Stereo Vision Measurement System for Low Earth Orbit Applications

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ABSTRACT

The Stereo Vision Measurement System (SVMS) is a generic purpose computer vision based sensor for Low Earth Orbit (LEO) applications, developed by Tecnomare on behalf of the Italian Space Agency. The system allows for real time measurement of position and attitude and contemporary tracking of objects based on stereo or single computer vision. Performances and main characteristics of the system are explained. In particular, the paper focuses on the qualification campaign of the Commercial Off The Shelf (COTS) cameras ruggedized by Tecnomare to withstand the LEO environment. Possible problem areas for space usage of the selected camera have been identified and investigated: the thermo-vacuum environment and the radiation environment (radiation of γ-rays, heavy ions and protons). Thermo vacuum, total ionizing dose and proton tests have been performed to evaluate camera performances and failure rate in LEO environment. On the basis of the results of these tests, the camera has been modified adding an heat sink for conduction cooling and two specific radiation shielding for γ-rays and protons. Through analysis and further testing the modified camera has been proved to fulfil mission requirements for the mission reference time (1 year).

INTRODUCTION

Modern space activities are evolving towards more and more complex tasks while costs and budget pressure compel every day more for "cheap" missions. In this environment, the use of robotic systems will be preferred to human manned missions. Stereoscopic vision sensors provide robotic systems the necessary sensorial information to perform certain complex tasks, such as navigation through an unknown environment (as in the recent Mars rover missions), satellite rendezvous and docking, EVR operations and so on.

Following two demonstration phases carried out on behalf of both ASI and ESA, Tecnomare is now completing a 4 years development project on behalf of ASI for a flight prototype of an enhanced vision system for space applications based on stereo and mono computer vision.

The system is based on requirements issued after an analysis of different space mission scenarios, implementing tasks such as geometric measurements, geometric modelling, real time tracking and so on. The program goal is to develop an Engineering Model of a general purpose space qualified sensor based on computer vision processing to be mainly used in the Low Earth Orbit (LEO) environment.

SVMS GENERAL DESCRIPTION

The SVMS has been designed as a generic purpose computer vision based sensor for LEO applications. As such, it is capable of performing monitoring, visual inspection and real time measurement of position and attitude of objects, as well as real time tracking of moving objects. Performance data, with a cameras baseline of 180 mm and lenses field of view of 40° are detailed in Table 1.

Table 1. SVMS optical performances

Pose measurement accuracy at 1 m		
stereo view	(position)	5.9 mm rms
	(attitude)	0.59 deg rms
single view	(position)	15 mm rms
	(attitude)	3 deg rms
Tracking rate		2 Hz
Point Measurement rate		10 Hz

SVMS is a complete vision system, implementing many different features. Its main functions are:

- measurement of 3D Euclidean coordinates, distance between two points, planar areas
- tracking of up to 6 points that can be contemporarily measured
- tracking of a target object by using its geometric model
- depth map reconstruction of the imaged scene
- fitting to extracted 3D data of different primitives (cylinder, plane and straight line)

A ground SVMS prototype is being used to develop and test the different software modules. Fig.1 shows the prototype, while Fig.2 shows a tracking sequence of a mockup object. On the left is represented the sequence of images acquired by the cameras, on the right the geometric model is matched on the image, measuring position and attitude of the mockup and allowing its tracking.

SVMS is composed of two main parts:

- The Flight Segment (FS), including all the flight hardware and software
- The Ground Segment (GS), acting as interface for the remote Operator who issues macro commands through the Ground Man Machine Interface. An auxiliary Man Machine Interface has been developed to allow astronauts to command the system directly on orbit.

The FS is composed of (see Fig.3):

- **Imaging Unit** (IU): two analogue black & white cameras and the mechanical structure supporting them, its main issue is to maintain the necessary mechanical stability of the cameras baseline over the range of different environmental conditions (flight vibrations and shocks, day/night cycles, orbit parameters etc.)
- **Illuminator**: four lamps to provide the capability to light objects at short distance (1 – 1.5 m)
- **Pan and Tilt (P&T)**: two degrees of freedom gimbal to reorient cameras and lamps.
- **Flight Electronics** (FE): algorithmic computation is performed on flight by the FE, which acquires and elaborates camera images, performs measurements and tracking, handles the communications with the SVMS GS, controls the P&T; the FE design is based on:
  - o 3 Aitech Systems VME boards (2 stereo pair frame grabbers and 1 video compressor), including communication interfaces (MIL-STD-1553 and Ethernet 10/100)
  - o 2 VME boards for P&T management designed and manufactured by Galileo Avionica in the frame of the SVMS contract
- **Flight Software**: software development is based on the RealTime extension of the Unified Modeling Language. This approach grants many advantages, among with: easier production of re-usable software modules, easy portability to different environments, simple test and debugging, quickness in documentation generation, etc. The communication between FS and GS is a key issue for the system behavior. Two channels have been implemented:
  - o The uplink channel (GS to FS) used to transmit macro instructions to the FS and for SW or data upload; it is based on the reliable MIL-STD-1553 protocol
  - o The downlink channel (FS to GS), based on MPEG transport stream, which presents two different elementary streams: a video stream with the compressed images and a metadata stream with the information on the global FS state, including the measurement data

While maintaining the required flexibility to various mission applications, the International Space Station (ISS) external scientific payloads application has been considered as baseline mission for the detail design. In this scenario, the FS is installed on an Express Pallet Adapter (ExPA) and is commanded from Earth trough the GS.

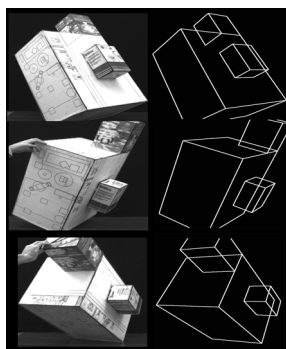

Fig.1 SVMS ground prototype
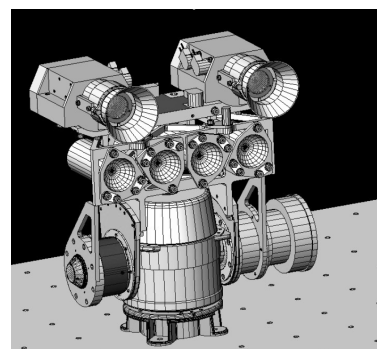

Fig.2 Tracking sequence

Fig.3 SVMS IU, Illuminator and P&T

The program policy the contract granted to Tecnomare implements is to use COTS when available, provided the corresponding Space Qualified items be actually available in the standard supplier directory. The components not fulfilling this condition are to be selected on the market as off-the-shelf products suitable to be space qualified on the basis of the mission requirement conditions. Should not be any of them available, a custom development is to be taken into account.

QUALIFICATION OF COTS CAMERAS

On the basis of the program policy of the SVMS project, Tecnomare has evaluated and tested different COTS cameras to be used for the Imaging Unit. In the end, trade-off studies indicated SONY XC-ST70CE as the best suitable camera for this application. The choice has been driven both by mechanical constraints (size and mass, vibrations and shock resistance, temperature ranges) and by optical constraints (Charged Coupled Devices (CCD) size and resolution, sensitivity, shutter control). Tecnomare is now endeavouring the space ruggedization and qualification of some of these units for the protoflight model of the SVMS.

The cameras had to be ruggedized and then tested to qualification levels for protoflight hardware. This included several issues to be verified and dealt with such as:

- **Thermovacuum Analysis and Qualification**: thermovacuum stability of materials and electronic components, as well as the operative temperature range of the camera in vacuum conditions, because of the lack of the cooling effect of natural air convection.
- **Radiation Analysis and Qualification**: radiation tolerance to γ-rays and to trapped protons and heavy ions up to LEO levels referred to mission duration.

The design choices and tests performed so far in the way of qualifying these cameras for the SVMS application are described in the following.

Thermovacuum Analysis and Qualification

The Sony XC-ST70CE is a high quality camera designed for operations in harsh terrestrial environments. It has optimal characteristics and a robust design, but it has not been specifically designed for operations in space and in vacuum in particular. The datasheet reports an operative temperature range of –5°C / +45°C. These data are referred to ambient temperature, with the implicit assumption that heat produced by the camera electronics can be dissipated by air natural convection, as a minimum. A test in vacuum at the foreseen operative camera pressure and temperature ($2 \cdot 10^{-3}$Pa and +44°C, including test margins according to [1]), highlighted local overheating of camera electronics with a decrease of the Mean Time Between Failure (MTBF). To guarantee the correct working of the camera in vacuum conditions, the camera has been modified adding an Heat Sink (HS) in the case design. The HS design, camera modifications and tests have been carried out in cooperation with CISAS (University of Padova). They consisted of two phases.

First, hot spots of the camera electronics have been identified using Infrared (IR) imaging, and their temperature relative to the camera base has been measured. Five main hot spots have been identified (see Fig.4), the DC/DC converter resulted the most critical component.

Next, an HS prototype has been implemented to evaluate the maximum thermal resistance value for an efficient conduction cooling. Different solutions have been evaluated on identical cameras measuring the temperature difference between the DC/DC converter and the camera base. Satisfying results were achieved with thermal resistance values of 46 K/W or less, as shown in Fig.5, where the temperature difference between the DC/DC converter and the base of two cameras has been monitored with resistance temperature detectors in vacuum conditions. Both cameras were inside a thermovacuum chamber, the scene was illuminated to have the cameras CCD work and dissipate heat, the cameras were turned on at the beginning of the test after their temperature had stabilized for some minutes. One of the cameras was equipped with the prototype HS while the other was unmodified. The temperature difference for the camera equipped with the prototype HS was of 25,6 °C in front of a difference of 51,7°C for the unmodified one.

To further validate the design of the HS, a full thermo vacuum qualification test according to requirements in [1] was performed. The modified camera and lens underwent three full thermal cycles (Fig. 6), with set point temperatures imposed at the camera base according to system thermal analyses. The following functional tests were performed:

- Test on measurement parameters at the maximum operative temperature of 44°C (at camera base). The temperature of the DC/DC converter reached a maximum temperature of 67°C during the test. The images of a reference target revealed no geometrical distortion or Mean Grey Level (MGL) alteration, both at local and image level, for the whole duration of the test.
- Cold start test at 0°C.
- Minimum temperature survival to –54°C, not operative.
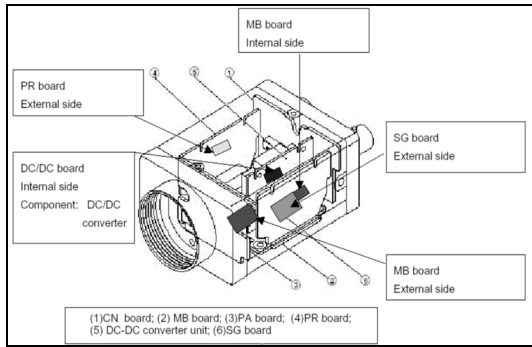
Fig.4 Camera Electronics hot spots
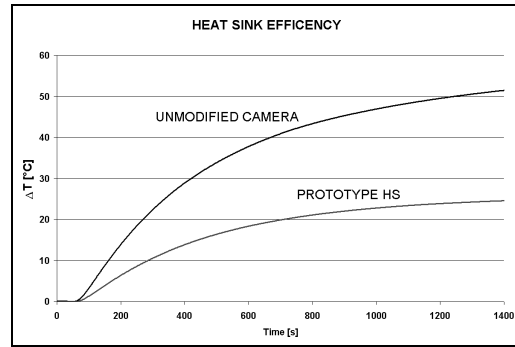
Fig.5 Prototype HS efficiency in vacuum

The qualification test demonstrated the capability of the modified camera with the prototype HS to withstand the SVMS thermal constraints with unaltered performances. On this basis, a final version of the HS has been designed to improve some structural issues of the prototype as well as some problems with poor contact conductance between the electronic components and the HS itself. The final HS has been compared to the prototype in still air, resulting in a temperature difference between the DC/DC converter and the camera base of 5°C, in front of a difference of 12°C for the prototype and of 22°C for the unmodified camera (see Fig.7).

Fig.6 Thermovacuum Qualification Test
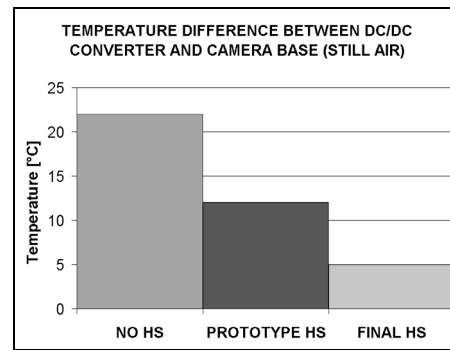
Fig.7 Final HS compared to prototype

Radiation Environment Analysis and Qualification

The radiation analysis and qualification has been carried out to determine the behaviour of the Sony ST-70 cameras when exposed to the radiation levels typical of the LEO environment. The most important analyses and tests for space application electronics are those relevant to the total ionizing dose (TID), the single event effect (SEE) and the bulk damage. These characterizations allow determining the expected reliability performances and whether possible fatal failure of the components might be accounted for.

For the radiation environment of LEO, the most important figure for this task is by far the component behavior versus TID, this parameter being an overall index of the possible impairments. The bulk damage is important as well for a camera qualification because is the principal cause of spoilage for its sensitive element, the CCD. In the LEO environment, the trapped protons are the most abundant source of bulk damaging particles, numerous enough to be able to bring about a significant degrading of CCD performances during the mission duration. This particle source is also, by chance, the easiest to be dealt with due to its high penetration depth even in standard components not prepared delidded on purpose for beam targeting and for such a reason is the preferred sort of ion for system level testing of COTS.

The SEE testing is usually carried out with heavy ion beams. This poses a big issue on the testing feasibility for COTS components, because the penetration depth of such beams, even at the most powerful accessible facilities, is too low to allow for testing of not delidded off-the-shelf components. However, two reasons allow to say that the proton testing is largely significant for the qualification for ISS environment:

- the whole TID a device undergoes, from ions of elements with Z=1 (protons) up to Z=28 (iron) is 83,44 Gy/year. The computing has been carried out with CREME96, considering heavy ions only. The TID a device undergoes from only protons is 83,43 Gy/year. Therefore, the protons account for more than 99.988 % of the heavy ions TID.
- several works in literature (see for example [7]) report the possibility of estimating Single Event Upset (SEU) performances in terms of Linear Energy Transfer (LET) on the basis of the component behavior under proton beam targeting due to several nuclear physics phenomena, the most notable being spallation. On the other hand, SEU is extremely important for component such as CPU boards including memories, especially when these

devices are to control tasks where the safety is a crucial issue, because an upset might lead either to a lock or, worse, to an unpredictable behavior of the whole board. An upset in the camera components leads to a temporary local image flaw and is therefore less important than the bulk damage which takes place through permanent pixel blemishes, thus impairing the measuring capability of SVMS. Other potentially destructive SEEs, such as latch-up, (if any might occur) are to be taken care of by suitable overcurrent protections, implemented in the power supply electronics.

TID Analysis & Tests

Two Sony cameras have been tested to TID: camera A was to test tolerance to radiations up to fatal failure, camera B was to measure parameter modifications after exposure to the TID level expected for the mission reference time (1 year), taking into account the shielding effect of the surrounding structure (3 millimetres of aluminum in every direction, as a minimum).

The first major issue was to choose an appropriate test procedure and test parameters. Standard test procedures for steady state irradiation testing currently available ([2] and [3]) define requirements for testing of integrated circuits and discrete semiconductors, not for complex electronic systems like a digital camera. Moreover, functional electrical tests requirements are designed for single components, and procedures for accelerated aging (to account for the Enhanced Low Dose-Rate Sensitivity (ELDRS) in MOS devices) require the test item to be baked at 100°C, a temperature by far higher than the maximum operative temperature of the camera. A system level approach for the camera as a whole was undertaken, thus implying tests carried out on the whole digitized image. The destructive test on camera A was to record the highest TID before camera image can no longer be processed by computer vision algorithms. The non destructive test on camera B was to evaluate alterations of the images acquired by the camera due to irradiation.

According to [4], the lowest value of the dose rate window (0.0001 Gy·s^{-1}) is low enough to account for ELDRS. For technical constraints the actual dose rate on camera B was 0.00016 Gy·s^{-1}.

Camera A was exposed to a very high dose rate to accelerate its spoilage. Test parameters of the two cameras are reported in Table 2 on the right. The tests have been performed in the CALLIOPE ^{60}Co irradiation plant at ENEA Casaccia premises. Images from both cameras have been acquired online and sequentially stored.

Table 2. TID test parameters

Unit	Dose Rate	TID
A	0.05600 Gy·s^{-1}	To failure
B	0.00016 Gy·s^{-1}	30 Gy (Si)

Camera A had a first failure at 643 Gy (Si), when the image suddenly became pitch black but the camera video output was still a valid video signal. Next definitive failure occurred at 7820 Gy (Si). The test was considered ended after the first failure according to the test policy.

Camera B withstood the whole test. The images of the reference target (a white PVC sheet) acquired all along the test duration showed a general progressive darkening. In table 3, on the right, the MGL of first and last image have been reported. The MGL reduced by 13.4 % from the beginning of the test to the final absorbed radiation total dose of 30 Gy (Si). This is the combined effect at system level of:

Table 3. MGL of camera B images

Image n°	TID	MGL
1	0 Gy (Si)	82
442	30 Gy (Si)	71

• formation of colour centres in lens and protective glass.
• camera spoilage.

To analyse and split the CCD radiation spoilage effects from the other factors, a physical model of the light flux acquired by the camera has been elaborated. The model accounts for lamp emitted energy spectrum, reflection index of target panel, transmission index of lens and protective glass (measured prior and past the test at Enea Casaccia, see Fig.8), sensitivity of the CCD.
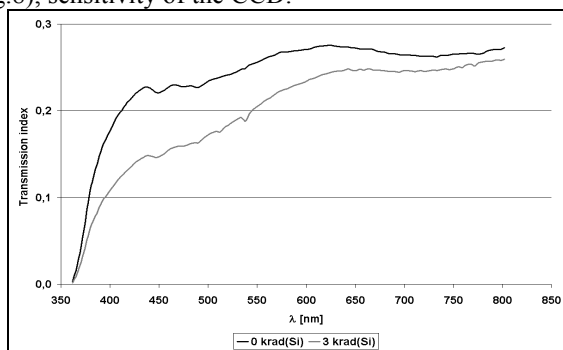

**Fig.8 Transmission index of lens, before and after irradiation. Lens iris fixed at f8.**
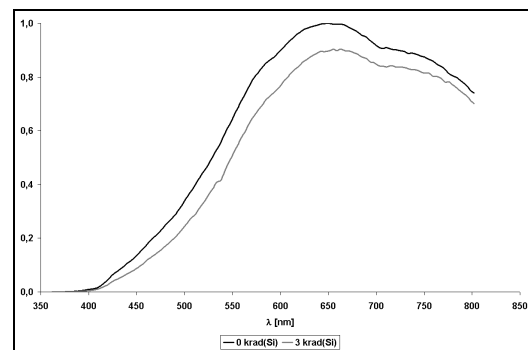
Fig.9 Illuminance framed by the camera CCD at the beginning and at the end of the low dose test.

Fig.9 shows the resulting illuminance spectrum seen by the CCD prior and past undergoing the test. Numerical integration of the curves points out an overall difference of 12.3 % in the light flux on the CCD prior and past testing, accounting for lens and protective glass darkening. The difference directly measured on the images turned out to be 13.4% accounting for all effects. The gap accounting for the camera spoilage only is then 1.1 % thus leading to the conclusion that the camera underwent no meaningful spoilage due to radiation during the test.

The analyses presented so far are referred to the whole image and do not provide any information on possible local effects (e.g. partial CCD spoilage or blemished pixels). The temporal variation of random selected rows of the image have been analyzed both in light and dark conditions to check for uneven darkening areas on the CCD and blemished pixels. Fig.10 shows the difference in luminance between every pixel of a row taken in the first image and assumed as a reference and the corresponding pixel of next images. The progressive decreasing of the luminance of pixels is consistent with the darkening effect detected on the whole image.
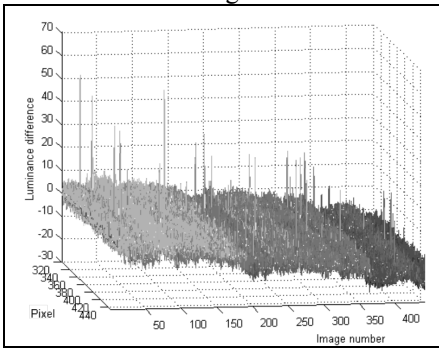
Fig.10 Temporal variation of illuminance difference between pixels of a row and corresponding pixels of reference image in light conditions.
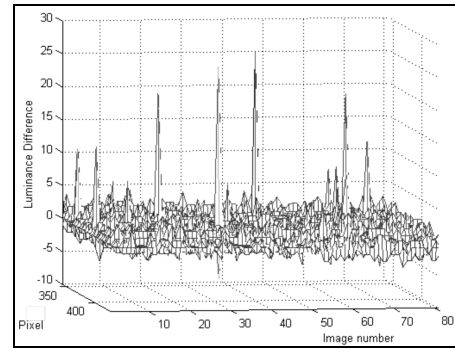
Fig.11 Temporal variation of illuminance difference between pixels of a row and corresponding pixels of reference image in dark conditions.

There has been no meaningful differences in these changes both from pixel to pixel and from row to row in all randomly selected rows used for testing, thus excluding local darkening effects. Fig.11 shows the same difference in luminance of images acquired in dark conditions. No change in the mean illuminance of the pixels is noticeable thus confirming that radiation effects upon the camera are negligible.

No blemished pixel has been detected.

Proton Analysis & Tests

The proton analysis and tests allow determining the bulk damages of the CCD undergoing radiation exposure and the degrading performances of other components included in the camera. The most remarkable effects of targeting with protons the active silicon of the camera devices are the particle recoiling and the nuclear reaction called spallation. The latter is the most interesting from the evaluation of the effects on electronics because brings about device behaviour typical of much more energetic particles. In practice, the clashes between the protons and the heavy silicon nuclei produce from secondary reaction nuclear "splinters" of nuclei lighter than silicon that, although at a very low percentage, behave like an heavy ion beam directly shot within the device. It's something like throwing a baseball at a bucket of balls, resulting in a few being immediately ejected and many more bouncing around and falling out.

The tests took place in the Istituto Nazionale di Fisica Nucleare (INFN) in Legnaro (Padova).

Two cameras were opened and spread over a plane by means of a suitable framework so as to make them "planar" and apt to be hit by a rastered beam of 25 MeV protons. Although the raster allowed to deal with an area of about 5 x 5 cm, four of such patches were necessary to expose the whole camera, thus giving in addition the possibility of correlating the sort of damages against the actual exposed devices that have caused them. The monitoring was made through three different instruments: a frame grabber to capture the camera output image, a first oscilloscope with the timing set to look at the single line time scale and a second oscilloscope with the timing set to look at the field/frame time scale, thus providing an overall description of the possibly flawed synchronisms signals in addition to the image capture to detect the blemishes.

The camera A underwent a fluence started from 10^{10} p's/cm^2 up to a cumulated fluence of 1.13×10^{11} p's/cm^2 when an overcurrent protection was triggered when the power supply neighbourhood was exposed. These first values, though a bit high to finely monitor the effects, have been chosen because the Faraday Cups used to gauge the beam had sensitivity of about 10 pA that yielded a minimum beam current of 1.5 nA for the noise to be negligible. On that basis, the beam current has been actually put a 5 nA. Such a high beam levels, however, led to quick material activation and to achieve high fluences in short time, thus limiting the possibility to discriminate the test results. Therefore, another camera underwent the tests with a beam current of 0.27 nA, quite at the limit of the Faraday Cup gauging capabilities.

The power supply damage however turned out to be not destructive because the camera worked over again 30 minutes after the irradiation ended. No SEEs were detected meanwhile.

The camera B underwent a fluence started from 10^9 p's/cm^2 up to a cumulated fluence of 8×10^{10} p's/cm^2 when an overcurrent protection was triggered. This camera was exposed so as to allow a very fine study of the CCD behavior, avoiding damages to other parts. Only at the test end, the beam current was raised up to 5 nA just for the exposure of the power supply area that led to the overcurrent protection in the test of the first camera. Again, the power supply damage turned out to be not destructive because the camera worked over again 30 minutes after the irradiation ended. No SEEs were detected meanwhile.

The fluences the device under tests underwent (from 1×10^9 up to 1×10^{10} depending on the trial) were usually shot in time intervals of 30-60 seconds. Their magnitude is to be compared with the level of trapped proton exposure in LEO in [5] which states the daily average flux to be maximum 3.3×10^6 p's/cm^2-day considering every energy level, regardless of the shielding to be conservative in the computing. In practice, the environment proton flux is then at least 6 order of magnitude lower than that of the tests.

The CCD exhibited an increasing number of blemishes at the increasing of the cumulated fluence. These blemishes, however, are not permanent, their amount decreasing from 283000 to 4400 two hours after the end of the irradiation. The analysis has been carried out for both permanent and temporary blemishes.

Considering the true flux to be 6 order of magnitude lower than that of the tests, the expected amount of blemishes in orbit conditions is that assumed as permanent after two hours, actually 4400 permanent blemishes past a fluence exposure of 4.87×10^{10} p's/cm^2 corresponding to more than 40 years of continuative LEO mission. Referring this figure to one year mission duration, the expected permanent blemishes is 11, namely less than 0.003 % of the CCD surface, which is practically unaffecting the measuring process and its accuracy on the long term.

The temporary blemishes turned out to be instead about 65 times more frequent which could start with affecting the measuring process, though not impairing it at all. Suitable shielding has been designed past the qualification process to heal this, as describe later on.

Shielding

The heavy ions coming with the cosmic rays cause large amount of LET to the devices, but are quite stoppable by shielding and, moreover, are scarcely abundant. CREME96 computing for iron (Z=28) yield an average abundance ratio in the order of 1×10^{-9} respect to protons (see also Fig.12), with flux for LEO in the order of 10^{-3} particle/cm^2-day, a figure rather negligible for 1 year mission duration. On the other hand, fully stopping high energetic ions coming from cosmic rays would entail shielding as thick as 50 cm of heavy metal such as tungsten, making the design utterly out of bound for the mass budget. Moreover, though in LEO most ionizing particles are protons, some electrons are present and bremsstrahlung might take place being the electron mass 3 order of magnitude lower than the proton one. For such reason the shielding has been designed taking into account the need for usage of COTS electronics among the mass budgets and the actual likelihood of particles in LEO along with their relevant damages.

CREME 96 allows to determine shielding efficiency only for aluminum. The TID a device undergoes, from protons with 6 mm Al shielding is 1.24 Gy/year with respect to the 83.43 Gy/year without shielding. The overall bulk damage effect is then reduced by a factor 67, thus leading the expected temporary blemishes to less than 0.003% of the CCD surface, and thus negligible. CREME96, however, does not take into account the trapped electrons which are a rather important source of damages (through bremsstrahlung) mostly in outer belt but also in the inner one due to the highly inclined orbit of the ISS and to the SAA passages. Higher Z materials are more effective at electron shielding as more electrons are scattered than in lower Z materials. However

Fig.12 Particle Flux vs. Energy in LEO

bremsstrahlung γ-ray production increases with Z number increasing. An even better trade turned out to be designing the shielding as a composite sandwich balancing the benefits of electron stopping power of high Z materials along with the lower bremsstrahlung production of lower Z materials. The design includes a 3 mm aluminum layer integrated in the outer SVMS imaging unit assembly and a 0.5 mm tungsten plus 2.5 mm polyethylene layer directly around the camera, thus limiting the possible bremsstrahlung and the mass while improving the shielding efficiency (see Fig. 13). Calculations were based on SRIM software, version 2003.40, available from www.SRIM.org (see [6] for details on this software).

Such a shielding carries several improvements over aluminum design or reversed layers because of:

- fully stopping other heavier energetic particles as in Table 4, making the camera even more unsensintive to high energy ions
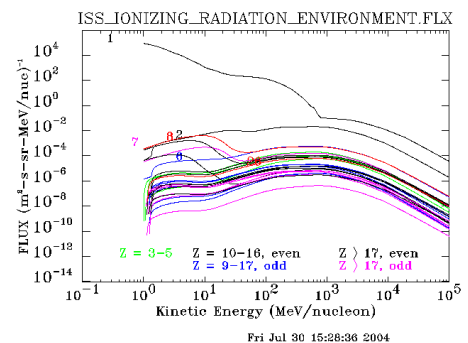
- increasing the particle scattering far from the silicon thus hitting camera neighborhoods less sensitive of CCD (see leftmost Fig.13 compared with Fig.14 and Fig.15)
- gathering most of the transferred energy in the stopping process (and also the damages) at the interface between tungsten and polyethylene, rather than at the first layer of the active silicon (see rightmost Fig.13 compared with Fig.14 and Fig.15)
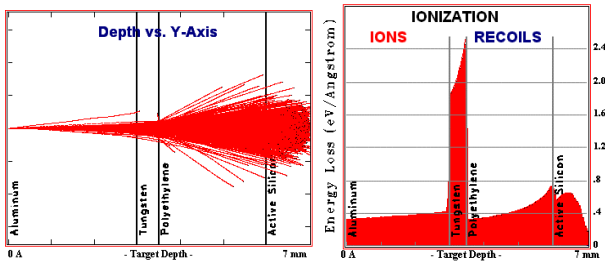

Fig.13 Penetration Depth and Ionization for 38 MeV protons with (3 mm Al + 0.5 mm W + 2.5 mm polyethylene) shielding
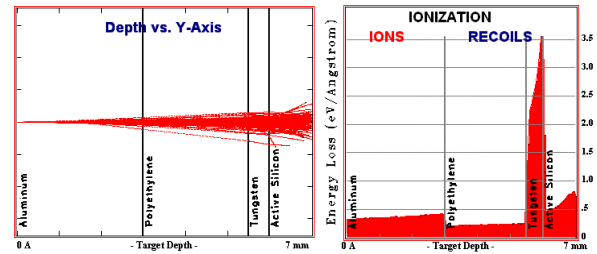

Fig.14 Penetration Depth and Ionization for 37 MeV protons with (3 mm Al + 0.5 mm W + 2.5 mm polyethylene) shielding

Table 4. Stopping Energy

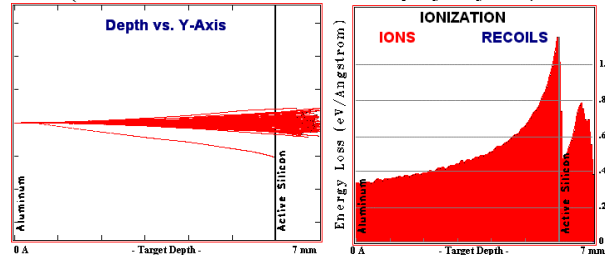| Element	up to energy (MeV)
He	152
Be	470
C	840
Si	3200
Fe	8500

Fig.15 Penetration Depth and Ionization for 37 MeV protons with 6 mm Al shielding

CONCLUSIONS

The main characteristics of the ASI program SVMS have been explained, with a particular attention to the qualification campaign of the Sony XC-ST70CE COTS camera for its use in the LEO environment. To guarantee the correct working of the camera, the effects of the thermovacuum and radiation environments on the camera MTBF have been tested and analyzed. This led to the necessity of a ruggedization adding a conduction cooling aluminum heat sink and a shielding of 3mm aluminum, 0.5mm tungsten and 2.5mm of polyethylene for both ionizing radiations and trapped particles. Tests and analyses conducted on the modified camera proved that:

- the camera can withstand a full thermovacuum qualification test for protoflight hardware without any alteration in performances with an heat sink having a thermal resistance of 46 K/W or less.
- camera spoilage after a TID of 30 Gy is negligible. No blemished pixels are present, the diminution in mean grey level of the images acquired during the test imputable to camera spoilage is 1.1%.
- permanent blemished pixels due to protons cumulated fluence corresponding to 1 year in LEO of the unshielded camera are less than 0.003 % of the CCD surface and thus negligible.
- temporary blemished pixels due to the same fluence of the camera shielded with 3 mm of aluminum, 0.5 mm of tungsten and 2.5mm of polyethylene are less than 0.003 % of the CCD surface and thus negligible.

On the basis of these results, the ruggedization campaign endeavoured by Tecnomare has demonstrated that the modified Sony XC-ST70CE cameras are suitable for usage in the SVMS program for LEO applications.

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