

Impact on satellites

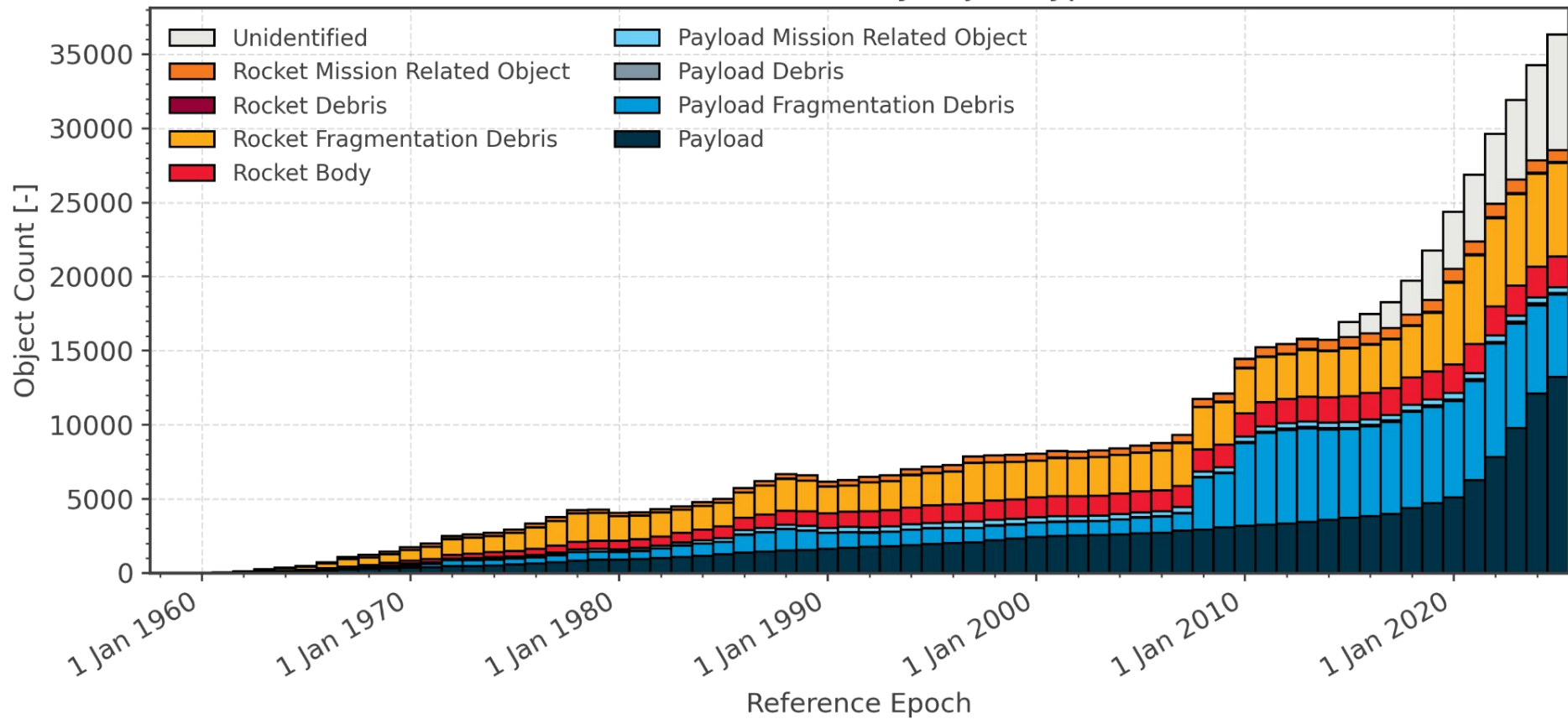
Acknowledgements

Thanks to NASA, NOAA & ESA for most of the graphics

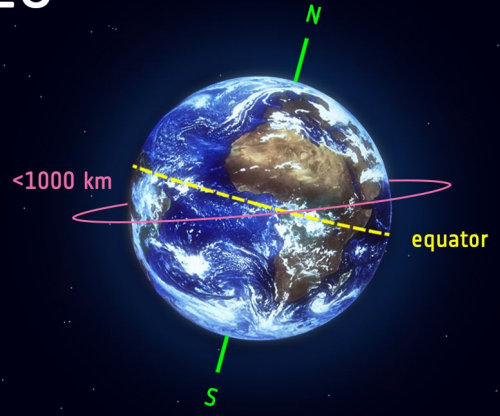
Thanks to WP van der Laan for the base slides

Image sources can be provided upon request

Count evolution by object type



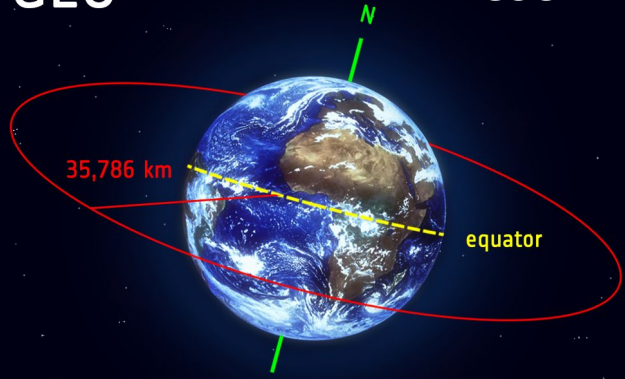
LEO



MEO semi-synchronous



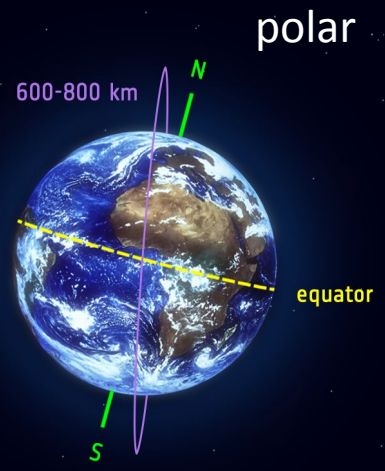
GEO



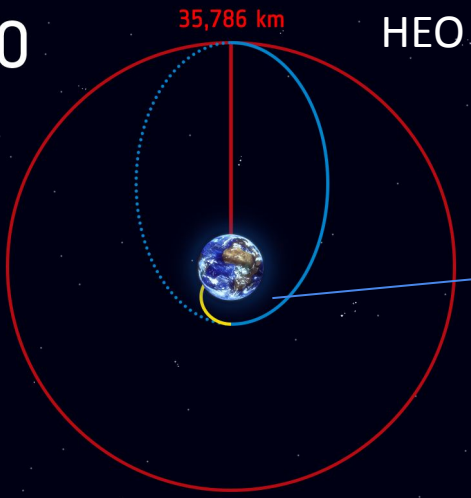
GSO

2012-07-05 12:18 EchoStar XVII

SSO



GTO



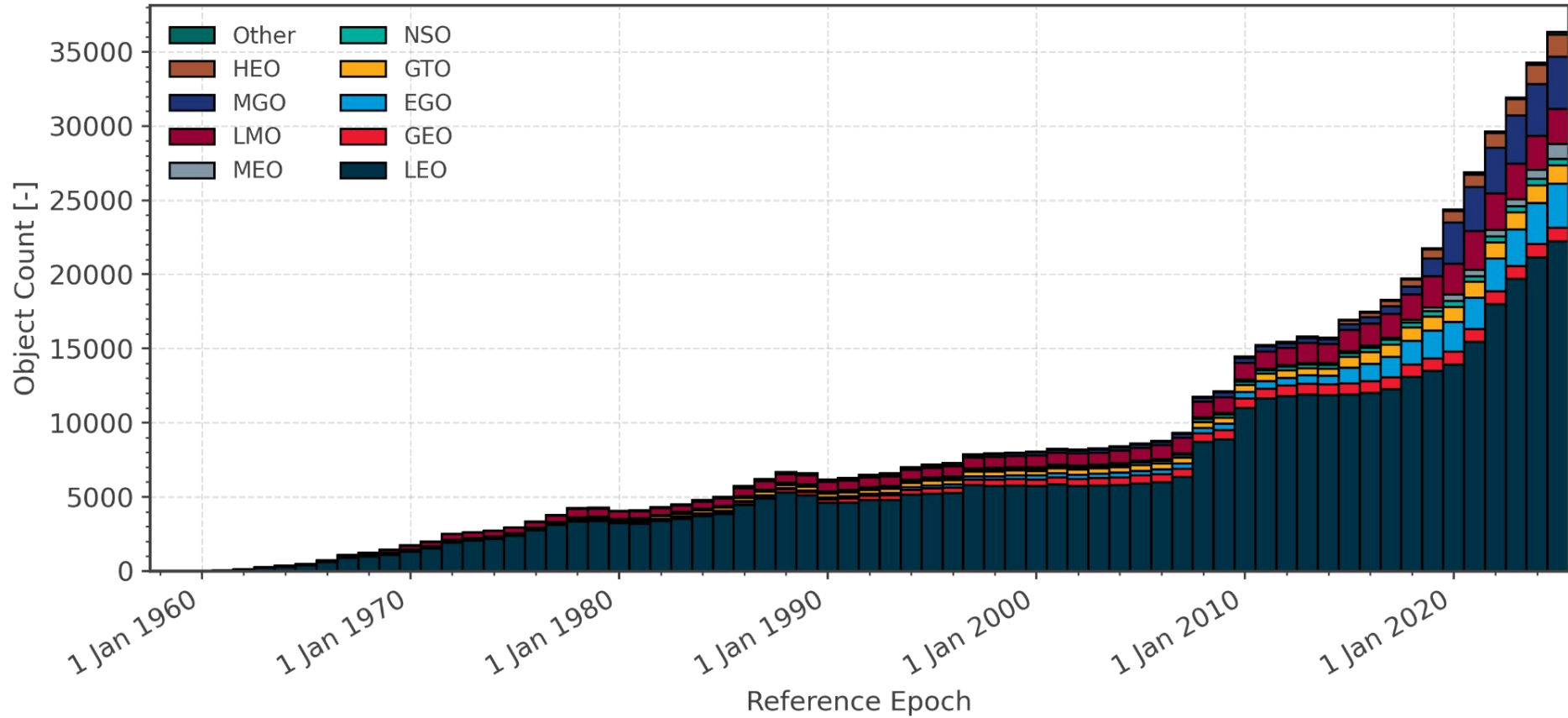
HEO



0.00km/s

18,368km

Count evolution by object orbit



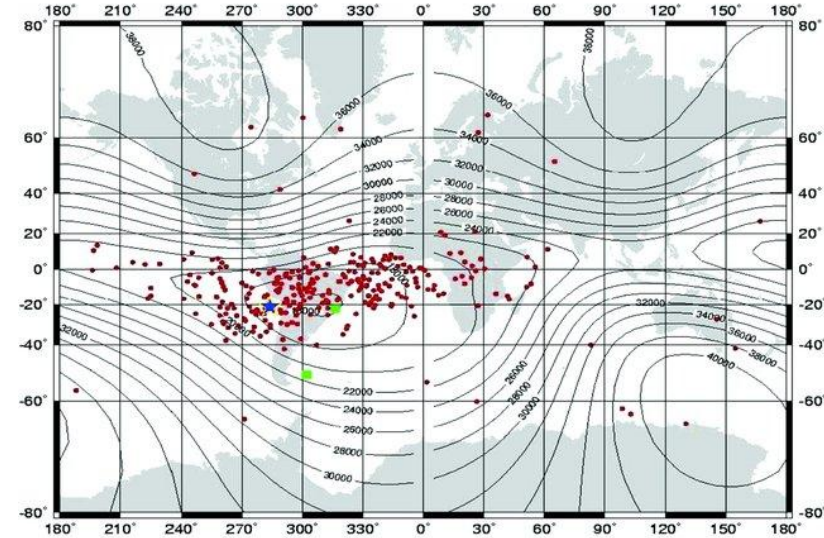
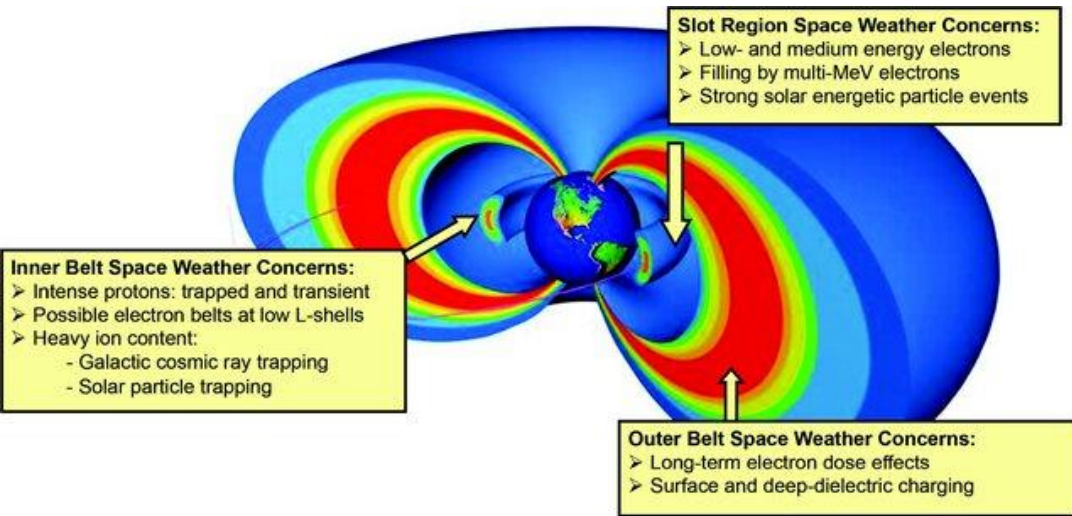
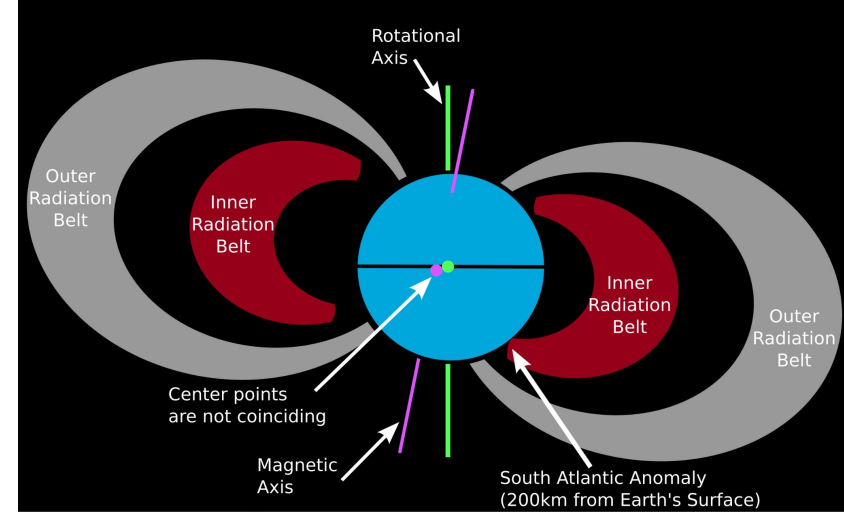
Satellite orbits

- each orbit has different preferential applications, e.g., LEO for manned missions, GEO for telecommunication satellites, SSO for imaging and reconnaissance

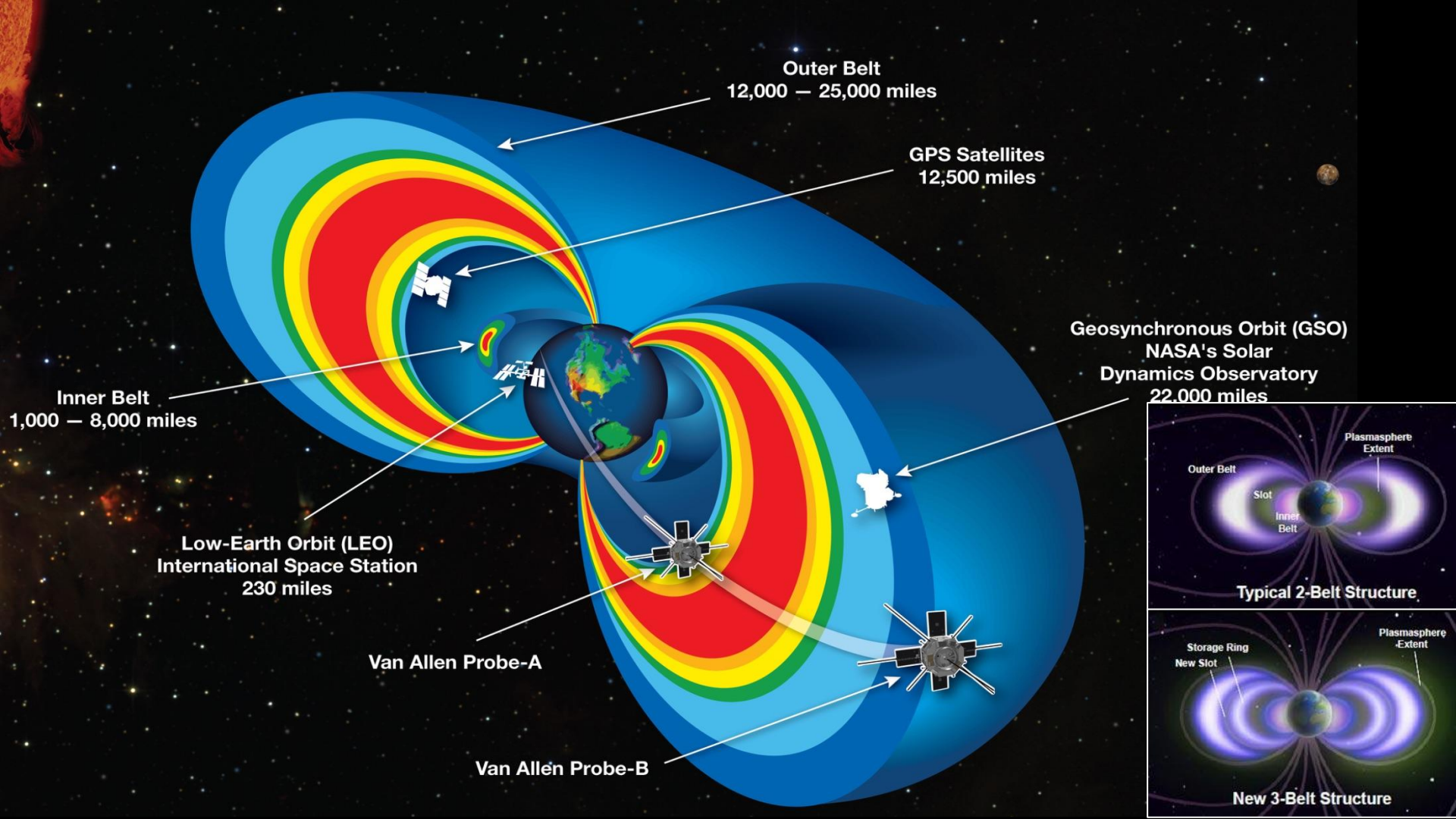
Orbital regime	Description	Limits
GEO	Geostationary Orbit	$i < 25^\circ$, $35586 \text{ km} < h_p < 35986 \text{ km}$, $35586 \text{ km} < h_a < 35986 \text{ km}$
IGO	Inclined Geosynchronous Orbit	$37948 \text{ km} < a < 46380 \text{ km}$, $e < 0.25$, $25^\circ < i < 180^\circ$
EGO	Extended Geostationary Orbit	$37948 \text{ km} < a < 46380 \text{ km}$, $e < 0.25$, $i < 25^\circ$
NSO	Navigation Satellites Orbit	$50^\circ < i < 70^\circ$, $18100 \text{ km} < h_p < 24300 \text{ km}$, $18100 \text{ km} < h_a < 24300 \text{ km}$
GTO	GEO Transfer Orbit	$i < 90^\circ$, $h_p < 2000 \text{ km}$, $31570 \text{ km} < h_a < 40002 \text{ km}$
MEO	Medium Earth Orbit	$2000 \text{ km} < h_p < 31570 \text{ km}$, $2000 \text{ km} < h_a < 31570 \text{ km}$
GHO	GEO-superGEO Crossing Orbits	$31570 \text{ km} < h_p < 40002 \text{ km}$, $h_a > 40002 \text{ km}$
LEO	Low Earth Orbit	$h_p < 2000 \text{ km}$, $h_a < 2000 \text{ km}$
HAO	High Altitude Earth Orbit	$h_p > 40002 \text{ km}$, $h_a > 40002 \text{ km}$
MGO	MEO-GEO Crossing Orbits	$2000 \text{ km} < h_p < 31570 \text{ km}$, $31570 \text{ km} < h_a < 40002 \text{ km}$
HEO	Highly Eccentric Earth Orbit	$h_p < 31570 \text{ km}$, $h_a > 40002 \text{ km}$
LMO	LEO-MEO Crossing Orbits	$h_p < 2000 \text{ km}$, $2000 \text{ km} < h_a < 31570 \text{ km}$
UFO	Undefined Orbit	
ESO	Escape Orbits	

Environment around the Earth

- inner and outer Van Allen radiation belts, intensity & position changes in time
- where closest → South Atlantic Anomaly

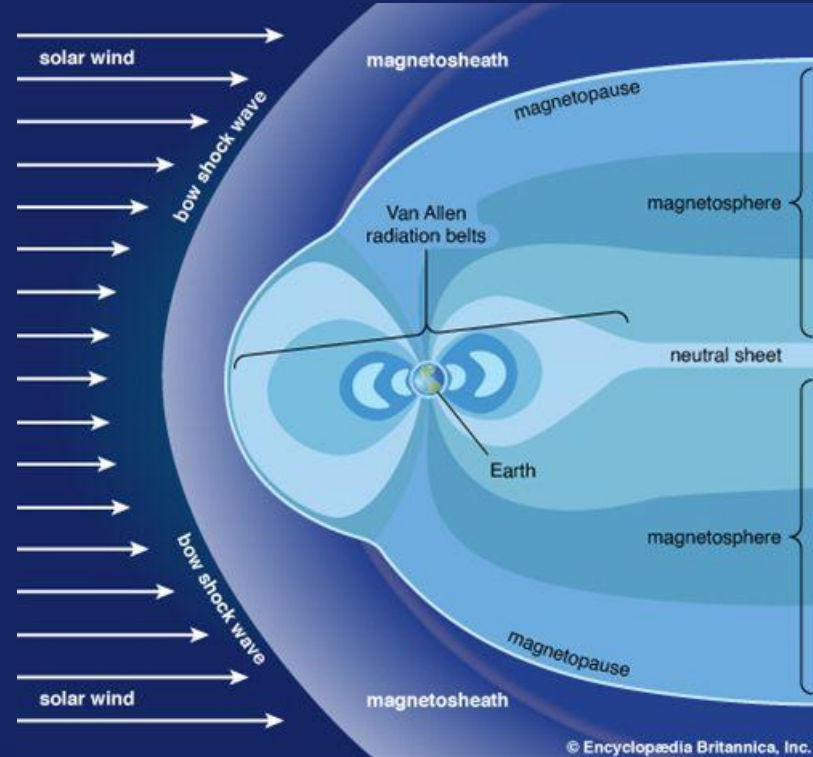


TOPEX (1992-1998) and TERRA-MODIS (2001)



Satellite SW influence factors

- spacecraft position determines its susceptibility to SW influences
- outside of the Earth's magnetic influence → S/C exposed directly to SEP precipitation and solar wind disturbances from the Sun
- inside of the Earth's magnetic influence:
 - orbit through the van Allen belts
 - orbit through the polar regions
 - orbit in low altitudes & SAA
- attitude wrt. the Sun



Satellite SW influences

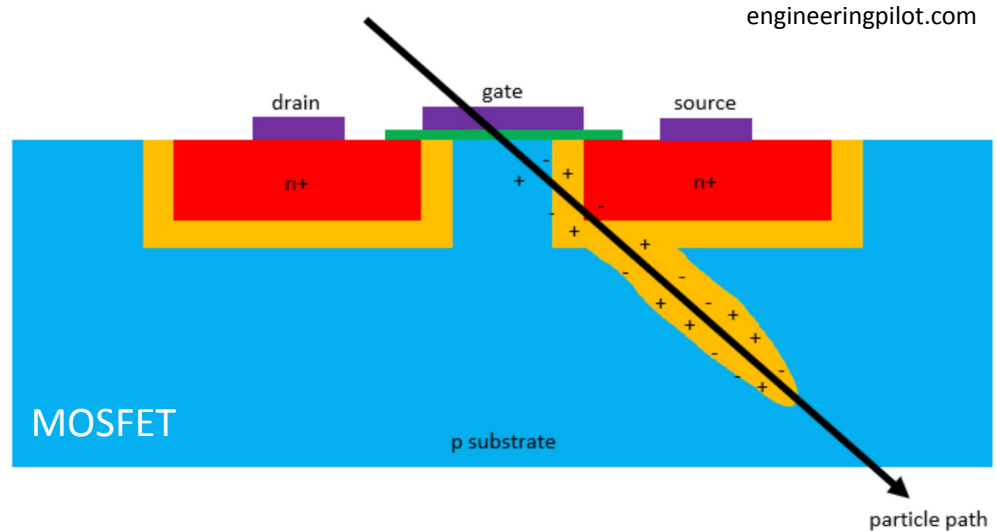
- high energy particles flux (e.g., van Allen Belts, direct SEP flux, auroral zones):
 - single event effects
 - surface charging
 - internal charging
 - cumulative degradation
- spacecraft drag increase due to thermospheric expansion (e.g., from geomagnetic events, SEP precipitation)
- communication interference due to solar radio bursts

Satellite SW influences

- high energy particles flux (e.g., van Allen Belts, direct SEP flux, auroral zones):
 - **single event effects**
 - surface charging
 - internal charging
 - cumulative degradation
- spacecraft drag increase due to thermospheric expansion (e.g., from geomagnetic events, SEP precipitation)
- communication interference due to solar radio bursts

Single event effects (SEE)

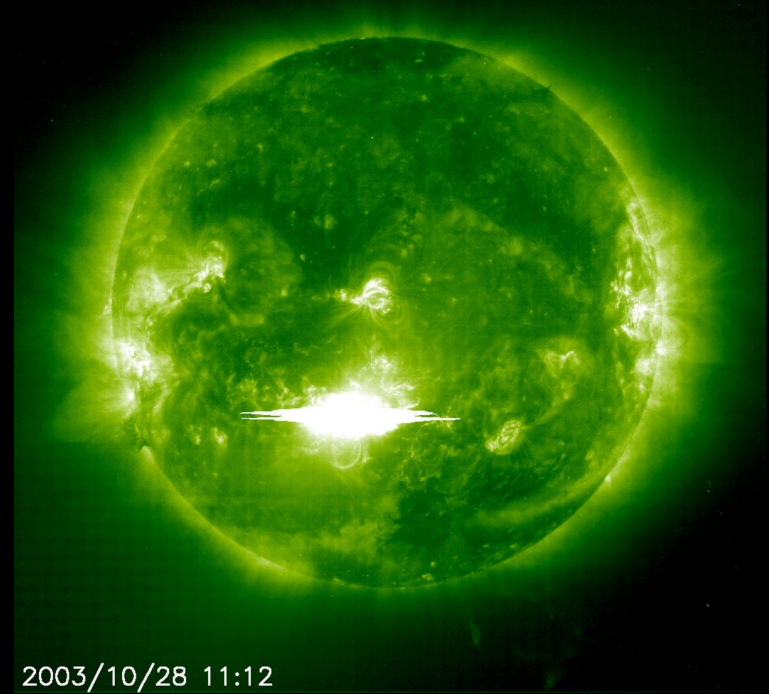
- ion components of cosmic rays, or protons trapped in radiation belts or from solar flares
- a high energy particle impacts the semiconductor material atoms
→ creates electron-hole pairs that can lead to local charge depletion
- depending how/ where this happens exactly, several types of SEE
 - **Single Event Upset (SEU)**: causes a change of state or a transient
 - **Single Event Latchup (SEL)**: causes a high current state, leads to a loss of functionality
 - **Multiple Bit Upset (MBU)**: upsets multiple bits/ causes multiple transients



Single event effects

- Halloween 2003 storms, October 29 2003, G5
- Goddard's SS Mission Operations Team: 59% of NASA's Earth and space science satellites were affected
 - data outages
 - reboots
 - unwanted thruster firings
- According to USAF operators: over half a satellites lost, up to 3 days to reestablish contact

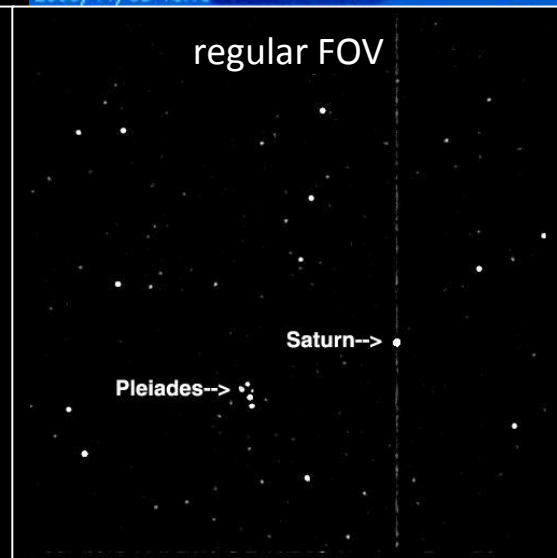
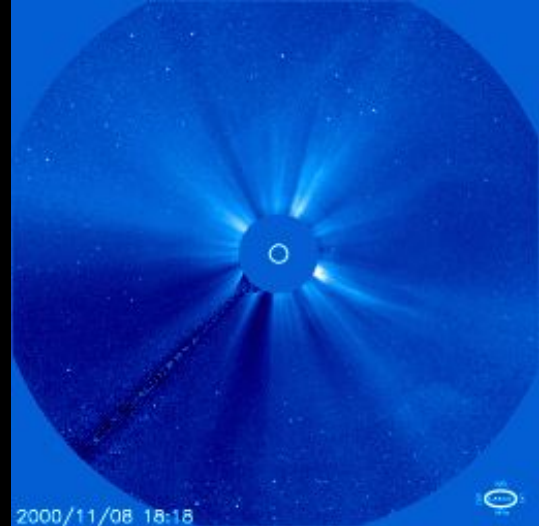
NASA: X45 solar flare



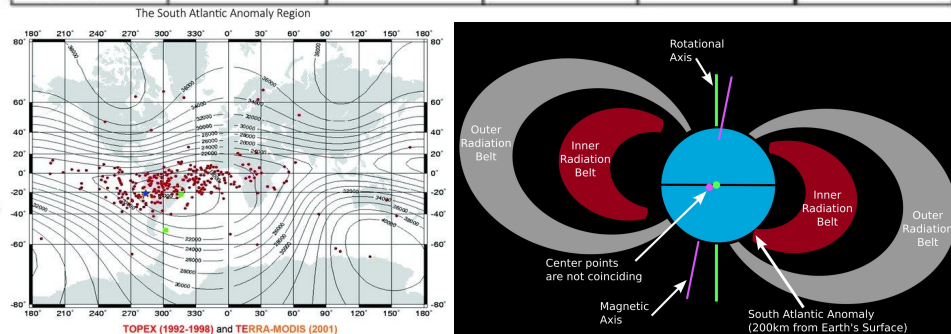
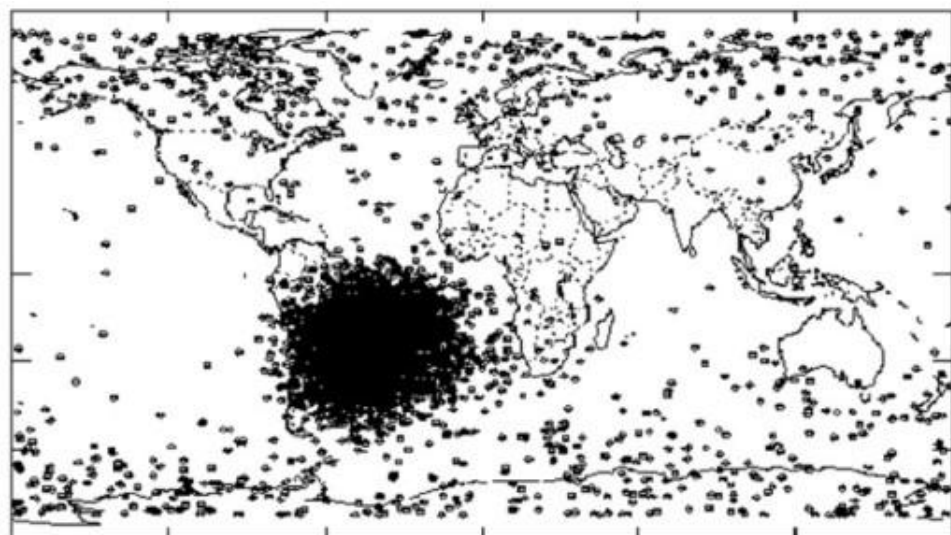
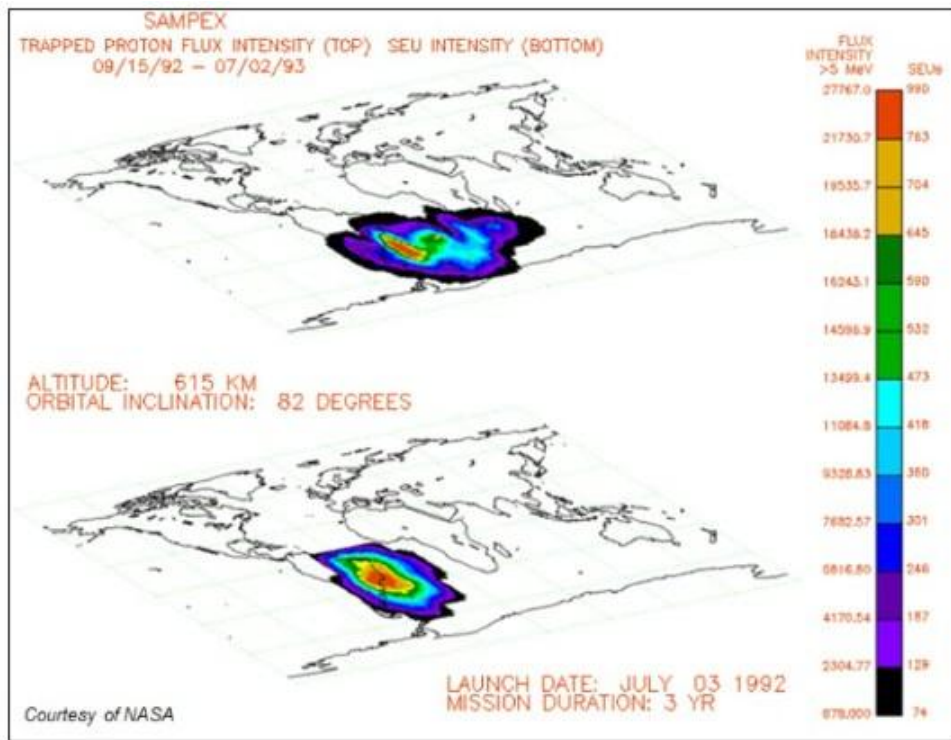
2003/10/28 11:12

Stardust blinding by SEPs

- Stardust navigation system partly relies on startracker
→ use the position of 12 brightest points to locate itself in space
- November 2000, solar flare associated high-energy protons impacted the S/C, and its 2 CCD arrays in the startracker
- proton hit to the CCD impart a charge to the pixels, producing star-like images and making the startracker temporarily dysfunctional



SAMPEX & UoSat-3 satellite SEU occurrences

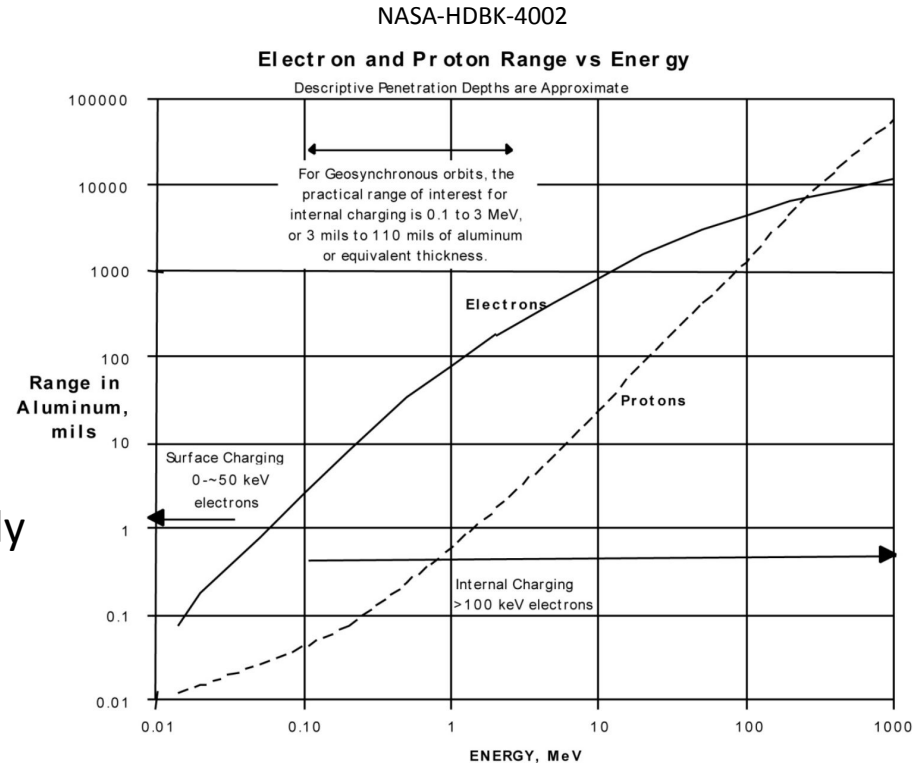


Satellite SW influences

- high energy particles flux (e.g., van Allen Belts, direct SEP flux, auroral zones):
 - single event effects
 - **surface charging**
 - **internal charging**
 - cumulative degradation
- spacecraft drag increase due to thermospheric expansion (e.g., from geomagnetic events, SEP precipitation)
- communication interference due to solar radio bursts

Spacecraft charging

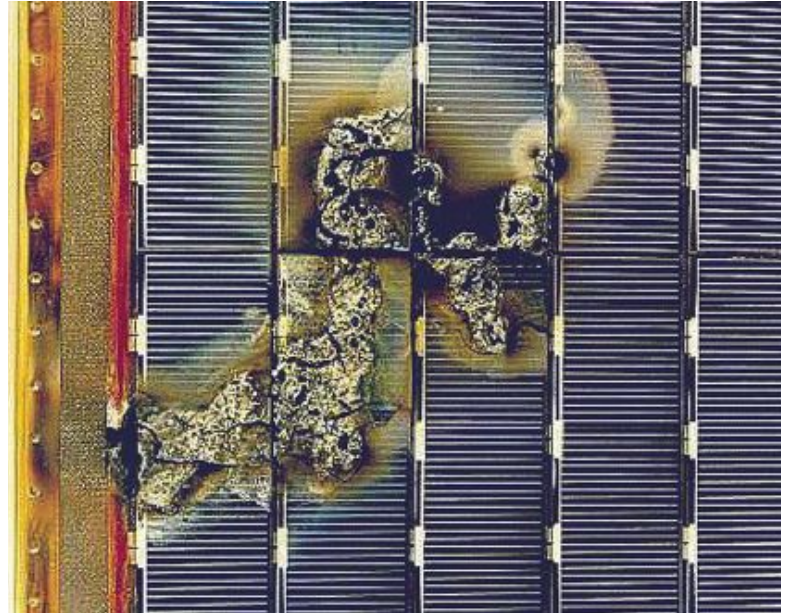
- surface charging due to hot e- forming above auroras (LEO) or due to solar flux from outer radiation belt (GEO)
- internal charging mostly by high energy electrons, largely inside dielectrics (deep-dielectric charging) or on electrically isolated conductors within the S/C
- both can lead to **Electrostatic Discharge (ESD)**



Spacecraft charging

- e.g. Galaxy 15 telecomm. sat lost for 8 months in April 2010, the ADEOS-II (570M USD) in a high inclination LEO lost its power system completely in October 2003
- damage to materials, electronics, PVAs, interference with measurements sometimes complete loss of power & control
- hot electron fluence can exhibit dramatic day-to-day variability due to shocks and/or geomagnetic storming exposing GEO satellites to high risk

ESA: EURECA sat PVA discharge damage

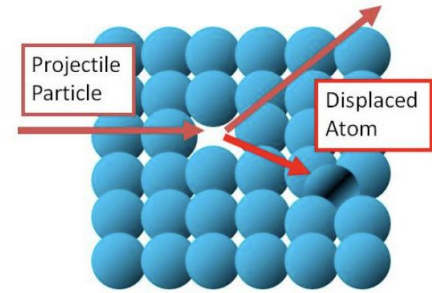


Satellite SW influences

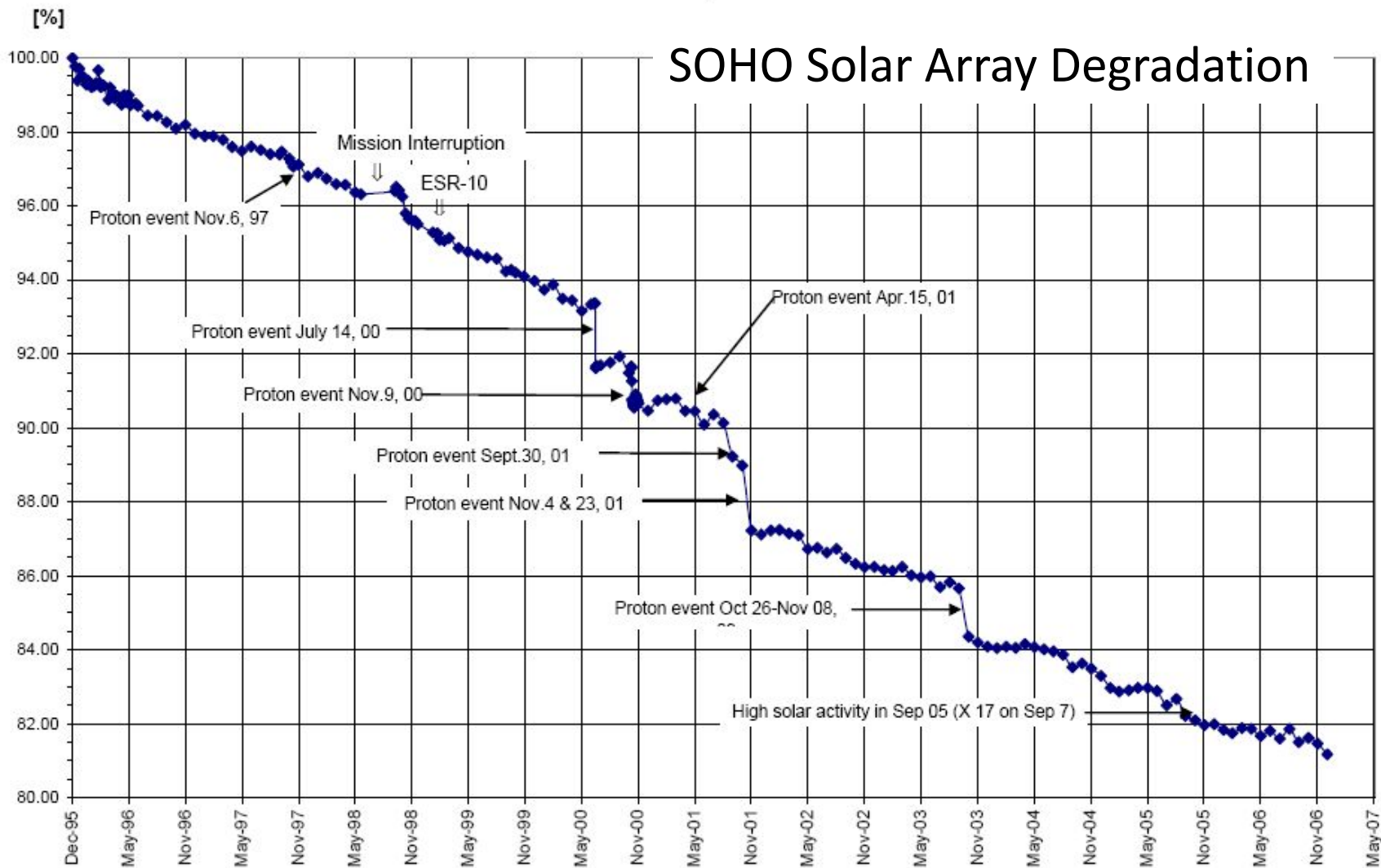
- high energy particles flux (e.g., van Allen Belts, direct SEP flux, auroral zones):
 - single event effects
 - surface charging
 - internal charging
 - **cumulative degradation**
- spacecraft drag increase due to thermospheric expansion (e.g., from geomagnetic events, SEP precipitation)
- communication interference due to solar radio bursts

Cumulative degradation

- a mix of total ionizing dose (TID) and displacement damage (DD)
- **total ionising dose, TID:** circuit-level behavior changes due to the induced charge buildup from charge penetrations, e.g., leakage, bias and quiescent currents and voltage offsets
- **displacement damage, DD:**
 - neutrons, protons, and electrons may scatter off lattice ions, locally deforming the material structure, affecting fundamental semiconductor properties
 - also is important for photonic and electro-optic integrated circuits such as CCDs and opto-isolators



SOHO Solar Array Degradation

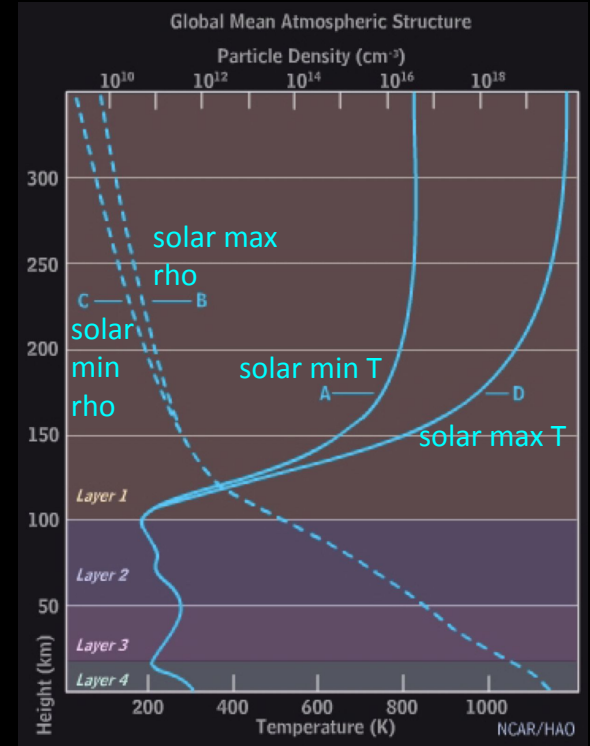


Satellite SW influences

- high energy particles flux (e.g., van Allen Belts, direct SEP flux, auroral zones):
 - single event effects
 - surface charging
 - internal charging
 - cumulative degradation
- **spacecraft drag increase** due to thermospheric expansion (e.g., from geomagnetic events, SEP precipitation)
- communication interference due to solar radio bursts

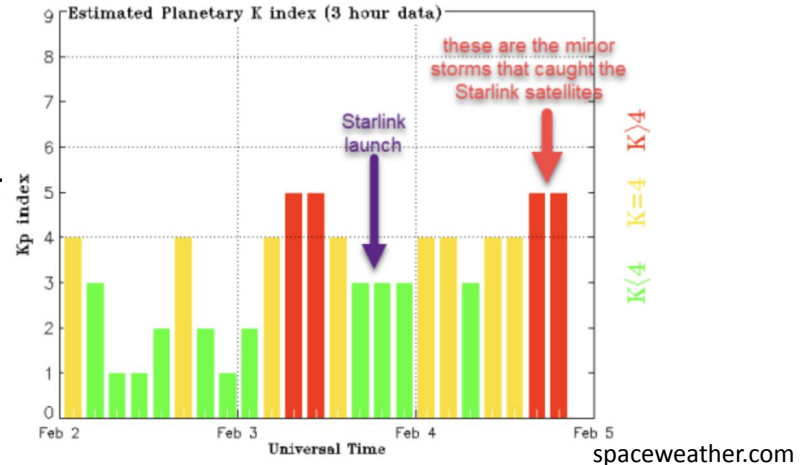
Spacecraft drag increase

- atmosphere warms up & expands, various mechanisms:
 - absorption of EUV (10 -200nm)
 - Joule heating (increased electrical currents)
 - particle precipitation
- most drag models use 10.7cm radio flux as a proxy for UV flux and K_p / A_p for short term atmospheric heating:
 - if 10.7 flux > 250 standard solar flux and $K_p > 6$
- 13-14 March 1989, a LEO sat recorded a loss of 30 km of altitude



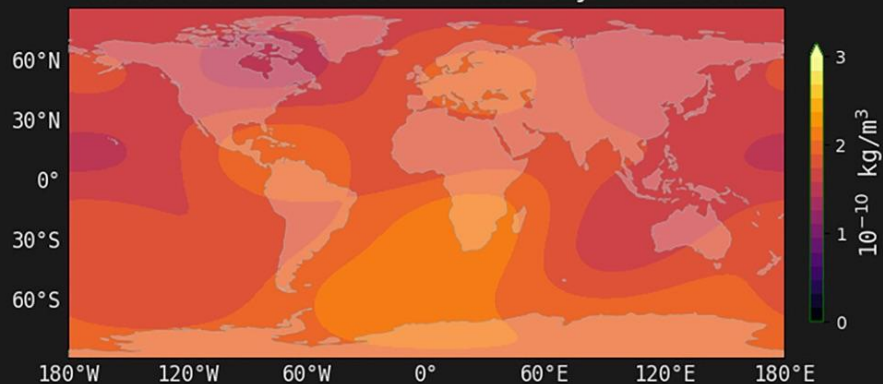
Starlink sats burn up in the atmosphere, Feb 2022

- 2 days before launch a minor G1, then Earth passed in the CME's wake → created another G1
- empirical models seem to have significantly under-predicted the enhancement of the neutral density at 200 - 400 km
- report: *"The Starlink team commanded the satellites into a safe-mode where they would fly edge-on to minimize drag ...[] ... Preliminary analysis show the **increased drag at the low altitudes** prevented the satellites from leaving safe-mode to begin orbit raising maneuvers, and up to 40 of the satellites will reenter or already have reentered the Earth's atmosphere."*



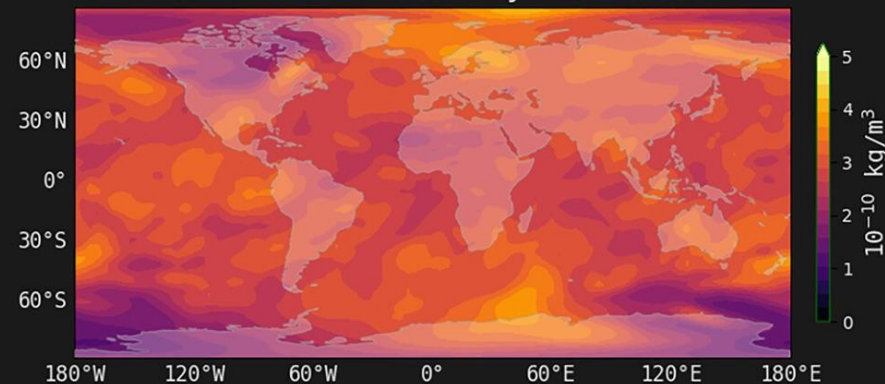
Global Neutral Atmosphere Valid at: Feb 4 2022 11:50 UTC

NRLMSISE-00 Neutral Density at 210km



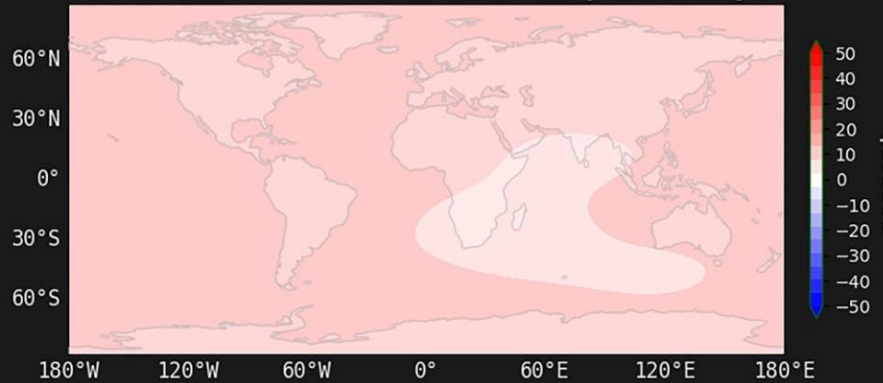
empirical modelling

WAM Neutral Density at 210km

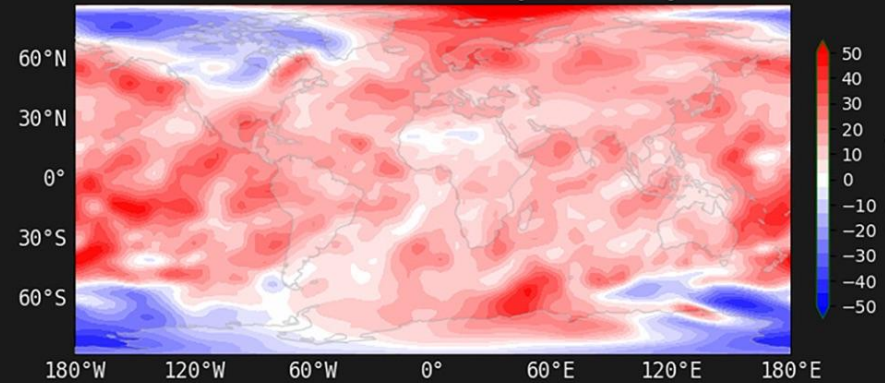


physical modelling

NRLMSISE-00 Neutral Density Anomaly



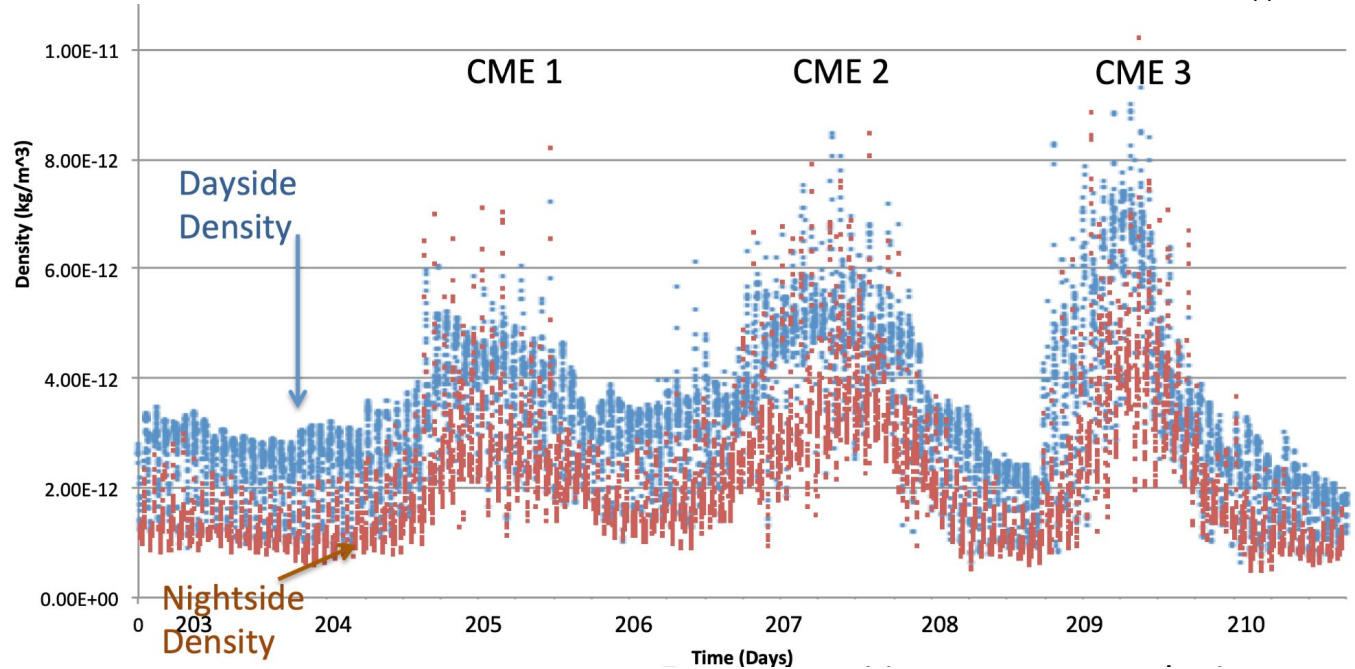
WAM Neutral Density Anomaly



Spacecraft drag increase

Knipp 2013

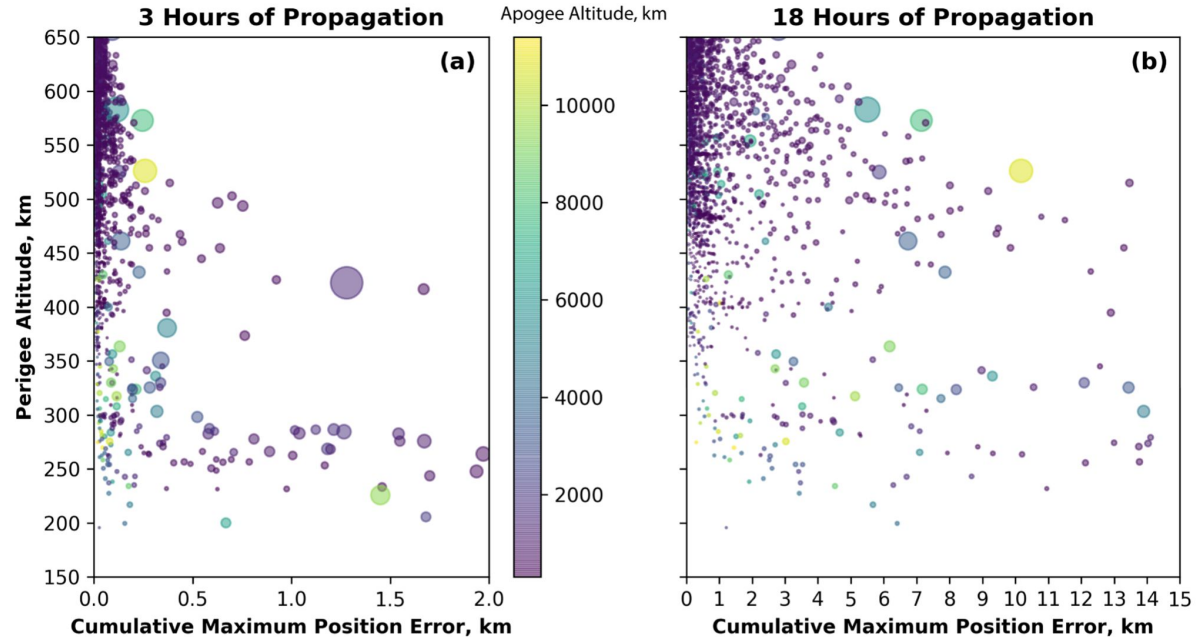
- density increase both on dayside and nightside
- 5x to even 10x the undisturbed profile
- drag scales proportionally to density



Spacecraft drag increase

Berger et al. 2020

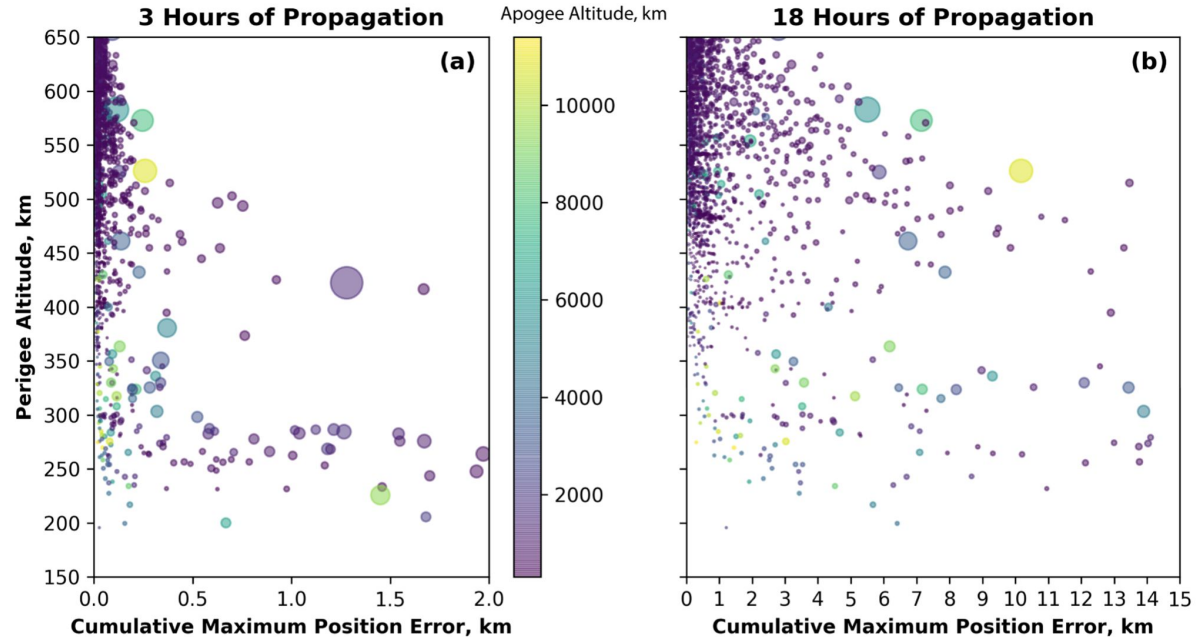
- Berger et al. 2020: a simulation of cumulative position errors of 2653 LEO objects in the USAF catalogue as a result of a G2 (Kp 6) storm due to increased atmospheric drag
- geomagnetic storms move all LEO objects to new locations → **collision risk**



Spacecraft drag increase

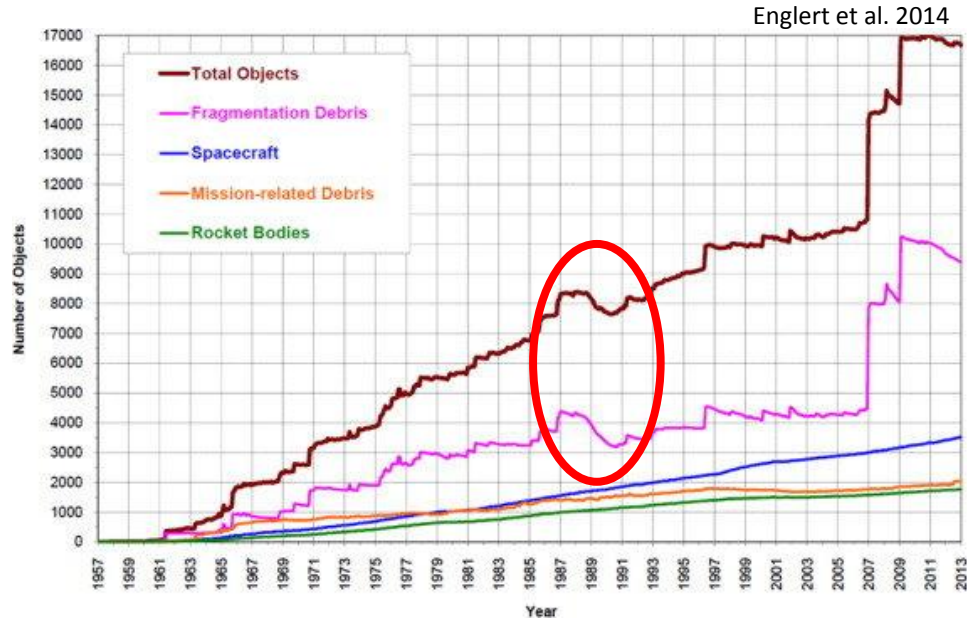
Berger et al. 2020

- May 2024 → Parker and Linares (2024): the entire collision avoidance pipeline was disrupted → the pipeline needed a full restart
- requires full attention of satellite operators on the ground



Spacecraft drag increase

- monthly # of objects in the Earth orbit cataloged by the US Space Surveillance Network

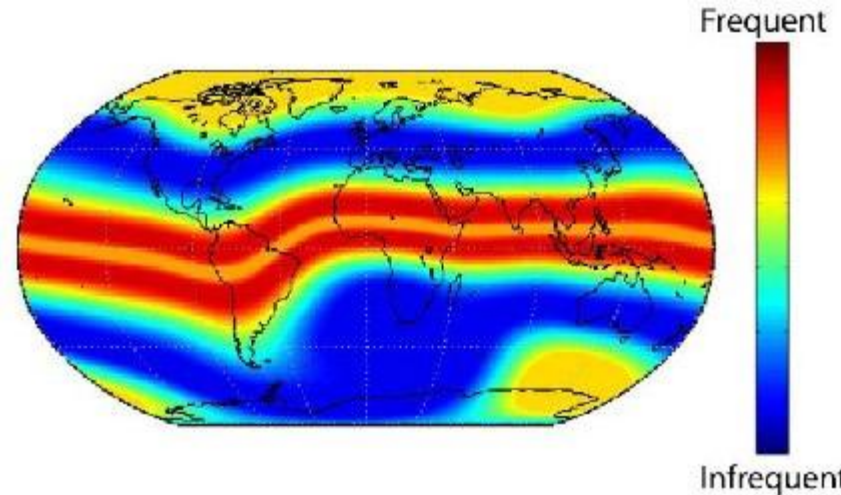
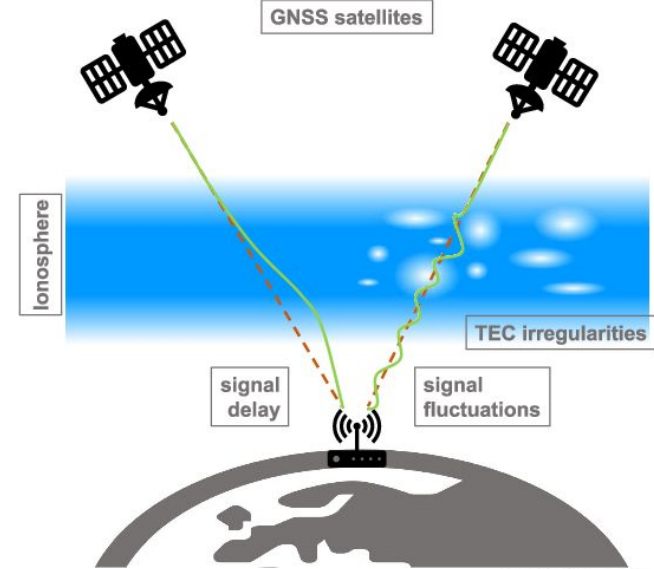


Satellite SW influences

- high energy particles flux (e.g., van Allen Belts, direct SEP flux, auroral zones):
 - single event effects
 - surface charging
 - internal charging
 - cumulative degradation
- spacecraft drag increase due to thermospheric expansion (e.g., from geomagnetic events, SEP precipitation)
- **communication interference due to solar radio bursts → a separate lecture!**

Satellite link: note

- even with the satellites fully working, link issues due to:
 - scintillation
 - ionospheric delay
(see lecture on GNSS)
- communication with the satellite interrupted
- can be remedied by having multiple available satellites and correction models
- scintillation usually lasts less than an hour



What can we do?

- high energetic particles:
 - more robust design:
 - with shielding sensitive devices from the particle flux
 - with resistant materials
 - prevent/ mitigate electrostatic potential differences
 - switching to a “safe-mode”
- increased thermospheric drag:
 - improving models to determine the necessary corrections/ risks
 - full attention of operators during SW events to avoid collision risks
- satellite communications: stay tuned!

To ask yourself

- For SAT users:
 - How do our operations depend on satellite services?
 - What happens if these stop being available?
 - Do we have other means to obtain the same information?
- For SAT operators:
 - In which orbits are our satellites flying?
 - Do our satellites contain any systems which could be especially sensitive to particle precipitation?
 - Do we have any means of reducing the potential damage (safe-mode)?

Thank you for your attention! Questions?