The Importance Of Single Event Effects For Atmospheric Radiation Scales, Alerts & Actions

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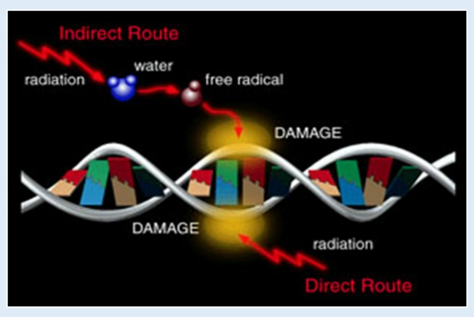
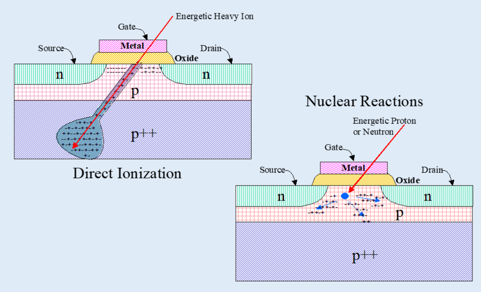
Introduction

- **Single Event Effects** are due to the interactions of individual particles of radiation with human cells and sensitive regions of microelectronics. These may be directly ionising (e.g. energetic ions) or by nuclear reactions (e.g. uncharged neutrons) causing recoils and emission of charged particles. In the case of human cells DNA strands can be broken and then mis-repair leading to cancers. For modern electronics results range from bit-flips to burnouts. Probabilities are dependent on the density of ionisation as expressed by linear energy transfer.
- Up to 60000 feet In the atmosphere the dominant radiations are secondary neutrons, electrons and protons generated by very energetic Galactic Cosmic Rays and Solar Energetic Particles. The former modulate in antiphase with the solar cycle while the latter are sporadic bursts over hours to days; many are capable of affecting spacecraft while a small but significant subset are sufficiently energetic to give ground level enhancements (some 76 since observations began in 1942). Above about 60000 feet both primary and secondary heavy ions are significant.
- Aircrew and passenger dose could significantly exceed recommended limits (see R Tanner paper) but would not be fatal.
    - 2.2mSv UK average from background, 10mSv per year action level for radon exposure in some areas; 6mSv CT scan, 10 to 20 mSv in GLE 05 on 23rd February 1956.
- However, malfunctions in electronics (single event effects) could be the major safety issue:
    - There could be ‘increased pilot workload’ from anomalies in avionics during GLEs at the same time as communications and navigation systems are compromised.
    - IEC TS62396 and EASA CM-AS-004 standards give methods for combatting SEEs in avionics in quiet time GCRs but **do not impose standards for GLEs**. This is unlikely to change in the near future
    - Peak SEE rates and effective dose rates would have been 1000x normal background rates from cosmic rays for the event of 23 February 1956 at 40000 feet on transatlantic flights (Dyer et al. IEEE TNS 2018).
    - Hence we need avoidance procedures (grounding, altitude and/or latitude lowering) based on both effective dose to crew and passengers **and hazardous levels of SEEs in avionics**. Without knowledge of safe engineering levels for GLEs , a conservative approach is required.





Recent & Current Work

SWPC/SWAG (26 Sept 2024) has published “Results of the First National Survey of User Needs for Space Weather” The following are some of the recommendations for the Aviation Sector:

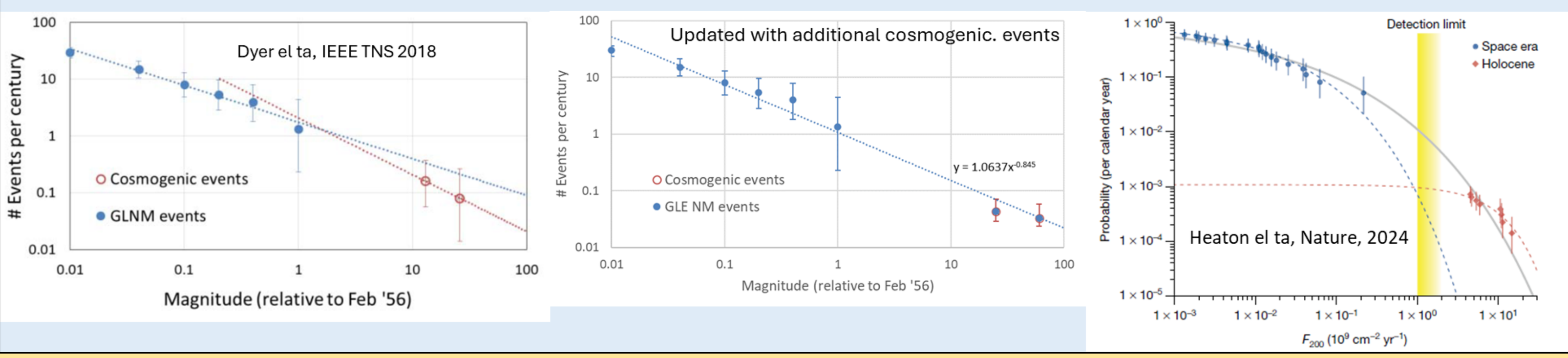
- need for improved education, information dissemination, and policy development to address space weather risks effectively across the aviation sector.
- need for more accessible resources and clearer guidelines to enable better risk-informed decision-making and management.
- there are no specific regulations mandating its use.
- need for radiation, navigation and communication measurements, modelling, and standardization across the aviation industry.
- concerns about health effects, data availability, and lack of resources for effectively incorporating space weather into flight planning, decision-making, and safety protocols.

ICAO has introduced MOD and SEV radiation alerts. These levels are under review. So far we have seen only false alert levels for March 24th and May 10th-14th 2024. Beware rapid recoveries from Forbush decreases and unvalidated models.

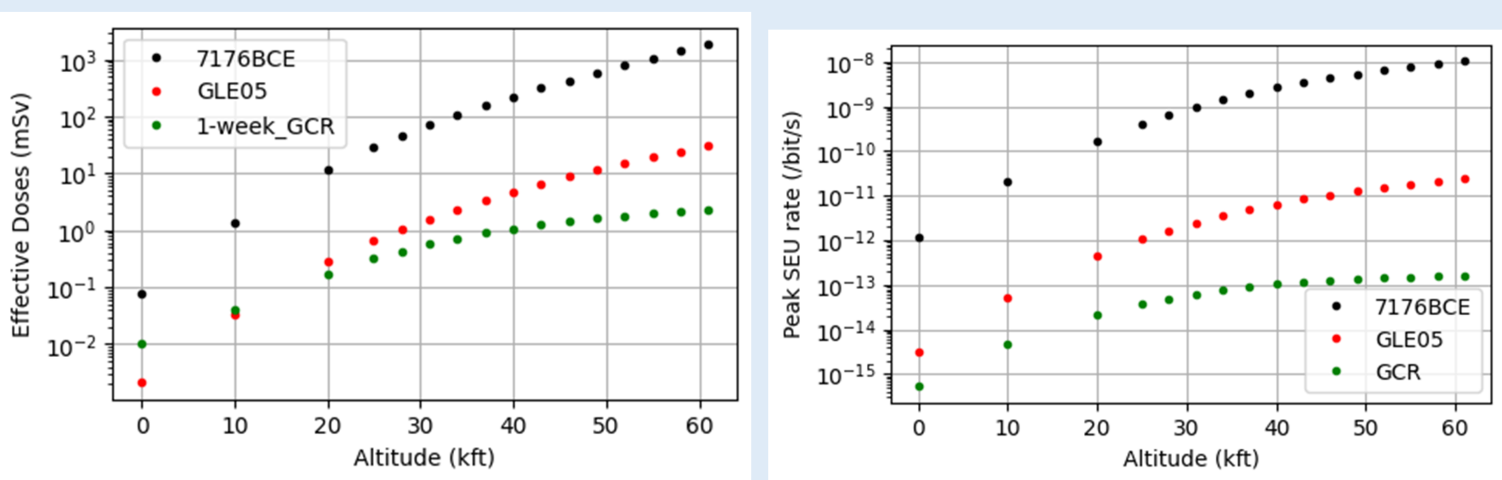
SWPC Revision of scales (TDM15). Survey of users shows desire to keep the same structure but S-scales not adequate for atmospheric radiation as > 10 MeV, whereas >300 MeV particles needed to give GLEs. Use of S-scale for aviation gives many false alarms.

We propose an AR scale based on high-latitude, ground-level neutron monitors and/or high energy proton channels on spacecraft (e.g. > 500 MeV on GOES, Cerenkov telescopes on other spacecraft.)This scale is for discussion and feedback is welcome.

Event Probabilities & Feb56 Scale



Doses and SEU rates vs Altitude for Background GCRs and worst-case recent history (GLE05, Feb56)and cosmogenic events for flights at < 1 GV cut-off rigidity



1 Week GCR is 168 flight hrs; GLE05 received in 1.6 hrs

For average SRAM 10^{-13} cm^2 per bit
5x worse often used.

MAIRE calculations with Kodolbski (2023) spectra

Impacts of a Carrington type geomagnetic storm on vertical cut-off rigidity

- Reduced so that
    - The polar regions expanded by ~ 15 degrees towards the equator
    - The whole UK airspace, and down to Florida in NA
- Modest increase in GCR doses
    - e.g. ~8 -> ~9 uSv/h for southern England @43kft
- Severe increase in GLE/SEP doses
    - e.g. GLE69 peak rate ~ 0 -> ~ 200 uSv/h for southern England @43kft
- For Carrington Event GLE could be 4xFeb56

Proposed Atmos Rad. Levels (AR)

Scale	Name	Potential Effects	Physical Measure	Average Frequency
AR5	Extreme	**Airflight:** 7 mSv per hr. European aircrew will exceed annual dose limits in 1-2 hours (route dependent). SEE rates at altitude at 35000 per Gbit-hr. Avionic system errors are highly likely to occur regularly/continuously *Avoidance action should be mandatory* **Safety Critical Infrastructure :** Electronic system problems at ground level (SEU rates 160 per Gbit-hr).	1xFeb56. 5000% increase in GLNM + >500 MeV protons at 240 pfu	Every 50 to 70 years
AR4	Severe	**Airflight:** 3.5 mSv per hr. Major contribution to annual crew dose. Passengers will exceed annual dose limits (1mSv, 0.5 mSv for pregnancy), European crew are likely to exceed annual limits in a single flight. Avionic system errors are likely to significantly increase. SEU rates at altitude at 17500 per Gbit-hr. *Avoidance action highly recommended* **Infrastructure:** Possible electronic system problems at ground level (SEU rate 80 per Gbit-hr).	0.5xFeb56. 2500% increase in GLNM + >500 MeV protons at 120 pfu	Every 30 years
AR3	Strong	**Airflight:** 700 µSv per hr. Passengers likely to exceed annual dose limits (1 mSv). Significant addition to crew dose limit. SEU rates at altitude at 3500 per Gbit-hr. *Avoiding action if possible. Maybe add to ICAO levels with new nomenclature for consistency.*	0.1xFeb56. 500% increase in GLNM + >500 MeV protons at 24 pfu	1 per 12 years
AR2	Moderate	**Airflight:** 80 µSv per hour. *Current ICAO Severe*. Change nomenclature. Add to annual records. Close to limits for pregnancy (FAA 0.5mSv per month) for 7 hr flight if no avoiding action. SEU rates at altitude at 350 per Gbit-hr. *Strongly consider avoiding action*	0.01xFeb56. 50% increase in GLNM + >500 MeV protons at 2.4 pfu	1 per 3 years
AR1	Minor	**Airflight:** 30 µSv per hr (@40 kft and < 1GV for all ARs). *Current ICAO Moderate*. No dose limits exceeded but add to annual dose records. SEU rates at altitude at 100 per Gbit-hr. *No satellite launches. (AR1>)*	0.003xFeb56. 18% increase in GLNM + >500 MeV protons at 0.8 pfu	1 per year

Notes: GLE time profile and anisotropy should also taken in to account, e.g., Feb56 was 1.6 hrs at 5 mSv per hour over UK, but Ottawa same integrated dose over more like 4 hrs. SEE rates are for an average SRAM as example. Can be 5x worse or better. S-scale should be limited to communications, navigation and space, For example AR5 for a Feb56 spectrum would also be S4/5. However only 10% of S4/S5 events would give AR4/5. Actions need discussion with aviation industry **including pilots**.

Outlook

Energetic solar particles events/GLEs will become increasingly important given potential impact in our modern society:

- Ever more autonomous transport (cars, trains, aircraft)
- Possible impact on the Cloud
- New supersonic aircraft (Concorde had no microelectronics)
- Lunar/Mars bases (electronics for life support)
- Safety-critical infrastructure can require reliability to 1-in-1000/10000 years (10 to 100xFeb56) New levels AR6 and AR7 could cover these. 70 and 700mSv in flight!

We need:

- Best science on extreme GLE environment (peak and integrated) to design to.
- More research on effects, mitigation, standards and tools.
- Harmonisation of standards, alerts and scales plus enforcement.
- Very immediate reaction in flight involving nowcasts and forecasts, flights of monitors.
- **With SWPC scales, ICAO levels and IEC standards under review now is the time to get it right.**