Spacecraft Environment Interaction

R7004R

SPENVIS Report

Analysis of the Cluster-II FM-8 (Tango) Mission

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Abstract

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Contents

1 Introduction

Since space applications become more and more important for our everyday life, be it direct-broadcast services, environmental monitoring or even space travel, the understanding of the environment those applications operate in is crucial to ensure proper and smooth functioning.

To improve the understanding of the space environment and to examine different effects of the space environment on a spacecraft, this report will give an in-depth analysis of the Cluster-II Mission, a mission carried out by the European Space Agency (ESA) to study the interaction between the solar wind and the earth's magnetosphere and provide an unprecedented 3D-model of those interactions [1].

This report is focused especially on the space radiation environment of the Cluster-II FM8 (Tango) satellite, one of the four satellites of the Cluster-II mission, and on the radiation effects on solar arrays and different electronic devices. For analysing the space environment a tool called SPENVIS (Space Environment Information System) developed by ESA is used. SPENVIS is a Web-interface with a powerful backend that provides access to numerical calculations and evaluations of a user-defined orbit or mission. It also provides data on different effects as "[...] cosmic rays, natural radiation belts, solar energetic particles, plasmas, gases, and "micro-particles" [...]" [2].

To provide an overview over the FM8 Tango Mission, the next chapter will introduce the mission objectives as well as the basic space environment this specific satellite faces. After, different radiation effects are examined and numerical calculations for solar arrays and memory devices are performed, followed by an analysis of their results. [2].

2 Mission Overview

2.1 Mission Definition

The Cluster-II Mission is planned and executed by the European Space Agency and was launched on 16th of July 2016. The whole mission consists of four identical spacecrafts flying in a tetrahedral formation in a highly elliptical orbit, where each spacecraft is collecting various data on the space environment with its 11 scientific payload instruments. These in-situ measurements are done to build a very accurate 3D-Model of the earth's magnetosphere and thus to observe the magnetosphere interaction with the solar wind not only in a spatial but also in a temporal resolution.

The main goal of this mission is to examine and gather data especially on the plasma structures in the bow shock region, the magnetopause, polar cusps, the earth's magnetotail and the auroral zone, all of them regions with very interesting properties when it comes to the interaction with solar wind [1].

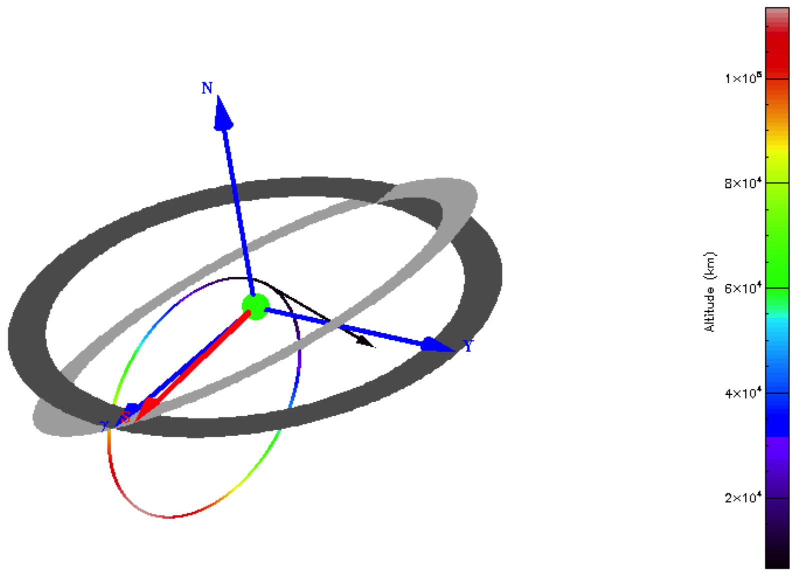

Figure 1: One Orbit of FM-8 Tango, the color bar shows the altitude

To model the Orbit of FM-8 Tango a set of TLE[1] data provided by CelesTrak was used [4].
Figure 1 shows one orbit of FM-8 Tango and indicates the altitude of the orbit. The orbit itself is a retrograde orbit with an inclination of 131.6 degrees. A complete set of TLE data describing all important orbit parameters can be found in the Appendix A.1.

[1]Two Line Element

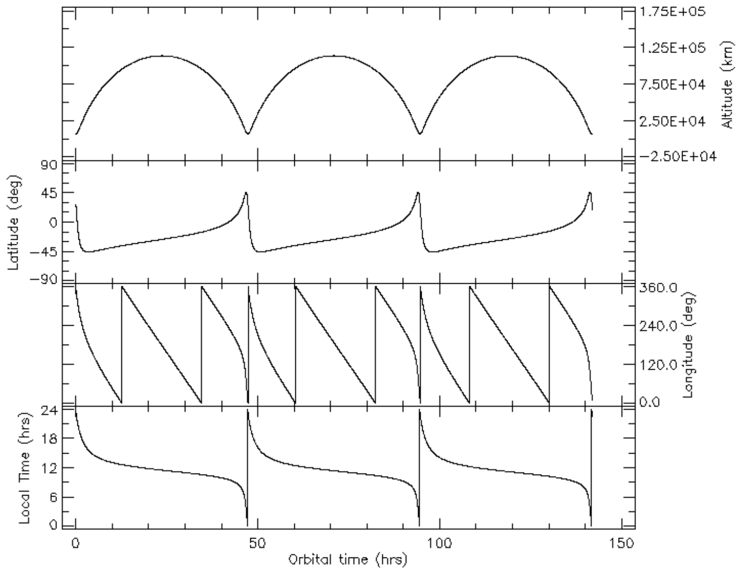

Figure 2: Various Data on 3 orbits of FM8 Tango

2.2 Space Environment

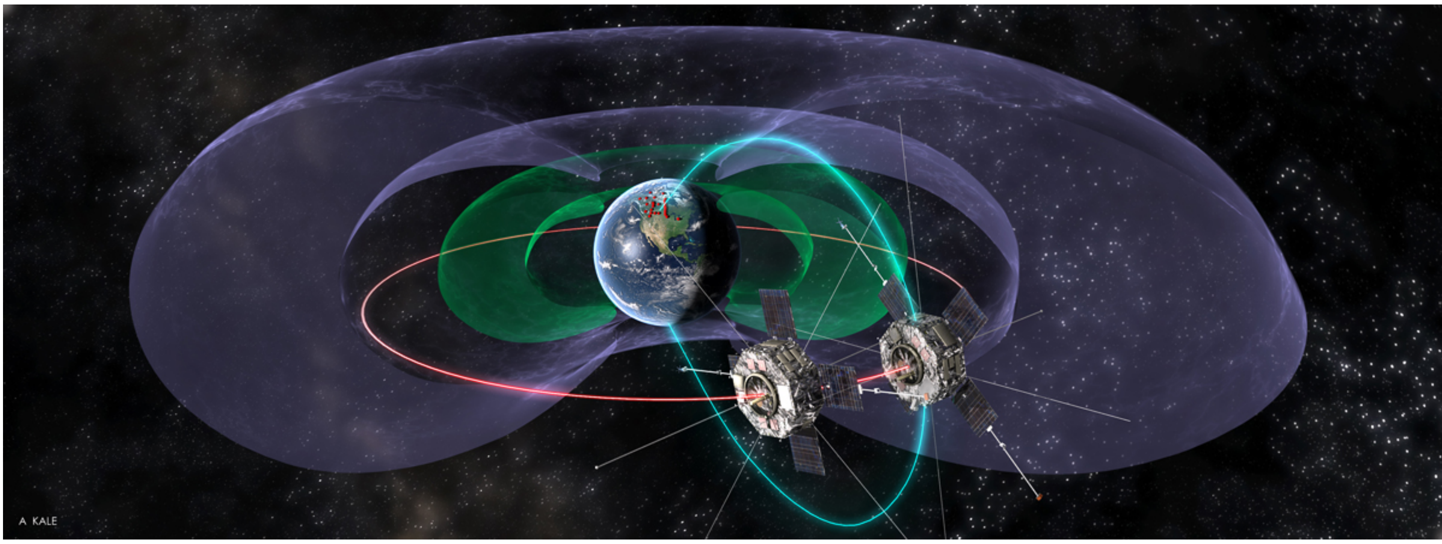

Figure 3: Van Allen Probes in the Van Allen Belt by phys.org

Due to its highly elliptical orbit as seen in Fig.1 and the relatively high perigee of 28000km and apogee of 104000km the satellite moves through different space environments, as for example the Van Allen Belt, and encounters different particles and plasma configurations on its way, which may lead to Spacecraft Charging and other effects, but may also be affected by Micrometeoroids and Space Debris, the so-called MMOD environment. Since these environments may be hazardous for the satellite, a proper investigation and analysis of these effects is necessary to ensure a proper satellite operation during its lifetime.

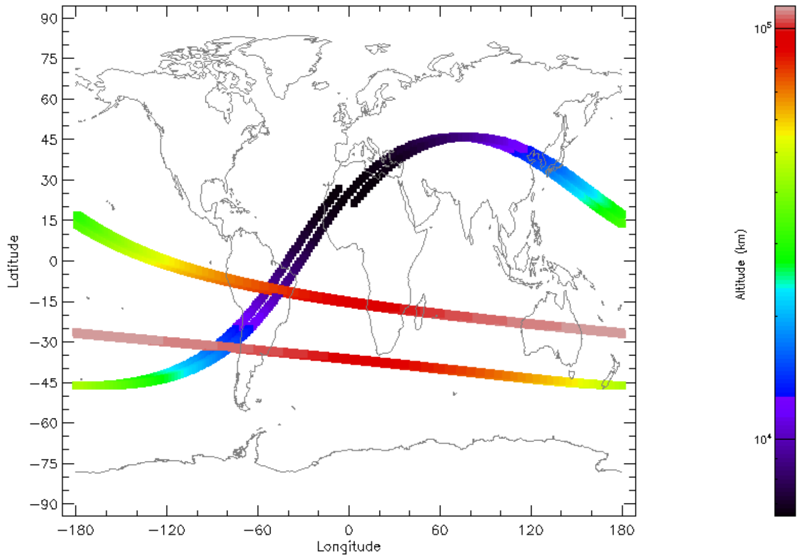

Figure 4: Groundtrack of 2 FM8 Tango Orbits

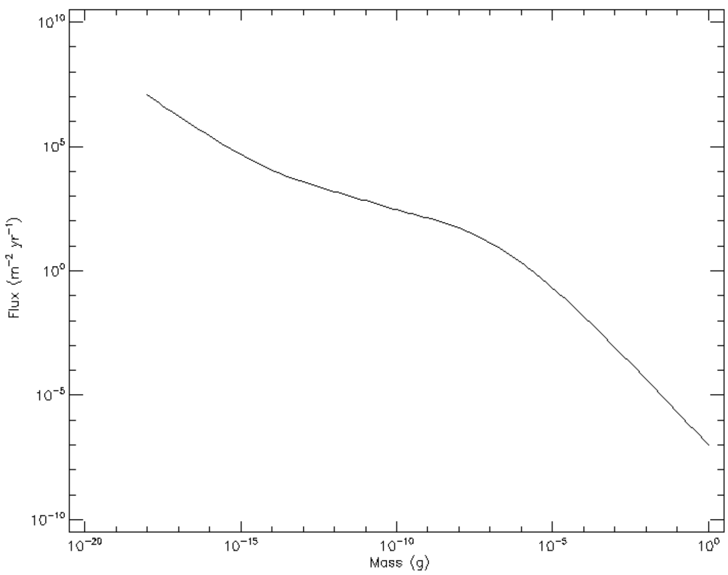

Figure 5: Flux of Meteoroids compared to their mass at perigee

An important point is the MMOD environment. Usually micrometeoroids and space debris also play a important role in the space environment a satellite encounters. Although in our case this is only a minor factor, since we expect most micrometeoroids and space debris to be in lower orbits. This is backed by our findings with the help of SPENVIS as may be seen in Figure 5.

2.3 Drag and Atmospheric Oxygen

But not only the MMOD environment exposes the spacecraft to risks. It is the atmosphere of the earth that affects the satellite in terms of drag forces, which occur due to the bombardment with atmospheric particles and slow the spacecraft down. Another risk is the Atomic Oxygen, which itself is highly reactive and degrades the spacecraft outer surfaces.

Since our chosen mission is in a quite high orbit, atmospheric effects do not play a big role and can be neglected [6]. Our simulations with SPENVIS support this statement, as can be seen in Figures 7. Only during the perigee the satellite encounters some particles, which are in the magnitude of 10^{-20} to 10^{-30} and thus can be neglected.

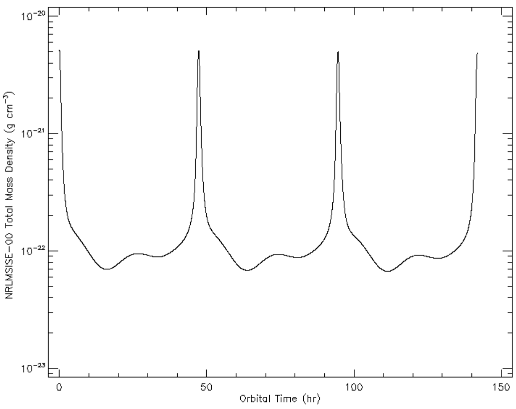

Figure 6: Total Mass Density during 3 Orbits

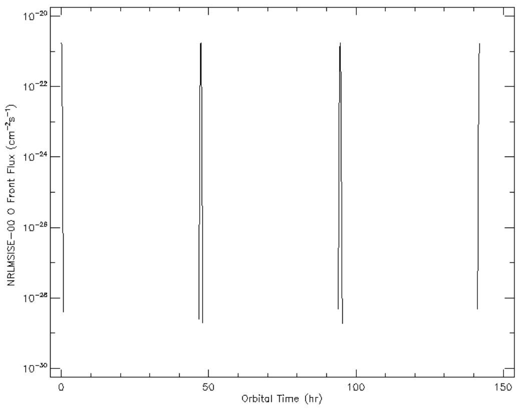

Figure 7: Front Flux of Oxygen during 3 Orbits

2.4 Plasma Environment

As already stated and is well known, the Van Allen belts extend from about 100km to 65000km and consists of two so-called "belts", whereas newer findings suggest a belt in-between them as well [5]. Since the FM-8 satellite's lowest point is its perigee, it only moves through the outer Van Allen Belt, where the satellite is bombarded with ions and electrons. Due to this bombardment the satellite gains a potential compared to its surrounding plasma, called the floating potential. The floating potential depends on multiple parameters, some of them being the flux of ions and electrons hitting the surface

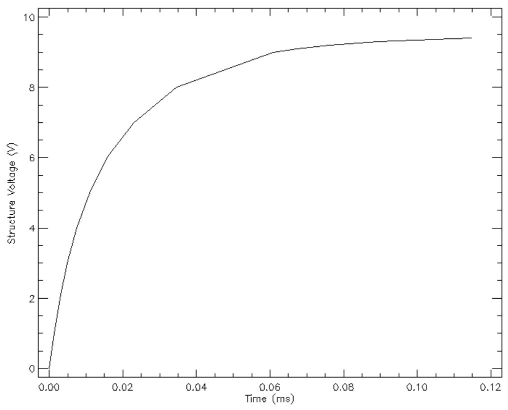

Figure 8: Structure Voltage in Sunlight

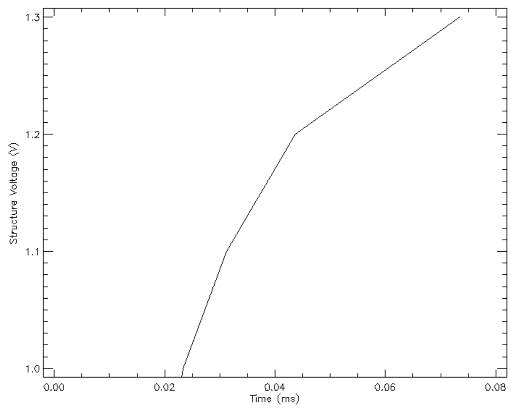

Figure 9: Structure Voltage in Eclipse

area of the satellite and photoionisation, when in sunlight. Usually spacecrafts in higher orbits gain a negative structure potential, since the electrons have a smaller mass and thus are faster and more energetic in terms of their thermal energy.

Running simulations on the satellite's potential we had some interesting findings, since the satellite's structure Voltage is positive. This is due to the fact, that FM-8 is almost always in the sunlight, it is bombarded with high-energy Ions, which leads to a positive structure potential, as may be seen in Fig. 8. And since FM-8 is only about seven minutes in eclipse during one orbit, the Potential stays positive during this time as well.

A detailed analysis on the necessary shielding will be explained in detail in Chapter 3.3.

3 Numerical Simulations

3.1 Environmental flux

SPENVIS uses the AP-8/AE-8 model to simulate the trapped proton and electron models, which can simulate the fluxes during solar maximum and minimum.

For the worst-case simulation the solar maximum is considered.

For the protons the number of trapped protons is higher during solar minimum due to the increased scale height caused by the increased UV radiation from the sun, but only for lower altitudes, for this orbit the difference between solar minimum and maximum for the proton flux is negligible, which is not the case for the electrons.

In figures 13 and 12 the integrated fluxes are displayed over the orbit in GEI mode.

The highes proton fluxes are expected at perigee, while for the electron flux the highes flux is expected during crossing of the radiation belts (c.f. fig. 14).

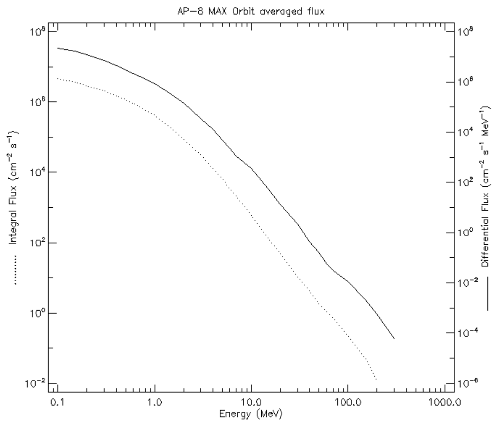

Figure 10: Proton Flux

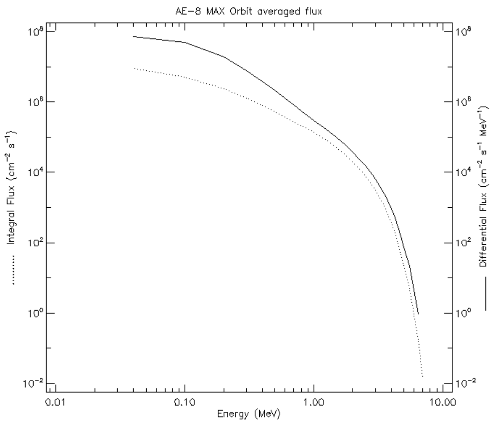

Figure 11: Electron Flux

3.2 Lifetime and Performance Degradation

The satellite is using Azur 3G28 solar cells, with an EOL power of 95% of the BOL power [3].

Using SPENVIS' MC-SCREAM for solar cells, it was determined that the shielding thickness should be around 230 µm which leaves an EOL powerloss of 3.3%.

3.3 Total Dose and Shielding

The satellite is using a memory device which can withstand a total radiation dose of 25 Krad before failure.

With 1mm of shielding the memory device exceeds its maximum radiation dose with a total dose of 1.5 Mrad, which is about 62 times the maximum allowed dose.

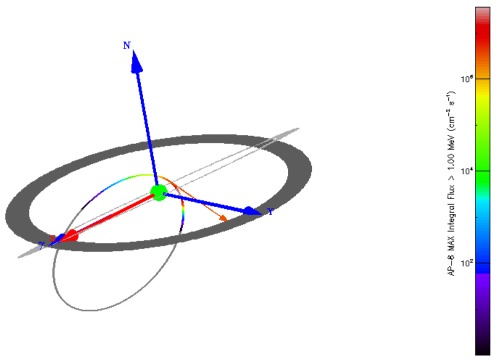

Figure 12: Proton Flux greater than 1 MeV

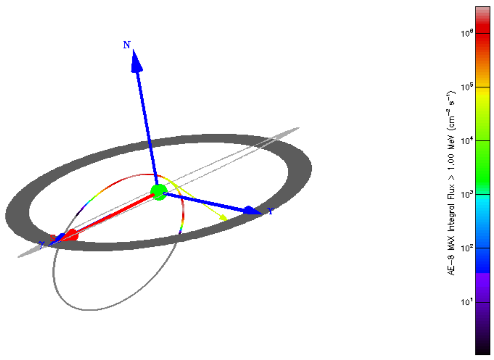

Figure 13: Electron Flux greater than 1 MeV

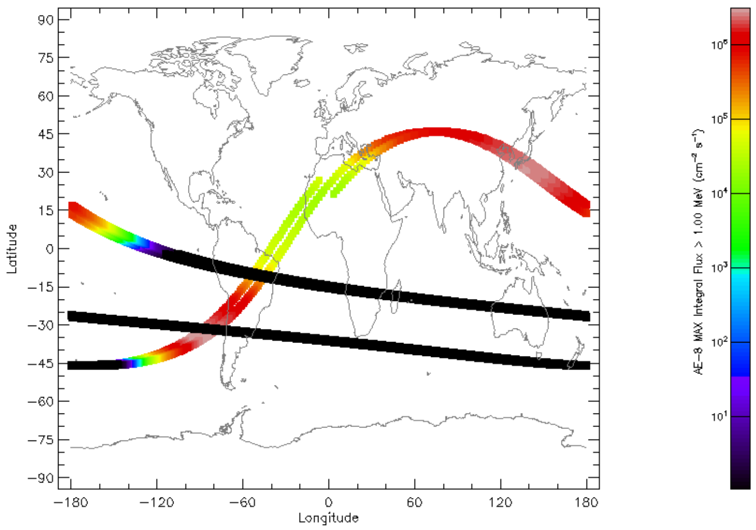

Figure 14: Electron Flux World map

To achieve a maximum dose of 25 Krad or less the shielding has to be increased to a minimum of 5.1mm, which will lead to a maximum dose of 26 Krad.

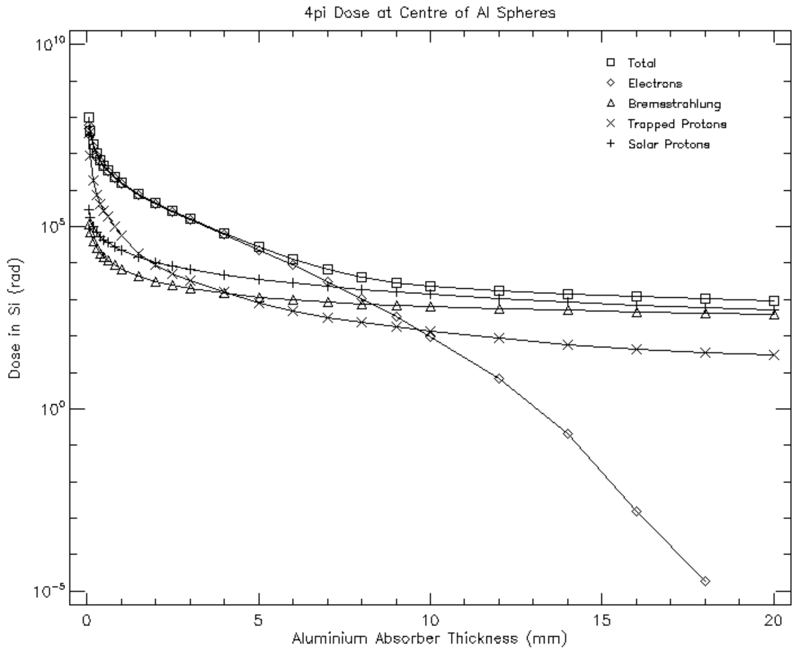

Figure 15: Dose received vs. Shielding in mm

3.4 Single Event Upsets

3.4.1 Linear Energy Transfer (LET) Spectrum

The LET spectra was calculated using SPENVIS, including solar particles, trapped protons and galactic cosmic rays, with a shielding of 1 g/cm^2 (c.f. fig. 16).

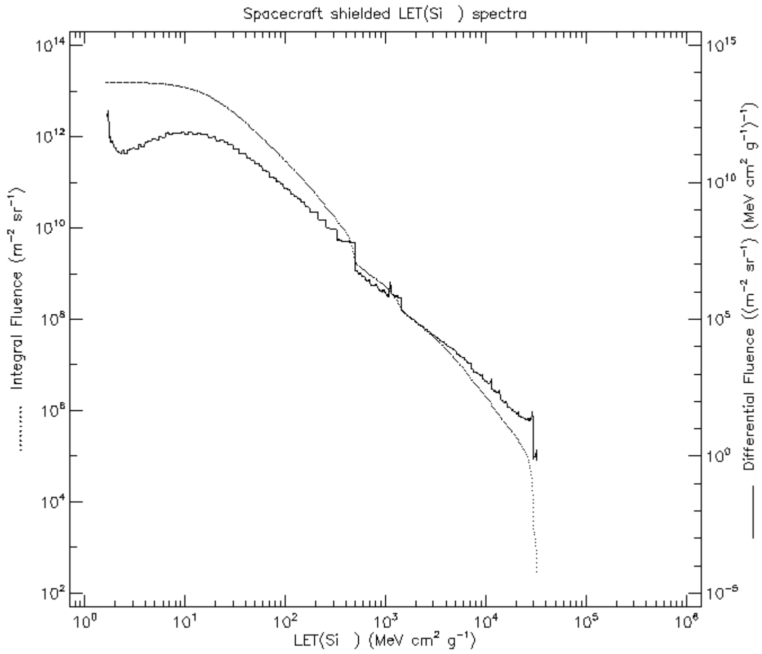

Figure 16: LET spectra for the full mission

3.4.2 Cross Section and Components Characteristics

For the SEU estimation several parameters are needed for the SMJ329C50GFAM66 to determine its cross-section which is determined by a Weibull function.

$$\sigma(L) = \begin{cases} 0 & L \geq L_0 \\ C_s \left(1 - e^{\left(\frac{L-L_0}{W}\right)^s}\right) & L < L_0 \end{cases}$$

Using the mono-beam experimental results ([3]) the final parameters calculated with a Weibull-fit in Matlab are:

L_0	$1.01 MeV \cdot cm^2/mg$	LET Threshold
C_s	$4.98510^{-6} cm^2$	saturated crosssection
W	$4.985 MeV \cdot cm^2/mg$	Weight of the distribution
s	0.7	shape parameter

Table 1: Results of the Weibull-Fit

The code responsible for the fit is generated using the Matlab Curve-Fit Toolbox (c.f. Listing 1) using data from [3] (c.f. Listing 2), the graphical result of the fit is shown in figure 17.

Listing 1: Autogenerated Matlabcode for fitting

```
function [fitresult, gof] = createFit(stopping, crossSec)
%CREATEFIT(STOPPING,CROSSSEC)
%  Create a fit.
%
%  Data for 'Weibull' fit:
%      X Input : stopping
%      Y Output: crossSec
%  Output:
%      fitresult : a fit object representing the fit.
%      gof : structure with goodness-of fit info.
%
%  See also FIT, CFIT, SFIT.

%  Auto-generated by MATLAB on 27-Mar-2016 22:16:28

[xData, yData] = prepareCurveData( stopping, crossSec );

% Set up fittype and options.
ft = fittype( 'C*(1-exp(-((x-L)/w)^s))', 'independent', 'x', 'dependent', 'y' );
opts = fitoptions( 'Method', 'NonlinearLeastSquares' );
opts.Display = 'Off';
opts.StartPoint = [0.0003 1 1 2];

% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );
```

Listing 2: Inputvalues for the fit

```
flips =[8 7497 22514 23986 33810 29991 21022 18043]; %from instructions
exTime = [5 5 5 5 5 10 10 15]; %from instructions
flux = [25e6 25e6 25e6 17e6 23e6 10e6 7e6 4e6]; %from instructions
energyBeam = [0.6 0.72 9.6 4.8 20 56 84 786]; %from instructions
u = [12 12 12 16 40 56 84 131]; %from instructions
energy = energyBeam./(u); %Where it has to be read from the table
crossSec=flips./(exTime.*60.*flux); %crosssection
LET = [2.73E+03 3.13E+03 4.65E+03 7.23E+03 1.77E+04 2.77E+04 3.74E+04 5.72E+04]./1000; %MEV cm^2/mg, read from table
```

3.4.3 SEU Estimation

To determine which device is best for the mission it is neccessary which possible device is most immune to radiation to minimize malicious operation or data corruption.

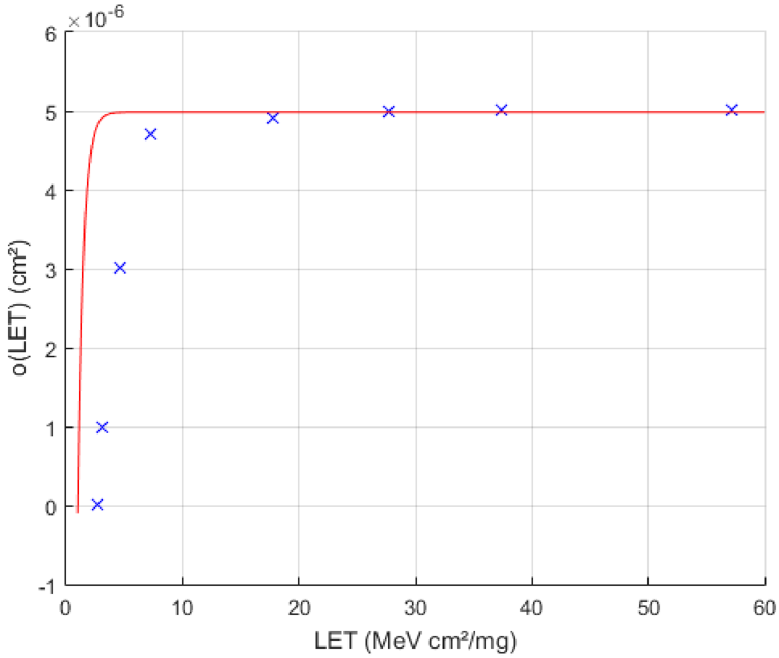

Figure 17: Weibull fit result

This is done by estimating the SEU (single-event upset).

The SEU is calculated with the following formula (assuming omnidirectional flux), which was done using the results from the SPENVIS simulation in Matlab.

$$\frac{dU}{dt} = 4\pi \int_0^\infty \sigma\left(LET\right) \sum_{z=92}^{z=0} h\left(LET\right) dLET$$

The resulting SEU in $frac1sec$ are

NMOS2164	$9.6 \cdot 10^{-3}$
CMOS R160-25	$2.5 \cdot 10^{-6}$
Bipolar 93L422	$13.8 \cdot 10^{-3}$
SMJ329C50GFAM66	$3.0 \cdot 10^{-3}$

Table 2: SEU rates

As one can see easily in table 3.4.3 the CMOS R160 has the lowest SEU rates of all devices, thus it is the best choice. The differential Flux is plotted against the LET for the four devices in Fig. 18.

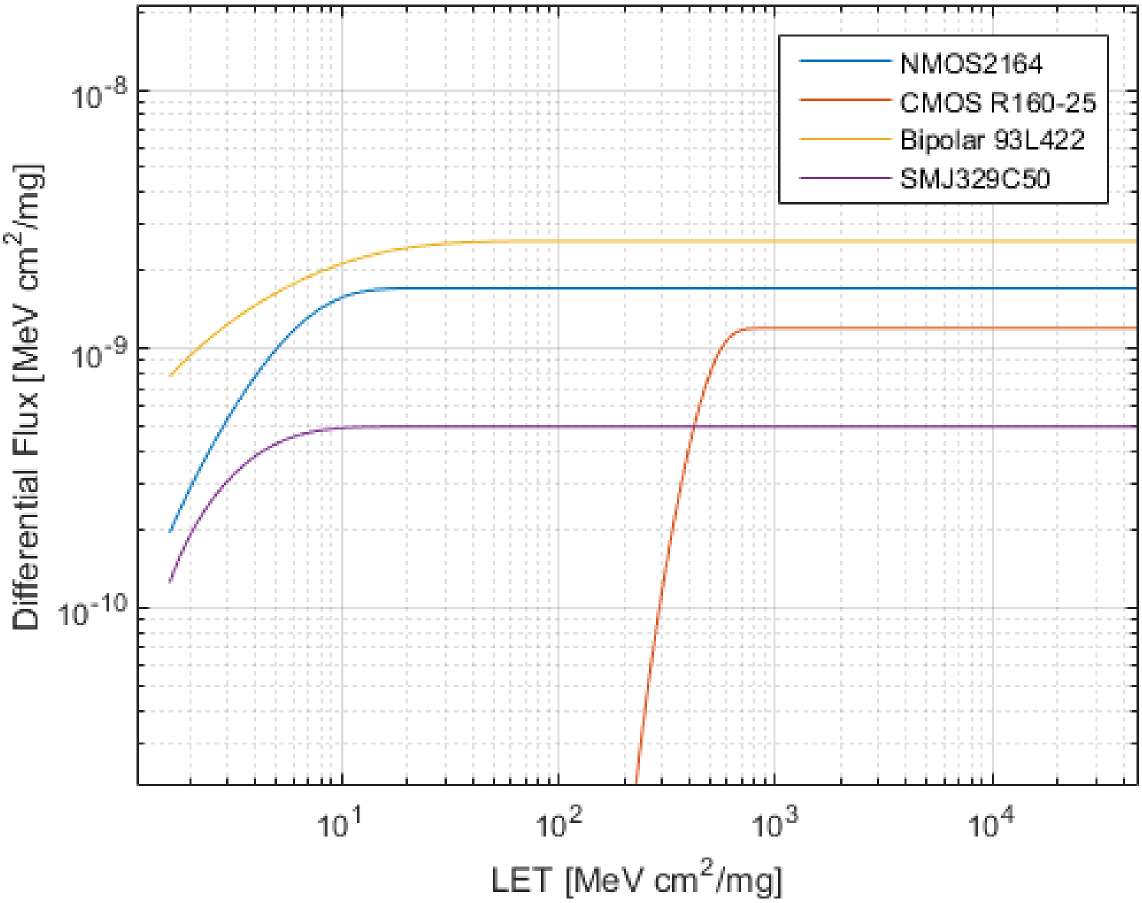

Figure 18: Plot of different LETs

4 Conclusion

In this report we analysed the Cluster-II FM-8 Tango Mission by the European Space Agency with regard to the space environment the satellite is in during its lifetime.

The first chapter introduced the mission of FM-8 Tango, where four similar satellites are building a very accurate 3D-Model of the earth's magentosphere to analyse and understand its regions better, and described the orbit and its different effects it has on the spacecraft, as drag, erosion and radiation effects.

Having defined these constraints, we modelled the mission with the tool SPENVIS, to run simulations on the spacraft environment, especially with focus on the radiation effects it has on the spacecraft. Due to the degradation of the Azur 3G28 solar cells, which we assumed to be used on the spacecraft, as stated in the report instructions, we found out that the shielding thickness for the mission time should be 230 μm to reduce the incoming flux to have an acceptable degradation at the EOL.

In addition, we analysed the total ionising dose on a memory device to determine the necessary shielding to achieve a maximum

References

[1] ESA science cluster mission, 2016. URL: `http://sci.esa.int/cluster/` [cited 2016-03-26].

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[3] Hugh D. R. Evans. Space environment laboratory work with spenvis radiation environment and effects v2.2, March 2016. SPENVIS Laboratory Instructions.

[4] Dr. T. S. Kelso. NORAD two-line element sets current data, 2016. URL: `https://www.celestrak.com/NORAD/elements/science.txt` [cited 2016-03-30].

[5] ESA Requirements and Standards Division. ECSS-E-ST-10-04C - space engineering - space environment, Nov 2008.

[6] David Vallado and David Finkleman. A critical assessment of satellite drag and atmospheric density modeling. In *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*. American Institute of Aeronautics and Astronautics (AIAA), Aug 2008. URL: `http://dx.doi.org/10.2514/6.2008-6442`, `doi:10.2514/6.2008-6442`.

Appendix

A.1 Orbital Parameters of Cluster-II FM8 Tango

```
CLUSTER II-FM8 (TANGO)
1 26464U 00045B 16087.81656212 .00000382 00000-0 00000+0 0 9996
2 26464 131.5572 328.3783 5181518 141.3516 0.4910 0.44219885 51441
```

Table 3: Cluster-II Tango Parameters extracted of TLE set

Parameter	Value
Satellite Common Name	CLUSTER II-FM8 TANGO
Satellite Number	26464
Elset Classification	U
International Designator	00
Launch Number of the Year	045
Epoch Year	16
Epoch	87.81656212
BSTAR Drag Term	0.00000382
Inclination (deg)	131.5572
RAAN (deg)	328.3782
Eccentricity	0.5181518
Argument of Perigee (deg)	141.3516
Mean Anomaly (deg)	0.4910
Mean Motion (rev/day)	0.44219885
Rev number at epoch	5144