Star Tracker Focal Plane Evaluation for the JIMO Mission

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Abstract—The Jupiter Icy Moon Orbiter (JIMO) mission[1] was planned as the first implementation of Prometheus, an ambitious space exploration project proposed by NASA. The mission would provide a rigorous scientific investigation of Jupiter and three of its moons Callisto, Ganymede, and Europa. To safely and efficiently power and maneuver the spacecraft in deep space, novel technologies would be incorporated.[1][2]

Though launch is currently indefinitely postponed, this mission, as conceived, already presents a significant technical challenge for a robust Attitude Control System (ACS) design due to severe radiation environment of the Jovian system, and because navigation sensors must survive and function properly throughout the mission. It is particularly relevant to a spacecraft's ACS that relies on star trackers for an accurate attitude determination.

A star tracker focal plane is very susceptible to impinging charged particles and cosmic gamma rays. The radiation will degrade the device performance through false signal appearance and increased noise.

At Jet Propulsion Laboratory, California Institute of Technology an extensive study has been initiated to understand available visible imager technologies such as charge coupled device (CCD), charge injection device (CID), active pixel sensor (APS) in applications for radiation-tolerant star trackers.

More specifically, this paper includes the results of a detailed technical study and presents relevant parameters and performance characteristics (e.g., read noise, dynamic range, dark current, hot pixel rates, quantum efficiency, linearity) that must be considered in a challenging star tracker design

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1. INTRODUCTION

Prior to its cancellation, the Jupiter Icy Moon Orbiter (JIMO) mission had reached a state where the preliminary spacecraft concept outlined its mission modules, segments and specified ACS sensors allocation [1]. Key mission requirements of pointing accuracy, pointing stability, pointing knowledge, slew rate, and angular rate had been identified and had revealed the requirements needed for the ACS sensors.

These requirements, together with the mission radiation environment impact and duration, will impose a serious constraint on currently available ACS sensors. As a result, the critically important correct choice of ACS sensor, its design, and later performance must be evaluated for sensor radiation tolerance, survival, and functionality. A radhard technology development roadmap, specified milestones, and irradiation testing and analysis will facilitate making the right choice of a particular ACS sensor for a successful JIMO mission.

To efficiently operate a three-axis-stabilized spacecraft, the JIMO ACS processor will compute the vehicle's current attitude, compare it to the desired attitude, and then determine and communicate the required torques for further spacecraft maneuvering and control.

As a typical combination of inertial and rate sensors, ACS will employ star trackers, sun sensors, and an inertial measurement unit (IMU). For low accuracy attitude acquisition and safe-hold mode, a combination of gyros and sun sensors might suffice. The star tracker and IMU would be used for the primary mode, with the gyros propagating attitude based on the sensed rate between star measurements [2].

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[1] U.S. Government work not protected by U.S. copyright.

[2] IEEEAC paper # 1075, Version 9, Updated Dec. 25, 2005

2. FOCAL PLANE CONSIDERATION

A star tracker, used for attitude determination in spacecraft navigation, is an important part of many spacecraft ACS. The core star tracker element is the optics-visible detector focal plane assembly. Key parameters for a star tracker typically include the following: field of view (FOV), accuracy at the beginning/end of life (BOL/EOL), sensitivity or limiting star magnitude, slew rate, update rate, mass, and power.

To meet those specifications, a key choice of the imager focal plane technology, whether it would be a CCD, CID, or complementary metal oxide semiconductor (CMOS) APS, is required. A potential focal plane evaluation would include evaluating responsivity, linearity, readout noise, dark current, dark current variation, and frame rate. Focal plane properties and geometry will also be described by its quantum efficiency (QE), fill factor (FF), full well capacity, as well as the imager's size, pixel size, and permissible amount and type of defects.

The next step is to characterize the radiation damage susceptibility of an imager. A star tracker focal plane is susceptible to impinging charged particles and cosmic gamma rays. Radiation degrades performance by inducing false signal and increasing noise. Different focal plane device technologies will respond differently, but generally all display particle-induced ionization transients, an increase in "hot pixels" count and rate, an increase in dark current rate, dark current non-uniformity, QE degradation, and full well capacity reduction. These effects are attributed to Total Ionizing Dose (TID), Displacement Damage Dose (DDD), and operating temperature.

Systematic studies, both theoretical and experimental, have been conducted to develop a reliable, radiation-tolerant focal plane. The proton-induced losses in CTE are of significant concern for CCD functionality, because they cause distortion of star images and lead to errors in centroid position measurements.

Once the focal plane technologies have been evaluated and understood, a star tracker system design can be made, where different parameters can be traded against one another to meet the overall requirements. The star tracker system design is not covered in this paper. Refer to [3] for star tracker trade studies.

3. CCD

Designed for visible photon detection, the silicon-based CCD can be defined as a monolithic array of closely spaced MOS capacitors that transfer an analog signal charge from one capacitor to the next, working as an analog shift register [4]. The quality of an acquired signal will significantly depend on the key parameters– QE, sensitivity, gain, and bandwidth of source follower amplifier– that contribute to image quality and sensor performance. Radiation will degrade silicon imager performance even further. It is represented by high-energy photons, protons, electrons, neutrons, and heavy ions, as well as gamma rays. Displacement- and ionization induced damage present the most severe consequences for the CCD.

Displacement damage occurs when Si atoms are kicked off their equilibrium positions by energetic bombardment. This process is accompanied by the appearance of vacancies that become trapped near lattice impurities within a CCD signal channel. Because a signal charge has to be moved through the silicon from the generation sites to the readout preamplifier each time a trap is encountered, charge losses take place. The resulting loss in CTE can vary by over three orders of magnitude [5]. In case of ionization-induced damage, electron-hole pairs and new interface states are created making a charge transfer very problematic.

Radiation effects have to be taken into account when making performance predictions for a CCD-based star tracker space science missions. Therefore, extensive studies on CCD irradiation have been initiated immediately as the imagers become available.

Among the first imagers were Ford Aerospace CCDs exposed to Fe-55 X-ray photons, each producing 1620 electrons per photon interaction. Initial CTE showed 0.999997, but after only 5 krad of Co-60 radiation added at 10 rad/sec the CTE number had changed to 0.9991 [6]. Radiation damage in the form of enhanced dark current spikes has also been observed during described tests. To alleviate this problem, a new technology was implemented. The Multi-Pinned-Phase (MPP) technology allows the CCD to operate totally inverted during both integration and readout while maintaining other performance characteristics [6].

Current CCD technology has matured over the past decades, and CCD performance has continuously advanced: CTE was improved by buried channel implant, dark current was reduced by MPP mode, and QE and anti-blooming were increased by backside illumination, open-gate, or thinning of the device.

High QE (~ 90%), low readout noise (2-3 e^- rms), very low dark current (10-20 pA/cm^2), and high dynamic range (~75 dB, front illumination and ~90 dB for back-side illumination) are among the spectacular performance [7] characteristics (Fig. 1) of contemporary CCDs [8].

Despite significant progress in CCD hardness design, visible CCD imagers remain susceptible to high-energy penetrating protons that cannot be effectively shielded against [9, 10].

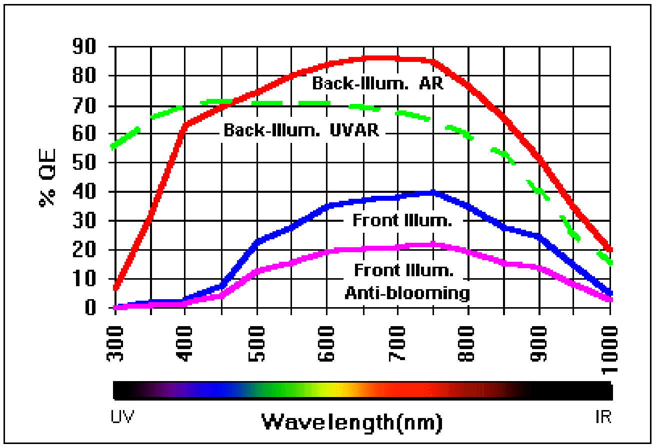

Figure 1. Typical QE curves for the current front- and back-illuminated CCDs (after [8]).

Just TID of 1 krad (Si) due to proton irradiation is able to cause more than a 100 electrons/pixel/sec increase (Fig. 2) in the CCD dark current. Recently performed [11-13] CCD ground testing with high-energy proton and gamma irradiation has shown significant performance degradation, although the same basic phenomena (TID, DDD, and transients effects) are also featured with high-energy electrons.

Over the last decade, extensive radiation studies were conducted by Sira Ltd. (UK) under several contracts with the European Space Agency (ESA) [11-13]. Recently [13], they have focused on the frame transfer CCDs (typically employed by star trackers) manufactured by two European suppliers: e2v Technologies (UK) and Atmel (France). The following devices were investigated under irradiation: CCD47-20 (1024 x 1024 pixels), CCD02-06 (288 x 385) [12], CCD57-10 (512 x 512) and CCD55-20 (770 x 572) made by e2v Technologies (UK); and TH7863D (288 x 384) and TH7890M (512 x 512) made by Atmel (France) [13].

Among the parameters of the interest were CTI, conversion gain, flatband voltage shift, linearity and full well capacity, responsivity, dark current, random telegraph signal (RTS) behavior, and output drain current

The impact of radiation on star tracker performance was also a subject of studies [12] aimed at relating induced changes in CTE to a shift in position of artificial star images. By comparing the two spot images (in proton damaged, and not irradiated region), star tracker precision was estimated [12, 14]. Added signal background reduced errors to less than 0.1 pixel (typical of a medium accuracy star tracker) after receiving 10 krad (Si) TID from a proton environment [14] if windowed readout was used.

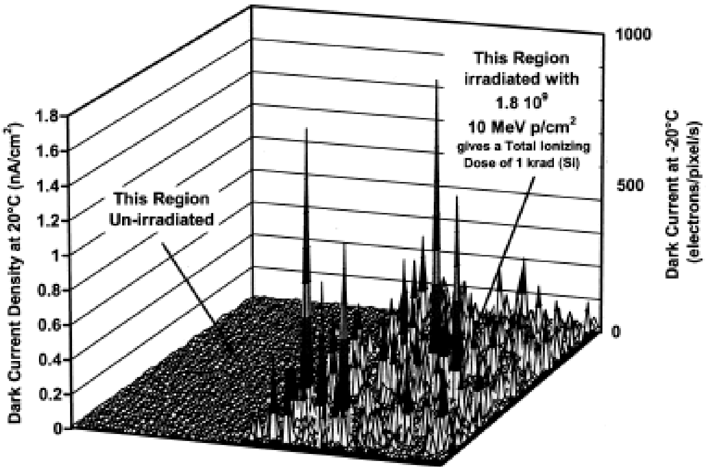

Figure 2. Dark current spikes in proton-irradiated CCD (after [10]).

4. CID

Reliance on CCDs and their vulnerability to displacement damage can be mitigated by switching to CID technology. Very much like CCDs, CID imagers were designed to collect and store photon-generated charges using two-dimensional arrays of MOS coupled capacitor sites. The main difference between these devices is reflected in their readout mechanism. In the case of a passive CID, non-destructive readout operation (NDRO) is represented either by parallel injection or row readout techniques [15] where signal charge is sensed by measuring the voltage change induced by a charge transfer between two storage capacitors (photo-gates) within the same pixel.

The non-destructive readout mechanism makes the CID imager less susceptible to the radiation environment, because only a single charge transfer is required to read out a CID pixel. As a result, CTE losses would not be as prominent as in CCD.

New developments have additionally improved the radiation hardness of CIDs. New double-metal, double-poly, high-resistivity P-channel process technology was exclusively implemented at CIDTEC (USA), culminating in the development of 1 Mrad (Si) TID resistant cameras [16] based on the CID22 imager. The CID's architecture has obvious advantages: radiation hardness, NDRO, random accessibility, high fill factor, anti-blooming, and adaptive exposure control. But higher readout noise levels than in the CCD (due to high bus capacitance of the row) and pixel crosstalk will drive the system design of a star tracker to typically be more bulky and less accurate than the CCD equivalent star tracker.

Nevertheless, extensive CID radiation studies [17-19] have been continued. Recently high-energy electron testing of CID22Q has been reported [20]. The goal was to measure transient effects utilizing both 10 and 68 MeV electrons, as well as TID responses with 30 MeV electrons. Each device was operated as a framing camera during the irradiation. Though data showed a significant increase in the dark current and excessive read noise, the device was still able to operate as a video camera after receiving a TID of 1 Mrad (Si) [20]. Figure 3 provides values of the dark current for the CID-based cameras irradiated in a stepped fashion up to 500 krad (Si) and 1Mrad (Si), respectively.

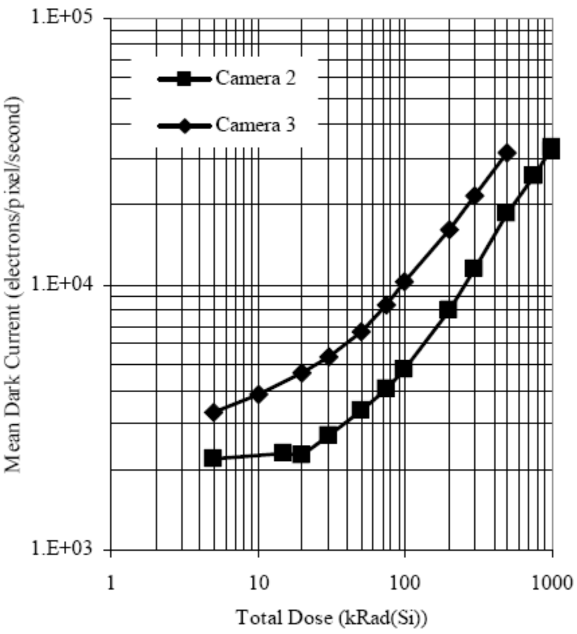

Figure 3. Mean dark current in CID due to electron irradiation (after [20]).

Based on CID inherent radiation resistance, a new effort was initiated in the mid-nineties by JPL under the Europa Orbiter mission conceptual design study to develop a star tracker that could survive in the high-energy electron Jovian environment and function after 4Mrad (Si) TID behind 100 mils of aluminum equivalent. This initiative culminated in the fabrication of the CID816 imager. The device featured a pre-amplifier per row design and underwent a series of radiometric and radiation tests [21]. With a relatively small variation, CID816 (512 x 512 pixels) imager mean read noise was ~350 e^- with QE values of 35%.

5. APS

Further innovation in CID design, an insertion of a transfer gate between the sensing and storage photo-gates in CID pixel, brought to life a new class of imagers: active pixel sensors, that are essentially a family of active pixel CIDs based on CMOS technology. With a pre-amplifier per pixel, row selection, and preset switches, APS architecture was expected to eliminates crosstalk, reduce a fixed pattern noise (FPN), and increase the dynamic range [22]. Recent improvements in the CMOS fabrication process not only brought APS dark current rate values lower (50 to 200 pA/cm^2) [7] but also ensured good dark current uniformity and reduced readout noise to 39-74 e^- rms [23], less than current CIDs.

The prospect of even more enhanced radiation hardness and better noise performance was the main reason for pursuing APS development for future environmentally challenging space applications. For that reason, ESA conducted unprecedented and comprehensive gamma, proton, and heavy ion radiation evaluation [13] of the Fillfactory (Belgium) STAR-250 [23] CMOS APS based on a standard 0.5 micron Alcatel Microelectronics technology. The sensor (512 x 512 pixels) had on-chip circuitry to perform double sampling to reduce the FPN with a maximum 30 frames/sec rate with the output of 10 bit ADC [24].

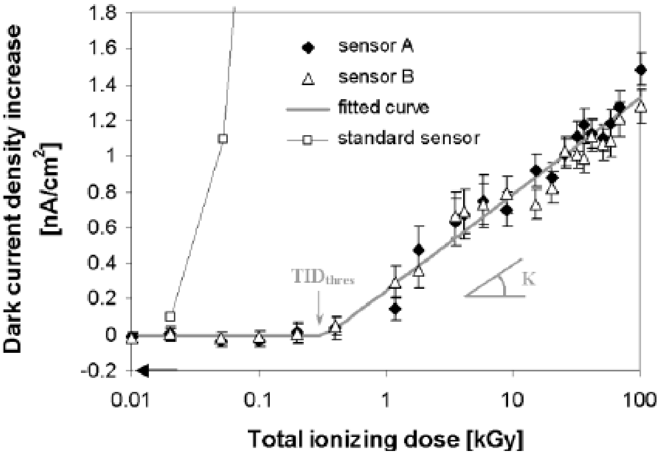

Figure 4. Dark current density increase versus TID measured on two STAR-250 sensors. Standard APS sensor performance data are shown for comparison (after [24]).

Before irradiation at 27°C, the mean dark current value was 200 pA/cm^2. Experiments with TID up to 10.2 Mrad (Si) were done on biased STAR-250 with a Co-60 gamma source. A factor of K=0.54 nA/cm^2 per decade (Fig. 4) has been found for the dark current increase that was explained by the flatband and threshold voltage shifts resulting from the build-up of positive charges in the field oxide [24]. The TID_{thres} was the total ionizing dose threshold necessary to observe a dark current increase. Another important result was the fact that FPN was not affected by ionizing radiation and remained well below 0.4% of full well for the whole device due to the presence of column amplifiers [24]. Responsivity of the device has also been affected by the radiation, both non-ionizing and ionizing [24, 25]. Although the shape of the spectral response did not change, its absolute values showed a factor of 2 reduction after 80 krad (Si) TID [25] explained by a reduction in the pixel's gain.

During heavy ion testing with Kr ions at 60-degree incidence and a fluence of 1e6 ions/cm^2, transients effects on STAR-250 were monitored and no single event latch up (SEL) was observed up to the maximum LET of 68 MeV/(mg/cm^2) [25]. No single event upsets (SEU) or functional interrupts were seen in the array shift registers or the on-chip ADC as well. Linearity and full well capacity measurements were performed [13, 25] by varying illumination and integration time. Random telegraph signal behavior in the photodiode dark current data [25] were similar to the ones previously reported [24].

6. VENDORS

Major star tracker manufacturers are represented by the following vendors: Ball Aerospace and Technologies Corp. (USA) [26], Goodrich Corp. (USA) [27], Sodern (France) [28], Jena-Optronik (Germany) [29], and Galileo-Avionica (Italy) [30]. Existing star trackers primarily use the CCD as their sensing elements. But for an outer planetary mission like JIMO, imager survival and functionality in a severe radiation environment will become a prime concern. Therefore, design of future star trackers for that kind of mission will have to address the focal plane technology development presented by APS. Two vendors, Galileo-Avionica and Sodern, have already initiated work in that direction.

7. SUMMARY

Survival and functionality of an imager and its radiation tolerance will be among the key criteria in the focal plane sensor selection. Despite attractive current CCD sensors performance characteristics [7], they will fall short in the severe radiation environment of the Jovian system. Further progress in CMOS technology allows contemporary APS to become an attractive candidate for space applications which are facing a harsh radiation environment.

Several programs have already been funded by ESA to support development of APS-based ACS sensors [31] and vision cameras utilizing STAR250 APS. The latest project will employ Galileo Avionica resources and expertise to integrate a novel ACS star tracker with the enhanced STAR250 imager performance characteristics.

Sodern decided (in early 2003) to start developing a new star tracker product line HYDRA that is based on APS detector technology. The first flight models are anticipated [32] to be available for delivery around 2007.

Based on APS, radiation characteristics of the mission Star Tracker are expected to be improved and finally tested by electron irradiation to reflect the existing severe Jovian environment. That eventually will permit delivery of a radiation hardened ACS Star Tracker for the mission to comply with the Key Pointing Requirements outlined in [1].

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BIOGRAPHY

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