PROCEEDINGS OF SCIENCE

SEP Protons in GEO with the ESA MultiFunctional Spectrometer

L. Arruda[∗†], **P. Gonçalves**
Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal
E-mail: luisa@lip.pt

I. Sandberg, I. A. Daglis
Institute of Accelerating Systems and Applications, P.O. Box 17214, GR-10024 Athens, Greece.

A. Marques, J. Costa Pinto, A. Aguilar, P. Marinho, T. Sousa
EFACEC, Moreira da Maia, Portugal

A. Menicucci, P. Nieminen
ESA European Space Research & Technology Centre, Noordwijk, The Netherlands

The AEEF-TDP8 (ESA Alphasat Environment and Effects Facility - Technology Demonstration Payload 8) integrates the radiation monitor Multi-Functional Spectrometer (MFS) and the CTTB (Component Technology Test Bed). The two units are installed on the X panel of the Alphasat satellite as a hosted payload. MFS is an instrument specifically designed to characterise the Space Radiation environment while CTTB was built to monitor the effect of radiation on electrical components (GaN transistors, Memories and Optical Transceivers) in geostationary orbit. The mission lifetime of AEEF/TDP8 is 3 years with possible extension to 5 years and TDP8 is expected to be acquiring scientific data during the whole period. On ground, correlation between radiation environment and radiation effects can be established. Before launch, MFS was submitted to proton and electron beam tests at Paul Scherrer Institute in Switzerland in 2010. The main purpose was the validation and calibration of the MFS proto-flight model together with the estimation of particle energy resolution and identification capability. A full Geant4 simulation with the MFS in-flight configuration was built and used to validate the results from ground tests. The full detector simulation has proved to be a valuable tool for the unfolding of MFS channel counts into particle spectra based on a Single Value Decomposition (SVD) method. Results for Proton spectra measured with the MFS in GEO will be presented, in particular for the case of Solar Energetic Particle (SEP) events registered in 2014 during periods of maximum solar activity of solar cycle 24.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

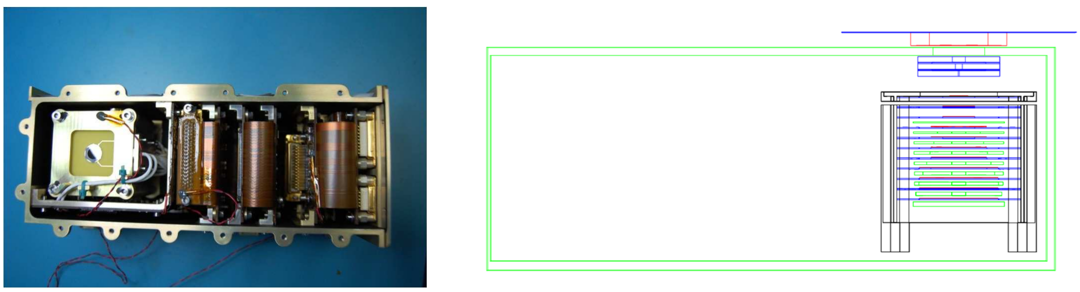
[∗]Speaker.

[†]This work has been supported by ESA/ESTEC contracts 3-14025/13/NL/AK and 4000112863/14/NL/HB (the last in the framework of the HERMES project).

PoS(ICRC2015)137

1. Introduction

Future telecom missions will encounter a severe radiation environment including the heart of the Earth's trapped electron radiation belts and the Solar Particle Events (SPE). Moreover, the miniaturization of low power and high speed microelectronics drives technology designs that are increasingly sensitive to radiation effects. The primary objective of the ESA Alphasat Program[1] is to facilitate an early first flight, and in-orbit validation of the Alphabus platform for communication satellites, currently under development with European industry. Alphabus [1] [2] was successfully launched on the 25th July 2013 from Kourou in French Guyana and is in geosynchronous (GEO) orbit. In addition to the operational payload, ESA also provided four Technology Demonstration Payloads (TDPs) aboard the Alphasat spacecraft. One of these (TDP8) was the ESA Alphasat Environment and Effects Facility (AEEF) [4], which includes two experiments: Component Technology Test Bed (CTTB) and a Multi-Functional Spectrometer (MFS), whose development was led by EFACEC (Portugal). The objective of the TDP8 is to study radiation effects by employing several technology experiments in conjunction with radiation monitoring at GEO orbit.



(a) MFS radiation monitor.

(b) Geant4 transversal view of the MFS stack detector.

Figure 1

2. MFS Technical Overview

MFS is an instrument tailored and targeted to be a light (< 3 kg), low-power (< 5 W), easily integrated and general purpose radiation monitor. Figure 1a illustrates the MFS apparatus. Its particle detection principle is based on the measurement of the energy loss (dE/dx) in a stack of 11 silicon detectors each with 300 μm of thickness, with areas from 50 mm^2 to 900 mm^2, equally spaced and interleaved by layers of shielding material (aluminum and tantalum) with increasing thicknesses from 0.6 mm up to 2 mm. In order to handle high particles fluxes of 1×10^7 particles/cm^2/s at energies $\sim$1 MeV, collimator disks with different appertures are placed in the top of the stack. The stack is surrounded by an aluminium shield to veto side particles out from the field of view which

[1] Alphasat is a large telecommunications satellite primarily designed to expand Inmarsat's existing global mobile telecommunication network, launched in July 2013. It was built by Airbus DS through a public-private partnership (PPP) between the European Space Agency (ESA) and Inmarsat. Alphasat is based on Alphabus, the large European telecom platform developed by Airbus DS and Thales Alenia Space under a joint contract with ESA and France's CNES space agency.

is of 35°. An external aluminium box of 242.5×97.0×96.0 mm^3 houses the MFS stack detector and the corresponding readout electronics.

MFS front-end electronics is based in an ASIC from IDEAS [5] with the input performed through a charge sensitive amplifier. Its noise is at the level of 4-5 fC and the front-end integration time is $\sim$2.125 μs with a discharge curve of $\sim$10 μs, both configurable. For the back-end electronics MFS uses a FPGA with memories running: particle and energy recognition process, communications (TM/TC), drivers for memories (SRAM and EEPROM) and health housekeeping processes (analogue multiplexer plus an ADC). MFS operates with the regulated secondary power supplies of the CTTB. The apparatus was designed to measure electrons from 450 keV up to 7 MeV, protons from 1 MeV up to 200 MeV and alpha particles from 5 MeV up to 100 MeV. Electrons and alpha particles are required to have energy resolution better than 20%, while for protons this value is 10%. The mission lifetime of AEEF/TDP8 is at least 3 years and MFS is expected to be acquiring scientific data during the whole period.

MFS was constructed by EFACEC, SA, Portugal and its operation is under their responsability. MFS operations are made through TDP8 Control Centre (OPS) installed in Maia, Portugal. MFS generates two different raw data packs of Level 1: housekeeping and scientific data which are transmitted to ground via CTTB. On OPS, TDP8 In Flight Data Analysis receives CTTB data and is responsible for interpreting, separating and storing in different database tables. The satellite attitude and orbital data is made available from Immarsat. Housekeeping data includes temperature, voltage and power current consumptions. The scientific data includes particle counters, electron, proton, alpha particles, heavy ion and other particle histograms. Level 2 data for MFS is created by processing the Observational Data Files from Level 1.

3. MFS Geant4 simulation

A detailed Monte Carlo simulation of MFS was implemented using Geant4 [6], [7] version 4.9.4.p02 with the description of the detector's geometry and materials that compose it. The Shielding physics list was used, which is based on former list FTFP_BERT_HP with improved neutron cross sections. Figure 1b shows the Geant4 implementation of the MFS geometry including the stack detector, the collimators and the outer aluminium box. The output of the Geant4 simulation is a ROOT file with a tree of events storing all the relevant variables. A set of ROOT macros was built to perform the analysis and to produce the output histograms. The deposited energy in each detector was converted in ADC channel output according to the result of detector's calibration (see next section). Calibration and front-end electronics response was simulated and added at the analysis level.

4. Ground test data analysis

The MFS ProtoFlight Model (PFM) was tested under different radiation conditions at the Proton Irradiation Facility (PIF) [8] and with the monochromator chamber with a radioactive source of ^{90}Sr to provide a monoenergetic electron beam at Paul Scherrer Institute (PSI) in Switzerland in 2010. The objective of the PSI tests was the verification and calibration of the equipment under radiation. The ability to simulate in-orbit environment on Earth enabled to take this hazard into consideration in the design stage and to approve the PFM design producing several ground data sets that were used to validate the Geant4 model for the MFS PFM. Beam particles were simulated using the G4GeneralParticleSource (GPS) which is a part of the Geant4 toolkit for Monte Carlo, high energy particle transport and allows the specification of the spectral, spatial and angular distribution of the primary source particles. Proton beams were simulated with the corresponding beam energies of 9.6, 18.95, 31.2, 61.9, 76.1, 91, 106.2, 120.2, 134.84 and 150 MeV. A Gaussian dispersion in energy was assumed since it is known that there is energy straggling from the initial proton beam of 74.3 MeV and 150 MeV. A flat, circular proton beam with a radius of 4 mm, without angular dispersion and placed 10 cm far from the top of the monitor reproducing the experimental position was simulated. The beam area is equivalent to the first silicon plane area in order to recreate the particle trigger with the first tracker plane. A multi-layer insulator was covering the apparatus during the tests and so it was included in the simulation according to the manufacturer specifications. The measured pedestals in the campaign were assumed. Figure 2 shows the comparison between data measurements and results obtained with MFS PFM simulation for the test beam conditions for the first four planes for a proton beam energy of 31.2 MeV. Simulation results are in very good agreement with the test beam data.

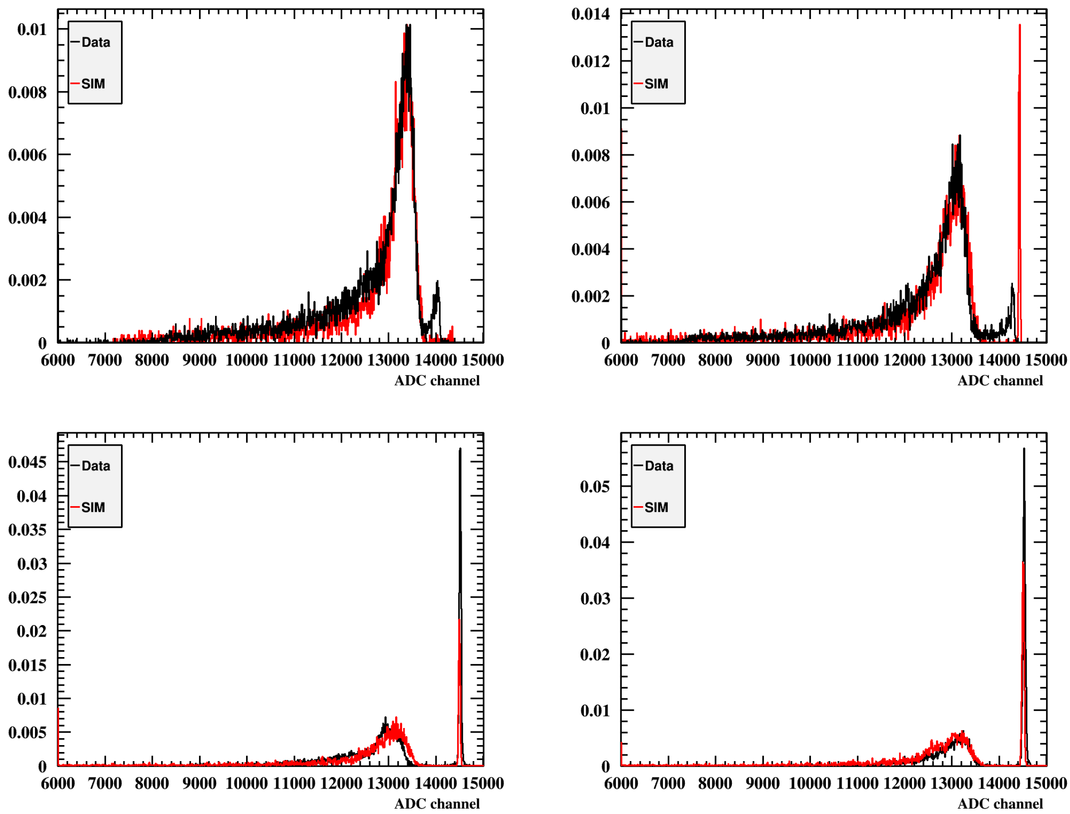


Figure 2: Proton beam with 31.2 MeV - Simulation results (red line) compared with measured data (black line) for different silicon planes.

PoS(ICRC2015)137

5. Particle Identification and Energy reconstruction with MFS

The MFS particle identification algorithm is based in a Look-Up Table (LUT), which was built based on the analysis of Monte Carlo MFS response to simulated protons, electrons, alpha particles and heavier nuclei. The thresholds for deposited energies by each species in ADC channels are stored in the LUT and the maximum energy deposited together with the energy left in the detector before the one with maximum allows the particle identification procedure. The energy reconstruction is possible based on the information about the detector with maximum energy and on the deposited energy in the previous detector.

6. MFS flux spectra reconstruction method

6.1 Derivation of MFS response functions

The response matrix $RF_{i,q}(E)$ for each MFS channel has been derived by the simulations of omni-directional fluxes of electrons and protons using the Geant4 MFS model. The background in each channel was also evaluated using Monte Carlo simulation. MFS samples the spectra in broad in overlapping energy bands as can be seen from the instrument response functions and the main reason is due to the effect of the collimator with different thicknesses above the first MFS silicon sensor which is not segmented. This fact leads to multiple patterns of deposited nergy in the different sensors for the same initial kinetic energy and is more critical for protons and alphas than for electrons. In fact electrons with less than 5.8 MeV are stopped by the tantalum collimator. An improved definition of the MFS energy channels is foreseen and already established but the RFs used in the analysis correspond to those implemented in the flight electronics at the time of the SEP events studied.

6.2 Unfolding MFS data

The measurements of MFS unit are provided in terms of count-rates, C_i, $i = 1, 17$, given by the sum:

$$C_i = \sum_{q=p,e} C_{i,q} = \sum_{q=p,e} \left[\int_0^\infty f_q(E) RF_{i,q}(E) dE \right]. \tag{6.1}$$

Each term in the sum is attributed to measurements of the incident proton and electron fluxes. Here, $f_q(E)$ denotes the differential omni-directional fluxes in units of $[cm^{-2} MeV^{-1} s^{-1}]$ while $RF_{i,q}(E)$ describes the corresponding response functions for $q = p, e$. The calculation of proton and electron differential fluxes $f_q(E)$ requires the solution of Eq. 6.1 which is a Fredholm integral equation of the first kind.

For the efficient conversion of MFS measurements to particle flux the deconvolution technique presented in [10] was applied. The technique applies iteratively the unfolding of measurements - using a singular value decomposition (SVD) approach over different proton and electron energy ranges.

This method does not require any assumption on the spectral shapes and it was initially developed for the unfolding of ESA/SREM measurements. The results extracted have been successfully used for the estimation of solar proton fluxes [10] and energetic trapped particles in the radiation belts [11].

6.3 Results

In the current section, characteristic results based on the measurements of MFS unit during the moderate solar proton event of January 2014 are presented. For the determination of the numerical solution of 6.1 the proton response functions were binned in 20 logarithmically spaced bins within $E_p = 4 - 150$ MeV and the electron response functions in 7 logarithmically spaced bins within $E_p = 1 - 8$ MeV in order to apply the SVD unfolding method [10].

The derived results show that the unfolding of MFS data in a proton dominated environment using the SVD approach provides consistent differential proton flux results for proton energies above 40 MeV. Figures 3 and 4 present differential proton flux series based on Alphasat/MFS

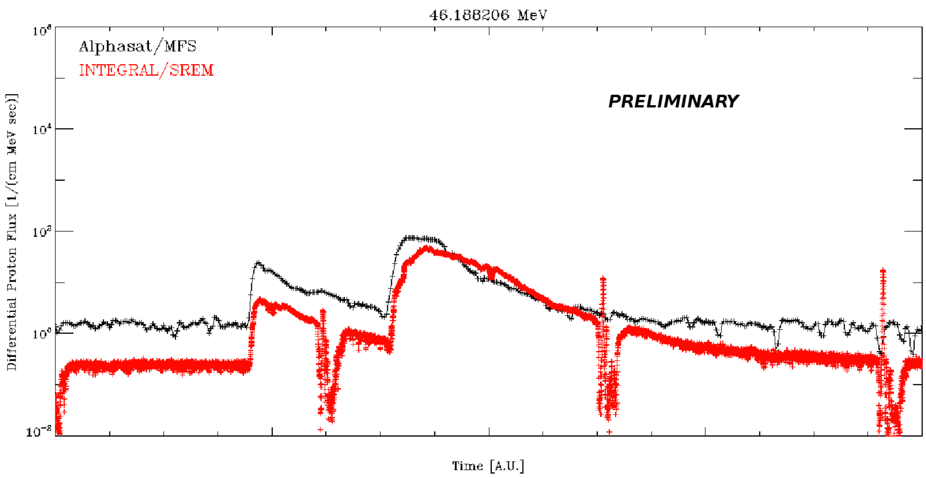


Figure 3: Differential proton flux series at $E = 46$ MeV derived using Alphasat/MFS data (black crosses) and INTEGRAL/SREM (red crosses) measurements.

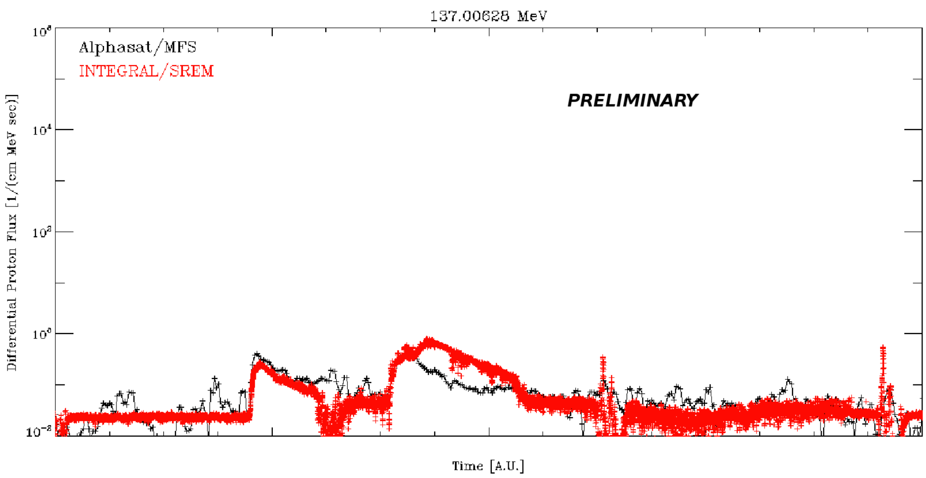


Figure 4: Differential proton flux series at $E = 137$ MeV derived using Alphasat/MFS data (black crosses) and INTEGRAL/SREM (red crosses) measurements.

and INTEGRAL/SREM measurements for $E = 46$ and 137 MeV. It can be seen that despite the different orbital characteristics of the considered missions, and the different characteristics of the considered radiation monitors, the derived fluxes are in good agreement - within an order of two. The same conclusions are reached for all the differential proton flux series at energies above 40 MeV. In addition, figures 5 and 6 present measurements of Alphasat/MFS P5 and P9 channels

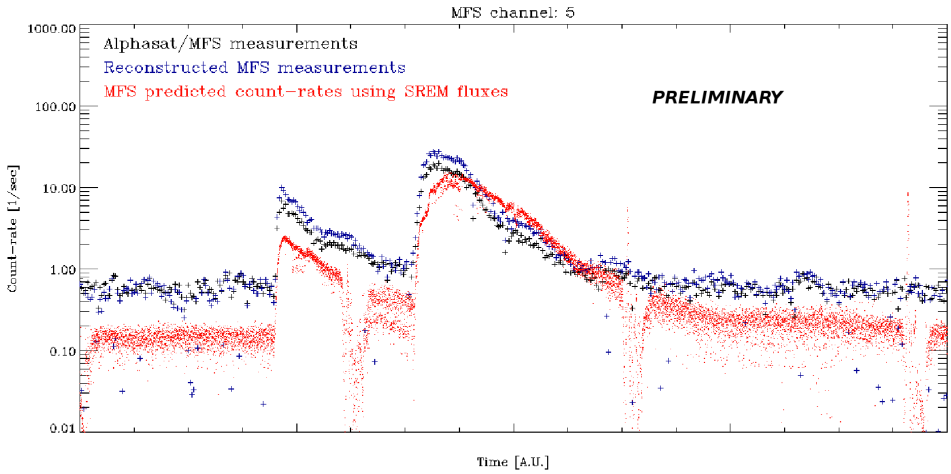


Figure 5: Time series of Alphasat/MFS/P5 measurements (black line) compared to virtual data reconstructed by folding INTEGRAL/SREM (red line) and MFS (blue crosses) proton fluxes with P5 proton response function.

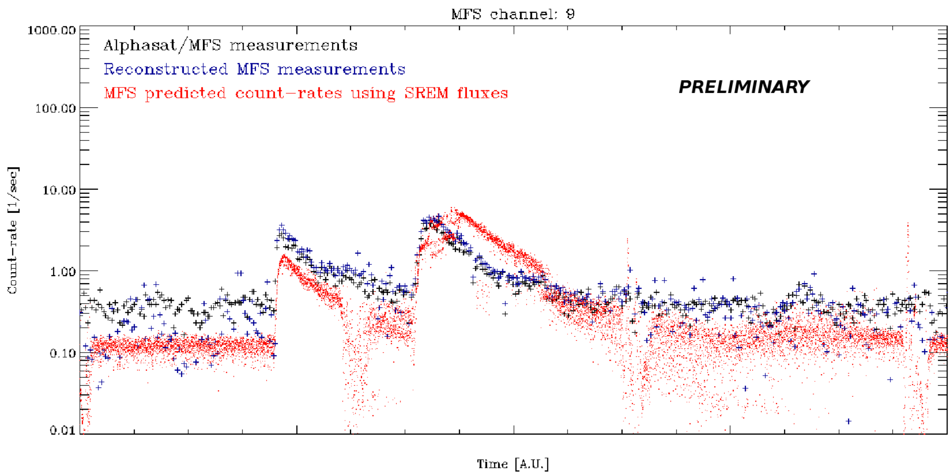


Figure 6: Time series of Alphasat/MFS/P5 measurements (black line) compared to virtual data reconstructed by folding INTEGRAL/SREM (red line) and MFS (blue crosses) proton fluxes with P9 proton response function.

and compare them with MFS reconstructed count-rates derived by folding the derived differential proton flux series of Alphasat/MFS and INTEGRAL/SREM with MFS proton response functions.

The comparisons performed for the MFS P-channels show that the measurements and the derived response functions for P5-P9 channels are consistent with the INTEGRAL/SREM proton fluxes.

An evaluation of the performed comparisons shows that MFS measurements in P1-P4 channels and the derived proton flux series for energies below 40 MeV are not consistent with INTEGRAL/SREM measurements. The observed inconsistency can be attributed to the proton response functions of MFS channels which provide coherent information of statistical significance at energies above 40 MeV.

References

[1] Cussac, T. *et al.* , *Alphabus, a successful European Public Private Partnership*, Proceedings of the 61st International Astronautical Congress, Prague, Czech Republic, Sept. 27-Oct. 1, 2010, IAC-10.B2.1.7

[2] *Alphabus Fact Sheet*, ESA, May 5, 2011, URL: http://telecom.esa.int/telecom/media/document /Alphabus%20factsheet%2010-5-2011%20JH%20%281%29.pdf

[3] https://directory.eoportal.org/web/eoportal/satellite-missions/a/alphasat

[4] Alphasat TDP8 AEEF technical specification phases B, C, D, E1 reference ASA-ESA-SP-TDP8-010, no. 3, 2009

[5] Marques, A., *Efacec Space Radiation Monitors MFS* & *BERM*, oral comunication at Space Radiation and plasma Environment Monitoring Workshop, ESTEC, Noordwijk, The Netherlands, 13th and 14th May 2014

[6] Agostinelli, S; *et al.* , Nucl. Instrum. Methods A 506, 3 (2003) 250.

[7] Allison, J; *et al.* , *Geant4 developments and applications*, IEEE Transactions on Nuclear Science Vol 53, 1, pp: 270-278, 2, FEB 2006

[8] Hadjas, W. *et al.* , *The proton irradiation facility at the Paul Scherrer Institut.*, Nucl. Instrum. Methods Phys. Res. B 113, 54

[9] Sandberg, I. *et al.* , *Unfolding and Validation of SREM Fluxes*, IEEE Transactions on Nuclear Science 59, 1105 (2012).

[10] Höker, A. *et al.* , *SVD Approach to Data Unfolding*, Nucl. Instrum. Methods A 372 (1996) 469.

[11] Sandberg, I. *et al.* , *Development and Validation of the Electron Slot Region Radiation Environment Model*, IEEE Transactions on Nuclear Science, DOI10.1109/TNS.2014.2304982, (2014)