Space Weather radiation impacts on aviation

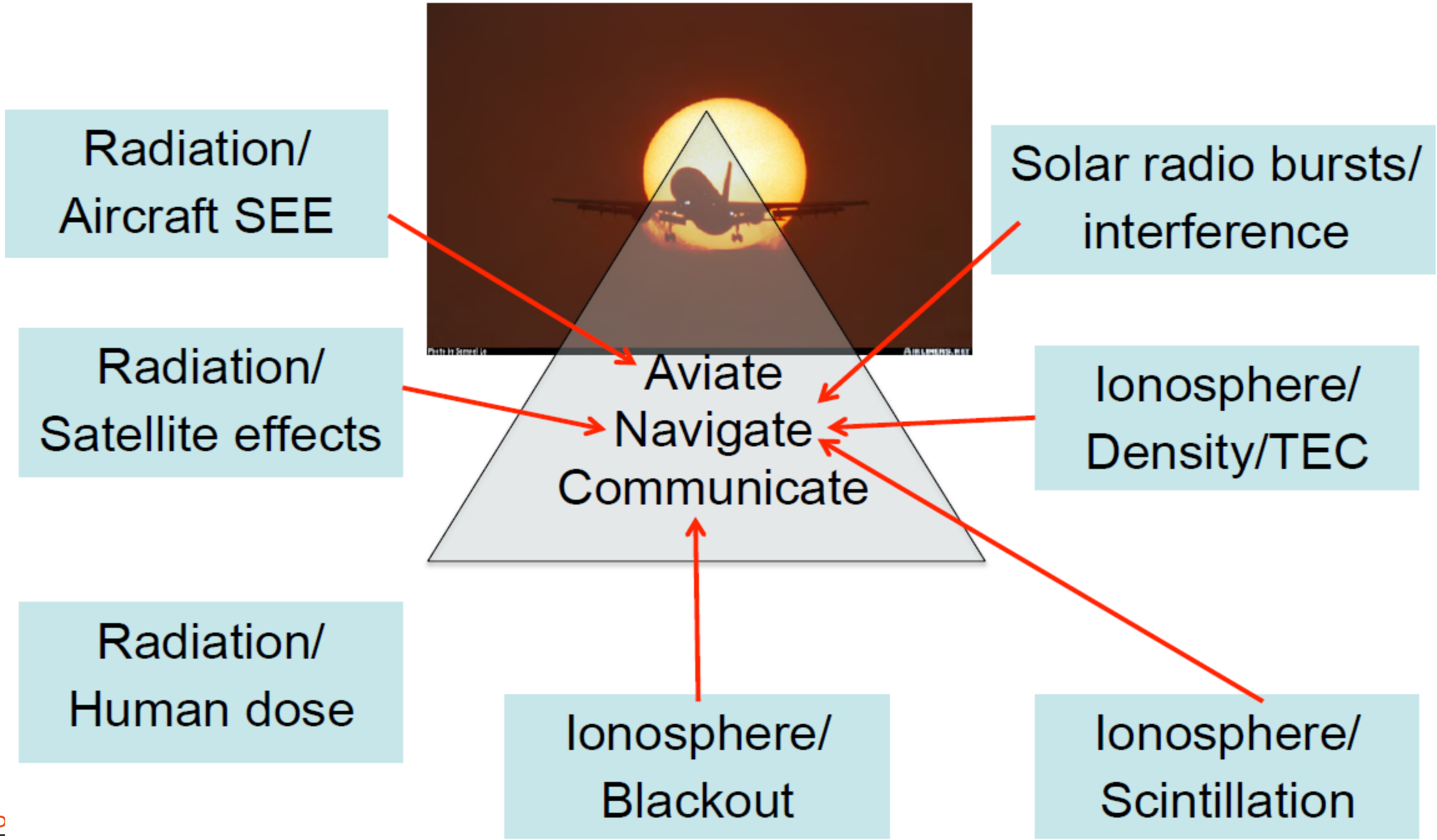
Name: Rendani Nndanganeni
rnndanganeni@sansa.org.za

Date: 14 June 2024

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

SANSA
SOUTH AFRICAN NATIONAL
SPACE AGENCY

Why space weather is important to aviation

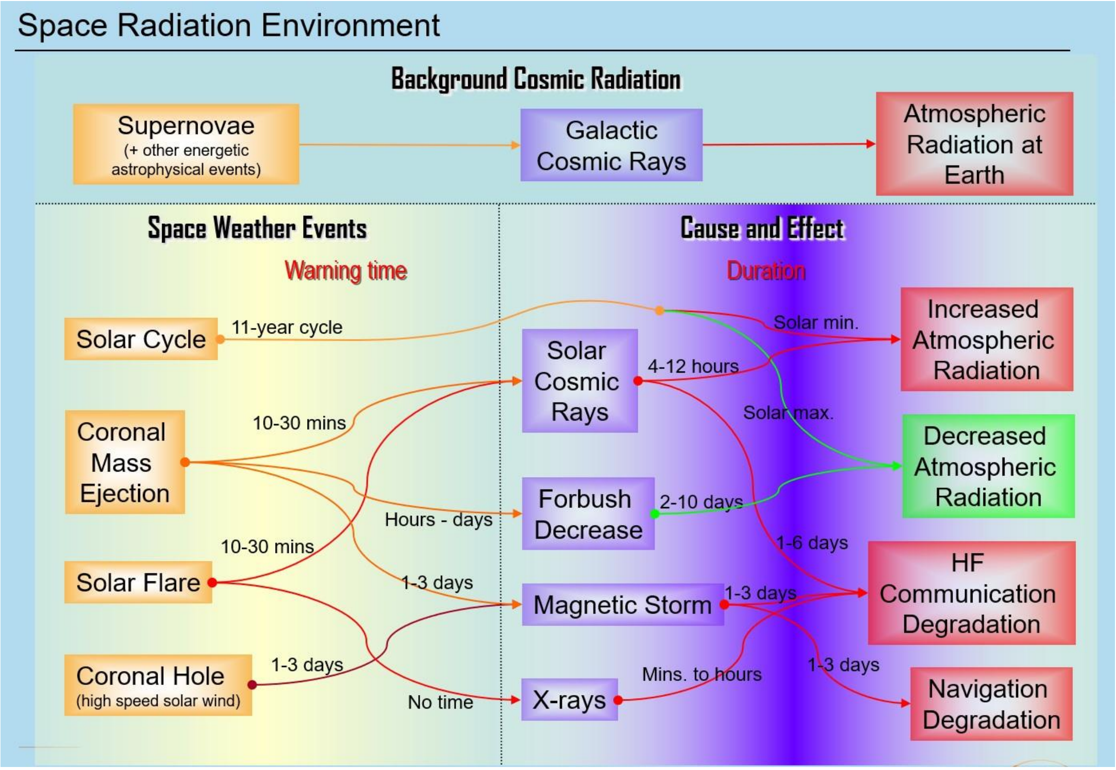


science & inno
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

SANSA
SOUTH AFRICAN NATIONAL
SPACE AGENCY

SPACE WEATHER EVENTS THAT AFFECTS AVIATION

SOLAR EVENT	Solar Flare				CME		Solar Wind	Galactic Cosmic Rays	
SECONDARY EFFECT	X-Ray Emissions	Ultraviolet emissions	Radio Bursts	Solar Energetic Protons (SEPs)	Plasma	Solar Energetic Protons (SEPs)	Enhances Radiation Belts		
EFFECT ON EARTH SYSTEM	Increase Ionosphere Density	Ionospheric disturbances			Geo-magnetic Storms		Aurora	Radiation	Ionospheric Scintillation
AVIATION-RELATED SYSTEMS									
Passengers/Crew (Biological)				X	X	X		X	
Avionics				X		X		X	
HF Communication	X	X		X	X	X			
GPS/WAAS	X	X	X	X	X	X	X		X
Satellites (Navigation, Communication)	X	X	X	X	X	X	X	X	X
Low Frequency Communication	X		X		X				
ATC facilities		X			X				



Courtesy: https://www.gwu.edu.

ICAO - Summary of Annex 3 Amendments 78

Provider States need to be able to:

A) monitor relevant ground-based, airborne and space-based observations to detect, and predict, when possible, the existence and extent of space weather conditions that have an impact in the following areas:
   - high frequency (HF) radio communications;
   - Satellite communications;
   - GNSS-based navigation and surveillance; and
   - **radiation exposure at flight levels;**

B) Issue advisory information

C) Supply the advisory information to appropriate aviation channels

D) Maintain a 24-hour watch

E) Ensure active collaboration with other regional centres and global centres to ensure a continuity of information

ICAO DECISION (13 Nov 2018)

GLOBAL CENTRES

(provide information from 2019)

1. ACFJ consortium (formed by Australia, Canada, France and Japan)
2. PECASUS consortium (formed by Austria, Belgium, Cyprus, Finland, Germany, Italy, Poland, Netherlands and United Kingdom)
3. United States

REGIONAL CENTRES

(provide information no later than November 2022)

1. China/Russian Federation consortium *(later converted to Global)*
2. South Africa

South Africa, through SANSA, has received designation as a Regional Centre for Space Weather Information Provision from the International Civil Aviation Organisation (ICAO)

ICAO requirements to service the aviation sector: 2019 several space weather centers began issuing advisories alerting users to enhancements in the radiation environment at aviation flight levels.

The effects of radiation storms for aviation sectors are two-fold: increased radiation exposure to aircrew and passengers and single event upsets to onboard systems.

How/ requirements:

- ❑ Health-related impacts of solar radiation storms: measure the effective dose rate at several altitudes, but these measurements are rare and the effective dose rates are most of the time derived from model outputs (e.g. MAIRE, CARI7, AVIDOS, NAIRAS, WASAVIS, PANDACO).
- ❑ The inputs of these models include the measurements of energetic particles (satellite data for protons above 100 MeV and/or ground-based neutron monitor data for GeV incident protons as well as magnetic field data (presence or not of a geomagnetic storm). GOES > 100 MeV data are commonly used as a proxy for advising airlines of increased radiation.
- ❑ Near real-time measurements of energetic protons above 100 MeV or near real-time measurements from ground-level radiation doses at aircraft altitudes using input from particle data

https://doi.org/10.3389/fspas.2023.1149014

ICAO threshold

Doc10100: Space weather manual

Infrastructure	Explanation
Near real-time information and data services on the current state of radiation	Information on radiation storms Protons > 100 MeV and/or data from ground-based neutron monitors
Near real-time measurements of the earth's magnetic field	Information on geomagnetic storm conditions (extent of the polar cap)
Models providing forecasts of radiation doses at aircraft altitudes	Effective dose rate used as a threshold for space weather advisory.

Table 3-2. Thresholds for space weather advisory

		Moderate	Severe
GNSS			
	Amplitude Scintillation (S4)(dimensionless)	0.5	0.8
	Phase Scintillation (Sigma-Phi)(radians)	0.4	0.7
	Vertical TEC (TEC Units)	125	175
RADIATION			
	Effective Dose (micro-Sieverts/hour)*	30	80
HF			
	Auroral Absorption (Kp)	8	9
	PCA (dB from 30MHz Riometer data)	2	5
	Solar X-rays (0.1 - 0.8 nm)(W-m^{-2})	1X10^{-4} (X1)	1X10^{-3} (X10)
	Post-Storm Depression (MUF)**	30%	50%

ICAO example– Space Weather Advisory Information

Space weather advisory about RADIATION:

```
SWX ADVISORY
DTG:                 20191108/0000Z
SWXC:                DONLON*
ADVISORY NR:         2019/2
NR RPLC:             2019/1
SWX EFFECT:          RADIATION MOD
FCST SWX:            08/0100Z HNH HSH E18000 - W18000 ABV FL 350
FCST SWX +6 HR:      08/0700Z HNH HSH E18000 - W18000 ABV FL 350
FCST SWX +12 HR:     08/1300Z HNH HSH E18000 - W18000 ABV FL 350
FCST SWX +18 HR:     08/1900Z HNH HSH E18000 - W18000 ABV FL 350
FCST SWX +24 HR:     09/0100Z NO SWX EXP
RMK: RADIATION LVL EXCEEDED 100 PCT OF BACKGROUND LVL AT FL350
AND ABV. THE CURRENT EVENT HAS PEAKED AND LVL SLW RTN TO BACKGROUND LVL.
SEE WWW.SPACEWEATHERPROVIDER.WEB
NXT ADVISORY:        NO FURTHER ADVISORIES
```

Laws and regulations

The legally stipulated radiation protection measures primarily consisted of an individual assessment of the radiation exposures of crew members, of taking into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed aircrew, of informing the workers concerned of the health risks their work involves, and of limiting the doses of pregnant crew members after reporting pregnancy to 1 mSv for the remainder of the pregnancy.

•Global standards and regulations regarding the exposure limits: Aircrew are classified as exposed radiation workers according to the International Commission for Radiological Protection (ICPR 1991, 1993).

•International Commission on Radiation Protection (ICRP) recommendation: Radiological Protection from Cosmic radiation in Aviation

i. In South Africa, the ICRP system for radiation exposure assessment and protection is incorporated in the National Nuclear Regulator act (NATIONAL NUCLEAR REGULATOR ACT, 1999 (ACT NO. 47 OF 1999). But the pilot and crew members are not mentioned explicitly here.

ii. Dosimetric quantities and dose limits (discussed in the subsequent sections) used in South Africa National Nuclear Regulator are based on ICRP60 [1991].

iii. The International Commission on Radiological Protection (ICRP) and the Federal Aviation Administration (FAA) consider aircrews to be occupationally exposed to ionizing radiation (ICRP 1991, Federal Aviation Administration (1994). Crewmember Training on In-Flight Radiation Exposure, Advisory Circular No. 120-61, Washington, DC.).

iv. The International Commission on Radiological Protection (ICRP) recognizes the need to control the exposure of the person representing the flight professional group , like pilots and crew as this group is exposed to radiation levels that are comparable to the average levels of radiation received by professionals working with radiation in Medicine and Nuclear technology(ICRP,1998).

International Commission on Radiological Protection (ICRP) 2016 recommendation for air crew

More recently, the International Commission on Radiological Protection (ICRP) have made specific recommendations for air crew (ICRP, 2016)

- At typical commercial flight altitudes, the dose rate is generally in the range of 2–10 mSv h1 , depending primarily on latitude, altitude, and level of solar activity (ICRU, 2010).
- In addition, this publication affirms that exposure of aircraft crew to cosmic radiation is occupational, and thus employers have a role to play in protection, even if options are limited in this case.
- **For aircraft crew (**recommendations for air crew (ICRP, 2016)**)**, the Commission recommends that the operating management:

  (i) inform the aircraft crew individually about cosmic radiation through an educational programme;

  (ii) assess the dose of aircraft crew;

  (iii) record the individual and cumulative dose of aircraft crew. These data should be made available to the individuals and should be kept for a reasonable period of time that is, at a minimum, comparable with the expected lifetime of the individuals; and 13

  (iv) adjust the flight roster when appropriate, considering the selected dose reference level and after consultation with the concerned aircraft crew.
- The Commission also recommends that national authorities or airline companies disseminate information to raise awareness about cosmic radiation and support informed decisions among all concerned stakeholders, and foster a radiological protection culture for occupationally exposed individuals

Ref: ICRP, 2016. Radiological Protection from Cosmic Radiation in Aviation. ICRP Publication 132. Ann. ICRP 45(1), 1–48.

Radiation risk to aviation and challenges

Aircrew are classified as radiation exposed by International Commission for Radiological Protection (ICRP)

Induce Single Event Effects into electronics
Critical implications to avionic and safety systems –Fly by Wire

- Airlines are resistant to carrying radiation monitors.
- Little or no aboard aircraft radiation measurements
- Limited Ground Level Event (GLE) data for aviation altitudes.

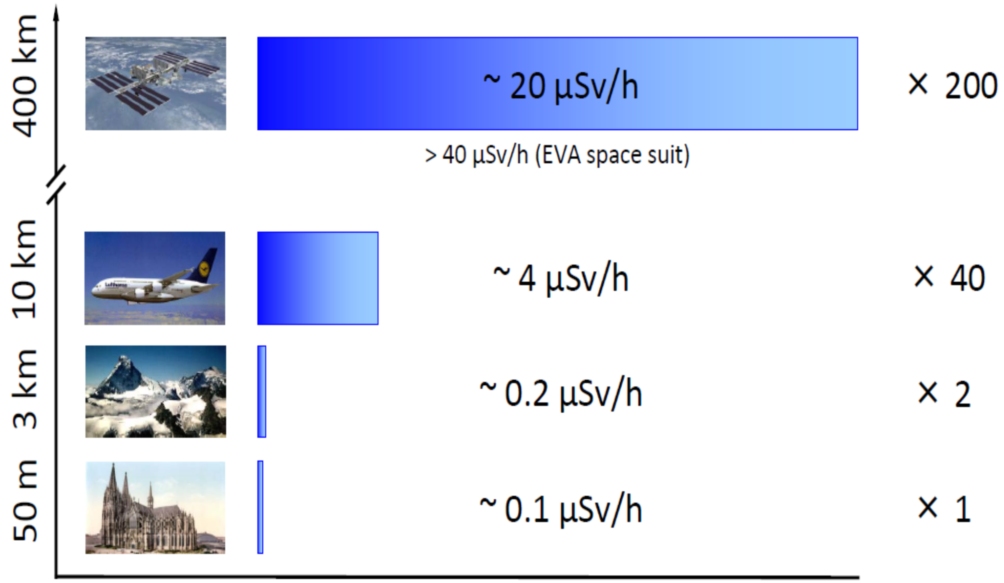
- Risk of exceeding annual radiation dose in 1 flight.
- Pilots and flight crew appear to have higher than normal rates of prostate cancer, skin cancer, and acute myeloid leukemia in addition to cellular evidence of chromosome damage.

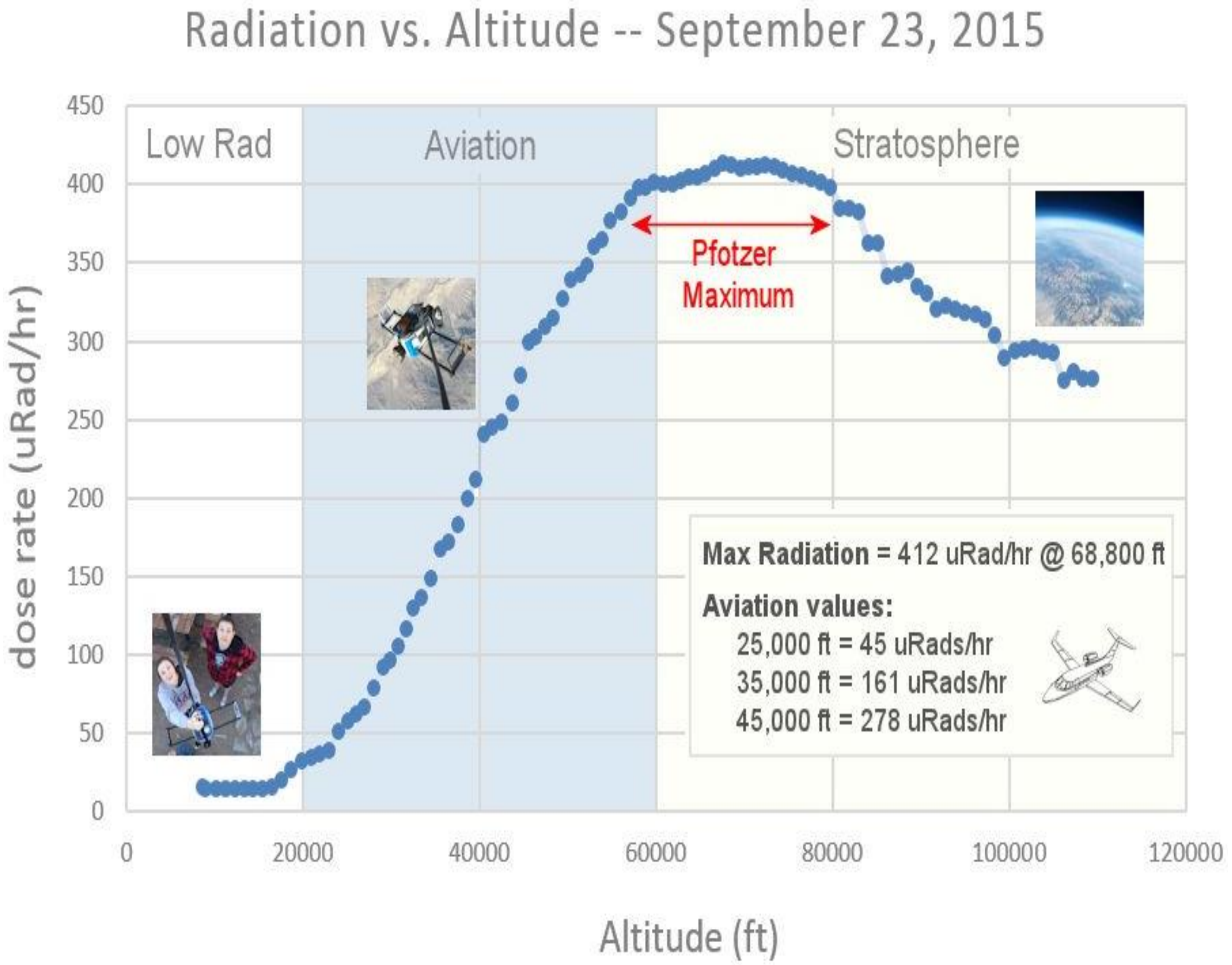
There are three main factors that can affect the amount of exposure to cosmic radiation: – **Altitude:** the higher we go, the greater the dose – **Latitude**: the closer we get to the poles, the greater the dose – **Duration**: the longer we stay , the greater the dose
Solar cycle: solar minimum or solar maximum

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

SANSA
SOUTH AFRICAN NATIONAL SPACE AGENCY

Comparison of Radiation Exposure





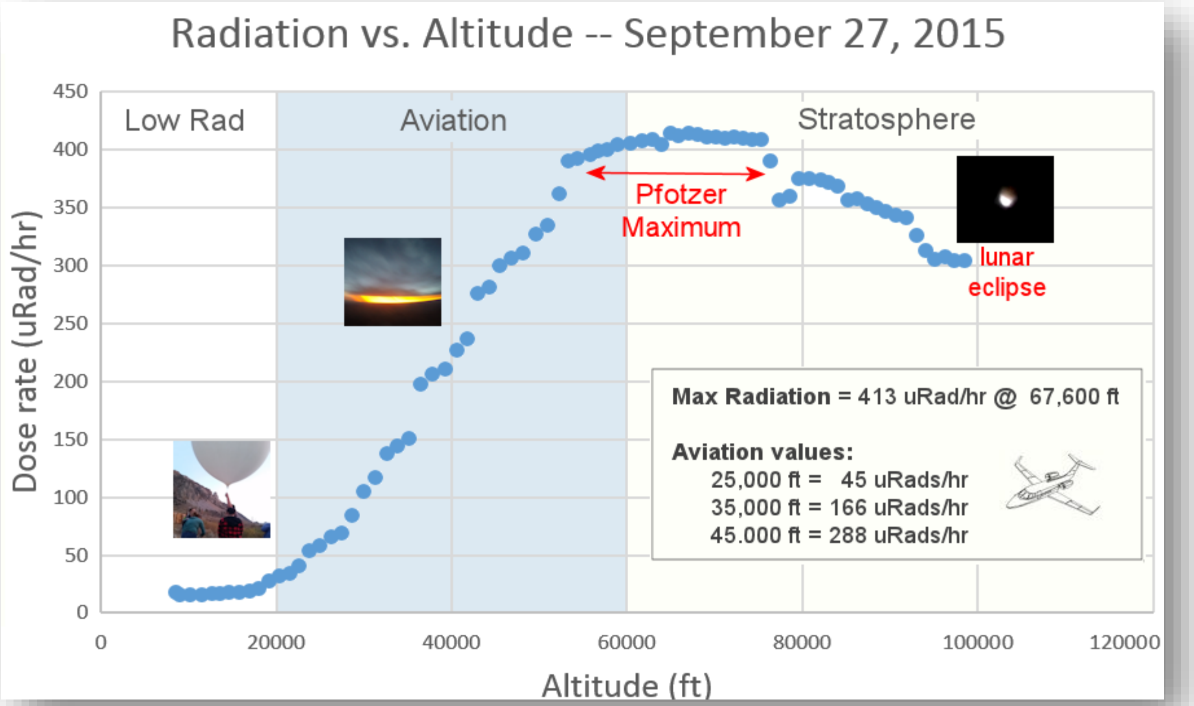
mSv: the average accumulated background radiation dose to an individual for 1 year.

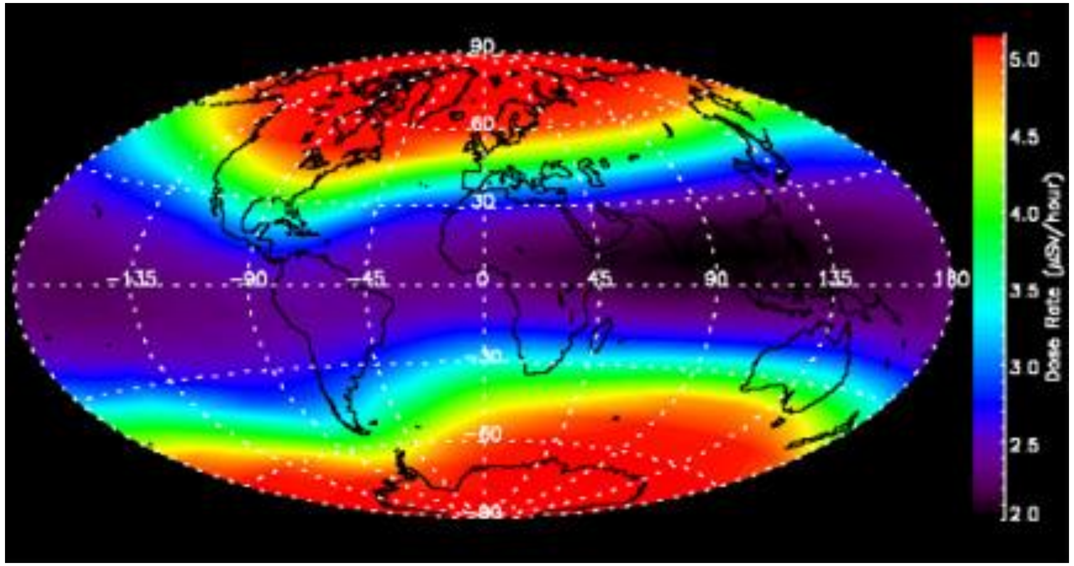
1 mSv = **1000** µSv.

1 ft = 3.048×10^{-4}

35000 ft = 10.6 km

Radiation exposure:





Typical background radiation dose: courtesy of 19hubbl01

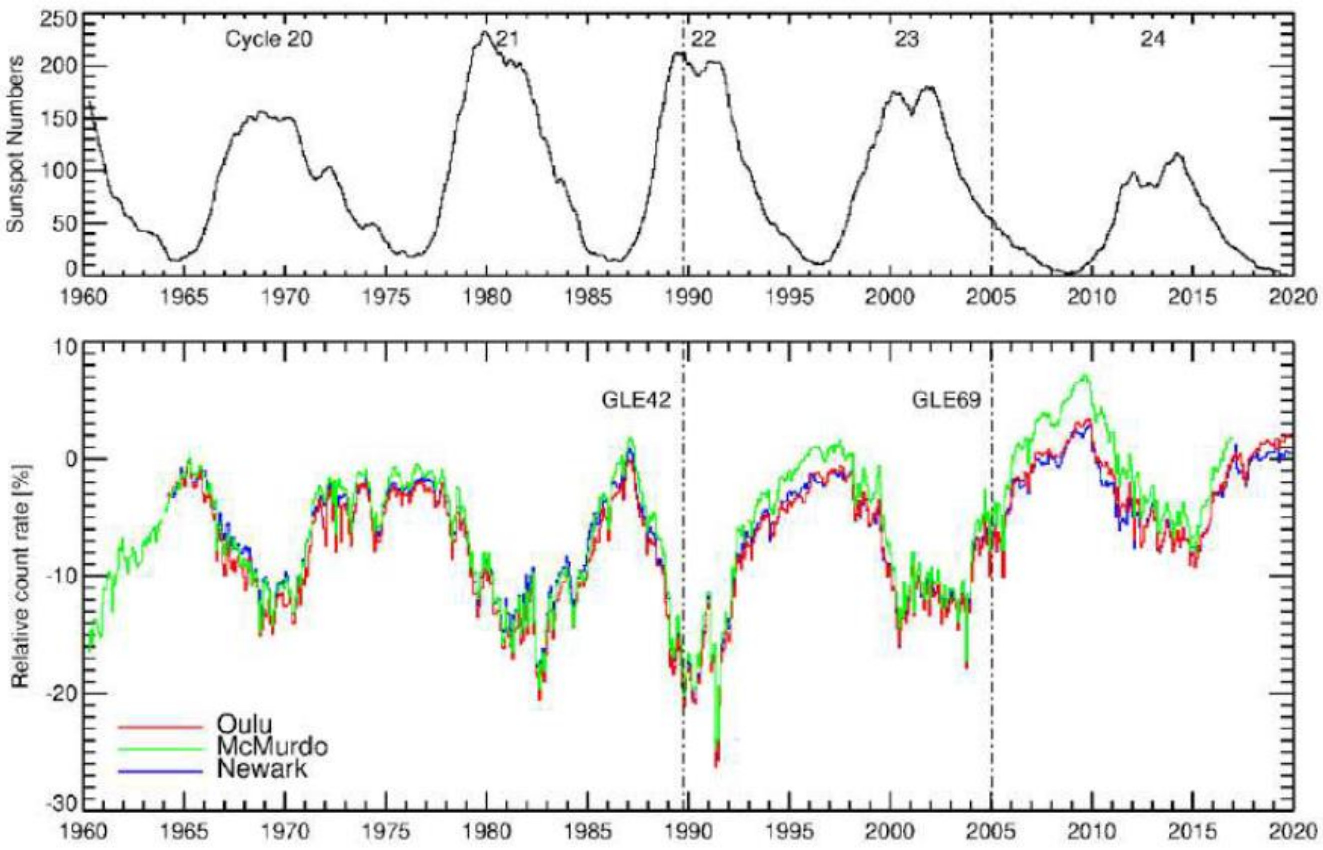
ALTITUDE (feet)	HOURS AT LATITUDE 60 N	HOURS AT EQUATOR
27,000	630	1330
30,000	440	980
33,000	320	750
36,000	250	600
39,000	200	490
42,000	160	420
45,000	140	380
48,000	120	350

- The radiation dose at the poles, with normal solar activity is about 3 to 5 times greater than in in equatorial latitudes.
- For practical purposes, Table 2 presents estimates for the number of flying hours per year required to reach an effective dose of 1 mSv for a given flight level and latitude.

SANSA SOUTH AFRICAN NATIONAL SPACE AGENCY

- → At aviation altitude passengers and aircrew are routinely exposed to elevated level of comic rays.
- → Dose rates is dependent on the altitude, geomagnetic latitude, and duration of the flight, and solar cycle.
- → Models have shown that the amount of radiation exposure on an aircraft is subjected to change and during a solar storm it can increase.
- → The more time you spend flying the more exposure you get.
- → So it is important to monitor and evaluate the dose amount being received by air travellers to asses the long term effects.

Solar cycle dependent of cosmic rays



The analysis of Bütikofer, R., et al. 2008 shows a maximum increment of the effective dose rate due to solar cosmic rays in the south polar region around 70°S and 130°E at flight altitude of almost three orders of magnitude for GLE69 https://doi.org/10.1016/j.scitotenv.2007.10.021.

science & innovation
Department: Science and Innovation
REPUBLIC OF SOUTH AFRICA

SANSA
SOUTH AFRICAN NATIONAL SPACE AGENCY

Example showing shielding of CR Radiation

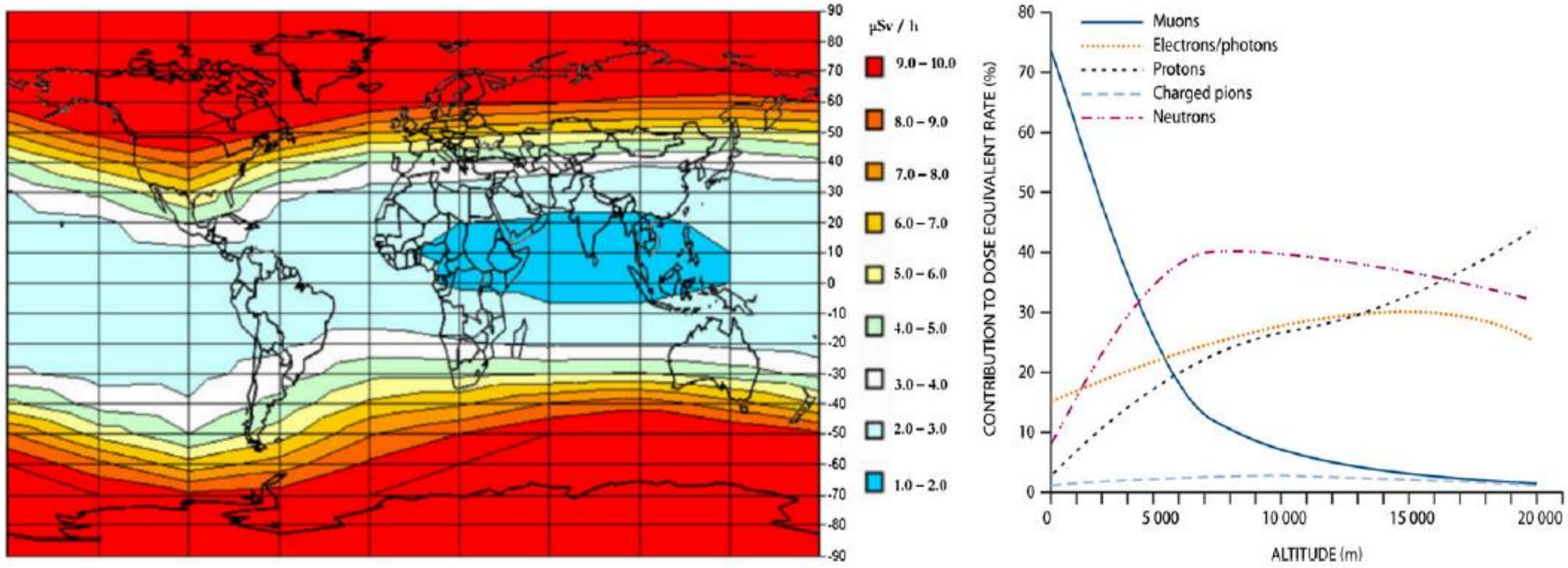
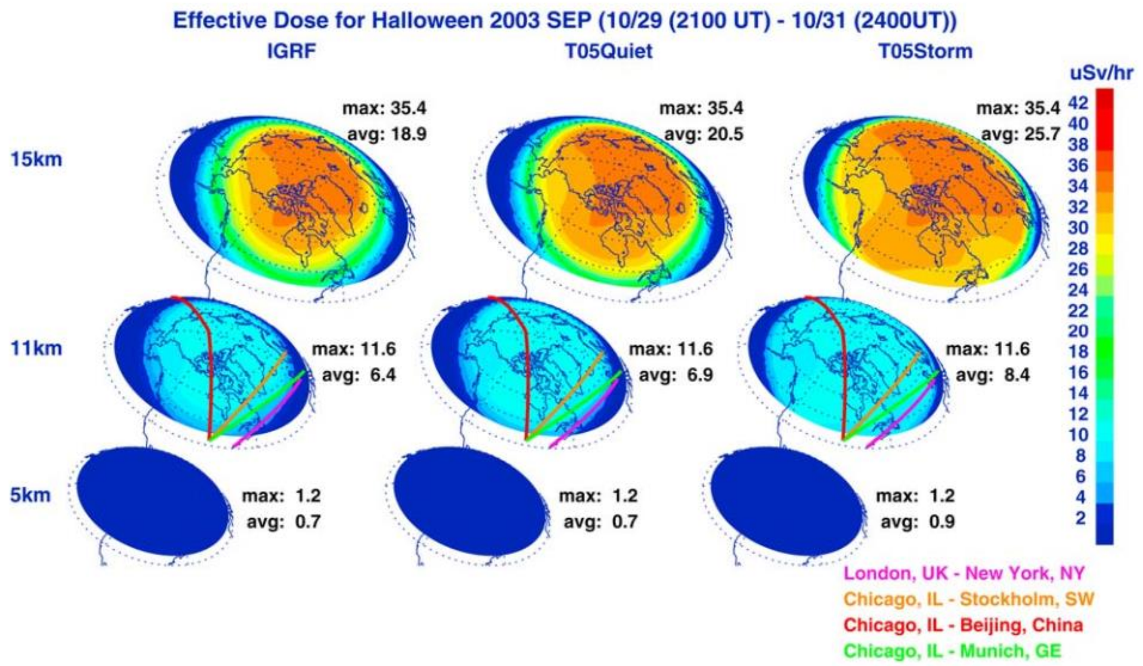


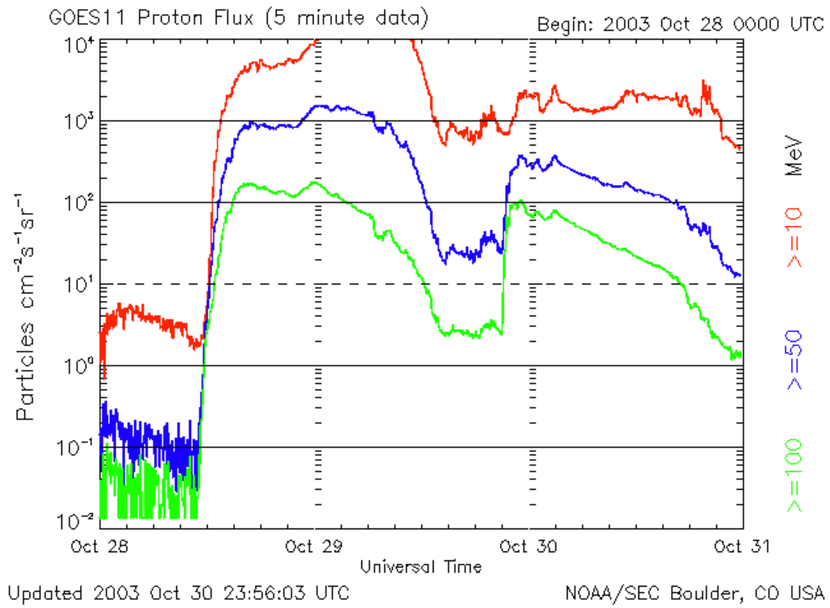
Fig. 1 Geomagnetic shielding of cosmic radiation by latitude and longitude at an altitude of 11 km Frasch et al. [27] and components of the dose rate due to the cosmic rays in the atmosphere

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

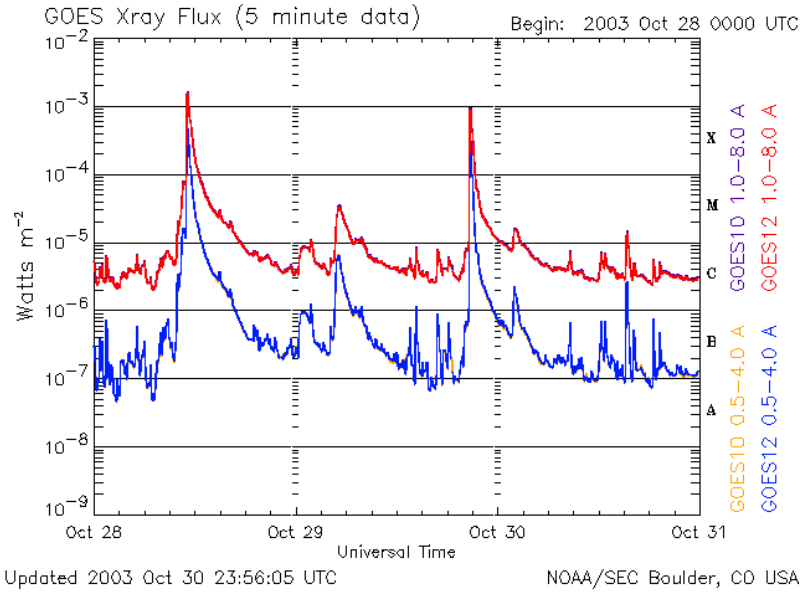
SANSA
SOUTH AFRICAN NATIONAL SPACE AGENCY

Halloween Storm and its impact



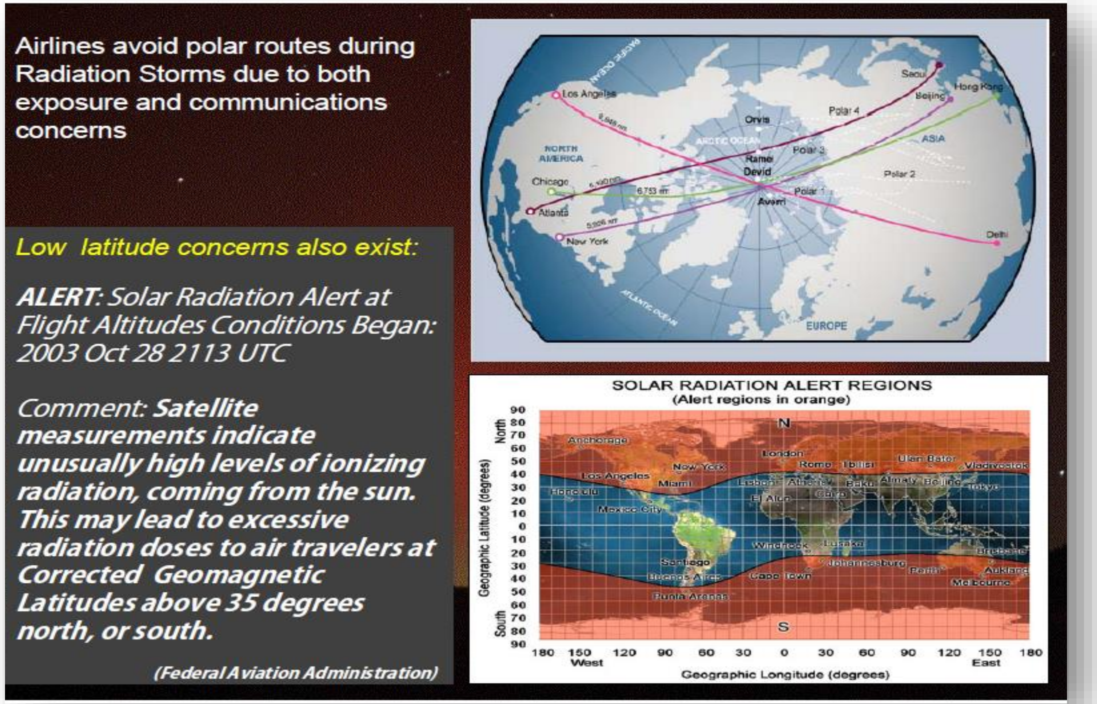


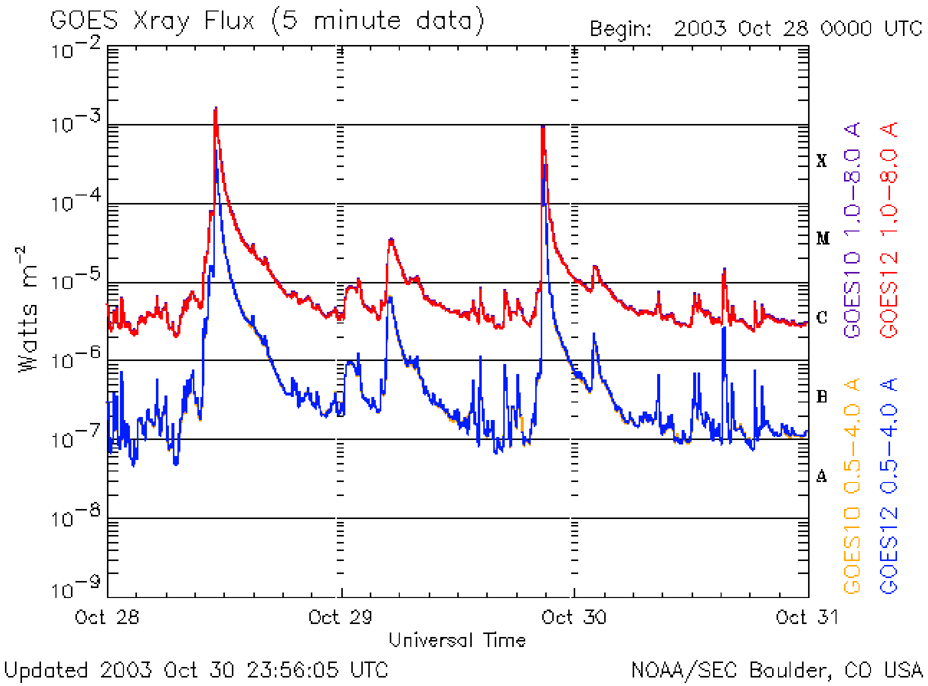
Mertens, Christopher J., et al. "Geomagnetic influence on aircraft radiation exposure during a solar energetic particle event in October 2003." *Space weather* 8.3 (2010).



science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

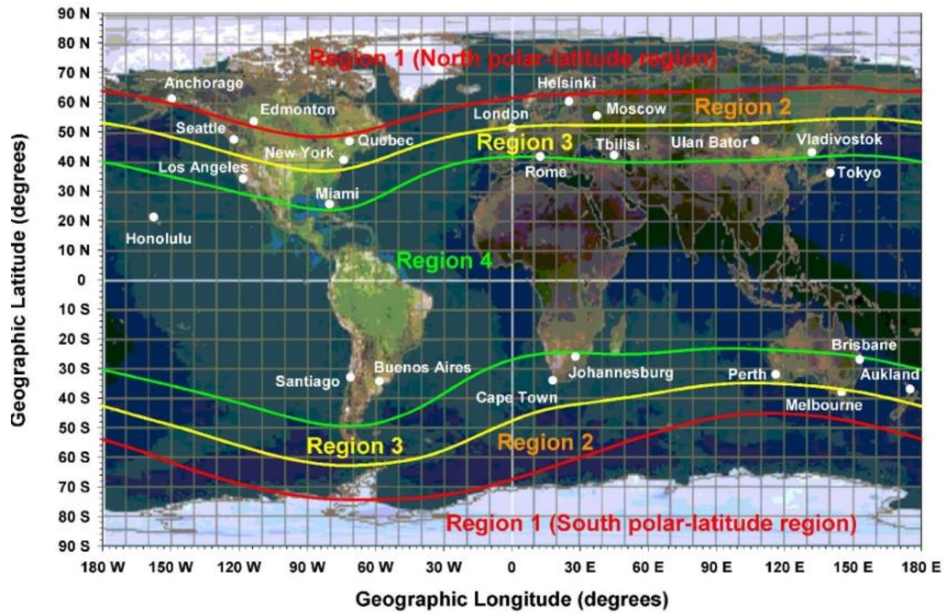
SANSA
SOUTH AFRICAN NATIONAL SPACE AGENCY

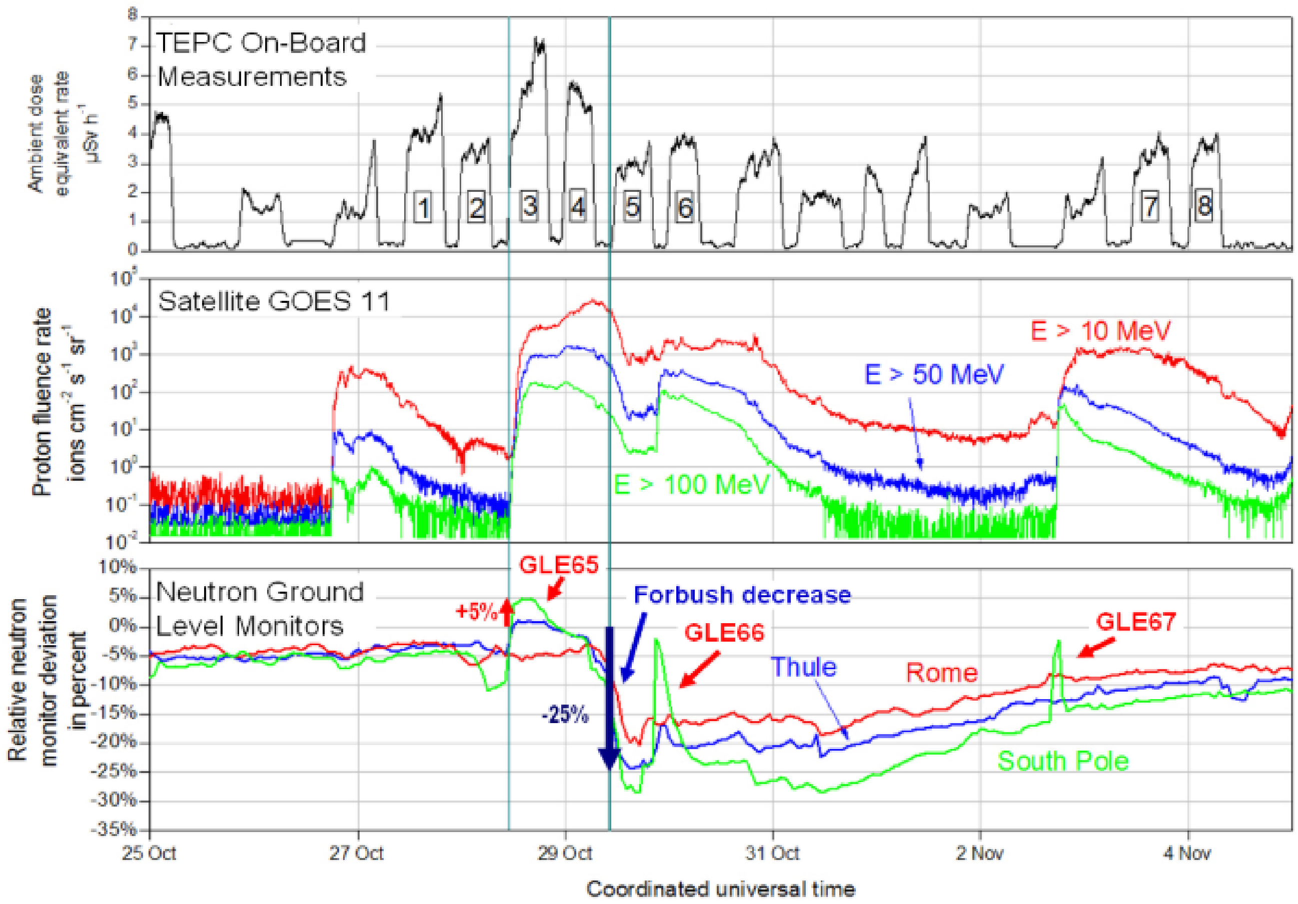


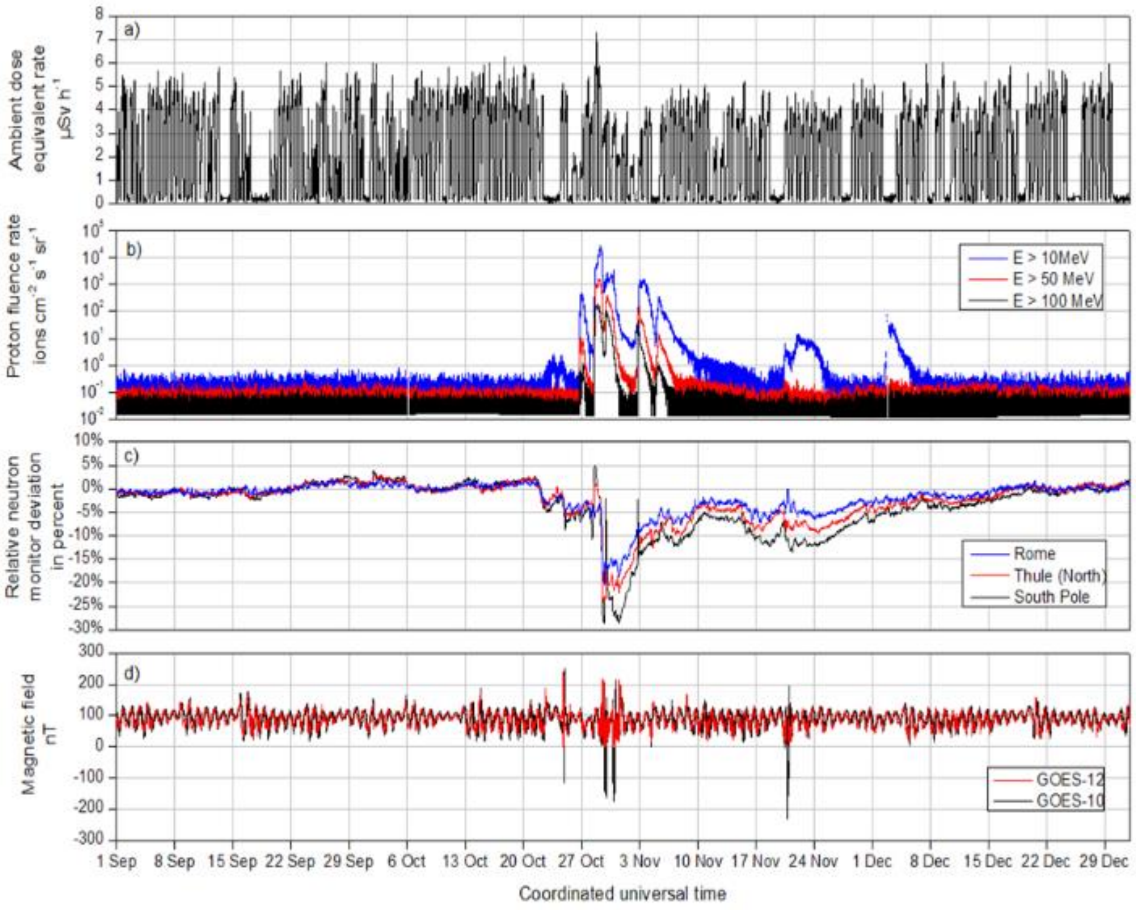


- The electronic system within the aircraft is subjected to high levels of ionizing radiation which can generate transients causing operating errors that can affect system functions and data.
- The most common effect is the so-called single event effect (SEE), which is caused by the high neutron flux at the cruising altitude and single event upset (SEUs) caused by ionizing radiation from galactic cosmic rays.

•FAA issued its first ever alert on radiation doses received by airline passengers above 25,000 ft. Doherty, P., Coster, A.J. & Murtagh, W. Space weather effects of October–November 2003. *GPS*







Beck, Peter, et al. "TEPC reference measurements at aircraft altitudes during a solar storm." *Advances in Space Research* 36.9 (2005): 1627-1633.

Measurements performed during Sep and Dec 2003 by TEPC, Beck et al .2005

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

SANSA
SOUTH AFRICAN NATIONAL SPACE AGENCY

Example January 2005

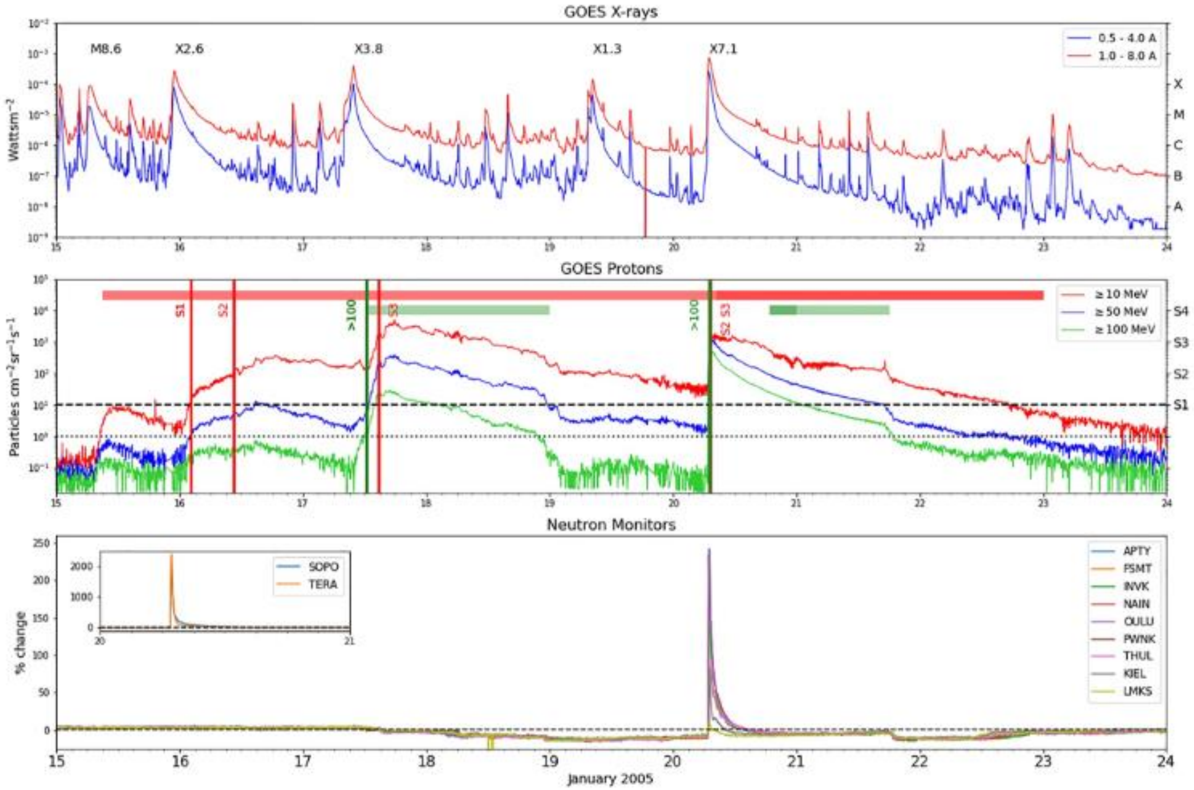


Figure 2. Summary of the January 2005 solar activity. Top: Geostationary Operational Environmental Satellites (GOES) X-rays showing solar flare activity. Middle: GOES ≥10 MeV (red), ≥50 MeV (blue) and ≥100 MeV (green) proton measurements with timings for SWPC ≥10 MeV and ≥100 MeV Warning (horizontal bars) and Alert (vertical lines) products plotted. Dashed and dotted black lines indicate the ≥10 MeV particle flux exceeding 10 p.f.u. (S1 storm) and ≥100 MeV particle flux exceeding 1 p.f.u. thresholds. Bottom: Relative change in neutron count rate at selected high latitude neutron monitor stations with inset showing South Pole (SOPO) and Terre Adelie (TERA).

Table 4
ICAO Radiation Advisories for GLE69 on the 20th of January 2005

Issue time (UT)	Advisory	Latitude	Longitude	Flight levels
2005-01-20 06:55	SEV	HNH MNH MSH HSH	E180–W180	ABV FL320
2005-01-20 06:55	MOD	HNH MNH MSH HSH	E180–W180	ABV FL250
2005-01-20 07:25	SEV	HNH MNH MSH HSH	E180–W180	ABV FL410
2005-01-20 07:25	MOD	HNH MNH MSH HSH	E180–W180	ABV FL320
2005-01-20 08:00	SEV	HNH MNH MSH HSH	E180–W180	ABV FL470
2005-01-20 08:25	MOD	HNH MNH MSH HSH	E180–W180	ABV FL390
2005-01-20 10:15	SEV	HNH MNH MSH HSH	E180–W180	ABV FL540
2005-01-20 11:05	MOD	NO SWX EXP		
2005-01-20 12:20	SEV	HNH MNH MSH HSH	E180–W180	ABV FL600
2005-01-20 13:30	SEV	NO SWX EXP		

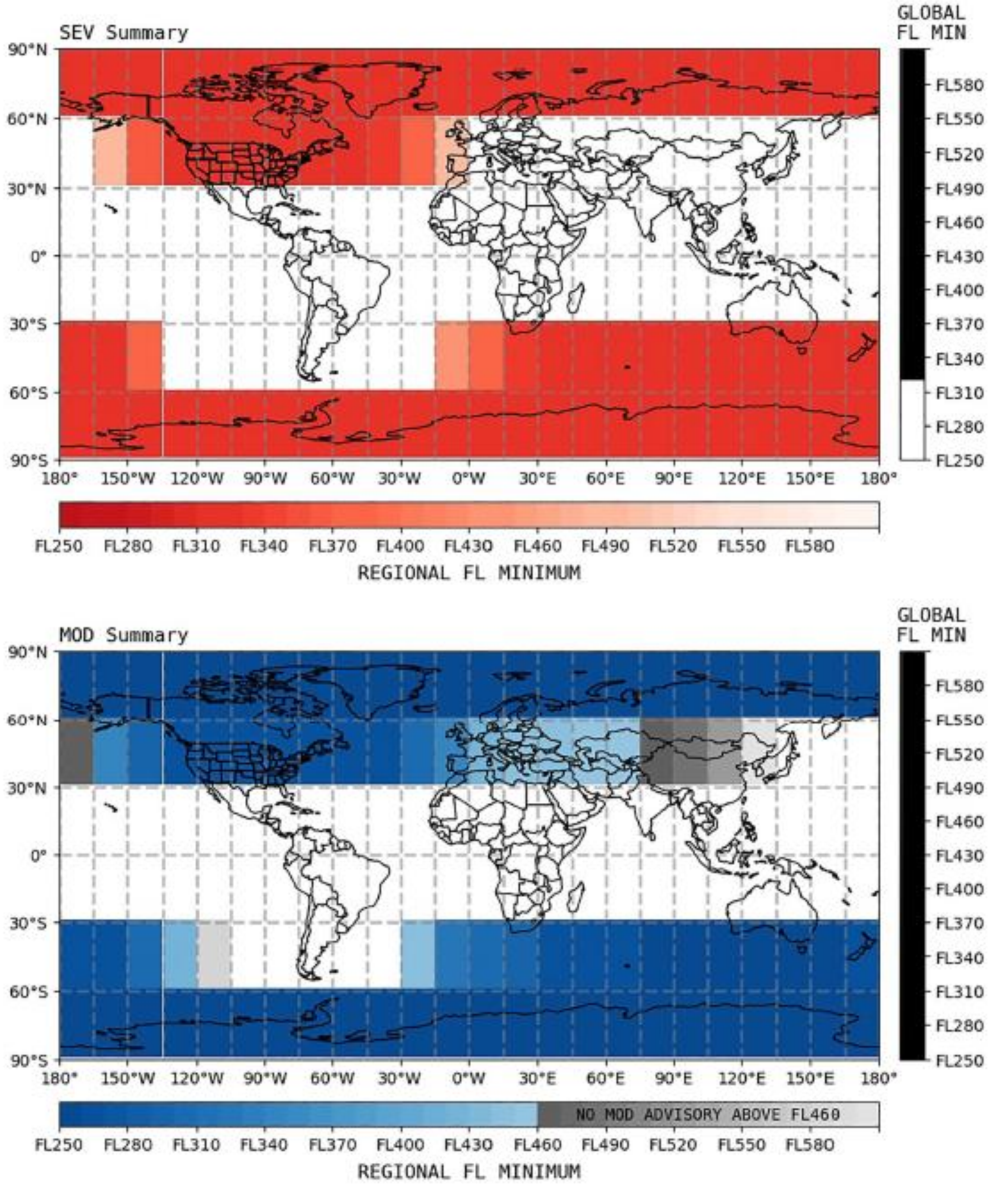
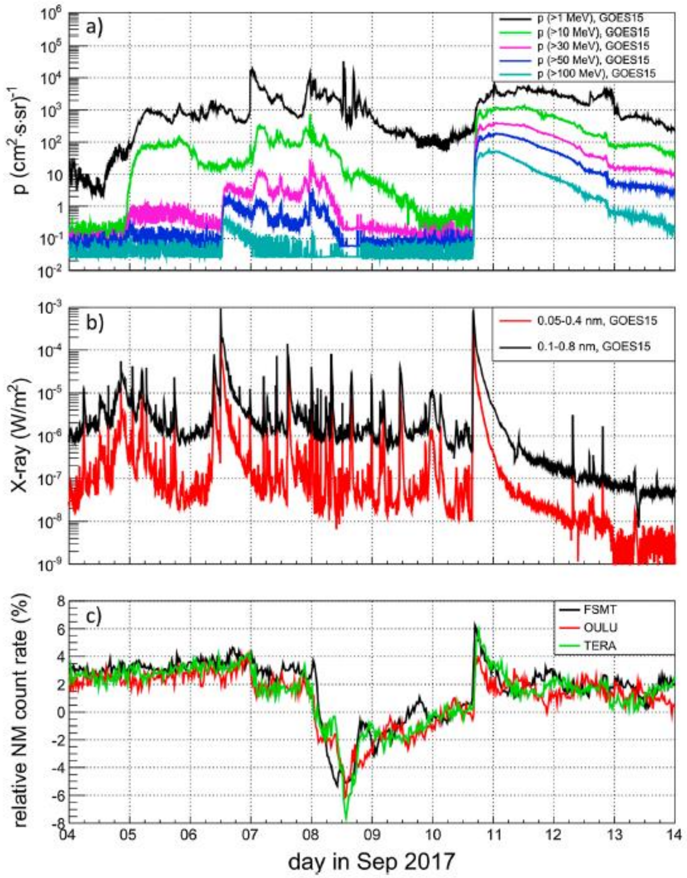
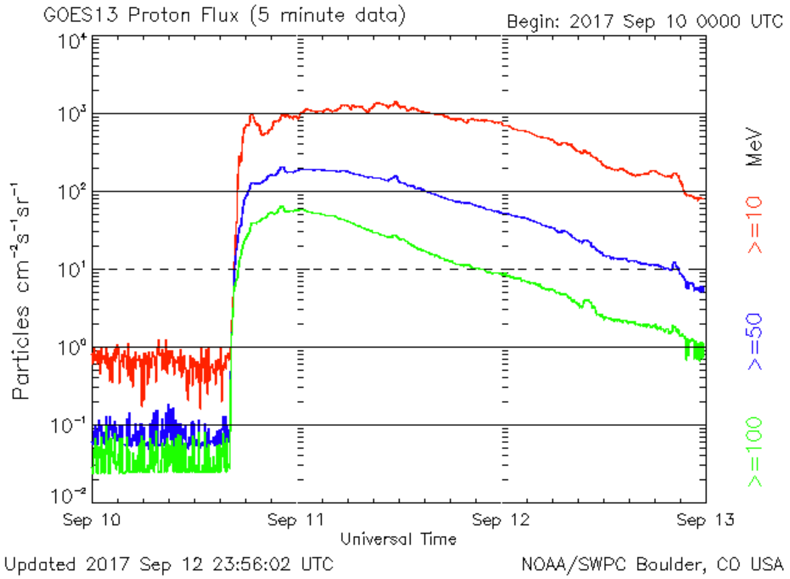


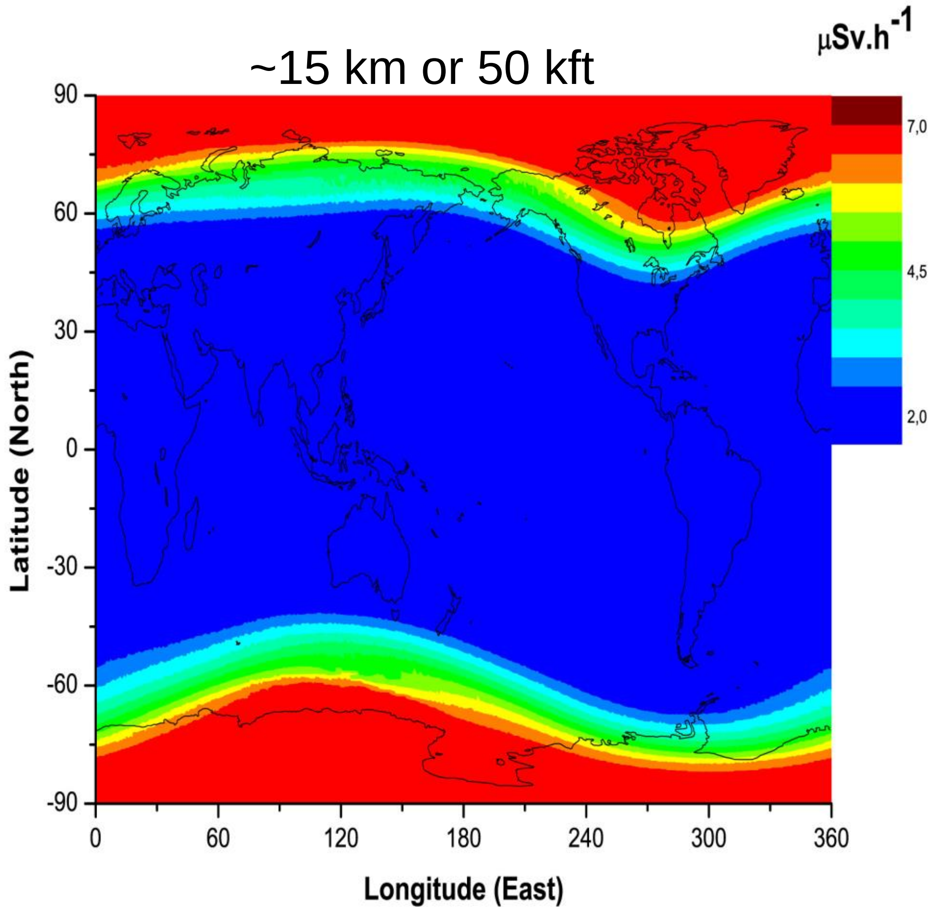
Figure 3. CARI-7A radiation summary maps thresholded to show regions exceeding the SEV (top:red) and MOD (bottom:blue/gray) ICAO thresholds. Shaded gray cells in the MOD summary map (bottom) show regions ≤FL460 where the radiation effective dose rate has surpassed the MOD threshold, but for which an advisory is not required. Horizontal regional FL Minimum colorbar indicates the minimum flight level reached in each individual region. The vertical global FL minimum colorbar shows the lowest flight level reached globally. The inclusion of MOD and SEV advisories at mid geographic latitudes, due to the tilt of the geomagnetic pole, is discussed Section 6.

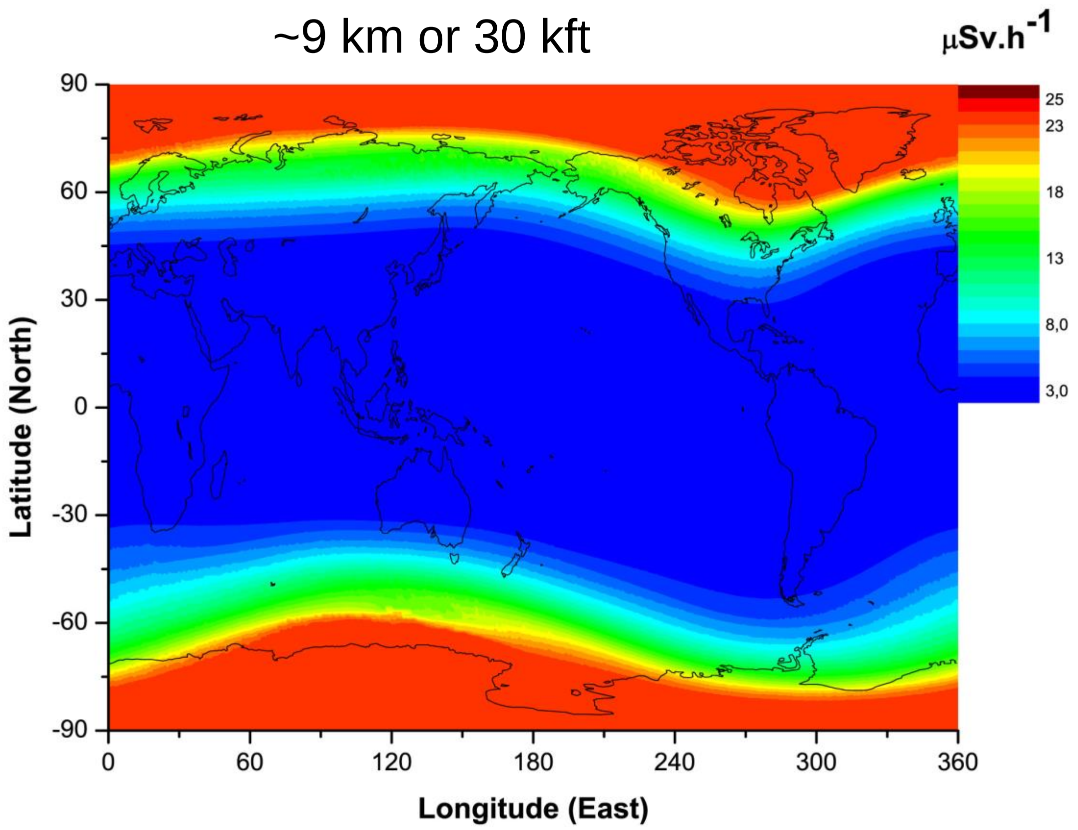




"Assessment of the Radiation Environment at Commercial Jet-Flight Altitudes During GLE 72 on 10 September 2017 Using Neutron Monitor Data. Radiation levels jumped about 6%," reports Clive Dyer, a visiting Professor at the University of Surrey Space Centre. "In historical terms, it was a relatively small one -- only about one thousandth as strong as the event of 23 Feb 1956, which is the largest measured."
Nevertheless, it could have made itself felt at aviation altitudes. Dyer says that "passengers flying on high-latitude routes at 40,000 feet could have absorbed an extra 10 microsieverts of radiation," approximately doubling the usual dose on such a flight."

In the worst-case scenario, in which the airplanes took off close to the onset of the GLE and maintained a high cruise altitude of 40,000 feet (12 kilometers), passengers on a flight from Helsinki, Finland, to Osaka, Japan, would have received a roughly 90-microsievert dose of radiation, the team found. A flight from Helsinki to New York would have received a slightly higher dose, around 110 microsievert.
Such levels are far below an average American's annual radiation exposure of 1 millisievert. But they remain above typical background radiation and could pose a cumulative health risk for aircraft crew and pilots, who already receive roughly triple the average yearly dose of radiation. Radiation can also upset or damage the sensitive electronics aboard commercial aircraft, underscoring the importance of preparing for severe space weather. (*Space Weather*, https://doi.org/10.1029/2018SW001946, 2018)



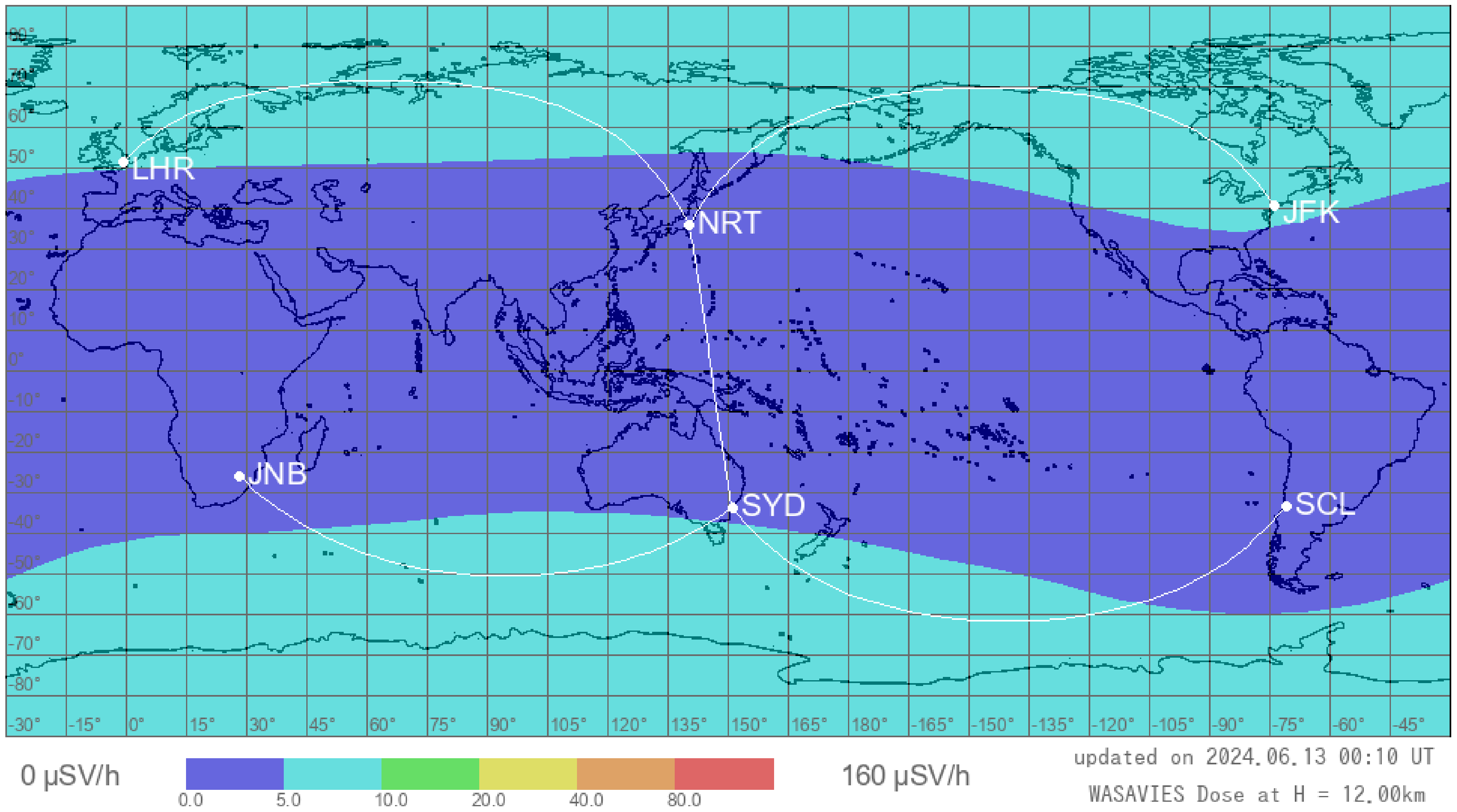


The exposure at cruise flight altitudes during strong SEP events can be significantly enhanced compared to quiet periods. It is a superposition of contributions of GCRs and SEPs. As a result, during strong SEP events and GLEs, crew members/passengers may receive doses well above the background level due to GCRs (e.g., Matthiä et al., 2009; Tuohino et al., 2018). Copeland et al., 2018; Kataoka et al., 2018;

Matthiä et al., 2018. Mishev, A. L., and I. G. Usoskin. "Assessment of the radiation environment at commercial jet-flight altitudes during GLE 72 on 10 September 2017 using neutron monitor data." ***Space Weather*** **16.12 (2018): 1921-1929.**

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

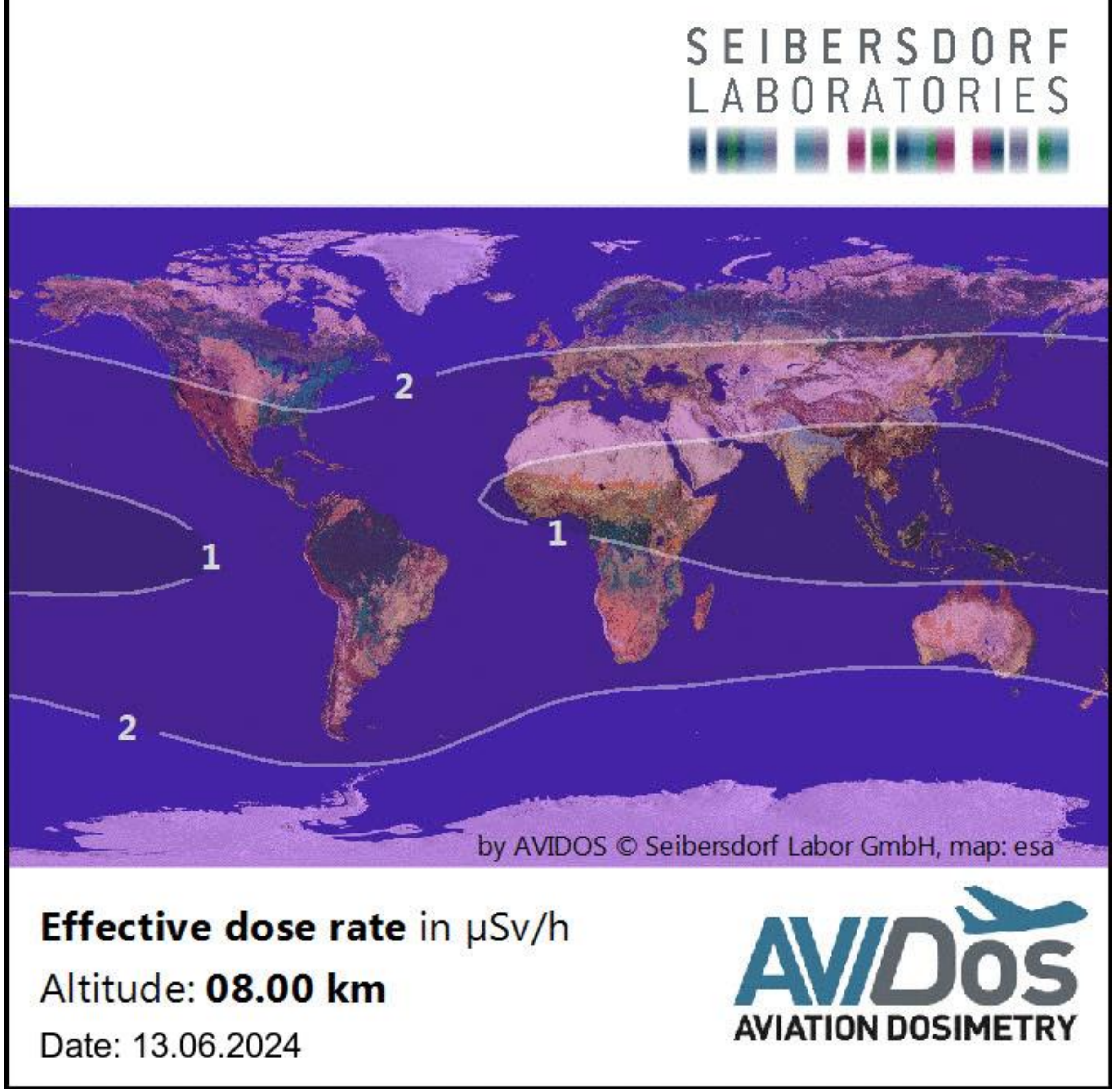
SANSA
SOUTH AFRICAN NATIONAL
SPACE AGENCY



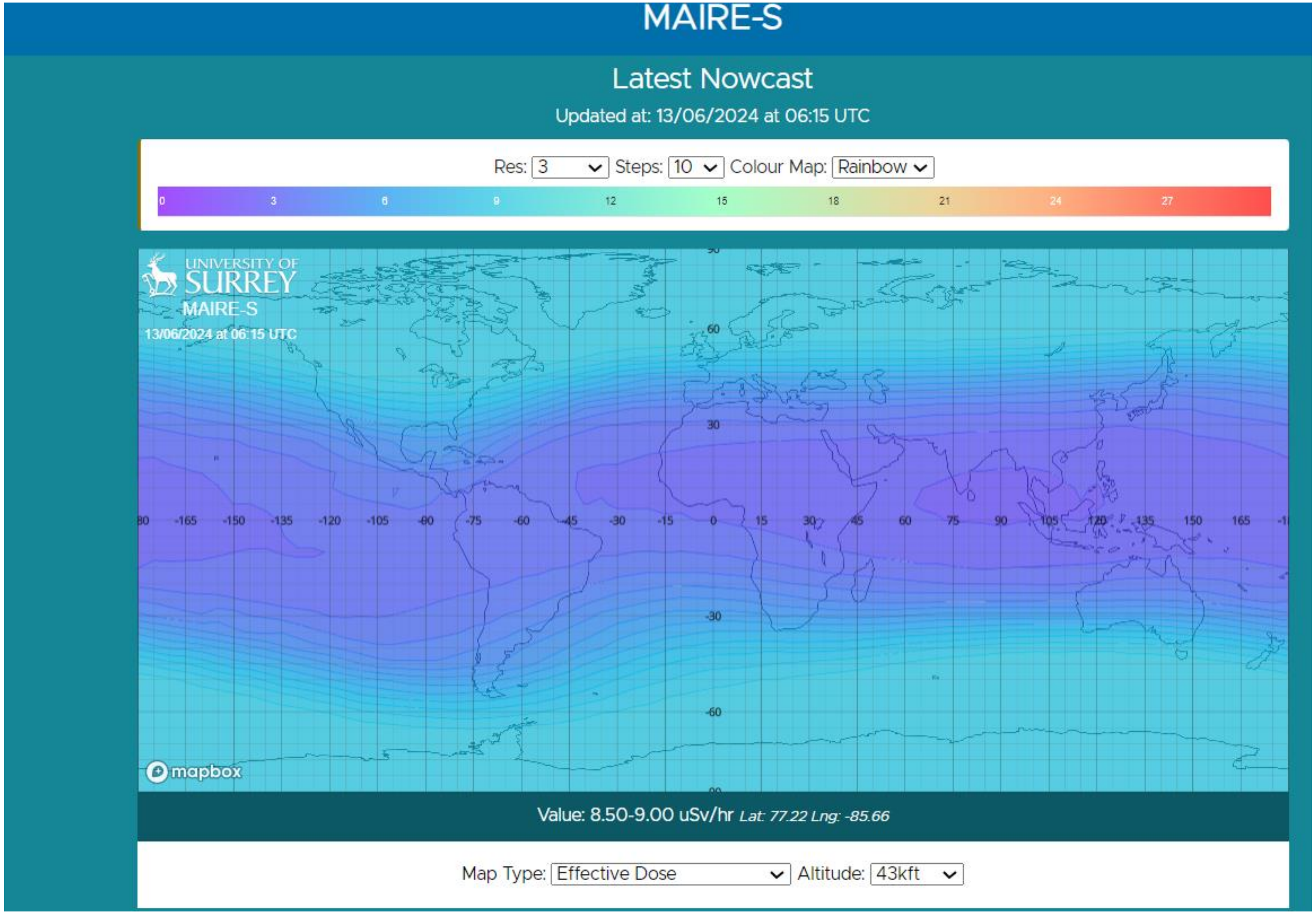
(https://wasavies.nict.go.jp/WorldDose.html).

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

SANSA
SOUTH AFRICAN NATIONAL SPACE AGENCY



(https://www.seibersdorf-laboratories.at/en/products/ionizing-radiation/dosimetry/avidos/current-exposure).



[MAIRE-S Nowcast (surrey.ac.uk)]

Challenges

- The complexity of the radiation field at aviation altitude
- Financial support is required to ensure the robust operation and availability of globally distributed neutron monitors for research and space weather operations.
- Designing an instrument that is best suited for the environment and does not interfere with the aircraft's operation and still be able to measure all the different components of the complex mixed radiation field.
- There is a scarcity of measurements of the ionizing radiation environment at aviation altitudes, even though there are ~10,000 aircraft in the air around the world at any time.
- Radiation measurements in the steady state atmospheric ionizing radiation environment(SSAIRE) are particularly lacking immediately before, during, and after SEP events.

Challenges …

- Insufficient onboard measurements especially during GLE(SEPs) events
- Solar energetic particle forecasting must be improved to move aviation radiation nowcasts to forecasts to meet customer requirements for longer lead times for planning and mitigation.
- Radiation measurements obtained at, and above aircraft altitudes are needed to better understand the impact SEPs are likely to have on aircrew, passengers, and avionics as functions of the magnitude, spatial extent, and magnetic influence of the SEP event.
- Furthermore, what is the appropriate response of pilots and air traffic planners/controllers in light of the possible onset of a SEP?
- Financial implications: Rerouting aircraft or reducing aircraft altitude may reduce the radiation exposure of an aircraft and its occupants but comes at a high cost in terms of time and fuel.

References

- ICRU, 2010
- https://doi.org/10.1029/2018SW001946, 2018)
- ICRP, 2016
- FAA 2003

https://doi.org/10.3389/fspas.2023.1149014

- Bain, H. M., et al. "NOAA space weather prediction center radiation advisories for the international civil aviation organization." *Space Weather* 21.7 (2023): e2022SW003346.
- MAIRE-S Nowcast (surrey.ac.uk)
- https://www.seibersdorf-laboratories.at/en/products/ionizing-radiation/dosimetry/avidos/current-exposure
- 10.1029/2020SW002593
- courtesy of 19hubbl01
- https://doi.org/10.1029/2018SW001932
- Conker at al. (2003)
- Kintner et al., Inside GNSS, Aug. 2009
- *courtesy of https://www.gwu.edu*
- (https://wasavies.nict.go.jp/WorldDose.html).
- https://doi.org/10.1051/swsc/2018029
- Shouop, Cebastien Joel Guembou, et al. "Radiological protection requirements with regard to cosmic ray exposure during air travel." *The European Physical Journal Plus* 135.5 (2020): 438.

Ref: ICRP, 2016. Radiological Protection from Cosmic Radiation in Aviation. ICRP Publication 132. Ann. ICRP 45(1), 1–48.

THANK YOU

http://www.sansa.org.za
http://spaceweather.sansa.org.za
http://research.sansa.org.za