SPACE WEATHER INTRODUCTORY COURSE

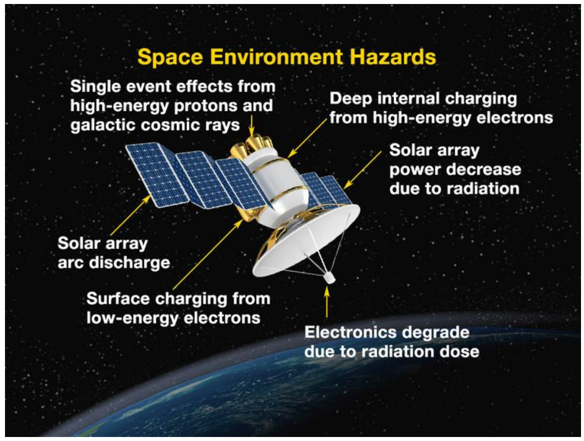
Collaboration of:

Solar-Terrestrial Centre of Excellence

Koninklijke Luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

May 2017



IMPACT ON SATELLITES

Basics of satellites and how they are disturbed by SPWX

Willem-Pieter van der Laan

SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI

Satellite in space: seems peaceful, though encounters a lot of hazards.

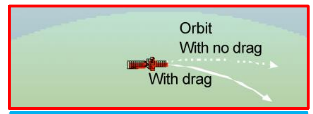
CREDITS & THANKS TO

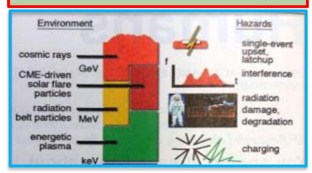
- Wikipedia
- US Air Force
  - Advanced Space Ops School
  - 557^{TH} Weather Wing
- Satellite Database by the Union of Concerned Scientists
- "*Space Weather and the Physics behind it*" by Delores J. Knipp
- "*Extreme Space Weather*" by Royal Academy of Engineering
- Michel Bulte & Petra Wijnja for their help

OUTLINE

- Introduction
- Satellites
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

MECHANICAL





ELECTRICAL

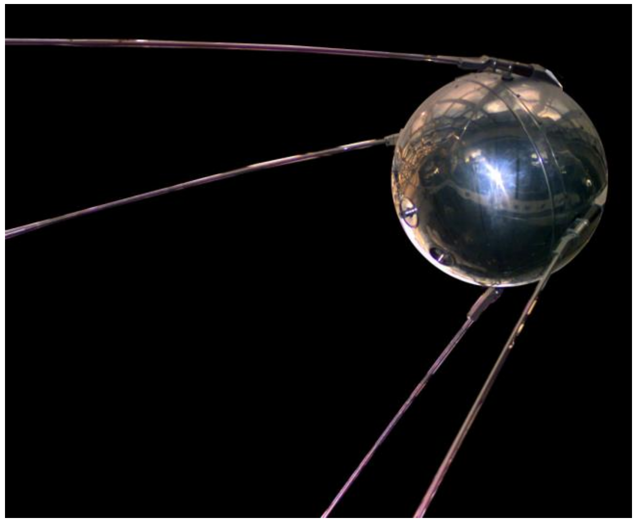
SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI 4

We'll start with a short introduction on the history of satellites, then move on to the satellite itself (what is it made of) and continue with satellite orbits. The type of satellite and its orbit determine its mission. We'll discuss that going on. We'll finish this module with the impact of SPWX at satellites in their different orbits, which we can roughly divide in mechanical and electrical effects. The electrical effects are ranked here from high energy to low. Or from 'radiation effects' to 'plasma effects', drag being a 'neutral effect'.

OUTLINE

- Introduction
- Satellites
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

HISTORY



1957 Sputnik 1

https://en.wikipedia.org/wiki/Sputnik_1

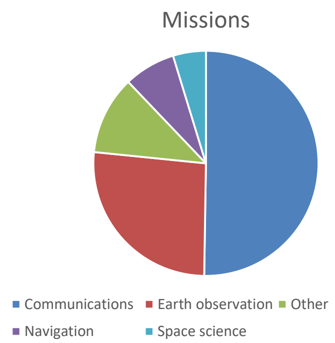
THEN AND NOW

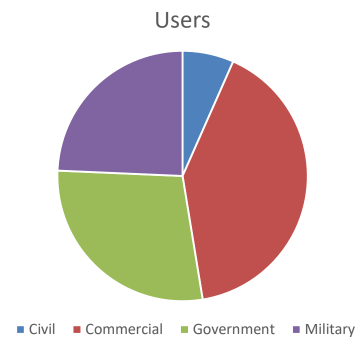
http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.WP5vFvnyjIU

https://www.quora.com/How-many-artificial-satellites-have-been-launched-and-are-in-orbit-around-the-Earth

NUMBERS (2016)

Satellites	Number
In orbit	4256
Operational	1419



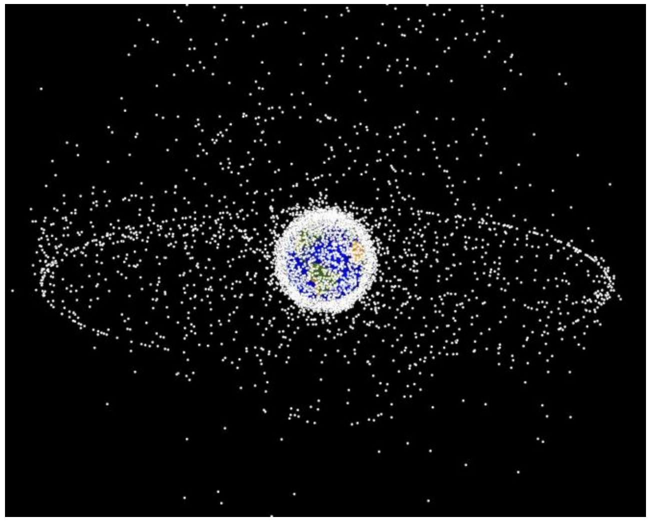


SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI 8

Since 1957, about 6,600 satellites from more than 40 countries have been launched. According to a 2016 estimate, 4,256 remained in orbit. Of those, about 1,419 were operational; the rest (2/3) have lived out their useful lives and become space debris. About 100 satellites are in MEO, the rest is roughly equally divided by LEO en GEO. Largest satellite owners are the USA (576), China (181) and Russia (140). UK has 41 and ESA has 36 satellites.

http://www.pixalytics.com/sats-orbiting-earth-2016/

DEBRIS



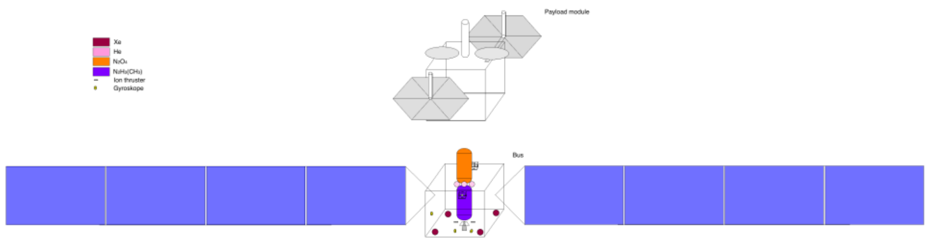
SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI 9

Mainly in LEO & GEO
Old satellites, spent rocket stages, fragments from erosion and collision
2007: Fengyun-1C ASAT test
2009: Russian satellite struck US Iridium satellite
Kessler syndrom
Kinetic impact
Monitoring, changing orbit and shielding
https://en.wikipedia.org/wiki/Space_debris
https://www.youtube.com/watch?v=9cd0-4qOvb0
http://stuffin.space/
https://www.nasa.gov/mission_pages/station/news/orbital_debris.html
http://www.space.com/topics/space-junk-orbital-debris-news

OUTLINE

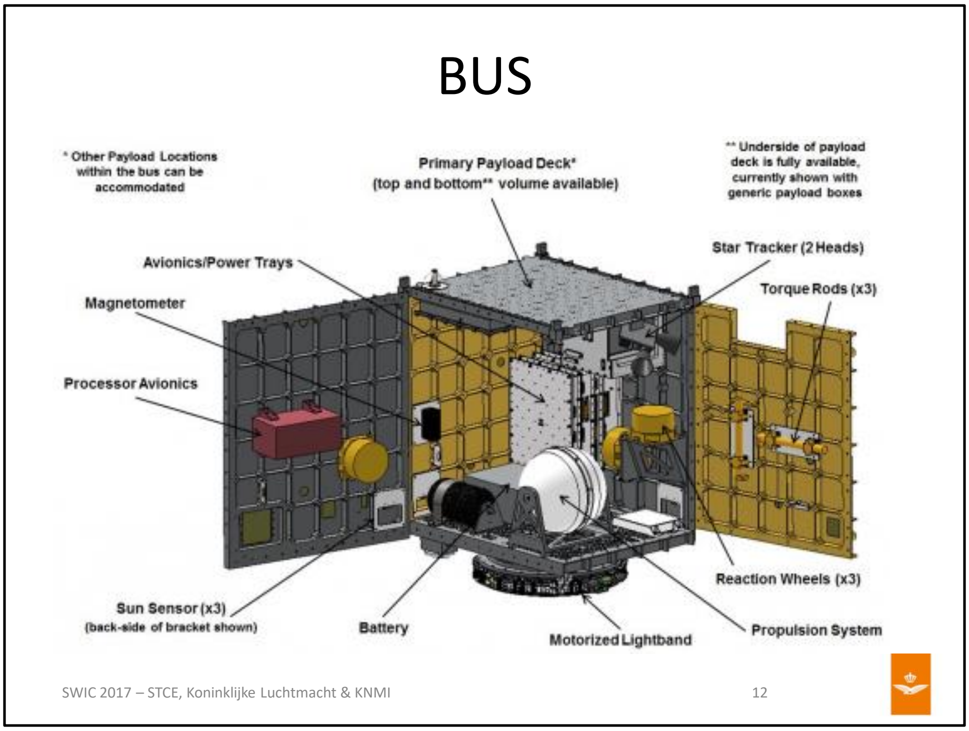
- Introduction
- Satellites
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

BUS, PAYLOAD & SOLAR CELLS



Satellites are made up of a bus, a payload and solar cells. Satellites are usually semi-independent computer-controlled systems.

https://en.wikipedia.org/wiki/Spacecraft
https://en.wikipedia.org/wiki/Satellite_bus
https://en.wikipedia.org/wiki/Payload
https://en.wikipedia.org/wiki/Solar_cell



The bus exists of many subsystems which attend many tasks, such as power generation, thermal control, telemetry, attitude control and orbit control.

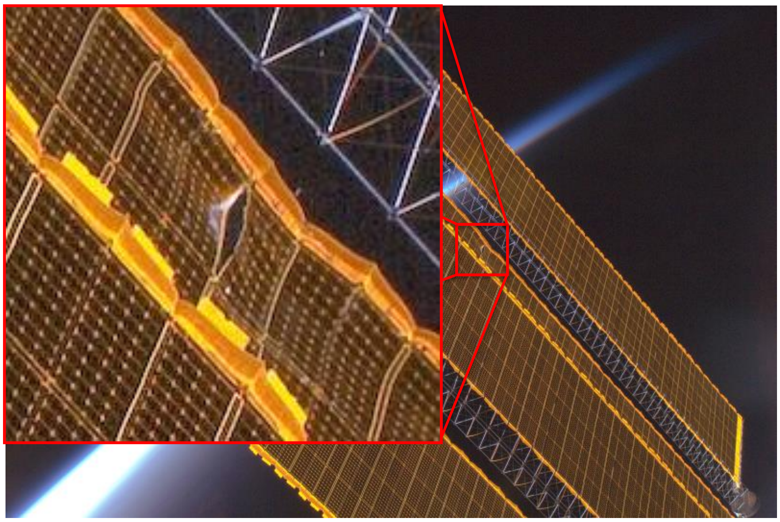
https://en.wikipedia.org/wiki/Satellite_bus

The payload o/b of a satellite depends on its mission. Roughly three categories: sensors, communications & PNT.

1) AEHF (https://en.wikipedia.org/wiki/Communications_satellite)
2) Aqua (https://aqua.nasa.gov/ | http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Meteosat/index.html)
3) GPS Block III (http://www.gps.gov/multimedia/images/ | https://en.wikipedia.org/wiki/Global_Positioning_System)
4) DSCOVR (https://www.ngdc.noaa.gov/dscovr/portal/index.html)
5) Hubble (https://en.wikipedia.org/wiki/Hubble_Space_Telescope)

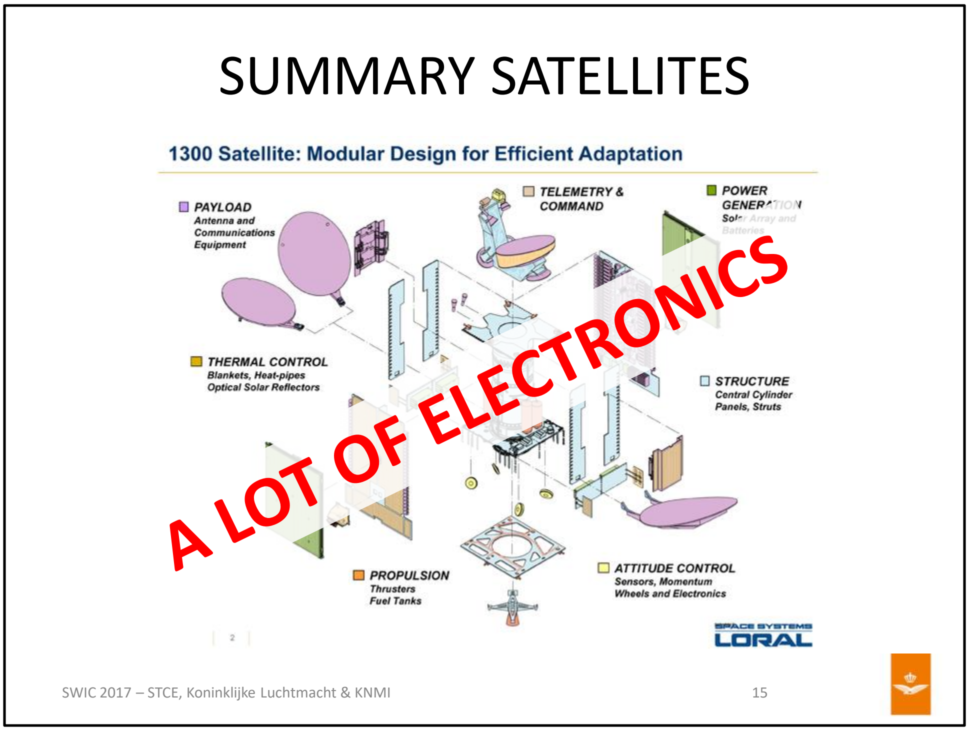
And there is a lot more: SIGINT, EWC, S&R, Meteorology, Ionopsheric & Atmospheric Research etc.

SOLAR CELLS

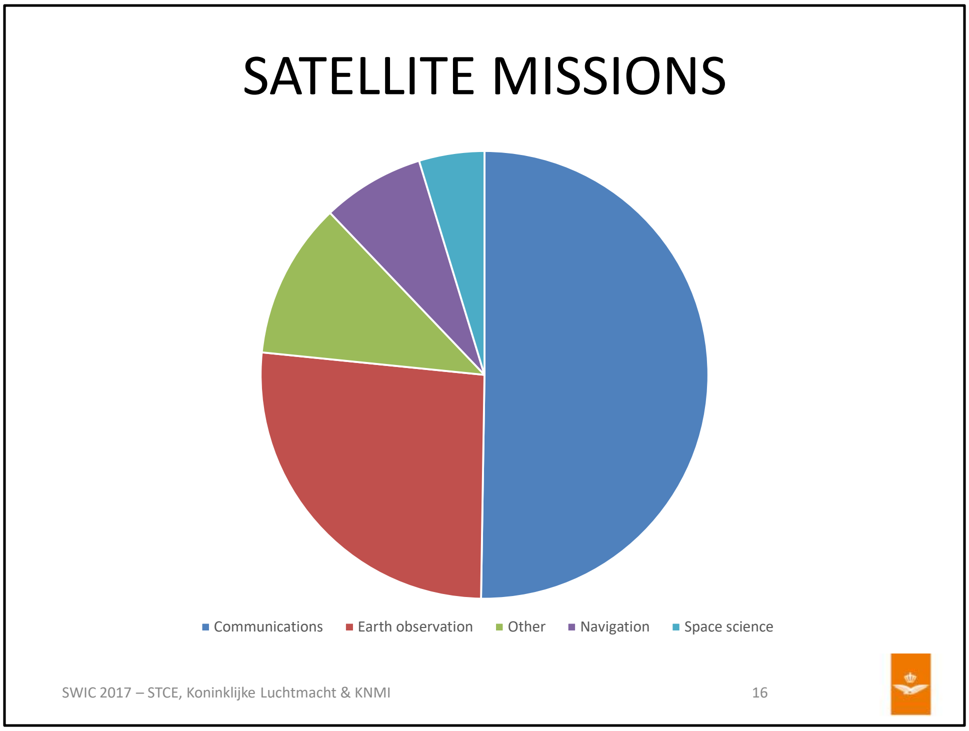


A solar panel array of the International Space Station (Expedition 17 crew, August 2008).

https://en.wikipedia.org/wiki/Solar_panels_on_spacecraft



Bus, payload and solar cells: altogether quite a lot of (semi-conductor) electronics (detectors, transistors).



Satellite missions are a combination of the payload and the orbit. Now. let's have a look at the different orbits and what they are used for.

http://www.pixalytics.com/sats-orbiting-earth-2016/
http://allthingsnuclear.org/lgrego/ucs-satellite-database
https://www.quora.com/What-are-the-various-applications-of-satellites

OUTLINE

- Introduction
- Satellite missions
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

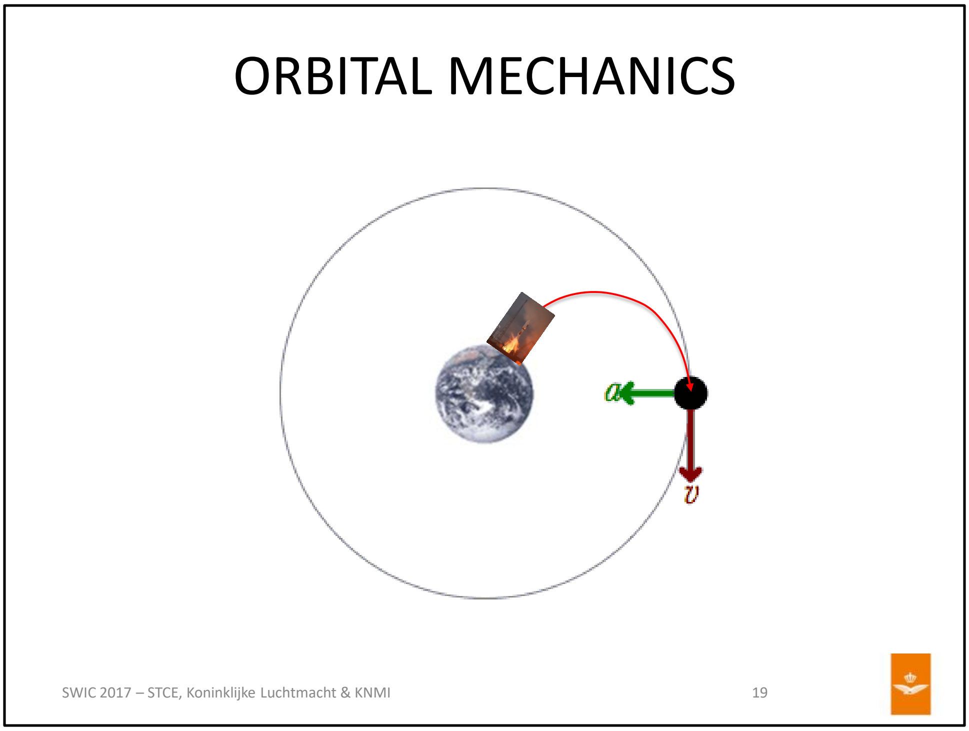
LAUNCH

SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI 18

Space. How do we get there? By launching.

A launch vehicle is a rocket that throws a satellite into orbit. Usually it lifts off from a launch pad on land. Some are launched at sea from a submarine or a mobile maritime platform, or aboard a plane (see air launch to orbit).

https://en.wikipedia.org/wiki/Rocket_launch
https://en.wikipedia.org/wiki/ASM-135_ASAT



The centripetal force needed for orbital motion (m*v^2/r) is generated by gravity (Fg = G*M*m/r^2). If these equal the satellite stays in its orbit.
To get there: launch in the right direction and with the right angle, the earth will do the rest.

Johannes Kepler's three laws (1605): (1) orbits are elliptical, (2) equal areas of the ellips in equal times and (3) T^2/A^3 = constant.

[Changing orbits is a bit counter intuitive: increase tangential velocity → eccentricity increases ~ increase in heigth (Conservation of Energy) → tangential velocity drops → satellite lags behind.]

https://en.wikipedia.org/wiki/Orbital_mechanics

SIX CLASSICAL ORBITAL ELEMENTS

Orbit size	Semi-major axis	a
Orbit shape	Eccentricity	e
Orbit tilt	Inclination	i
Orbit twist	Right ascension of the ascending node	Ω
Perigee location	Argument of perigee	ω
Satellite location	True anomaly	ν

The position of a satellite is exactly known if we know the next six variables or elements:

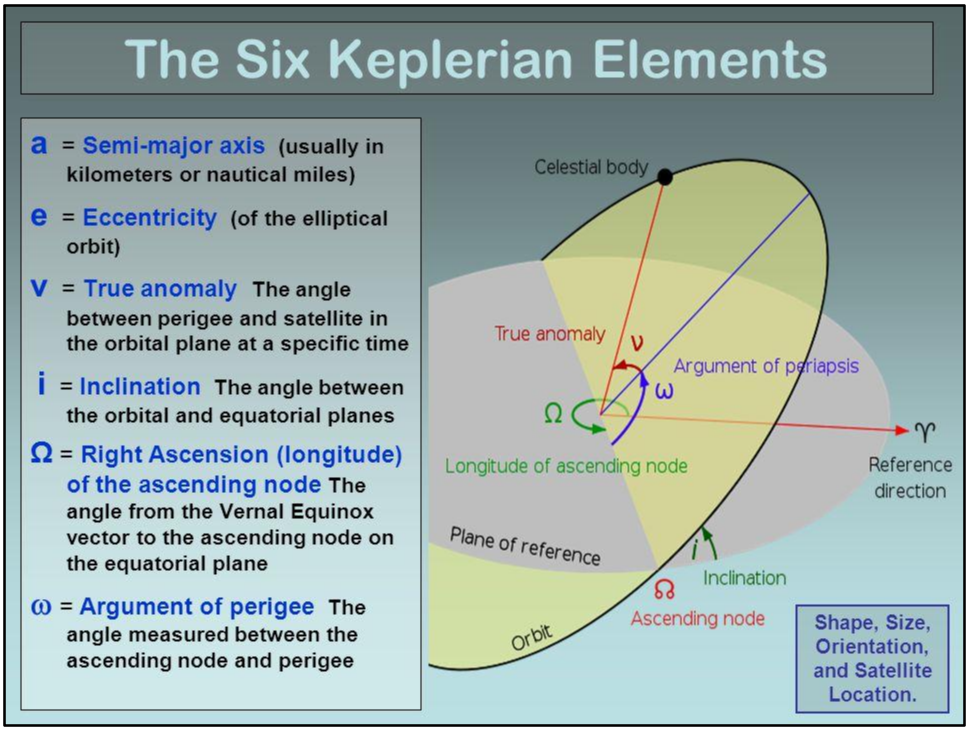
a = size of orbit
e = shape of orbit

ν = point at orbit

i = tilt of orbit vs. equatorial plane
ω = roll of orbit vs. equatorial plane
Ω = twist of orbit vs. equatorial plane

Perigee = point of least distance to earth. [Apogee = point of greatest distance to earth.]

https://earthobservatory.nasa.gov/Features/OrbitsCatalog/



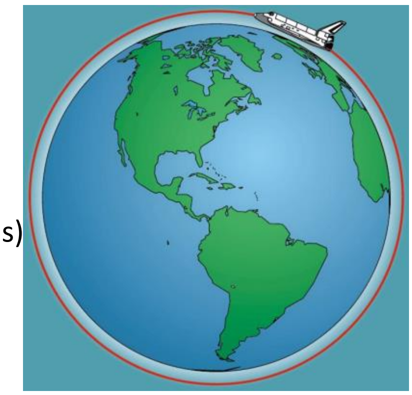
a = size of orbit
e = shape of orbit

v = point at orbit

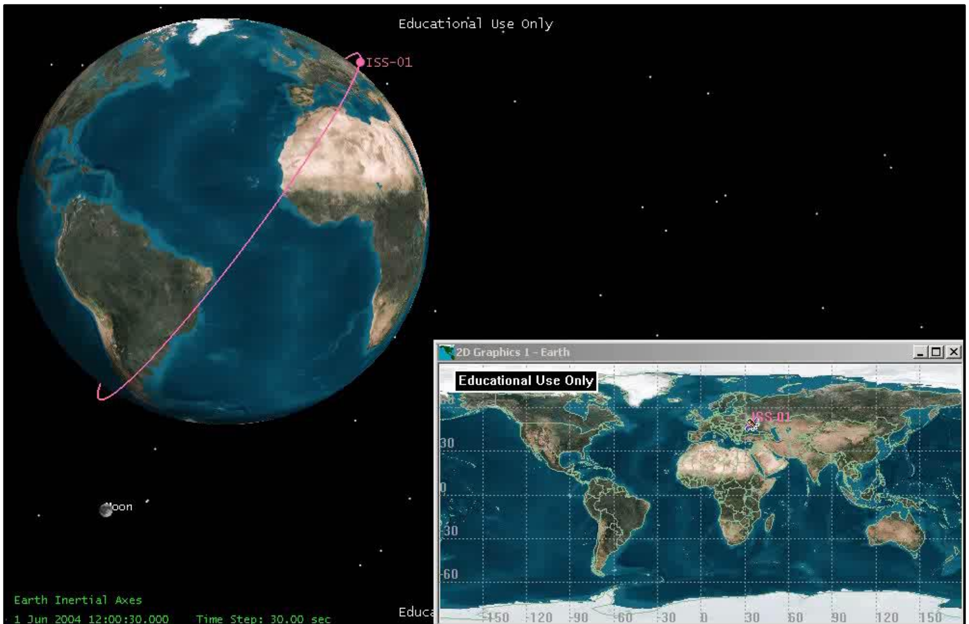
i = tilt of orbit vs. equatorial plane
ω = roll of orbit vs. equatorial plane
Ω = twist of orbit vs. equatorial plane

LOW EARTH ORBIT (LEO)

- Altitude: Up to about 1500 km
- Period: 90 – 120 min
- Limited coverage
- Short dwell time over target
- Missions:
  - Manned (ISS)
  - Communications (constellations)
  - Observation
    - Weather
    - Earth sensing
    - Military reconnaissance
    - Astronomy

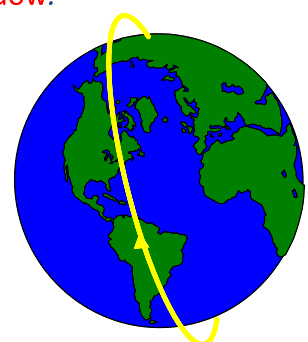


Iridium, ISS, Hubble, Sputnik.

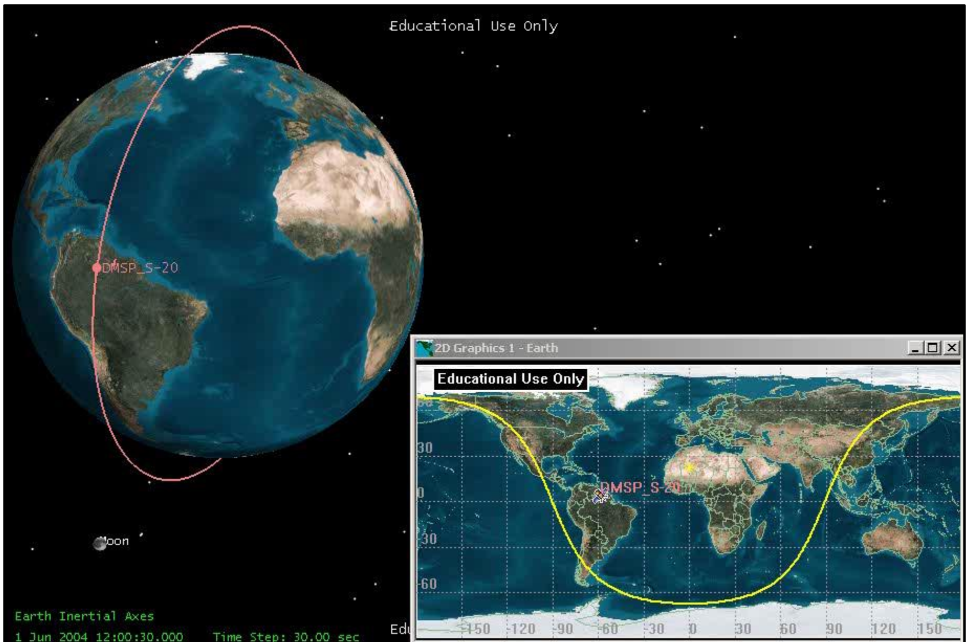

Educational Use Only
ISS-01
Moon
Earth Inertial Axes
1 Jun 2004 12:00:30.000
Time Step: 30.00 sec
2D Graphics 1 - Earth
Educational Use Only

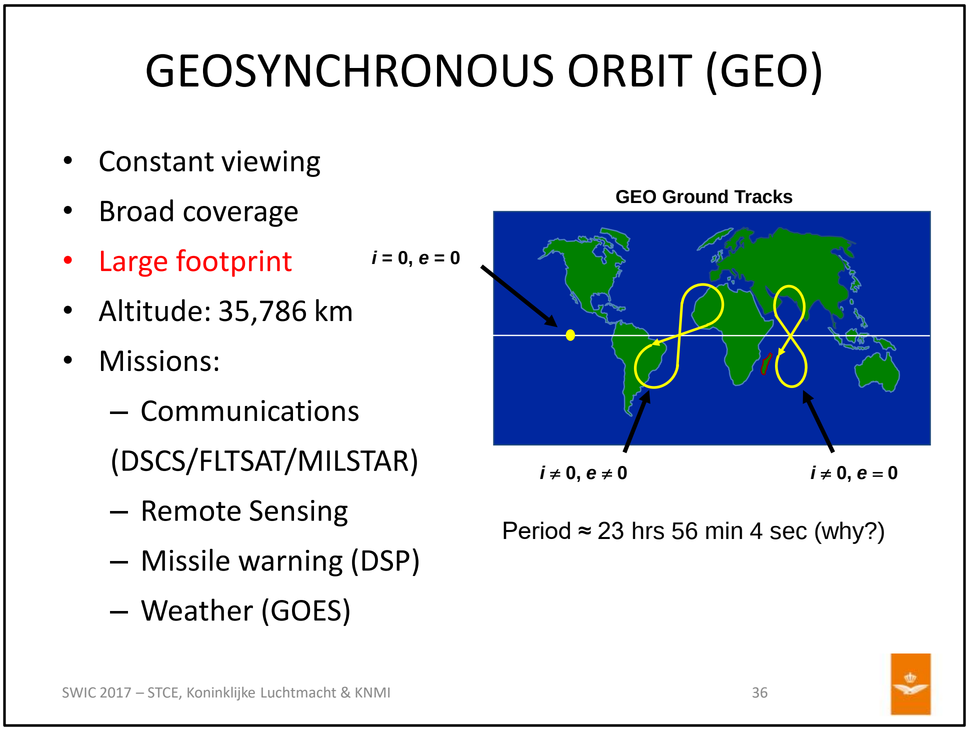
LEO SUN-SYNCHRONOUS ORBIT (SSO)

- A special, near-polar inclination, low earth orbit with retrograde motion
- Passes over target same time of day (but *doesn't pass over the target everyday*): same sun angle or shadow.
- Missions:
  - Reconnaissance
  - Weather (DMSP/TIROS)
  - Earth sensing (LANDSAT)



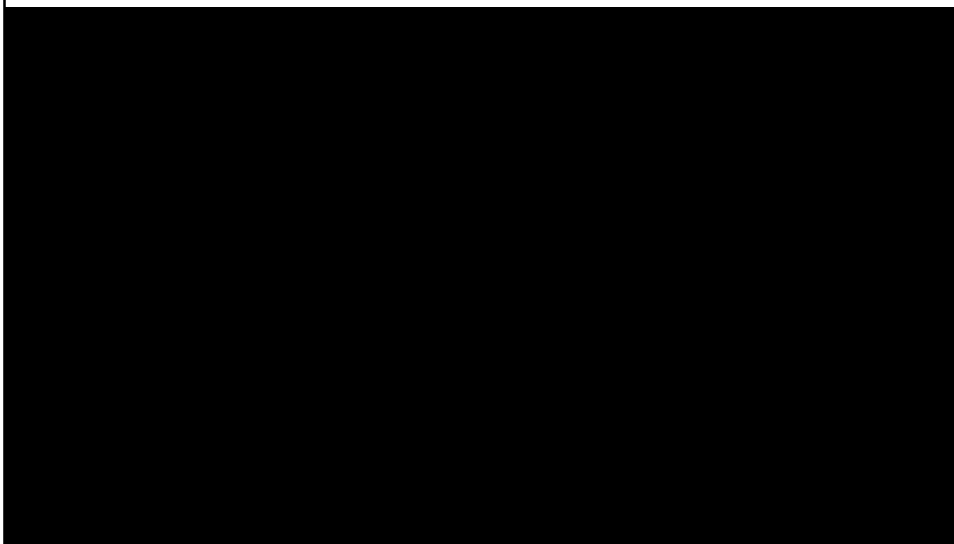
PROBA-2, Aqua, Terra, spy satellites.


Educational Use Only
DMSP_S-20
Moon
Earth Inertial Axes
1 Jun 2004 12:00:30.000 Time Step: 30.00 sec
2D Graphics 1 - Earth
Educational Use Only
DMSP_S-20



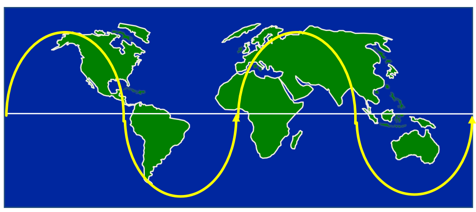
Three satellites in GEO can give “global” coverage (with the exception of the polar regions – latitudes above 81°).

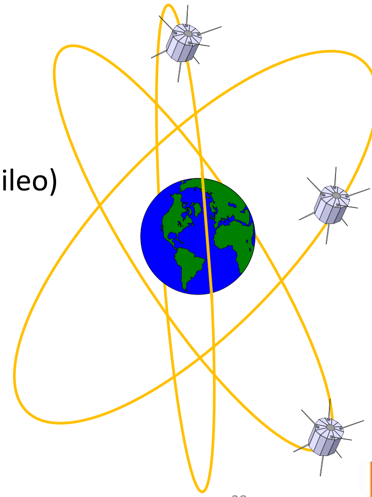
https://en.wikipedia.org/wiki/Sidereal_time

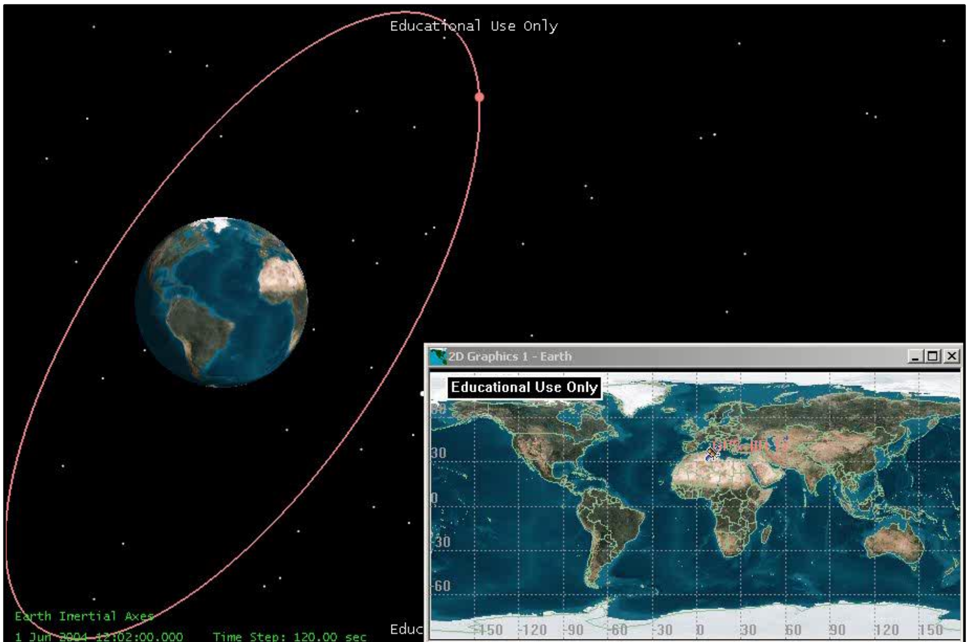


MEDIUM EARTH ORBIT (MEO)

- Another "special" orbit that repeats its ground track every day
- Period: ~12 hours
- Altitude: 20,184 km
- Mission:
  - Navigation (GPS, Glonass, Galileo)

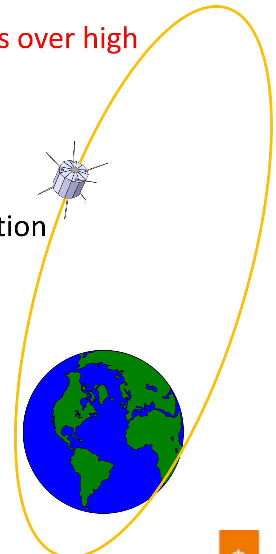




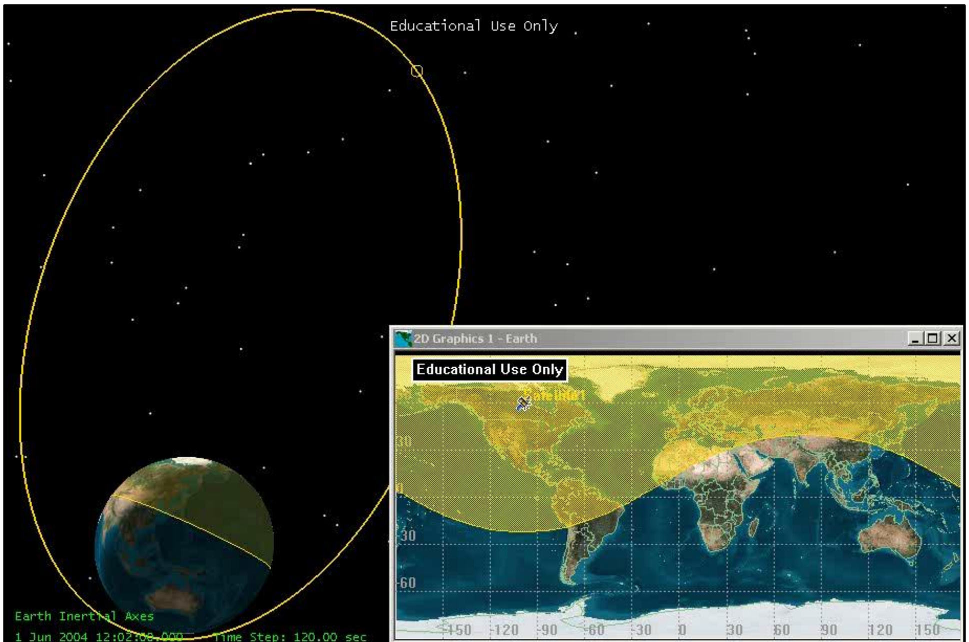

Educational Use Only
2D Graphics 1 - Earth
Educational Use Only
Earth Inertial Axes
1 Jun 2004 12:02:00.000
Time Step: 120.00 sec

HIGHLY ELLIPTICAL ORBIT (HEO)

- Another "special" orbit with long dwell times over high northern latitudes
  - Approximately 8 hours of a 12 hour orbit
- Max coverage at higher latitudes
  - Covers the "hole" left by a GEO constellation
- Missions:
  - Communication
  - Remote Sensing
  - Reconnaissance
  - Warning

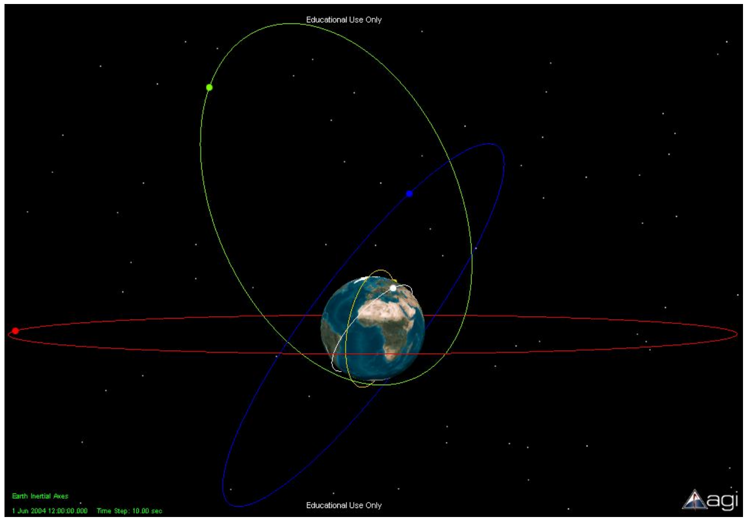


AKA Molniya orbit.



AKA Molniya orbit.

ALL-IN-ONE



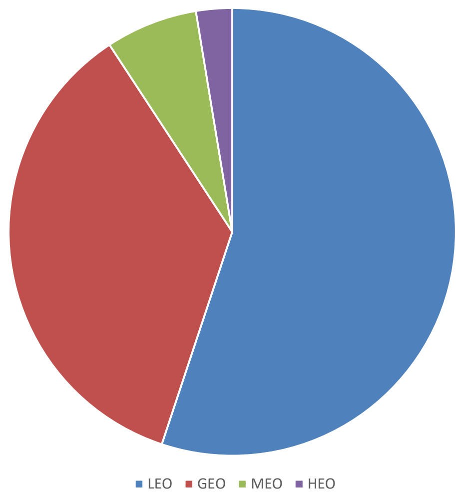
Educational Use Only
Earth Inertial Axes
1 Jun 2004 12:00:00.000   Time Step: 10.00 sec
Educational Use Only
agi

GUESS ORBIT AND MISSION

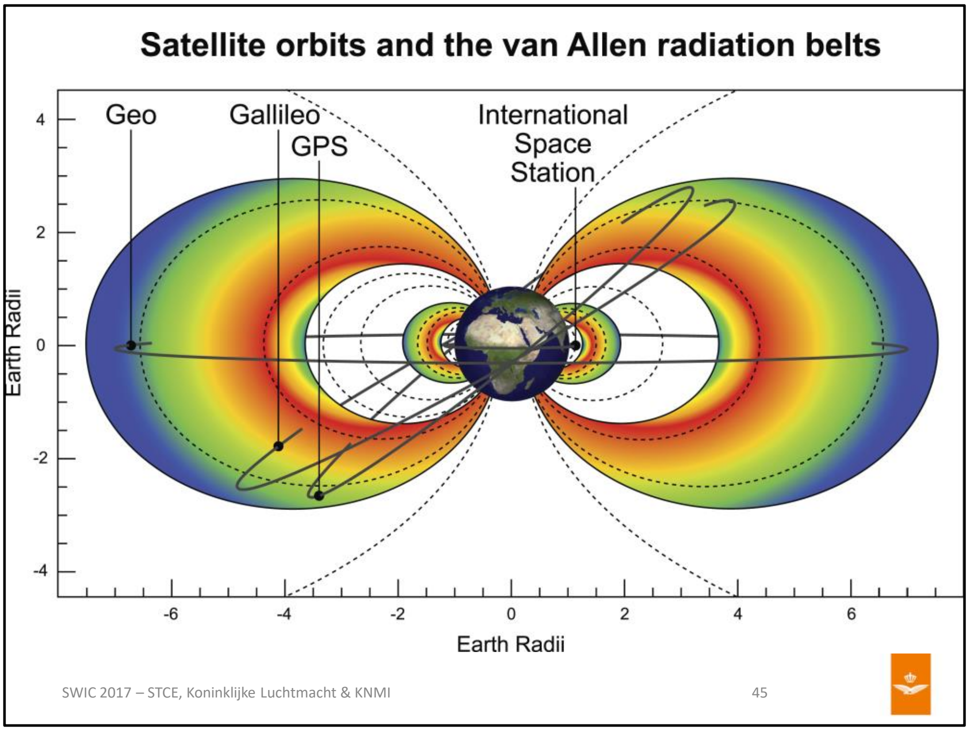
Orbit	a	e	i	ω	Orbit Type	Potential Mission?
1	6978 km	0	28.5º	N/A	**LEO**	**Hubble**
2	6678 km	0	96.67º	N/A	**Sun Synch**	**Imagery**
3	26562 km	.75	63.4º	270 º	**Molniya**	**Polar Comm**
4	42164 km	0	0º	N/A	**GEO**	**Equat. Comm**

Radius of the Earth = 6378.137 km

SUMMARY SATELLITE ORBITS



http://allthingsnuclear.org/lgrego/ucs-satellite-database



Before we move on to impact of SPWX on satellites, find the discussed orbits and the radiation belts in one picture.

OUTLINE

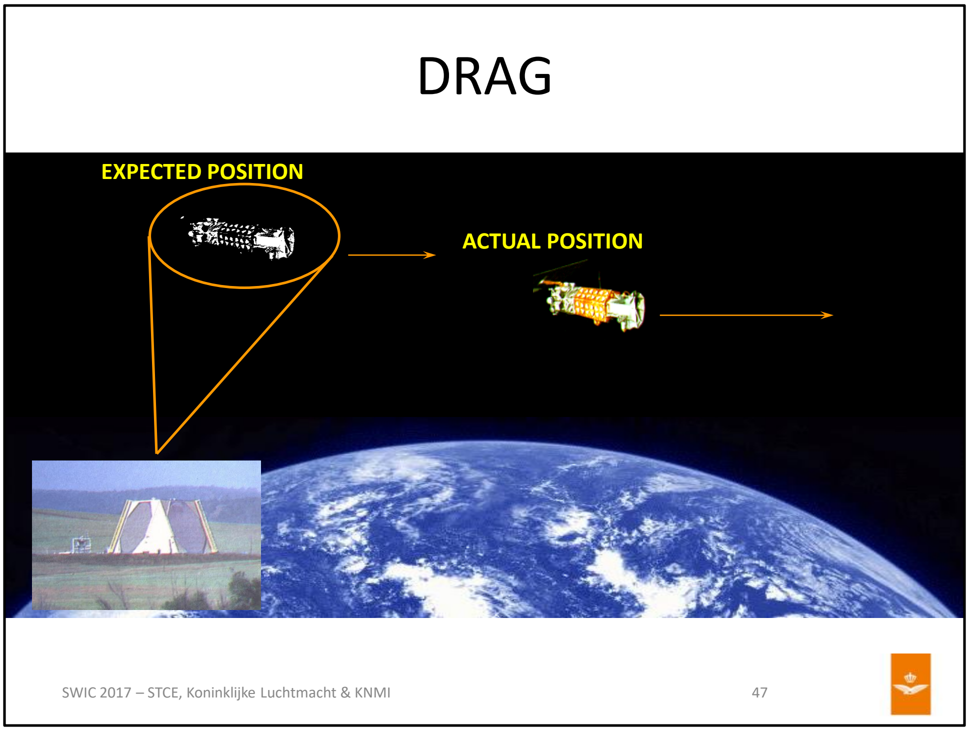
- Introduction
- Satellites
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

Space Environmental Impacts on Space Systems			
Anomaly Diagnosis	Koons et al, 2000	NGDC DB, 2006	Satellite Digest, 2014
ESD-Internal, surface, and indeterminate	54%	31%	10%
SEU (GCR, SPE, SAA, etc.)	28%	17%	5%
Radiation Dose	5%	---	---
Meteoroids and Orbital Debris	3%	---	5%
Atomic Oxygen	< 1%	---	---
Atmospheric Drag	< 1%	---	---
Design	---	---	25%
Other or Unknown	8%	52%	55%

Table from NASA/CCMC. Absolute numbers unknown.

This overview tries not to be complete. It tries to arrange the several impacts of space weather and the space environment on satellites a bit, as there are many.

@radiation effects:
- specific details are unique because SC are unique;
- Space Climatology: mitigate by design;
- Space Weather: mitigate by design and control.



After the Quebec Blackout, March 1989, hundreds of satellites were lost.

A **geomagnetic (super)storm** will cause expansion of the Earth's atmosphere, causing drag on **LEO satellites**; orbits will be disturbed and predictions of satellite positions will be degraded. Satellite orbit data then needs to be re-acquired which may take some days to complete. In extreme cases, low altitude satellites may experience significant aerodynamic torques which overcome the vehicle's attitude control system capability leading to termination of the mission as happened to Astro-D (~450km altitude orbit) during the storm of 14-15 July 2000.

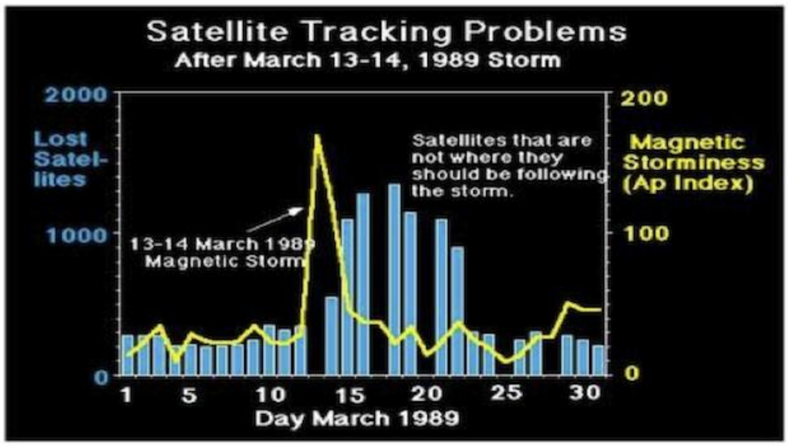
Another known example is the one of Skylab. Greater-than-expected **solar activity** heated the outer layers of the Earth's atmosphere and thereby increased drag on Skylab. Causing it to re-enter earlier than planned.

Notice that launch trajectories and the right moment for payload jettison are compromised too during geomagnetic storms.

Besides drag, satellites can also lose their attitude control during geomagnetic storms when their magnetometers get disrupted. Another way of losing attitude control is because of high energy protons bombarding the CCD-cameras of their star trackers. More on this in the next slides.

https://en.wikipedia.org/wiki/Skylab#Solar_activity
http://www.swpc.noaa.gov/impacts/satellite-drag

CASE 1: LOST SATELLITES

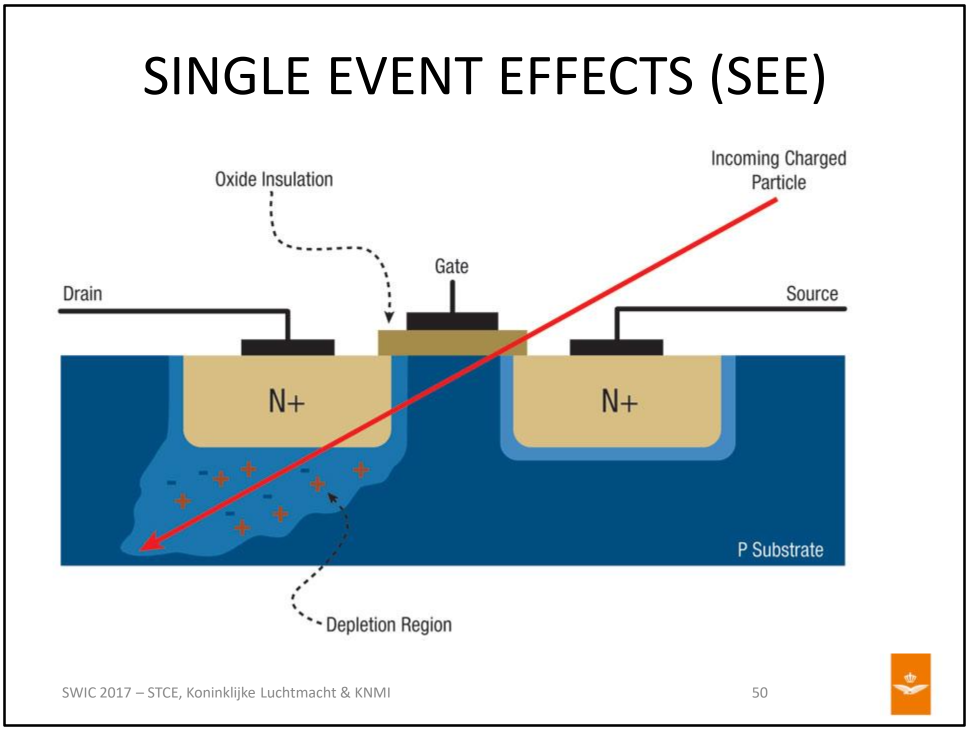


OUTLINE

- Introduction
- Satellites
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

Space Environmental Impacts on Space Systems			
Anomaly Diagnosis	Koons et al, 2000	NGDC DB, 2006	Satellite Digest, 2014
ESD-Internal, surface, and indeterminate	54%	31%	10%
SEU (GCR, SPE, SAA, etc.)	28%	17%	5%
Radiation Dose	5%	---	---
Meteoroids and Orbital Debris	3%	---	5%
Atomic Oxygen	< 1%	---	---
Atmospheric Drag	< 1%	---	---
Design	---	---	25%
Other or Unknown	8%	52%	55%

Table from NASA/CCMC, McKnight (2015). Absolute numbers unknown.



Example of an incoming charged particle on a MOSFET (transistor). Unwanted currents = unwanted effects.

SEE are the deposition of charge in an electrical circuit caused by the interaction of a single particle. The main sources are 1) galactic rays, 2) solar particles and 3) the radiation belts. This implies that all satellite orbits are exposed to this hazard.

1) GCR & high energy neutrons: anticorrelation with solar activity. More pronounced / intense during solar minimum. Cause: supernovas.
2) High energy (>10MeV) protons during flares & CMEs (Solar Energetic Particles). Also contribute to total charging. Elemental composition (may vary event by event):
– 96.4% protons
– 3.5% alpha particles
– 0.1% heavier ions (not to be neglected!)
3) low-energy (< 10MeV) protons in the inner radiation belt. The South Atlantic Anomaly (SAA) dominates the radiation environment for altitudes less than about 1000 km.

- Caused by tilt and shift of geomagnetic axis relative to rotational axis.
- Inner edge of proton belt is at lower altitudes south and east of Brazil.

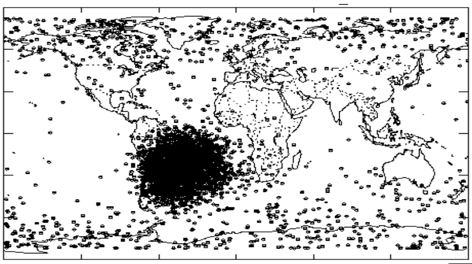
Effects: 1) data corruption, 2) noise on images, 3) system shutdown and 4) electronic component damage.

[Changes in the radiation belts are driven by the interaction of the solar wind with the Earth's magnetosphere. The inner radiation belt (within about 2 Earth radii) consists of energetic protons and electrons while the outer radiation belt (3-7 Earth radii) is dominated by electrons. The high-energy electrons cause a range of problems for satellites, particularly satellite charging effects [Iucci et al., 2005] while protons in the inner belt produce cumulative dose and damage as well as prompt Single Event effects. Satellites in geostationary orbit (GEO) pass through the outer edge of the radiation belts, whereas those in medium Earth orbit (MEO) pass through the heart of the outer radiation belt. Satellites in low Earth orbit (LEO) operate mainly underneath the belts, but encounter the inner radiation belt in a region known as the South Atlantic Anomaly. LEO satellites that have orbits inclined more than about 50 degrees to the Equator will, in addition, encounter the outer radiation belt in the high latitude auroral regions. High inclination LEO satellites are also vulnerable to SEPs encountered over high latitude regions.]

[SEU: arise from the charge depositions of individual particles in the sensitive regions of microelectronics. Such depositions occur via direct ionisation (dominant for the heavy ions) and nuclear interactions (dominant for protons and neutrons). Effects range from soft (correctable) errors to hard (permanent) errors, which can include burnout of some devices such as metal oxide semiconductors. With feature sizes reducing to tens of nanometres and critical charges reducing to femtoCoulombs these are a growing problem and a number of systems have been damaged or compromised.]

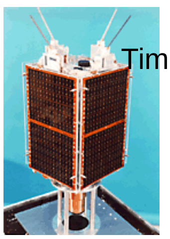
http://www.spaceweather.gc.ca/tech/se-sat-en.php
http://www.sws.bom.gov.au/Educational/1/3
http://holbert.faculty.asu.edu/eee560/see.html

CASE 2: UO-14 SEU

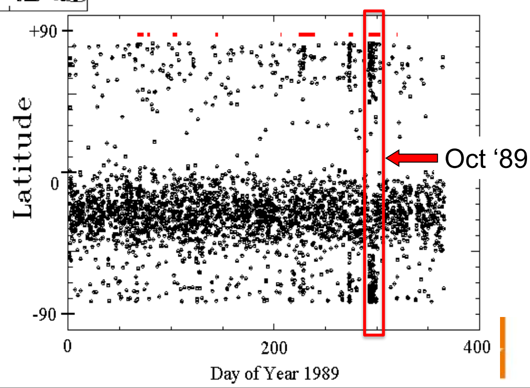


- Cosmic rays and solar ions at high latitude Radiation belt
- proton nuclear reactions in the South Atlantic Anomaly (SAA)

Mapped



Time behaviour

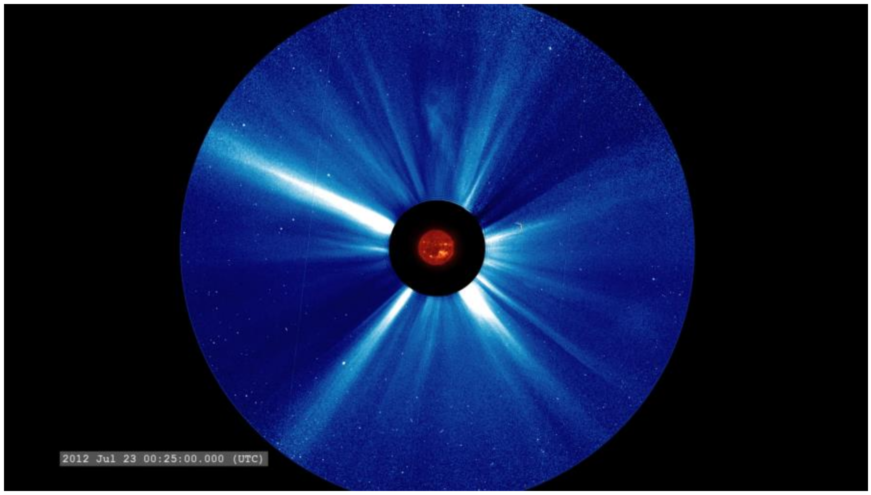


SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI

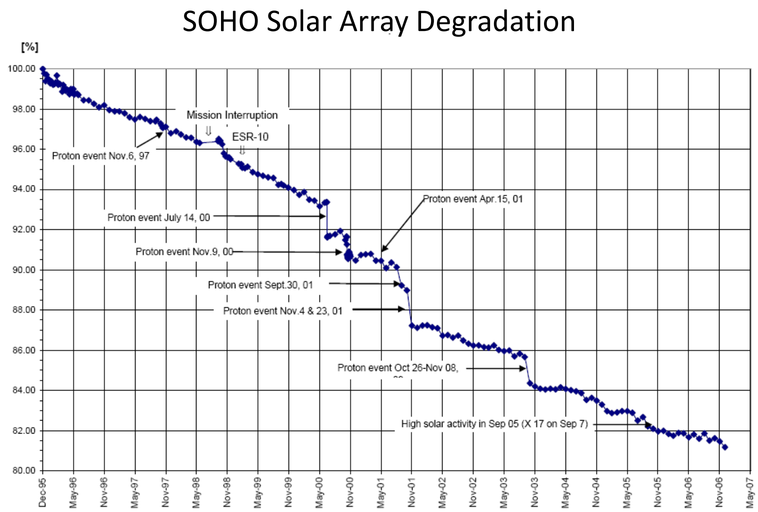
SEUs on UoSAT-3 microsatellite memory

https://en.wikipedia.org/wiki/UoSAT-3

CASE 3: SNOW @ SOHO



CASE 4: SOLAR CELL DEGRADATION



SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI 53

Bridge to ‘Degradation’: degradation can be caused by high energetic particles (see figure SOHO) as well as by the cumulative dose of less energetic particles.

OUTLINE

- Introduction
- Satellites
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

Space Environmental Impacts on Space Systems			
Anomaly Diagnosis	Koons et al, 2000	NGDC DB, 2006	Satellite Digest, 2014
ESD-Internal, surface, and indeterminate	54%	31%	10%
SEU (GCR, SPE, SAA, etc.)	28%	17%	5%
Radiation Dose	5%	---	---
Meteoroids and Orbital Debris	3%	---	5%
Atomic Oxygen	< 1%	---	---
Atmospheric Drag	< 1%	---	---
Design	---	---	25%
Other or Unknown	8%	52%	55%

Table from NASA/CCMC. Absolute numbers unknown.

DEGRADATION

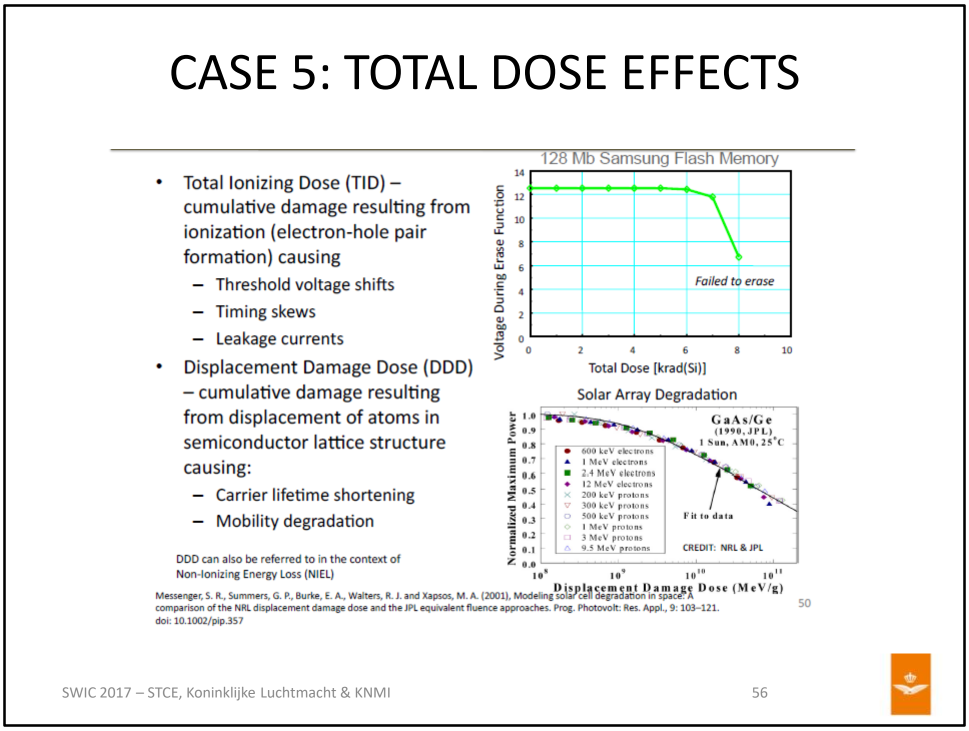
Total Radiation Dose

- Degradation of micro-electronics
- Degradation of optical components
- Degradation of solar cells

Sources

- Solar Energetic Particles (SEP)
- Radiation Belts (trapped particles)

As the radiation belts and solar energetic particles are the sources, all orbits can be affected.



Displacement Damage Dose: disrupts the crystalline structure of materials used in microelectronic devices. These defects reduce the performance of transistors and are especially important for optoelectronic devices such as opto-couplers where current transfer ratios are reduced and for solar cells where efficiency is degraded.

Cumulative dose damage has rarely been a cause of satellite failure since it is relatively straightforward to analyse and large safety margins are used. This might not be so in the event of a solar superstorm.

OUTLINE

- Introduction
- Satellites
- Satellite orbits
- Impact of SPWX
  - Drag
  - Single event effects
  - Degradation
  - Charging

Space Environmental Impacts on Space Systems			
Anomaly Diagnosis	Koons et al, 2000	NGDC DB, 2006	Satellite Digest, 2014
ESD-Internal, surface, and indeterminate	54%	31%	10%
SEU (GCR, SPE, SAA, etc.)	28%	17%	5%
Radiation Dose	5%	---	---
Meteoroids and Orbital Debris	3%	---	5%
Atomic Oxygen	< 1%	---	---
Atmospheric Drag	< 1%	---	---
Design	---	---	25%
Other or Unknown	8%	52%	55%

Table from NASA/CCMC. Absolute numbers unknown.

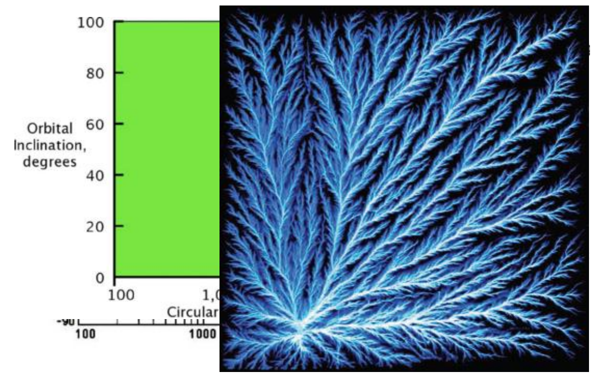
ESD = ElectroStatic Discharge

CHARGING

Charging

- Surface
- Internal

→ Discharging



Sources

- Radiation belts

SWIC 2017 – STCE, Koninklijke Luchtmacht & KNMI 58

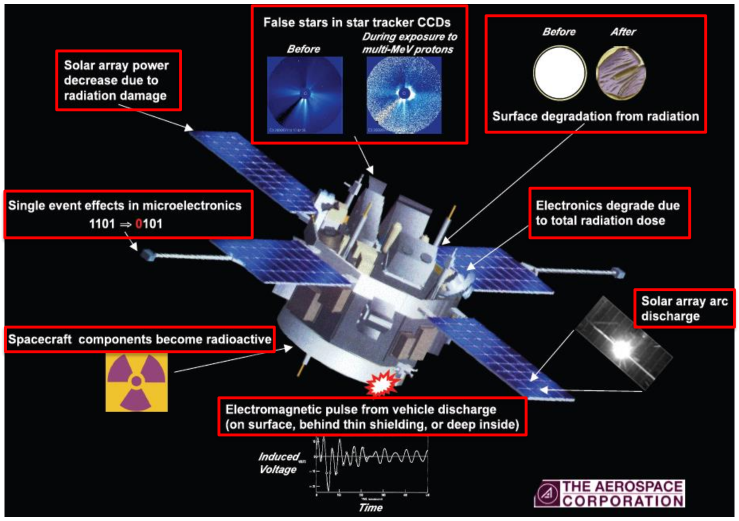
- Surface charging: high energy (>100keV) electrons from outer radiation belt (GEO). Also, but to a lesser extent: low energy (<100keV) electrons inner magnetosphere during magnetospheric substorms (LEO). Surface charging can lead to Electrostatic Discharge (ESD).
- Deep dielectric (internal) charging is caused by high energy electrons. Effects: biasing instrument readings, electrical discharging and physical damage. Buildup: ~2 days (UK report).

- Remember the interaction between de (fast) solar wind and the outer radiation belts, exposing GEO satellites to high concentrations of high energy electrons.
- http://www.swpc.noaa.gov/products/relativistic-electron-forecast-model

CASE 6+: TO NAME BUT A FEW

Date	Event	Satellite	Orbit	Cause (probable)	Effects seen
8 March 1985		Anik D2	GEO	ESD	Outage
October 1989	CME-driven storm	TDRS-1	GEO	SEE	Outage
July 1991		ERS-1	LEO	SEE	Instrument failure
20 January 1994	Fast solar wind stream	Anik E1	GEO	ESD – note: all three satellites were of same basic design	Temporary outage (hours)
		Anik E2	GEO		6 months outage, partial loss
		Intelsat K	GEO		Temporary outage (hours)
11 January 1997	Fast solar wind stream	Telstar 401	GEO	ESD	Total loss
19 May 1998	Fast solar wind stream	Galaxy 4	GEO	ESD	Total loss
15 July 2000	CME-driven storm	Astro-D (ASCA)	LEO	Atmospheric drag	Total loss
6 Nov 2001	CME-driven storm	MAP	Interplanetary L2	SEE	Temporary outage
24 October 2003		ADEOS/MIDORI 2	LEO	ESD (solar array)	Total loss
26 October 2003	CME-driven storm	SMART-1	HEO	SEE	Engine switch-offs and star tracker noise
28 October 2003		DRTS/Kodama	GEO	ESD	Outage (2 weeks)
14 January 2005		Intelsat 804	GEO	ESD	Total loss
15 October 2006	Fast solar wind stream	Sicral 1	GEO	ESD	Outage (weeks)
5 April 2010	Fast solar wind stream	Galaxy 15	GEO	ESD	Outage (8 months)

SUMMARY



False stars in star tracker CCDs
Before
During exposure to multi-MeV protons
Before
After
Surface degradation from radiation
Solar array power decrease due to radiation damage
Single event effects in microelectronics
1101 ⇒ 0101
Electronics degrade due to total radiation dose
Solar array arc discharge
Spacecraft components become radioactive
Electromagnetic pulse from vehicle discharge (on surface, behind thin shielding, or deep inside)
Induced Voltage
Time
THE AEROSPACE CORPORATION