BS ISO 12208:2015

BSI Standards Publication

Space systems — Space environment (natural and artificial) — Observed proton fluences over long duration at GEO and guidelines for selection of confidence level in statistical model of solar proton fluences

National foreword

This British Standard is the UK implementation of ISO 12208:2015. It supersedes DD ISO/TS 12208:2011 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee ACE/68, Space systems and operations.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2015

ISBN 978 0 580 89355 1

ICS 49.140

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 December 2015.

Amendments/issued since publication

Date	Text affected

INTERNATIONAL STANDARD

ISO 12208

First edition
2015-10-01

Space systems — Space environment (natural and artificial) — Observed proton fluences over long duration at GEO and guidelines for selection of confidence level in statistical model of solar proton fluences

Systèmes spatiaux — Environnement spatial (naturel et artificiel) — Fluences de protons observées sur une longue durée au GEO et lignes directrices pour la sélection du niveau de confiance dans le modèle statistique des fluences de protons solaires

Reference number
ISO 12208:2015(E)

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The committee responsible for this document is ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

This first edition of ISO 12208 cancels and replaces ISO/TS 12208:2011.

Introduction

This International Standard is intended for use in the engineering community.

It is well known that solar energetic protons (SEPs) damage spacecraft systems, i.e. electronics and solar cells, through ionization and/or atomic displacement processes. This results in single-event upsets and latch-ups in electronics, and output degradation of solar cells.

Solar cells of spacecraft are obviously one of the key components of spacecraft systems. Degradation of solar cells by energetic protons is unavoidable and causes power loss in spacecraft systems. Estimation of cell degradation is crucial to the spacecraft’s long mission life in geosynchronous earth orbit (GEO). Therefore, an estimation of SEP fluences in GEO is needed when designing solar cell panels.

Solar cell engineers use a statistical model, the jet propulsion laboratory (JPL) fluence model for example, for estimating solar cell degradation. However, with regard to solar cell degradation, a statistical model predicts higher SEP fluences than the values actually experienced by spacecraft in GEO, especially seven years after the launch. Nowadays, spacecraft manufacturers are very conscious of minimum cost design of spacecraft because the lifetime of spacecraft is becoming longer (15 years to 18 years) and the cost of manufacturing spacecraft is increasing. Therefore, the aerospace industry requires a more accurate SEP fluence model for a more realistic design of solar cells.

Space systems — Space environment (natural and artificial) — Observed proton fluences over long duration at GEO and guidelines for selection of confidence level in statistical model of solar proton fluences

1 Scope

This International Standard describes a method to estimate energetic proton fluences in geosynchronous earth orbit (GEO) over a long duration (beyond the 11-year solar cycle), and presents guidelines for the selection of a confidence level in a model of solar proton fluences to estimate solar cell degradation.

Many of the proton data observed in GEO are archived, for example from GMS (Japan), METEOSAT (ESA) and GOES (USA). This method is a direct integration of these fluence data (or the observed data over 11 years is used periodically).

As a result, the confidence level can be selected from a model of solar proton fluences.

This International Standard is an engineering-oriented method used for specific purposes such as estimating solar panel degradation.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
confidence level
level used to indicate the reliability of a cumulative fluence estimation

2.2
extremely rare event
solar energetic proton (SEP) event that occurs about once in a solar cycle and whose fluence dominates that for the entire cycle

Note 1 to entry: Examples are those which took place in August 1972, October 1989 and July 2000.

2.3
flux
number of particles passing through a specific unit area per unit time

2.4
fluence
time-integrated flux

2.5
***n*-year fluence**
fluence during a mission of *n* years duration

3 Symbols and abbreviated terms

EOL	end of life
ESA	European Space Agency
JPL	Jet Propulsion Laboratory
METEOSAT	Meteorological Satellite
GEO	Geosynchronous Earth Orbit
GMS	Geosynchronous Meteorological Satellite
GOES	Geostationary Operational Environmental Satellite
RDC	relative damage coefficients
SEP	solar energetic proton
SSN	sun spot number

4 Principles of the method (see Reference [3])

4.1 Cumulative fluence

The *n*-year fluence for a given mission life of *n*-years is shown in Figure 1 and estimated as follows.

a) The *n*-year fluence is calculated by integrating observed daily fluences for *n*-years from archives. The start day for integration is January 1st in the first year (defined as A). The integration windows are shifted each day from January 2nd in the first year to December 31 in *n*-years later (defined as B, C ... Z). These are possible fluences that a spacecraft might experience during its mission life (see A, B, C ... Z in Figure 1).

b) The maximum of the *n*-year fluences, $F_{\max}(t)$, for the *n*-year mission life is obtained. Maximum fluence of an *n*-year mission is calculated using Formula (1):

$$F(t) = \max(\mathrm{A}, \mathrm{B}, \mathrm{C} \ldots \mathrm{Z}) \tag{1}$$

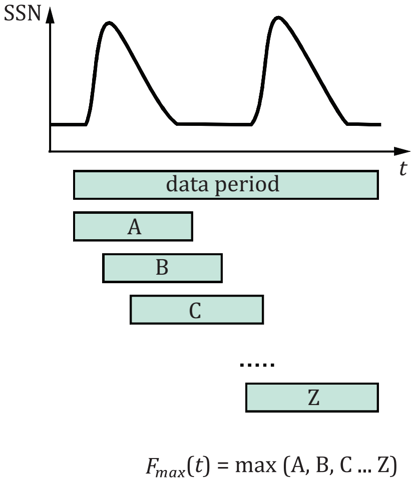


Figure 1 — Cumulative fluencies (the data period is larger than 1,2 solar cycle)

4.2 Confidence level

The confidence level for a given mission duration of *n*-years is shown in Figure 2 and estimated as follows.

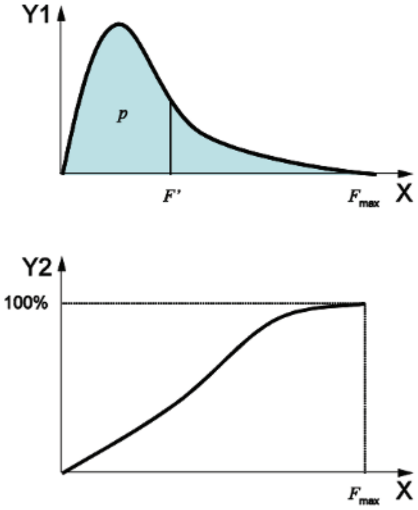
a) A set of *n*-year fluences is made by integrating proton flux data while shifting the integration window daily.

b) Occurrence distribution, f(F), of the data set of fluences, F, is built. The occurrence distribution of fluences is defined as the histogram of fluences F.

c) Distribution is normalized to have unity when integrated over maximum fluence, $F_{\max}$.

d) Distribution from 0 to F' is integrated to obtain the confidence level, p, for an *n*-year mission life.

NOTE The confidence level reaches 100 % because this method does not include extremely rare events that did not happen during the period.



Key

X	fluence, F
Y1	occurrence
Y2	confidence level, p

Figure 2 — Confidence level

4.3 Archives of observed energetic protons in GEO

The following are examples of archives and their longitudes in GEO:

a) GMS (E140);

b) METEOSAT (E63, E0); https://www.spenvis.oma.be/intro.php (European Space Agency,SPENVIS);

c) GOES (W75, W135); http://spidr.ngdc.noaa.gov/spidr/ (National Ocean and Atmospheric Administration).

4.4 Remarks

If it is necessary to adjust the magnitude and probability to exceeding the given estimates (the biggest event on September to October 1989 events which is included in this IS), the historical analyses results described in References [1] and [2] may be used.

5 Guidelines for selection of a confidence level in a statistical model of solar proton fluences

Select the confidence level as follows:

a) predict solar proton fluences using the confidence level of a statistical model;

b) estimate cumulative fluence with the method in 4.1;

c) select a confidence level in 4.2 a) that will not exceed 4.2 d).

Annex A
(informative)

Example of estimation and selection

A.1 Background information

Design of a solar panel is mainly limited by the end-of-life (EOL) output power, i.e. an estimation of the predicted radiation environment during mission life. Therefore, the radiation environment itself and estimation of the radiation environment are essential.

The radiation environment consists of electrons and protons that affect the solar panel. In GEO, trapped electrons and solar energetic protons are the main factors. Trapped electrons are generally in a steady state and are easy to estimate. However, solar energetic protons are very intense and occur randomly, making them hard to estimate.

A solar panel is comprised of a panel, solar cells and a cover glass that acts as a shield against the radiation environment and is generally about 100 microns thick. With this cover glass, cosmic rays, especially proton energy, are attenuated, and low-energy protons are stopped within the cover glass, never reaching the solar cell. When degradation is estimated, attenuation by the cover glass is obviously included.

A.2 Degradation of solar cells by radiation

A.2.1 Mechanism of degradation

High-energy charged particles (namely electrons or protons) penetrate solar cells while losing energy. They damage solar cells uniformly along a direction of thickness. At this time, cosmic rays cause an elastic/non-elastic collision with the atoms of single-crystal solar cells, which, in turn, causes a lattice defect. Due to this defect, the characteristics of solar cells, short-circuit currents (Isc), open-circuit voltage (Voc), and maximum power (Pmax) are degraded. The mechanism of degradation is called displacement damage, which is the same as bulk damage in semiconductor devices such as bipolar semiconductors.

A.2.2 Method of degradation estimation (relative damage coefficients method)

The JPL handbook[4] adopts the relative damage coefficients method, i.e. accumulated electron and proton fluences during the mission period are converted into numbers of 1-MeV electrons that damage equivalently, then degradation of the solar cells with these numbers of 1-MeV electrons is estimated.

Relative damage coefficients are obtained by measuring the degradation of solar cells caused by particles (electrons and protons) of various types of energy.

The parameters needed to estimate degradation are (1) energy dependence of degradation by electrons and protons, and (2) ratio of electron and proton degradation.

The basis for degradation parameters is normalized fluence dependence of characteristics of solar cell parameters.

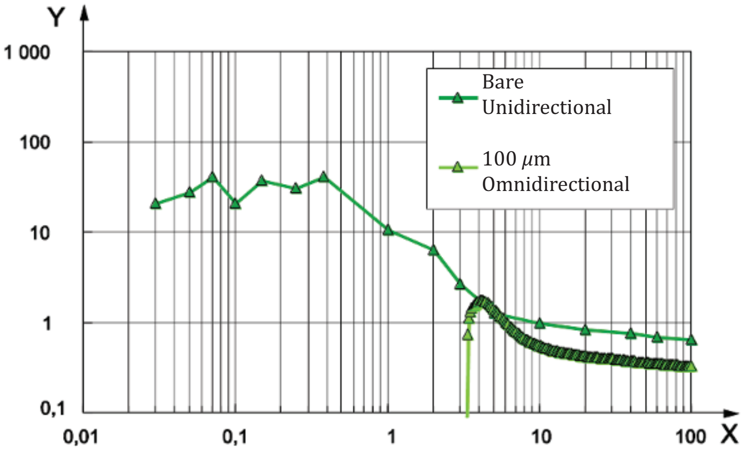
First, the normalized fluence dependence of characteristics is obtained from ground experiments of various types of electron and proton energy. The experimental data are fitted to empirical curves. From the curve data, fluence that gives the same degradation is obtained for each type of energy and particles. These fluences are normalized to 10 MeV for protons and to 1 MeV for electrons. These normalized values are called relative damage coefficients and are used as an index for the degree of degradation of solar cells.

Next, empirical curves of 10-MeV protons and 1-MeV electrons provide the ratio (conversion factor) of 10-MeV protons to 1-MeV electrons.

A.3 Estimation of solar cell degradation in GEO

A.3.1 Step 1: Radiation sources in GEO and prediction of their fluences

A multi-junction solar cell, which is commonly employed today with a cover glass of 100 microns, shown in Figure A.1, degrades mainly by 3-MeV to 10-MeV protons.



Key

X proton energy (MeV)

Y relative damage coefficient

Figure A.1 — Relative damage coefficient of triple-junction cell (maximum power)

The proton environment in GEO consists of galactic cosmic rays, trapped protons, and solar energetic protons. Galactic cosmic rays can be ignored since their fluence is very small and trapped protons can be absorbed by the cover glass. Therefore, solar energetic protons are the only factor and can be estimated by the method in this International Standard and/or statistical models.

The electron environment in GEO consists of trapped electrons. Since trapped electrons are generally in a steady state, they are easy to estimate using the AE-8 model,[6] which is commonly applied to all projects.

A.3.2 Step 2: Prediction of solar cell degradation

Because fluence distributions (obtained in Step 1) and relative damage coefficients (measured by separate experiments with solar cells of the same type) are multiplied and integrated with energy, we can predict the equivalent fluence in GEO during the mission for 1-MeV equivalent electron fluence and for 10-MeV equivalent proton fluence. 10-MeV equivalent proton fluence is then converted to 1-MeV equivalent electron fluence using the conversion factor obtained in experiments. This number is summed with the 1-MeV equivalent electron fluence and we get the “gross 1-MeV equivalent electron fluence”.

Normalized fluence dependence of characteristics curves at 1-MeV equivalent electron fluence and “gross 1-MeV equivalent electron fluence” provide the degradation for each characteristic during the mission period.

A.4 Example of estimation

A.4.1 Cumulative fluences

The proton fluence (4 MeV to 16 MeV) calculation with GOES data (1986-2005)[3] is shown in Figure A.2 (solid line).[3] The JPL fluence model[5] (>4 MeV) predictions (dotted lines) are also plotted for comparison.

The $F_{\max}(t)$ for the n-year, which is proton fluence (4 MeV to 8 MeV) estimation with GMS data (1982 to 1995), is shown in Figure A.3 (solid line).[3] The JPL fluence model[5] (>4 MeV) predictions (dotted lines) are also plotted for comparison. It is clear that the JPL fluence model predicts too harshly for longer periods.

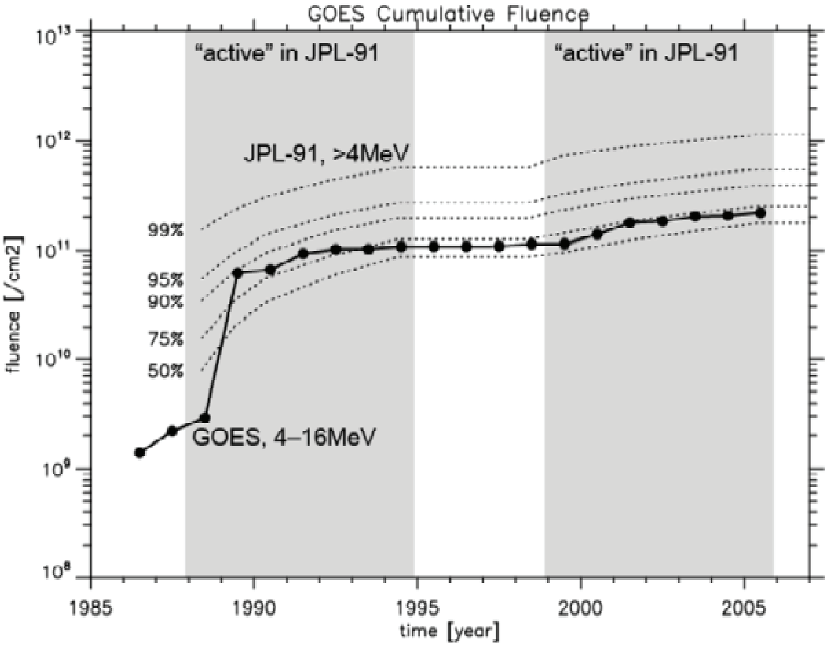


Figure A.2 — Example of cumulative fluences of protons (>4 MeV)[3]

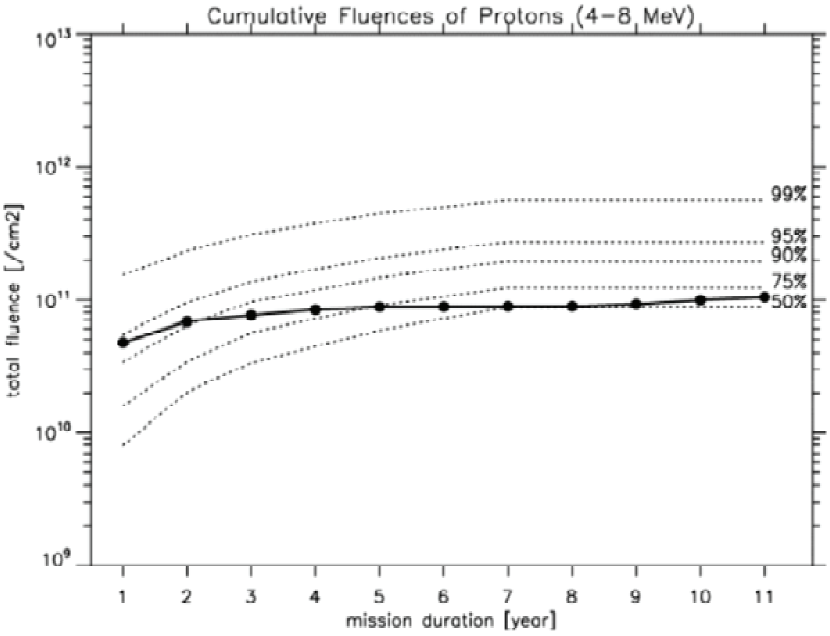
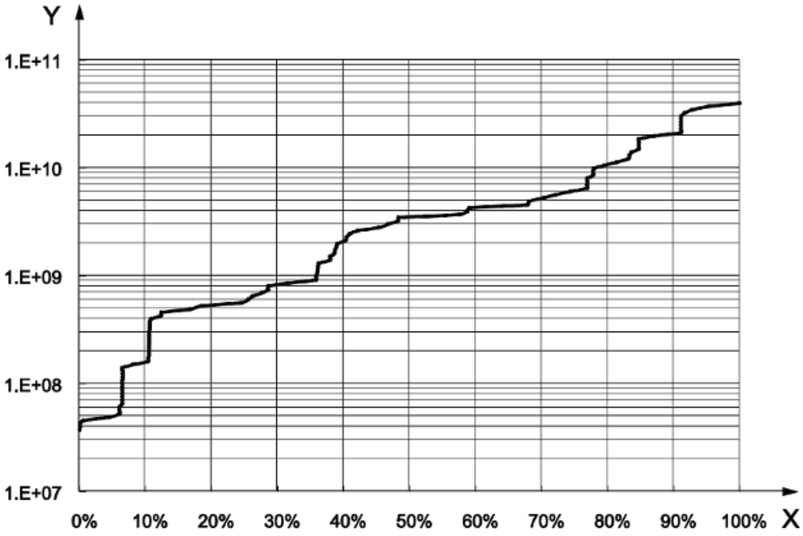


Figure A.3 — Example of cumulative fluences of protons (4 MeV to 8 MeV)[3]

A.4.2 Confidence level

The confidence level of proton fluence (4 MeV to 8 MeV) for one year with GMS data (1982 to 1995) is shown in Figure A.4. Data that include the solar event of November 1989 are flat at 92 % to 100 %.



Key

X confidence level

Y fluence (/cm^2)

Figure A.4 — Example of confidence level of proton fluence (4 MeV to 8 MeV) for one-year duration

A.4.3 Guideline for selection of confidence level of statistical model

Predicted solar proton fluences with a statistical model using the confidence level and estimated cumulative fluences, which are $F_{\max}(t)$s for the n-years, are shown in Figure A.3.

The confidence levels of the JPL model are 95 % (1 year), 90% (2 years), 80% (3 years to 4 years), 75% (5 years), 60% (6 years), 50 % (7 years to 9 years) depending on mission duration.

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ICS 49.140

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