SPACE WEATHER INTRODUCTORY COURSE

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

May 2017

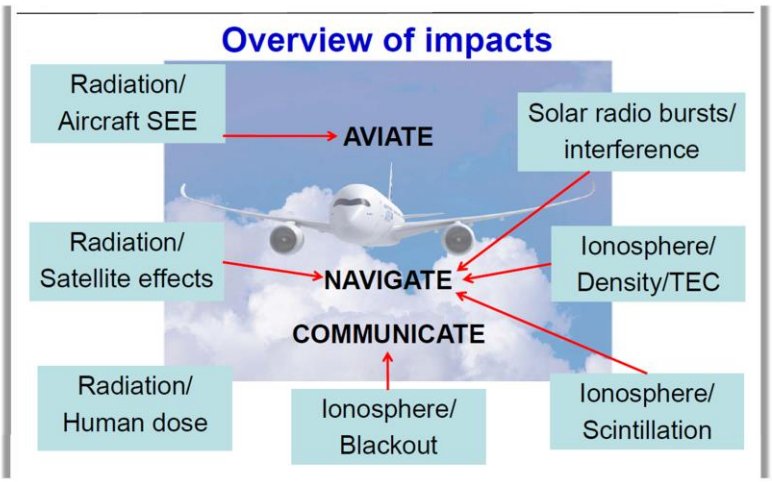
IMPACTS ON AVIATION

Description of space weather effects on aviation

Bert van den Oord

SWIC 2017 – collaboration between STCE, Koninklijke Luchtmacht, KNMI

AVIATION IMPACTS



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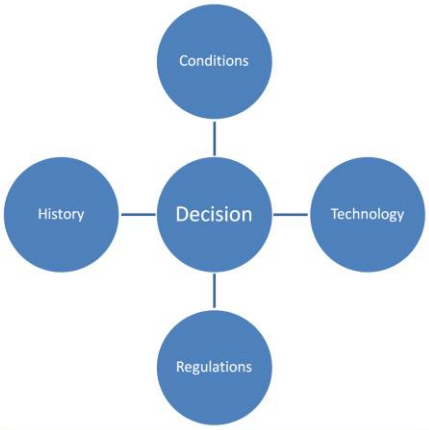
There are three impacts: AVIATE: radiation events/damage; COMMUNICATE: radio communication blackouts; NAVIGATE: GNNS
Human health risk.

AVIONIC OPERATIONS FROM SPACE WEATHER PERSPECTIVE



ICAO: Concept of Operations for Space Weather information in support of International Air Navigation

A decision for avionic operations depends on:

- Meteorological and space weather conditions in operations area.
- Technology used:
  - Frequencies and antennas
  - Radiation hardness electronic components
- History:
  - Accumulated radiation dose humans and airplane
- Regulations:
  - ICAO and military standards

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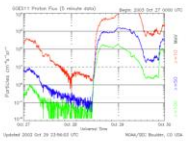
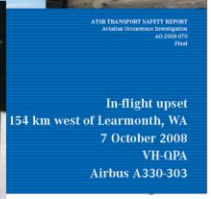
The conops document for space weather by ICAO is under development

IMPACTS ON AVIATION: PARTICLES

- Ionising radiation
  - Risk for passengers and crew
  - Effects on avionics: Single Event Effects
- Avionic upsets, failures

- Fewer radhard components
- More advanced electronics = more susceptibility
- Upset rate/hr in memory chip (avg 2.5/hr)
  - Sep 1989 – 84.7/hr
  - Feb 1956 – 493/hr
  - Sep 1859 – ? 5-10x 1956





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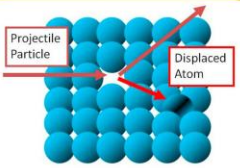
Note ICAO moves to using 100 MeV proton flux as baseline

PARTICLE RADIATION EFFECTS

- **Sources:**
  - Cosmic rays (0.1-20 GeV)
    - 85% protons, 14% α particles, 1% heavy ions
  - Solar particles (several tens MeV)
    - Protons and heavy ions
- **Effects:**
  - Lattice displacement chips by heavy ions
  - Ionization effects: transient glitches, also by low energy particles



Affected systems: i. fly-by-wire technology, ii. autopilot, iii. flight warning, iv. communication (voice and data), v. navigation ,vi. Displays vii. FADEC (Full Authority Digital Engine Control), viii. Any other aircraft system, containing electronic components

- Remedies:
  - Shielding
  - Substrate hardening
  - Clock (bias) voltage chip

Gray: absorbed energy J/kg
Sievert: biological equivalent of cumulative absorbed J/kg

Commercial chips withstand doses of 50-100 Gray. Military & space chips factors of tens more.

Note that also polymers, ceramics and metals can be affected.

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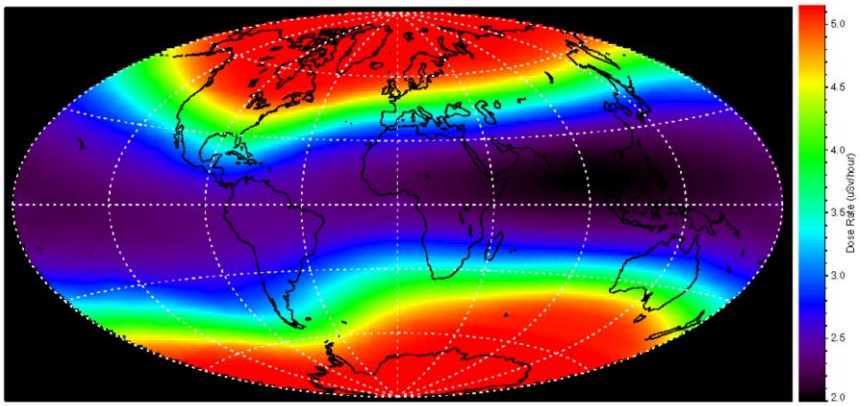
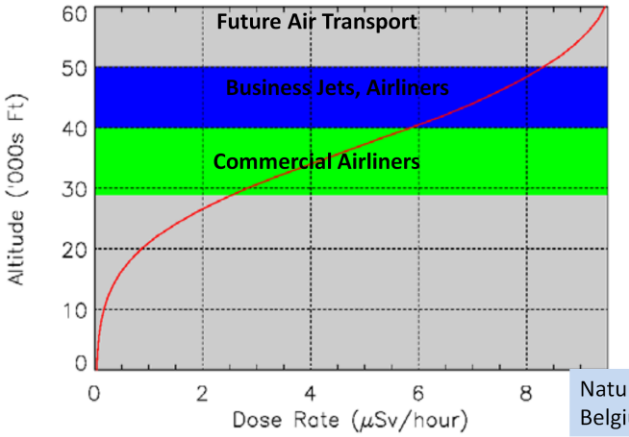
Affected i.fly-by-wire technology,ii. autopilot, iii. flight warning, iv. communication (voice and data), v. navigation ,vi. Displays vii. FADEC (Full Authority Digital Engine Control), viii. Any other aircraft system, containing electronic components

RADIATION LOAD



Projected global dose rate at 35,000 ft (Image courtesy SolarMetrics Limited).

DOSE RATE

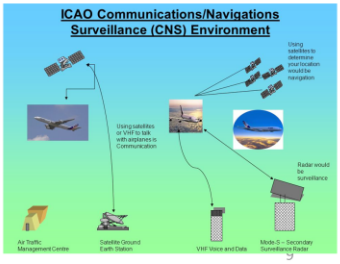


Natural background: 2,5 mS/yr
Belgium professionals: 20 mS/yr

Change in dose rate due to cosmic radiation (GCR component) as a function of altitude and aircraft operational type (Image courtesy SolarMetrics Limited).

IMPACTS ON AVIATION: COMMUNICATION

- Poleward flight lose contact with geosynchrous communication satellites (Earth curvature).
- Need to swith to HF communication that is also used by civil aviation.
- HF communications is susceptible to polar cap absorption (solar proton events) and auroral absorpton (geomagnetic storm activity and sudden ionospheric disturbances caused by strong X-ray flares. These effects are called radio blackouts and last minutes, hours to even days.
- Alternative is L-band communication using polar Iridium satellites but not all planes are equipped for this.
- At lower lattitudes sporadic interference of VHF communication due to effect of strong X-ray flares



COMPLEXITY OF HF COMMUNICATION

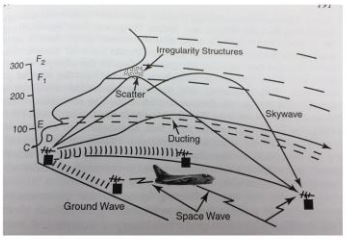


Table 4-5: List of HF Propagation Mechanisms

Mode or Mechanism	Description
Groundwave	Propagates along surface of the earth or ocean (i.e., surface wave)
Spacewave	Superposition of LOS, earth-reflected signals, and secondary ionospheric modes
Terrestrial Line-of-Sight	Subionospheric rectilinear propagation
Earth-Space Line-of-Sight	Transionospheric quasi-rectilinear propagation
Reflected One-Hop	Earth-to-Earth propagation with intermediate reflection from an ionospheric layer.
Reflected Multi-Hop	Earth-to-Earth propagation with multiple hops using a single ionospheric layer or different layers
Ducted	Wave is trapped between two ionospheric layers (i.e., the E-F "valley" of ionization)
Chordal	Wave, launched from an earth terminal, skips along the base of an ionospheric layer without an intermediate ground reflection (i.e., transequatorial "supermodes")
Scatter	Wave is scattered from ionospheric inhomogeneities or features (i.e., auroral and sporadic-E sidescatter, spread-F scatter)

Radiowaves can propagate at frequencies below the plasmafrequency $f_p = 9\sqrt{Ne}$ with f_p in Hz and N_e in electrons/m^3.

At plasmafrequency waves are reflected and at higher frequencies absorped.

The electron density in the ionosphere has a complex structure that supports many propagation modes.

The structure & HF communication is affected by:

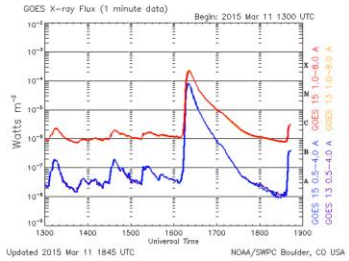
- Ionizing X-rays from flares (especially important for commercial airliners that use 1-30 MHz HF)
- Radiation storms with energetic protons 1-100 MeV bombarding polar regions

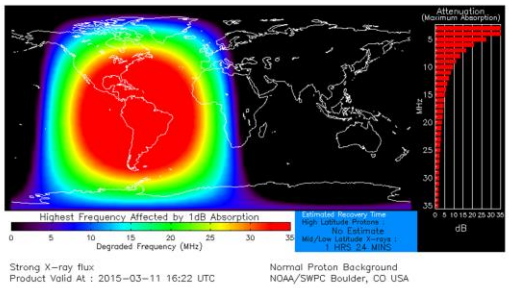
Note that both phase & amplitude can be affected.

Source: Space Weather & Telecommunications Goodman

EFFECTS FROM SOLAR FLARES: COMMUNICATION & NAVIGATION

- Radio blackouts
  - Sunlit side
  - M1 flares or higher
    - D-region
    - Short-term effects
  - Affected technology
    - HF radio
    - LF navigation
    - Satellite navigation
  - Various users
    - Naval and aviation
    - Military
    - Broadcasting





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Kumar et al. (2014): Space weather effects on the low latitude D-region ionosphere during solar minimum
http://adsabs.harvard.edu/abs/2014EP%26S...66...76K
The solar flares and geomagnetic storms are the phenomena associated with the space weather. The solar flares, particularly with X-ray having wavelengths typically of tenths of a nanometer, penetrate the D-region of the ionosphere and increase the electron density via extra ionization (e.g. Mitra 1974). The increase in the D-region electron density can produce significant perturbations in the received phase and amplitude of VLF signals propagating in the Earth ionosphere waveguide (EIWG). The normal unperturbed daytime D-region from which VLF signals are usually reflected is maintained mainly by direct Lyman-α radiation (121.6 nm) from the sun that partially ionizes the minor neutral constituent nitric oxide (at a height around 70 km). Under normal conditions, the solar X-ray flux is too small to be a significant source for ionizing the D-region; however, when a solar flare occurs, the X-ray flux from the sun increases dramatically. The X-ray flux with wavelengths appreciably below 1 nm penetrates down to the D-region and markedly increases the ionization rate of the neutral constituents particularly nitrogen and oxygen hence increases the D-region electron density.

More info at:
SWPC: http://www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts

SWS: http://www.sws.bom.gov.au/Educational/1/3/5

Realtime charts on affected areas at http://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap

Example from STCE: http://www.stce.be/news/299/welcome.html

IMPACTS ON AVIATION: EFFECTS ON NAVIGATION

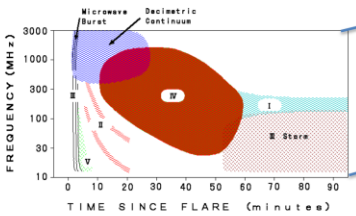
- GPS disurbances occur more frequent at the poles and near the equator
- Near equator: ionospheric varability and scintillation, esp after sunset impact quality GNSS and satellite communication
- Sunlit hemisphere: solar radiobursts may degrade GNSS for minutes

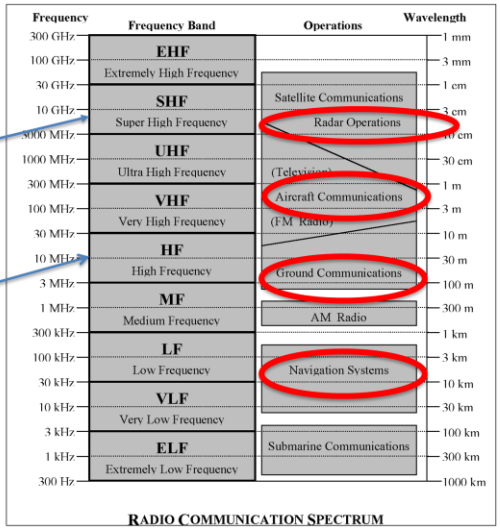
IMPACTS ON AVIATION: GROUND SUPPORT

Effects on ground support equipment

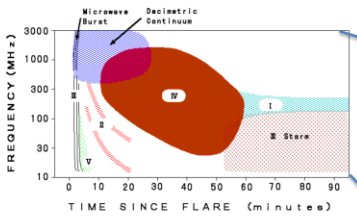
- GPS errors
- Power disruptions
- ATC disturbances by radioflares

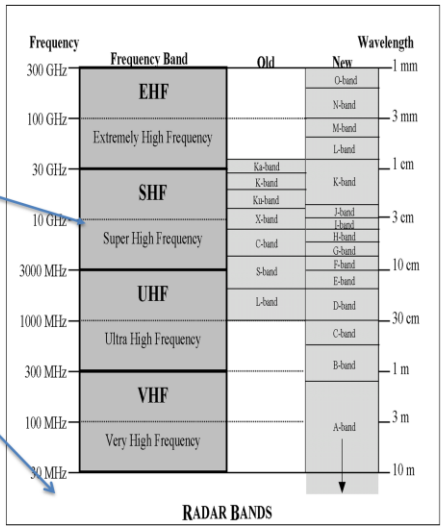
RADIOFLARES DISTURB ATC AND COMMUNICATION





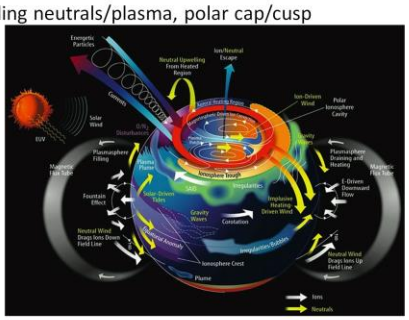
RADIOFLARES DISTURB ATC

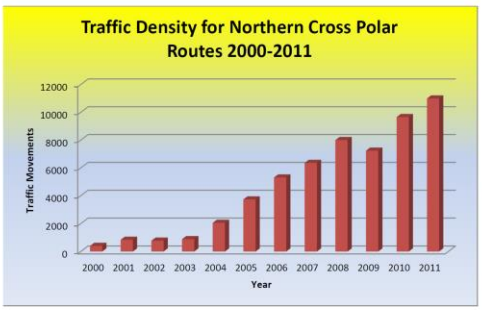


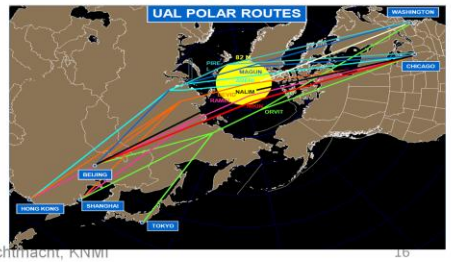


POLAR REGION

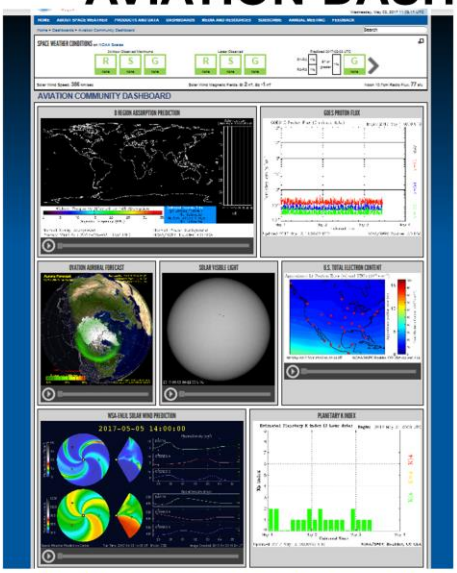
- Structure very complex: **E**x**B** drifts, collisional coupling neutrals/plasma, polar cap/cusp
- Impact on Communication
- Impact on radiation levels







AVIATION DASHBOARD NOAA

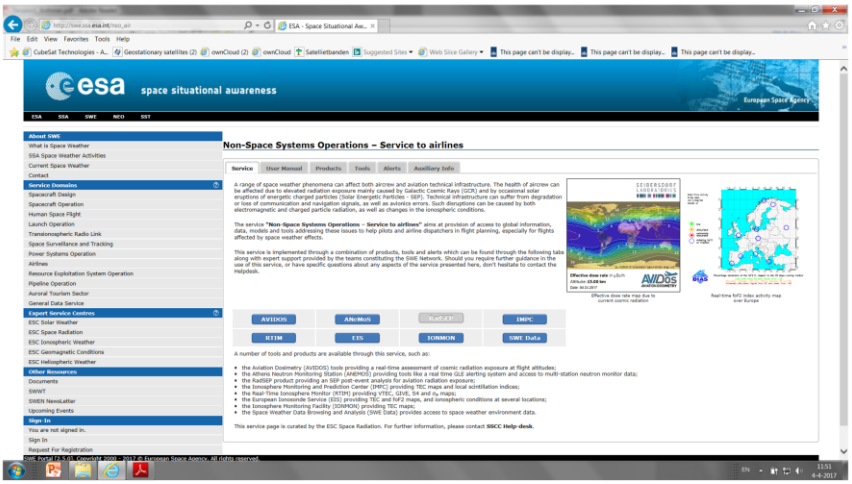


- D REGION ABSORPTION PREDICTION
- GOES PROTON FLUX
- AURORAL FORECAST
- SOLAR VISIBLE
- TOTAL ELECTRON CONTENT
- ENLIL MODEL
- PLANETARY INDEX

http://www.swpc.noaa.gov/communities/aviation-community-dashboard

ESA SERVICES FOR AVIATION

http://swe.ssa.esa.int/nso_air



REQUIREMENTS ICAO

Type of Impact	Observations required
Radiation	Proton flux, radiation dose, neutron flux density
Navigation (GNSS)	Total electron content, scintillation and other ionospheric variables (eg height of the F2 region); EUV flux
HF communications	Total electron content, ionospheric radio absorption and other ionospheric variables (eg foEs (highest ordinary-wave frequency reflected back from a sporadic E layer)), proton and X ray fluxes

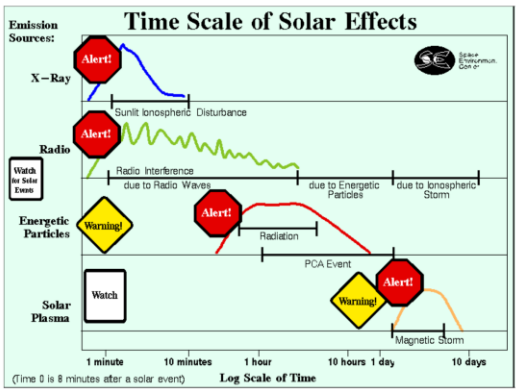
ICAO AVIATION USER NEEDS

AUN-1	Define the impacts of space weather
AUN-2	Provide the following types of information: observations, forecasts, and climatology
AUN-3	Provide information in text and graphical format
AUN-4	Present information using standardized format and content
AUN-5	Describe/display the severity of impact in standardized text and graphical reports
AUN-6	Provide text and graphical reports using specified timelines and durations
AUN-7	**Provide an estimate of the accuracy of the information**
AUN-8	**State the regions affected**
AUN-9	Utilize stated transmission methods for space weather reports
AUN-10	**Provide information on disruptions to HF communications**
AUN-11	**Provide information on disruptions to VHF communications**
AUN-12	**Provide information on disruptions to UHF communications**
AUN-13	**Provide information on fading and loss of lock to SATCOM**
AUN-14	**Provide information on the radiation environment that will affect avionics**
AUN-15	**Provide information on the radiation environment that will affect humans**
AUN-16	**Provide Information that will affect GNSS**
AUN-17	Define space weather information and decision-maker matrices
AUN-18	Define communication and integration of space weather information
AUN-19	Provide space weather education and training

ICAO DECISION TABLE

Decision-makers		Airline Flight Planners or Support			Pilots						Air Traffic Controllers			
Decisions → / Information Types ←	Disruption/loss of HF Comms	Interruption of VHF Comms	Reduced UHF Performance	Interruption of SatCom	Radiation Environmental levels and variability	GNSS integrity, accuracy and outages	Airport/Spaceport SW Reports	Airport/Spaceport Terminal SW Forecasts	En Route SW Forecasts	SW Alerts and Warnings	Route/Altitude Selection	Go/No Go Decision	In-flight Route/Altitude Change	Route/Altitude Selection
Route/Altitude Selection	x			x	x	x	x	x	x	x	x	x	x	x
Go/No Go Decision	x			x	x		x	x	x	x	x	x	x	x
In-flight Route/Altitude Change	x			x	x		x	x		x	x	x	x	x
Route/Altitude Selection	x	X		X	x	X	x	x	x	x	x	x	x	x
Go/No Go Decision	x	X		X	x	X	x	x	x	x	x	x	x	x
In-flight Route/Altitude Change	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hazardous Weather Deviation	x	x	x	x	x	X	x	X	X	X	x	x	x	x
Approach Commencement	X	x		X	X	x	x	X			x	x	x	x
Landing Decision	X	x		X		x	x				x	x	x	x
Metering/Spacing Decision	x			X	x	x	x	x	x	x	x	x	x	x
Route/Altitude Selection	x			X	x	x			x	x	x	x	x	x
Approach/Departure Route Selection				X		x	x				x	x	x	x
Approach/Departure Clearance		x		X		x	x							

TIMESCALES RELEVANT FOR AVIATION



Later this year WMO will, on behalf of ICAO start auditing space weather service providers to arrive at a limited number certified providers that can provide the above information. Below xx ft it will remain reponsibility of National Authorities