IEC TR 62396-6

Edition 1.0 2017-07

TECHNICAL REPORT

colour inside

Process management for avionics – Atmospheric radiation effects – Part 6: Extreme space weather – Potential impact on the avionics environment and electronics

IEC TR 62396-6:2017-07(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

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IEC TR 62396-6, which is a technical report, has been prepared by IEC technical committee 107: Process management for avionics.

This first edition cancels and replaces the first edition of IEC PAS 62396-6 published in 2014. This edition constitutes a technical revision. The technical changes with respect to the previous edition are the contents of the present document.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
107/298/DTR	107/305/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62396 series, published under the general title *Process management for avionics – Atmospheric radiation effects* can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This document provides information intended to improve the understanding of extreme space weather events.

Rarely occurring natural hazards can have a high impact to society and national economies. Natural events have no respect for national boundaries and the whole world can suffer. The April 2010 Icelandic (Eyjafjallajökull) volcano eruption and resulting ash cloud and the March 2011 Japanese earthquake and tsunami demonstrated how devastating rarely occurring natural events can be.

In 2011 the UK recognised “extreme space weather” (ESW) events (also referred to as solar super storms and sometimes simply as super storms) as one of these rare, but high impact, hazards. There is evidence of the impact of ESW events in the past. During an event in February 1956, which was monitored at ground level, a rise in radiation flux of more than 2 orders of magnitude was derived for aircraft environments.

The document does not consider high altitude nuclear explosions or any other man-made modifications of space weather.

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PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 6: Extreme space weather – Potential impact on the avionics environment and electronics

1 Scope

This part of IEC 62396, which is a technical report, provides information intended to improve the understanding of extreme space weather events; it details the mechanisms and conditions that produce “extreme space weather” (ESW) as a result of a large increase in the activity on the surface of the sun and it discusses the potential radiation environment based on projection of previous recorded ESW.

This document does not detail the solutions with regard to the ESW events whose occurrence is extremely rare. As the stakes related to ESW environment go widely beyond the electronics issues and there are a lot of other elements in consideration (human concern for example), this document does not detail potential specific provisions or mitigations.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62396-1:2016, *Process management for avionics – Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62396-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
Carrington event
largest solar storm on record, which took place from 1 to 3 September 1859, and is named after British astronomer Richard Carrington

3.2
coronal mass ejection
CME
large burst of solar wind plasma ejected into space

3.3
extreme space weather
ESW
solar activity leading to the endangerment of engineered systems or human health and safety

3.4
geo-effective
storm causing

3.5
geomagnetic storm
worldwide disturbance of the Earth's magnetic field induced by a solar storm

3.6
single event effect
SEE
response of a component caused by the impact of a single particle (for example galactic cosmic rays, solar energetic particles, energetic neutrons and protons)

Note 1 to entry: The range of responses can include both non-destructive (for example upset) and destructive (for latch-up or gate rupture) phenomena.

[SOURCE: IEC 62396-1:2016, 3.53]

3.7
solar energetic particles
SEP
high-energy particles coming from the sun

3.8
AD774
large ground level enhancement (GLE) implied by radiocarbon-dating of tree rings to have occurred in AD774-775

4 Abbreviated terms and acronyms

ATC	air traffic control
CAA	Civil Aviation Authority
CME	coronal mass ejection
ConOps	concept of operation
EDAC	error detection and correction
ESW	extreme space weather
FAA	Federal Aviation Administration
GCR	galactic cosmic rays
GEO	geostationary orbit
GLE	ground level enhancement
GLNM	ground level neutron monitor
GNSS	global navigation satellite systems
GPS	global positioning system
GRB	gamma ray burst
HF	high frequency
IAVWOPSG	International Airways Volcano Watch Operations Group

ICAO	International Civil Aviation Organization
ICRP	International Commission on Radiological Protection
LF	low frequency
MBU	multiple bit upset
NATS	National Air Traffic Control Service
NOAA	National Oceanic and Atmospheric Administration
QARM	Quotid Atmospheric Radiation Model
RAE	Royal Academy of Engineering
SEB	single event burnout
SEE	single event effects
SEIEG	Space Environment Impact Expert Group
SEPE	solar energetic particle event
SEU	single event upset
SRAM	static random access memory

5 Extreme space weather (ESW)

5.1 General

Space weather is defined in the 2013 report by the Royal Academy of Engineering as "variations in the Sun, solar wind, magnetosphere, ionosphere, and thermosphere, which can influence the performance and reliability of a variety of space-borne and ground-based technological systems and can also endanger human health and safety" [1][1]. A great deal of additional information on the many different varieties of both space weather environments and effects is provided in the report. The probability of occurrence of extreme space weather events is very difficult to determine, especially for the types of events most relevant to avionics. There are approximately seventy years' worth of direct measurements of events affecting the atmospheric radiation environment. Recently this record has been partially supplemented by solar events not directed at the Earth, for example the large solar eruption in July 2012 that was measured by the Stereo A spacecraft [2]. However, it is still the case that the upper limit for the severity of extreme space weather is unknown, and ultimately estimates should be made based on various assumptions.

5.2 Space weather relevant to avionics

The vast majority of space weather phenomena are not directly relevant to avionics. Some, for example ionospheric disturbances that potentially affect GPS navigation and radio communication, are relevant to aviation generally but not to avionics specifically. This document concerns itself solely with solar energetic particle events (SEPEs), as these pose the primary hazard to electronic components within aircraft. Like galactic cosmic rays (GCR), SEPEs are comprised of highly energetic protons and ions that interact with molecules in the upper atmosphere and produce cascades of secondary particles, of which neutrons are of primary interest in this context. The secondary neutrons are able to penetrate the atmosphere at aviation altitudes and below, where they can pose a threat to avionics through single event effects (SEEs) in sensitive components. Much more detail on this general SEE phenomenon is given in IEC 62396-1 and more background on the threat of ESW to aviation and other infrastructure is given in the RAE report. [1]

Knowledge of the SEPE environment is dependent on measurements and thus uncertainties increase substantially with more historical events. In the space era (1960s onwards) there are relatively good measurements from space-borne instruments of SEPE proton fluxes at the

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1 Numbers in square brackets refer to the Bibliography.

lower end of the relevant spectral energy range (i.e. a few hundred MeV and below). These data provide an effect characterisation of such events on satellites where lower energy protons dominate single event effects rates. For terrestrial effects, including the aviation environment, it is crucial to supplement these data with measurements pertaining to the higher energy part of the proton spectra. Protons need a minimum energy of around 300 MeV to instigate secondary cascades that can penetrate to aircraft altitudes. At low latitudes, even higher energies are required for primary particles to penetrate the shielding provided by the Earth's magnetic field. Indeed, it is this geomagnetic shielding that effectively enables knowledge of the higher energy end of the proton spectrum to be obtained. A global network of ground level neutron monitor (GLMN) stations provides continuous measurement of high energy neutron fluxes at the Earth's surface over a broad range of latitudes. These record not only the background GCR-induced neutron flux that varies with an eleven-year period in anti-phase with the solar cycle, but also the infrequent and transient enhancements caused by the most powerful SEPEs. A minority of SEPEs produce a sufficient number of very high energy (~GeV and above) protons to cause measurable neutron flux increases over a range of latitudes within the GLNM network. During these ground level enhancements (GLEs) the geomagnetic field effectively acts as a giant spectrometer, providing proxy information on the incident proton spectrum via relative neutron flux increases at different vertical cut-off rigidities. Vertical cut-off rigidity is the ratio of momentum to charge required by a charged particle (e.g. a proton) to reach the upper atmosphere at a certain point within the magnetosphere. It is a function of both latitude and longitude. If a number of neutron monitors at similar rigidities show differing levels of neutron flux increase, this is a measure of the anisotropy of the event. Tylka and Dietrich [3] have used a combination of neutron monitor data and satellite instrument data to fit proton spectra for 53 of the 67 GLEs recorded since 1956.

5.3 Examples of proton spectra for GLEs

Comparison plots from Tylka and Dietrich [3] of the 23 February 1956 event and the 19 October 1989 ground level events, both of which were large solar events, are given below; these are based on ground level radiation monitoring of the event.

A significant difference between the spectra is that the 1956 spectrum contains more (over an order of magnitude) high energy protons (above 1 000 MeV) than the 1989 event. The events have been termed ground level events because there has been a large increase in atmospheric radiation at ground level which has been monitored. The radiation levels monitored at ground level were significantly higher for the February 1956 event than the October 1989 event. Radiation ground level monitoring has only been available in modern times for about the last 100 years and the February 1956 event can be considered a nominal ESW event. At that time during the 1950s electronics was in its infancy with most systems based on thermionic valves and less prone to influence from atmospheric radiation.

The 23 February 1956 and 19 October 1989 solar proton spectra are given as examples of the different fitting methods in Figure 1 and Figure 2 respectively. It should be noted that only the fits are shown in these plots (symbols do not represent data). The band spectral form, comprised of a double power-law, was deemed to be the best fit to data.

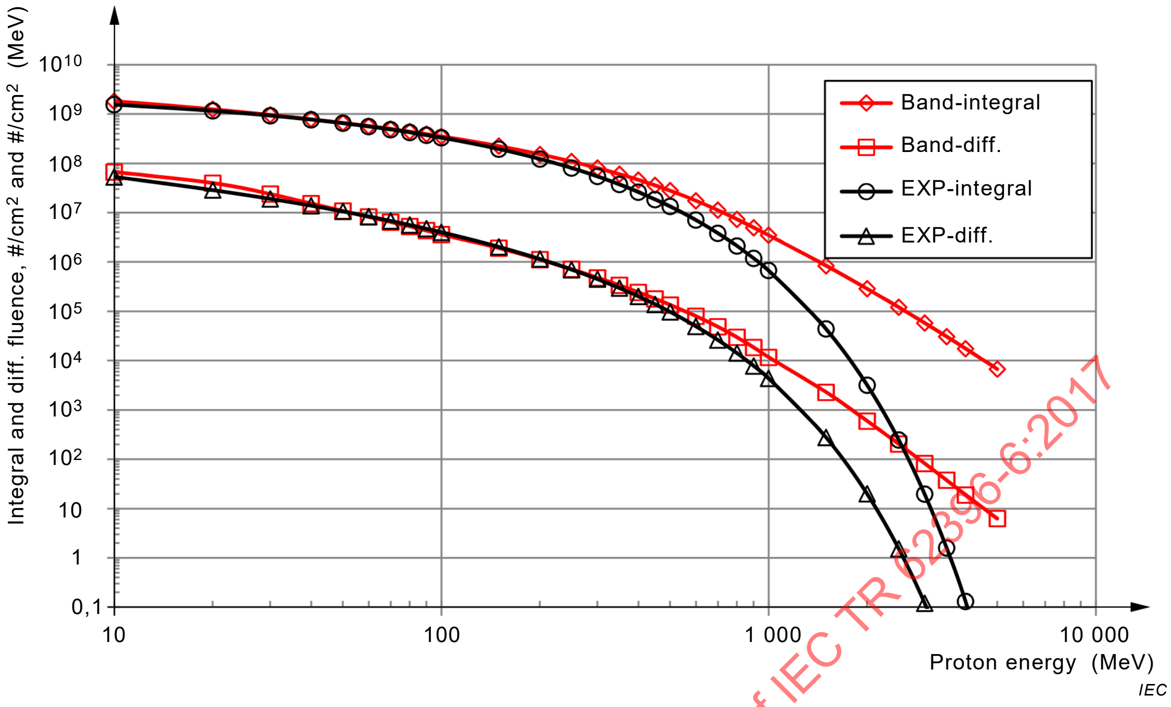

Figure 1 – 23 February 1956 GLE – Integral and differential proton spectra fitted with band and exponential functions

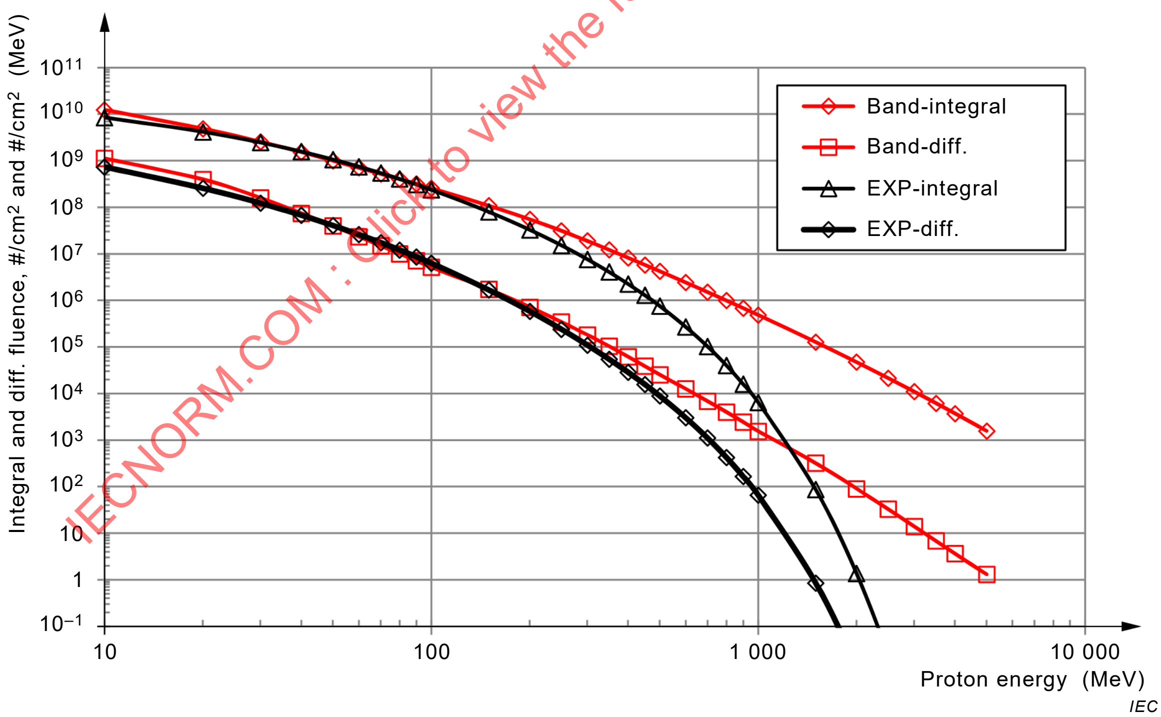

Figure 2 – 19 October 1989 GLE – Integral and differential proton spectra fitted with band and exponential functions

5.4 GLEs in recent history

Since 1942 a total of 71 GLEs have been recorded by ground-based instruments. In the very early years these were measured by ionisation chambers, with the invention of neutron monitors coming a few years later in 1948. Thus, the frequency of GLEs is approximately one per year, although it is notable that there has only been one GLE in the 2007 to 2015 time frame. The largest GLE on record occurred on 23 February 1956, leading to a 50-fold increase in count rates at the neutron monitor station in Leeds, UK. This can be considered as the most extreme directly-observed space weather event in the context of threats to avionics, however it is not a worst possible case (see 5.5.1). Tylka and Dietrich have calculated the integral proton fluence for this event above a rigidity of 1 GV (435 MeV) as ~4 x 10^7 proton·cm^{-2} [3]. Another common metric for characterising SEPEs and GLEs is the integral proton fluence above 30 MeV, F_{30}. A more physically relevant threshold for atmospheric neutron production, however, is 300 MeV. Thus, for completeness, both thresholds are used in this document. Estimates of F_{30} and F_{300} for the February 1956 event vary, though commonly used figures that are consistent with the Tylka and Dietrich analysis are as follows:

$$F_{30} \text{ (Feb '56)} \approx 10^9 \text{ proton·cm}^{-2}$$

$$F_{300} \text{ (Feb '56)} \approx 8 \times 10^7 \text{ proton·cm}^{-2}$$

These figures are used later in the document to scale other event magnitudes and worst case scenarios relative to the February 1956 event. As this is the largest event for which there is reliable information on the proton spectrum, it makes sense to use February 1956 as the benchmark against which to measure other historical events (for which fewer quantitative data are available).

5.5 GLEs inferred from historical data

5.5.1 General

Several methods for inferring the historical occurrence of large SEPE or GLE events have been suggested in the scientific literature [4 to 10]. These involve using proxy data to infer the enhancement of primary (proton) or secondary (neutron) particles in the upper atmosphere. For example, Antarctic ice cores have been used to reconstruct a long-term record of the galactic cosmic ray intensity using the relative abundance of beryllium-10, which is created through interactions between cosmic rays and molecules in the upper atmosphere and precipitates down to the ground and is subsequently encapsulated in ice layers. Spikes in ^{10}Be concentration in these long-term (hundreds or even thousands of years) records are then interpreted as enhancements in the radiation environment, from which proton fluences can be calculated. Other cosmogenic isotopes are also used. It should be noted that in all cases the time resolution is poor, for existing studies this means a minimum of a few months and more likely of the order of a year. Therefore, in order to convert these fluences to peak fluxes – which is the most relevant metric for single event effects in avionics – assumptions should be made as to the temporal profile of the inferred event.

5.5.2 The Carrington event

The Carrington event of 1859 is commonly regarded as the most extreme space weather event of the last few hundred years. The extreme magnitude of this event in terms of magnetic field disturbance, solar wind speed and auroral intensity is clear. The magnitude in terms of high energy proton flux (or fluence) is far less clear. McCracken et al. used the presence of different types of nitrates in ice cores to infer the occurrence of a large GLE at the time of the Carrington event [5]. They calculated a value for F_{30} of approximately 2 x 10^{10} proton·cm^{-2}, or 20 times the February 1956 event. However, more recently considerable doubt has been cast on the nitrate technique and this figure is now considered not to be reliable [11]. It remains unclear whether a GLE can be associated with the Carrington event, and therefore this event will not be used as a basis for the worst case for avionics.

5.5.3 The AD774-775 event

Another technique for inferring the occurrence of GLEs based on cosmogenic isotope data is to use radiocarbon dating of tree rings. Carbon-14 is created in the upper atmosphere through thermal neutron interactions with molecular nitrogen, and is thus directly linked to the neutron intensity resulting from primary cosmic ray interactions. Tree rings provide an effective way of converting radiocarbon dating from organic material into an annualised record of cosmic ray intensity. Several papers have attempted to examine the spike in carbon-14 abundance that occurred in around AD774-775 in the context of a GLE. Other cosmic origins for this spike have been postulated, for example an astronomical phenomenon known as a gamma ray burst (GRB), but a GLE has been identified as the most plausible cause. Using ^{14}C production rates in conjunction with models of the global carbon cycle, the observed enhancement can be used to calculate the total incident proton fluence of the solar event leading to the GLE. Estimates of F_{30} for this event vary in the range 2×10^{10} proton·cm^{-2} to $4{,}5 \times 10^{10}$ proton·cm^{-2}, or 20 times to 45 times the nominal February 1956 fluence (Cliver et al. [6] give a figure of 8×10^{10} proton·cm^{-2}, however this is based on an upscaling of the February 1956 fluence by a factor of 1,8 and thus maintains a ratio of ~45). Given the significant uncertainties surrounding the derivation of these numbers, for this document a fluence at the lower end of this ratio range is assumed. Therefore, it is assumed that:

$$F_{30} \text{ (AD774 event)} \approx 2 \times 10^{10} \text{ proton·cm}^{-2} \text{ (20 x Feb '56)}$$

This fluence is not only coincidentally consistent with McCracken's estimate for the Carrington event fluence, it is also consistent with independent proton fluence estimates for large GLEs inferred from ^{14}C records going back over ten thousand years [4]. Also, although Mekhaldi et al. [8] found that AD774 cosmogenic records are slightly more consistent with the spectrum of the January 2005 GLE than with February 1956, a factor of 20 with respect to February 1956 is nevertheless consistent with their analysis at 30 MeV. This worst case fluence is also close to the upper limit of $1{,}3 \times 10^{10}$ proton·cm^{-2} derived from fits to empirical space-borne instrument data by Xapsos et al. (see Figure 2 in [12]). For F_{300} the estimate of Mekhaldi et al. [8] is directly used, due to their finding that the spectrum of the AD774 event is slightly harder than that of the February 1956 event. This gives:

$$F_{300} \text{ (AD774 event)} \approx 2{,}4 \times 10^{9} \text{ proton·cm}^{-2} \text{ (30 x Feb '56)}$$

The higher ratio with respect to February 1956 (factor 30 at 300 MeV, see factor 20 at 30 MeV) is a consequence of the harder spectrum of the AD774 event. As the 300 MeV threshold is more relevant to atmospheric neutron production, in 5.6.1 this factor of 30 is used to estimate neutron fluxes in the AD774 event. It is noted that this factor also represents the geometric mean of the range previously discussed for F_{30} (i.e. between 20 and 45).

5.6 Defining an extreme space weather environment

5.6.1 General

For this document, it is necessary to simplify the information above so that it may be used to scale neutron fluxes from the quiescent cosmic ray background to enhanced or worst case environments. In order to achieve this an atmospheric radiation transport model is required to fill the gap between derived proton spectra at the top of the atmosphere and neutron flux increases measured at ground level. To calculate neutron fluxes during ESW environments the QARM model [13] is used.

Two levels of extreme storm are defined:

1) An event of the same magnitude as the February 1956 GLE. The proton spectrum for this event is the one calculated by Tylka and Dietrich [3].
2) An event thirty times as large as the February 1956 GLE. In the absence of detailed knowledge of the spectrum or light curve for any event of this magnitude in the historical record, the same parameters as used for the February 1956 event are considered.

For comparison with other natural phenomena, levels 1) and 2) could reasonably be interpreted as representing worst case events for 1-in-50 and 1-in-1 000-year timescales respectively. This is, of course, an approximation, but not unreasonable given data limitations. The earliest direct evidence of GLEs (a series of ionisation chamber measurements in the 1940s [14]) implies that events of similar size to February 1956 could be significantly more frequent.

5.6.2 ESW level 1: February 1956 GLE

The proton spectrum of the February 1956 GLE [3] is shown in Figure 3 alongside a nominal spectrum of the GCR background in solar minimum conditions. The ratio between the two spectra shows how soft the GLE spectrum is compared to the GCR spectrum, rising sharply from parity at around 8 000 MeV (8 GeV) to several orders of magnitude at lower energies. This has profound implications for the radiation environment at different rigidities (latitudes) in the Earth's atmosphere.

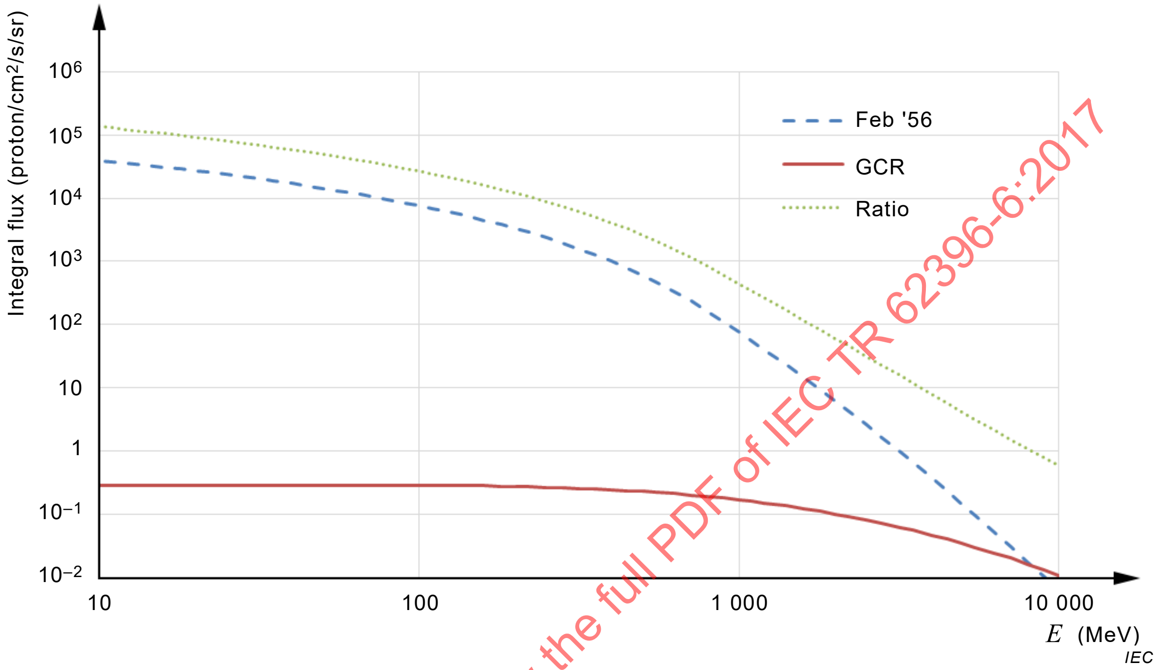

Figure 3 – Proton spectra for galactic cosmic ray background (solid red line) and February 1956 GLE (dashed blue line), and ratio between the two (green dotted line)

At low latitudes, where geomagnetic cut-off rigidities are high, the increase in neutron flux during a GLE event such as February 1956 may be relatively modest. At high latitudes, however, where there is little or no geomagnetic shielding, the effect is quite dramatic. This can be seen in the atmospheric neutron spectra plotted in Figure 4.

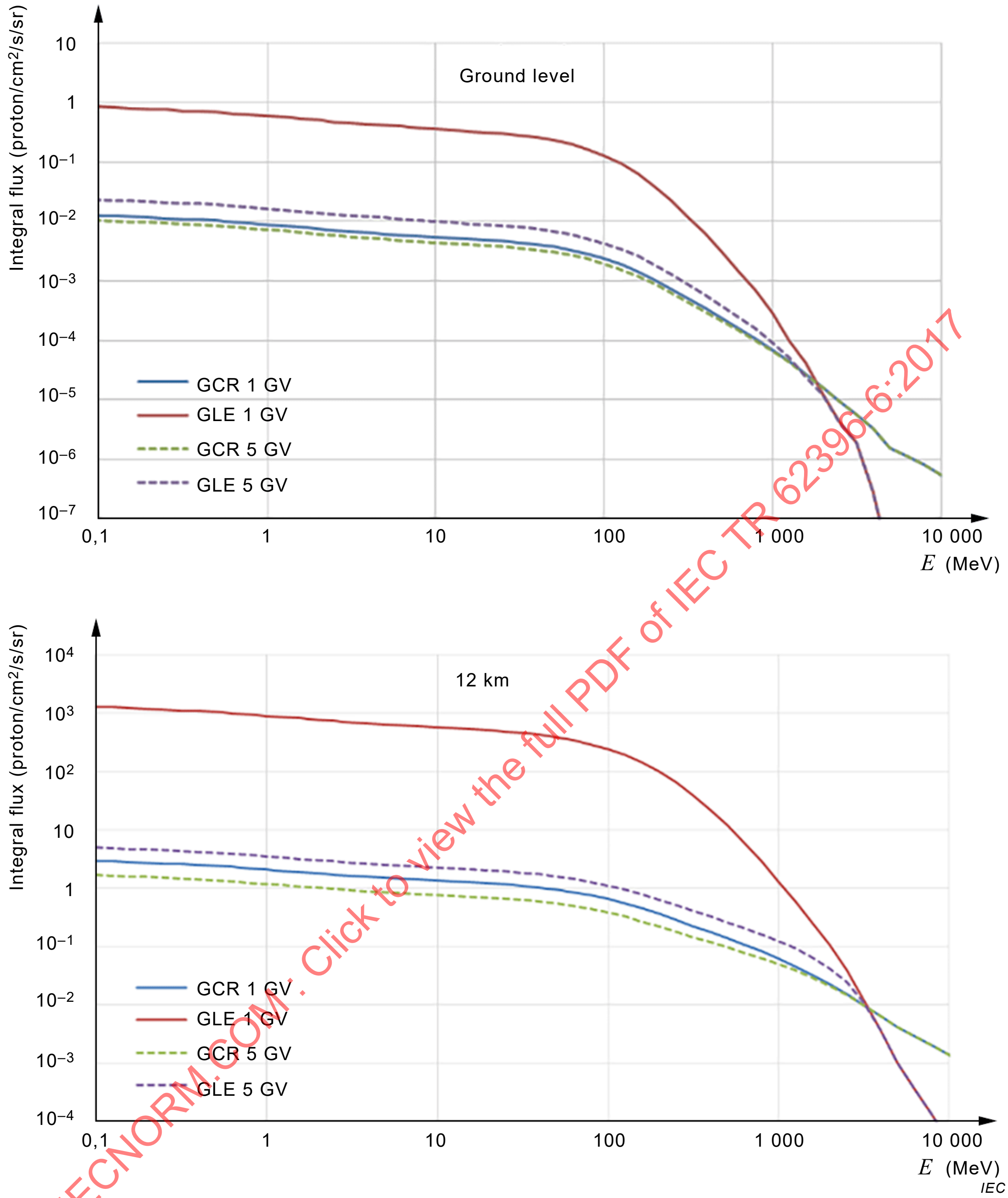

Figure 4 – Integral neutron spectra at ground level (top) and 12 km altitude (bottom) for GCR and GLE conditions at two cut-off rigidities

At a cut-off rigidity of 5 GV (corresponding to mid-latitude locations such as France or California), the additional ground level neutron flux (above 10 MeV) during a February 1956 GLE is approximately double the level due to background GCR (thus the total flux trebles). Even at 12 km altitude the overall increase is not much higher at approximately a factor of four. However, at a cut-off of 1 GV (corresponding to higher latitudes such as Southern Canada or Scandinavia), the factor increase in neutron flux above 10 MeV is 65 at ground level and 430 at 12 km altitude. The equivalent value at 12 km altitude for zero cut-off rigidity, i.e. the maximum increase during this event at aviation altitudes, is approximately a factor of 600. In actual fact, anisotropies in the incident proton flux mean that this figure could well be significantly higher, especially during the early phase of an extreme event. For example, the proton spectrum used for these calculations implies an increase in ground level neutron flux at a cut-off rigidity of 2 GV of around a factor of 25. This is consistent with the factor 20

(2 000 %) increase observed in February 1956 at the Chicago neutron monitor station. However, by contrast the neutron monitor in Leeds, UK (similar cut-off rigidity), recorded an increase of more than a factor of 45. This reflects significant anisotropy during the early phase of the event and justifies increasing the worst-case enhancement factor from 600 to 1 000. Anisotropies could be a lot greater than this, but in the absence of more evidence for the February 1956 specifically, this increase is a conservative additional margin.

In summary, during a GLE of magnitude equivalent to that observed in February 1956, the neutron flux above 10 MeV at aviation altitudes would be expected to increase by up to three orders of magnitude. This implies that single event effects rates could also rise by this factor. For example, the autopilot reported by Normand et al. [15] to be upsetting every 200 flight·h in a quiescent environment, may be expected to upset every 12 min during the peak of a February 1956 GLE at high latitudes. In terms of neutron flux for ground testing and certification of avionics, the background GCR neutron flux (> 10 MeV) is given IEC 62396-1 as 6 000 neutron·cm^{-2}·h^{-1} (this is based on a geographic latitude of 45° and approximately 12 km altitude, but the hard cosmic ray spectrum means that an equivalent figure at high latitude is very similar). With an enhancement factor of 1 000 for the February 1956 event the neutron flux for level 1 becomes:

$$F_{\text{neutron}} \text{ (ESW level 1)} = 6 \times 10^6 \text{ neutron·cm}^{-2}\text{·h}^{-1} \text{ (> 10 MeV at 12 km)}$$

5.6.3 ESW level 2: An event much larger than the February 1956 GLE, approximately representative of a 1-in-1 000-year event

Level 1 is derived from a real event with a well understood time profile and incident proton spectrum. It is also a reasonable estimate for a 1-in-50-year event, though this could be conservative. However, it is not by any means a worst case. As outlined above, the historical record implies events have occurred with up to, and possibly exceeding, thirty times the proton fluence of February 1956 (using a 300 MeV threshold). If this scale factor is taken as our worst-case event (or approximately a 1-in-1 000-year event) and an event duration similar to February 1956; then the peak proton flux scale factor relative to background GCR becomes 30 000. This gives a peak atmospheric neutron flux of:

$$F_{\text{neutron}} \text{ (ESW level 2)} = 1{,}8 \times 10^8 \text{ neutron·cm}^{-2}\text{·h}^{-1} \text{ (> 10 MeV at 12 km)}$$

This worst-case flux is not endorsed as a minimum threshold for design standards. It is an informative indication of the radiation environment that could be encountered by avionics during a very rare extreme space weather event. During such an event, multiple failures of various discrete components and systems would be expected, and indeed are unavoidable without major changes to radiation hardening design within avionics components. For example, Hands et al. [16] show estimates of single event burnout (SEB) rates in power transistors during quiescent and enhanced (GLE) conditions. This document shows that a worst-case environment may increase these rates by nearly two orders of magnitude leading to high failure rates in components that could be used in engine controls systems, even under significant de-rating conditions.

5.7 Forecasting the occurrence of an extreme space weather event

During an ESW event the high-energy protons (> 10 GeV) will travel at velocities above 99 % of the speed of light and they will arrive at the Earth minutes after the solar event and begin to interact with the atmosphere. Consequently, the atmospheric radiation levels (neutron and proton) flux will rise steeply at avionics altitudes, which will identify the onset of the ESW (GLE). Therefore, without a major leap forward in solar and heliospheric physics, virtually no warning is possible. An operational US warning system based on lower energy spacecraft data exhibits an extremely high false alarm rate (at least ten to one), while still giving almost no warning and missing important events. This has a significant cost, by virtue of the additional fuel burnt at lower altitudes and the disruptive time delays that are incurred.

The solar particle events of 23 January 2012, 7 March 2012 and 17 May 2012 illustrate the problems with these forecasts. A number of US airlines use the NOAA scale S1 to S5 for radiation intensity and take action for S3 levels corresponding to 1 000 particles $cm^{-2} \cdot s^{-1} \cdot sr^{-1}$. However, these proton measurements are obtained from the GOES spacecraft with an energy threshold of 10 MeV. These produce no radiation hazard at aircraft altitudes. At least 300 MeV protons are required to produce such a hazard and an accompanying ground level event. Of the three events, only the last was a GLE and hence of any significance at aircraft altitude. This event was S2 on the NOAA scale and did not trigger descent criteria for US airlines whereas the former two were S3 and led to unnecessary descents.

5.8 Acceleration factors in ground testing

As identified in Clause 1, this document does not detail the solutions or potential mitigations with regard to ESW events, whose occurrence is extremely rare, and the effects related to ESW environments go far beyond electronics issues. Nevertheless, if ground testing were to be considered, then the use of ground-based facilities for accelerated testing is well established and several suitable facilities are listed in IEC 62396-1:2016, Annex C. Considerations relating to extreme space weather impose an additional constraint on the suitability of facilities. In high flux neutron environments the primary danger to an electronic component or system might not come simply from elevated rates of known errors that occur infrequently in quiescent environments. Rather it could come from compound errors that occur only above a threshold intensity, where the error rate exceeds the recovery rate of the system. An example of this is multiple bit upsets (MBUs) in a data word, which may occur if the SEU rate per word is higher than the scrubbing rate for applying simple error detection and correction (EDAC) algorithms to stored data.

These are hypothetical but plausible concerns relating to system overload in extreme environments. In order for ground experiments to adequately address these concerns it would be essential that the facility can, as a minimum, recreate the intensity of the extreme environment. In practical terms, based on the analysis in this document, this means an acceleration factor above background neutron flux levels of at least 30 000, or a neutron flux above 10 MeV of at least 1,8 x 10^8 neutron $\cdot cm^{-2} \cdot h^{-1}$ (5 x 10^4 neutron $\cdot cm^{-2} \cdot s^{-1}$).

5.9 Real-time atmospheric radiation monitoring and aircraft in-flight radiation monitoring

Ground level neutron monitors can identify extreme space weather events (GLEs) but by the time such information reaches the aircraft it is too late to reduce atmospheric radiation fluxes significantly in-flight because the maximum dose rates are reached in a matter of ten minutes or so. Satellite based detectors are generally poorly matched to the particle spectrum of such events and, therefore, can generate misleading data. Even so, a sensible first step is to provide an alert service relaying information about current atmospheric radiation conditions to aviation authorities, airlines, pilots and other parties as part of normal meteorological reports: mitigating action can then be taken (e.g. to delay take-off) in line with the operating procedures of each affected body.

On-board, real-time monitoring is a way to measure the effects of solar particle events from a super storm. Concorde was compelled to carry a radiation warning monitor [17] and all commercial aircraft operating above 49 000 feet are compelled to carry a radiation monitor. Practically, this is currently of no significance. A similar requirement has not been extended to other aircraft despite the fact that subsonic routes at high latitude are more exposed than Concorde due to the higher latitude effect exceeding the influence of the reduced altitude [18]. Consequently, the avionic infrastructure to implement this measurement strategy is not currently in place. It is noted that were high latitude routes to be combined with high altitude supersonic aircraft in the future, the neutron fluxes specified for ESW levels 1 and 2 would be significantly higher (by a factor of approximately 3 to 4).

One possible solution is, therefore, widespread use of radiation monitors on board aircraft with real-time communication to air traffic control (ATC) and other aircraft. Altitude reduction brings a reduction in radiation but unilateral and uncoordinated height reductions are operationally highly risky.

The onset of a super-storm is marked by a steep rise in radiation flux over a period of minutes. A high integrity radiation monitor for aircraft suitable to detect extreme solar flares should be capable of measuring sudden increases in radiation flux (maximum integration time of 1 min) and also if predetermined radiation flux levels are exceeded. For example, a monitor could be set to trigger an alert when an increase in radiation flux (> 10 MeV neutrons) of ten times over the preceding average 10-min period flux is observed.

6 Considerations of ESW impact on infrastructure related to flight operations

During an extreme space weather event, it is possible that flight operations infrastructure (such as ground-based air traffic control) would experience anomalous events in their systems. These are not part of this document but it is expected that flight procedures in the event of an extreme space weather event are covered by a standard operating procedure. A draft concept of operations (ConOps) for the provision of space weather information has been produced in support of international air navigation at the request of the International Airways Volcano Watch Operations Group (IAVWOPSG) [21].

NOTE This draft ConOps document presents an initial set of operational, functional, and performance requirements for space weather information which have been derived from a set of user needs. This initial set of functional and performance requirements can be viewed as a baseline and not as an end state. The intent is to achieve global harmonization through a set of global standards for space weather information.

The stakes related to an ESW environment go widely beyond the electronics issues and there are a lot of other elements to consider (human concerns, for example). The event occurrence is extremely low. Potential effects on aircraft systems during an ESW event may include disturbances to high frequency (HF) communications and low frequency (LF) navigation systems, and potential disruption to GPS navigation systems. These potential effects, described in detail by the Royal Academy of Engineering [1], primarily relate to perturbation disturbances to the Earth’s ionosphere. Depending on the nature of the event, they may or may not occur concurrently with the enhanced particle environment (and consequent single event effects) described in this document.

For all these reasons, this document does not detail potential solutions; the potential risk needs to be globally considered beyond electronics and addressed in a different way than through only a specific design of electronic equipment.