SSC22-WKIII-05

High-Energy Proton Testing of Sensitive electronics for use on Modular Infrared Molecules and Ices Sensor (MIRMIS) Instrument

S.Thirumangalath[1], E.Briede[1],A. Näsilä[2],
VTT Technical Research Centre of Finland Ltd., Espoo, Finland[1,2]
+358503060378; swati.thirumangalath@vtt.fi

V. Gupta[2], C.Boatella[2], H.Wojciech[3], V. Kletzl[3],
ESA/ESTEC, European Space Agency, Noordwijk, AG[2]
Paul Scherrer Institut (PSI), Villigen, Switzerland[3]

R.Trops[4] and N.E.Bowles[4],
VTT Technical Research Centre of Finland Ltd., Espoo, Finland[4]
Department of Physics, University of Oxford, UK[4]

ABSTRACT

The Comet Interceptor (CI) mission is ESA's first "F" class mission, selected in June 2019. This mission consists of three spacecraft: Spacecraft A (main spacecraft), Spacecraft B1 (supplied by the Japanese space agency JAXA), and Spacecraft B2. In this paper, we highlight the Modular Infrared Molecular and Ices Sensor (MIRMIS) instrument, which is integrated into the CI Spacecraft A's scientific payload. In addition to hardware contributions from Finland (VTT Finland) and the UK (University of Oxford), the MIRMIS instrument team includes members from the University of Helsinki and NASA's Goddard Space Flight Centre. MIRMIS covers the spectral range of 0.9 to ~25 µm.

This paper presents the preliminary high-proton-energy radiation test results of MIRMIS' near-infrared detector array-sensitive electronic components. Proton beam testing is performed to estimate Single Event Effects (SEE) on the PCB boards and SEE and Total Non-Ionizing Dose (TNID)/ Displacement Damage (DD) on the detectors. The tests were conducted at the Paul Scherrer Institute (PSI) Proton Irradiation Facility (PIF), Villigen, Switzerland. The levels for the tests were based on the mission requirements for the ESA Comet Interceptor mission: 3 years (at 1 AU- Segment 1) and 2 years (at 0.9 AU- Segment 2). The DD levels from the analysis were equivalent to 1e11 protons/cm2 with an energy of 50 MeV. The electronics are exposed to high-energy protons causing Single Event Effects (SEE) which may induce potentially destructive and non-destructive effects. The test items primarily included the InGaAs image sensors (SCD Cardinal640, standard and low noise), Xilinx Spartan-6 FPGAs (Field Programmable Gate Arrays), and other proximity electronics. The proton energies were varied from 50 to 200 MeV, at fluxes of 10^6 to 10^8 particles/cm2/s. No events were observed on the standard Cardinal640 sensor at target fluences between 1.00E+10 to 1.00E+11 particles/cm². FPGAs did not show any susceptibility to TNID at fluences up to 1.00E+11 (particles/cm^2).

INTRODUCTION

The Comet Interceptor mission [9,10] concept was selected by ESA as the first of its new "F" class of missions in June 2019. Comet Interceptor (CI) intends to be the foremost mission to visit a long-period comet, preferably, a Dynamically New Comet (DNC). With origins in the Oort cloud, these are a subset of long-period comets and may reserve some of the most primitive material from early in our Solar System's history. In 2028, CI is scheduled to launch to the Earth-Sun L2 point with ESA's ARIEL [11] mission. Here it will wait for a suitable DNC target. This new approach is made possible by the Large Synoptic Survey Telescope (LSST [12]) which provides large sky surveys and increased detection rates for comets. Furthermore, this allows ~ 5 years between the discovery of a target and interception by CI.

Three spacecraft constitute the CI mission. Spacecraft A is the main spacecraft that will pass by the target nucleus at a distance of ~1000 km. Due to the wide range of possible encounter velocities (e.g., 10 – 80 km/s), a safe distance will mitigate dust hazards.

Smaller Spacecrafts B1 (supplied by the Japanese space agency JAXA) and B2 are provided communication hub from Spacecraft A. The goal for Spacecrafts B1 and B2 is to provide higher risk/higher return measurements and the probability of their survival post-encounter is less due to closer approaches to the nucleus.

Modular Infrared Molecular and Ices sensor (MIRMIS) instrument is a part of the payload designed for CI Spacecraft A. The MIRMIS consortium includes hardware contributions from the UK (University of Oxford, STFC RAL Space) and Finland (VTT Finland). The details of the radiation testing for VTT's NIR (Near-Infrared) channel components are detailed in this paper.

MIRMIS Instrument Overview

To constrain the formation and evolution of the CI target's nucleus and coma, measurements of the spatial distribution of ices, minerals, gases (e.g. H2O, CO2, CH4, etc.), and surface temperature are essential. Mapping of the compositional variety and thermal physical distinction (via the thermal inertia) could show whether the nucleus is a rubble pile object with unalike evolutionary histories or a uniform body formed as a solitary process. MIRMIS covers the spectral range of 0.9 to ~25 µm and will map the mineral, ice, and gas composition of the target's coma and nucleus (Figure 1) and the distribution of surface temperatures on the nucleus.

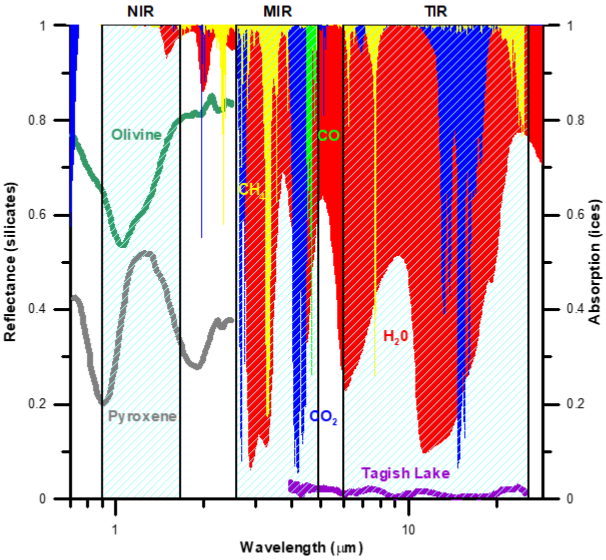


Figure 1: Spectral range and main compositional species covered by the MIRMIS instrument's spectral range.

A single compact (210 x 105.5 x 460 mm^3) instrument combines three integrated MIRMIS modules. The three modules are (Figure 2):

a) A Near-Infrared (NIR) – hyperspectral camera covering the wavelength range ca. 0.9 to 1.7 µm.

b) A Mid-Infrared point spectrometer (MIR) covering the spectral range ca. 2.5 -5.0 µm.

c) TIRI is a multispectral thermal infrared imaging radiometer (TIRI) that maps the surface temperature and composition of nuclei using thermal imaging and filter radiometry. TIRI covers the wavelength range from ~6 to 25 µm.

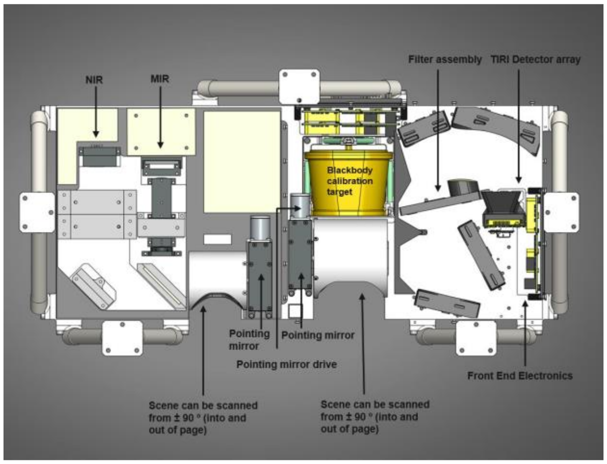


Figure 2: MIRMIS TIRI/MIR/NIR mounted on a common optical bench

RADIATION REQUIREMENTS

ESA RHA requirements

The ESA Comet Interceptor requirements are used to further investigate if any radiation-hardened component upgrade is envisioned. The requirements include the following:

1. Parts that have an ion-induced SEE threshold less than 15 MeV cm2/mg shall also have their SEE rate calculated for proton nuclear interaction induced SEE.
2. Parts with a LET threshold over 60 MeV cm2/mg may be considered SEE immune.

Comet Interceptor Fly by -Probability of events

The Comet Interceptor Fly-by duration is totaled for 7 minutes. Considering the short duration flyby event, an upset rate threshold of 0.1 /device/day is set as a benchmark for analysis and testing.

Radiation Requirements component checklist

Component No	Part No	Description	TID Requirements (from analysis) [krad]	LET threshold [MeV cm2/mg]	DDEF [(p/cm2) @ 50MeV]	Upset rate [device/day]
			NIR Detector			
1	Cardinal640 (LOON)	Low-noise InGaAs SWIR detector	< 6	> 60	1.00E+11	< 2e-01
2	BSS138K	N-Channel MOSFET	< 6			< 2e-01
3	ZXMHC3F381N8TC	N-Channel MOSFET Quad	< 6			< 2e-01
4	ES2AA-13-F	Diode rectifier 50V 2A	< 6			< 2e-01
5	ADP3338AKCZ-3.3RL7	+3.3V voltage regulator	< 6	> 60	9.51E+10	< 2e-01
6	SPX3819M5-L-1-8	+1.8V voltage regulator	< 6	> 60	9.51E+10	< 2e-01
7	SPX3819M5-L-1-5	+1.5V voltage regulator	< 6	> 60	9.51E+10	< 2e-01
8	MAX660M/NOPB	Switched Capacitor Voltage Converter	< 6	> 60	9.51E+10	< 2e-01
9	ADR361BUJZ	Voltage reference 2.5V	< 6	> 60	9.51E+10	< 2e-01
10	SPX3819R2-L	Linear voltage regulator adjustable	< 6	> 60	9.51E+10	< 2e-01
11	MIC4469YWM	Low side gate driver	< 6	> 60	9.51E+10	< 2e-01
12	INA181A4QDBVRQ1	Current-Sense Amplifier	< 6	> 60	9.51E+10	< 2e-01
13	ADS1118QDGSRQ1	Analog to digital converter 4-channel	< 6	> 60	95100000000	< 2e-01
			NIR Readout			
14	TLP170J	Optocoupler MOSFET output	< 6	> 60	1.00E+11	< 2e-01
15	SPX3819M5-L-1-8	+1.8V voltage regulator	< 6	> 60	9.51E+10	< 2e-01
16	SPX3819M5-L-1-2	+1.2V voltage regulator	< 6	> 60	9.51E+10	< 2e-01
17	ADP3338AKCZ-3.3RL7	Low Dropout Regulator 3.3 V	< 6	> 60	9.51E+10	< 2e-01
18	XC6SLX9-3FTG256I	Spartan-6 FPGA	< 6	> 60	1.00E+11	< 2e-01
19	IS42S32800J-7TLI	SDRAM memory	< 6	> 60	9.51E+10	< 2e-01
20	25Q16BVSIG	Serial flash memory	< 6	> 60	9.51E+10	< 2e-01
21	M4FR5969SPHPT-MLS	Microcontroller	< 6	> 60	9.51E+10	< 2e-01
22	ECS-2033-200-BN	20 MHz CMOS crystal oscillator	< 6	> 60	95100000000	< 2e-01

Figure 3: Radiation requirements checklist

The figure above shows the radiation requirements for all the components. The goal is to ensure that these requirements are met during the test campaigns. These prerequisites are identified from the ESA Environment specifications together with the radiation analysis.

RADIATION TESTING

The NIR sensor components which were sensitive to SEE were selected for the radiation test.

Test Setup

The component placement for the test items is shown in Figure 4. Table 1 lists the individual descriptions for each of the test items. One sample for each of the Standard Cardinal 640 and LOON Cardinal 640 sensors was tested.

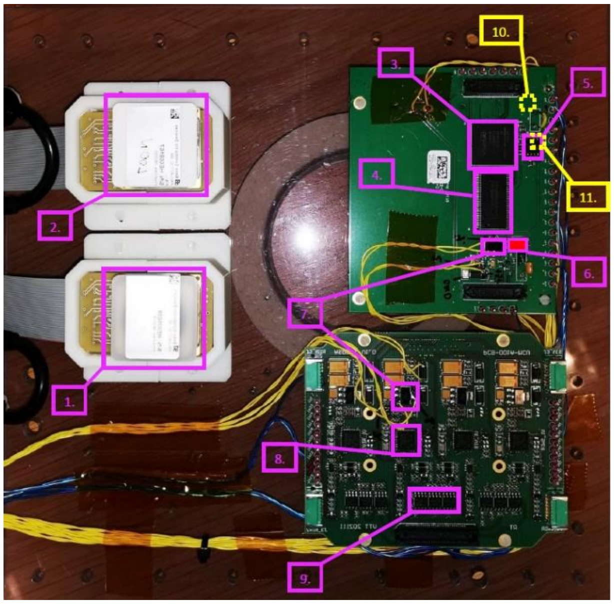


Figure 4: Irradiated Component Locations

Component	PCB side	Part No	Description
1	Top	Cardinal 640	Image sensor (regular)
2	Top	Cardinal640 (LOON)	Image sensor (low noise)
3	Top	XC6SLX9-3FTG256I	Spartan-6 FPGA
4	Top	IS42S32800J-7TLI	SDRAM memory
5	Top	25Q16BVSIG	Serial flash memory
6	Top	SN74CB3T3125PW	HEX buffer/driver

7	Top	ADP3338AKCZ-3.3RL7	+3.3V voltage regulator
10	Bottom	SPX3819M5-L-1-8	+1.8V voltage regulator
11	Bottom	SPX3819M5-L-1-2	+1.2V voltage regulator

Table 1: Irradiated component description

Test Procedure

The testing consisted of three phases:

- Case 1- Image sensor SEL test (200 MeV) with a focused beam
- Case2- Image sensor displacement damage test (50 MeV) with a focused beam
- Case 3- FPGA board electronics SEE test at board level (200 MeV) with a broad beam

Image sensor SEL test (200 MeV)

A 4x4 cm² collimator was used for the focused beam tests. The distance between the DUT and Collimator was 7.5 cm. The X and Y beam profiles for the case setup are shown in Figure 5.

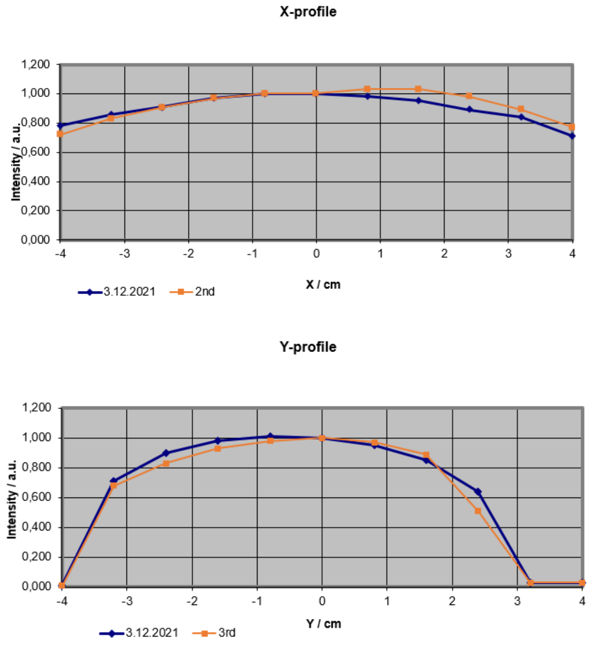


Figure 5:Case 1 - Beam Setup

Test run 1 focused the beam on the Cardinal InGaAs sensor. The alignment of the breadboard w.r.t the beam is shown in Figure 6.

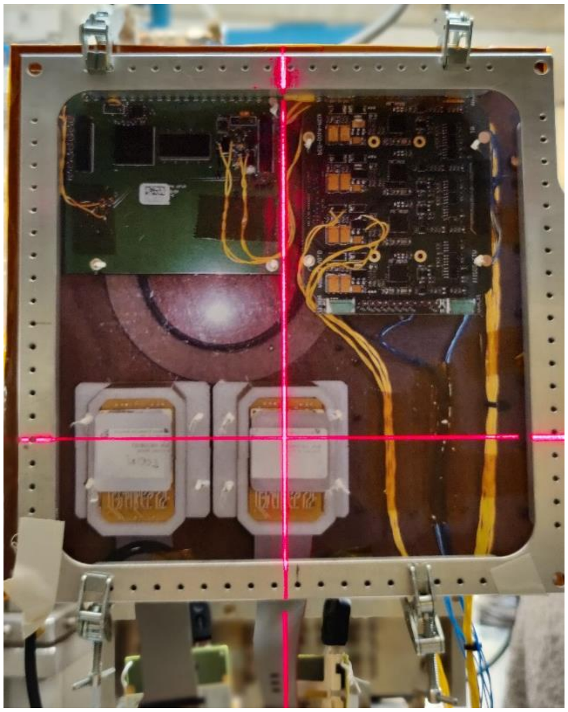


Figure 6: Beam centered at the Cardinal InGaAs sensor

Test run 1 was conducted for the following parameters:

Energy (MeV)	Flux target (/cm2/s)	Fluence (/cm2)	Type of test
200	2.50e+08	1e+10	SEE on sensor biased
		8e+10	
		1e+11	

Table 2: Standard Cardinal 640 test parameters

For the case of the Cardinal InGaAs sensor, the current levels did not peak above the set threshold [350 mA] for SEEs. No events were observed on the standard Cardinal640 sensor at a target fluence of 1.00E+10 particles/cm².

Test run 2 used the parameters outlined in the table below.

Energy (MeV)	Flux target (/cm2/s)	Fluence (/cm2)	Type of test
200	2.50e+08	5e+10	SEE on sensor biased
		1e+11	

Table 3: LOON Cardinal 640 test parameters

In the case of the LOON Cardinal 640 sensor (low noise), the following observations were made:

- SEL threshold was set to 350 mA. Increasing the fluence value up to 3.35E+10 particles/cm² does spike the current levels upto 360 mA, following which the device was turned off.

- The beam was stopped after SEL occurrence, and the sensor was kept running for 3 minutes to observe the current levels. The SEL mode did not self-recover. The current profile after the SEL is shown in Figure 7.

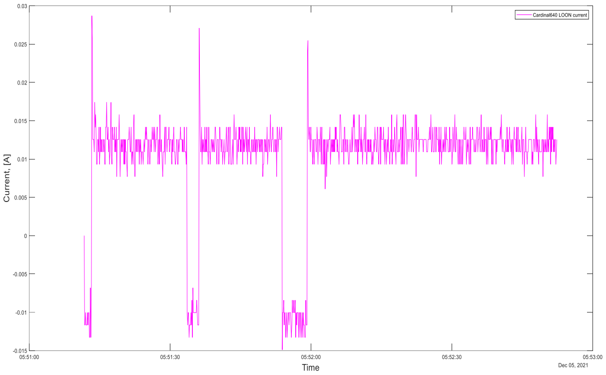


Figure 7 : Cardinal LOON current profile

Image sensor displacement damage test (50 MeV)

The X and Y beam profiles for the case 2 setup is shown in **Error! Reference source not found.**

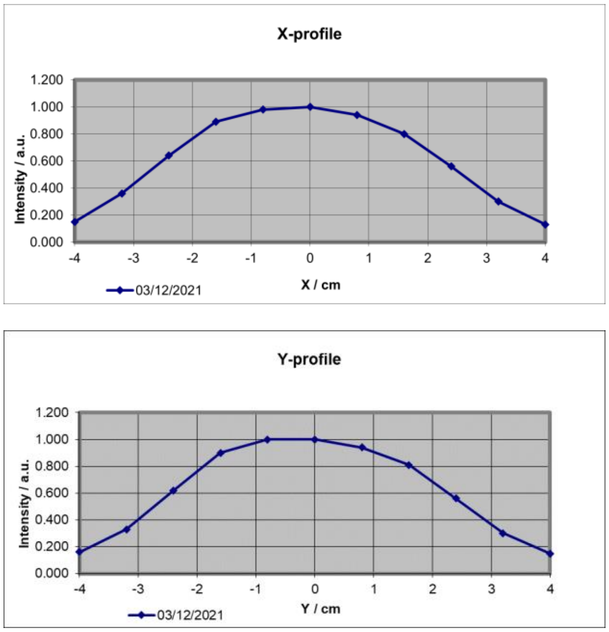


Figure 8: Case 2 - beam profiles

Test run 3 for the standard cardinal sensor was conducted for the following parameters:

Energy (MeV)	Flux target (/cm2/s)	Fluence (/cm2)	Type of test
50	8.00E+07	1e+11	TNID on sensor part unbiased

Table 4: Standard Cardinal 640 test parameters

The current levels again did not peak above the set threshold for SEEs. No events were observed on the standard Cardinal 640 sensor at a target fluence of 1.00E+11 particles/cm².

Test run 4 for the LOON cardinal sensor was conducted for the following parameters:

Energy (MeV)	Flux target (/cm2/s)	Fluence (/cm2)	Type of test
50	2.50e+08	1e+11	TNID on sensor unbiased

Table 5: LOON Cardinal 640 test parameters

Test run 4 was conducted after a test run 2. The sensor was already in the SEL state during the test run 2. After powering on the sensor, no current was detected.

FPGA board electronics SEE test at board level (200 MeV)

A 2x2 cm² collimator was used for the FPGA tests. The distance between the DUT and Collimator was 7.5 cm. The X and Y beam profiles for the case setup are shown in ***Figure 9***.

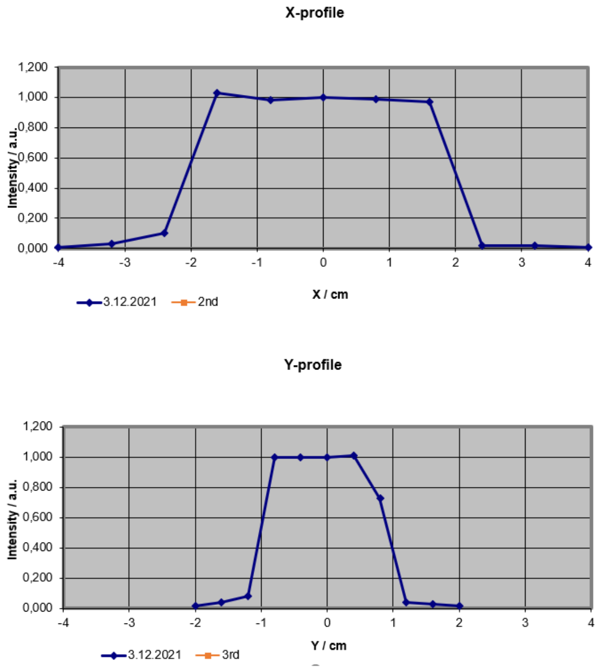


Figure 9: Case 3 - beam profiles

Test run 5 for the FPGA board was conducted for the following parameters:

Energy (MeV)	Flux target (/cm2/s)	Fluence (/cm2)	Type of test
200	Between 4e+06 to 5e+08	Between 1e+8 to 1e+10	SEE on FPGA board

Table 6: FPGA full board test parameters

The calibration files were incorrect and the actual fluences and fluxes were unknown (approximate values are highlighted in the above table). The SRAM and the FPGA current levels did not increase beyond the threshold SEL limits, the flash current increased gradually from 10 mA to 13 mA.

SPI interface was used to read out counter data from FPGA. No failure was detected after radiation beam exposure in measured data.

RESULTS

Test Observations

The test sequence along with the observations and records made for the TID and fluence levels are listed in this section. The Calibration files on the FPGAs were unknown and the fluences were recorded accurately only for a test run 13.

Standard Cardinal 640 Sensor

Table below lists the test runs for the standard cardinal 640 sensor at 200 MeV.

Run	Duration (sec)	Fluence actual (/cm^2)	Flux actual (/cm^2/s)	Run dose (krad)	Observations
1	41	1.01E+10	2.46E+08	0.59	-
2	82	2.03E+10	2.47E+08	1.18	No event
3	—	—	-	-	-
4	324	8.03E+10	2.48E+08	4.67	No event, no current increase visible.

Table 7 : Standard Cardinal 640 sensor test - 200MeV

Table 8 lists the test runs for the standard cardinal 640 sensor at 50 MeV.

Run	Duration actual (sec)	Fluence actual (/cm^2)	Flux actual (/cm^2/s)	Run dose (krad)	Observations
5	1246	1.00E+11	8.03E+07	15.80	Unbiased. A test run was done after test 3. Nothing particular was noticed visually on the current profile.

Table 8: Standard Cardinal 640 sensor test -50MeV

LOON Cardinal 640 Sensor

The low noise cardinal sensor was tested for 200 MeV energy in runs 6 and 7.

Run	Duration (sec)	Fluence actual (/cm^2)	Flux actual (/cm^2/s)	Run dose (krad)	Observations
6	235	5.53E+10	2.35E+08	3.22	3.35E10 fluence the current increase but below the SEL limit of 350 mA. Will be useful to see the current level during the current increase. The beam stopped & sensor left running. The SEL mode did not go back to normal. The sensor was PC by hand.
7	206	5.11E+10	2.48E+08	2.97	2.4E10 fluence the current increase above 350 mA. The set-up did not allow to PC automatically.

Table 9: LOON Cardinal 640 sensor test -200MeV

The beam energy was then lowered to 50MeV for run 8.

Run	Duration (sec)	Fluence actual (/cm^2)	Flux actual (/cm^2/s)	Run dose (krad)	Observations
8	1242	1.00E+11	8.06E+07	15.80	Sensor was unbiased. After irradiation, when powering on the sensor, there is no current.

Table 10: LOON Cardinal 640 sensor test -50MeV

FPGA

The FPGA board was subjected to a beam energy of 200 MeV with varying fluences.

Run	Duration (sec)	Fluence actual (/cm²)	Flux actual (/cm²/s)	Run dose (krad)	Observations
9	45	2.05E+08	4.55E+06		NOTE: Wrong calibration profile kept, actual flux & fluence are unknown. NOTE for FPGA board: Test component 13 might not be irradiated with the current beam profile. Wide beam profile: X=8cm* Y=6-7cm.
10	80	2.00E+09	2.50E+07		NOTE: Wrong calibration profile kept, actual flux & fluence are unknown.
11	189	9.85E+10	5.21E+08		NOTE: Wrong calibration profile kept, actual flux & fluence are unknown. No overcurrent seen. One manual PC after the end of the run.
12	120	2.38E+10	2.35E+08		NOTE: Wrong calibration profile kept, actual flux & fluence are unknown. The test was not stopped at the end of this run and continued until the restart of run 13.
13	427	1.00E+11	2.35E+08		Test run kept running, check with the start time later. FLUENCE INJECTED ON THE BOARD UNKNOWN since run 9. The current run fluence is confirmed.

Table 11: FPGA full board test - 200MeV

Image Sensor Measurements

Image sensor performance was tested by capturing frames before and after radiation. Dark images before testing for low noise Cardinal (LOON Cardinal) sensors can be seen in Figure 10 and Figure 12. Dark frames after testing can be seen in Figure 11 and Figure 13. The number of dead pixels has increased by 2% for Standard Cardinal and by 1.5% for LOON Cardinal. The 'before' images were captured before the 200 MeV and 50 MeV beam tests for both the sensors. The 'after' images were captured after the tests when the radiation levels were considered safe for handling the devices.

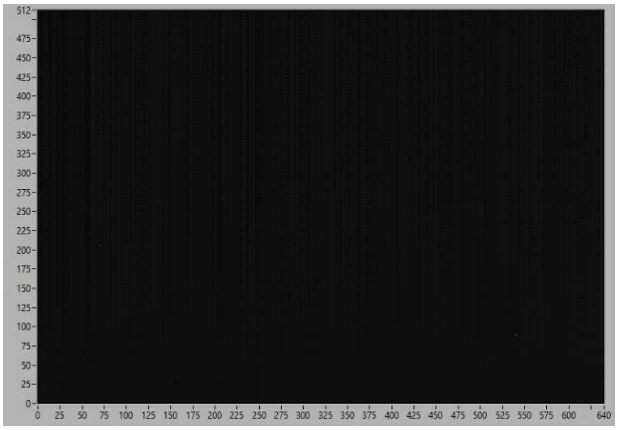


Figure 10: Standard Cardinal InGaAs sensor dark image before radiation tests

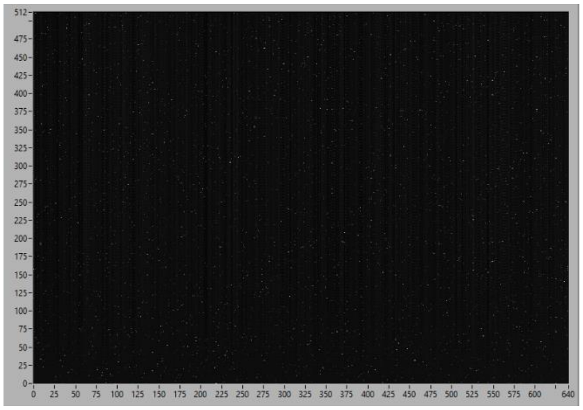


Figure 11: Standard Cardinal InGaAs sensor dark image after radiation tests

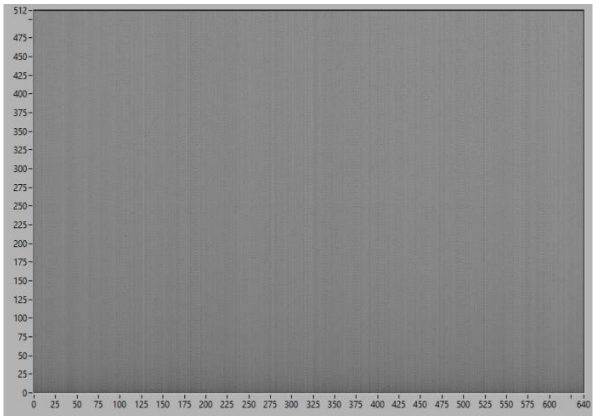


Figure 12: LOON Cardinal InGaAs sensor dark image before radiation tests

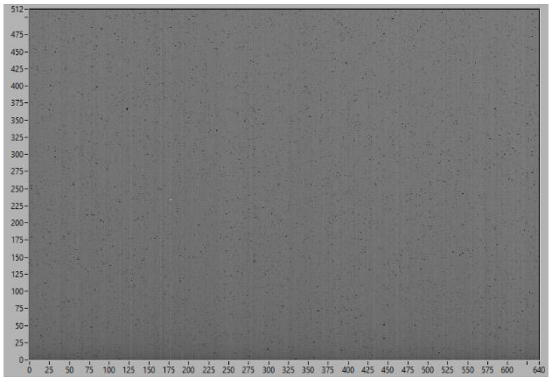


Figure 13: LOON Cardinal InGaAs sensor dark image after radiation tests

Upset Rate Calculations

The upset rates were calculated using the following

- Existing device cross-section data for a few components and
- Plotting device cross-sections from some SEE events observed from experiments (using OMERE^{TM}).

The requirements used to further investigate if any radiation-hardened component upgrade is envisioned include the following:

1. Parts that have an ion-induced SEE threshold less than 15 MeV cm2/mg shall also have their SEE rate calculated for proton nuclear interaction induced SEE.
2. Parts with a LET threshold over 60 MeV cm2/mg may be considered SEE immune. However, further TID testing is needed to confirm this.

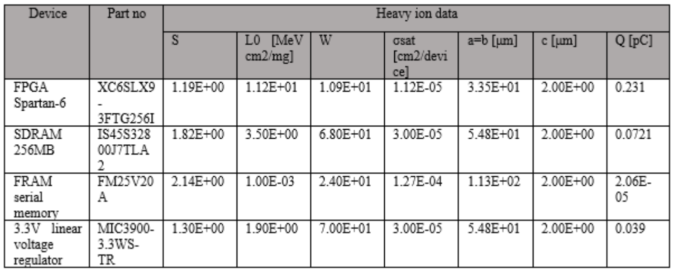
Comet Interceptor Fly by -Probability of events

The Comet Interceptor Fly-by duration is totaled for 7 minutes. Considering the short duration flyby event, an upset rate threshold of 0.1 /device/day is set as a benchmark for analysis and testing.

Device cross-section data

The sensitive volume is usually considered to be a rectangular parallelepiped (RPP). OMERE provides an estimate of the critical charge and device sensitive volume cross-section using the LET threshold and saturated cross-section respectively. Sensitive volume depth is taken as 2um. By using worst-case scenarios, we obtain a much more conservative and higher estimate of the upset rate for protons with a profit model.

The list of SEE sensitive components and their device cross-sections, Weibull parameters, sensitive volume for heavy ions and protons in the current study are shown in figures 12 to 17. For the present discussion, SEE was counted as error [Table 12 and Table 13].



Device	Part no	Heavy ion data						
		S	L0 [MeV cm2/mg]	W	σsat [cm2/device]	a=b [µm]	c [µm]	Q [pC]
FPGA Spartan-6	XC6SLX9-3FTG256I	1.19E+00	1.12E+01	1.09E+01	1.12E-05	3.35E+01	2.00E+00	0.231
SDRAM 256MB	IS45S32800J7TLA2	1.82E+00	3.50E+00	6.80E+01	3.00E-05	5.48E+01	2.00E+00	0.0721
FRAM serial memory	FM25V20A	2.14E+00	1.00E-03	2.40E+01	1.27E-04	1.13E+02	2.00E+00	2.06E-05
3.3V linear voltage regulator	MIC3900-3.3WS-TR	1.30E+00	1.90E+00	7.00E+01	3.00E-05	5.48E+01	2.00E+00	0.039

Table 12: SEE rate estimation parameters

Device	Part no	Proton data	
		σsat [cm2/device]	Energy [MeV]
Pico electronics DC/DC converter 5V/100V, 1 W	5AV100S	3.00E-11	2.00E+02

Table 13: Pico DC-DC converter proton test cross-section

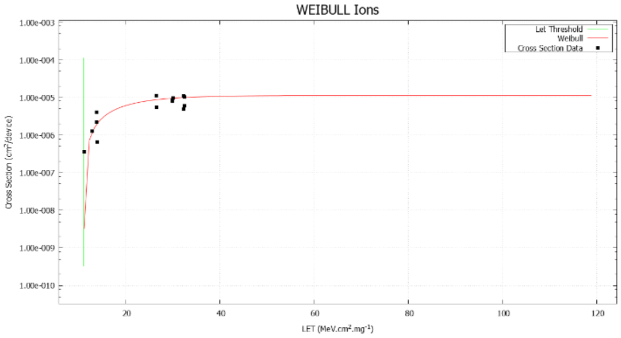


Figure 14 : FPGA Weibull curve -Heavy Ions [4]

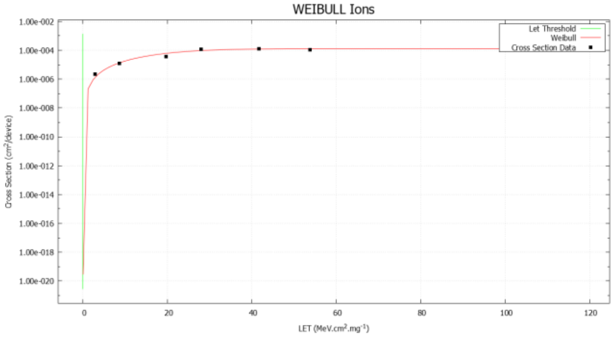


Figure 15 : FRAM Weibull curve - Heavy Ions [6]

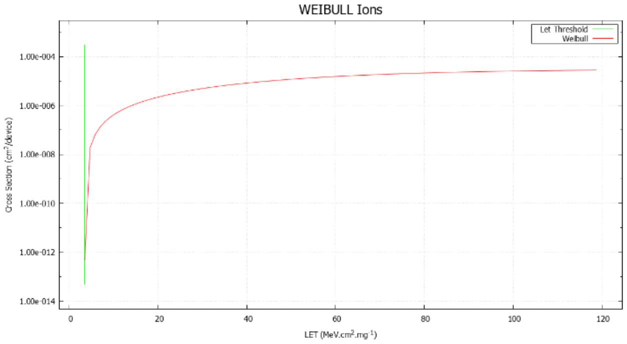


Figure 16: SRAM Weibull curve- Heavy ion [5]

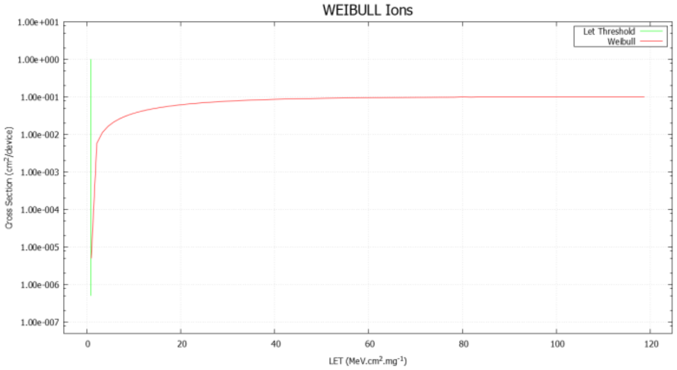


Figure 17: Voltage regulator Weibull curve -heavy-ion [7]

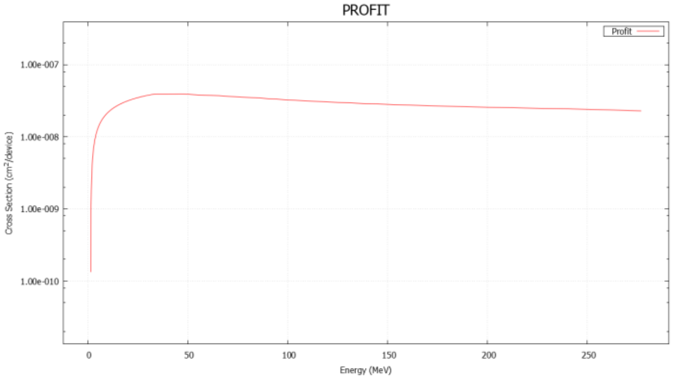


Figure 18: Voltage regulator Weibull curve – proton

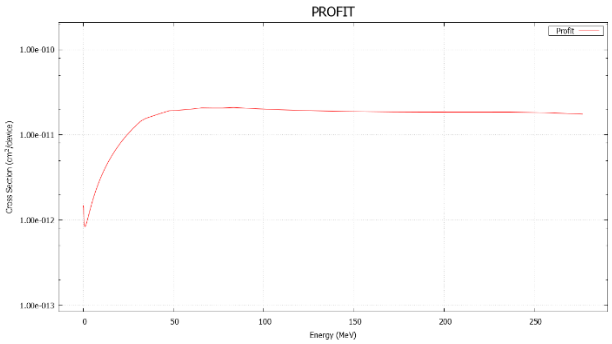


Figure 19: FRAM Weibull curve – proton

OMERE Upset Rate Assessment

To determine the device error rate, integrate the cross-section and sensitive device volume with the LET spectrum.

The mission parameters for solar protons and LET spectrums were added to OMERE from the Environment Specifications. The resulting SEU rates for the devices are shown in the table below.

Component	**Heavy Ions total rate**	**Protons total rate**	**Total rate**
	/device/day	/device/day	/device/day
FPGA	4.55E-04	3.71E-04	8.27E-04
SDRAM	8.46E-04	6.91E-02	7.00E-02
FRAM	3.43E-01	6.30E-01	9.72E-01
DC-DC converter	________	1.48E-01	1.48E-01
Voltage regulator	7.31E-03	2.69E-02	3.42E-02
LOON Cardinal 640 Sensor	____-___	5.09e-01	5.09e-01

CONCLUSION

- All NIR systems have been tested. The sensors and the FPGA board passed the radiation test. The MCU board was not functional while beam testing and hence the results were unavailable.
- SEL was not observed for the standard Cardinal640 sensor. The Standard Cardinal 640 sensor is safe from TNID for operation at the mission fluence of 1e11 (/cm²).
- The probability of SEE was higher for the low noise Cardinal 640 sensor as compared to the standard one.
- Despite the varying levels of fluences tested, FPGAs did not undergo any SEE.
- Failure modes were detected for the MCU and the precise cause for this is yet to be determined. MCU did not undergo narrow beam testing.
- The upset rates and the LET threshold values are within the specified requirements for all the 10 test components except the LOON Cardinal Sensor. The NIR components meet the radiation tolerances needed for the Comet fly-by mission.

REFERENCES

1. Comet Interceptor Environment Specification.
2. Damage correlations in semiconductors exposed to gamma, electron, and proton radiations, G.P. Summers et al
3. Space product assurance, Radiation hardness assurance - EEE components, ECSS-Q-ST-60-15C.
4. Single Event Effect Test Report on the Xilinx 3090A FPGA, Amy K. Moran, Kenneth A. LaBel, Report Date: 1/3/1997.
5. Heavy Ion Single Event Effects Measurements of 512Mb ISSI SDRAM, Farokh Irom, and Mehran Amrbar.
6. Compendium of Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA, Martha V. O’Bryan, Kenneth A. LaBel, Stephen P. Buchner, Ray L. Ladbury, Christian F. Poivey, Timothy R. Oldham, Michael J. Campolo, Martin A. Carts, Melanie D. Berg, Anthony B. Sanders, and Susan R. Mackey, IEEE NSREC 2008.
7. Heavy Ion Test Report for the AD9257-EP Analog-to-Digital Converter, Dakai Chen1, Hak Kim2, Ali Feizi3, Ted Wilcox2, Christina Seidleck2, and Anthony Phan2, NASA Goddard Space Flight Center 1, Code 561, Greenbelt, MD 20771, ASRC Space & Defense, c.o. NASA Goddard Space Flight Center 2, A.K. Aerospace Technology Corporation, c.o. NASA Goddard Space Flight Center 3, Test Date: June 27-28 and August 10, 2016.

8. ESA CubeSat Picasso radiation test results, 2016.
9. Snodgrass and Jones, 2019, Nature Comms. 10, 5418.
10. Jones et al. 2020, 'Comet Interceptor A Mission to a Dynamically New Solar System Object A Phase-2 Proposal in Response to the European Space Agency's Call for a Fast Class Mission.'
11. Tinetti et al. 2018, Exp. Astron. 46, 135-209.

Ivezic, Z. et al. 2008, Astrophys. J. 873, 111.