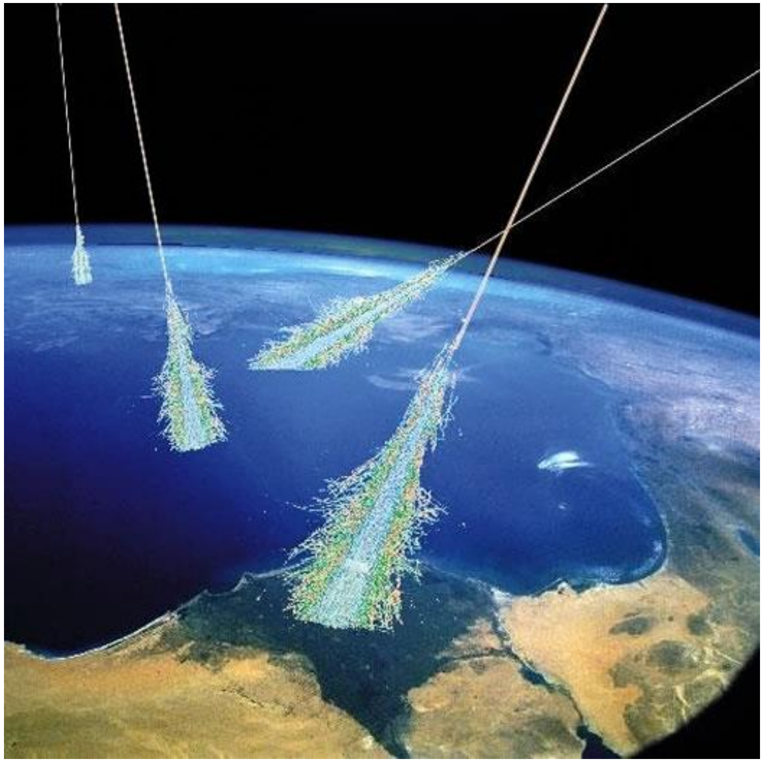
SPACE WEATHER
AND THE IMPACT ON AIR TRAFFIC



Cosmic Particle Shower on the Earth
http://www.wissensnetz.org/seiten/themenseiten/kosmische_strahlung/

Roland Winkler

Outline

- Definitions
- Basics about Space Weather – Scientific Fundamentals
- Influence of Space Weather on Air Traffic

Definiton

What is meant by the term space weather?

The term space weather refers to the change in physical conditions in near-Earth space.

The current state of space weather is always an interplay between the processes on the Sun, in interplanetary space, as well as in the Earth's magnetosphere and the Earth's atmosphere.

Definiton

What is meant by cosmic radiation?

Is an umbrella term for the ionized radiation that exists in the atmosphere and has its origin outside the solar system.

The solar wind is not actually counted for cosmic radiation - but for historical reasons we will discuss it under the umbrella of the cosmic radiation.

Cosmic radiation consists of primary and secondary particles.

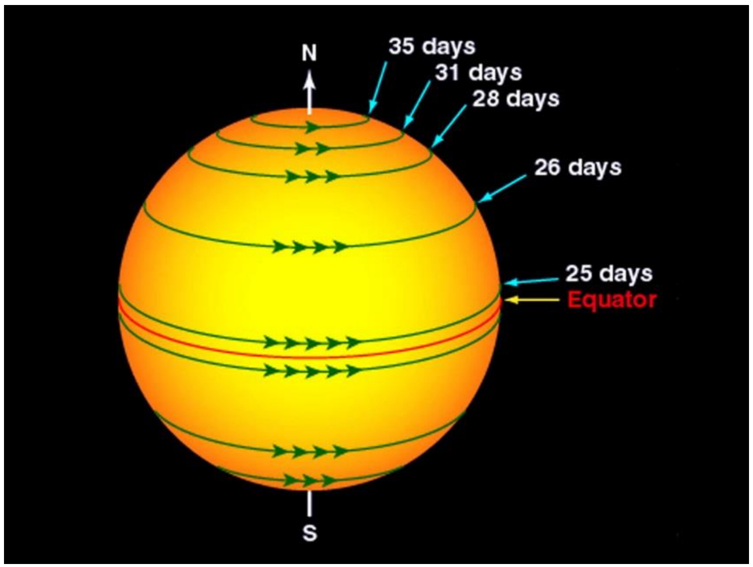
Definiton

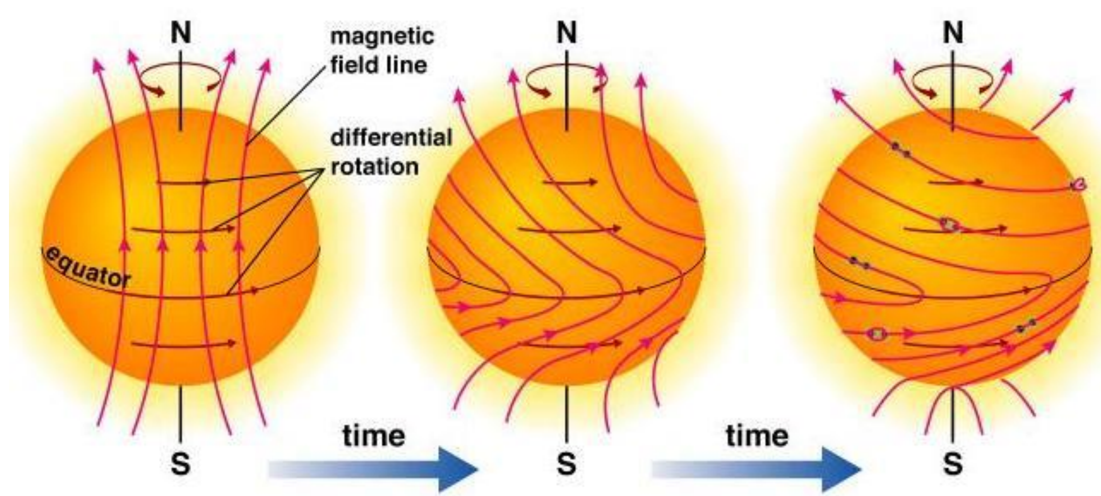
Composition of cosmic radiation in the vicinity of our solar system:

- 86 % positively charged hydrogen protons
- 11 % Helium (alpha particles)
- 2 % electrons (beta particles)
- 1 % heavy metal ions and antimatter (positrons)

Basics about Space Weather Scientific Fundamentals

The Sun





Credit: Holly Zell, NASA; https://www.nasa.gov/mission_pages/sunearth/science/solar-rotation.html

Credit: Courtney Seligman – Online Astronomy eText: The Sun; https://cseligman.com/text/sun/sunrotation.htm; from Bennett et al., The Essential Cosmic Perspective

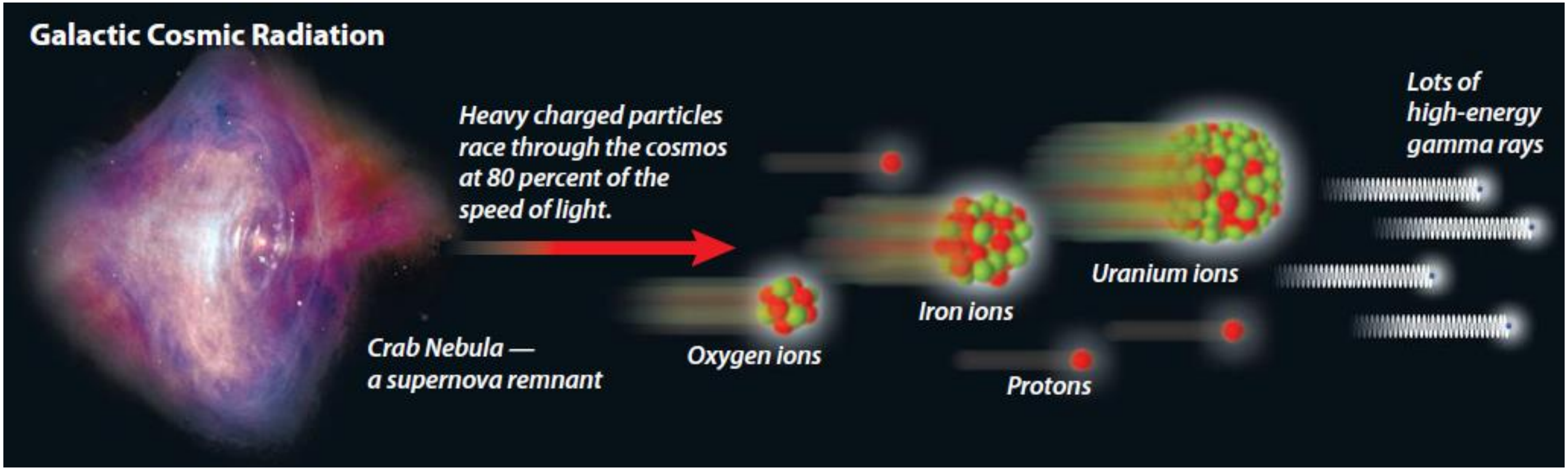
Basics about Space Weather
Scientific Fundamentals

Space Weather components:

- Galactic Cosmic Rays
- Coronal Mass Ejections
- Solar Flares
- Solar Energetic Particles or Solar Cosmic Rays
- Solar Wind

Basics about Space Weather
Scientific Fundamentals

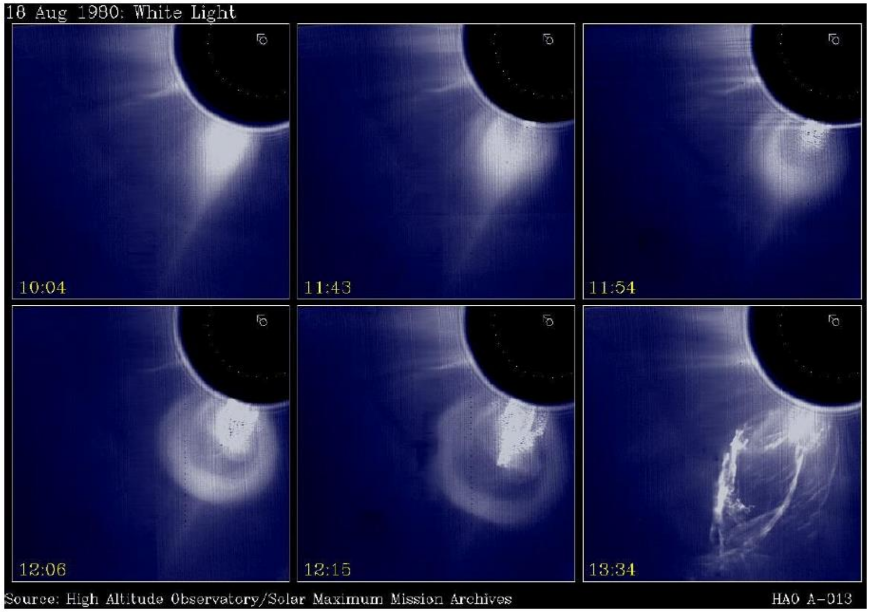
Galactic Cosmic Rays



Credit: Yihua Zeng and Rebekah M. Evans; Source: NASA SOHO solar observatory, NASA Hubble and Chandra images; Graphic by John Bretschneider

Basics about Space Weather
Scientific Fundamentals

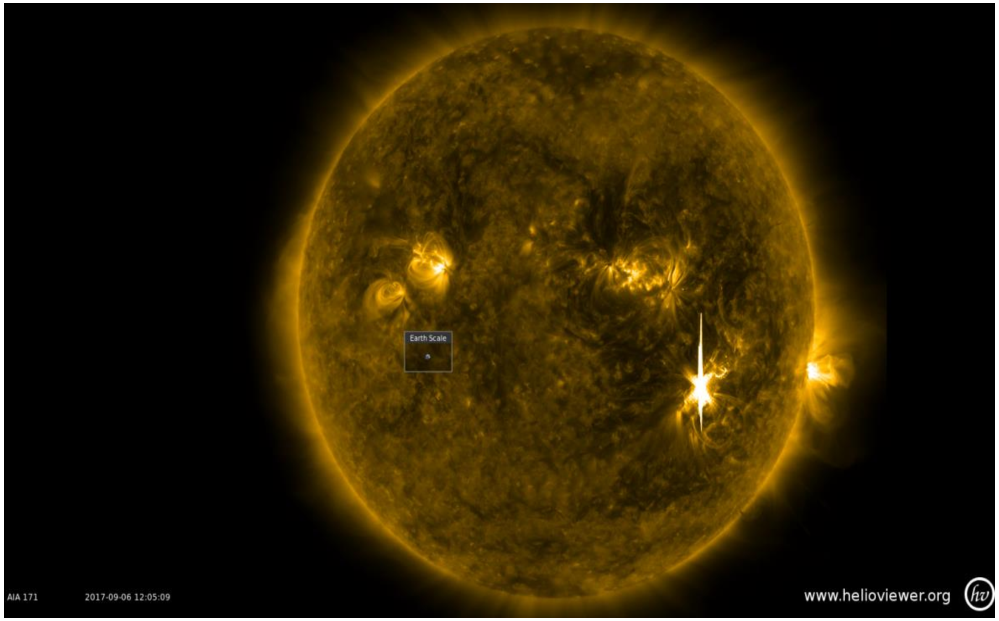
Coronal Mass Ejections



Credit: Mathias Scholz – Kleines Lehrbuch der Astronomie – Die Sonne als Stern

Basics about Space Weather Scientific Fundamentals

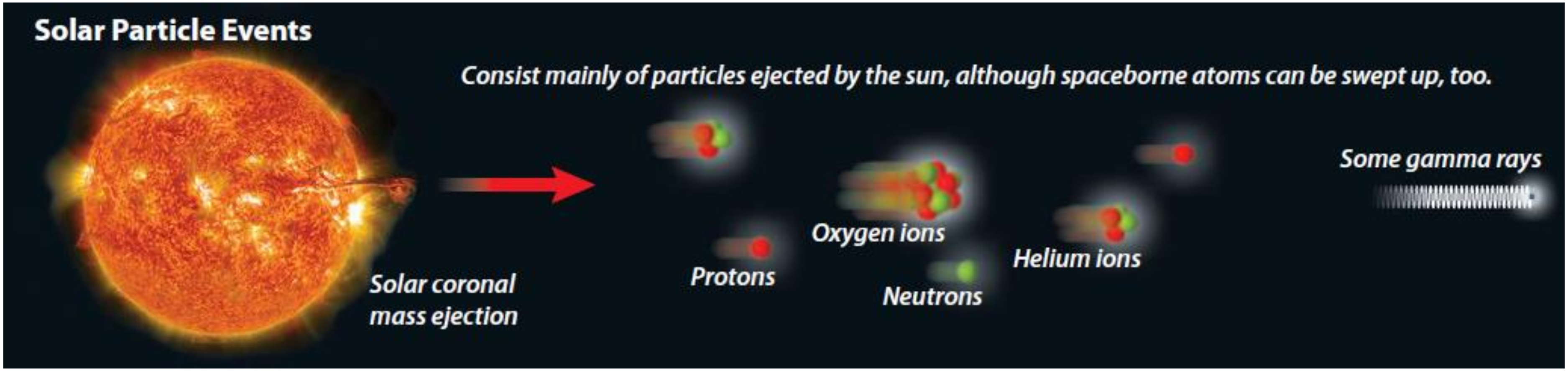
Solar Flares



Credit: CBC News – aus www.helioviewer.org – Picture: NASA

Basics about Space Weather Scientific Fundamentals

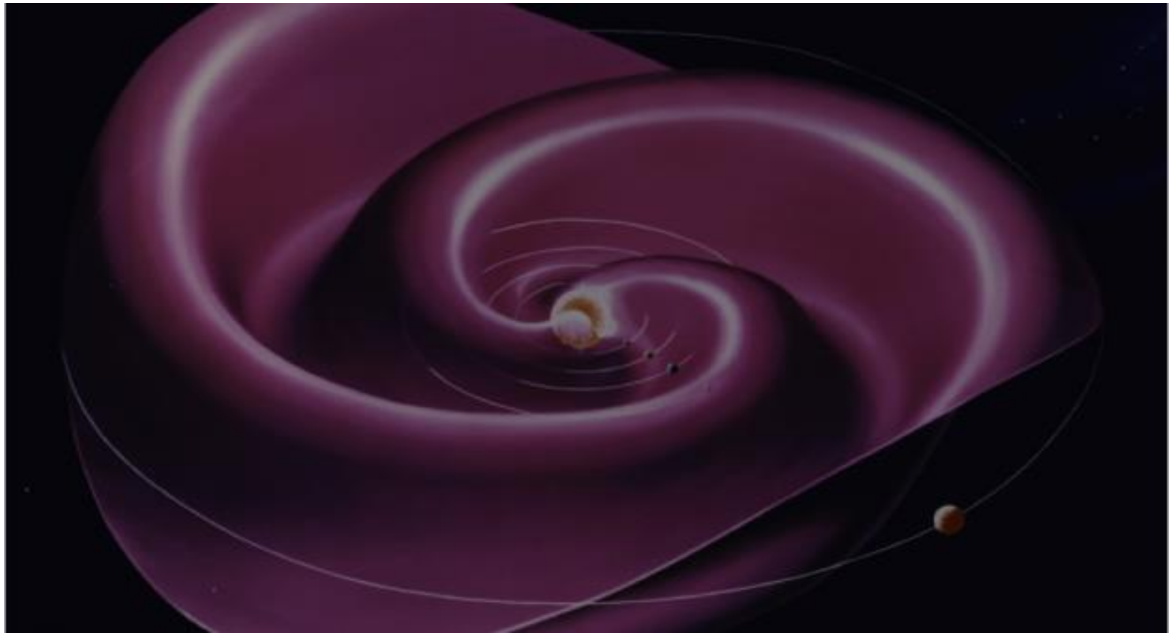
Solar Energetic Particles or Solar Cosmic Rays



Credit: Yihua Zeng and Rebekah M. Evans; Source: NASA SOHO solar observatory, NASA Hubble and Chandra images; Graphic by John Bretschneider

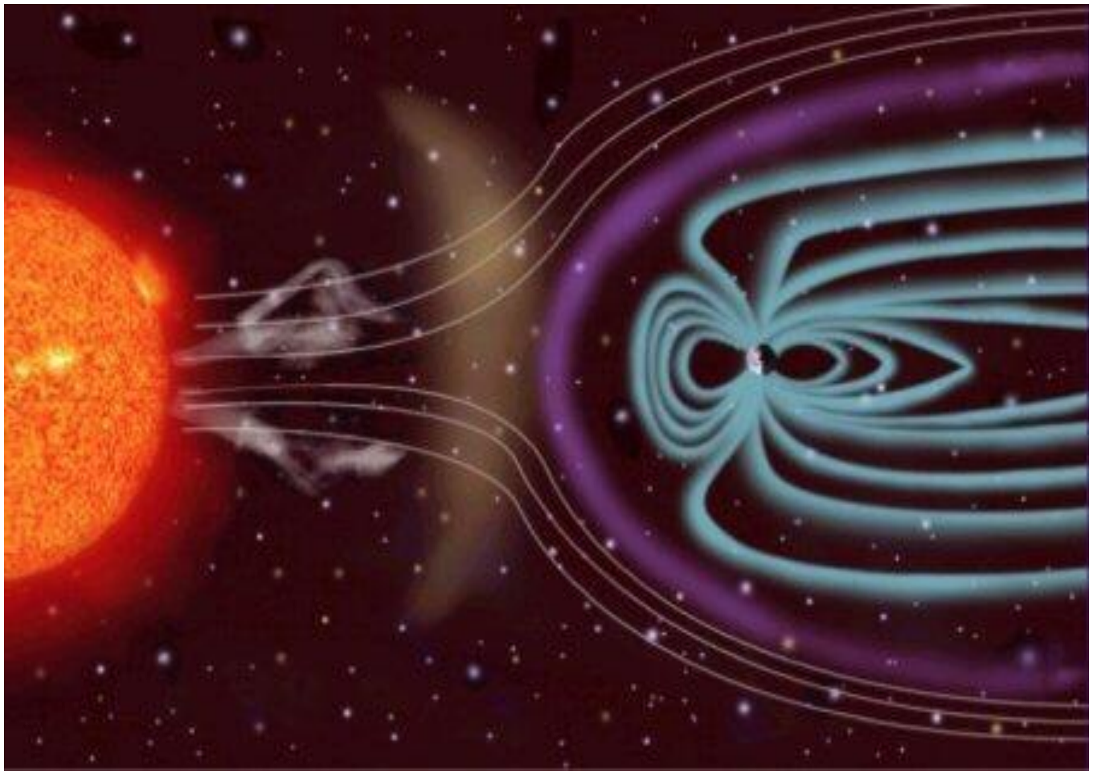
Basics about Space Weather
Scientific Fundamentals

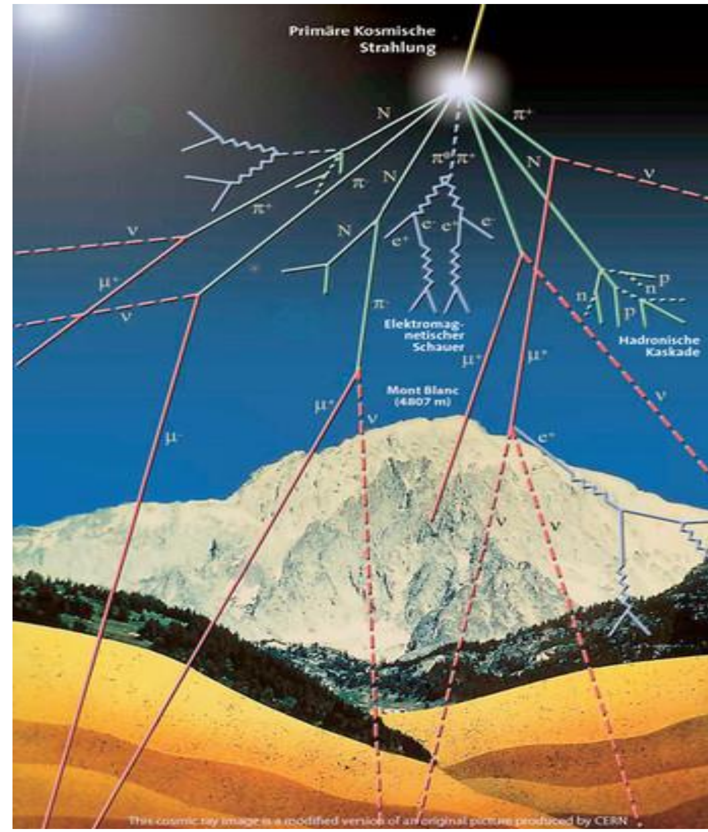
Solar Wind



Credit: NOAA – Space Weather Prediction Center; Picture: NASA

Basics about Space Weather
Scientific Fundamentals





Credit: Kryakunova – Kosmische Strahlung: Hochenergetische Teilchen aus dem Universum – Neutron Monitor Database – Bild: ESA

Credit: HEPY – Institut für Hochenergiephysik

Basics about Space Weather
Scientific Fundamentals

Space Weather Storms - Subdivision into three categories after NOAA:

- Geomagnetic Storms
- Solar Radio Storms
- Radio Blackouts

Basics about Space Weather Scientific Fundamentals

Geomagnetic Storm

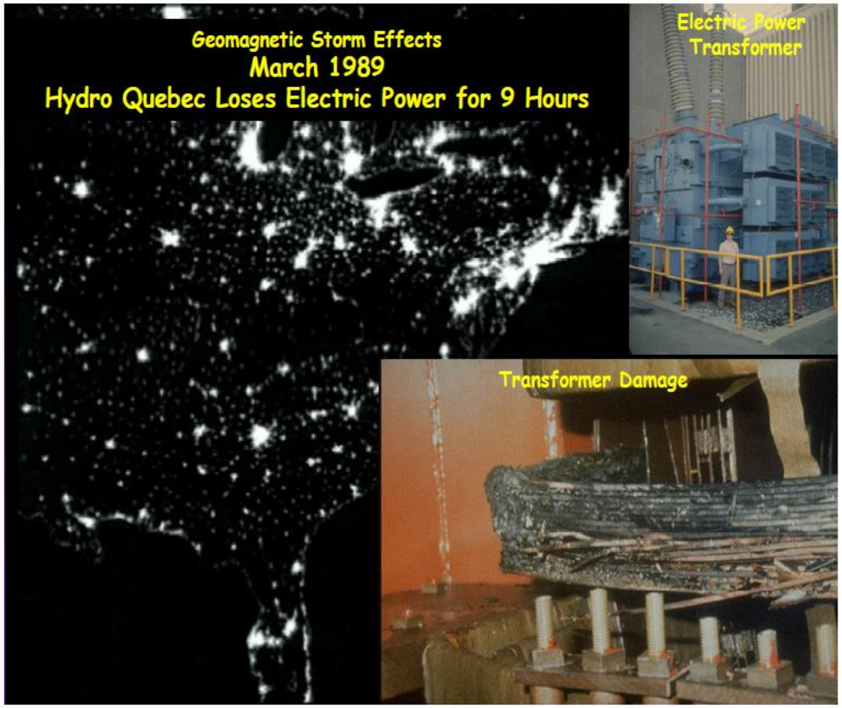
Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Credit: NOAA – Space Weather Prediction Center

Basics about Space Weather
Scientific Fundamentals

Geomagnetic Storm

- March 13-14 1989 Quebec, Canada
- third strongest geomagnetic storm
- within one minute – current induction in power transmission lines – cascade effect
- failure of the backup systems
- estimated damage - 6 billion US dollars
- failure US satellite navigation system



Credit: Committee on the Peaceful Uses of Outer Space – Scientific and Technical Subcommittee, 2014

Basics about Space Weather
Scientific Fundamentals

Solar Radiation Storms

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

Credit: NOAA – Space Weather Prediction Center

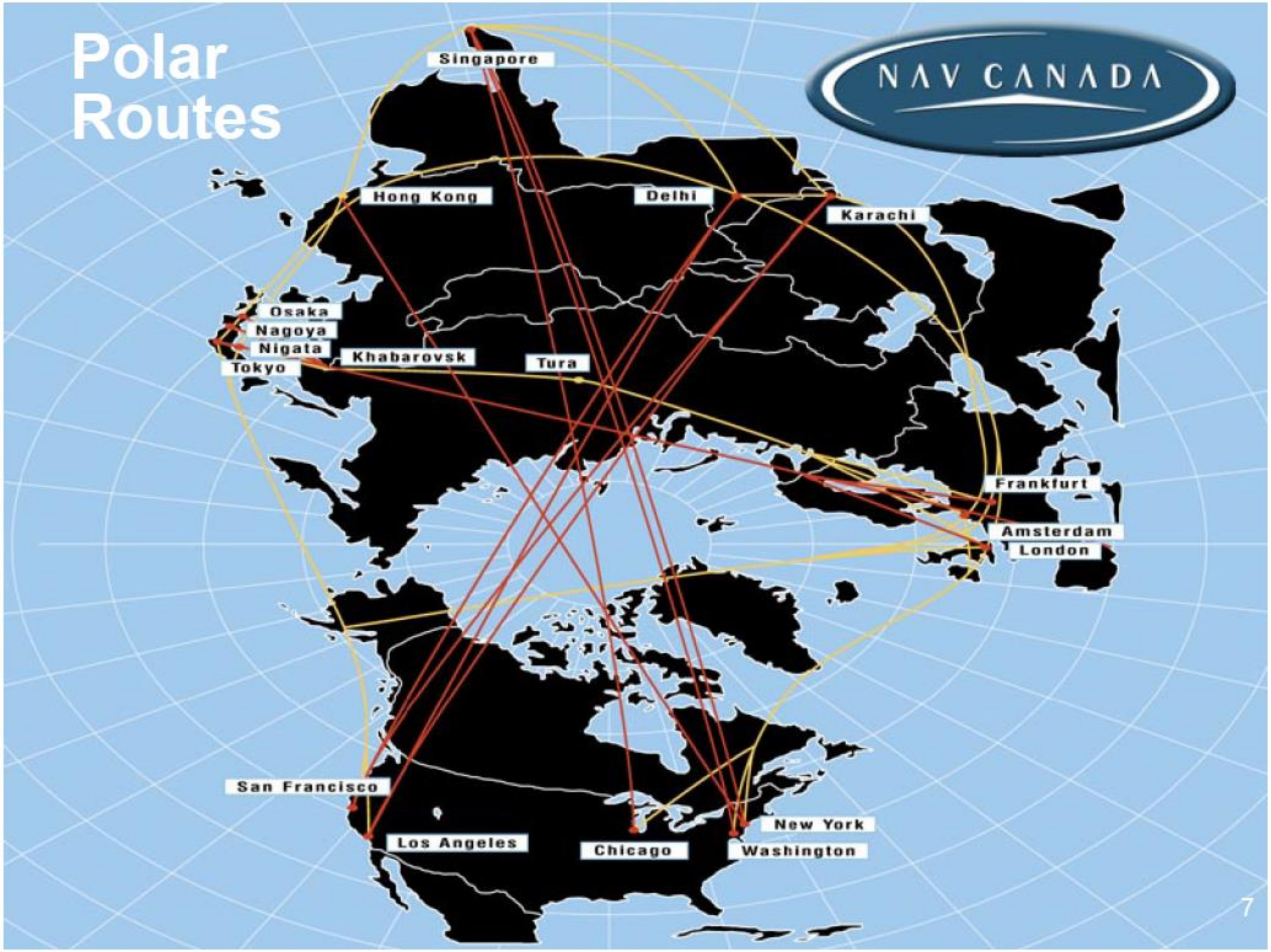
Basics about Space Weather
Scientific Fundamentals

Radio Blackouts

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

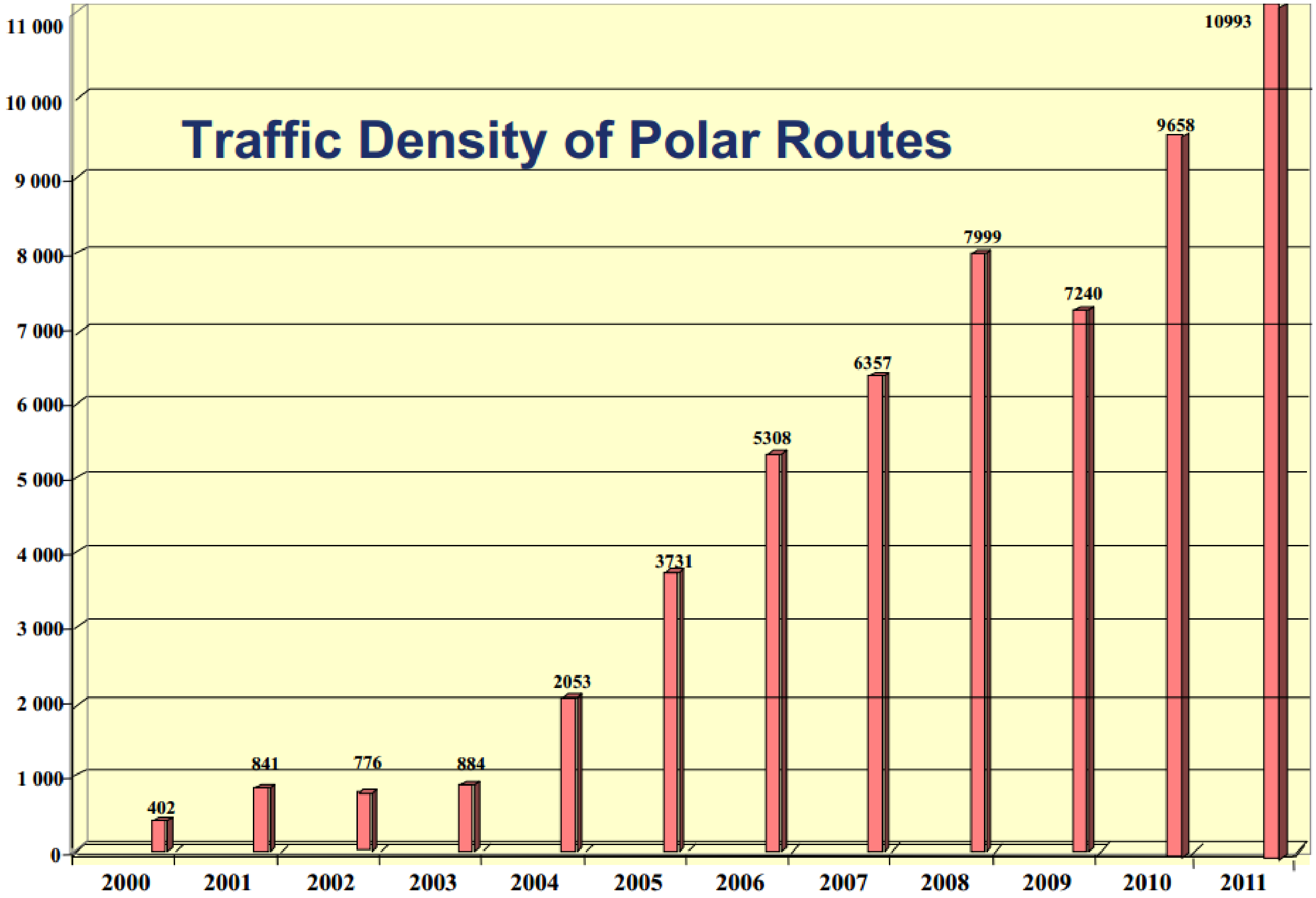
Credit: NOAA – Space Weather Prediction Center

Impact on Air Traffic



Credit: Bryn Jones - SolarMetrics

Impact on Air Traffic



Credit: Albersheim Steve (FAA), Gunzelman Mark (AvMet Applications Inc.)

Impact on Air Traffic

- Affects air traffic in especially higher latitudes (> 50 degrees) and in the polar regions (>78 degrees)

- 2011 11 000 flights over the polar regions

- Reasons:
  - shorter flight times
  - less headwinds
- Fuel savings $ 35 000 – $ 40 000 per flight

- Re-routing due to a solar storm – additional costs easily $ 100 000 or higher

Impact on Air Traffic

- disruption of electronic devices in aircrafts
- protection for the flight crew and frequent flyers by ionizing radiation
- disruption of communication
- disruption of navigation

Impact on Air Traffic
Disruption of Electronic Devices

Credit: European-Aviation.Net – Austrian Airlines;
Photo: AUA

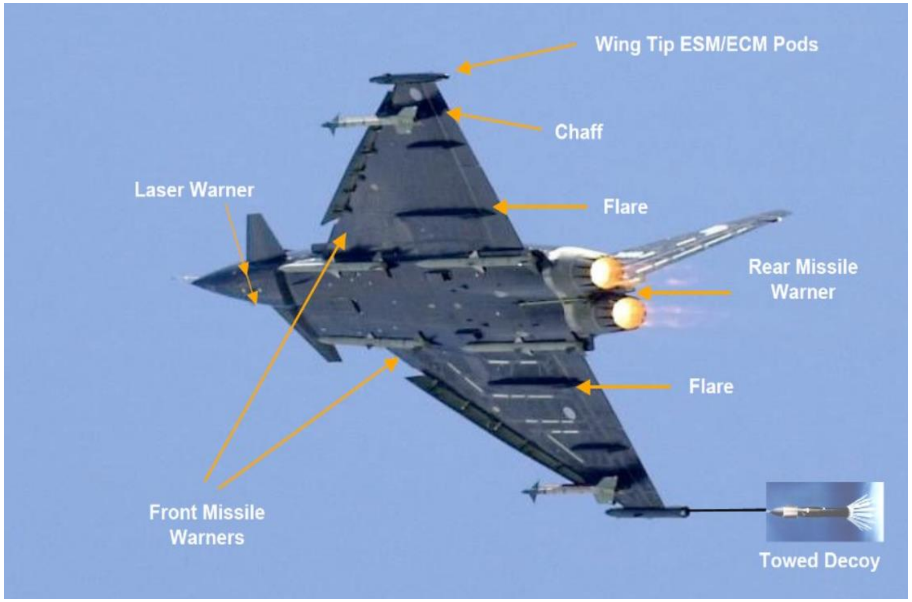
Credit: Aviation Week Network – Graham Warwik;
Photo: Gulfstream Aerospace

- height of operation between 30 000 and 45 000 ft
- flight control – fly by wire
- electronic on board (flight control, navigation, engine control, landing aids, communication, …)

- estimate: 20% of the purchase price costs the electronics

Impact on Air Traffic
Disruption of Electronic Devices

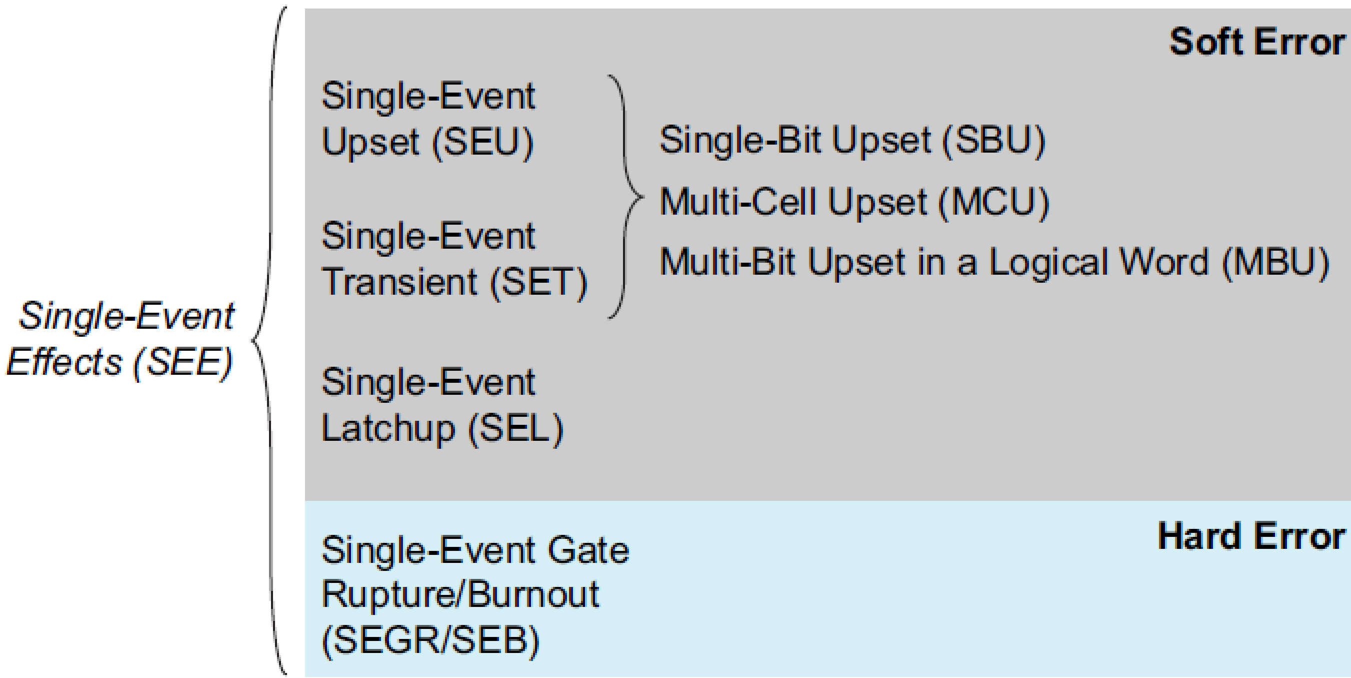
Credit: Austrian Federal Bureau of Defence;
Photo: Markus Zinner



Credit: mil news, july 8 2017; author: Markus;
Photo: EADS

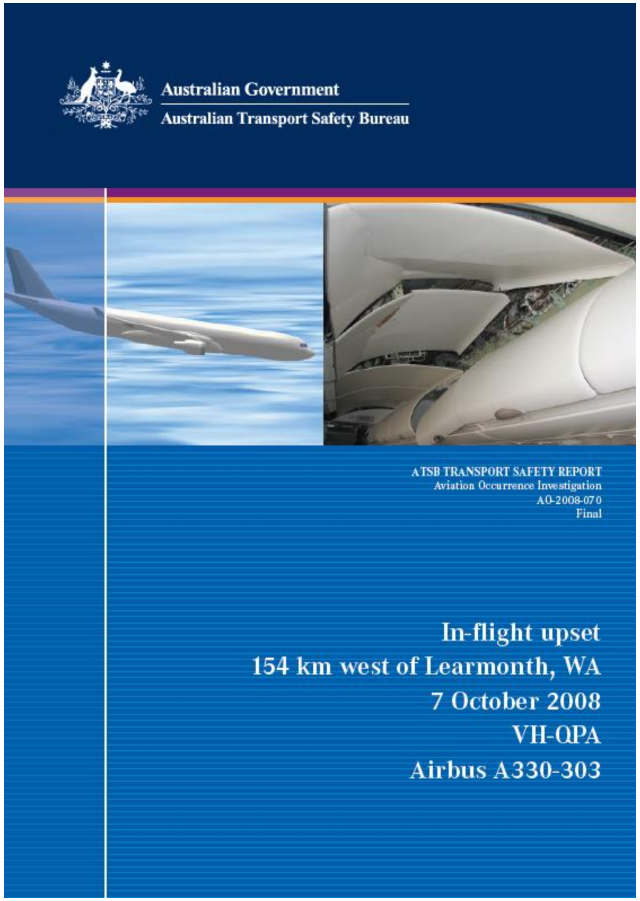
- height of operation between 30 000 and 60 000 ft
- flight control – fly by wire
- electronic on board (flight control, navigation, engine control, landing aids, communication, weapon systems, electronic defence systems, …)

Impact on Air Traffic
Disruption of Electronic Devices



Credit: Altera Corporation – Introduction to Single Event Upsets

Impact on Air Traffic
Disruption of Electronic Devices



Credit: Australian Transport Safety Bureau – Australian Government

Impact on Air Traffic Protection for Human Being

Beginning of an article by NASA:

The next time you step onto an airplane, consider the following: In any given year, the pilot of your aircraft probably absorbs as much radiation as a worker in a nuclear power plant.

Credit: Tony Phillips – NASA Science Beta
https://www.nasa.gov/content/goddard/effects-of-space-weather-on-aviation/

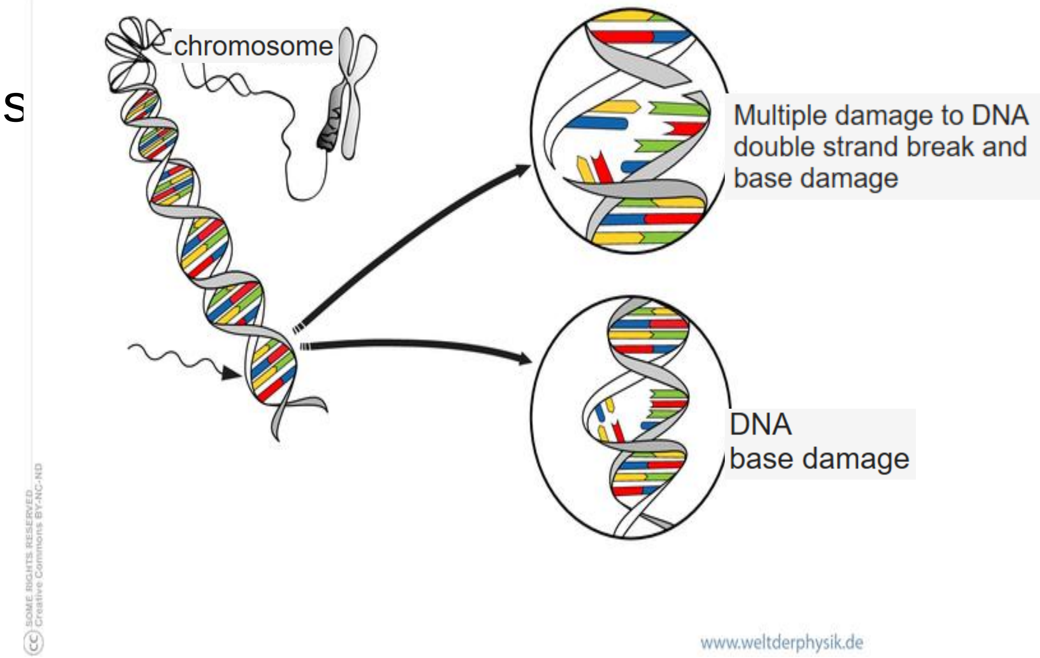
Impact on Air Traffic
Protection for Human Being

Different kind of damages:

damage to the enzymes, proteins
RNA-molecules, …

Damage within the DNA:

- single-strand break
- double-strand break
- base damage
- faultiy network
- chromosome damage



Credit: www.weltderphysik.de – Einfluss der kosmischen Strahlung auf den Menschen

Impact on Air Traffic
Protection for Human Being

1 Gray

3000 base damages

1000 single-strand breaks

40 double-strand breaks

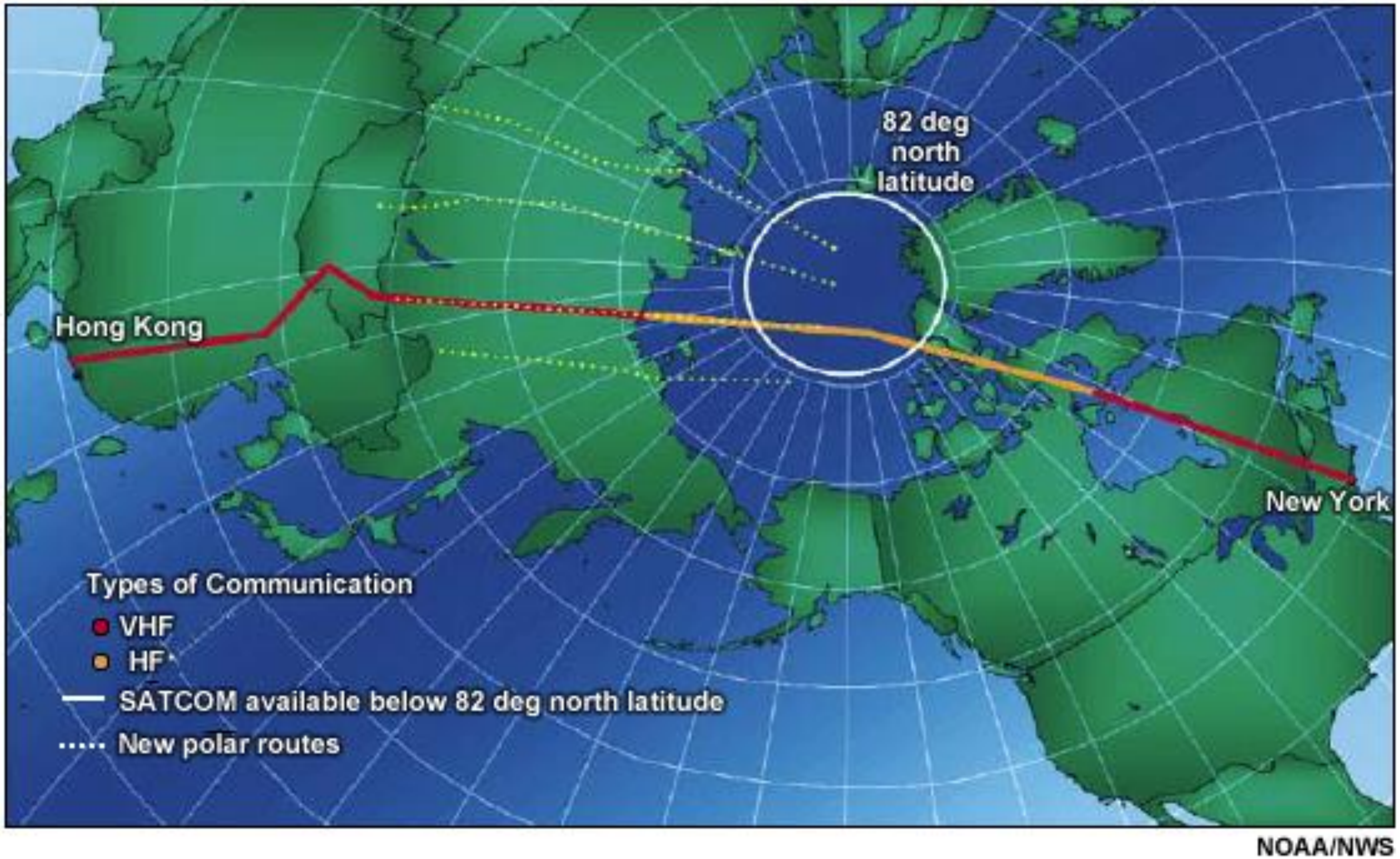
approximately 5000 damages per cell and per gray

full, proper repair → reproductive integrity (~80 %)

incomplete or incorrect repair → cell death

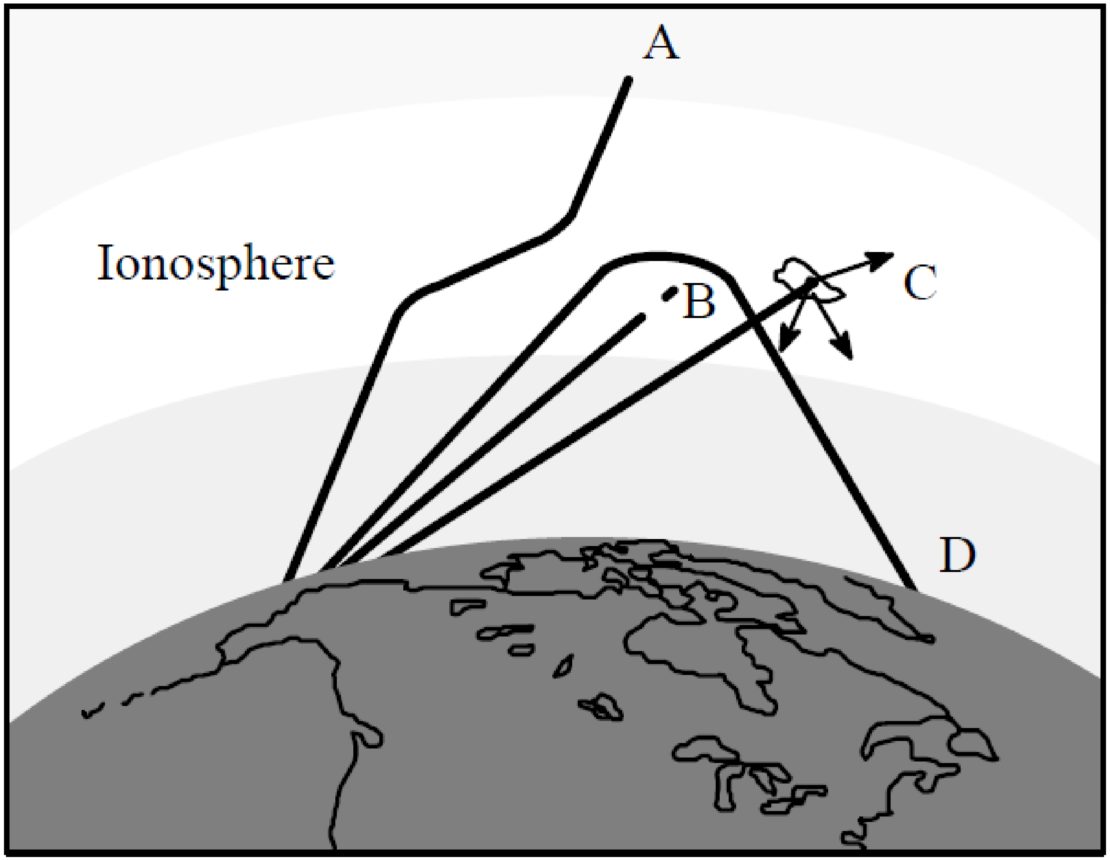
Credit: Wolfgang Dörr – OncoRay – National Center for Radiation Research in Oncology

Impact on Air Traffic
Disruption of Communication



Credit: UCAR – COMET, MetEd; Original: NOAA

Impact on Air Traffic
Disruption of Communication

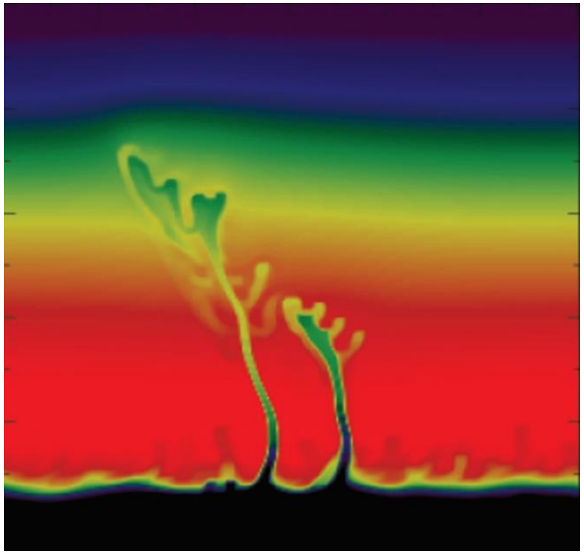


Credit: NOAA – Space Weather Prediction Center (Space Environment Center)

Impact on Air Traffic
Disruption of Communication

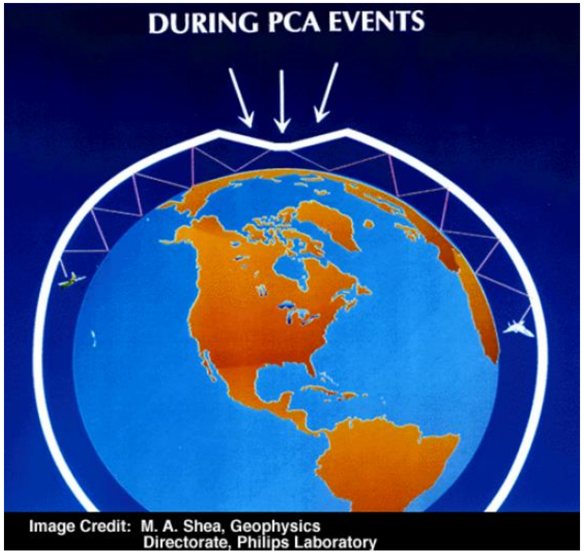
Fluctuations of the ionosphere due to increased solar activity:

Sudden Ionospheric Disturbance (SID)



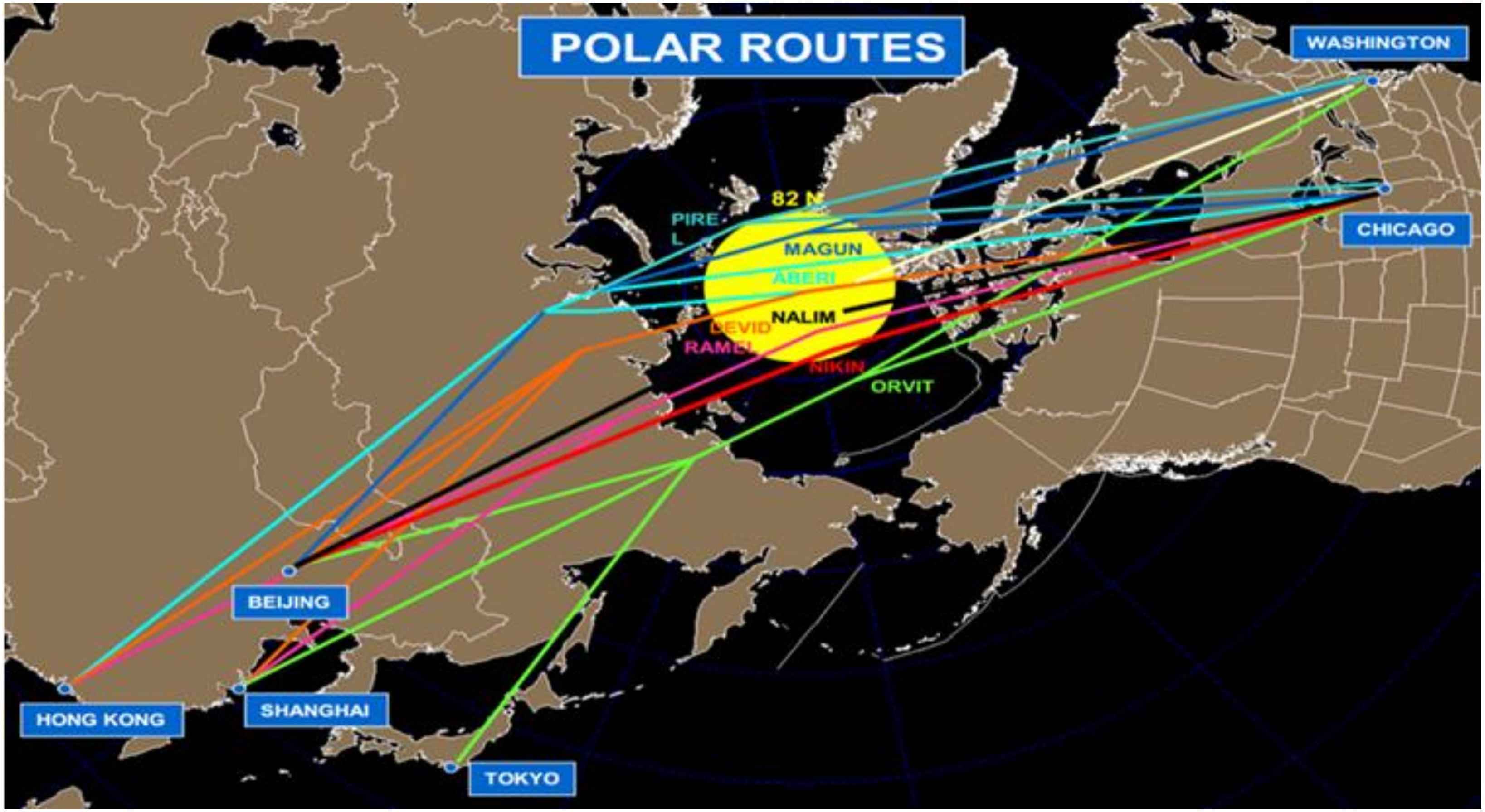
Credit: PHYS.ORG – Brett Carter, The Conversation, December 4, 2014 – Science X Network; Picture: John Retterer – Boston College

Polar Cap Absorption (PCA)



Credit: Committee on the Peaceful Uses of Outer Space – Scientific and Technical Subcommittee

Impact on Air Traffic
Disruption of Communication



Credit: Albersheim Steve (FAA) von Stills Michael – Polar Operations and Space Weather

Impact on Air Traffic
Disruption of Communication

January 2005 – Adverse Weather due to Space Weather:

26 flights of United Airlines using polar routes have to be re-routed:

Flight	Additional Flight Time
Chicago – Hong Kong (additional stop in Anchorage on four consecutive days)	180 – 210 minutes
Chicago – Beijing	18 – 55 minutes
Beijing – Chicago	55 – 80 minutes

Credit: Bill Murtagh – NOAA Space Weather Prediction Center, Boulder, Colorado,
NASA – Workshop Report on Space Weather Risk and Society, NASA/CP-2012-216003

Impact on Air Traffic
Disruption of Navigation

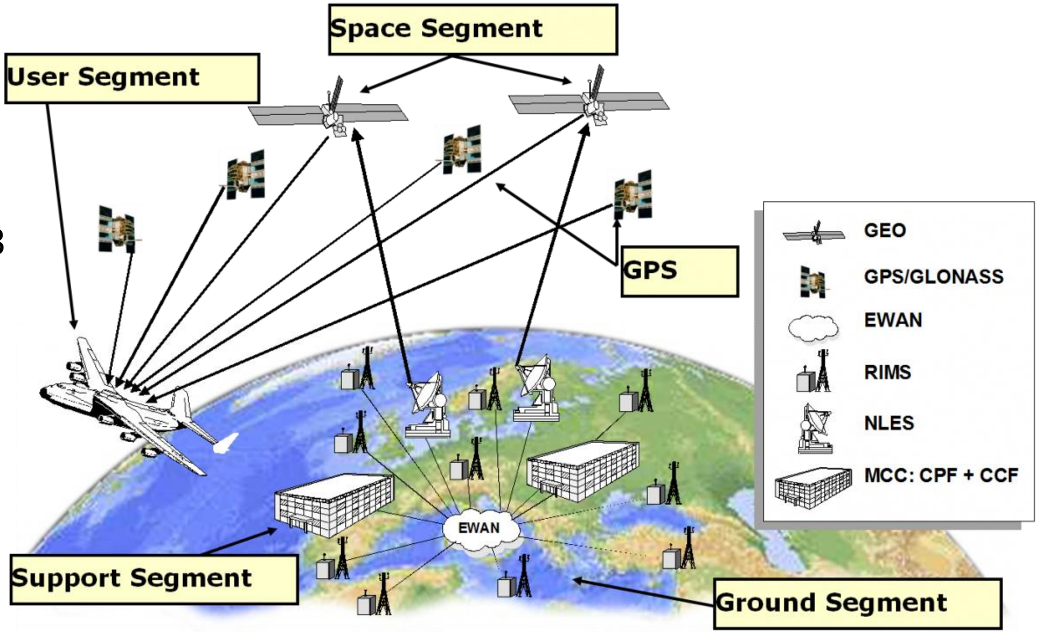
NDB

Credit: Groundspeak – http://www.waymarking.com/waymarks/WMWVE3_NDB_Steinhof_Wien_Schwechat_Wien_Austria

VOR

Credit: Wikimedia Commons – https://commons.wikimedia.org/wiki/File:Funkfeuer-Heringsdorf.jpg

SBAS



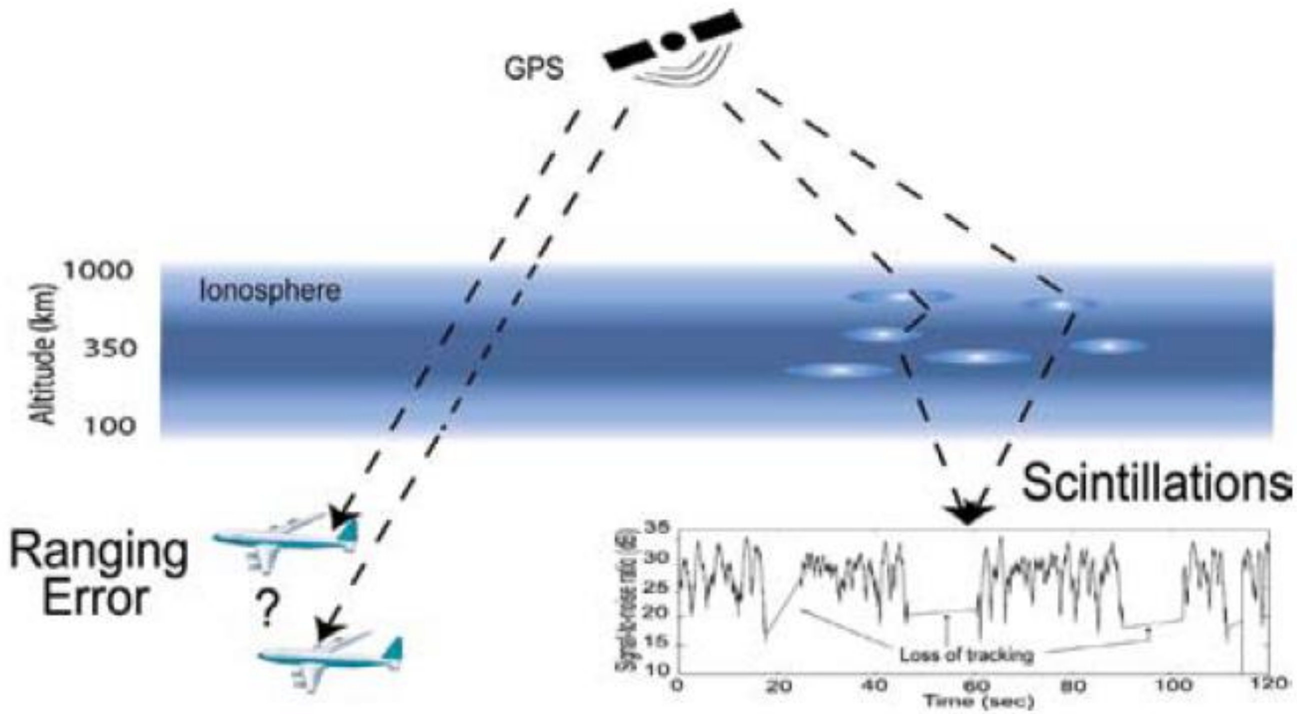
Credit: ESA - navipedia

Impact on Air Traffic
Disruption of Navigation

Effects from Space Weather on Satellite Navigation:

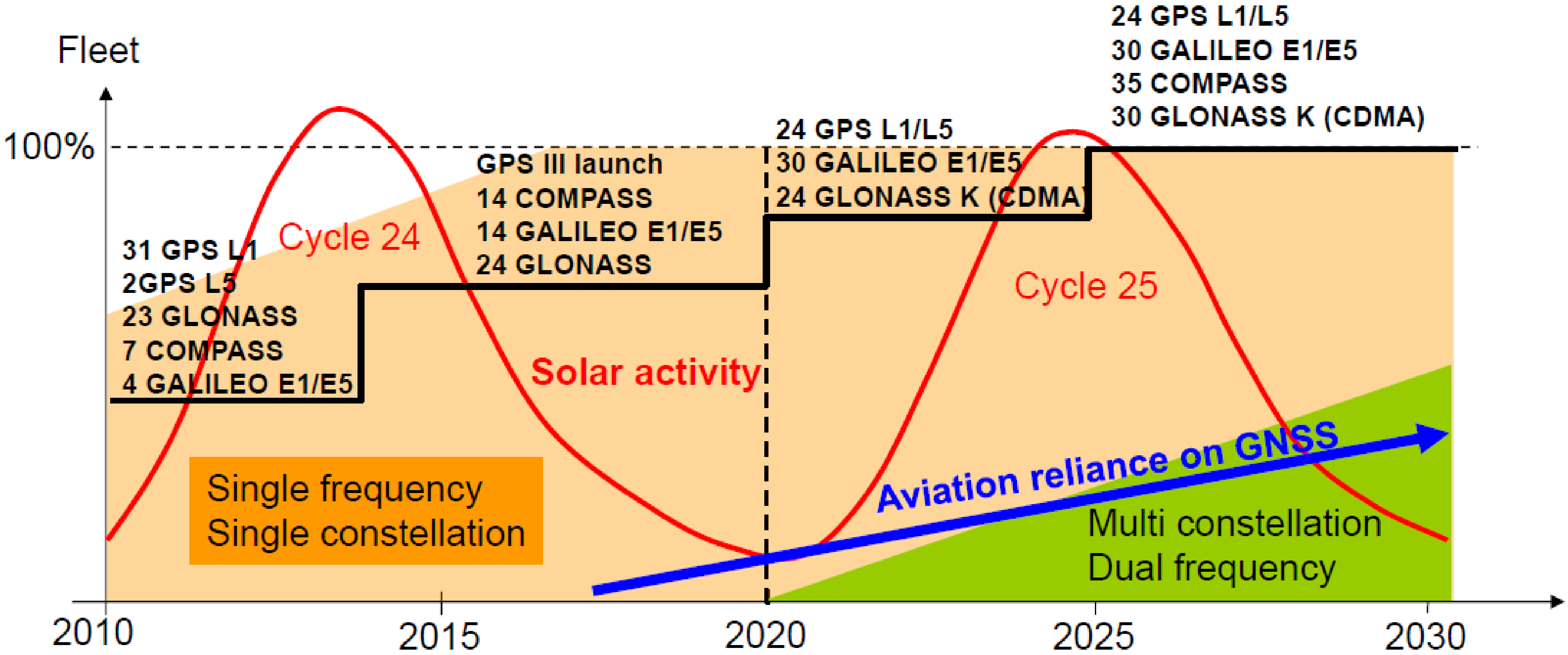
- loss of the continuous connection between the satellite and the receiver
- navigation signals can be superimposed with interference signals coming from the sun
- increase of the error in the determination of the position

Impact on Air Traffic
Disruption of Navigation



Credit: Committee on the Societal and Economic Impacts of Severe Space Weather Events: A Workshop, Space Studies Board, Division on engineering and Physical Sciences, National Research Council of the National Academies – Original: Paul M. Kintner, Jr., Cornell University

Impact on Air Traffic
Disruption of Navigation

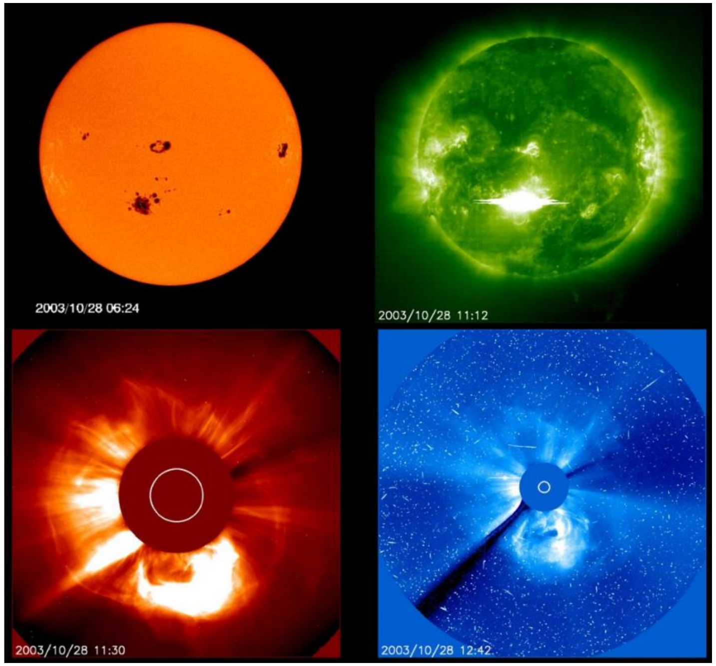


Credit: Robert Emilien – Eurocontrol

Impact on Air Traffic
Disruption of Navigation

October 28 – 30 2003 – Halloween Storm

- SEP and geomagnetic storm in the decreasing phase of the solar cycle
- failure of HF communication
- moderate to severe effects on satellites (disruption of the GPS)
- WAAS – was above the fault tolerance for 26 hours
- FAA – first warning for radiation exposure in flight



Credit: C. Alex Young, The Sun Today – Solar Facts & Space Weather; Image: NASA http://www.thesuntoday.org/historical-sun/x17-solar-flare-and-solar-storm-of-october-28-2003/

Impact on Air Traffic

Adverse Weather due to Space Weather:

- Cruise on deeper flight levels (solar storm 2012) – only for small number of airplanes – otherwise chaos
- Study of Canadian air traffic control from the year 2000 of pairs of cities which are benefiting from routes across the poles

city pair (flight route)	saved flight time (minutes)	saved costs (canadian dollar)
Atlanta – Seoul	124	44 000
Boston – Hong Kong	138	33 000
Los Angeles – Bangkok	142	33 000
New York – Singapore	209	44 000

Credit: American Meteorological Society & Solar Metrics Policy Workshop Report

Impact on Air Traffic

Future:

- Development of new ultra-long-haul aircraft

  Flight distance > 15 000 km, altitude 43 000 ft
- Longer non-stop connections

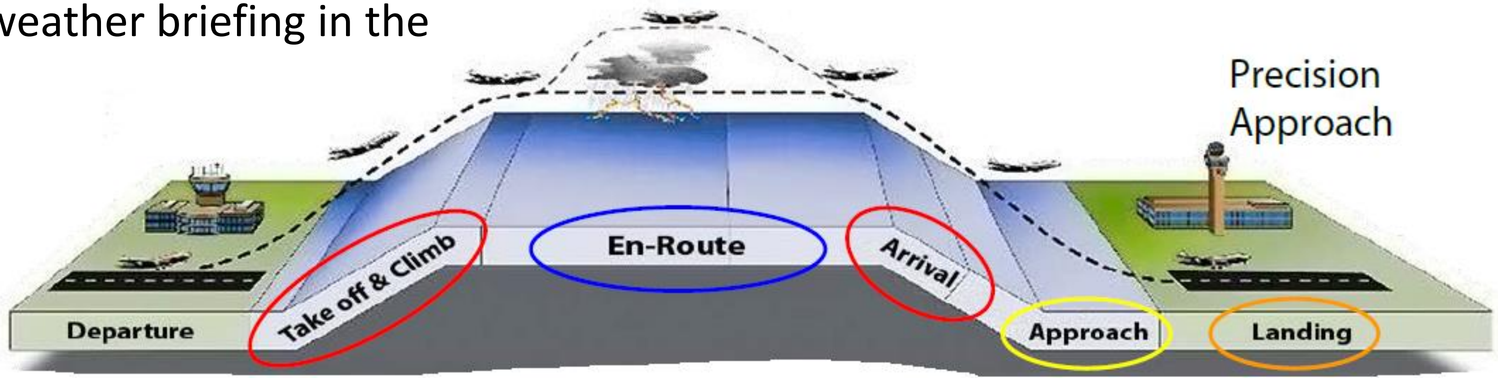
  Flight time > 15 hours for example Singapore – New York
- Increase in the dose for long-haul flights of 30 – 50%

  (Estimation by VC Cockpit, Germany)

Credit: Frasch Gerhard – Bundesamt für Strahlenschutz, Germany

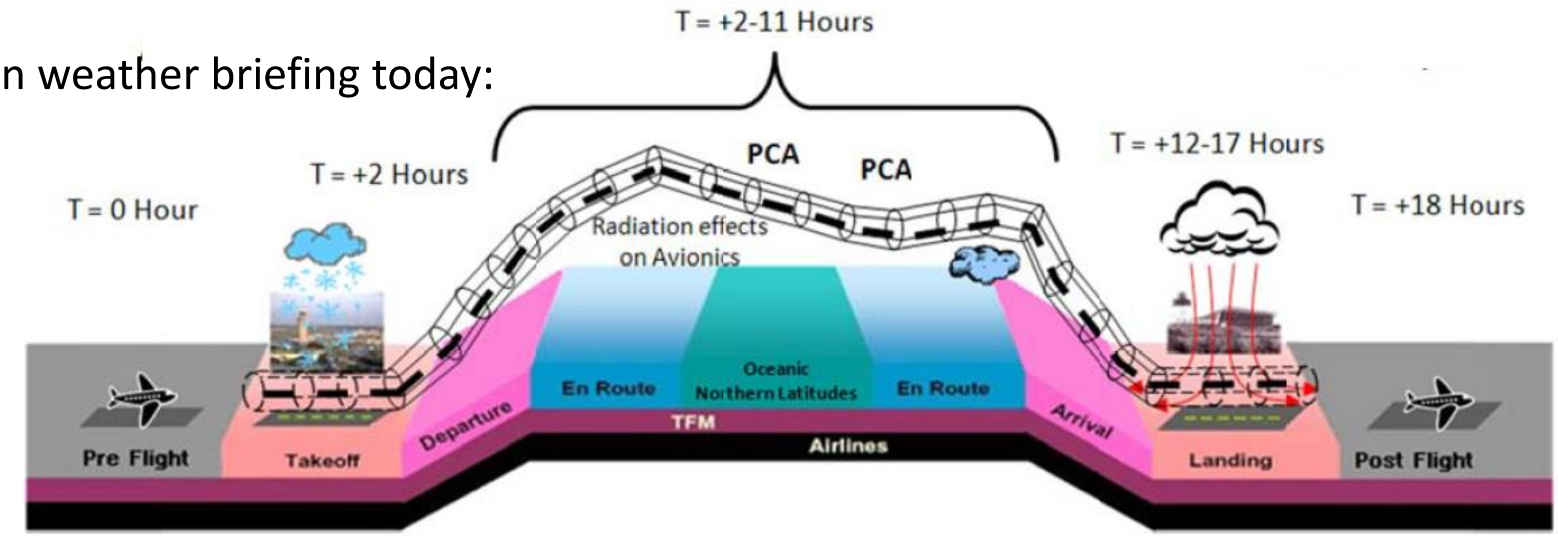
Impact on Air Traffic

Aviation weather briefing in the past:

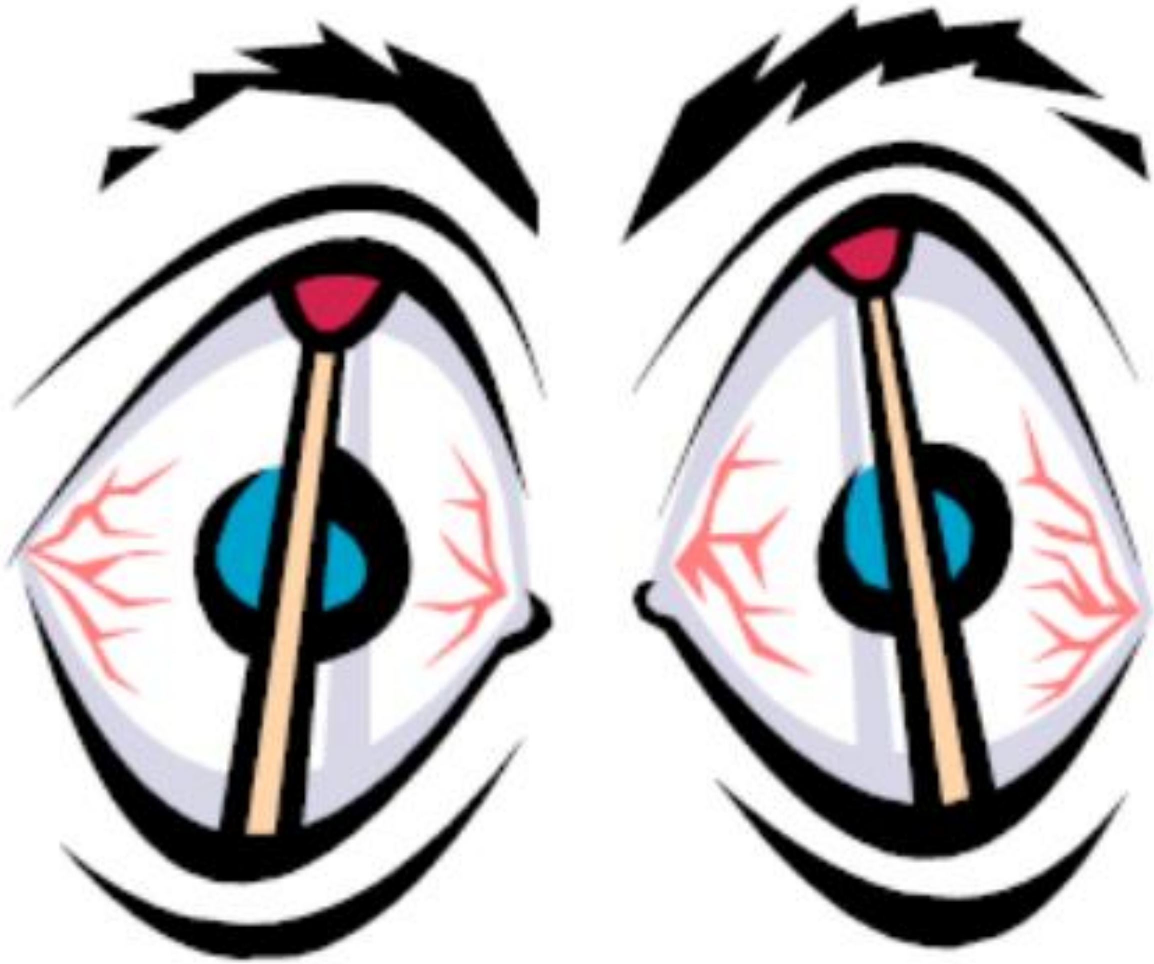


Credit: Lendina Smaja – Eurocontrol

Aviation weather briefing today:



Credit: ICAO / WMO



Credit: HUMOR.COM; https://www.humour.com/photos/je-deteste-le-lundi-matin.htm