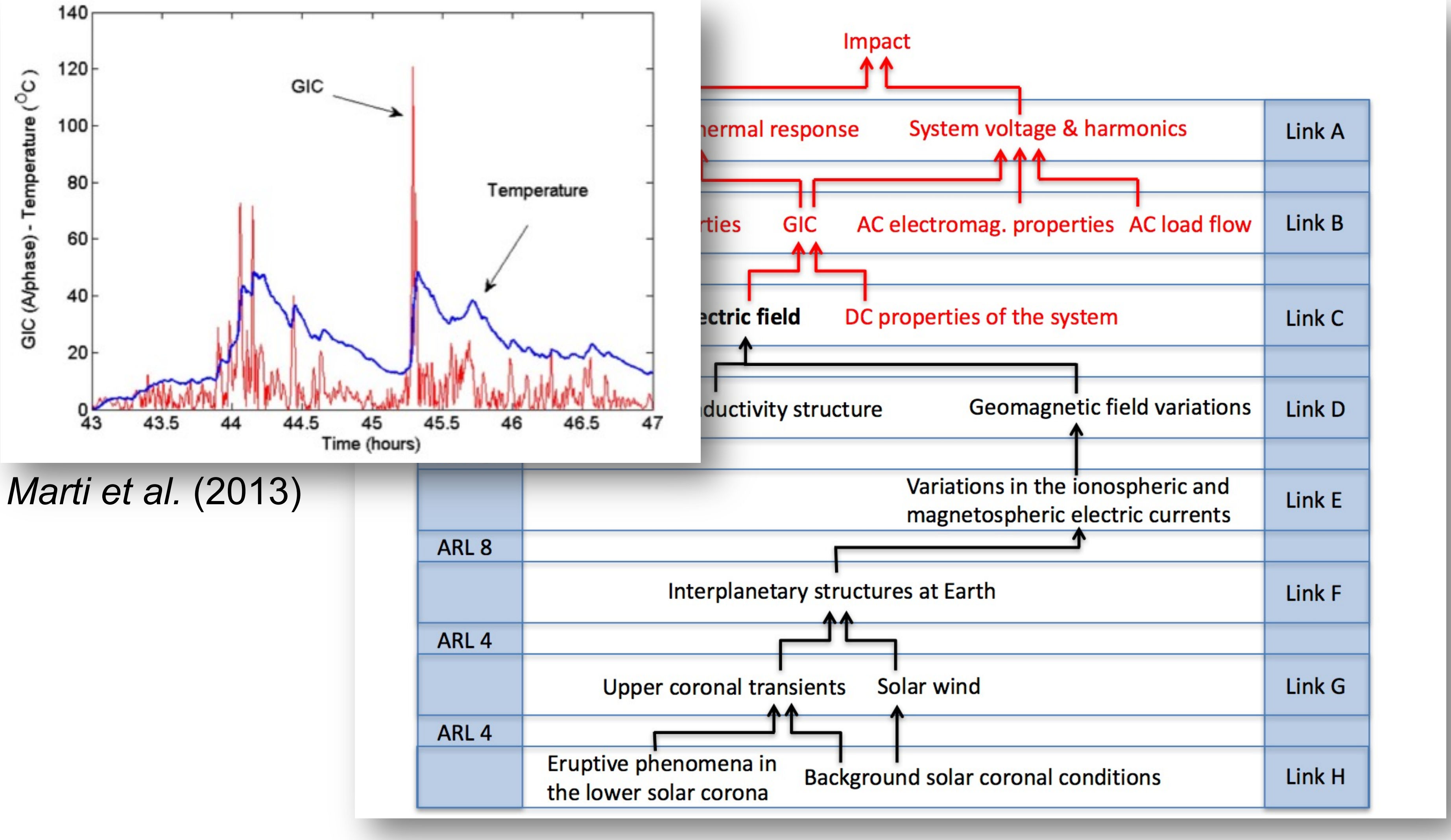


Hydro-Québec March 1989

GIC-driven half-cycle saturation of power transformers can cause:

- Leakage magnetic fields.
  - → Transformer heating
- Harmonic currents.
  - → Relay tripping
- Increased reactive power consumption.
  - → Voltage instability

The GIC systems science



Marti et al. (2013)

Pulkkinen et al. (2017)

Impact

ermal response
System voltage & harmonics
Link A

rties
GIC
AC electromag. properties
AC load flow
Link B

ectric field
DC properties of the system
Link C

ductivity structure
Geomagnetic field variations
Link D

Variations in the ionospheric and magnetospheric electric currents
Link E

ARL 8

Interplanetary structures at Earth
Link F

ARL 4

Upper coronal transients
Solar wind
Link G

ARL 4

Eruptive phenomena in the lower solar corona
Background solar coronal conditions
Link H

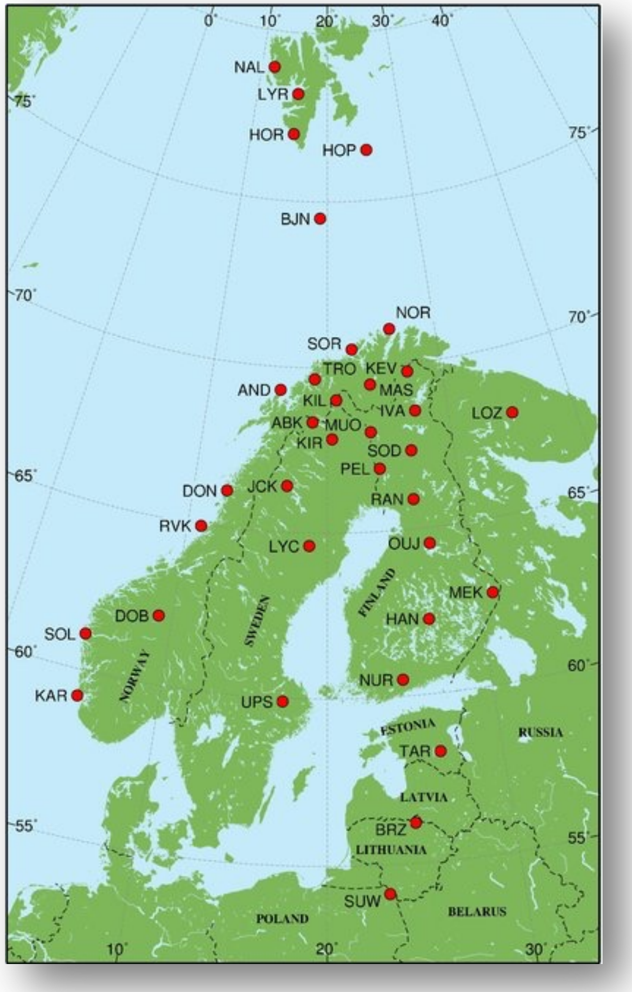
Extreme GIC

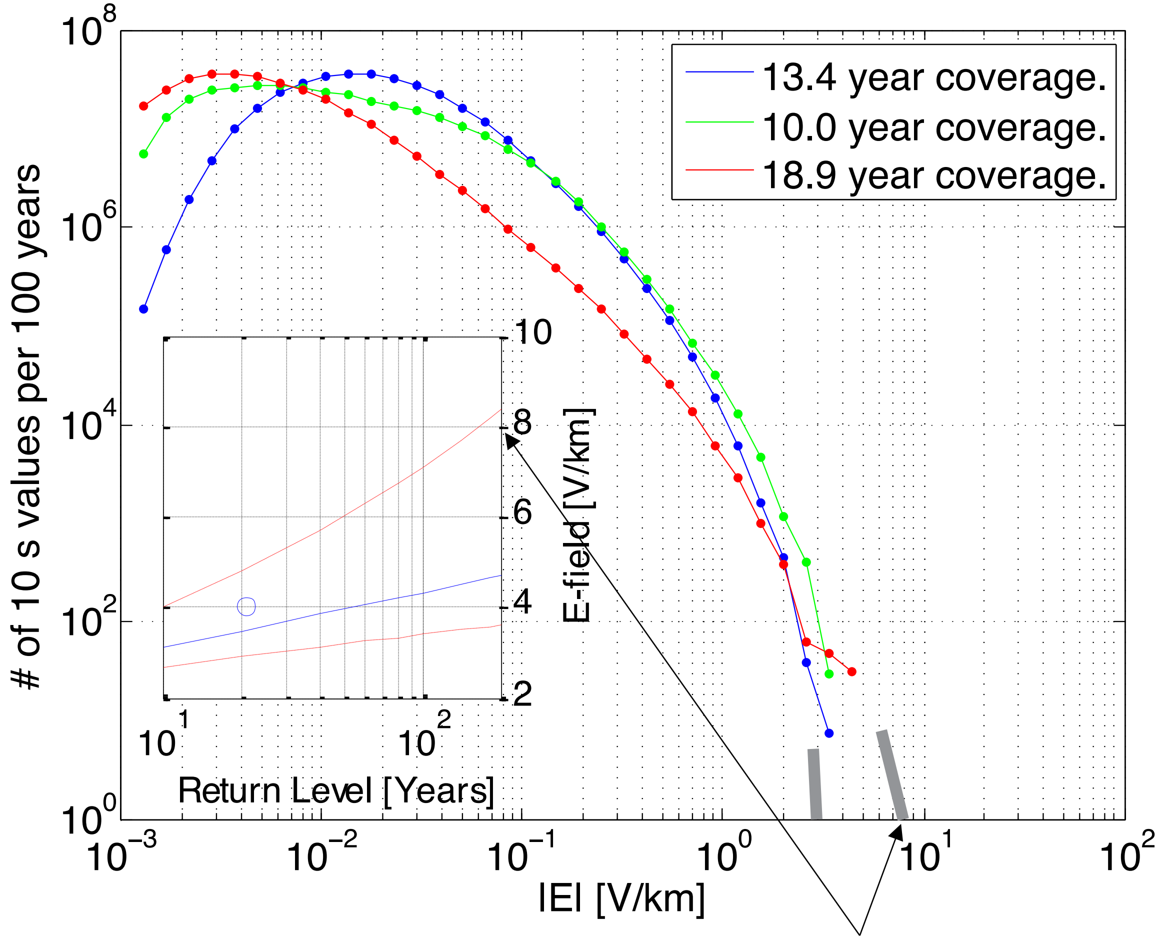
- Current focus of the GIC work (at least in the U.S.) is to understand the Carrington storm-like extreme events.
- Extreme events were the core in the U.S. Federal Energy Regulatory Commission and National Space Weather Action Plan proceedings.

Extreme GIC

While the impact is highly system dependent, I use the following rule of thumb: “0.1 V/km - nobody cares, 1 V/km - hey pay attention, 10 V/km - lights out.”

IMAGE magnetometer chain

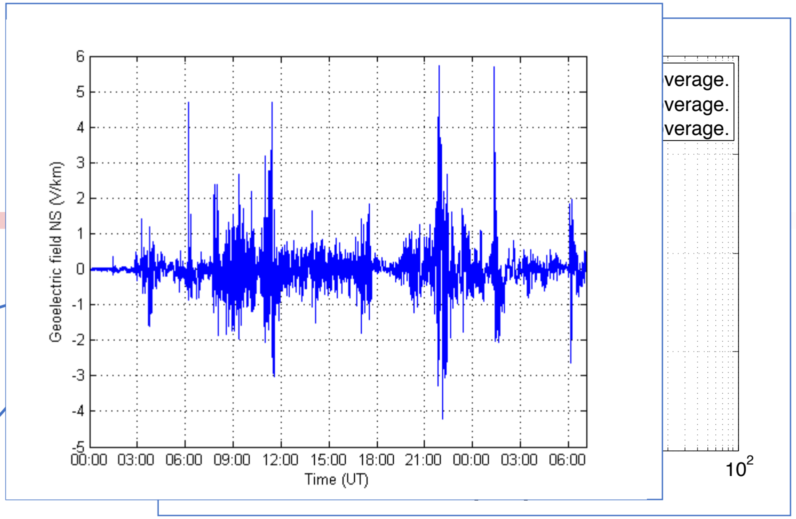




Pulkkinen et al. (2015)

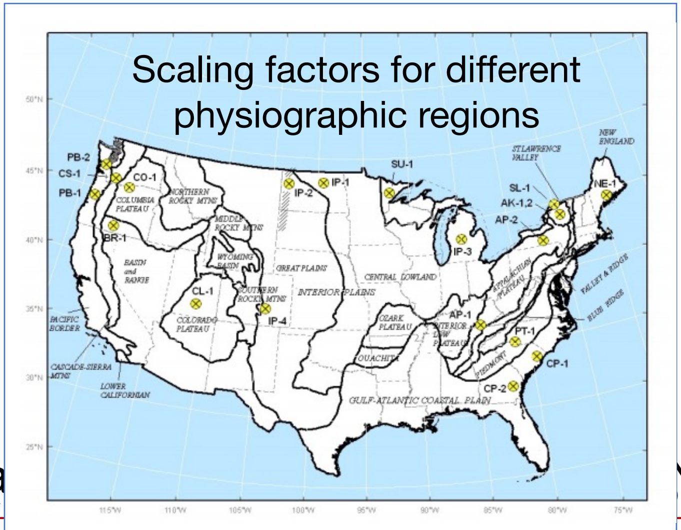
“The magic” 8 V/km

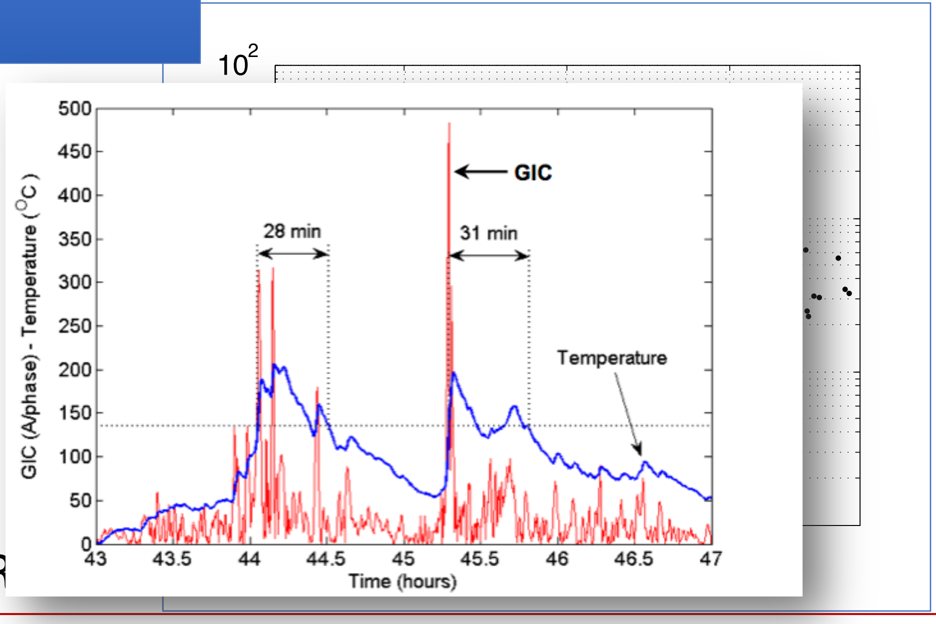
Extreme E-field scenarios



- Element 1: amplitude
- Element 2: spatial structure
- Element 3: reference temporal waveform
- e dependence
- ocal ground

And this E-field information feeds into AC load flow, harmonics and transformer thermal assessments


Scaling factors for different physiographic regions



More on GICs

AGU PUBLICATIONS

Space Weather

REVIEW ARTICLE

10.1002/2016SW001501

Special Section:
NASA's Living With a Star: Geomagnetically Induced Currents

Key Points:
- We provide a broad overview of the status of the GIC field
- We utilize the Applications Readiness Levels (ARL) concept to quantify the maturity of our GIC-related modeling and applications
- This paper is the high-level report of the NASA Living With a Star GIC Working Group findings

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Citation:
Pulkkinen, A., et al. (2017), Geomagnetically induced currents: Science, engineering, and applications readiness, *Space Weather*, *15*, doi:10.1002/2016SW001501.

Received 14 AUG 2016
Accepted 26 JAN 2017
Accepted article online 30 JAN 2017

Geomagnetically induced currents: Science, engineering, and applications readiness

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Abstract This paper is the primary deliverable of the very first NASA Living With a Star Institute Working Group, Geomagnetically Induced Currents (GIC) Working Group. The paper provides a broad overview of the current status and future challenges pertaining to the science, engineering, and applications of the GIC problem. Science is understood here as the basic space and Earth sciences research that allows improved understanding and physics-based modeling of the physical processes behind GIC. Engineering, in turn, is understood here as the "impact" aspect of GIC. Applications are understood as the models, tools, and activities that can provide actionable information to entities such as power systems operators for mitigating the effects of GIC and government agencies for managing any potential consequences from GIC impact to critical infrastructure. Applications can be considered the ultimate goal of our GIC work. In assessing the status of the field, we quantify the readiness of various applications in the mitigation context. We use the Applications Readiness Level (ARL) concept to carry out the quantification.

1. Introduction

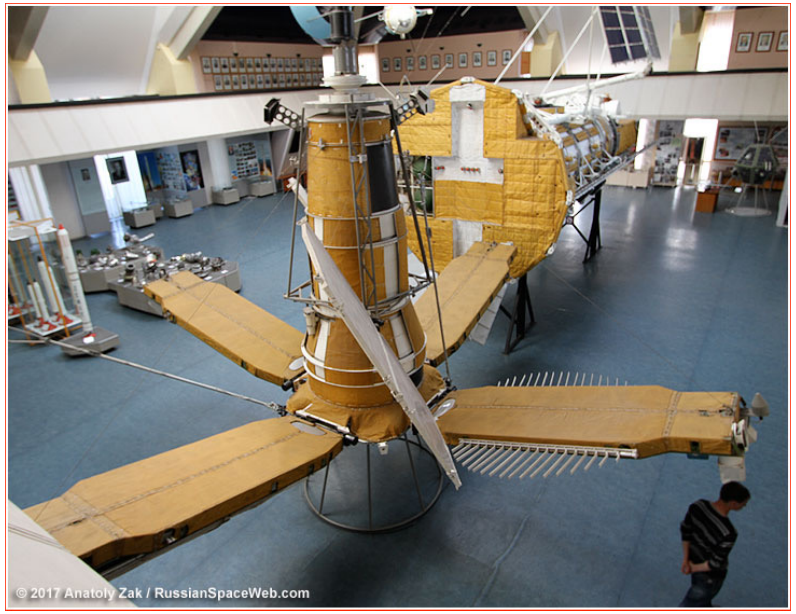
Geomagnetic disturbances (GMD) cause geomagnetically induced currents (GIC) to flow in long engineered conductor systems such as power grids, pipelines, and railway systems. GIC have become one of the main space weather concerns, and the potential for widespread problems in operating high-voltage power transmission systems during major geomagnetic storms has prompted increasing international policy, science, industry, and public interest in the problem. In the U.S., the latest high-level attention on GIC and power grids is centered around regulatory action initiated by the Federal Energy Regulatory Commission and GIC-related elements of the National Space Weather Strategy and National Space Weather Action Plan [*United States of America Federal Energy Regulatory Commission*, 2013; *National Science and Technology Council*, 2015a; *National Science and Technology Council*, 2015b]. In the UK, GIC are part of the space weather element in the National Risk Registry [*Cabinet Office*, 2015]. In addition, the power transmission industry is quickly elevating awareness to address the GIC issue, acknowledging that the problem pertains to middle and low latitudes as well as high latitudes [e.g., *Gaunt and Coetzee*, 2007; *Liu et al.*, 2009; *Torta et al.*, 2012; *Carter et al.*, 2015]. Consequently, power system operators in nations such as the US, UK, Canada, Finland, Norway, Sweden, China, Japan, Brazil, Namibia, South Africa, and Australia have launched GIC measurement and hazards assessment campaigns to understand and mitigate the possible GIC impact on their systems. The field of GIC has evolved over the past several years from a somewhat separate field of space science research into a full systems science addressing not

PULKKINEN ET AL. GIC OVERVIEW 1

Pulkkinen et al. (Space Weather, 2017)

NASA TIMED & Russian Kosmos 2221 – Feb 28, 2024

TIMED



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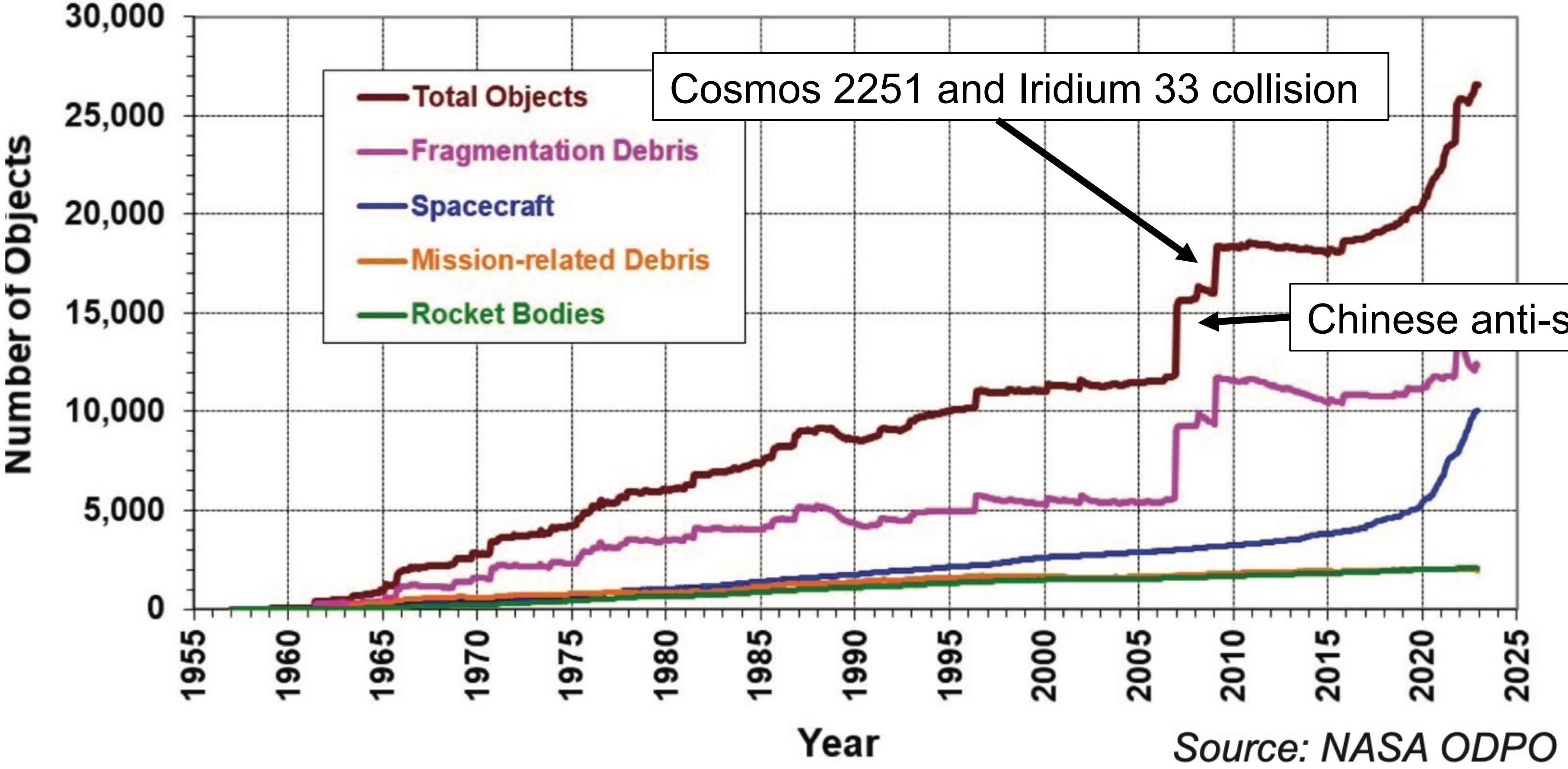
Kosmos 2221-like Electronic and Signals Intelligence satellite

Low-Earth Objects (LEO) objects



Cosmos 2251 and Iridium 33 collision

Chinese anti-satellite missile test

Source: NASA ODPO

Starlink incident – Feb 3, 2022

The Washington Post
Democracy Dies in Darkness

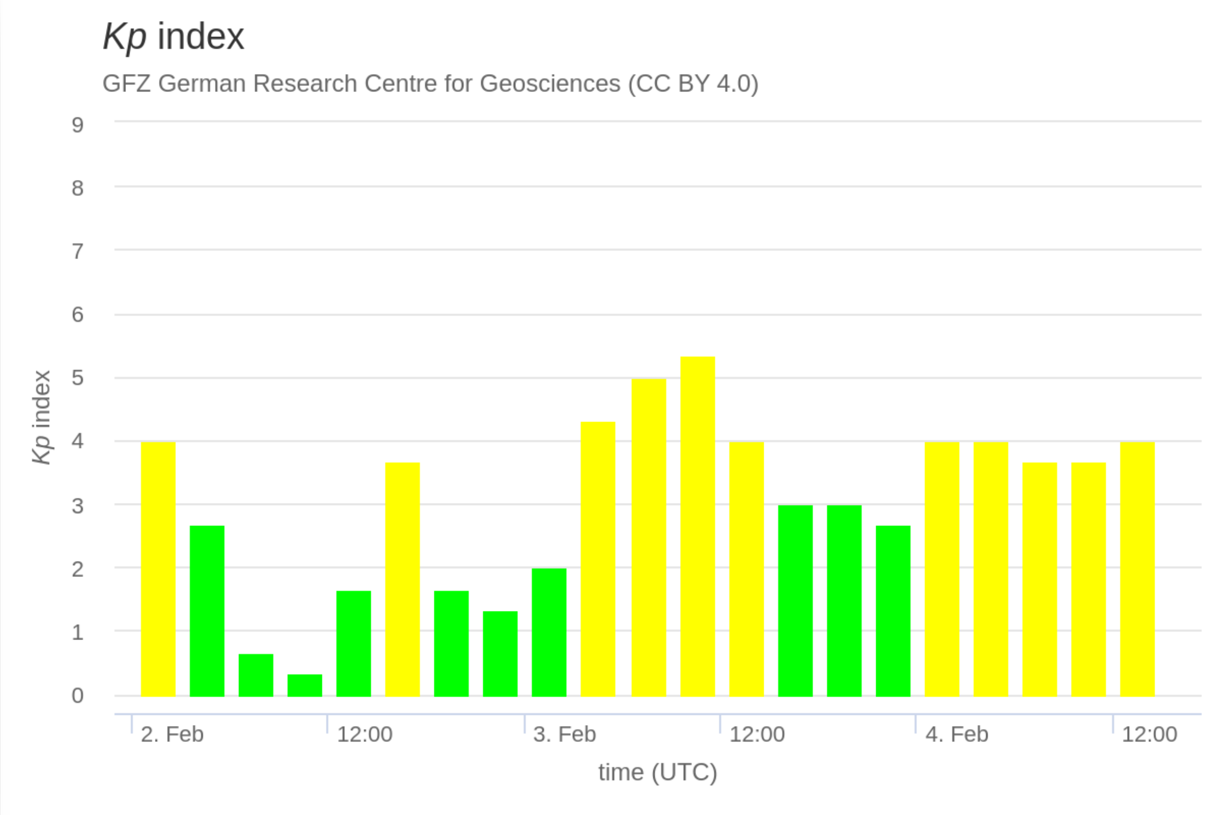
How a rather mundane space storm knocked out 40 SpaceX satellites

As the sun enters a more active phase, even minor geomagnetic activity could pose problems for smaller SpaceX satellites.

By Kasha Patel

February 12, 2022 at 9:00 a.m. EST

An aurora appeared near Rogart in Sutherland, Scotland, as a minor geomagnetic storm struck Earth's atmosphere on Feb. 4, 2022.



Kp index

GFZ German Research Centre for Geosciences (CC BY 4.0)

Atmospheric drag

(highly dynamic)
Atmospheric density

Thermosphere Heat Sources:
- Solar EUV
- Auroral particles and currents
- Upward propagating atmospheric waves

$$a_D = -\frac{1}{2}\left(\frac{C_D A}{m}\right)\rho V^2$$

Drag acceleration

Ballistic coefficient

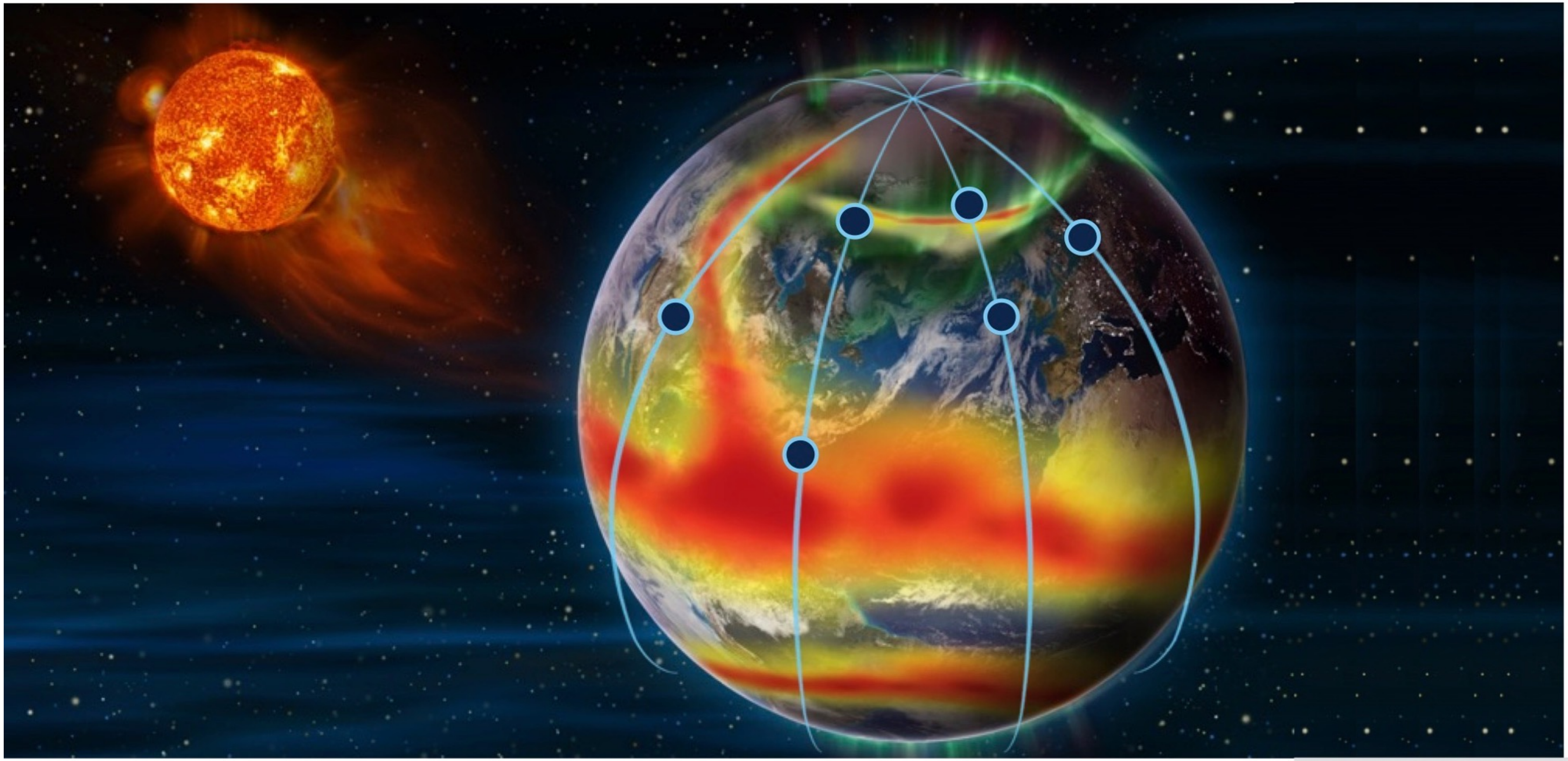
Total atmospheric velocity relative to the satellite velocity (incl. neutral winds)

- Poorly characterized atmospheric drag conditions are the single most significant source for LEO orbit propagation uncertainty (both “live” space assets and debris)

- While empirical assimilative models such as High Accuracy Satellite Drag Model (HASDM) are being used, first-principles understanding and real-time measurements in this domain are lacking.

- Due to potential major impact to all LEO space assets and exponentially worsening congestion of the domain, this is in my personal opinion the most significant space weather growth area.

Geospace Dynamics Constellation (GDC)



Radiation effects on humans

- Energetic charged particle radiation in space and at high altitudes poses a problem for biological systems such as humans.
- The key problem is *ionizing radiation* – radiation (typically > 10 MeV ions) with sufficient energy to ionize atoms and molecules along the path of penetration.
- Primary sources for energetic ions contributing to possible problems include galactic cosmic rays, SEPs and inner radiation belt.

Radiation effects on humans

- The radiation exposure connecting to radiobiological data is commonly measured in terms of Gray (Gy) and Sievert (Sv).
- Gy *absorbed dose* or *energy dose* is the amount of absorbed energy divided by the mass of the body (J/kg). 3 Gy homogenous whole-body exposure would typically be lethal.
- To account for different effects of different types of radiation one defines *relative biological effectiveness* (RBE) as:

$$RBE = D_r(E) / D_q(E)$$

where *E* is the biological effect (e.g. mortality), *D* absorbed dose, *r* reference type of radiation (usually X-rays) and *q* radiation type.

Radiation effects on humans

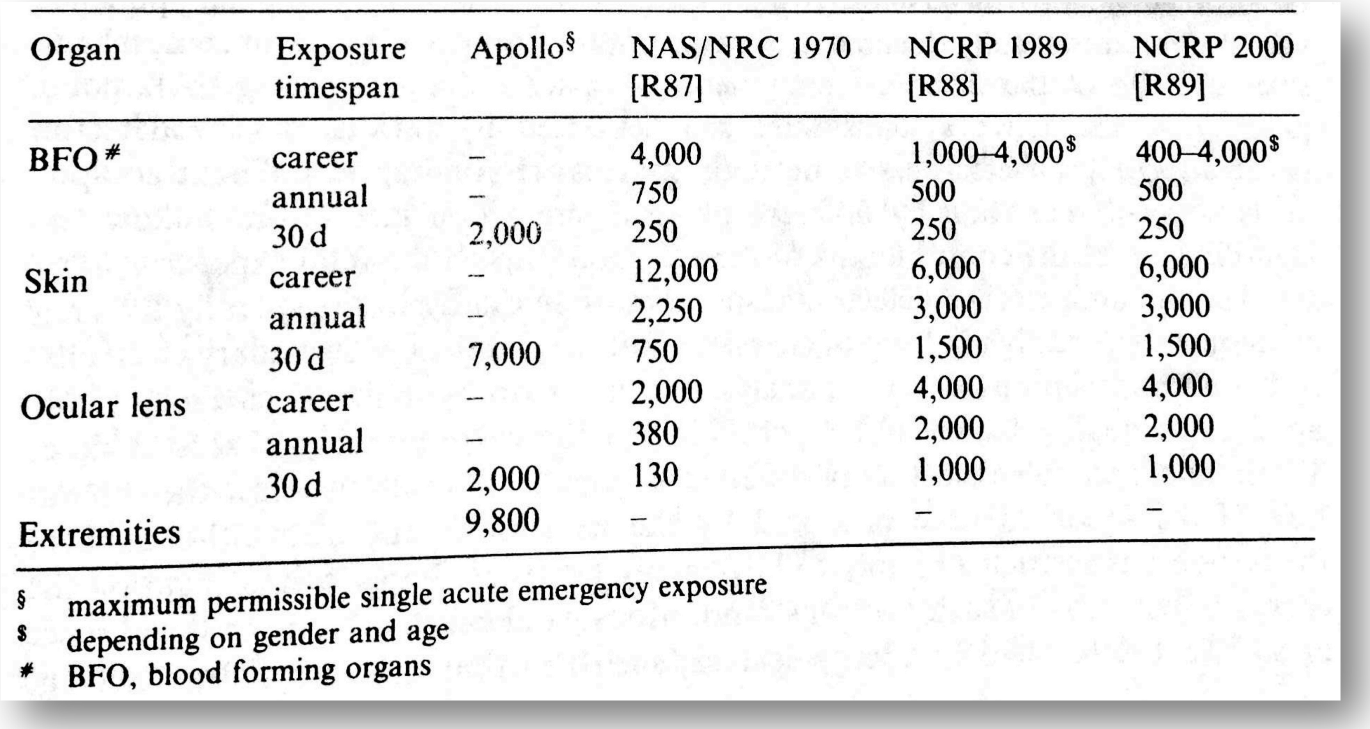
- One obtains biologically weighted *equivalent dose* by multiplying absorbed dose by RBE. Equivalent dose has SI unit of Sievert (Sv).
- Note that although absorbed dose Gy and equivalent dose Sv both have dimension J/kg they represent different things. Equivalent dose takes into account radiobiological effects and the radiation type and scales things into “universal” radiation units.
- Whole body exposures are quantified as *effective dose* (also in Sv), which is a (tissue factor) weighted sum of equivalent dose over different types of tissue.

➔ I know, this is a bit confusing.

- Dose rates of 50 mSv/a and equivalent doses 200 mSv in the realm of *stochastic effects*, i.e. likelihood of effect increases as a function of dose. The primary late effect is cancer.
- High end dose rates of 3 Sv/h and equivalent doses 3 Sv implying likely lethal dose in the realm of acute *deterministic effects*, i.e. severity of the damage increases as a function of dose.

Radiation effects on humans - NASA

- For NASA, all crewmember radiation exposures are to be minimized using As Low as Reasonably Achievable (ALARA) principle.
- NASA has used U.S. National Council on Radiation Protection and Measurements (NCRP) guidance for setting the exposure limits for astronauts.



Organ	Exposure timespan	Apollo§	NAS/NRC 1970 [R87]	NCRP 1989 [R88]	NCRP 2000 [R89]
BFO#	career	–	4,000	1,000–4,000$	400–4,000$
	annual	–	750	500	500
	30 d	2,000	250	250	250
Skin	career	–	12,000	6,000	6,000
	annual	–	2,250	3,000	3,000
	30 d	7,000	750	1,500	1,500
Ocular lens	career	–	2,000	4,000	4,000
	annual	–	380	2,000	2,000
	30 d	2,000	130	1,000	1,000
Extremities		9,800	–	–	–

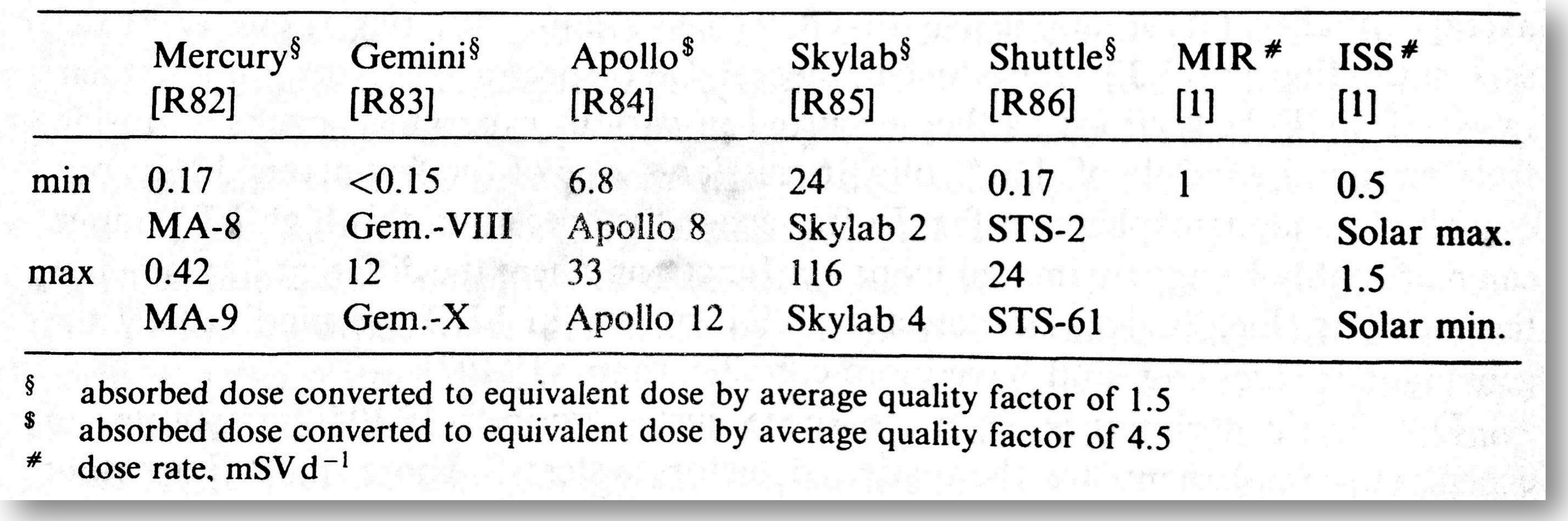
§ maximum permissible single acute emergency exposure
$ depending on gender and age
# BFO, blood forming organs

Recommended radiation exposure limits in mSv for astronauts (Credit: Facius and Reitz et al., 2004)

Radiation effects on humans - NASA

- Both geomagnetic field and spacecraft provide shielding (increase in secondary radiation products possible). Consequently, doses at LEO are quite low.

Typical exposures in mSv measured during human spaceflight missions (Credit: Facius and Reitz et al., 2004)



	Mercury§ [R82]	Gemini§ [R83]	Apollo$ [R84]	Skylab§ [R85]	Shuttle§ [R86]	MIR# [1]	ISS# [1]
min	0.17	<0.15	6.8	24	0.17	1	0.5
	MA-8	Gem.-VIII	Apollo 8	Skylab 2	STS-2		Solar max.
max	0.42	12	33	116	24		1.5
	MA-9	Gem.-X	Apollo 12	Skylab 4	STS-61		Solar min.

§ absorbed dose converted to equivalent dose by average quality factor of 1.5

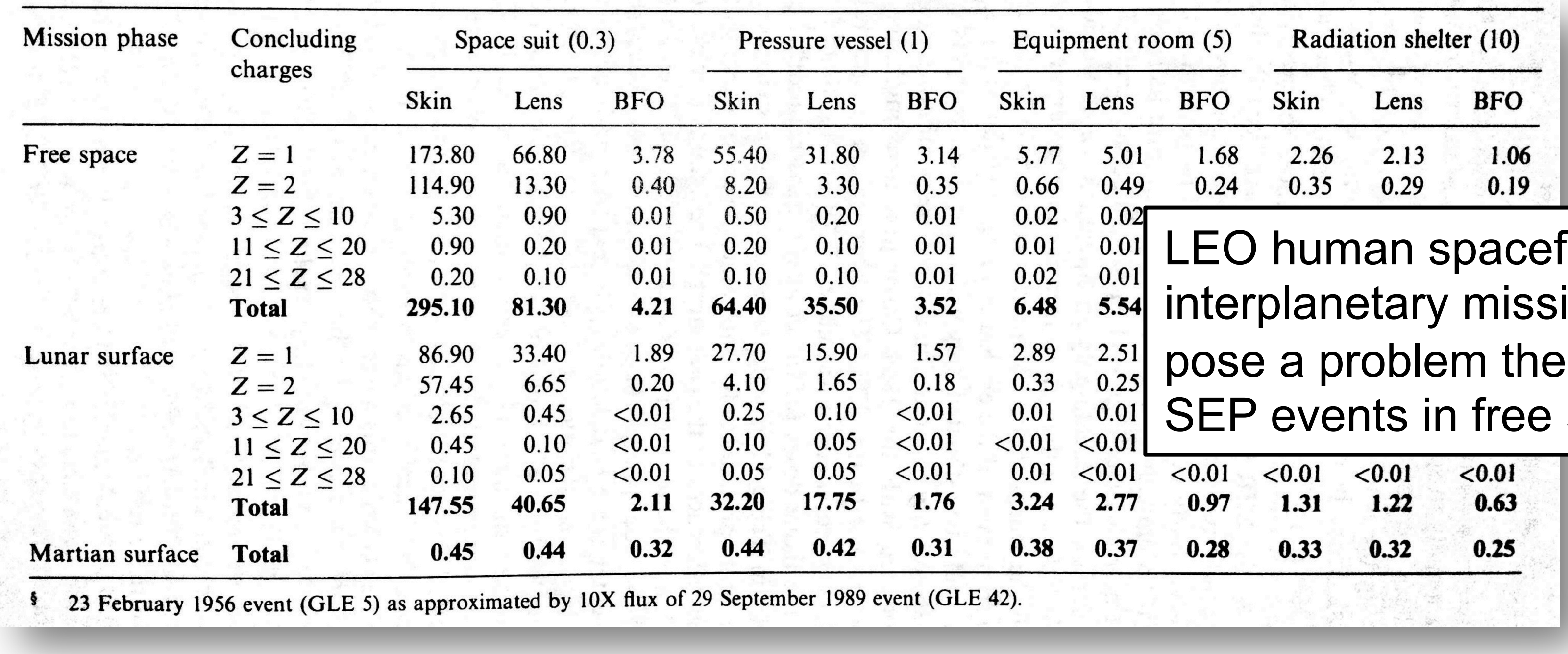
$ absorbed dose converted to equivalent dose by average quality factor of 4.5

dose rate, mSV d^{-1}

Radiation effects on humans - NASA

- Outside the magnetosphere we will have no geomagnetic shielding. GCR component for extended 2-3 year interplanetary missions 10-1000 mSv depending on the shielding. However, major SEPs pose a problem:

Worst-case SEP scenario exposure in Sv. Parenthesis in equivalent g/cm^2 aluminum and BFO = blood forming organs (Credit: Facius and Reitz et al., 2004)



Mission phase	Concluding charges	Space suit (0.3)			Pressure vessel (1)			Equipment room (5)			Radiation shelter (10)		
		Skin	Lens	BFO	Skin	Lens	BFO	Skin	Lens	BFO	Skin	Lens	BFO
Free space	$Z = 1$	173.80	66.80	3.78	55.40	31.80	3.14	5.77	5.01	1.68	2.26	2.13	1.06
	$Z = 2$	114.90	13.30	0.40	8.20	3.30	0.35	0.66	0.49	0.24	0.35	0.29	0.19
	$3 \leq Z \leq 10$	5.30	0.90	0.01	0.50	0.20	0.01	0.02	0.02				
	$11 \leq Z \leq 20$	0.90	0.20	0.01	0.20	0.10	0.01	0.01	0.01				
	$21 \leq Z \leq 28$	0.20	0.10	0.01	0.10	0.10	0.01	0.02	0.01				
	Total	**295.10**	**81.30**	**4.21**	**64.40**	**35.50**	**3.52**	**6.48**	**5.54**				
Lunar surface	$Z = 1$	86.90	33.40	1.89	27.70	15.90	1.57	2.89	2.51				
	$Z = 2$	57.45	6.65	0.20	4.10	1.65	0.18	0.33	0.25				
	$3 \leq Z \leq 10$	2.65	0.45	<0.01	0.25	0.10	<0.01	0.01	0.01				
	$11 \leq Z \leq 20$	0.45	0.10	<0.01	0.10	0.05	<0.01	<0.01	<0.01				
	$21 \leq Z \leq 28$	0.10	0.05	<0.01	0.05	0.05	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Total	**147.55**	**40.65**	**2.11**	**32.20**	**17.75**	**1.76**	**3.24**	**2.77**	**0.97**	**1.31**	**1.22**	**0.63**
Martian surface	**Total**	**0.45**	**0.44**	**0.32**	**0.44**	**0.42**	**0.31**	**0.38**	**0.37**	**0.28**	**0.33**	**0.32**	**0.25**

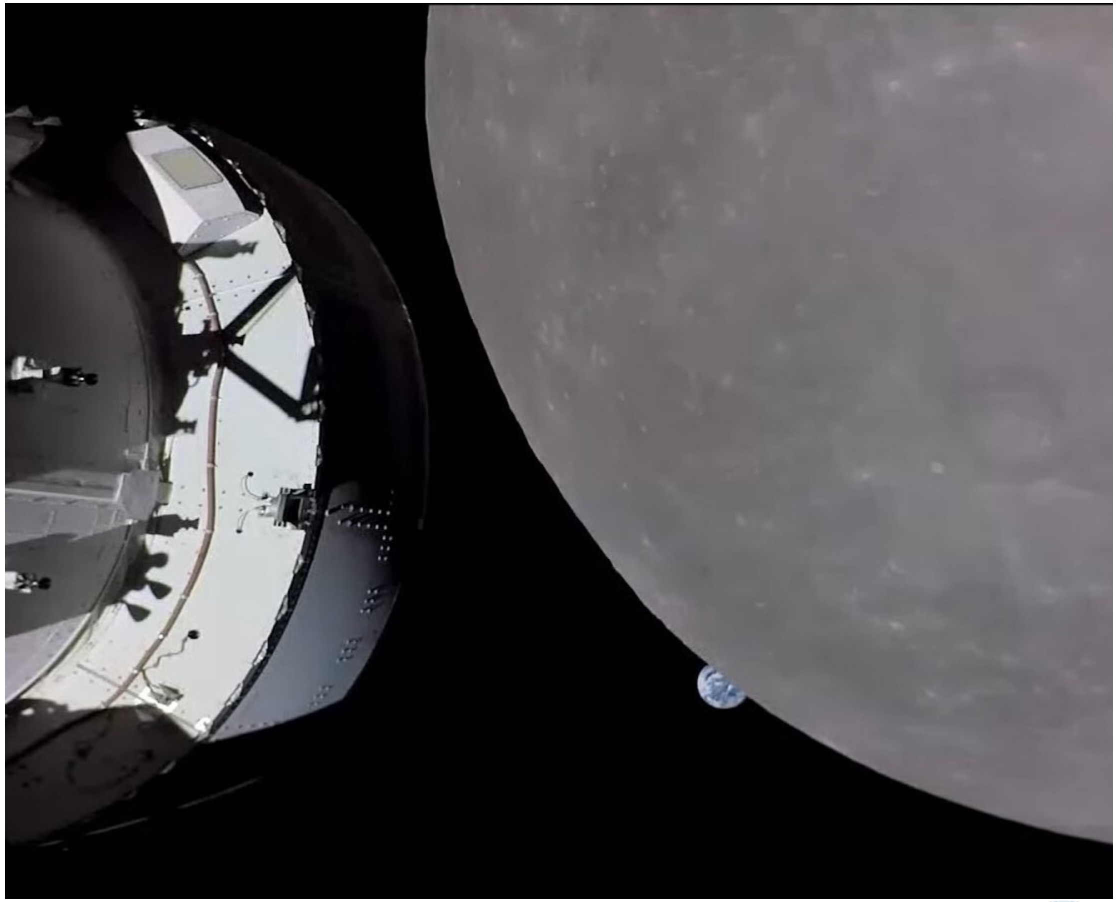
§ 23 February 1956 event (GLE 5) as approximated by 10X flux of 29 September 1989 event (GLE 42).

LEO human spaceflight missions mostly safe. For interplanetary missions while galactic cosmic rays also pose a problem the risk may be manageable. Major SEP events in free space pose a possible problem.

Moon to Mars (M2M) Space Weather Analysis Office

- Given the new challenges with deep space exploration missions, additional support is needed in analyzing the space weather environment especially beyond the Sun-Earth line.
- The M2M Office will support the JSC SRAG console operators by providing the necessary state-of the-art tailored space weather information.

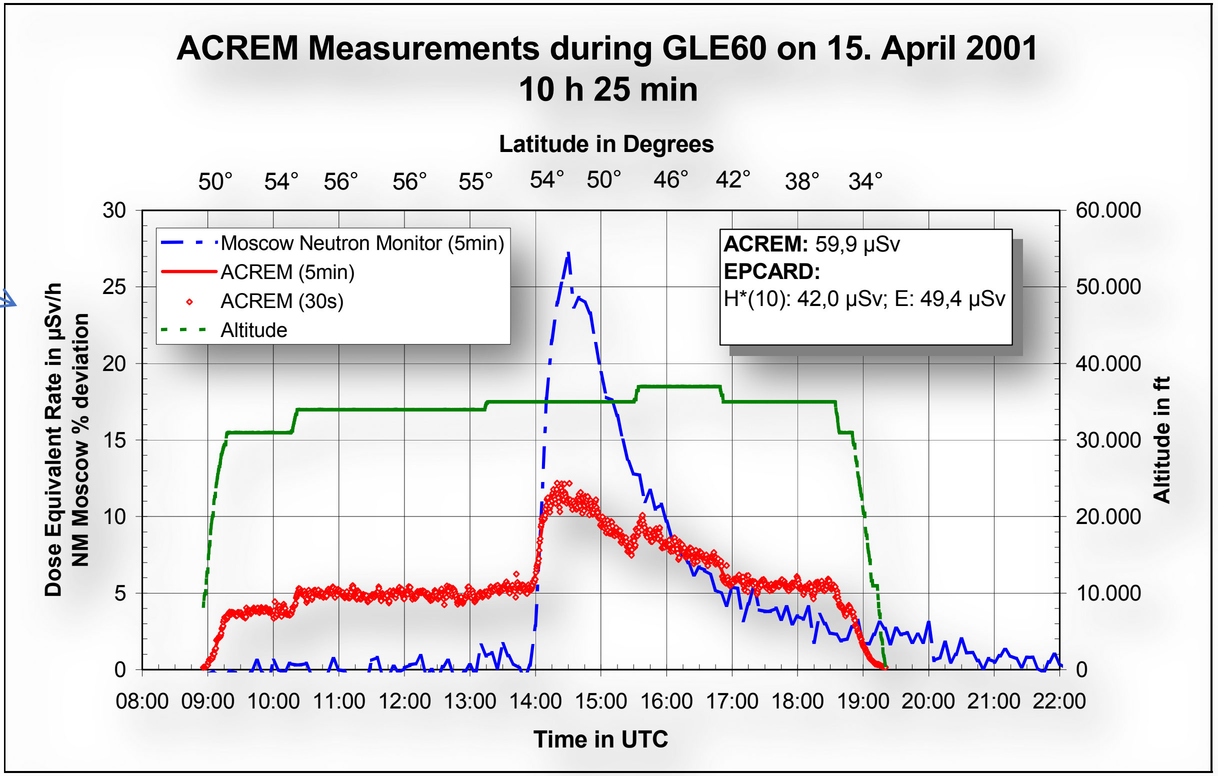
➔ Artemis 1 support was a major success for the M2M team!



Aviation radiation impact

- At airline altitudes ionizing radiation is composed of “showering” particles.
- In Europe and US airline crew considered as radiation workers and the corresponding dose limits apply.

This is still fairly low compared to what we saw above



Dose observations from a commercial FRA-DFW flight (Credit: Bartlett et al., 2002)

Aviation radiation impact

- Due to atmospheric and geomagnetic shielding radiation not necessarily a major problem for commercial airlines at this time.
- Only in worst-case SEP scenarios equivalent dose may approach 1 mSv limit for pregnant crew members.
- Significant impact on HF radio communications the primary concern causing rerouting from the polar paths.

Gannon superstorm of May 10-13, 2024

iSWA layout

Gannon superstorm of May 10-13, 2024

GOES Primary X-ray Flux

2024-05-14 14:28:00

ACE Magnetic Field

2024-05-14 14:29:00

Observed Kp vs. Predicted Kp

(May 8, 2024, 18:00, 2) NOAA_KP_P3H / KP_3H KP Index

1.84 Predicted_KP_P1M / KP KP Index

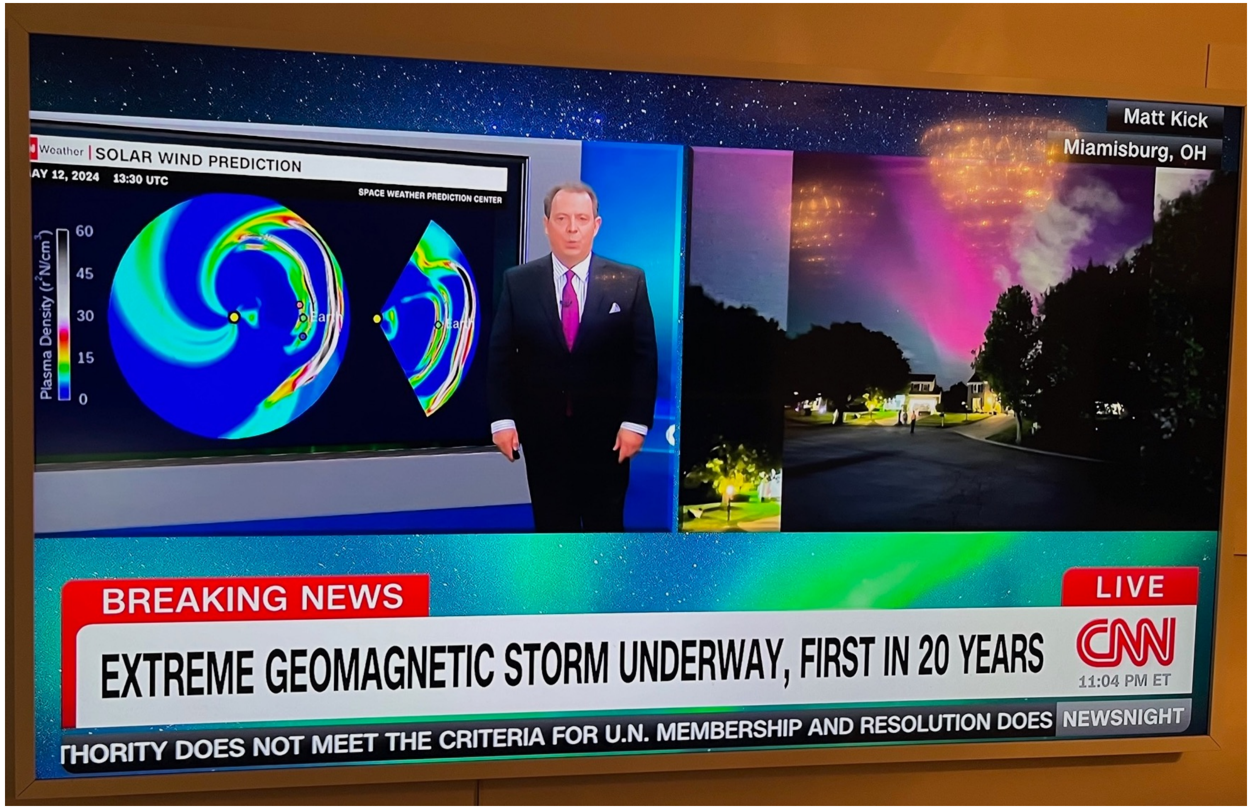
May 8, 2024, 18:16

2024-05-14 14:11:00

Impacts

Impacts

Blue Ridge Parkway in Virginia Fri May 10, 2024 (Washington Post)



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