

# SPACE WEATHER INTRODUCTORY COURSE



May 2017

Collaboration of



Solar-Terrestrial Centre of Excellence



Koninklijke luchtmacht



Koninklijk Nederlands  
Meteorologisch Instituut  
*Ministerie van Infrastructuur en Milieu*



## **IMPACTS ON AVIATION**

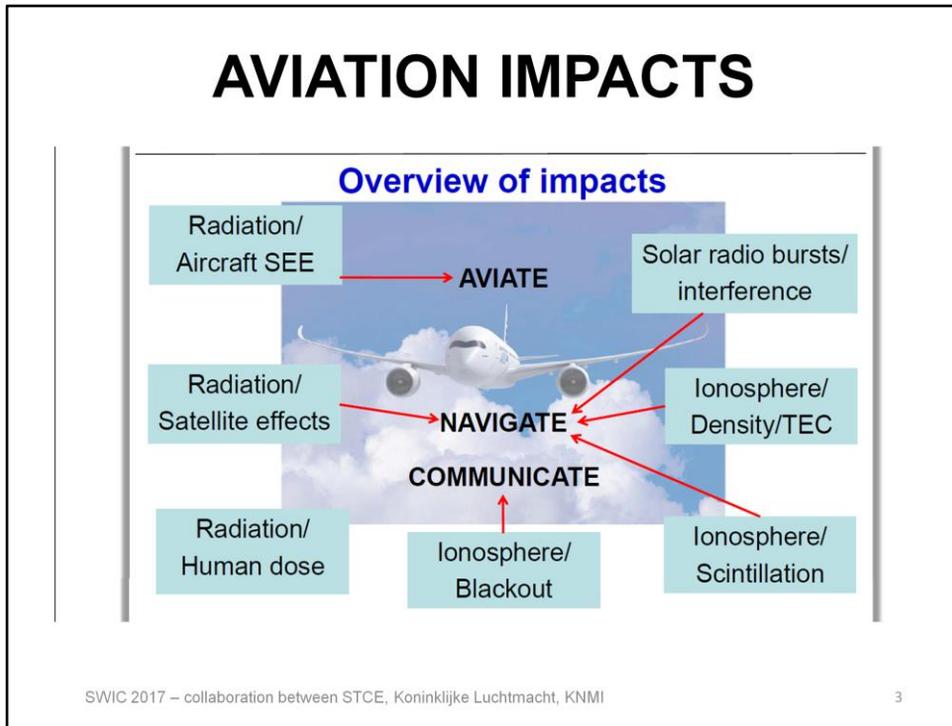
Description of space weather effects on aviation

Bert van den Oord

SWIC 2017 – collaboration between STCE, Koninklijke Luchtmacht, KNMI

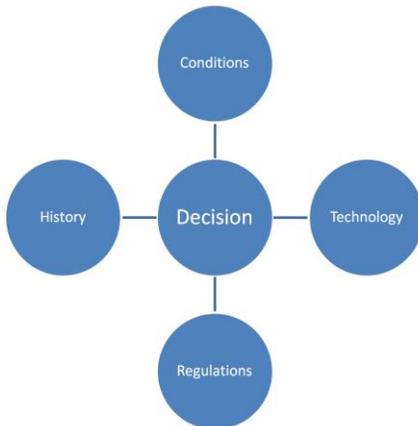


# AVIATION IMPACTS



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

## AVIONIC OPERATIONS FROM SPACE WEATHER PERSPECTIVE



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

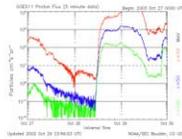
ICAO: Concept of Operations for Space Weather information in support of International Air Navigation

The conops document for space weather by ICAO is under development

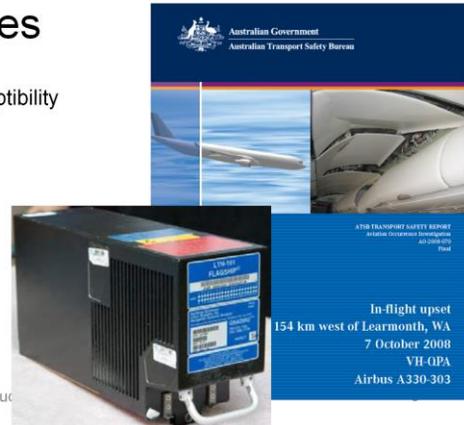
## IMPACTS ON AVIATION: PARTICLES

- 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

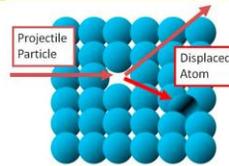
# PARTICLE RADIATION EFFECTS

- **Sources:**

- Cosmic rays (0.1-20 GeV)
  - 85% protons, 14%  $\alpha$  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

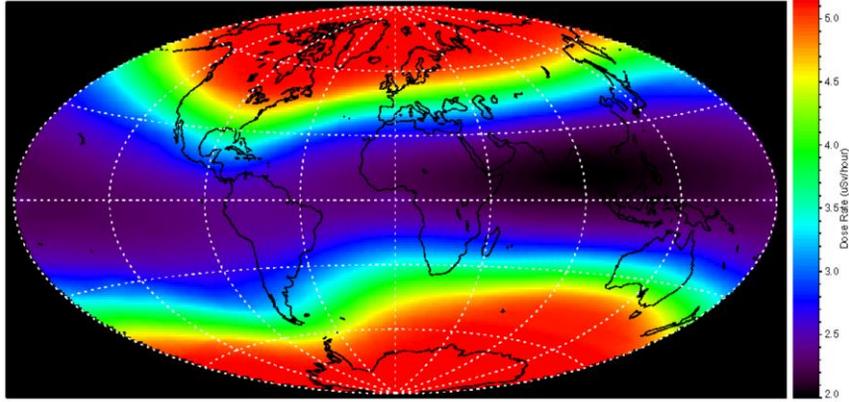
Gray: absorbed energy J/kg  
Sievert: biological equivalent of  
cumulative absorbed J/kg

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.

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

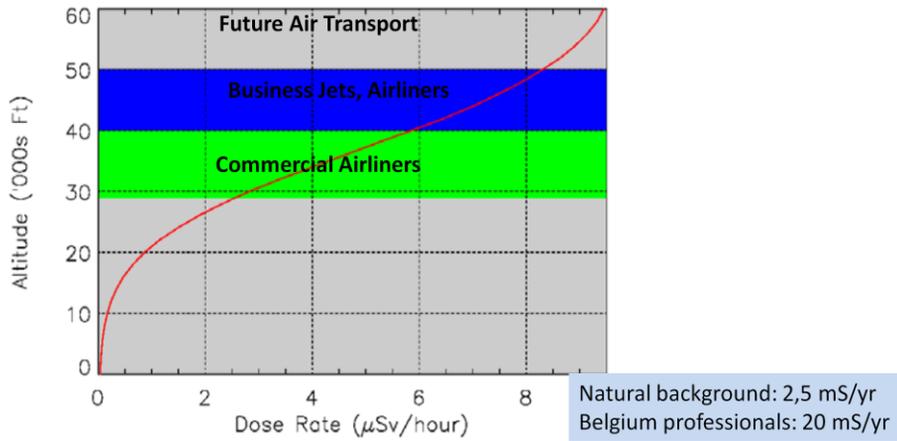
# RADIATION LOAD



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

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# DOSE RATE



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

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## IMPACTS ON AVIATION: COMMUNICATION

- Poleward flight lose contact with geosynchronous communication satellites (Earth curvature).
- Need to switch to HF communication that is also used by civil aviation.
- HF communications is susceptible to polar cap absorption (solar proton events) and auroral absorption (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 latitudes sporadic interference of VHF communication due to effect of strong X-ray flares



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## COMPLEXITY OF HF COMMUNICATION

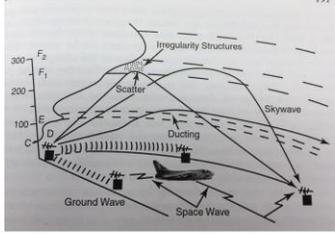


Table 4-5: List of HF Propagation Mechanisms

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 refractive 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., trans-equatorial "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  $f_p = 9 \sqrt{N_e}$  with  $f_p$  in Hz and  $N_e$  in electrons/m<sup>3</sup>.

At plasmafrequency waves are reflected and at higher frequencies absorbed.

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

The structure & HF communication is affected by:

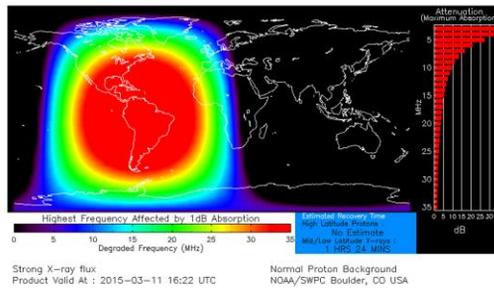
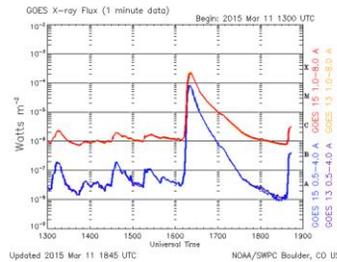
- Ionizing X-rays from flares (especially important for commercial airliners that use 1-30 MHz HF)
- Radiation storms with energetic protons 1-100 MeV bombarding polar regions

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- $\alpha$  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 disturbances occur more frequent at the poles and near the equator
- Near equator: ionospheric variability 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

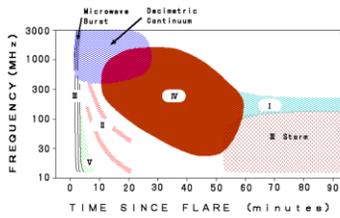
## Effects on ground support equipment

- GPS errors
- Power disruptions
- ATC disturbances by radioflares



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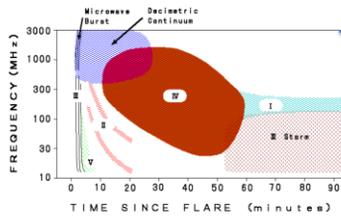
# RADIOFLARES DISTURB ATC AND COMMUNICATION



Frequency	Frequency Band	Operations	Wavelength
300 GHz	<b>EHF</b>		1 mm
100 GHz	Extremely High Frequency		3 mm
30 GHz	<b>SHF</b>	Satellite Communications	1 cm
10 GHz	Super High Frequency	Radar Operations	3 cm
3000 MHz	<b>UHF</b>		10 cm
1000 MHz	Ultra High Frequency	(Television)	30 cm
300 MHz	<b>VHF</b>	Aircraft Communications	1 m
100 MHz	Very High Frequency	(FM Radio)	3 m
30 MHz	<b>HF</b>		10 m
10 MHz	High Frequency	Ground Communications	30 m
3 MHz	<b>MF</b>		100 m
1 MHz	Medium Frequency	AM Radio	300 m
300 kHz	<b>LF</b>		1 km
100 kHz	Low Frequency	Navigation Systems	3 km
30 kHz	<b>VLF</b>		10 km
10 kHz	Very Low Frequency		30 km
3 kHz	<b>ELF</b>		100 km
1 kHz	Extremely Low Frequency	Submarine Communications	300 km
300 Hz			1000 km

**RADIO COMMUNICATION SPECTRUM**

# RADIOFLARES DISTURB ATC



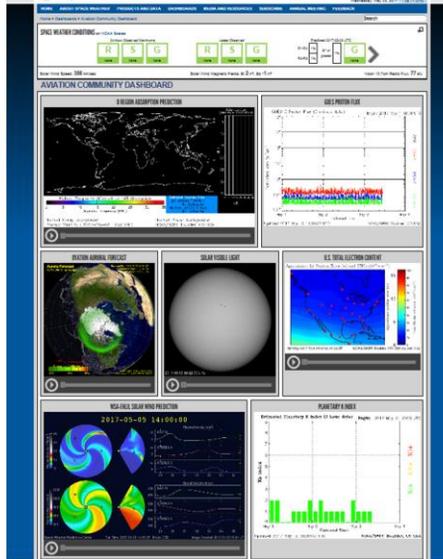
Frequency	Frequency Band	Old	New	Wavelength
300 GHz	EHF Extremely High Frequency		O-band	1 mm
100 GHz			N-band	3 mm
30 GHz			M-band	L-band
10 GHz	SHF Super High Frequency	Ka-band	K-band	1 cm
		Ku-band		3 cm
		Kv-band		3 cm
		X-band		10 cm
3000 MHz	UHF Ultra High Frequency	C-band	E-band	10 cm
		S-band		30 cm
		L-band		1 m
		D-band		3 m
100 MHz	VHF Very High Frequency		A-band	10 m

**RADAR BANDS**

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# 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>  
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# ESA SERVICES FOR AVIATION

http://swe.ssa.esa.int/nso\_air

The screenshot shows a web browser displaying the ESA Space Situational Awareness website. The page title is "Non-Space Systems Operations - Service to airlines". The left sidebar contains a navigation menu with categories like "About SWA", "Spacecraft Design", "Spacecraft Operation", "Human Space Flight", "Launch Operation", "Trans-European Radio Link", "Space Surveillance and Tracking", "Flight Systems Operation", "Airlines", "Resource Exploitation System Operation", "Spacecraft Operation", "Aircraft Trajectory Factor", "General Data Service", "Expert Service Elements", "ESC Solar Weather", "ESC Space Radiation", "ESC Ionospheric Weather", "ESC Geomagnetic Conditions", "ESC Ionospheric Weather", "Other Resources", "Documents", "SWAFT", "SWA Newsletter", "Upcoming Events", "Help Us", and "Sign In".

The main content area features a header "Non-Space Systems Operations - Service to airlines" and a sub-header "Service". Below this, there is a paragraph explaining that a range of space weather phenomena can affect both airframe and aviation technical infrastructure. It mentions the health of airframe can be affected by increased radiation exposure caused by Galactic Cosmic Rays (GCR) and by disturbance and ionospheric charged particle (Solar Energetic Particles - SEP). Technical infrastructure can suffer from degradation or loss of communication and navigation signals, as well as antenna errors. Such disruptions can be caused by both electromagnetic and charged particle radiation, as well as changes in the ionospheric conditions.

The service "Non-Space Systems Operations - Service to airlines" aims at provision of access to global information, data, samples and tools addressing these issues to help pilots and airline dispatchers to flight planning, especially for flight profiles for space weather events.

The service is implemented through a combination of products, tools and alerts which can be found through the following table along with expert support provided by the teams contributing the SWA Network. Should you require further guidance in the use of this service, or have specific questions about any aspects of the service presented here, don't hesitate to contact the helpdesk.

Below the text is a table of services:

<a href="#">AVIATION</a>	<a href="#">AIR-WEATHER</a>	<a href="#">TRACKING</a>	<a href="#">EMSC</a>
<a href="#">ELM</a>	<a href="#">ESC</a>	<a href="#">IONOSPHERE</a>	<a href="#">SWA DATA</a>

A number of tools and products are available through this service, such as:

- The Aviation Dynamic (ADIOS) tool provides a real-time assessment of cosmic radiation exposure at flight altitudes;
- The Airframe Monitor Station (AIMS) providing tools like a real-time GUI alerting system and access to multi-station neutron monitor data;
- The flightplan product providing an IIR post-flight analysis for radiation exposure;
- The Ionosphere Monitoring and Prediction Center (IMPC) providing TEC maps and local ionosphere indices;
- The Real Time Ionosphere Monitor (RTIM) providing TEC, GUF3, MUF3000, and virtual height of F2 layer maps;
- The European Ionosphere Service (EIS) providing TEC and total electron content maps;
- The Ionosphere Monitoring Facility (IMF) providing TEC maps; and ionospheric conditions at several locations;
- The Space Weather Data Mining and Analysis (SWDA) tool provides access to space weather environment data.

This service page is owned by the ESC Space Radiation. For further information, please contact SWA helpdesk.

# 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

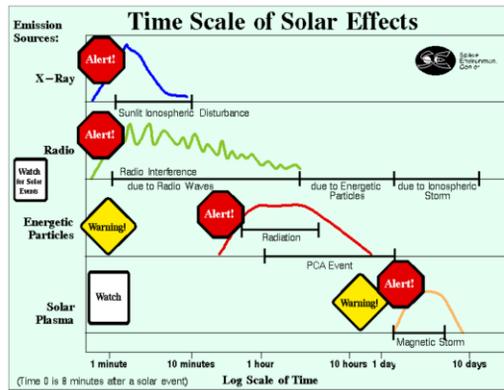
AUN-1	Define the impacts of space weather
AUN-2	Provide the following types of information: observations, forecasts, and climatology
AUN-3	Provide information in text and graphical format
AUN-4	Present information using standardized format and content
AUN-5	Describe/display the severity of impact in 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					
	Route/Altitude Selection	Go/No Go Decision	In-flight Route/Altitude Change	Route/Altitude Selection	Go/No Go Decision	In-flight Route/Altitude Change	Hazardous Weather Deviation	Approach Commencement	Landing Decision	Metering/Spacing Decision	Route/Altitude Selection	Approach/Departure Route Selection	Approach/Departure Clearance
Information Types													
Disruption/loss of HF Comms	x	x	x	x	x	x	x	x	x	x	x	x	x
Interruption of VHF Comms				x	x	x	x	x	x				x
Reduced UHF Performance						x	x	x	x				
Interruption of SATCOM	x	x	x	x	x	x	x	x	x	x	x	x	x
Radiation from ground levels and variability	x	x	x	x	x	x	x	x	x	x	x	x	x
GNSS integrity, accuracy and outages	x			x	x	x	x	x	x	x	x	x	x
Airport/Spaceport SW Reports	x	x	x	x	x	x	x	x	x	x	x	x	x
Airport/Spaceport SW Reports	x	x	x	x	x	x	x	x	x	x	x	x	x
En Route SW Forecasts	x	x	x	x	x	x	x	x	x	x	x	x	x
SW Alerts and Warnings	x	x	x	x	x	x	x	x	x	x	x	x	x

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# 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 responsibility of National Authorities