The role of space weather monitoring in ensuring the sustainability of space-based technological systems.

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Introduction

- The 2030 Space agenda is a forward-looking strategy that aims to re-affirm and strengthen the contribution of space-based technologies in the achievement of the Sustainable Development Goals(SDGs).

- It builds upon the achievements of the Millennium Development Goals(MDGs) and addresses their unfinished business through the 17 SDGs.

- The SDGs adopted at the United Nations in 2015, are a great summary of the world's current challenges.

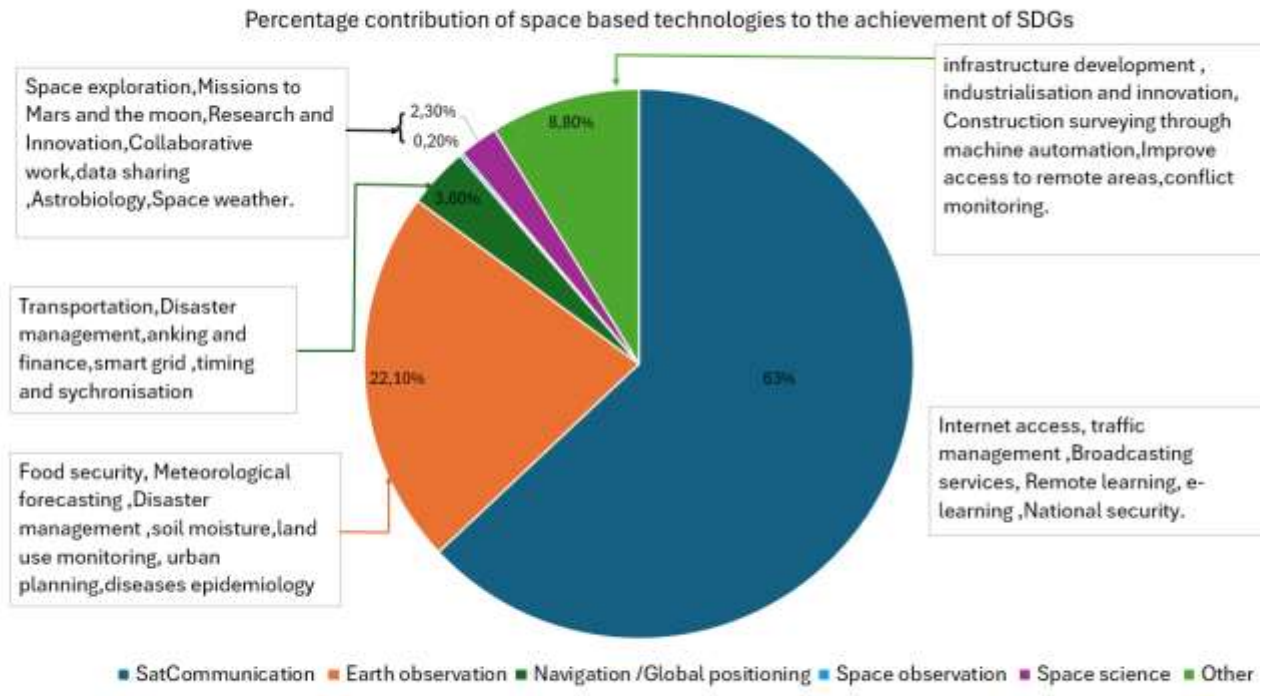
- Built upon three pillars of sustainability: economy, society, and the environment.

- Although the SDGs were compiled as a set of goals that are to be achieved globally, they also resonate with regional, national, continental and Intercontinental development agenda.

- The achievement of SDGs is relies on continuous use of Space based technologies .However space weather events may cause disruption or interruptions potentially limiting access to these technologies for a period of time.

The role of space-based technologies

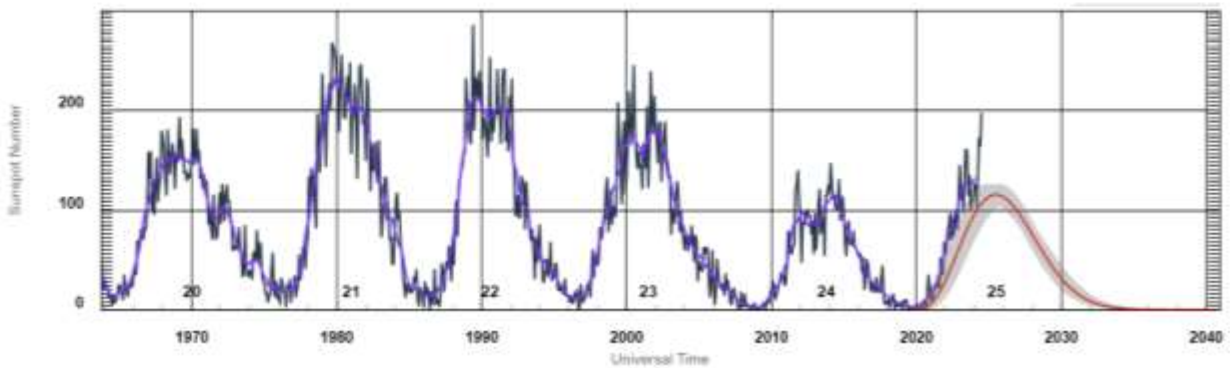
- Space technologies contribute to economic growth and the overall improvement of the quality of life.
- These technologies have become a critical part of our everyday hence the growing reliance.
- Space weather can significantly impact space-based technology and infrastructure.



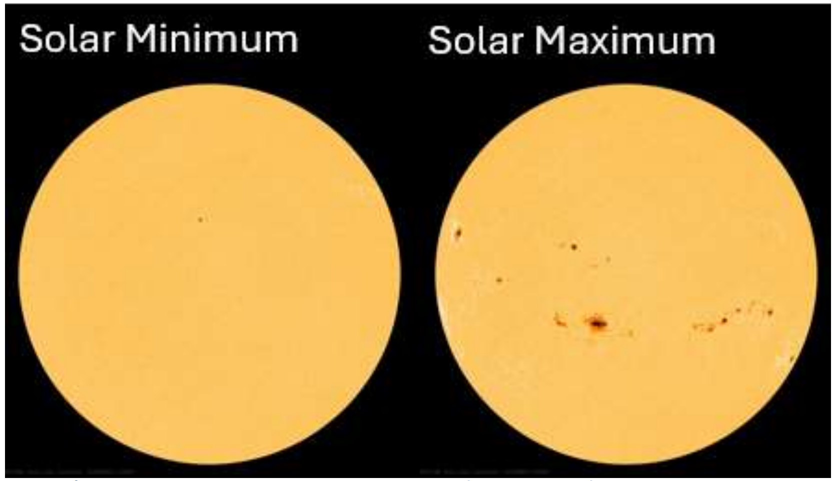
(Baumgart *et al.*, 2021), [Every Satellite Orbiting Earth and Who Owns Them | Dewesoft]

What is Space weather?

Space weather refers to the conditions on the Sun and in space including the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of technological systems both airborne and ground based.



[Solar Cycle Progression | NOAA / NWS Space Weather Prediction Center]



[SDO | Solar Dynamics Observatory (nasa.gov)]

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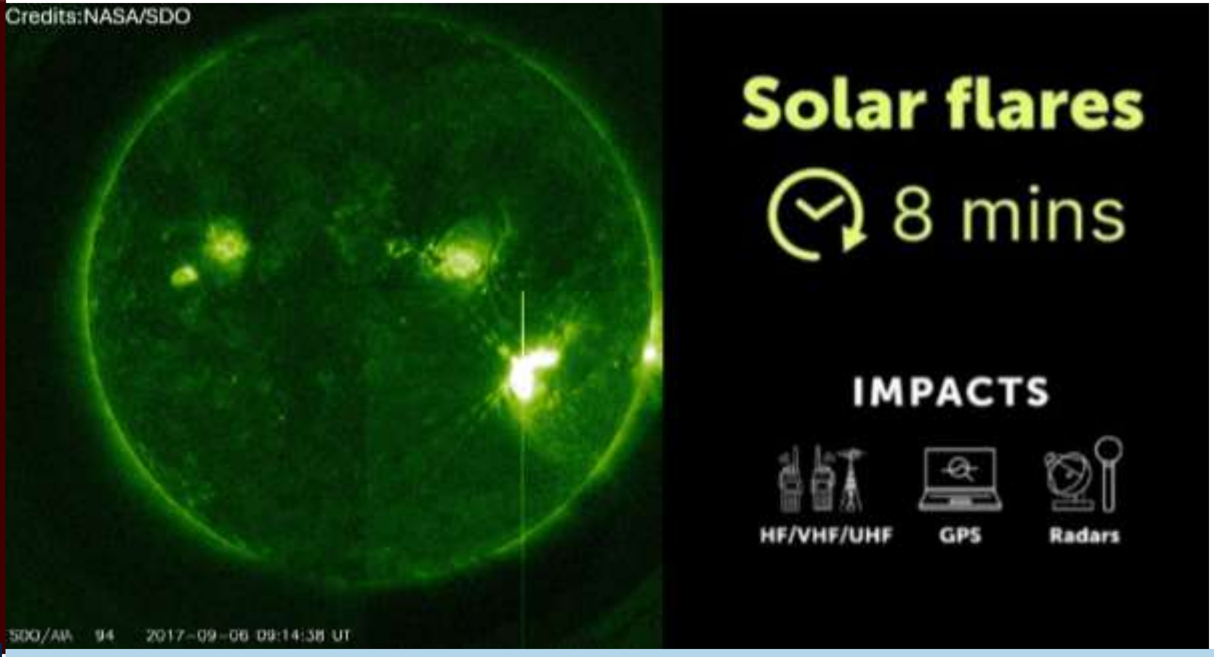

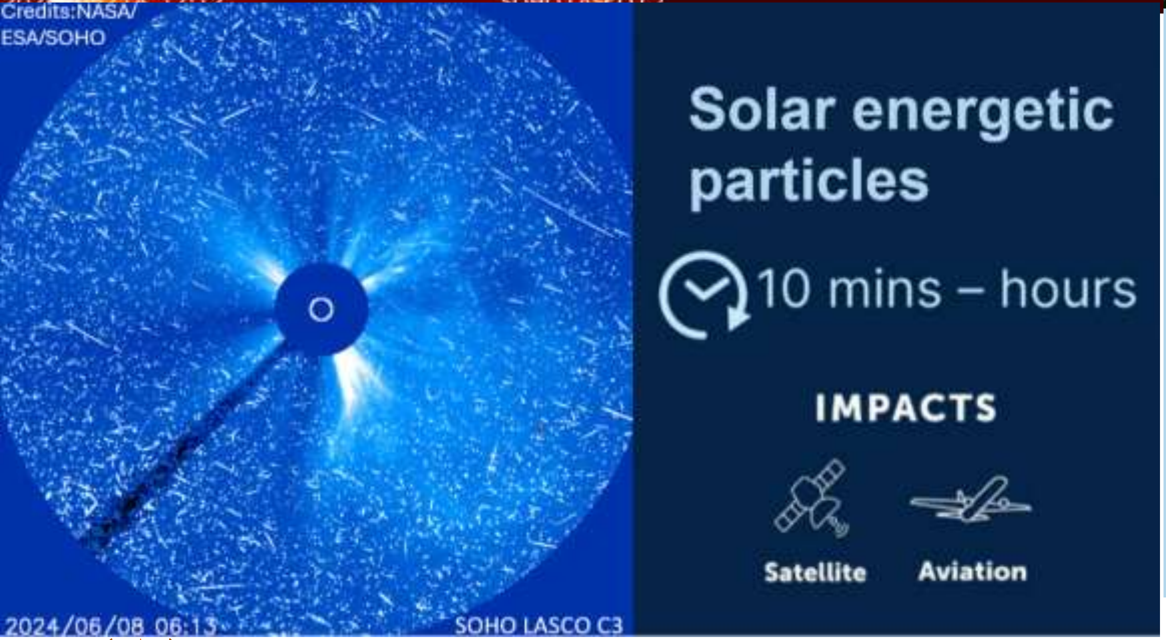

Coronal mass ejection- an ejection of material from the sun's surface into interplanetary space. If the material is directed towards the Earth, the event may result in a Geomagnetic storm.

Solar flare- A sudden bursts of magnetic energy in the form of electromagnetic radiation(X-ray and UV).Only has day side Impact.

Solar Energetic Particles -High energy electrically charged particles that can travel with speed close to the speed of light.

Geomagnetic storm - a temporary disturbance in the Earth's magnetosphere.

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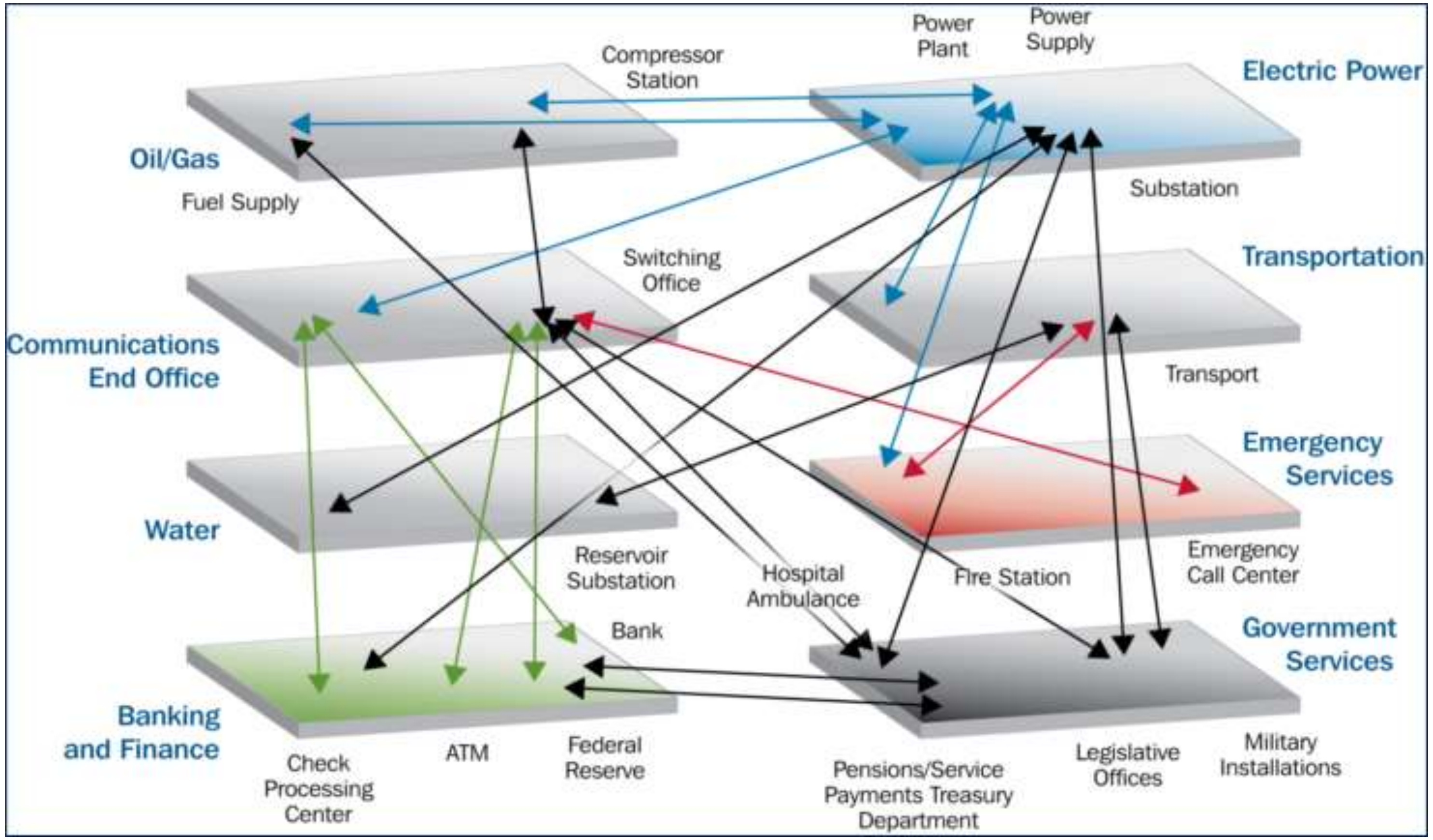
Space weather impact on critical infrastructure due to Interdependencies

Loss of key infrastructure for extended periods due to the cascading effects from a space weather event (or other disturbance) could lead to a lack of food, given low inventories and reliance on just-in-time delivery, loss of basic transportation, inability to pump fuel, and loss of refrigeration. Emergency services would be strained, and command and control might be lost. Medical care systems would be seriously challenged. Home dependency on electrically operated medical devices would be jeopardized.



[National Infrastructure Protection Plan and Resources | CISA]

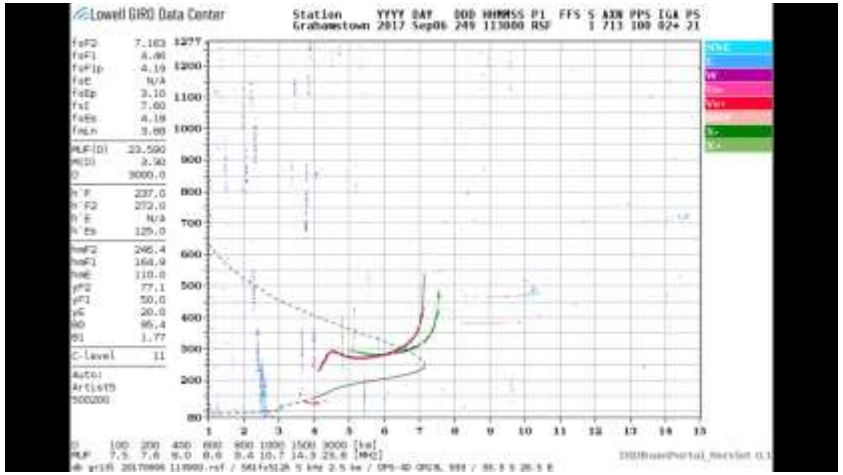
Selected space weather events since the beginning of the Space Age

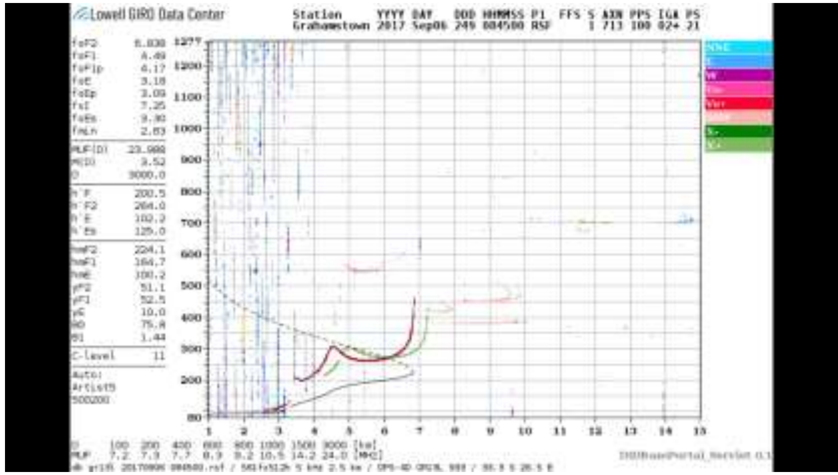
Year	Event	Description	Impacts on satellites
1972	Solar storm of August 1972, solar particle event	Coronal mass ejection with the fastest transit time to Earth recorded (14.6 hours) that created severe technological disruptions and caused the accidental detonation of numerous naval mines.	
1989	March 1989 geomagnetic storm	Caused a nine-hour power outage in the province of Quebec and led to the loss of positional knowledge of space objects for nearly a week	Multiple satellite anomalies, loss of altitude, signal disruptions
1991	Geomagnetic storm, November 1991	An intense solar storm with about half the energy output of the March 1989 storm. Auroras were visible in the United States as far south as Texas	
	Bastille Day solar storm, 14 July	Involved a solar flare, solar particle event and a coronal mass ejection, creating a severe geomagnetic storm. Caused minor damage to power transformers and satellites. Strong enough to be observed by Voyager 1 and 2 spacecraft	Astro-D (ASCA), Japan/United States, scientific satellite in low-earth orbit, loss of altitude
2001	Geomagnetic storm of November 2001	A fast-moving coronal mass ejection with auroras visible as far south as Texas, California and Florida	
2003	Halloween solar storms, mid-October to early November	Series of solar flares and coronal mass ejections. Auroras visible as far south as Texas and the Mediterranean region. Caused rerouted aircraft and power outages in southern Sweden	Reportedly some 10% of the total satellite fleet suffered anomalies, including MIDORI 2 (ADEOS), Japan/United States, France scientific satellite in low-earth orbit, anomaly
2006	Solar flare, 5 December 2006	Disrupted satellite-to-ground communications and GPS signals for about ten minutes	Damaged solar X-ray imager on the GOES-13 weather satellite
2010	Coronal mass ejection, 3 April 2010		Caused a critical failure on the Galaxy-15 communications satellite
2017	Solar flares, 6 September 2017	Involved a solar flare, solar particle event and a coronal mass ejection, creating a severe geomagnetic storm. Radio blackout from both flares	Civil aviation reported a 90-minute loss of communication with a cargo plane.
2023	Coronal mass ejection, 4 February 2022	First recorded mass satellite failure caused by an increase in atmospheric density.	38 out of 49 recently launched Starlink satellites (SpaceX, United States) destroyed on premature re-entry into the atmosphere
2024	10 May Geomagnetic storm	Multiple CME arrivals with auroras visible in the Midlatitude (South Africa and Namibia)	

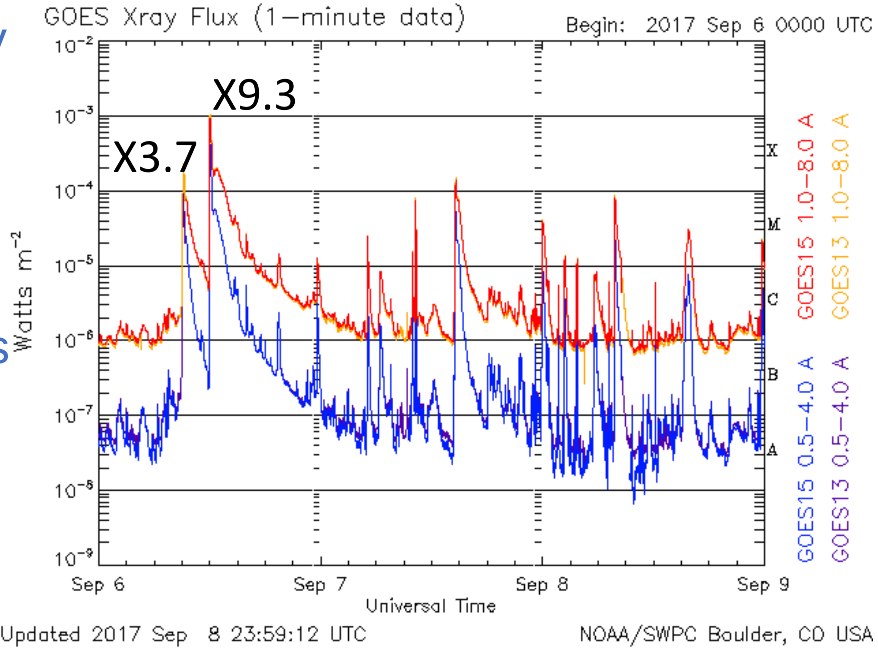
2. Space sustainability as the next major societal challenge | Earth's Orbits at Risk : The Economics of Space Sustainability | OECD iLibrary (oecd-ilibrary.org)

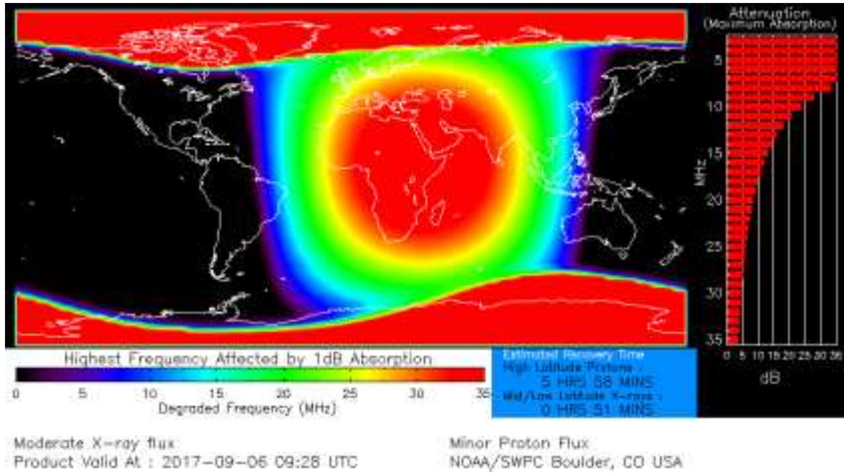
Case study: High solar flaring activity (Radio blackout)

- On 06 September 2017 the sun emitted two X-class which flares resulted in a total radio blackout over the African region.
- This caused absorption in the lower ionospheric D layer, which resulted in degradation or complete absorption of frequencies.
- NOAA reports that high frequency radio, used by aviation, maritime, ham radio, and other emergency bands, was unavailable for up to eight hours. For example, civil aviation reported a 90-minute loss of communication with a cargo plane.









[GOES X-ray Flux | NOAA / NWS Space Weather Prediction Center]

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Case study: Geomagnetic storm


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Space Weather

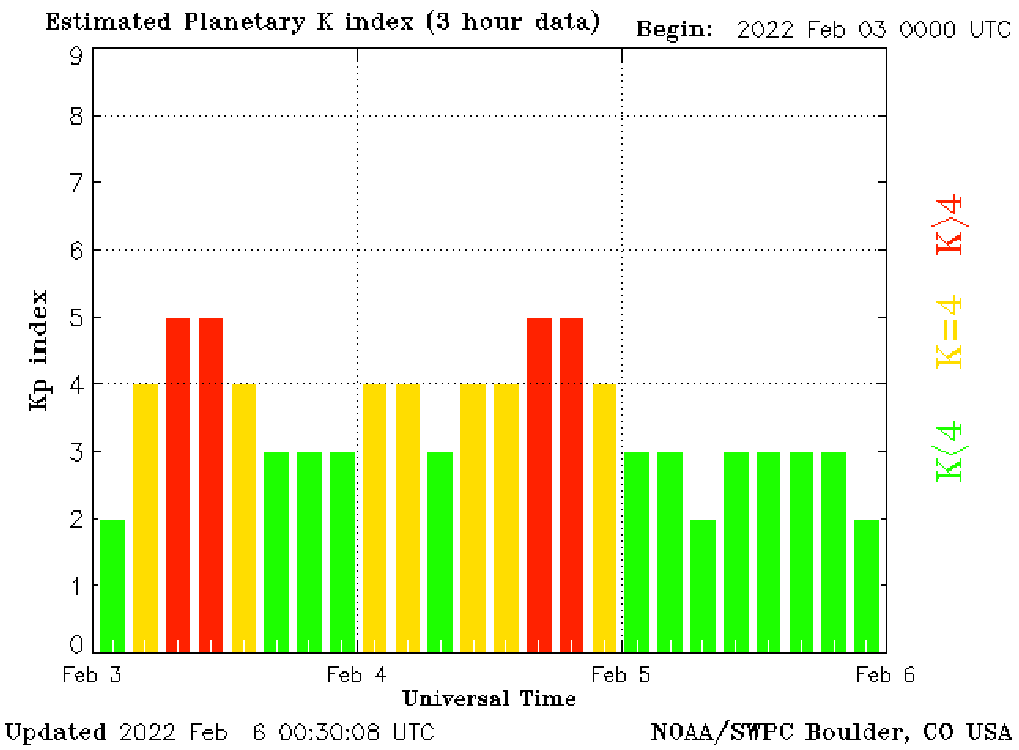
RESEARCH ARTICLE

10.1029/2022SW003152

Tong Dang and Xiaolei Li contributed equally to this work.

Unveiling the Space Weather During the Starlink Satellites Destruction Event on 4 February 2022

Tong Dang[1,2,3], Xiaolei Li[1,2,3], Bingxian Luo[4,5], Ruoxi Li[1,2,3], Binzheng Zhang[6], Kevin Pham[7], Dexin Ren[1,2,3], Xuetao Chen[1,2,3], Jiuhou Lei[1,2,3], and Yuming Wang[1,2,3]



- ❑ Two CMEs led to complex geomagnetic activity during 3rd and 4th February resulting in consecutive G1/Minor storms intervals in 48-hours.
- ❑ The combined effects of the two storms resulted in the expansion of the atmosphere which increased atmospheric drag.
- ❑ Starlink launched and subsequently lost 38 of 49 satellites due to enhanced neutral density associated with a geomagnetic storm.
- ❑ This event indicates that even small storms may have severe astronautic and financial consequences.

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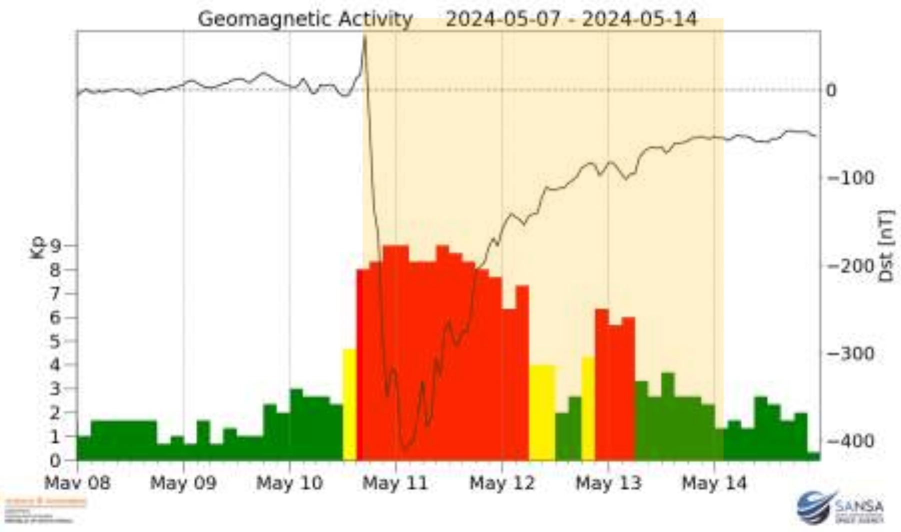
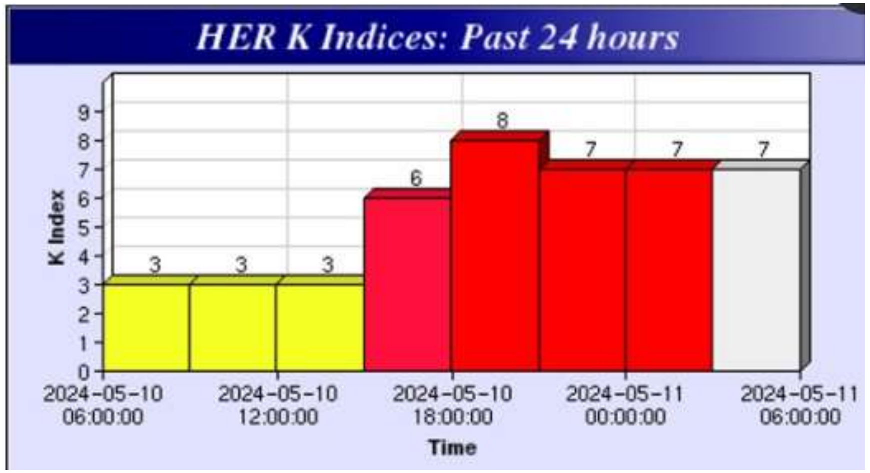
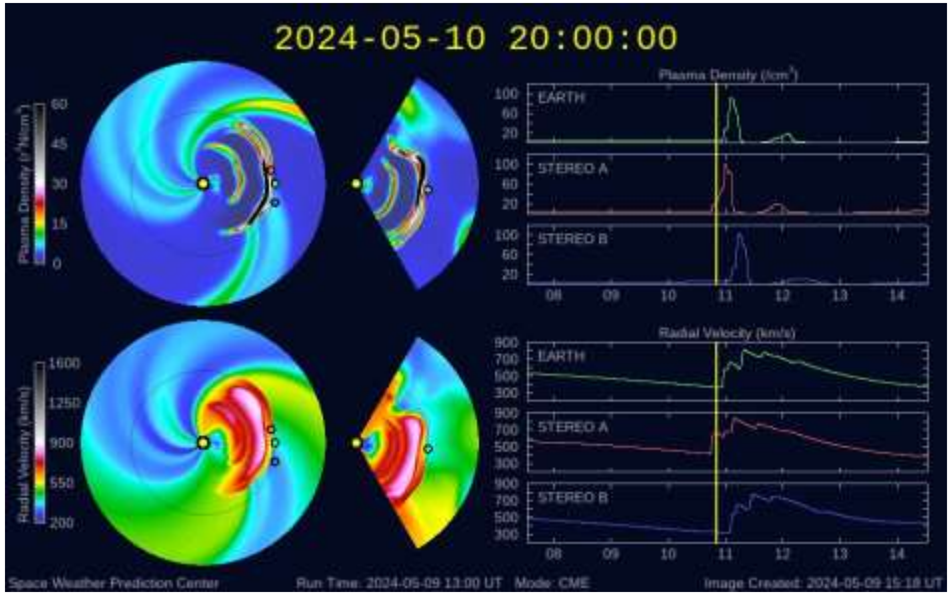
Case study: Geomagnetic storm



Aurora Australis captured by Johan le Roux from Gansbaai,South Africa

- Multiple CMEs associated with filament eruption and flaring activity that occurred from 06-08 May impacted Earth on 10-13 May 2024 resulting in the biggest storm over 20 years.
- Geomagnetic condition reached G5/Extreme storm (Kp 9) on 10 May 2024
- Auroras were seen in the midlatitude regions including South Africa and Namibia.





WSA-ENLIL Solar Wind Prediction | NOAA / NWS Space Weather Prediction Center

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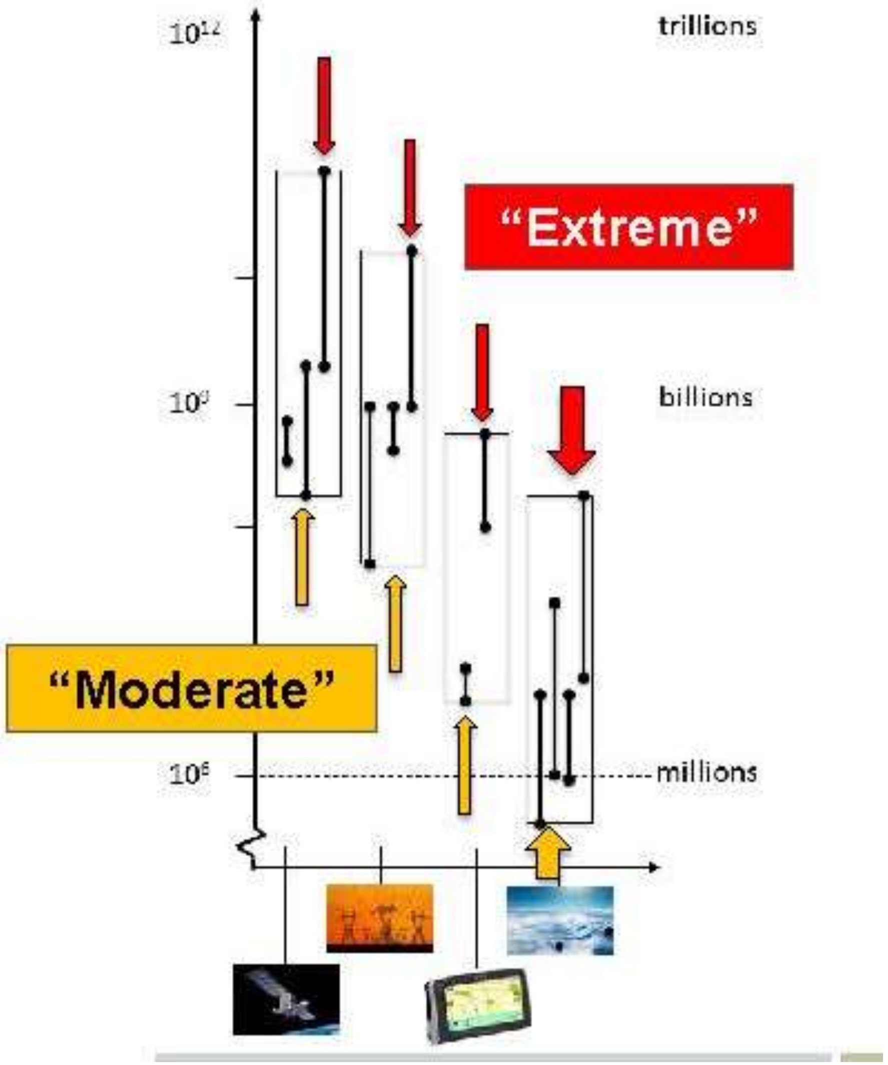
Economic Impacts of Space weather



Satellite Technology
- cost of engineering & loss of applications
- Moderate , 1 satellite
- Extreme , 10 – 100 satellites

Energy
- Wide-spread blackouts
- Moderate , R 600 million in losses
- Extreme , R 1 – R 2 trillion in losses
- Recovery could be 4 – 5 years

Communication & Navigation
- Loss of GNSS capability
- GNSS outage could cost $1 billion / day
- Can have devastating social and economic repercussions

Security
- Radio blackout in all cases

Transport
- Aviation, rail, maritime
- Severe economic repercussions

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What about space sustainability?

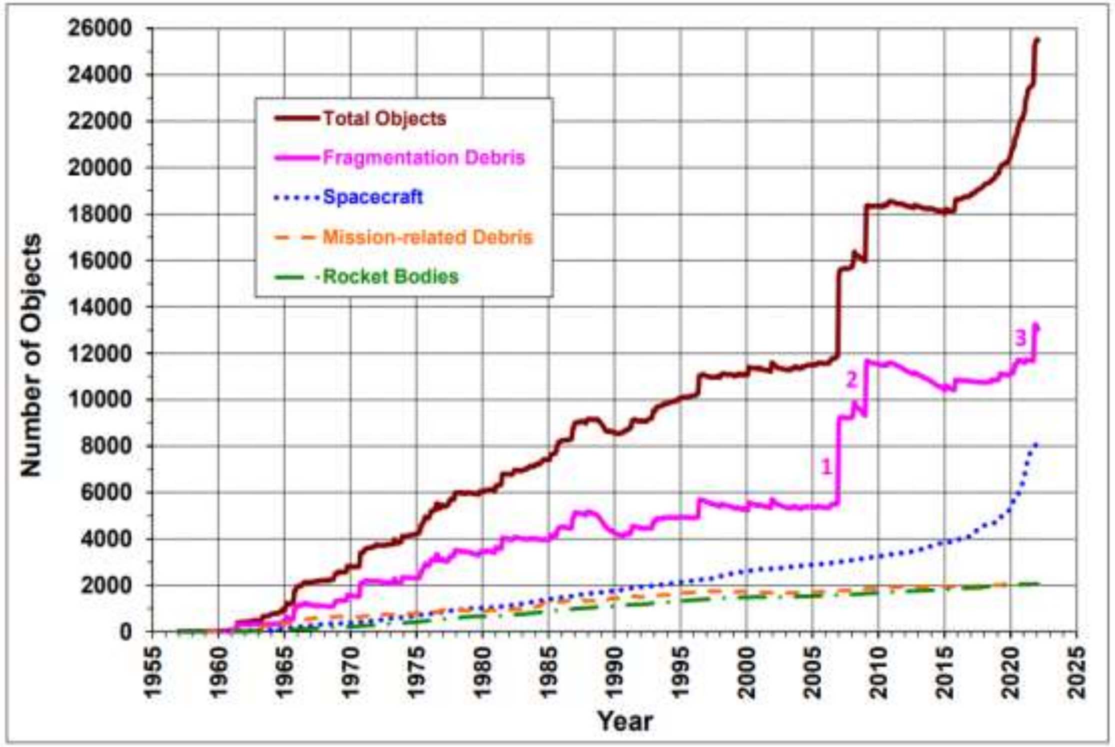
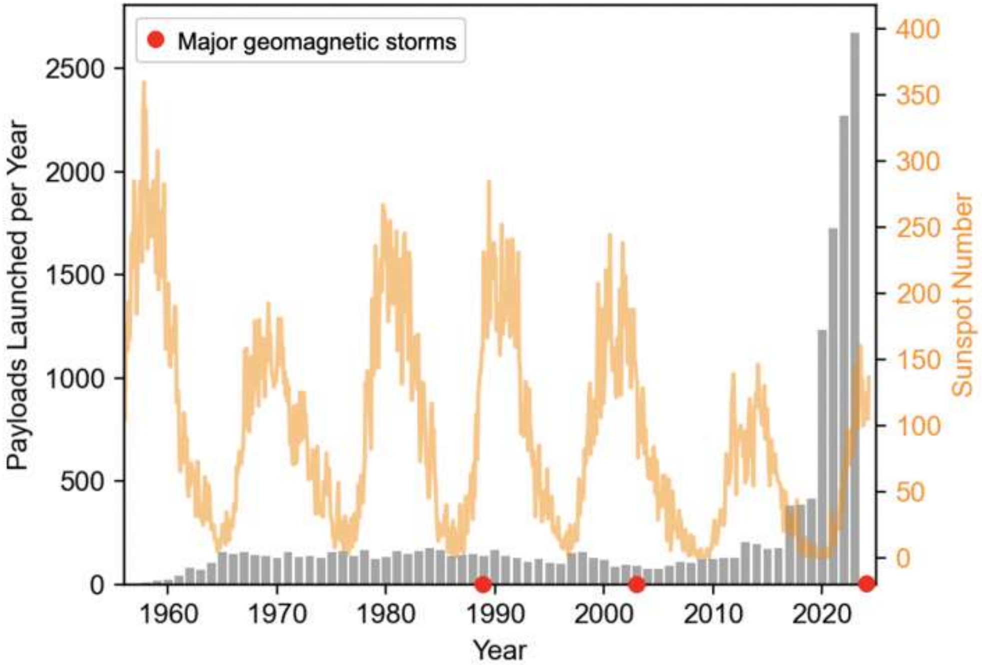


Figure 4. Historical increase of the cataloged objects based on data available on 1 March 2022. The three upward jumps in fragmentation debris correspond to (1) the ASAT test conducted by China in 2007, (2) the accidental collision between Iridium 33 and Cosmos 2251 in 2009, and (3) the ASAT test conducted by the Russian Federation in November 2021. More Cosmos 1408 fragments are expected to the added to the catalog in the coming weeks and months.

[ARES | Orbital Debris Program Office | Quarterly News (nasa.gov)]

- A large number of satellites and space debris operating between 100 and 600 km altitude are significantly affected by space weather due to atmospheric drag.
- With an increasing number of rocket launches and space weather activities the issue of space debris is a growing concern.
- The increase in space debris poses a challenge for the long-term sustainability of space operations, as it reduces available orbital slots and increases the risk of collisions.



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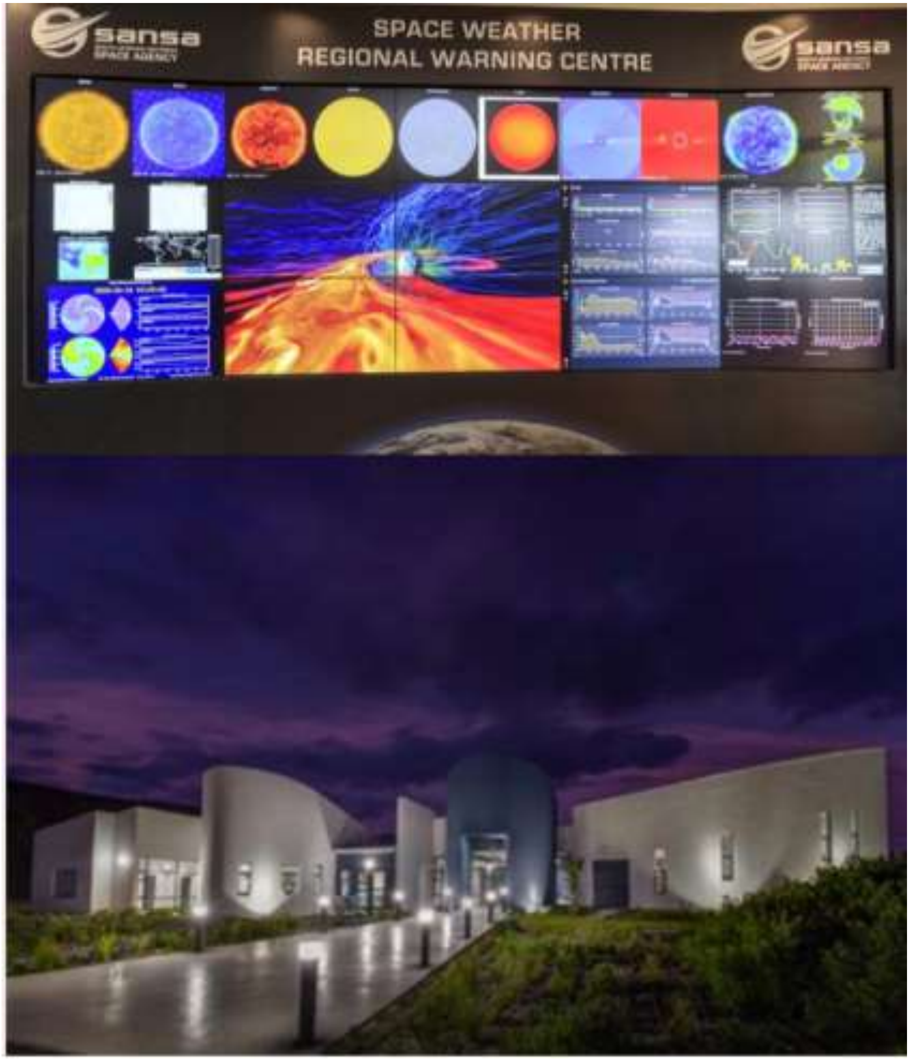
What about space sustainability? The role of SANSA

- South Africa through SANSA, has received designation a regional centre for space weather from the international Civil Aviation Organization (ICAO).
- The space weather centre is responsible for the provision of space weather information and forecasting.
- 24/7 Operational Centre & capability was launched on 3 November 2022
  - ICAO Compliant
  - ISO 9001: 2015 Certified
- Research, Forecasting and Prediction in the domains
  - GNSS (navigation)
  - Communications (HF and Satellite)
  - Radiation Exposure.
- The timely availability of reliable and consistent space weather information (observations and forecasts) is essential to mitigate the impacts of Space weather.



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Conclusion

- The increasing use of space-based technologies in our daily lives and global infrastructure highlights the critical role of space in driving sustainable development.
- However, with this growing dependence comes a heightened vulnerability to space weather.
- The potential disruptions to satellite operations, HF communication, power grids, and GNSS systems can have severe socioeconomic impacts.
- To ensure the sustainability of space-based technologies , continuous monitoring, forecasting, and development of predictive models for space weather are essential.
- These efforts will not only protect critical space infrastructure but also support informed decision-making across affected industries.

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