Solar-B
**EIS**
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EUV
Imaging
Spectrometer

# Radiation Shielding Considerations for the Solar-B EIS CCDs - initial discussion

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| Title | Radiation Shielding Considerations for the Solar-B EIS CCDs - initial discussion |
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## Introduction

In Low Earth Orbit (LEO) Solar-B EIS will be subject to a radiation dose, mainly electrons and protons, and shielding will be necessary to reduce the overall radiation flux. The amount of shielding that is required should ideally be at a minimum (to minimise the mass). Consequently it is important to try and identify where shielding is important, and any radiation-induced problems which may require an increase in shielding density above some nominal figure.

Radiation effects may affect the Solar-B CCDs in a number of ways:

- ionisation effects will cause an increase in dark current and flat band voltage shifts;
- radiation induced displacements may lead to an increase in the CTI per pixel and dark current non-uniformity;
- ionising radiation will cause spurious counts within the CCD - these counts can be considered "transient" as they will be removed each time the CCD is read out. Nevertheless, they will affect the quality of individual images.

The increase in dark current, dark current non-uniformity and CTI may be reduced by appropriate temperature control of the CCD. The appropriate temperature which should be selected to minimise these effects is discussed in discussion note two. However, an appropriate temperature may not be achievable to reduce these effects sufficiently to ensure that all the Solar-B scientific goals can be met and additional shielding will be required to reduce the overall dose to acceptable levels.

In addition, there are several radiation induced effects which will not be improved through cooling:

- flat band voltage shifts - these can be removed by allowing the CCD operating voltages to be changed in flight;
- transient radiation - induced "spikes" on the image - these may require sufficient shielding to minimise the instantaneous radiation flux if the effects cannot be minimised with software.

The aim of this design note is to identify where shielding can be used to minimise the effects of radiation. It firstly discusses the actual radiation dose likely to be experienced by Solar-B (for a nominal 3mm of Al shielding). Given the dose rates identified, the likely consequences for the CCDs are discussed. Finally, the effect of different shielding configurations on the overall dose, and hence the likely radiation induced effects, are considered.

## The Solar-B radiation dose

The Solar-B orbit is a LEO at 600km and 97.79°. At this height, the main contributions to the overall radiation flux will be from electrons and trapped protons from within the Earth's magnetic belts. Proton dose is highly anti-correlated with Solar activity, possibly with a one year lag.

Two models  have been used for calculating the overall dose:

1. *CREME* - this is used for single event upset prediction and calculates the differential and integral energy and LET spectra of trapped particles incident on a spacecraft in Earth orbit.
2. *JPL 91* - a solar statistical model

A number of studies have been performed to calculate the total dose likely to be encountered by Solar-B during the mission lifetime. I do not have the detailed results from these studies, but do have a summary of the results.

<u>MHUI analysis</u>

A shielding of 3 mm Al was assumed and a total mission lifetime of 5 years from launch in 2004. The following particle flux was calculated:

| | |
|---|---|
| trapped proton | 137 rad/year |
| trapped electron | 935 rad/year |
| galatic cosmic ray | 352 rad/year |
| flare - normal | 727 rad/year |
| flare - 90% worst | 4390 rad/year |

The total dose for five years was assumed for the contribution of the trapped protons, the trapped electrons and the galactic cosmic rays, plus either the normal flare contribution only, or the 90% worst flare contribution only.

| | |
|---|---|
| Total dose assuming only the normal flare contribution | 9010 rads |
| Total dose assuming a 90% worst flare case | 27300 rads |

<u>EEV</u>

The radiation dose was also calculated by EEV (pers comm) using JPL91.

For 3 mm Al shielding using CREME a dose of 1.8krad/year

Using JPL91 with 3mm Al shielding gives a total dose of around 1.4krad/year.

The non-ionising spectra was calculated to be around 6E9 protons/cm$^2$ for 10 MeV protons using JPL91, and using CREME it was calculated to be around 1E10 protons/cm$^2$.

The overall dose will not be received uniformly over the orbit, but will be highly concentrated in the South Atlantic Anomaly (SAA) and the Polar Cusps. An example of how much radiation will be encountered through passage of the SAA can be seen by examining results for the Defence Meteorological Satellite Programme (www.ngdc.noaa.gov). DMSP flew from 1983-1987 with a LEO orbit of 840 km @ 99°. On board dosimeters measure the radiation dose from protons and electrons behind 4 hemispherical domes of aluminium. The most significant dose comes from high energy protons in the South Atlantic Anomaly (SAA). For example, the SAA was encountered for 10 out of the 16 orbits and during passes through the SAA, the average count rate for protons >75MeV increased from around 9 counts/s to up to 1000 counts/s (about 6 occasions) and 100 counts/s (four occasions). Each encounter with the SAA takes around 20 minutes. Thus, in that case, in a 24 hour orbit over 91% of the protons encountered over 75MeV occur during the passages through the SAA.

For a 600km LEO (i.e Solar-B) the dose rates in rads Si/s will be about half that as for a height of 800km.

Both calculations performed above give a total dose of around 1.4-1.8 krad a year. The overall proton spectrum is important, and the EEV calculation gives a value of about 6 E9 protons/cm$^2$. The dose rate likely to be experienced in the Solar-B orbit will not be constant, and the majority of the dose will accrue during passages of the SAA.

# The effects of ionising radiation on CCD performance

### Dark current

Ioninsing radiation will lead to an increase over time of the dark current of the device. This increase is reasonably well characterised and an increase of 100 pA/cm$^2$/krad(Si) is assumed for the EEV 42-10 devices (EEV presentation). Minimisation of this problem by appropriate temperature control of the CCD is discussed in discussion note two, and a CCD operating temperature of between -70 to -80 °C should be sufficient to minimise the dark current increase to acceptable levels - assuming a minimum shielding of 3 mm Al is used (i.e the radiation doses used have been calculated assuming 3 mm Al).

### Flat band voltage shifts

Flat band voltage shifts should be about 50mV - 120mV /krad(Si) (EEV presentation) and voltage shifts of this magnitude could be accommodated by allowing the CCD operating values to be updated in flight.

### Transient effects

"Transient" radiation effects can be caused by either ionising or non-ionising radiation. However, their effects will be discussed in this section. Protons of MeV energies encountering a CCD will deposit between 1-30 keV of energy per micron due to electron/hole pair creation (30 keV corresponds to the creation of about 8000 e/h pairs).

Transient effects are seen during readout of an image, and consist of spurious charge generated in a pixel due to electron/hole generation by the ionising radiation. A number of pixels may be affected, or all the charge may be deposited in a single pixel. If the first case, a spurious "streak" will be seen across a number of pixels, and if the latter, the bright pixels may appear as "snow" in the image. The number of pixels affected by a single radiation event will vary depending on the particle’s geometry, energy and the device structure (for example, more energy will be deposited in devices with larger depletion depths), but will typically be more than one.

## "Typical" transient event rate

The problem of cosmic ray hits for WFPC(2) on board HST in discussed in the WFPC handbook and in Holtzman et al. (1995) where a cosmic ray "hit" rate of about 1.8 events/chip/s were observed. Each event affects an average of 6.7 pixels, for about 12 affected pixels/chip/second. For a 2000s exposure, this results in about 24,000 affected pixels, or 3.8% of all pixels. As cosmic rays are expected to be randomly placed, a pair of such exposures would have about 900 pixels affected in both exposures; cosmic ray correction is impossible for such pixels. For a pair of 1000s exposures, about 220 pixels will be affected in both frames. Over time, a difference in cosmic ray events of no more than two was found over a one month period.

Other data on transient events comes from measurements on Single Event Upsets (SEU) with UoSat 2, which is in polar orbit @ 700km. (Daly et al. 1991) SEUs arise in microelectronics due to the effects of radiation and can be considered similar to the effects on a CCD image as there effects are also transient. With UoSat the vast majority of SEUs occurred in the SAA, with the majority of the remaining events occurring in the Polar regions. The total number of cosmic ray events was measured for a 30 day period in 1991. Peak counts of 100000 events were detected in 30 days at the maximum of the SAA, and around this area peak counts of 5000-10000 events were detected. From September 1988 to May 1992, UoSAT-2 monitored almost 9000 Single Event Upsets (SEU), and the majority of these (75%) occurred in the South Atlantic Anomaly (SAA) region. Events at higher latitudes are attributed to galactic cosmic rays and solar proton events (source: www.ee.surrey.ac.uk/Research/CSER/UOSAT/science/science_uo2_seu.html).

Using the calculations of Hopkinson (1996), an estimate of the number of events that could be expected for Solar-B can be made given the overall proton flux of 6E9 protons/cm$^2$ over a five year period. If we assume that 92% or so of this dose is accrued during passage of the SAA (using data above), then this corresponds to about 3 E6 per day. During a day about 200 minutes are spent in the SAA, this corresponds to an event rate of about 252 events/cm$^2$/s. Thus over a 42-10 CCD (512x2048, 13.5µm square pixels) 1 in every 2000 pixels would be effected each second (481 events/s) - this number is substantially larger than that found on Hubble above although Janesick et al. 1989 estimate a proton flux of 2000 protons/cm$^2$/s whilst passing through the SAA - assuming each proton caused a transient image event, then this would lead to over 1 in every 274 pixels effected each second (3800 pixels/s).

## Maximum transient event rates

An idea of the effect of larger proton events can be found from EIT data (which is in an L1 orbit). The proton event of 6 November 1997 caused a very large number of transient events detected by the CCD. At the peak of the event, up to 2% of the CCD overall area was affected. However, within 24 hours of the event this figure had dropped to 0.5% (source: Lockheed Martin Solar and Astrophysics laboratory: http://www.lmsal.com//eit/eit_proton_19971106.html). Analysis of this work also showed that the number of particle hits in an image were best correlated with the numbers of protons observed from 50-100MeV and >100MeV.

This figure is very high, and would certainly severely restrict any measurements which could be done during this proton event. However, the frequency of such events is rare.

## Mitigation of the effects of transient events using software

As well as shielding the CCD to minimise the transient events, the effect of these transient events can be minimised with appropriate software. A number of routines exist within the SolarSoft software, and are being used on missions such as TRACE (for example). It is recommended that this software be investigated to see how effective such routines may be used on images with the transient event rates discussed in this note.

# The effect on non-ionising radiation damage on CCDs

Non ionising radiation damage occurs when protons create displacement damage in the lattice, a certain proportion of this damage will lead to Charge Transfer Inefficiency (CTI) and "hot" or "flickering" pixels. CTI is discussed extensively in discussion note 2, and it is thought that CTI effects could be sufficient to cause to a worst case loss of charge of 13% at -50°C (although these calculations provide only a ball park figure) and the reader is directed to discussion note two for a detailed discussion of CTI.

A second effect will be the creation of hot and flickering pixels, which will increase the dark signal non-uniformity. Again the increase in hot pixels is directly proportional to incident radiation flux and to the Non Ionising Energy Loss of the incident radiation. Unfortunately, it is beyond the scope of this discussion note to model the variation on a pixel to pixels basis. As with CTI, the most effective approach will be to measure the effect of radiation dose on hot pixel distribution with a representative EEV 42-10 device. It should be noted that much of the hot pixel damage can be annealed out over reasonable (~20 hours or so) bakeouts at room temperature. For example, on HST, it has been found that up to 80% of the hot pixels can be annealed out after a 12 hour anneal at room temperature.

A third effect is known as "Random Telegraph Signals" (RTS). RTS occurs as a result of bulk displacement damage, and consists of the dark currrent associated with a particular pixel switching between two noise states. The duration during which each pixel remains in each state will have an associated time constant. However, at low temperatures (-30°C) the duration of the time constant is several days, and consequently RTS would not be expected to contribute the variation in the dark current.

# Shielding

In the above discussion, a baseline shielding of 3mm Aluminium has been assumed (as these figures were used for the dose calculations). The purpose of this section is to try and establish the extent to which the radiation induced effects could be mitigated by the use of additional shielding. It is assumed that, as weight is an important constraint, large depths of shielding will not be possible. The greatest benefit from shielding will come from the first few mms as this will greatly decrease the lower energy protons (which are the most damaging). Additional shielding continues to decrease the damage, but the per unit thickness the benefit diminishes as average proton energy becomes larger as the average proton energy increases with increase depths of shielding.

It is intended that this document will be upgraded as more information is available leading to the eventual decision on radiation shielding values for Solar-B EIS. Consequently, in this initial version, a very basic estimation of the potential effects of shielding is presented from examination of the open literature. Several dose estimation programs (such as CREME96 and the ESA SPENVIS programs) are currently being evaluated and updated versions of this note may include more detailed shielding calculations using those tools (see below).

## Effect of shielding on the proton fluence

The effect of shielding on the overall dose has been discussed in a number of papers. For example, Acton and Morrison (1991) calculate the effect on the 3 year proton fluence for Yohkoh (which had a 31° inclination @ 600 km). The presence of 10mm of Al (thought to be the effective shielding provided by the spacecraft and other instruments) heavily attenuated the low energy (<5 MeV) protons by a factor of between 103 and 102 compared to the proton flux with no shielding. At proton energies of 10 MeV, the proton flux was reduced by about a factor of 10.

## Predictions of the effect of proton fluence

Dale and Marshall (1991) describe how the radiation response of many devices can be predicted based on calculations of the amount of damage energy imparted. The NIEL can be calculated based on differential collisions cross-sections and interaction kinematics. Measurements on a CCD can be used to establish the change in CTI with proton fluence (which should be linear over the energy range is question). Measurements were made on a Ford CCD with 1024x1024 pixels operating at -50°C and at 50 kHz. The prediction was made in terms of change in CTI for the CCD using the measured damage factors for the CCD and the orbit parameters of the Hubble Space Telescope (593 km @28°). Table one below shows how the change is CTI was effected by an increase in Al shielding:

| Density | equivalent depth | change in CTI | over 3 years |
|---|---|---|---|
| 10 $g/cm^2$ Al | 40 mm | .00000013 | .00014 |
| 4 $g/cm^2$ | 15 mm | .00000025 | .00025 |
| 0.1 $g/cm^2$ | 0.4 mm | .0000007 | .00076 |

*Table one: the change in CTI with increasing radiation depth calculated for a Ford CCD*

These figures are converted into charge loss in table two below.

| density | 1000 trans | 2000 trans | change |
|---|---|---|---|
| 10 $g/cm^2$ | 87% | 75% | 3.5 |
| 4 $g/cm^2$ | 78% | 60% | 2.9 |
| .1 $g/cm^2$ | 47% | 21% | - |

*Table two: the CTI figures in table one converted into charge loss*

Clearly, an increase in shielding from 0.4mm to 15mm has a proportionally much greater effect than the increase from 15mm to 40mm.

## Predictions for Solar-B

An approximate estimation of the CTI that could be expected at the end of the mission (i.e after a 7krad dose) has been accumulated was calculated in discussion note 2, based on the figures presented below in table three. As can be seen, there is a linear relationship between the total proton flux (converted to the equivalent flux @ 10 MeV) and the displacement damage in Silicon.

| Trap concentration | Total proton flux (@10 MeV equivalent) | Total dose | Source |
|---|---|---|---|
| 5.2 E10 traps/$cm^2$ | 6 E 9 protons/$cm^2$ | - | Hardy et al (1998) |
| 1.3 E10 traps/$cm^2$ | 1.5 E 9 protons/$cm^2$ | - | Hardy et al (1998) |
| | 1.79 E 9 protons/$cm^2$ | 1 krad | Hopkinson (1995) |
| | 1 E 10 protons/$cm^2$ | 7 krad | Hopkinson (1995) |

*Table three: the approximate relationship between proton flux, trap concentration and dose*

Using the calculated CREME flux of 1E10 protons/$cm^2$ (for a 7krad total dose), a displacement concentration of 8.4E10 displacments/$cm^2$ was used, which gave a worst case CTI figure of around 0.00125 @ -50°C. This corresponds to a charge loss of around 23% for 220 pixel transfers. It should be remembered that this dose rate assumes 3mm of Al shielding.

An approximate estimate on the change in both the CTI and the transient event rate due to increased shielding can therefore be made be estimating how strongly the proton flux is reduced for a given shielding dose. Owens et al. (1997) empirically derive a formula for the decrease in trapped proton fluence (@10 MeV equivalence) for various Al shielding depths. Using these figures for a first approximation, the decrease in CTI with additional shielding can be approximated as follows (taking CTI @ 3mm Al as unit CTI - 6.6e-4 (13% charge loss) as worst case).

| shielding depth of Al | Reduction in CTI | % charge loss | worst case transient event rate (through the SAA) |
|---|---|---|---|
| 3 mm | 1 | 23 | 480 events/s |
| 4 mm | .66 | 15 | 316 events/s |
| 5 mm | .48 | 11 | 230 events/s |
| 6mm | .37 | 9 | 177 events/s |
| 10 mm | 0.18 | 2.3 | 86 events/s |

In contrast however, the reduction in transient events for protons is discussed in Dale and Marshall (1991) for the decrease in primary trapped proton flux for the LDEF mission (450 km, 28 °) at Solar minimum. Approximate flux values, and the equivalent transient event rate, are given below

| Depth Al | Flux | change | event rate |
|---|---|---|---|
| 0 | 2E9 | - | 136 |
| 10 | 1.5e9 | 0.75 | 102 |
| 20 | 1e9 | 1 | 68 |
| 40 | 6e8 | 3.3 | 41 |
| 200 | 6e7 | 33 | 4 |

This figures are much more conservative than calculated by Owens (1997) and are in closer agreement with the figures presented in Dale et al. (1993) which show a decrease in displacement damage of about 25% when increasing Aluminium shielding thickness from 3 mm to 6 mm (compared to a 66 % decrease in CTI in Owens).

### Shielding Material

For equivalent thicknesses of material, a higher atomic number material will be more efficient, although Aluminium is a more effective shield in terms of stopping power per unit mass. In addition, as the atomic number increases, then the number of secondary electrons produced in the shielding material also increases. Consequently, the thickness which can be tolerated from a high Z material is quite small. Figures in Dale et al. (1993) showing the variation in displacement damage with shield thickness of both Aluminium and Tantalum show that AL is superior in terms of unit mass, although Tantalum is superior in terms of unit thickness.

## Conclusions and future work required

- the baseline shielding assumed for Solar-B is 3mm Al. Such a depth of shielding would produce a dose rate of between 1.4-1.8 krad per year;
- such an overall dose rate would probably lead to a transient event rate which could be as high as 480 pixels/s. The CTI figure has been estimated to be 6.6E-4 per pixel (at -50°C, for 1000 electrons). However, it should be emphasised that, firstly: these calculations are very simplistic, and should be used to provide a ball park figure only and, secondly; CTI is a very complex issue and can be improved by a range of techniques (described in discussion note 2) which could be used to reduce the CTI significantly without resort to further shielding;

- the effects of transient event in an event can also be mitigated by the use of appropriate software, and **it is recommended that some studies be made to see how effective this software is**;
- as the majority of the proton flux occurs during passage of the SAA then, as a worst case, the CCD would have to be switched off (or the data disregarded) whilst the CCD is within that area;
- the baseline shielding figure could be partially achieved by screening from the satellite itself, and from other areas of the structure such as the electronics box, etc. Thus, if a baseline shielding of 3mm could be adopted around the CCD itself, the radiation induced effects would be less than described above;
- if additional shielding is required, then an estimation of the effect of this shielding can be made. Doubling of the shield thickness to 6mm could reduce both the CTI and the transient event rate by a factor of 3. However, these results should be used to provide a ball park estimate only;
- at this stage, it is important to establish a good methodology for determining the optimum shielding thickness. Detailed shielding calculations will be very difficult to perform, and **it is recommended that the shielding methodology adopted in recent camera designs is examined in detail. It may then be necessary to use detailed environment models (such as those identified above) to calculate the effect of shielding on the total dose and on the proton flux.**

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