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Space systems — Evaluation of radiation effects on Commercial-Off-The-Shelf (COTS) parts for use on low-orbit satellite

Systèmes spatiaux — Évaluation des effets des radiations sur les parties commerciales sur étagère (COTS) destinées aux satellites à orbite basse

Reference number
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Foreword

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document describes methods of evaluating the radiation effects on COTS (Commercial-Off-The-Shelf) parts used in low Earth orbit (LEO) satellites. Many small (<180 kg) and nano/microsatellites (1 kg to 50 kg) are launched to LEO altitudes where space radiation exists but is less than at higher altitudes. As a result, the designers and manufacturers of such satellites are using COTS semiconductor devices for their satellite components and boards. New industries taking advantage of nano/microsatellite and CubeSat [1,33 kg × (1U-3U)] satellite capabilities now include IT ventures, mobile phones, and internet industries along with universities and research institutions.

Satellite manufacturers who prioritize investment efficiency also aim to extend mission lifetimes (up to three, five and ten years) longer than one-year missions that were common for educational and technical demonstrations using nano/microsatellites.

Even with relatively lower space radiation conditions in LEO compared to higher orbits, a longer mission life in LEO poses critical radiation environment constraints for COTS devices onboard small and nano/microsatellites as well as CubeSats.

While there are methods of evaluating the radiation resistance of space parts, there are limited methods for evaluating COTS parts used for LEO satellites and these are often based on legacy parts usage.

This document provides guidance for evaluating radiation tolerance of COTS parts that can help increase confidence levels of longer-term mission lifetimes.

Space systems — Evaluation of radiation effects on Commercial-Off-The-Shelf (COTS) parts for use on low-orbit satellite

1 Scope

This document outlines the evaluation methods for environmental tests that can be conducted on COTS (Commercial-Off-The-Shelf) spacecraft parts intended for use on LEO satellites. The radiation effects considered consist of total dosage, single event, and displacement damage. In addition, this document describes tests that are useful for satellites operating in LEO.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
galactic cosmic rays
GCR
high-energy-charged particle *fluxes* (3.2) penetrating the heliosphere from local interstellar space

Note 1 to entry: Galactic cosmic rays are composed primarily of high-energy protons and atomic nuclei. Upon impact with the Earth's atmosphere, cosmic rays can produce showers of secondary particles that sometimes reach the Earth's surface. There is evidence that a significant fraction of primary cosmic rays originate from stellar supernova explosions and perhaps from active galactic nuclei.

[SOURCE: ISO 15390:2004, 2.1, modified — Note 1 to entry has been added.]

3.2
flux
number of particles passing through a specific unit area per unit time

[SOURCE: ISO 12208:2015, 2.3]

3.3
fluence
time-integrated *flux* (3.2)

Note 1 to entry: Fluence is measured as the flux per unit area per unit time. This is used to express the environment during the operational lifetime of a spacecraft or space instrument. The integrated particles fluence unit is expressed as particles m^{-2}. The energy integral fluence unit is expressed as particles m^{-2} MeV^{-1}. When the directional fluence is included, add per steradian (sr^{-1}).

[SOURCE: ISO 12208:2015, 2.4, modified — Note 1 to entry has been added.]

3.4
absorbed dose
D
amount of energy imparted by ionizing radiation per unit mass of irradiated matter

Note 1 to entry: The quotient of $d\bar{\varepsilon}$ by *dm* where $d\bar{\varepsilon}$ the mean energy imparted by ionizing radiation to matter of mass d*m* is

$$D = \frac{d\bar{\varepsilon}}{dm}.$$

Note 2 to entry: The special name of the unit for absorbed dose is the gray (Gy). 1 Gy = 1 J·kg^{-1}.

[SOURCE: ISO 15856:2010, 3.1.1]

3.5
dose
idiomatic term which expresses the radiation dose and the absorbed energy

Note 1 to entry: Dose is used to express various meanings, such as the *absorbed dose* (3.4), exposure dose, etc.

3.6
total dose
total *absorbed dose* (3.4) received by components or materials to a specific point

3.7
single event effect
SEE
effect, such as malfunctions of circuit elements (software errors), or latch up, which are caused by the effect of a single high energy particle

3.8
bremsstrahlung
photon radiation, continuously distributed in energy up to the energy of the incident particle radiation, emitted from a material due to deceleration of incident particle radiation within the material, mainly due to electrons

Note 1 to entry: Bremsstrahlung is any radiation produced due to the deceleration (negative acceleration) of a charged particle, which includes synchrotron radiation (i.e. photon emission by a relativistic particle), cyclotron radiation (i.e. photon emission by a non-relativistic particle), and the emission of electrons and positrons during beta decay. The term is frequently used in the narrower sense of radiation from relativistic electrons (from whatever source) slowing as they penetrate matter.

[SOURCE: ISO 15856: 2010, 3.1.3 — The alternative term "brake radiation" has been removed; Note 1 to entry has been added.]

3.9
solar flare
explosion phenomenon which occurs on the surface of the sun, accompanied by the release of high energy particles

3.10
spectrum
array of entities, such as light waves or particles, ordered in accordance with the magnitudes of a common physical property, such as wavelength or mass

Note 1 to entry: In this document, the spectrum refers to the items that express the particle *flux* (3.2) density of the radiation for each energy.

3.11
anneal
phenomenon in which the characteristics degraded by radiation recover due to heat

3.12
linear energy transfer
LET
energy delivered by a charged particle passing through a substance and locally absorbed per unit length of path

Note 1 to entry: It is measured in joules per metre. Other dimensions are $keV \cdot \mu m^{-1}$, $J \cdot m^2 \cdot kg^{-1}$, $MeV \cdot cm^2 \cdot mg^{-1}$.

[SOURCE: ISO 15856:2010, 3.1.10]

3.13
dose rate
dose (3.5) per unit of time

3.14
heavy ion
ion particles with a large atomic number

Note 1 to entry: Heavy ion generally refers to particles of He or more.

3.15
non-ionizing energy loss
NIEL
damage not caused by ionization of the incidence particles

4 Abbreviated terms

CREME-MC	cosmic ray effects on microelectronics MC
SEU	single-event upset
SET	single-event transient
SEL	single-event latch up
SEB	single-event burnout
SEGR	single-event gate rupture
MCU	multiple bit upset
TID	total ionizing dose
HUP	direct ionization-induced SEE rate calculation
PUP	proton-induced SEE rate calculation
CCD	charge coupled device
CMOS	complementary metal oxide semiconductor
EOL	end of life
SPENVIS	space environment information system
HAST	high acceleration stress test
RTS	random telegraph signals
ADC	analog-to-digital converter

DAC	digital analog converter
NPN	negative-positive-negative
FPGA	field-programmable gate array
MOSFET	metal-oxide-semiconductor field-effect transistor
MSM	metal semiconductor metal
LED	light emitting device
DC	direct current
PN	positive-negative
PIN	P-intrinsic-N
FPL	focused pulsed laser
SOA	system operating area
ELDRS	enhanced low dose rate sensitivity
EDAC	error detection and correction
CTE	charge transfer efficiency
CTR	current transfer ration
TTL	transistor transistor logic
IC	integrated circuit
DD	displacement damage

5 Radiation resistance design

5.1 Overview

Satellite designers and manufacturers can implement measures against TID, SEU, SEL, and displacement damage as part of the radiation resistance design when using consumer parts on LEO satellites. See Annex A for radiation tolerance design procedures.

Generally, TID for a satellite is calculated using the knowledge of total dose in a satellite's orbit for a year timed by the design lifetime in years. To mitigate TID effects, the radiation shielding thickness is increased to a level such that the function and performance of the parts used are still acceptable. Programs such as SHIELDOSE-2 are often used to estimate total dose in parts. For satellite designers who cannot use the SHILDOSE-2 program, a contour map that easily estimates the total dose is shown in Annex C.

To estimate SEU as well as SEL, programs such as HUP and PUP are often used. Generally, if one concludes that there is no effect on reducing the occurrence frequency of SEU and SEL even after thickening the shielding material, the measures prescribed in Annex G and Annex H can be taken.

Displacement damage refers to lattice defects that are generated in a semiconductor due to the collision from energetic particles (heavy ions, alphas, protons, neutrons, or electrons) or high-energy photons. Such damage is inevitable regardless of COTS parts/space parts, and even increasing the shield thickness only has a limited effect. In lattice defects, a charge is captured and released, so the influence becomes conspicuous in CCD, CMOS sensors, photocouplers, solar cells, and other optical components. Often the magnitude of such lattice defect damage depends on the temperature and options may include lowering the operating temperature during use or applying sensor signal processing. Conversely, the radiation resistance design should also consider the state of deterioration (i.e., amount of deterioration) at the satellite's EOL. See Annex J.

5.2 Basic idea of using COTS parts

5.2.1 Concept of parts selection

In cases of failure regarding COTS parts, and unlike the parts for space, the user is responsible for failure analysis. Generally, support from the parts manufacturers cannot be expected. It is therefore important to select parts covered by failure analysis service or parts having a known internal structure.

With regard to radiation sensitivity that can depend on each manufactured lot of parts and, where possible, identification management of lots should be carried out.

5.2.2 COTS parts evaluation

As part of the evaluation methods, when the payload is an important or critical one, certain standard screening tests (e.g., temperature cycling, high-temperature burn-in test) can be conducted to assure the ruggedness of the COTS devices.

In the case where a long-life mission is planned, such tests as the HAST and sample life test can be conducted.

5.2.3 Concept of evaluation method

In addition to the task of evaluating each part separately, the merits of higher-level evaluation, such as at the board or unit level, should also be considered.

5.2.4 Concept of application of COTS parts/consumer technology

Risk assessment is based on the identity of the part being evaluated, the environment in which it will be used, and the criticality of the part used. Such an assessment usually helps to determine whether the parts should be used. A reference for parts risk evaluation methodology is RNC - CNES - Q - 60 – 516[6].

5.3 Space radiation environment prediction

5.3.1 Space environment

The natural space radiation environment can be classified into two populations:

1) transient particles that include protons along with heavier ions of all elements of the periodic table as well as atmospheric albedo (back scattered) neutrons; and

2) trapped particles that include protons, electrons, and heavier ions.

The transient radiation consists of GCR particles and particles from solar events (e.g., coronal mass ejections, solar flares, and interplanetary medium acceleration shocks). The solar-related events periodically produce energetic protons, alpha particles, heavy ions, and electrons. Table 1 lists the orders of magnitude of the maximum energy of the radiation particles.

Table 1 — Maximum energies of particles

Particle type	Maximum energy
Trapped electrons	10s of MeV
Trapped protons &heavier ions	100s of MeV

Table 1 *(continued)*

Particle type	Maximum energy
Solar protons	100s of MeV
Solar heavy ions	GeV
Galactic cosmic rays	TeV

5.3.2 Space radiation environment model

Space environment models that can be used for environmental specification include:

— trapped electrons: AE-8[7], AE-9[8];

— trapped protons: AP-8[9], AP-9[8];

— solar protons: JPL-91[10];

— galactic cosmic rays: CREME -MC[11], ISO 15390:2004;

— geomagnetic vertical cut-off model: ISO 17520:2016;

— ionizing dose model: SHIELDOSE-2[12];

— single event effects (SEE): HUP and PUP[11].

All models contain uncertainty and a good practice for evaluating a design is to add a margin in one of the following ways:

(a) add a margin to the model input parameters (shielding thickness, lifetime in environment, etc.) and conduct design evaluation;

(b) first, design and evaluate a part's use with a model using no margin then add the margin (including uncertainty other than in the model) to the obtained result.

5.3.3 Various parameters

Various model input parameters such as orbital conditions, mission period, solar activity cycle, and Earth's magnetic shield should be properly selected.

5.3.4 Environmental conditions necessary for evaluation

The following environmental conditions are necessary for evaluation:

— dose-depth curve;

— integrated energy spectrum of trapped electrons, trapped protons, and solar-related protons;

— LET spectrum of galactic cosmic rays.

Using these calculation results, conduct the radiation evaluation tests specified in Clause 6.

6 Radiation tolerance test

6.1 Types of irradiation test

6.1.1 Cobalt 60 (gamma ray) irradiation test

Cobalt 60 generates high energy gamma rays at 1,17 and 1,33 MeV and such a source decays at a rate of 1 % per month (half-life is 5,3 years). This test is suitable for total dose testing and cannot test single events.

6.1.2 Proton beam irradiation test

The proton irradiation test for silicon requires a cyclotron accelerator which can accelerate protons to at least 50 MeV. In this test, it is possible to simultaneously test the total dose and single event incidents, including the evaluation of displacement damage. Tests with LET of 25 MeV-cm^2/mg or more are also possible using secondary (metal) heavy ions generated by collisions between protons and metal atoms within the semiconductor.

6.1.3 Heavy ion test

For the heavy ion test, an accelerator should be used, or alternatively a radioisotope (such as Californium 256) should be used. The heavy ion test using an accelerator is very expensive. It is a difficult test to conduct, so it is excluded except when it is judged essential in 5.2.4. The method that uses spontaneous fission of radioisotopes (such as Californium 256) can irradiate a target with heavy ions.

6.2 Alternative irradiation test — Laser pulse test

Pulsed picosecond lasers can be evaluated for SEU in a number of different circuits, as can such devices as SRAM, DRAM, logic circuit, and an analog/digital converter.

6.3 Test procedure

6.3.1 Total dose test

The total dose test is conducted to evaluate the amount of deterioration accumulated during the mission due to radiation effects. Refer to MIL-STD-883 TM1019[13] and ESCC 22900[14] for details on how to conduct the total dose test.

6.3.2 Single event test

The single event test is conducted to evaluate the effects of energetic particles such as galactic cosmic rays and trapped protons. Refer to MIL-STD-883 TM1020[15]/1021[16] and ESCC 25100[17] for the test method.

6.3.3 Displacement damage test

This test is conducted to evaluate the displacement damage caused by particles of protons and ions entering the semiconductor. See Annex K for the displacement damage test method.

6.3.4 Laser pulse test for SEE test

An evaluation equivalent to that of radiation irradiation can be conducted by using a laser pulse. See Annex L for the laser pulse test method.

Annex A
(informative)

Radiation resistance design procedure

A.1 Total dose

A.1.1 Energy spectrum of electrons & protons

The radiation environment (total dose amount) received by the satellite is calculated by the radiation environment model, taking into account the operational conditions during orbit (e.g., launch date, six trajectory elements, mission period).

A.1.2 Calculation of the total dose received by parts

Calculate the shield thickness of the satellite as well as the shield thickness of each device. Calculate the total dose received by the parts used in the equipment. (The shield is generally made of different materials, but in order to simplify the evaluation, the value converted to the equivalent shield thickness of aluminum is used.)

A.1.3 Consideration of shield thickness

When it is difficult to secure the total dose resistance of the parts used, mounting of parts, mass of equipment etc., consider partial shielding or increase the shield thickness of the equipment housing. In this way, change to a shield that ensures the total dose tolerance of the parts.

Annex B describes the total dose prediction method in detail. And Annex B also gives the radiation guidelines for total dose using contour maps. Note that the total predicted values based on Annex B tend to be overestimated. Annex D describes a comparative example between model prediction including measured values. Annex E describes the radiation deterioration of electronic components. The design flow for total dose is shown in Figure A.1.

A.2 Single event upset, single event latch-up

A.2.1 Proton energy spectrum

The radiation environment (heavy ions and proton fluence) received by the satellite is calculated by using the radiation environment model, taking into consideration the operational conditions in orbit (e.g., launch date, six trajectory elements, mission period).

However, heavy ions need not be considered for the evaluation of parts other than those used in important equipment.

A.2.2 Calculation of SEE

Confirm the radiation tolerance data for the selected parts (or conduct an irradiation test if there is no data). Calculate SEE incidence in orbit from the data, heavy ions, and proton spectrum. Perform critical analysis of the equipment.

A.2.3 Measures for SEU and SEL

If SEU and SEL resistance is not acceptable in the system, reselect the parts or take countermeasures.

Consider countermeasures to avoid failure by SEU at the component level, circuit level, or equipment level. The design flow for a single event is shown in Figure A.2.

Annex F gives an overview of the single event effect.

Annex G describes the measures for single events of electronic components.

Annex H describes the measures for single events of devices.

A.3 Displacement damage

A.3.1 Fluence of protons

In consideration of the operational conditions in orbit (e.g., launch date, six trajectory elements, mission period), use the radiation environment model to calculate the radiation environment (proton fluence) received by the satellite.

A.3.2 Calculation of displacement damage

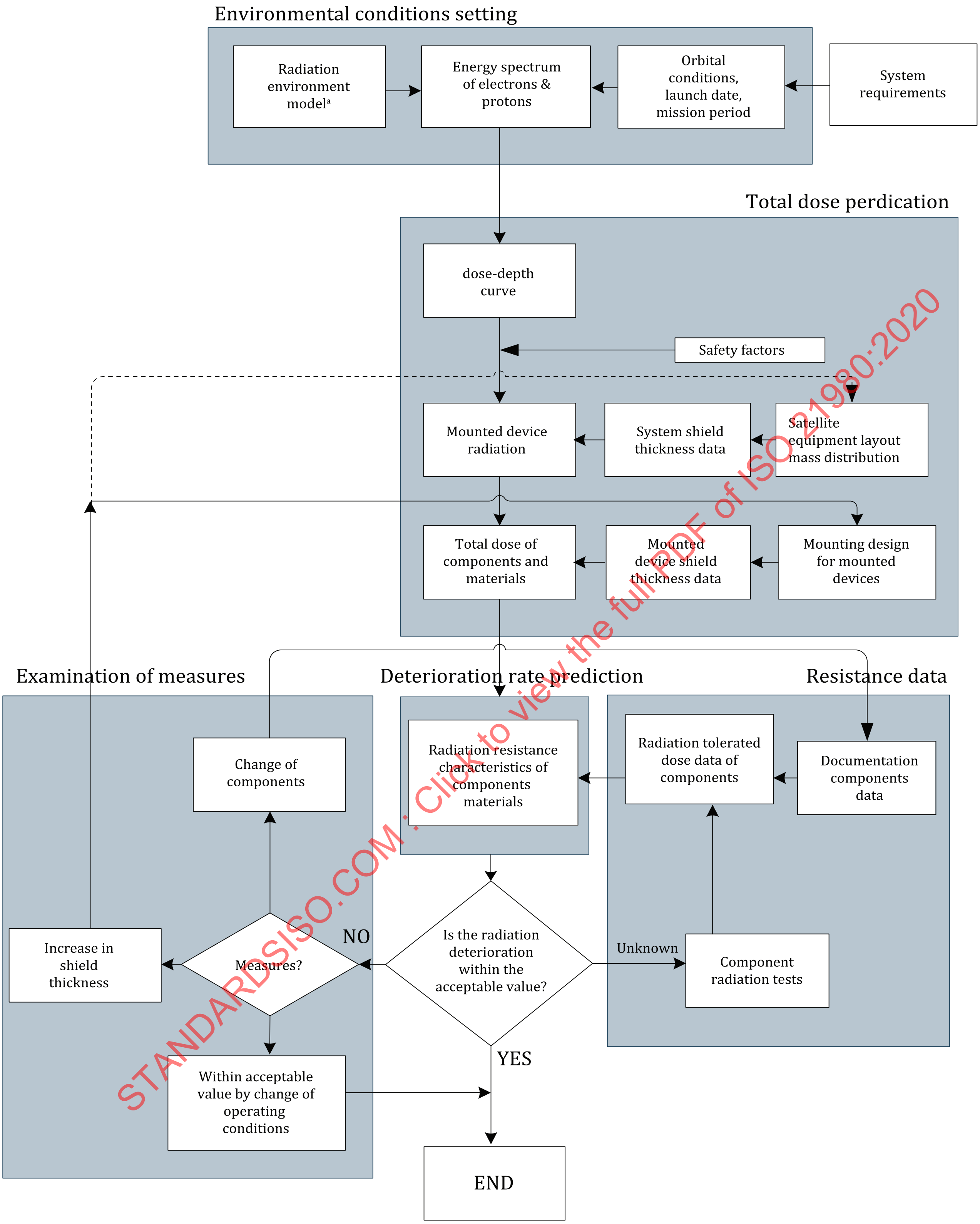
Confirm the radiation tolerance data for the selected parts (or conduct a proton irradiation test when there is no data), calculate displacement damage in orbit from the data together with the proton spectrum, and then predict possible degradation.

A.3.3 Measures for displacement damage

If the value of degradation in the system is not acceptable, reselect the parts or take countermeasures for the equipment. The deterioration prediction method by displacement damage to devices in orbit is shown in Figure A.3.

Annex I describes the prediction method of displacement damage.

Annex J describes the resistance to displacement damage of each device.



a Include the reliability level for solar flares.

Figure A.1 — Design flow for total dose

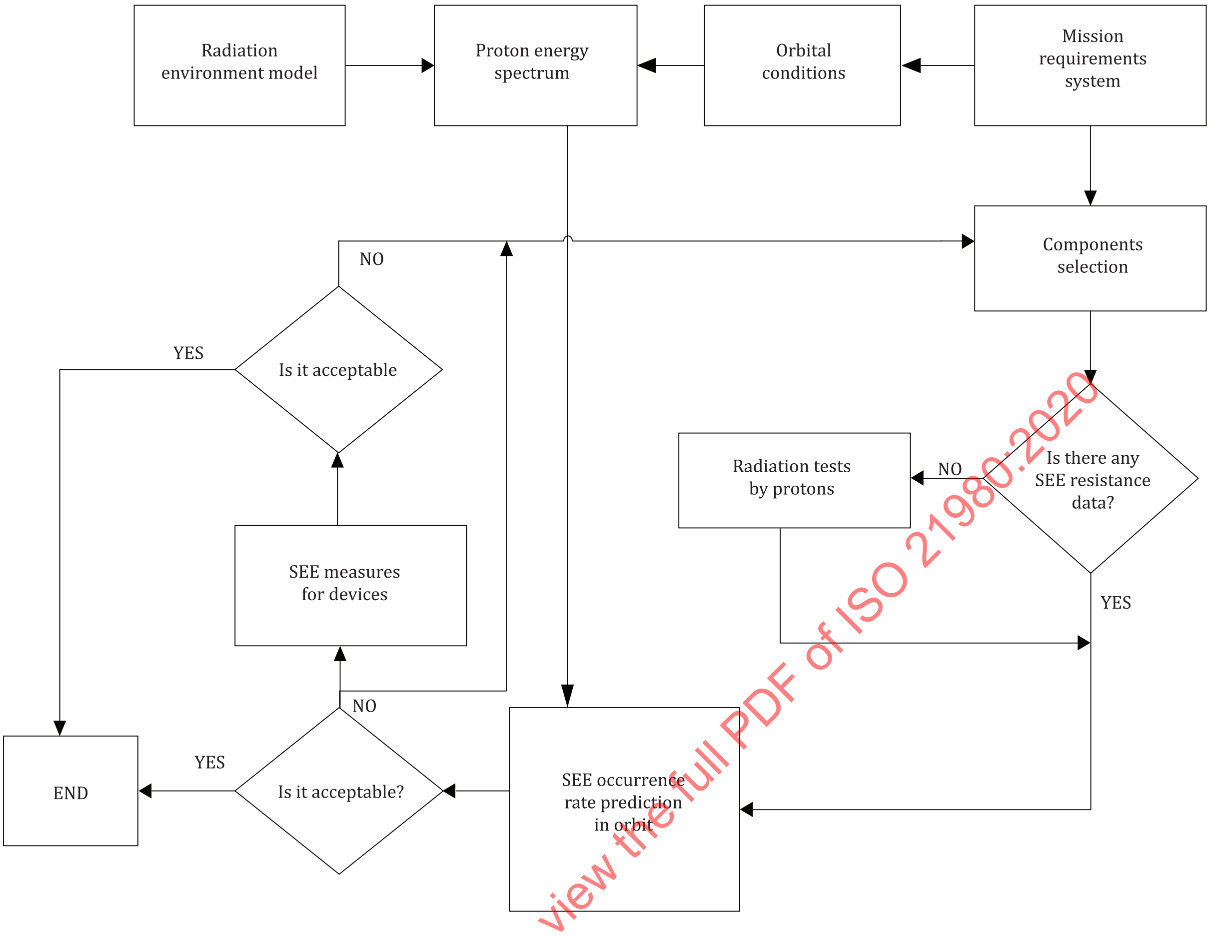


Figure A.2 — Design flow for single events

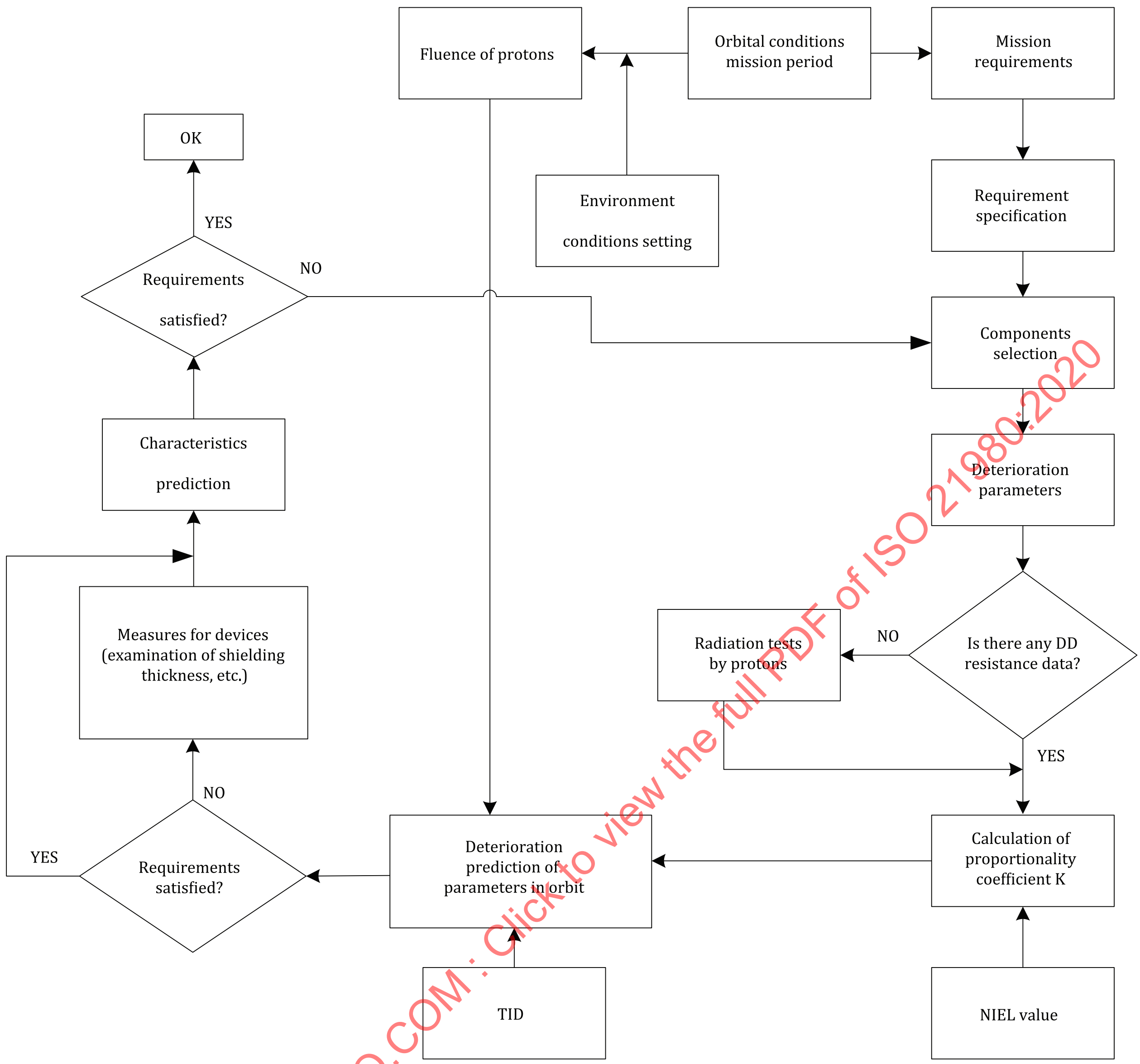


Figure A.3 — Deterioration prediction method by displacement damage to devices in orbit

Annex B
(informative)

Total dose prediction method

B.1 Overview

The types of radiation to be considered for predicting the total dose are trapped electrons, trapped protons, and solar protons. When these types of radiation penetrate materials, the radiation loses energy due to its interaction with, and absorption by the materials. In the case of electrons, bremsstrahlung will be generated due to their interaction with the materials. And since bremsstrahlung has a longer range than electrons, it can become dominant when a thicker shield is used.

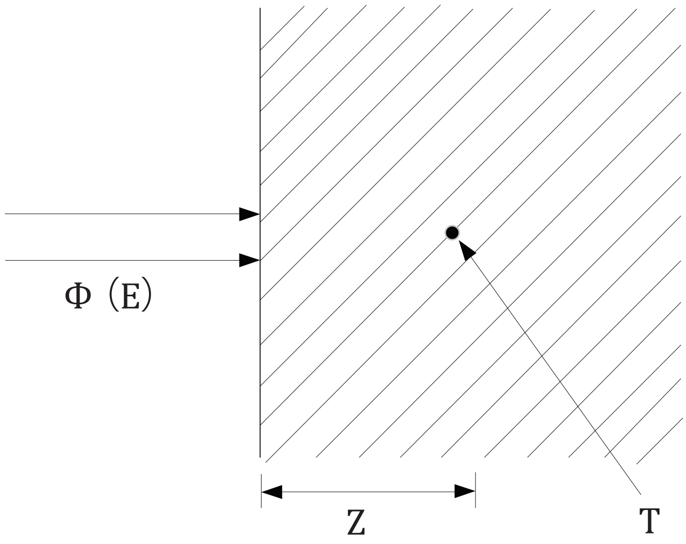
Figure B.1 shows the total dose calculated for parallel incidence radiation. Accordingly, this is equivalent to the spherical shell model as indicated in B.3.2 when a shield of equal thickness is used for the isotropic radiation incidence from all directions.

The radiation absorbed dose and amount of bremsstrahlung generated differs according to the types of materials used for the shielding and target components. However, the total dose is calculated by using aluminum as the shielding material, and thus converting the density into an equivalent aluminum thickness for shielding materials of other aluminum components is sufficient. The total dose calculation results are generally provided by the relationship between the shield thickness (depth) and the absorbed dose (i.e., dose-depth curve). Figure B.2 shows an example of a dose-depth curve.

B.2 Total dose prediction model

B.2.1 General

The following two methods can be considered as the prediction models used to calculate the actual radiation dose received by the components.



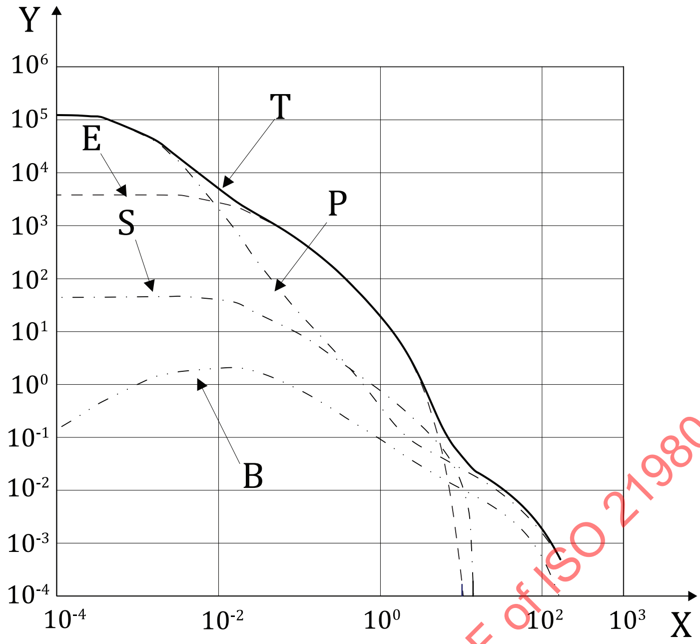
Key

ϕ (E) incidence radiation fluence (particles per square centimetre)

Z depth (g/cm^2)

T target components

Figure B.1 — Total dose calculation model



Key

T total

E electrons

P protons

S solar protons

B bremsstrahlung

X shield depth Z(g/cm^2)

Y dose [Gy(Al)]

Figure B.2 — Dose-depth curve (example)

B.2.2 Simplified method

The purpose of this prediction model is to acquire the relationship between the shield thickness and the total dose (i.e., dose-depth curve) assuming that the material and configuration of complex shielding is a simple shape, such as a spherical shell or a plate. Moreover, its purpose is also to acquire the total dose directly, calculated by using the shield thickness and surface density.

B.2.3 Three-dimensional model

The purpose of this prediction model is to acquire the distribution of the shielding thickness in each direction as viewed from the target (i.e., calculation point of the total dose), and acquire the total dose using this calculated value.

B.3 Simplified method

B.3.1 General

When calculating the dose-depth curve, three types of shielding material configurations (i.e., spherical shell model, semi-infinite plate model, finite plate model) will be used, in connection with use of the shielding effect calculation code for space (SHIELDOSE-II)[12]. Figure B.3 shows the three simple geometries considered by SHIELDOSE-II.

B.3.2 Spherical shell model

This model assumes that the model is covered with a shielding material of equal thickness for the isotropic radiation incidence. This model is the most basic model for performing the shielding calculation, and is acquired by the calculation method indicated in B.2.2. However, as the actual shielding configuration is close to a plate in many cases, the radiation dose calculated using this model may result in a larger value.

This model is used for the shielding calculations for shielding configurations similar to a spherical shell or semi-spherical shell, with basic data for the semi-infinite plate model and three-dimensional model indicated in the following diagram.

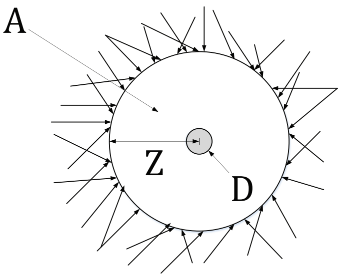
B.3.3 Semi-infinite plate model

This model assumes that the model is covered with a shielding material of an infinite width with a uniform thickness, having an infinite plane surface shielding material and a shielding material of infinite thickness in the opposite direction.

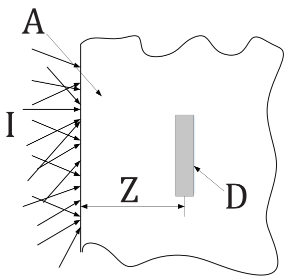
B.3.4 Finite plate model

This model assumes that the model is covered with a shielding material of a finite thickness, having a semi-infinite plane surface shielding material and a shielding material of a finite thickness in the opposite direction (i.e., radiation incidence from one surface of the plate).

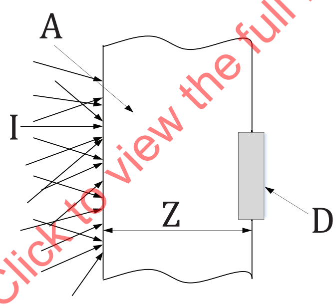
In the actually mounted devices, there are many cases where one direction of the shielding has a sufficiently large thickness compared to the other directions as viewed from the component's position. There are also many cases where the configuration of the shielding material is a plate or similar to a plate. Therefore, the semi-infinite plate model is effective when calculating the radiation absorbed dose using a simplified method.



(1) Spherical shell model



(2) Semi-infinite plate model



(3) Finite plate model

Key

A aluminum

D detector

Z depth (g/cm^2)

I incident protons and electrons

NOTE These figures are typically presented in order to easily understand the models, with the back diffusion scattering taken into consideration in the actual calculation.

Figure B.3 — Model configurations

B.4 Three-dimensional model

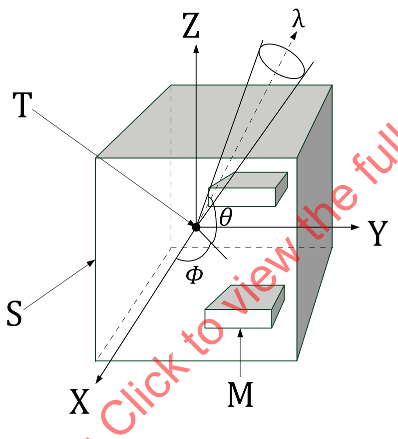
This model is used for calculating the total dose of the components and materials more accurately. The spherical shell model and semi-infinite plate model are simple. However, the total dose of the components and materials used in spacecraft changes according to the conditions of the surroundings, such as the mounting position, etc., and the actual shielding configuration is complex and may not necessarily work in conjunction with those conditions. Therefore, in order to calculate the total dose more accurately, it is necessary to acquire the mass distribution for each direction with the target as the center. This model converts the mass distribution into the shield thickness of standard materials, calculates the absorbed dose in each direction using the dose-depth curve of the spherical shell model, and then integrates the values for all solid angles. The formulae are as follows:

$$D_T = \frac{1}{4\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{2\pi} D(\ \ t(\theta,\varphi))\cos\theta\, d\varphi\, d\theta \tag{B.1}$$

where

D_T	is the absorbed dose of the target;
$D_{(x)}$	is the absorbed dose of the spherical shell model when assuming the shield thickness is x;
$t(\theta, \varphi)$	is the shield thickness of the (θ, φ) direction;
θ	is the longitude direction;
φ	is the latitude direction.

A conceptual diagram of the mass distribution in spacecrafts is indicated in Figure B.4.



Key

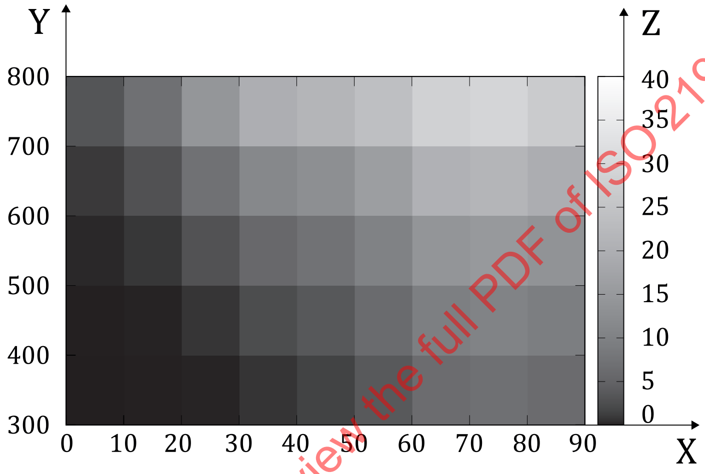
S	satellite
T	target
M	mounted device
X, Y, Z	axes
λ	incident protons and electrons

Figure B.4 — Mass distribution in spacecrafts

Annex C
(informative)

Radiation guidelines for total dose using contour maps

Figures C.1 to C.6 depict the total dose contour maps with circular orbital altitude (km) and orbital inclination (degree) in the solar maximum and minimum for a one-year mission using the AE-8/AP-8 NASA radiation belt models[7][9] and SHIELDOSE-2[12] dose calculation tool in solar maximum and minimum (at 2 mm to 4 mm Al thickness).



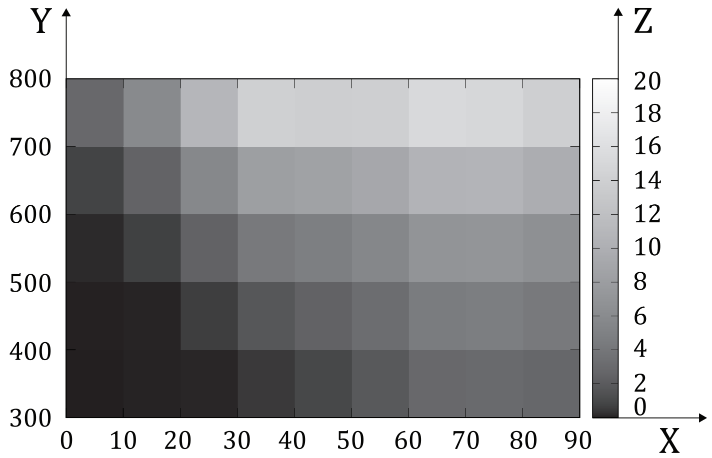
Key

X inclination (degree)

Y altitude (km)

Z dose (Gy)

Figure C.1 — Total dose contour map at 2 mm Al thickness (Solar minimum)



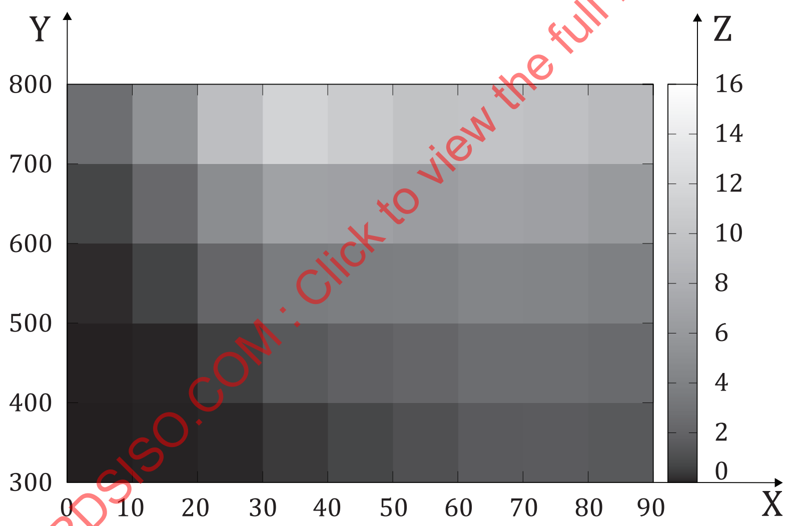
Key

X inclination (degree)

Y altitude (km)

Z dose (Gy)

Figure C.2 — Total dose contour map at 3 mm Al thickness (solar minimum)



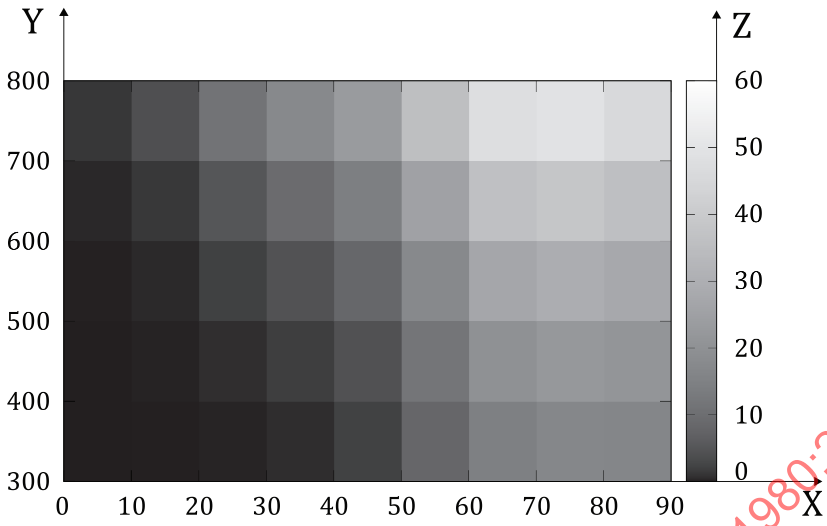
Key

X inclination (degree)

Y altitude (km)

Z dose (Gy)

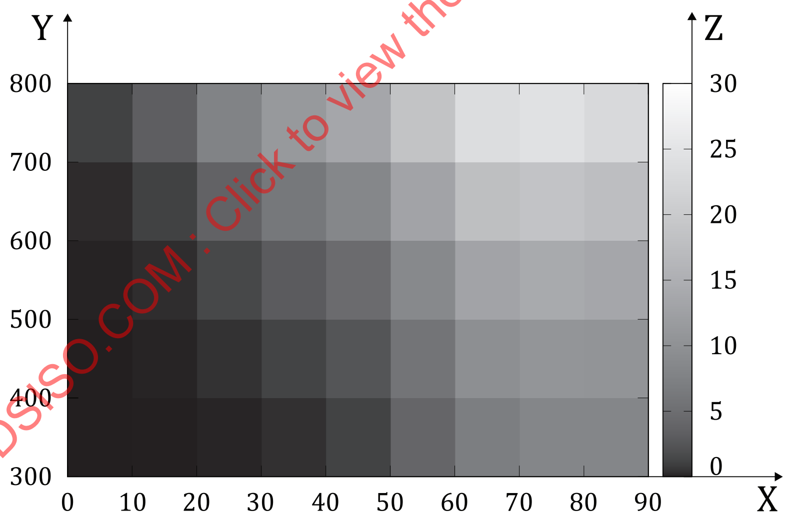
Figure C.3 — Total dose contour map at 4 mm Al thickness (Solar minimum)



Key

X inclination (degree)
Y altitude (km)
Z dose (Gy)

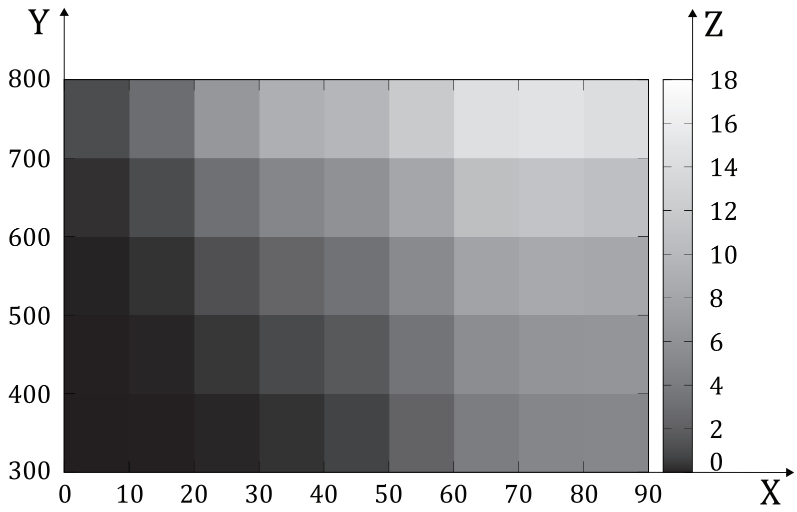
Figure C.4 — Total dose contour map at 2 mm Al thickness (Solar maximum)



Key

X inclination (degree)
Y altitude (km)
Z dose (Gy)

Figure C.5 — Total dose contour map at 3 mm Al thickness (Solar maximum)



Key

X inclination (degree)

Y altitude (km)

Z dose (Gy)

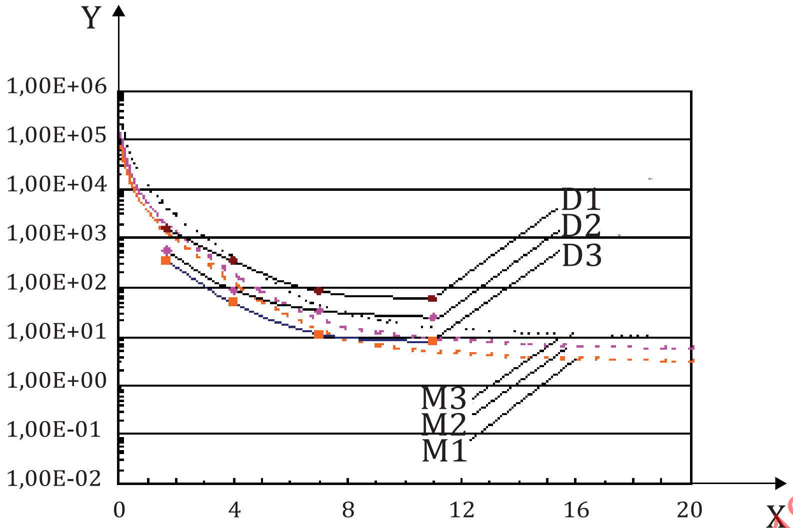
Figure C.6 — Total dose contour map at 4 mm Al thickness (Solar maximum)

Annex D
(informative)

Comparative example between model prediction and measured values

The overestimation of total dose calculation at 2 mm to 4 mm Al (aluminum) thickness was found using the total dose measurement data from a "Tsukuba" (MDS-1) satellite launched in February 2002, flying in a highly eccentric orbit, that is, a Geostationary Transfer Orbit (GTO) in 2002-2003[13]. The total dose is measured by the small dosimeter using 56 RADFETs mounted in several experimental modules in the satellites. Eight RADFETs are installed in the center of each of the four hemispherical aluminum shield domes (DOS-S) with Al (aluminum) thicknesses of 0,7 mm, 3 mm, 6 mm, and 10 mm. The RADFET sensor cover has Al thickness of 1 mm, and the total Al thicknesses are 1,7 mm, 4 mm, 7 mm, and 11 mm, respectively. The results were compared with calculation data using SHIELDOSE-2 based on the space radiation models (NASA AE8 and AP8: standard trapped radiation belt models), and solar proton JPL-1991 model (at a confidence level of 75 %)[5].

The model calculation is considered to overestimate the total dose in shields of 1,7 mm-4 mm thickness after 100 to 200 days @ GTO (roughly equivalent to the total dose after 5 to 10 years @ 700-km LEO). This result might reflect the expanded use of COTS (although flight data for shields thicker than 7 mm show a greater total dose than the model calculation). Figure D.1 shows the total dose data versus aluminum shield thickness, which is a dose-depth curve, of the flight data and model calculation.



Key

X thickness (Al) (mm)

Y total dose [Gy(Si)]

D1 430 days (Observed value by MDS-1 satellite)

D2 200 days (Observed value by MDS-1 satellite)

D3 100 days (Observed value by MDS-1 satellite)

M1 430 days (SHIELDOSE-2 model calculation)

M2 200 days (SHIELDOSE-2 model calculation)

M3 100 days (SHIELDOSE-2 model calculation)

Figure D.1 — Dose-depth curve from the flight data and SHIELDOSE-2 model calculation

Annex E
(informative)

Radiation deterioration of electronic components

E.1 Semiconductor electronic components — Outline of radiation deterioration

When there is constant radiation, the effect of a positive charge remains in the insulating layers such as SiO_2, and the occurrence of interface state density on the insulating layer and interface of the silicon crystals are the main issues with silicon semiconductors. These issues are expressed by a decrease in the current amplification factor and an increase in leakage current for bipolar transistors. In ICs, the circuit characteristics indicate a remarkable fluctuation due to variations of these parameters. Table E.1 lists the main variable parameters and tendencies of various semiconductor devices for the total dose. The parameters with the largest effect are as follows:

a) Bipolar transistors

Deterioration in current amplification factor h_{FE} is most remarkable in the low current range. Recently, ELDRS of linear bipolar components has been discovered in ground radiation tests, and with dose rates of 50 rad/s or less, the deterioration of the gain was larger in some linear bipolar components on which radiation tests were performed at low dose rates.

b) TTL

The output voltage (V_{OL}) and propagation delay time (t_{PHL}) increase remarkably due to the decrease in current amplification factor h_{FE}.

c) CMOS

Input levels V_{IH} and V_{IL} fluctuate, output driving capabilities I_{OH} and I_{OL} decrease, and propagation delay time t_{pd} increases remarkably. Power current I_{DD} increases when static due to internal leakage. The refinement entails thinning of the gate oxide film, thereby improving overall total dose tolerance. However, it should be noted that the leakage phenomenon specifically increased by irradiation has also been confirmed in oxide film on the order of several nm.

d) Memory devices (e.g., SRAM, DRAM)

The same tendency as CMOS basically occurs. In particular, there are many cases where a great fluctuation can be observed in the power current I_{DD} and the input leakage current when static.

e) FPGA (anti-fuse type)

Input levels $V_{IH\ \mathrm{and}}$ V_{IL} fluctuate, output driving voltages $V_{OH\ \mathrm{and}}$ V_{OL} decrease, and propagation delay time t_{pd} increases remarkably. Power current I_{DD} increases when static due to internal leakage.

E.2 Notes for use

Generally, the radiation tolerated dose of electronic components largely depends on manufacturing process factors, device design factors, operating conditions (e.g., existence of a bias application), type or energy of the radiation, and the dose rate. There are also cases where the radiation tolerated dose changes significantly depending on the manufacturer, production lot, etc. Therefore, the radiation tolerated dose data of each electronic component shall be sufficiently understood when designing the circuitry. Important points for the design of circuitry that can be predicted at the electronic component level include the need to consider an acceptable level of characteristic deterioration, how to use it, and whether to examine the introduction of a derating design. Examples of cautionary measures for the main variable parameters for the total dose are as follows:

a) Bipolar transistors

Given that current amplification factor h_{FE} changes significantly under smaller collector current, it should be designed so that the collector current and minimum necessary h_{FE} after exposure are compatible in the actual circuit.

b) TTL

In consideration of the deterioration of low-level output voltage (V_{OL}), a derating of fan-out is necessary.

c) CMOS, memory devices, FPGA

Caution is necessary in terms of preventing a conflict between signals, despite the variation of propagation delay time t_{pd} from the early stages to the final stages of exposure.

Table E.1 — Deterioration tendency of semiconductor devices by radiation

Semiconductor device	Main variable parameters		Change tendency
	Items	**Symbols**	
Bipolar transistors	Current amplification factor	h_{FE}	Decrease
	Leakage current	I_{CEO}	Increase
		I_{CBO}	Increase
	Saturation voltage	$V_{CE\ (SAT.)}$	Increase
TTL	Input current	I_{IH}	Increase
		I_{IL}	Decrease
	Output voltage	V_{OH}	Decrease
		V_{OL}	Increase
	Power current	I_{CC}	Decrease
	Propagation delay time	t_{PHL}	Increase
		t_{PLH}	Increase
CMOS, memory devices	Input level	V_{IH} V_{IL}	Varies
	I/O leakage	I_I I_{OZ}	Increase
	Power current	I_{DD}	Increase
	Drive capacity	I_{OH} I_{OL}	Decrease
	Propagation delay time	t_{pd}	Increase
FPGA (anti-fuse type)	Input level	V_{IH} V_{IL}	Varies
	Power current	I_{DD}	Increase
	Drive voltage	V_{OH} V_{OL}	Decrease
	Propagation delay time	t_{pd}	Increase

Annex F
(informative)

Overview of single event effect

F.1 Overview

When charged particles such as high energy protons, He ions, or heavy ions are exposed to electronic components, the particles will ionize along the trajectory of the particles and an electron hole pair will be generated. When a portion of a generated charge flows into the circuit of a device, malfunctions and overcurrent will occur due to a noise current. Such an effect can be generated with just one incidence particle and is called an SEE. Single event effects can be classified into a number of types due to the differences in the types of devices and the generating mechanism.

F.2 SEU

SEU is a phenomenon that occurs in memory devices, microprocessors, etc., in which a charge occurs from the incidence of high energy charged particles flowing into the memory circuit, causing malfunctions and reversing information in the memory. There are cases where adjoining multiple cells are upset by an incidence of one ion (called MCU) in recently made components with microstructures. MCU is used differently than MBU, in which multiple bits are upset in one phase.

F.3 SET

SET is a non-destructive behavior generated in linear ICs and logic circuits, such as optical semiconductor devices, OP amplifiers, and comparators. The noise pulse generated from charged particles that entered at the input stage is retained in the latch circuitry or transmitted to the output stage, where malfunctions occur in the circuitry.

F.4 SEL

SEL is mainly generated in devices of a CMOS structure. The thyristor structure is specifically included in CMOS structures. The thyristor changes to the ON state according to the noise current generated by incidences of high energy charged particles, and a large current continues to flow. Because a large current continues to flow locally unless the power supply is turned OFF, this particular thyristor shall be turned OFF before malfunctions are caused by electrodes fusing within the device and a voltage drop occurs within the same power supply system.

F.5 SEB

SEB is mainly generated in a particular power transistor, triggered by an incidence of high energy charged particles to the particular transistor included in the structure of a power MOSFET, and a large current flows into the device and destroys it.

F.6 SEGR

SEGR is a phenomenon generated in a power MOSFET, that destroys the gate oxide.

F.7 Other

Other new single event effects have been discovered accompanying the miniaturization of devices. However, the mechanisms of these new effects have yet to be completely clarified, and the names of such events have yet to be standardized. Figure F.1 shows the classification of SEE.

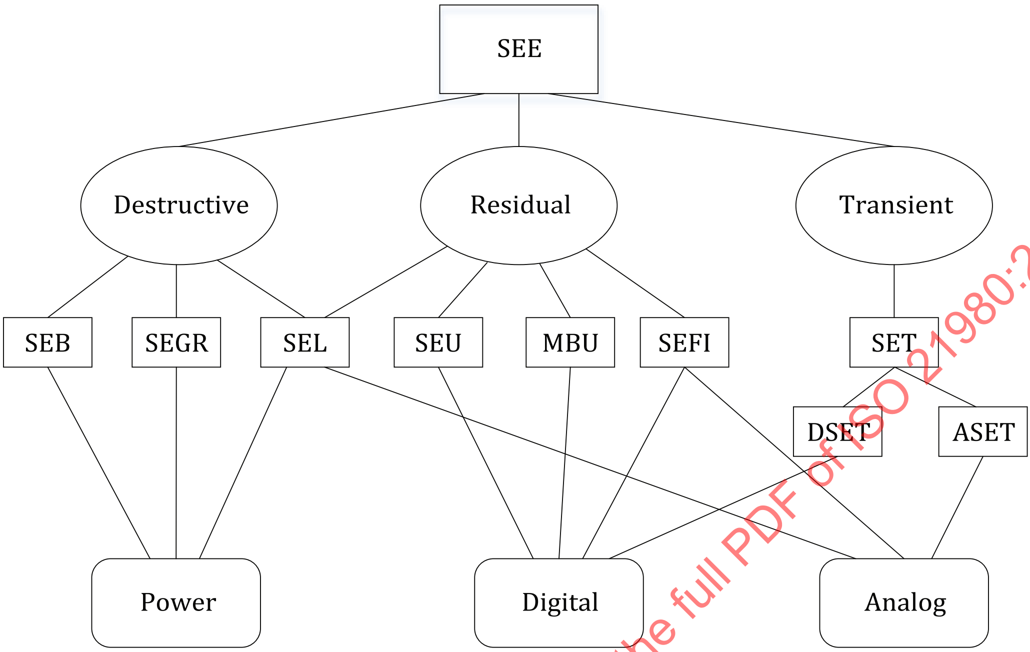


Figure F.1 — Classification of SEE

Annex G
(informative)

Measures for single events of electronic components

G.1 Overview

As basic measures at the component level, it is necessary to prioritize the use of devices with a larger resistance to a single event and devices in which the level of resistance has been clarified, or actually measuring the resistance of devices in which the resistance is unknown for reference in using basic measurements. Table G.1 lists the target devices for each single event. Be sure to perform an examination, as SET can be generated in all analog ICs.

G.2 IC

Numerous tests on the single event of ICs have been conducted worldwide, with test data being accumulated. It is necessary to collect information while referring to the database for selection, and then compare it to the mission requirements for determining its appropriateness.

The EDAC circuit is effective for SEU. The resistance to SEL changes significantly according to the device structure. As a device with an SOI structure has no parasitic thyristor, however, SEL will not occur. The collected charge can also be suppressed, which effectively improves SEU resistance.

The effect of SET that is generated in such linear ICs as operational amplifiers and comparators changes significantly with the device operating conditions. For example, it is easier for the comparator to be affected by SET when there is a smaller difference between the input voltage and reference voltage, and when there is a larger degree of amplification for the operational amplifier. Therefore, when referring to the existing SET data, it is necessary to confirm whether the data was collected under the worst possible conditions. When actually evaluating the resistance, evaluation under the worst possible conditions shall be performed, or at least under the actual operating conditions if it is difficult to determine the worst possible conditions. For selection of the components, those components that can be used under operating conditions where the effect from SET is as low as possible shall be examined.

G.3 Electronic components other than ICs

The power MOSFET is mainly used as a switching element of the power system, and thus precautionary measures shall be taken due to the high possibility of an immediate loss of functions in case of SEB or SEGR occurrence. It is preferable to select a power MOSFET having single event resistance as much as possible. SEB occurs in the n channel type MOSFET with a vertical mold structure. But because SEB does not occur in the p channel type MOSFET, one method is to adopt the p channel type depending on the application. SEB also does not occur at a voltage sufficiently lower than the rated voltage. However, SEGR could possibly occur in both the p channel type and the n channel type. SEGR tends to occur when reverse bias is applied to the gate voltage. Therefore, a large reverse bias should not be applied during operation. In order to adopt a power MOSFET, it is necessary to verify the SOA for a single event and set an appropriate derating according to the system requirements.

Overcurrent can be prevented by the load even when SEB occurs in bipolar transistors, provided that there is a resistance load. There are many cases where device damage can be avoided. However, the same measures as for the power MOSFET shall be taken for use of a switching application.

Table G.1 — Target device for each single event

Type	Target device
SEU	Memory devices, microprocessors
SET	Analog ICs (e.g., comparators, operational amplifiers, regulators, driver ICs, ADC, DAC), logic circuits, high-speed photocouplers, high-speed MPUs, high-speed memory devices, etc.
SEL	CMOS devices
SEB	N channel power MOSFET, NPN bipolar transistors
SEGR	Power MOSFET

Annex H
(informative)

Measures for single events of devices

H.1 Overview

Measures for devices are not required when adopting electronic components free of single events. If there is no electronic component with SEE resistance that meets the requirements, however, measures shall be taken at the device level. In this case, it is necessary to select components in consideration of the mission and probability of occurrence relative to the system. Furthermore, because the single event effect occurs due to high energy particles, it is necessary to keep in mind that a reduction in the probability of occurrence cannot be expected by increasing the shield thickness.

H.2 SEU measures

a) Correct the errors caused by SEU by using error correcting code or the EDAC circuit. If MBU may occur due to the structure of the devices, consider distributing the data bits over multiple devices to prevent MBU or use a code that may possibly correct the errors of multiple bits.

b) Prevent errors by having three or more of the same circuits handle most of the output as a redundant system.

c) Provide a watchdog timer. This is a measure to prevent the CPU from running out of control, and to reset the system when a specific address is not accessed for each fixed time.

H.3 SET measures

a) Correct the errors caused by SEU by using error correcting code or the EDAC circuit. If MBU may occur due to the structure of the devices, consider distributing the data bits over multiple devices to prevent MBU or use a code that may possibly correct the errors of multiple bits.

b) Prevent errors by having three or more of the same circuits handle most of the output as a redundant system.

c) Provide a watchdog timer. This is a measure to prevent the CPU from running out of control, and to reset the system when a specific address is not accessed for each fixed time.

H.4 SEL measures

H.4.1 General

a) Provide a current limiting circuit to prevent the ICs from being destroyed due to overcurrent. Threshold values at constant and at abnormal operation should be set in consideration of an increase in the power current due to the total dose of the IC concerned.

b) Use two or more of the same circuits as a redundant system.

H.4.2 SEB measures

The probability of SEB occurrence increases as the operating voltage approaches the rated voltage. Therefore, adopt a circuit configuration that is set with an appropriate derating value according to the mission requirements in consideration of the SEB resistance of each device.

H.4.3 SEGR measures

In consideration of the SEGR resistance of each device, adopt a circuit configuration set with an appropriate derating value according to the mission requirements within the specified range of the SOA.

Annex I
(informative)

Prediction method of displacement damage

The energy used to cause displacement damage to materials is expressed as NIEL. When semiconductor devices receive displacement damage, the parameters of the devices will deteriorate, as the degree of deterioration and NIEL are known to be proportionally related. Therefore, the damage factor (K) shall first be acquired from past data or through proton irradiation tests. Next, the NIEL value shall be calculated in an actual proton environment, so that the degree of deterioration in orbit of the parameters of the device concerned can be calculated by multiplying the damage factor (K) by the NIEL value.

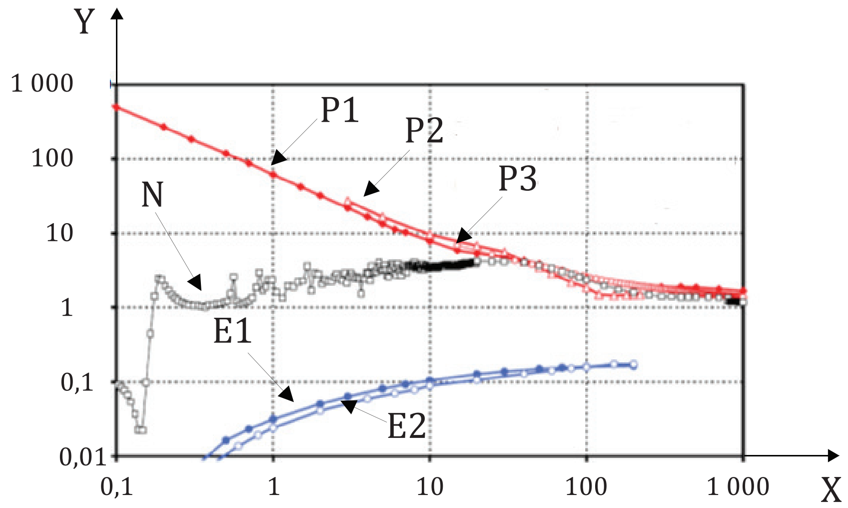
To see how NIEL can be used to estimate degradation, we define a damage factor (K). If a device parameter (P) varies linearly with fluence, $\varphi(E)$, a damage factor is defined as follows:

$$\Delta P(E) = K \times N(E) \times \varphi(E) \qquad \text{(I.1)}$$

where $N(E)$ provides the energy for particle dependence of the degradation relative to P. Experimental damage factors are required to predict the displacement damage effects throughout a mission. Caution should be taken here as damage factors may depend on the operating conditions, and because the damage factors employed shall be appropriate for the application and any annealing effects shall be acknowledged. Once the expected radiation environment has been modeled to give particle fluence spectrum $\mathrm{d}\varphi(E)/\mathrm{d}E$ as a function of energy (E), including the effects of shielding, the mission damage can be calculated from:

$$\Delta P_{\text{orbit}} = K \int N(E) \frac{\mathrm{d}\varphi(E)}{\mathrm{d}E} dE \qquad \text{(I.2)}$$

The NIEL values of various particles in silicon have been published by Dale et al.[19], Huhtinen et al.[20], Akkerman et al.[21], and Summers et al.[22]. Figure I.1 summarizes the values. Various calculations tend to agree within a factor of two, which is comparable with the uncertainties involved, including several NIEL models for the protons in Si, GaAs, and InP for calculating the damage equivalent dose for a user-defined mission[23].



Key

P1 proton: Dale et al.

P2 proton: Huhtinen and amio

P3 proton: Akkeman et al.

N neutron: Vasllescu & Lindstroem

E1 electron: Summers et al.

E2 electron: Akkeman et al.

X particle energy (MeV)

Y NEIL (keV cm^2/g)

Figure I.1 — Some of the published values of NIEL in silicon

Deterioration prediction flow for displacement damage is shown in Figure I.2.

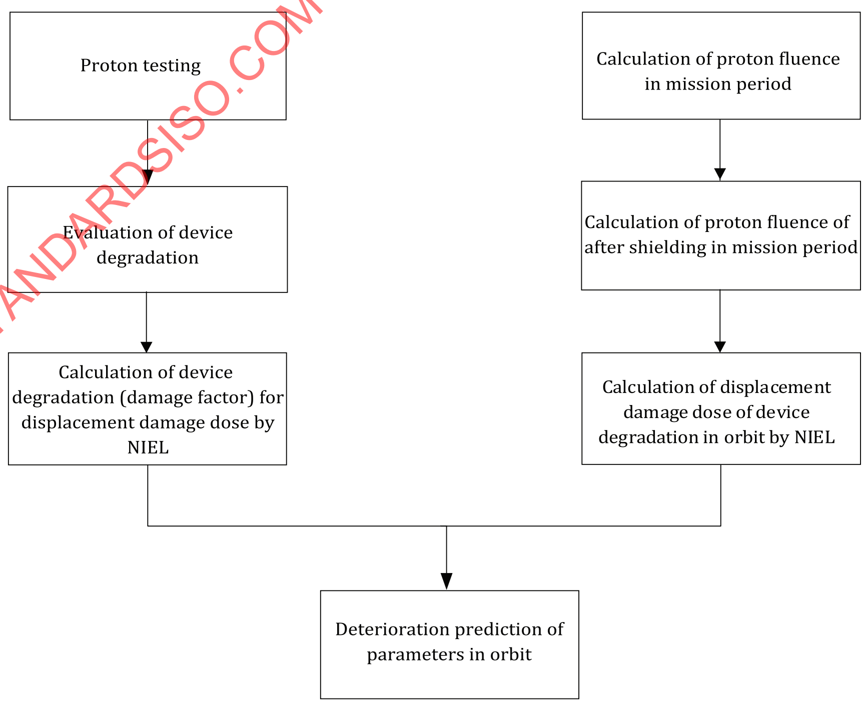


Figure I.2 — Deterioration prediction method by displacement damage to devices in orbit

Annex J
(informative)

Resistance for displacement damage of each device

J.1 Overview

Table J.1 summarizes the semiconductor devices that are affected by displacement damage. The resistance to displacement damage shall be evaluated in advance, along with a prediction of deterioration in orbit for devices that may be greatly affected by displacement damage. The effects of a single event or total dose shall also be evaluated as required. There are cases where the effects of both the total dose and displacement damage shall be evaluated, depending on the device. Generally, the devices in which the minority carrier lifetime and generation carrier lifetime dominate the characteristics, or those requiring extremely high performance in specific parameters have low resistance to displacement damage.

Table J.1 — Semiconductor devices affected by displacement damage

Device	Effect of displacement damage	Resistance to displacement damage
CCD	Deterioration of charge transport efficiency (CTE), increase in dark current	Easily affected by displacement damage. Linear CCDs are highly resistant.
Photo detectors	Deterioration in speed of response Increase in dark current	Resistance changes with applications. Photo-transistors tend to be affected easily by displacement damage. Metal-semiconductor-metal (MSM) photodiodes are highly resistant.
LEDs, laser diodes	Deterioration of optical output Increase in current threshold value (laser diodes)	Effect by displacement damage is relatively low. LEDs, laser diodes have less resistance than laser diodes. Amphoterically doped LEDs are less resistant.
Photocouplers	Deterioration of CTR	Response to radiation is complex. Resistance changes significantly with purpose & applications. Photocouplers that use photodiodes have the highest resistance. Photocouplers that use photo-transistors have less resistance. * Photocouplers with a high speed operation of 1 MHz or more require an examination on SET.
Si bipolar transistors, linear ICs	Deterioration of gain	Less resistance with horizontal type PNP transistors High resistance heterojunctions

J.2 CCD

When a CCD receives displacement damage, deterioration of CTE increases in the average dark current with an extremely large dark current in each pixel, resulting in increased noise in the output amplifier. CTE is the most important parameter for a CCD. However, when the signal charge is captured by the defective level formed by the radiation of the protons, and then released after the clock cycle ends at capture, the signal will appear in the image of the cycle when it is released. This does not produce an image of the original cycle and the quality of the image deteriorates. Therefore, the effect from displacement damage to CTE will be determined by the read method or clock frequency of the device. Given that the clock frequency of a linear CCD is as fast as 1 MHz or more, and the signal is transmitted without being captured by the defective level, the CCD is not easily affected by displacement damage. The measures for CTE deterioration are currently being researched. However, the deterioration of CTE can be slightly reduced by cooling the device to reduce capture of the carrier. When additional measures are required, a thicker shielding should be used. However, the effect of displacement damage by secondary particles due to collisions between the protons and shielding material becomes larger. As an average dark current and an extremely large dark current (spike) appear in each pixel, the signal to noise ratio (S/N) can be improved by using large area pixels.

The following items can be considered measures against CCD displacement damage. It is necessary to consider the effect on devices that are easily affected by the total dose as well.

a) Shielding of the devices.

b) Cooling of CCD.

c) Selection of devices which are highly resistant to displacement damage.

d) Selection of operating conditions which cannot be easily affected by displacement damage and signal processing.

e) Use of the CCD with the large area pixel.

J.3 Photo detectors

Photo detectors consist of PN junction photodiodes, PIN diodes, and photo-transistors, and an increase in dark current by the carrier generated in the depletion layer and a deteriorated response due to a deteriorated minority carrier lifetime are mentioned as effects due to displacement damage. And as the gain of photo-transistors is greatly affected by the minority carrier lifetime, it is also easily affected by displacement damage. However, the MSM photodiode is a majority carrier component and has high resistance to displacement damage. The resistance to displacement damage changes significantly by the application of each device.

Photodiodes specific to various applications should be provided; and the effect from radiation changes significantly according to the design. In addition to the permanent damage caused by displacement damage, there may be a temporary increase in output current due to ionization, depending on the application.

J.4 Light emitting devices

Laser diodes have relatively high resistance to displacement damage. However, the output may possibly deteriorate when the current threshold value changes significantly.

Even though LEDs are inferior to laser diodes, many LEDs have high resistance to displacement damage. However, the resistance changes according to the applications, such as large output and use at high speeds. As an exception, amphoterically doped LEDs are known to be affected by displacement damage.

J.5 Photo couplers

Photocouplers are hybrid modules that consist of LEDs (light sources), photo detectors, and optical couplings, and are extensively used for the purpose of separating circuits electrically. An important parameter of photocouplers is the current transfer ratio (CTR) expressed for the LED forward direction (drive) current of the collector current of photo detectors. There are various photocoupler designs, and the applications can also be largely divided into digital photocouplers and linear photocouplers. The response of photocouplers to radiation largely depends on the design and application. Photocouplers are also affected by the total dose or single events. In addition to displacement damage, the effects of SET in photocouplers used at high speeds of 1 MHz or more shall also be considered. Amphoterically doped AlGaAs LEDs tend to be the most affected by displacement damage among LEDs. Current photocouplers have less resistance than the earlier photocouplers.

The response of photocouplers to radiation becomes complex for the following reasons:

a) Because a photocoupler is a hybrid module, individual differences in radiation resistance are too large. (The origin of the configured components cannot be clarified.)

b) The observable deterioration is a combination of the total dose and displacement damage, and the impact is dependent on the photocoupler design or application.

c) When a photocoupler is a part of a much larger hybrid module, such as a DC-DC converter, the photocoupler may be affected by other components in the module as well.

d) CTR deterioration of photocouplers is mainly determined by the LED resistance to displacement damage. When photo-transistors are used for the photo detector, an effect from a deteriorated optical response may also be received. Photocouplers using photodiodes are the most resistant to displacement damage overall.

When evaluating the CTR, it shall be considered according to the application. For digital photocouplers, the CTR shall be evaluated across the entire wave range, and the CTR in a specific wave range to be used shall be evaluated for linear photocouplers.

J.6 Bipolar transistors

Bipolar transistors have relatively high resistance to displacement damage. However, analog bipolar ICs tend to receive displacement damage. Even though the resistance of linear ICs changes significantly according to the process and device design, linear ICs that include horizontal type PNP transistors are known to receive the most displacement damage, and such linear ICs that use horizontal type PNP transistors at low currents on the input portion may have less resistance. In devices where high performance is demanded (e.g., extremely small input offset), bias current and low noise also tend to be affected by displacement damage. Conversely, bipolar transistors with heterojunctions such as SiGe have high resistance to displacement damage.

