SIMULATION AND VERIFICATION OF PROTON-INDUCED TRANSIENT RESPONSES IN BILINEAR CCD IMAGING ARRAYS

Terrence S. Lomheim, Warren F. Woodward, Tracy E. Dutton, Ralph M. Shima,
Robert J. Chambers, Carol J. Choy, Lee W. Schumann, Linda S. Kalman, and Robert A. Keller

THE AEROSPACE CORPORATION
Sensor Systems Subdivision
P.O. Box 92957
El Segundo, California 90009-2957

Donna-Lynn Seely and Douglas R. Debs
LORAL-FAIRCHILD IMAGING SYSTEMS
1801 McCarthy Blvd.
Milpitas, California 95035

ABSTRACT

We report the first detailed measurements of the transient response of linear charge-coupled devices (CCD's) with integral bilinear multiplexers to controlled collimated low-intensity proton irradiation at energies of 18 and 50 MeV. Data were collected over a sequence of different incidence angles measured with respect to the CCD surface normal and azimuth angles measured about the surface normal. Individual experimental proton-induced responses were compared to the prediction of an analytical transient response simulation based on a CCD charge collection model. This model calculated individual CCD pixel charge collection based on: depletion, diffusion, and epi-layer thickness parameters; photosite and multiplexer gate topology; and incident proton kinematics. CCD's were modeled that had both a thin epitaxial layer and a thick (bulk) active layer. Experimental data were collected with both types of devices, and good agreement between the modeled and simulated responses was observed. One of the observed signatures, obtained from a high angle-of-incidence case, was interpreted as due to the rapid deceleration and stopping of a proton along the length of one of the multiplexers. The CCD proton response simulation was used in conjunction with several other simulation/analysis codes to predict proton-induced responses of a space-based optical sensor with a CCD focal plane to Van Allen belt proton bombardment in a low-earth-orbit (LEO) environment. The responses were assembled and displayed in the form of two-dimensional images.

BACKGROUND

Since their invention in 1970 [1], silicon CCD's have grown in importance in many commercial, scientific, and military applications including imaging, digital memories, and analog delay of video information. The trend in future planned advanced space borne optical sensors has been to use advanced focal plane technologies featuring improved responsivity and lower noise, coincident with a demand for system flexibility that includes higher sensor orbital altitudes and hence more hostile natural radiation environments. In low to medium altitude earth-orbiting sensor applications using CCD focal planes, protons effects are of concern. Here the South Atlantic (geomagnetic) Anomaly (SAA) permits relatively high fluxes of trapped energetic Van Allen belt protons and electrons to penetrate. While most trapped electrons can be removed with shielding, a substantial fraction of the trapped protons are sufficiently energetic to penetrate any practical level of sensor shielding. Passage of these penetrating ionizing particles through a CCD can generate sufficient numbers of electron-hole-pairs (EHP's) in the depletion and diffusion volumes of the device as to measurably modify its output behavior [2,3]. As its name implies, the SAA region is geographically located over the South Atlantic (off the coast of Argentina and Brazil) where the size of this region grows dramatically with increasing orbital altitude and at the higher altitudes is probably more aptly named the "southern hemisphere" anomaly. Concern over the effects of proton transients will depend on application. Point-source detection systems (e.g. star, space-object, and early warning trackers) which need to detect/track targets under all conditions, including when in the SAA region, must remove of the unwanted proton-induced signals using signal processing techniques. For down-looking extended image sensors (e.g. SPOT, EOS multispectral image sensors, Advanced LANDSAT) proton-induced artifacts will be imbedded in imagery collected over the SAA.

EXPERIMENTAL

In this paper we report the first detailed measurements of the transient response of linear CCD's with bilinear integral multiplexers to controlled low-flux levels of monoenergetic protons. This is an extension of work carried-out on a high-resolution area CCD [2]. Two linear CCD's [4], designed for detecting visible and near infrared optical radiation (400 to 1000nm), were exposed to a collimated beam of protons from the 88-inch sector-focused cyclotron of the Lawrence Berkeley Laboratory. The proton beam flux, energy, and angles with respect to the CCD surface normal were all controllable experimental variables. The beam flux was reduced to low levels which allowed easy identification of individual proton-induced events. The CCD was installed on a two-axis rotational mount that was remotely manipulated from outside the experimental vault enclosure. The two-axis mount allowed variation of the angle-of-incidence and azimuth of the collimated proton beam with respect to the CCD imaging normal over an octant of possible angles as depicted in Figure 1. This figure also shows a block diagram of the experimental set-up used to operate the CCD's while they were being irradiated with the proton beam. The proton-response data were digitally recorded and stored allowing subsequent precise reconstruction of individual events. The details of this experimental set-up have been described elsewhere [2].

The two devices tested were identical in their surface topology but had different substrate and active layer characteristics as shown in figure 2. The so-called "bulk" device had a conventionally doped thick (250 um) p-substrate, whereas in the "epi" device the active (depletion plus diffusion) region was an epitaxial p-layer 20 um thick, grown on a heavily-doped p-substrate. Each CCD structure (whether the photosite, transfer gate, or shift register) collects proton-induced electrons (minority carriers) in its depletion volume defined by the element area times the depletion depth. A depletion depth of 7 μm was assumed. For proton-induced charge generated in the depletion volume itself, charge is stored without danger of recombination. Carriers produced in the field-free diffusion region below the depletion volume can diffuse to the depletion/diffusion edge boundary and be collected, but since diffusion is a random process these carriers can be collected in any number of adjacent CCD elements.

The proton responses from the bilinear CCD's have unique signatures which reflect their imaging photosite, transfer gate and multiplexer shift register layout and gate structure combined with the details of a proton's trajectory as it passes through these structures. The architecture consists of a photosite strip down the center of the device with transfer gates and shift registers flanking the photosites on both sides. An optical line image is formed by integrating the optical signal in the photosites. This is followed by the parallel transfer of the signal charge (via the transfer gates) to the shift registers: the even photosite pixels are routed to the shift register on the right side of the photosite strip and the odd pixels are routed to the left shift register. Note that an integral aluminum light shield covers the CCD everywhere except over the photosite strip. The light shield is transparent to protons at the energies used in the experiment. A line of video is formed by multiplexing the odd and even pixels (this is done off-chip) together. Clearly protons which strike either the right or the left shift register will stimulate responses in either even or odd pixels in the output video. The effects of other more complicated proton trajectories are discussed below. In the next section we discuss the comparison of the experimentally-observed events with theoretical predictions based on a previously-developed [2] proton-induced CCD transient response simulation which was adapted to account for the bilinear CCD architecture.

COMPARISON OF MODELED AND EXPERIMENTAL PROTON EVENTS

For proton-induced events, we assume that the incident proton continues in a straight-line trajectory through the charge collection volume of the CCD. The protons are so energetic (> 18 MeV) that their range can be assumed to be much greater than the longest trajectory through the depletion and diffusion volumes of the device. It is also reasonable to assume that the proton EHP generation rate (or linear energy transfer, LET) is constant over the trajectory length for these high energies. An exception to this occurred when data were recorded with the beam energy reduced to 8 MeV by an aluminum degrader. The device was oriented with respect to the beam so that protons traveled parallel to the shift register and were incident at a large angle resulting in a few protons traveling long distances within the shift register depletion volume. The signature of these events approximated a Bragg curve, the signal increasing as the proton loses energy rapidly near its end of range. The LET was computed for silicon and the given proton energies using TRIM90 [5].

Figure 3 shows (lower left side) the experimental CCD composite video response for an 18 MeV proton as it traverses the epitaxial CCD with an angle-of-incidence of 30 degrees and an azimuth of 90 degrees. The simulated response is also shown (upper left side) using a theoretical model of the charge collection process. Here the incident proton entered the CCD hitting near the right shift register traveling perpendicular and away from the photosite and left shift register with a downward trajectory. The epitaxial device shows little adjacent pixel response due to charge from the epitaxial diffusion volume, which is greatly reduced compared to the bulk device diffusion volume.

The lower right side of figure 3 shows the video response of the bulk CCD to an 18 MeV proton event entering the right shift register at an angle-of-incidence of 70 degrees and an azimuth of 60 degrees, moving in the direction toward the left shift register. Here the contribution of charge from the large diffusion volume of the bulk CCD is obvious. The proton enters the right shift register with a substantial downward trajectory, and hence passes under the left shift at a considerable depth below it in the diffusion volume. The smooth and smaller left shift register response (odd pixels) is due to diffusion whereas the larger right shift register response (even pixels) is due to both depletion and diffusion contributions. The peaks of the right and left shift register responses are shifted in the composite video due to the 60 crossing azimuth of the proton trajectory. These are but two examples of a myriad of individual events representing the different incidence and azimuth angles and the 18 and 50 MeV proton energies.

The result of the simulation applied to each of the two specific cases in Figure 3 shows the success of this model in predicting the details of the CCD proton response events. This success was observed for a large variety of proton-induced events taken with different parametric conditions. Note that the model used in the simulation requires inputs of the device architecture, topology, layer thicknesses, and the proton kinematics. The proton energy and incidence/azimuth angles are known from experiment. However, the specific entry point of a proton on the CCD surface is clearly unknown a priori. The procedure used was to systematically vary the entry point in the simulation for a given event until the best match of the data and simulation were obtained. This, while tedious, proved to be quite successful.

SPACE BORNE SENSORS PROTON SIMULATION

Given the experimental validation of the proton-response simulation for both area [2] and linear CCD's, this simulation was enhanced and then used in conjunction with several other simulation/analysis codes to predict in detail, the expected proton response characteristics of a space-based optical sensor during conditions known proton irradiation conditions.

Figure 4 shows a block diagram that describes the main elements of the overall sensor level simulation. The proton environment external to the spacecraft is estimated using the AP-8 trapped proton and CREME solar event proton models incorporated into the software program Space Radiation available from Severn Communications Corporation. The software computes the proton energy spectrum (protons/MeV/cm^2/sr/s) as a function of solar epoch and satellite orbit.

The proton environment at the detector is computed from the external environment through a transport calculation available within Space Radiation for a shielding mass distribution approximated as spherical shell segments surrounding a representative focal plane array, the center point of which is used as the origin of the spherical mass distribution coordinate frame. Each major shielding component is represented on this coordinate sphere by a figure simplified in outline but having the same solid angle subtense and angular direction relative to the array location at the coordinate center. The proton environment is the superposition of the environments computed for each spherical shell segment.

The event generator interprets the user specified, local proton environment energy spectrum and makes random selections of event energies with probability conforming accordingly. Impact coordinates (x,y) are chosen randomly assuming a uniform distribution over a surface equal to the active area of the detector being modeled. For anisotropic proton trajectories, the user can specify a mean angle-of-incidence with respect to the normal of the device surface and the standard deviation of angles about that mean. Particle azimuths are uniformly distributed between 0^0 and 360^0. Event time is determined by randomly selecting the time interval between events according to an exponential probability density function which is consistent with a Poisson process. The output of the proton event generator consists of event by event values for proton impact coordinates (x,y), trajectory (Θ,Φ), energy, LET, and event time.

The CCD focal plane response model computes the responses to events created by the random event generator according to the architecture of the relevant focal plane device by calculating the intersection chord lengths of the event trajectory in each pixel as the particle propagates from the surface of the device through the discrete elements representing the depletion layer. The individual chord lengths are multiplied by the LET to determine the charge collected by each pixel. In the following segment of the trajectory (the diffusion layer), the charge is generated in a line segment extending to the substrate. This portion of the charge can diffuse and is collected by all nearby pixels in the region above. The result of the simulation is an array of numbers representing the total radiation-induced charge collected by the sensor.

The simulated detector responses can be studied statistically for their effect on system performance, they can be used to stimulate radiation event rejection algorithms, or they can be used in an imaging model to overlay simulated images in order to visualize their degradation of image quality.

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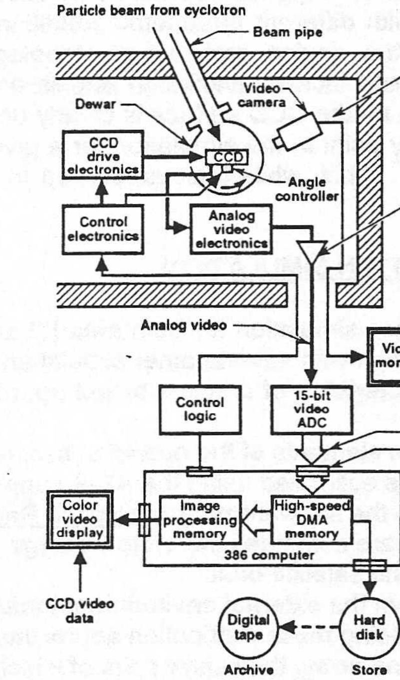
CCD Transient Proton-Induced Response Setup

Figure 1.



Block diagram of experimental arrangement used for CCD data collection during charged-particle irradiation

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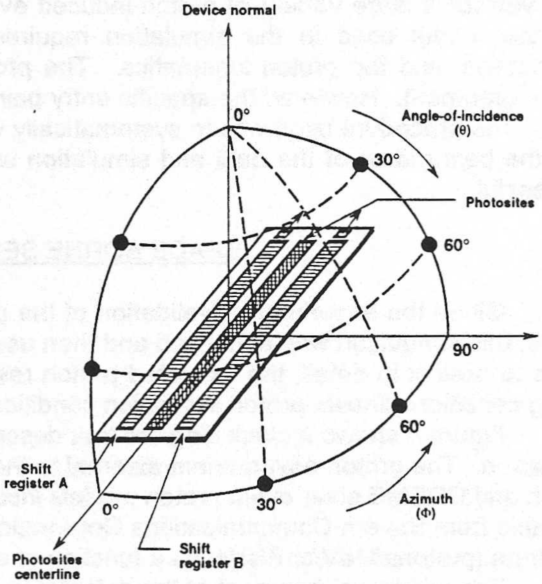
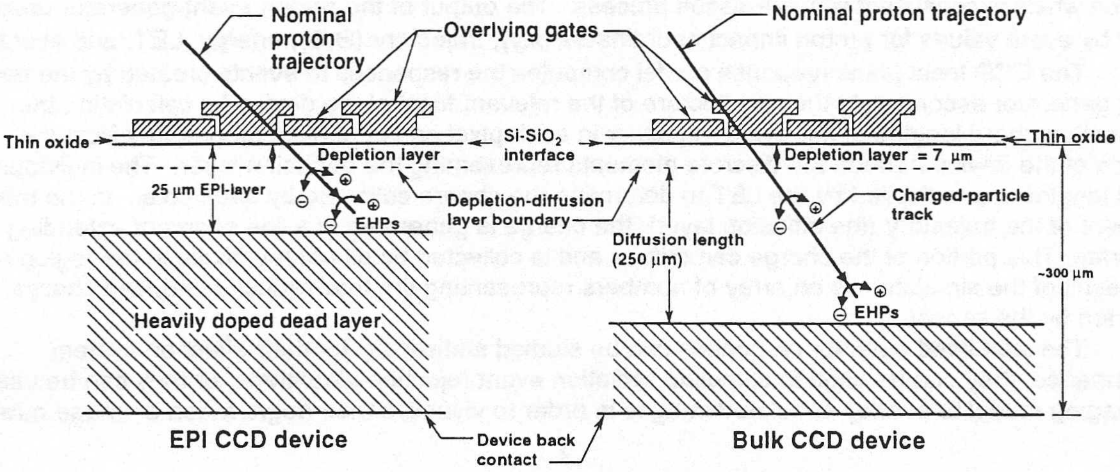


Definition of charged-particle geometry used for CCD irradiation

Bilinear CCD Architecture

Figure 2.

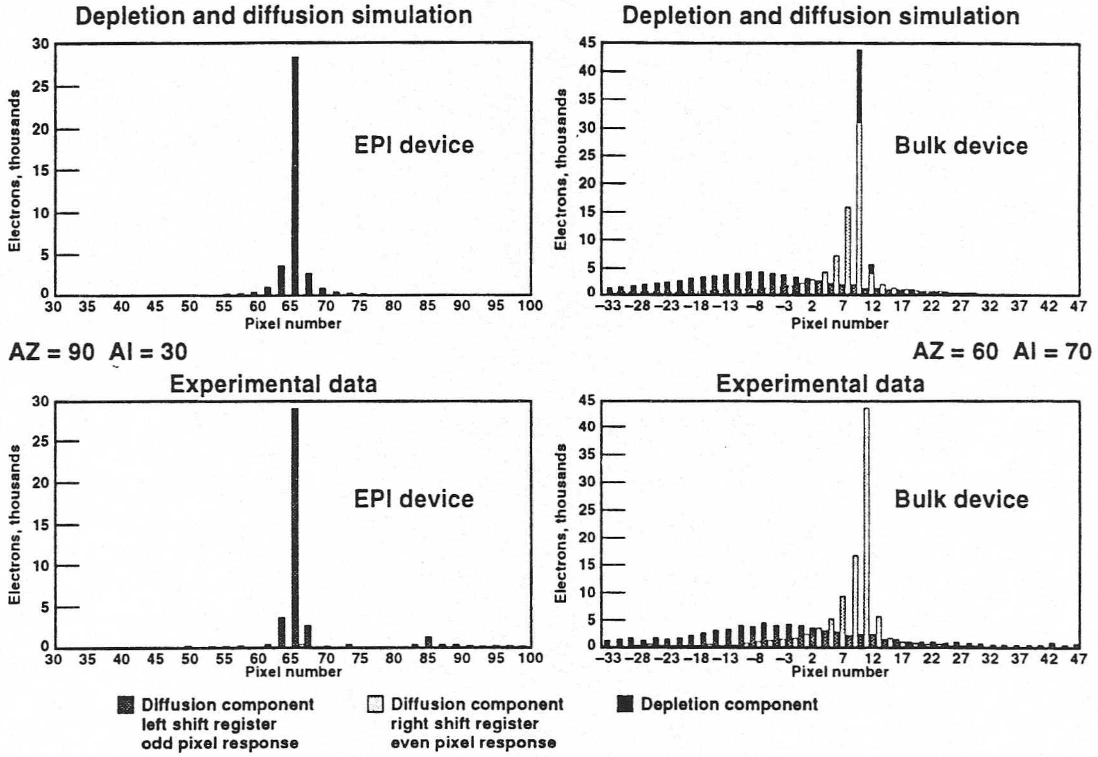


- EHP = Electron-hole pairs
- Layer thicknesses not to scale

Single 18 MeV Proton Events: Bilinear CCD

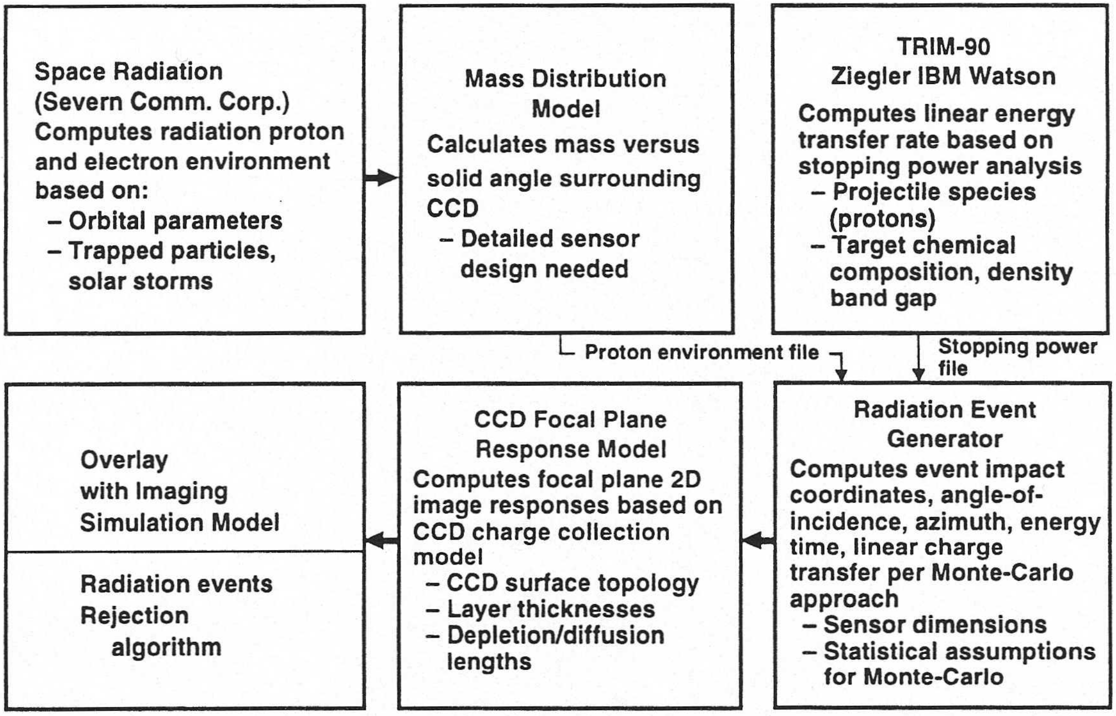
Experimental versus Modeled Responses

Figure 3.



Proton Imaging Simulation

Figure 4.



Space Radiation
(Severn Comm. Corp.)
Computes radiation proton and electron environment based on:
- Orbital parameters
- Trapped particles, solar storms

Mass Distribution Model
Calculates mass versus solid angle surrounding CCD
- Detailed sensor design needed

TRIM-90
Ziegler IBM Watson
Computes linear energy transfer rate based on stopping power analysis
- Projectile species (protons)
- Target chemical composition, density band gap

Radiation Event Generator
Computes event impact coordinates, angle-of-incidence, azimuth, energy time, linear charge transfer per Monte-Carlo approach
- Sensor dimensions
- Statistical assumptions for Monte-Carlo

CCD Focal Plane Response Model
Computes focal plane 2D image responses based on CCD charge collection model
- CCD surface topology
- Layer thicknesses
- Depletion/diffusion lengths

Overlay with Imaging Simulation Model

Radiation events Rejection algorithm