

Building the Foundation for Geodetic Excellence in Africa workshop, October 5-7, 2026, Nairobi, Kenya

Impact of Space Weather on Geodesy

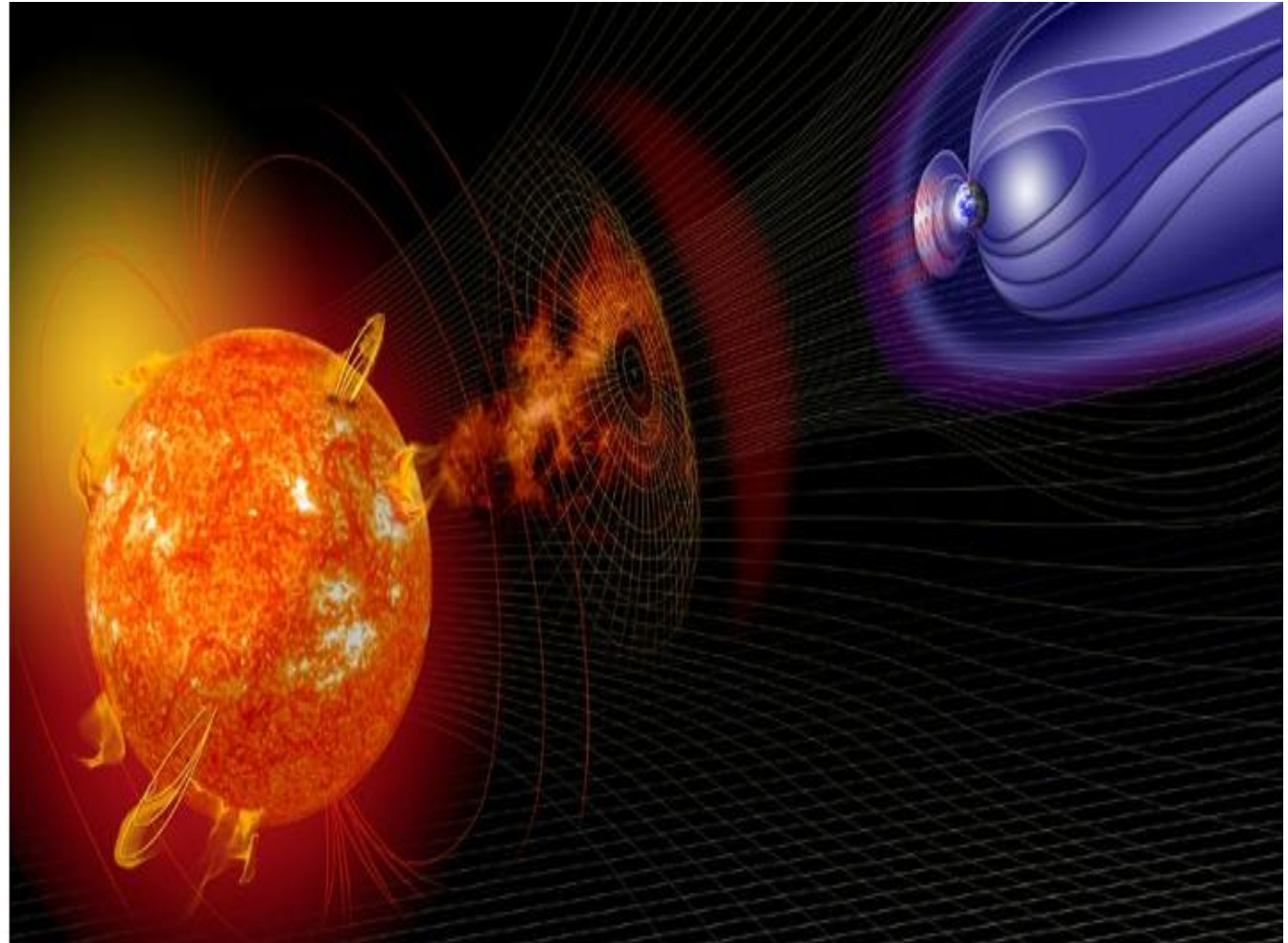
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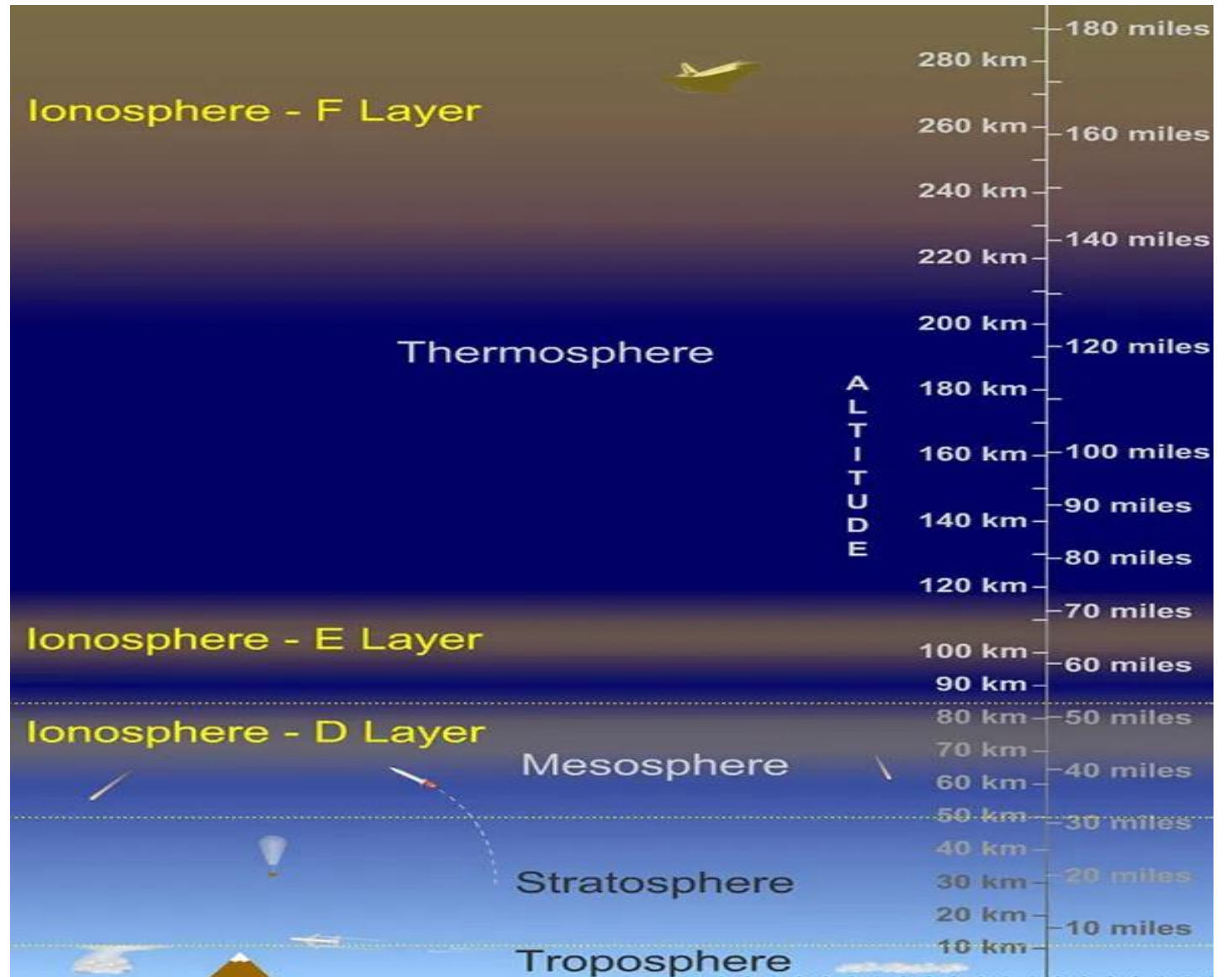
1. What is space weather?

- ❑ Condition in the space environment between the Sun and Earth that affects space based and terrestrial technological systems.



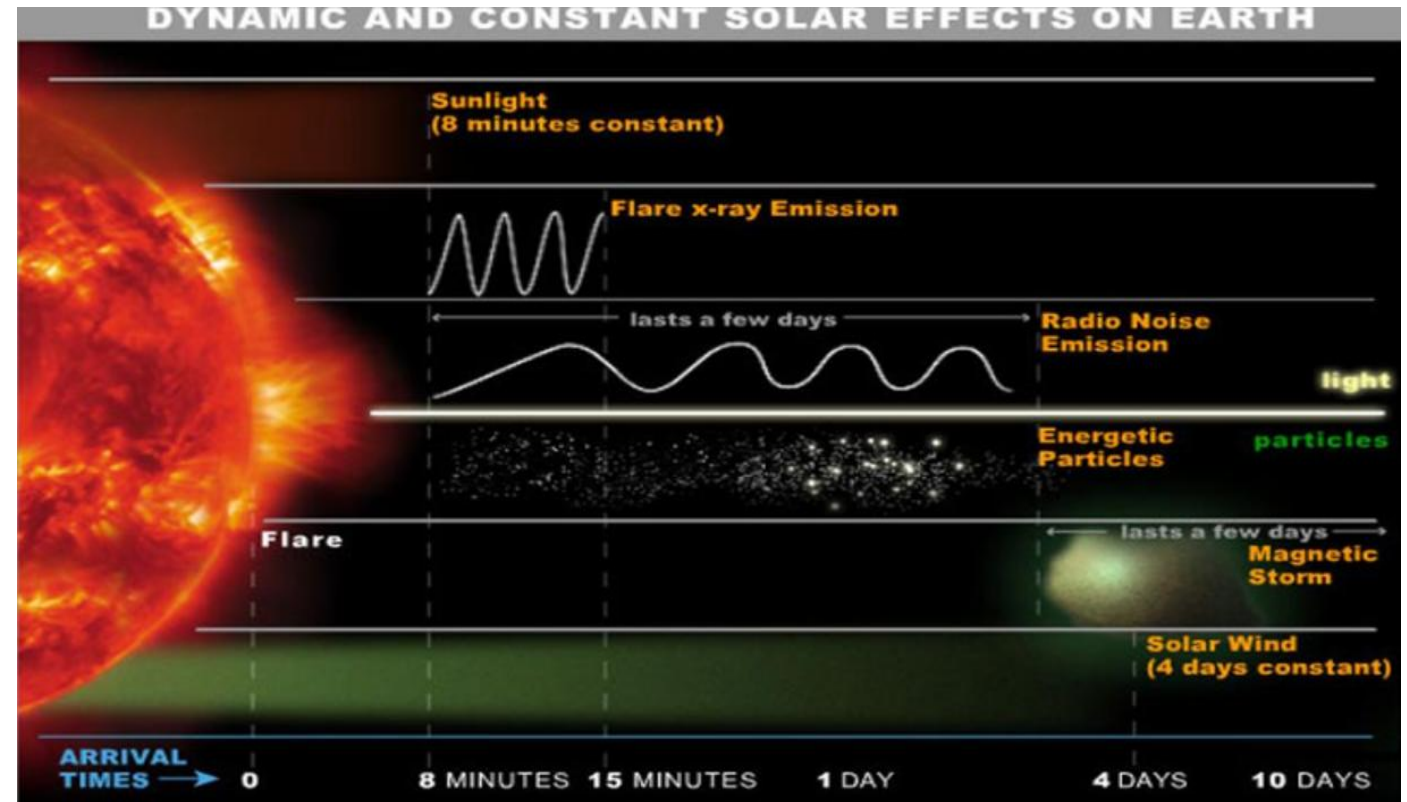
Layers of the earth's atmosphere & ionospheric regions

- ☐ Mesosphere
- ☐ Thermosphere
- ☐ Stratosphere
- ☐ Ionosphere



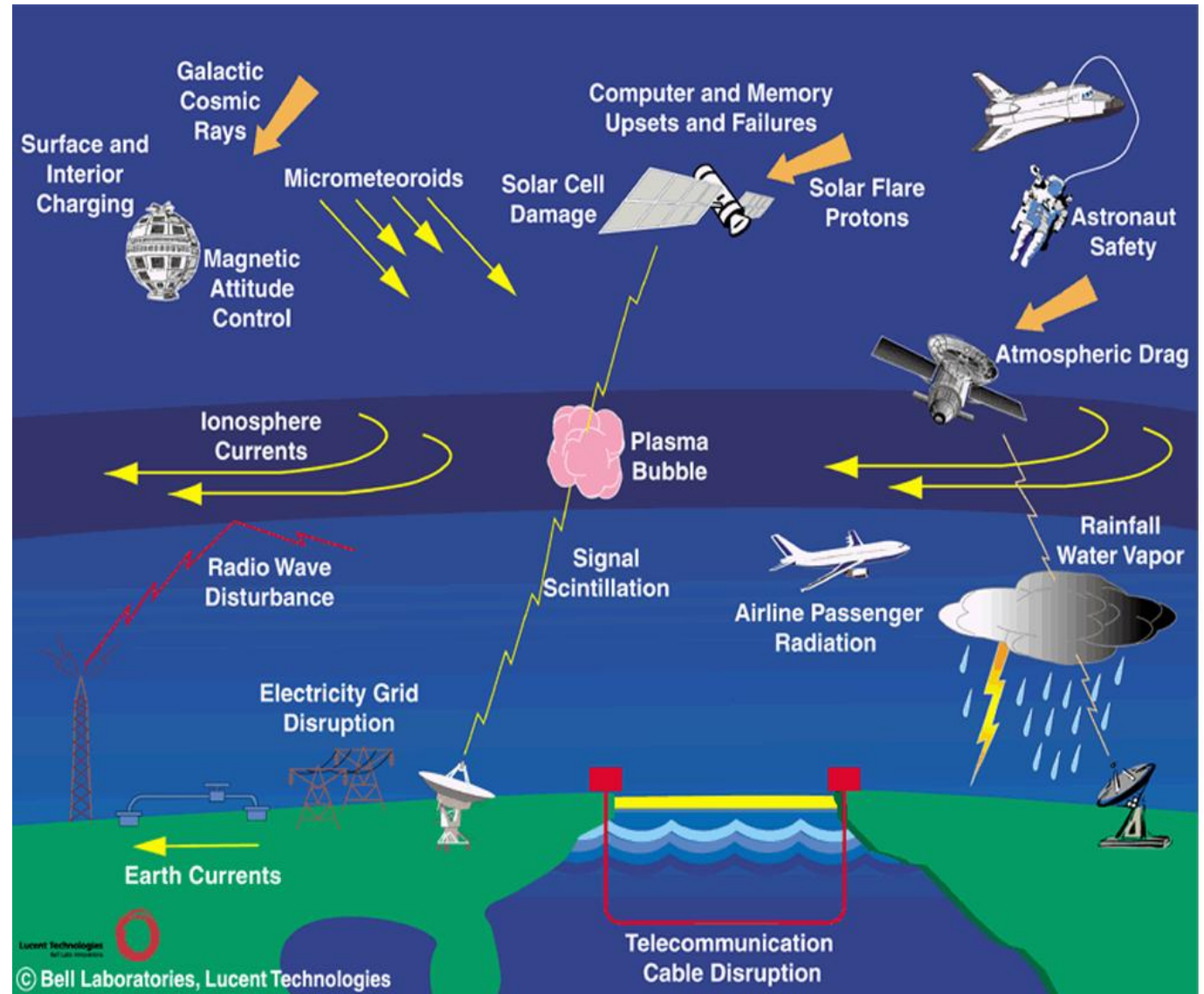
Causes

- ❑ **Solar Wind:** A constant stream of electrically charged gas and particles (plasma) flowing outward from the Sun's corona into the solar system.
- ❑ **Solar Flares:** Sudden, intense explosions on the Sun's surface that blast bursts of X-rays, light, and energy toward Earth at the speed of light.
- ❑ **Coronal Mass Ejections (CMEs):** Massive clouds of magnetized solar plasma and particles hurled into space, which can take anywhere from 12 hours to a few days to reach Earth



Causes for particular human concern

- ❑ Radio, GPS, and navigation difficulties due to ionospheric scintillations & changed radio propagation
- ❑ Magnetic field changes $\Rightarrow$ induced EMFs and currents $\Rightarrow$ power, communication, & pipeline failures and difficulties with high-tech industry & prospecting.
- ❑ Radiation damage, dielectric charging & breakdown of space systems like satellites
- ❑ Increased ionospheric drag etc. for satellites
- ❑ Radiation damage to humans (airlines, astronauts)



Space Weather Monitoring

Space weather is monitored using a combination of dedicated deep-space observatories, Earth-orbiting satellites, and ground-based instruments that track solar activity, the solar wind, and the planet's magnetic field

Space based monitoring

- ❑ **Lagrange Point 1 (L1) Satellites:** Positioned about 1.5 million kilometers toward the Sun, spacecraft like **DSCOVR** (Deep Space Climate Observatory) measure the incoming solar wind and magnetic fields in real time to provide early warnings for geomagnetic storms.
- ❑ **GOES Satellites:** Geostationary Operational Environmental Satellites capture continuous X-ray, extreme ultraviolet imagery of solar flares, and coronal mass ejections (CMEs) while measuring particle radiation in Earth's upper atmosphere.
- ❑ **Solar and Heliospheric Observatory (SOHO) and Solar Dynamics Observatory (SDO):** These dedicated solar observatories track sunspot evolution, solar eruptions, and the outer solar corona.

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Ground based monitoring

- ❑ **Magnetometers and Neutron Monitors:** Global ground networks track rapid fluctuations in the Earth's magnetic field: Global ground networks track rapid fluctuations in the Earth's magnetic field and detect high-energy particle increases (Ground Level Enhancements) reaching the surface.
- ❑ **Solar Telescopes:** Optical and radio telescopes monitor solar flares, sunspot numbers, and coronal mass ejections from the ground.
- ❑ **Sudden Ionospheric Disturbance (SID) Monitors:** These receivers track very low frequency (VLF) radio waves bouncing off the ionosphere to detect sudden plasma disruptions caused by solar X-rays

2. Geodesy

- ❑ Geodesy is the science of accurately measuring and understanding the Earth's geometric shape, orientation in space, and gravity field, as well as how these properties change over time.
- ❑ Geodesy is studied and measured using a combination of high-precision space-based techniques, terrestrial instruments, and gravity-monitoring tools

Space Geodesy Techniques

- ❑ Global Navigation Satellite Systems (GNSS) Systems track precise ground coordinates, satellite positions, and tectonic plate movements.
- ❑ **VLBI** (Very Long Baseline Interferometry): Uses radio astronomy telescopes to measure signals from distant quasars, determining Earth's orientation and rotation.
- ❑ **SLR** (Satellite Laser Ranging): Bounces lasers off satellites to measure precise orbits and track the center of mass of the Earth
- ❑ **DORIS** (Doppler Orbitography and Radio-Positioning by Integrated Satellite): Uses radio doppler signals from satellites to track precise positioning and orbits.
- ❑ **InSAR** (Interferometric Synthetic Aperture Radar): Uses radar satellite images over time to measure ground deformation like volcanic uplift or fault movement.

The nexus

- ❑ The measurements of most of the space-geodetic observation techniques depend on the properties of the ionosphere along the ray path of an electromagnetic wave between transmitters on satellites and receivers on the ground.
- ❑ The thermospheric drag is the most important deceleration effect on Low-Earth Orbiting (LEO) satellites that affects the lifetime of such satellites, which are often used for Earth observation
- ❑ Geodesy and space weather are linked because solar activity disturbs Earth's upper atmosphere, which interferes with the high-precision satellite and radio signals that geodesy relies on to measure our planet.
- ❑ The Global Navigation Satellite System (GNSS) is extensively used for Geodesy and is subject to Space Weather impacts in several ways.
- ❑ These impacts all have the potential to reduce the accuracy of geodetic measurements utilizing GNSS
- ❑ Space weather directly disrupts high-precision geodetic measurements and satellite positioning by perturbing the Earth's upper atmosphere, ionosphere, and geomagnetic field

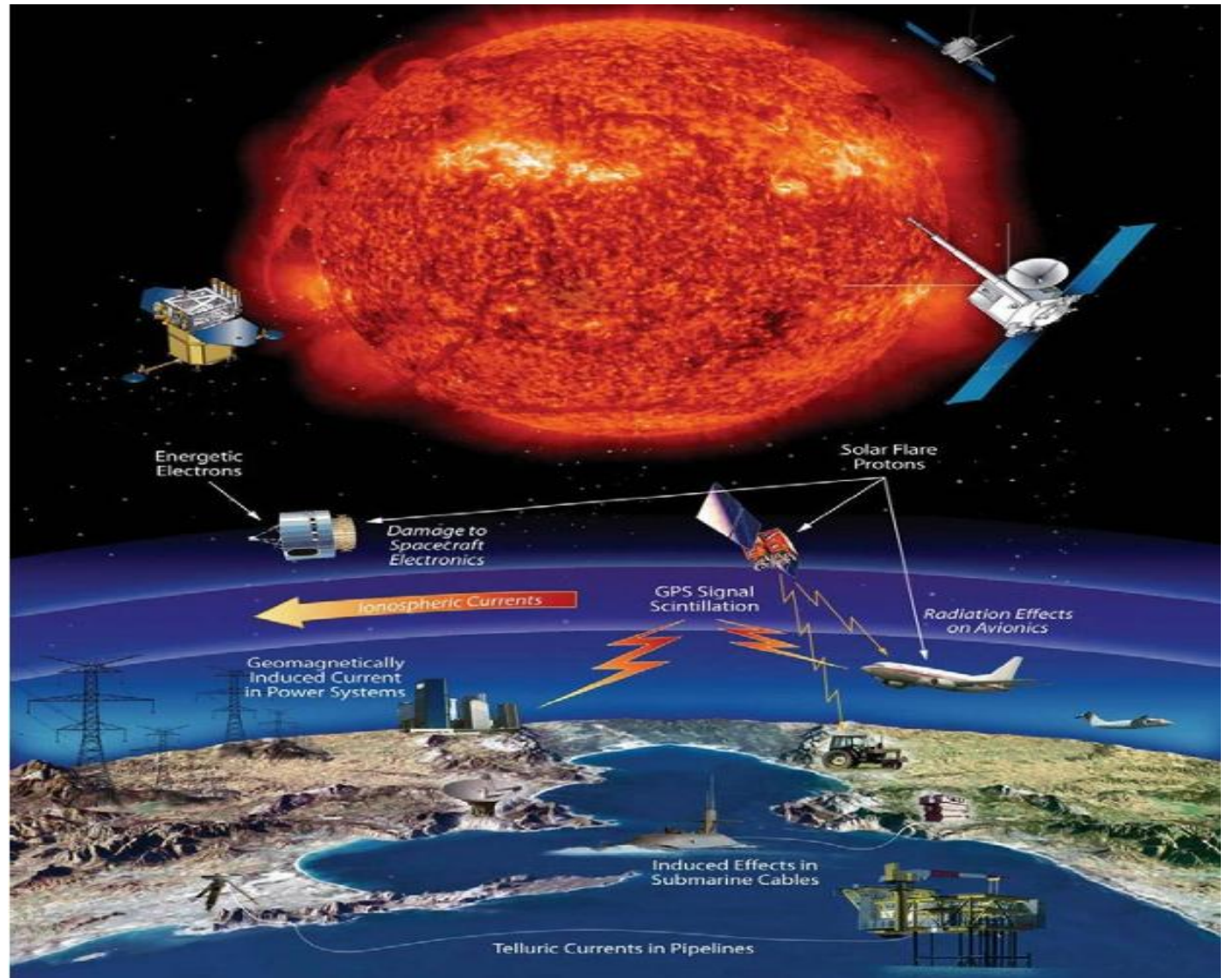
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Ionospheric Signal Delays and Scintillation

Total Electron Content (TEC) Spikes: Solar flares and coronal mass ejections increase free electrons in the ionosphere, slowing down and bending radio signals from Global Navigation Satellite Systems (GNSS).

Signal Scintillation: Rapid plasma density irregularities cause signal fading, phase fluctuations, and cycle slips, destroying millimeter-level positioning accuracy needed for geodetic surveying.

Solar Radio Bursts: Intense solar radio emissions in the L-band directly interfere with receiver tracking performance on the sunlit side of Earth.



3. Inter-connectedness of Geodesy and Space Weather

- ❑ The Global Navigation Satellite System (GNSS) is extensively used for Geodesy and is subject to Space Weather impacts in several ways. These impacts all have the potential to reduce the accuracy of geodetic measurements utilizing GNSS
- ❑ **Ionospheric Disturbances and GNSS Errors:** Solar storms increase electron density in the **ionosphere**. This layer delays or distorts Global Navigation Satellite System (GNSS) signals, causing scintillation and positioning errors that disrupt millimeter-level geodetic measurements
- ❑ **Thermospheric Drag on Satellites:** High solar radiation increases the density of the **thermosphere**. This creates atmospheric drag on low-Earth-orbit (LEO) satellites, changing their orbits and complicating precise orbit determination for geodetic missions.
- ❑ **Geodesy as a Monitoring Tool:** Conversely, the global networks of ground-based GNSS receivers and satellite-altimetry systems used in **satellite geodesy** double as powerful sensors. They measure changes in electron content to help scientists model and forecast space weather events.

Mitigating space weather effects for geodesy

- ❑ Geodesists model and correct ionospheric errors by exploiting the dispersive nature of the ionosphere using dual-frequency measurements, applying empirical mathematical models, and utilizing regional or global mapping networks.
- ❑ As satellite radio signals pass through the electrically charged ionosphere, free electrons slow down code measurements and advance phase measurements. Geodesists counteract these propagation delays using several specialized techniques:

Dual-Frequency (or Multi-Frequency) Combinations

- ❑ **Dual-Frequency Method:** Because the ionosphere is a dispersive medium, the delay is inversely proportional to the square of the signal's frequency (f^2). By simultaneously receiving signals on two or more distinct frequencies (e.g., L1 and L2/L5 on GPS), geodesists combine the measurements linearly to cancel out the first-order ionospheric delay almost entirely.
- ❑ **Higher-Order Corrections:** For ultra-precise geodetic applications, standard dual-frequency formulas leave behind tiny second- and third-order residuals. Advanced models compute these remaining errors by factoring in the Earth's geomagnetic field and signal bending paths.

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Mapping and Network-Based Corrections

- ❑ **Global Ionosphere Maps (GIM):** International services like the International GNSS Service (IGS) and associated analysis centers process worldwide tracking station data to generate global vertical total electron content (VTEC) maps in IONEX format. [\[1\]](#)
- ❑ **Network RTK and PPP:** Real-Time Kinematic (RTK) networks and Precise Point Positioning (PPP) services estimate spatial and temporal ionospheric gradients across regional reference stations, interpolating precise, localized delay corrections directly to field rovers
- ❑ **Geodesists treat space weather both as an engineering hurdle to overcome and as a scientific metric to measure.** Because geodesy relies on ultra-precise measurements using tools like Global Navigation Satellite Systems (GNSS), Very Long Baseline Interferometry (VLBI), and satellite altimetry, space weather—which alters Earth's atmosphere and magnetic field—can completely throw off calculations if left unchecked.
- ❑ **Dynamic Atmospheric Density Scaling for Orbiters :** Space weather heats and expands Earth's thermosphere. This creates massive, unpredictable "thermospheric drag" that slows down Low Earth Orbit (LEO) satellites. Geodesists incorporate real-time solar indices (like the F10.7 and Kp indices) into **numerical orbit propagators**. By continuously feeding this data into mathematical drag equations, they help satellite operators dynamically predict orbital decay, allowing them to pre-emptively fire thrusters or reorient solar arrays into a streamlined "safe mode" to dodge the expanded atmosphere

Concluding Remarks

- ❑ The importance of Space Weather to the Geodesy community has been recognized by the establishment of the Focus Area on Geodetic Space Weather Research (FA-GSWR) <https://ggos.org/about/org/fa/geodetic-space-weather-research/>
- ❑ Space Weather Community addressing potential impact on geodesy: Cilliers, P. and Lotz, S.: Space weather impacts on Geodesy, 2nd Symposium of IAG Commission 4 “Positioning and Applications”, Potsdam, Germany, 5–8 Sep 2022, iag-comm4-2022-17, [https://doi.org/10.5194/iag-comm4-2022-17, 2022](https://doi.org/10.5194/iag-comm4-2022-17,2022)