Proceedings of RADECS 2008, 10th-12th September 2008, Jyväskylä, Finland.

Radiation monitoring in Medium Earth Orbit over the solar minimum period

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***Abstract*— This paper presents analysis of radiation measurements taken by the Merlin monitor on Giove-A, which is located in a 23,300 km circular, 56° inclination medium Earth orbit (MEO). The period covered by the data is from December 2005 to May 2008 which includes the solar minimum in March 2008 (to be confirmed). The internal charging currents measured at three shielding depths are presented and compared to both NASA safety guidelines and DICTAT/FLUMIC model predictions. Also, the net accumulation of total ionizing dose at two shielding depths is reviewed in terms of dose per day which is of interest for enhanced low dose rate sensitivity (ELDRS) applications. Finally, it is observed that a substantial total ionizing dose increment which followed a solar energetic particle event in December 2006 was not caused by protons but was entirely due to the electron belt enhancement following passage of the CME.**

***Index Terms*—Internal Charging, Energetic Electron Belts, Medium Earth Orbit.**

I. Introduction

THE European Space Agency (ESA) has launched a test satellite, Giove-A (built by SSTL), into a 23,300 km circular, 56 degree inclination orbit in advance of deployment of the Galileo constellation. One key objective for Giove-A is to measure the radiation environment encountered in medium Earth orbit (MEO) and data from the two monitors on-board, have already been reported [1], [2]. This paper provides further interpretation of the data obtained from the Merlin instrument over the period from December 2005 to May 2008 which includes solar minimum in March 2008 (exact date is yet to be confirmed [3]). Merlin, which is mounted on the outside wall of Giove-A under a thermal blanket, includes measurements of internal charging currents (SURF detector), total ionizing dose (RadFETs), energetic proton flux (diode telescope) and ion linear energy transfer spectrum (also a telescope). In the Galileo MEO orbit the hazards of special concern are internal charging and ionizing dose which are anticipated to be worse than, for example, in geostationary orbit. In this paper the measurement of internal charging current, total ionizing dose and proton flux are discussed in terms of their engineering significance.

Manuscript received September 12th, 2008. This work was supported in part by the European Space Agency, Surrey Satellite Technology Limited and the QinetiQ Fellowship scheme.

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II. Detectors

Fig. 1 shows the shielding configuration of the SURF and RadFET detectors. SURF [1], [4] comprises three shielded aluminium collector plates mounted in a stack as shown in Fig. 1. Note that the bottom plate is 1mm thick compared to the other two which are 0.5mm thick. Each of the collector plates is connected to an electrometer to measure deposited current (i.e internal charging rate). SURF calibration is achieved through both irradiation and electrical stimulation as described in [1].

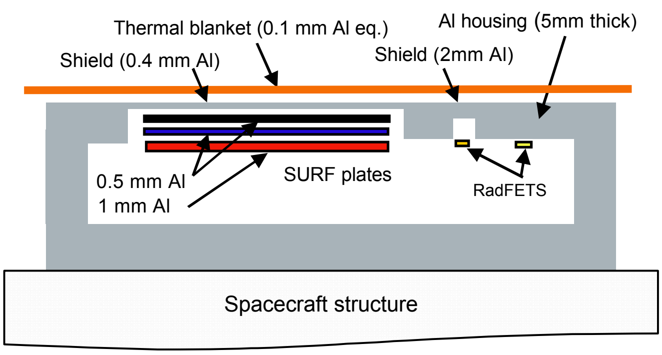


Fig. 1. Illustration of the general shielding configuration of the SURF plates and RadFETs in Merlin-Giove-A.

Total ionizing dose is measured using two RadFETs which are located just underneath the Merlin lid at differing shielding depths. The devices used are sourced from Tyndall and are type ESAPMOS04 (400nm oxide thickness). The shielding seen by one of the devices is simply the Merlin box wall thickness i.e. 5mm Al. For the other device the lid is thinned down locally to 2mm thickness in the form of a blind hole of diameter 3mm just above the RadFET. Note however that the RadFET transistors come with a Kovar lid of thickness 250µm which equates to approximately a further 1mm Al-eq. of shielding in the 'upward' (as in Fig. 1) direction and the ceramic dual-in-line packages increase shielding in other directions. The RadFETs are referred to as the '3mm' and '6mm' Al-eq shielded devices even though this applies strictly only in the one direction. The RadFETs are zero-biased except during the readout which occurs every five minutes, to avoid effects due to occasional power outages. The readout bias current is chosen to minimize the temperature co-efficient of the device. Calibration curves are obtained from the supplier based on batch testing.

Protons are measured using a particle telescope operating in co-incidence mode – the detector is the same form as flown in CREDO [5]. The diode detectors are shielded to exclude protons of energy less then 40MeV (the upper limit on proton detection is around 100MeV).

III. Results And Discussion

A. Summary of Data Recorded

Fig. 2 shows a convenient summary of the data obtained from December 2005 to May 2008 which shows the daily average charging current in the bottom SURF plate, the total ionizing dose recorded by each RadFET and the >40 MeV proton flux (outside of the belts at L >7).

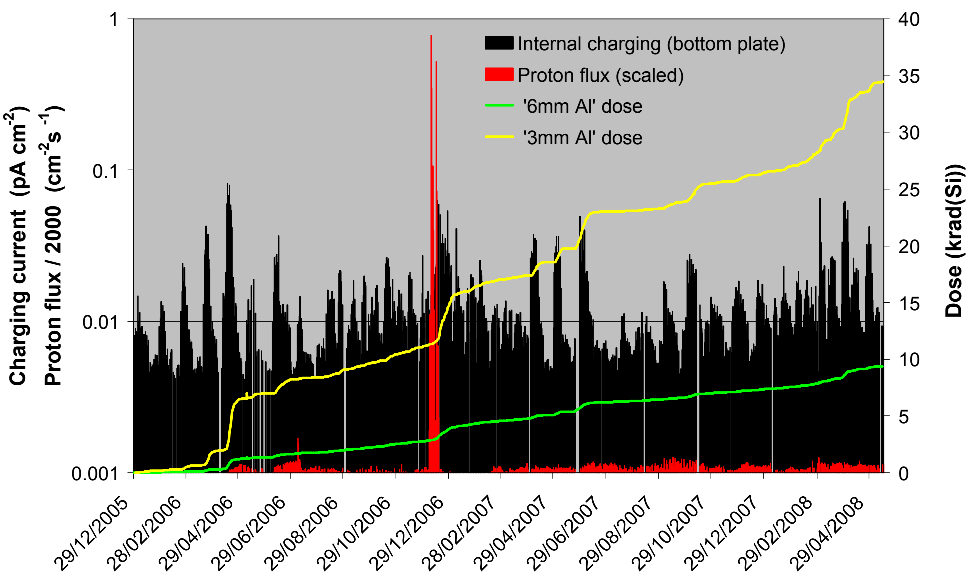


Fig. 2 Summary plot of daily average charging current in the bottom SURF plate, total dose readings from the RadFETs and the >40 MeV proton flux (outside of the belts) for the period from December 2005 to May 2008. Dose increments obviously correlate strongly with the charging (electron enhancement) events. Just two significant solar particle events occurred over this period.

As expected, close to solar minimum, energetic electron enhancements are common [6], [7], and these are reflected in the charging current data. The dose increments recorded by the RadFETs are generally co-incident with the charging events showing that they are both due to electron enhancement events. Just two solar particle events (SPEs) were recorded, one on 6th December 2006 and the other on the 13th of the same month. It can be seen from Fig. 2 that around the time of the SPEs there was both a substantial increase in dose and a strong electron enhancement. It might be assumed that protons would be a significant contributor to the dose increment, however it will be seen later that the proton dose was in fact negligible and the electron enhancement was almost solely responsible.

B. Internal Charging Measurements

Risk of electrostatic discharge only arises in practice if the flux of penetrating electrons persists for a substantial period, usually at least a day, due to the characteristically long timescale of the internal charging problem [8], [9]. Short term transients are not generally significant except in so far as they contribute to the daily mean. Hence we are concerned here with reporting daily average charging currents. Existing NASA guidance [10] is that internal charging problems are essentially absent where average deposited[1] currents (over at least 10 hours) are less than 0.1 pA cm^{-2}. For design purposes it is necessary to calculate such currents in advance which requires knowledge of the shielding present as well as the worst case electron spectrum for the given orbit. Unfortunately while [10] provides a defined worst case electron environment for geostationary orbit it does not propose an equivalent worst case for medium Earth orbit. Therefore the FLUMIC model [7] is often used instead. FLUMIC provides a 'reasonable worst case' 1-day internal charging spectrum for all Earth orbits. Note of course that average electron models such as AE8 [11] are unsuitable for analyses of internal charging.

To calculate the deposited currents in shielded items the DICTAT tool available via Spenvis [12], [13] can be conveniently used in conjunction with the built-in FLUMIC

[1] Note that [10] is not definitive on whether deposited or incident current should be used. We take deposited current which is physically more logical.

model (other spectra can also be used). DICTAT enables the risk of discharge to be calculated in terms of the internal electric field within a dielectric, taking account of dielectric and environment parameters e.g. dielectric thickness, conductivity, temperatures and leakage paths. On the other hand the NASA current threshold (0.1 pA cm^{-2}) approach avoids the need for detailed knowledge of materials parameters (which are rarely well characterized) and also enables items such as electrically isolated metal to be more readily analysed. Sometimes a combined approach has been used i.e. DICTAT/FLUMIC is employed to predict the charging currents which are then compared to the NASA safety threshold. In either case it is clearly of interest to compare our measurements of daily mean charging currents to the NASA 0.1 $pAcm^{-2}$ threshold and also to the DICTAT/FLUMIC 'worst case' prediction of deposited current.

The observed current in the SURF top plate is plotted in Fig. 3(a) and it is clear that the NASA safety threshold is regularly exceeded. Also plotted is the current obtained using the DICTAT2.0/FLUMIC2.0 internal charging tool: this is the version currently available via Spenvis and therefore of general interest. It is seen that the DICTAT2.0/FLUMIC2.0 model prediction for the top plate clearly displays the seasonal modulations contained within FLUMIC and also part of the solar cycle modulation.

The DICTAT2.0/FLUMIC2.0 model predicts that currents above the 0.1 $pAcm^{-2}$ threshold should be expected over most of the year. However it does indicate substantially lower currents around the winter solstice periods and these predictions are breached in both of the winter solstice periods so far observed. It is seen from Fig. 3(b) that the charging current in the bottom plate has not exceeded the 0.1 $pAcm^{-2}$ threshold since launch, although it has come close on several occasions. The same general pattern is reflected in the middle plate. However since most missions are greater than 1 year in duration it is the equinox results from DICTAT/FLUMIC which have greatest importance: these predictions have not yet been exceeded and show a satisfactory safety margin. The excursions at the solstices are therefore not in themselves a major concern: it is more pertinent to ensure that users are fully aware of the seasonal modulation.

Although not yet implemented in Spenvis, FLUMIC has been updated to version 3.0 [14] and DICTAT to version 3.5. We have previously compared the 2006 SURF data to the DICTAT3.5/FLUMIC3.0 predictions [1], finding that the seasonal modulation is less pronounced and only the bottom plate current exceeded the prediction for the 2006 winter solstice period.

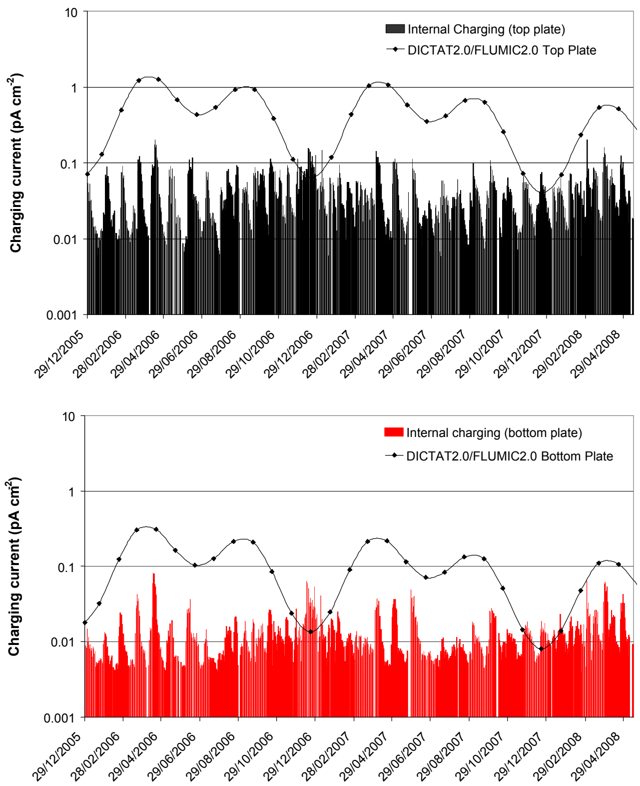


Fig. 3 Plot of daily average charging currents in (a) the top SURF plate (top panel) and (b) bottom plate over the mission to date along with the DICTAT2.0/FLUMIC 2.0'worst case' prediction. The prediction is exceeded in both the 2006 and 2007 winter solstice periods. A similar plot applies to the middle plate.

In order to summarise the increasingly large quantity of data it is convenient to plot the percentage of days for which the daily average currents in the plates exceed a given threshold as shown in Fig. 4. The top plate has exceeded the NASA 0.1 $pAcm^{-2}$ threshold on 5% of days: the other two plates have not yet exceeded this threshold on any day. Also included for interest is a similar curve based on the total current in all three plates which is equivalent to a 2mm thick Al collector plate under a 0.5mm shield which shows that, for this geometry, the NASA safety threshold has been exceeded on 20% of days. If required, extrapolations of these curves might help to establish the likelihood of even more severe conditions. However it should be remembered that the very largest enhancements (anomalously large enhancements or ALEs) are usually associated with sporadic Earth-directed CMEs [7] and, as yet, our data contains only one of these types of event [1].

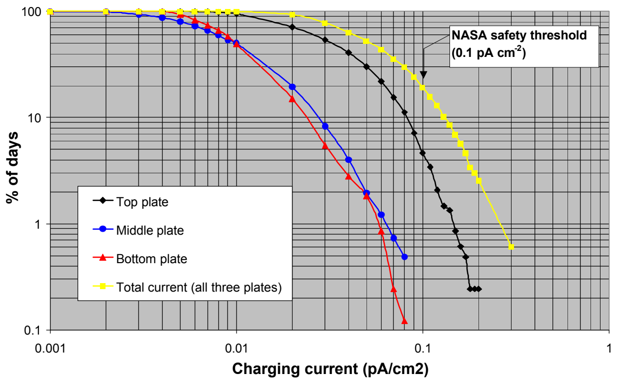


Fig. 4 Plot showing the percentage of days for which the daily average charging current in each SURF plate exceeds a given threshold.

C. *Average Electron Spectrum*

Information on the electron spectrum is available from the SURF plate currents since their 'response curves' (i.e. current generated per electron of given energy) may be calculated. We have previously found response curves and developed a simple fitting process [1] to obtain an exponential approximation of the spectrum. In that work we examined the spectra of selected enhancement events in 2006, but here we fit the average currents over the mission to date to obtain the average orbital spectrum. SURF instrument background currents (as seen outside the belts) were subtracted prior to the fitting process. The resulting differential spectrum is:

$$F(E) = 1.1 \times 10^{6} \cdot \exp(-E_0/0.53) \qquad (1)$$

where F is the orbit average flux in $cm^{-2}\ s^{-1}\ sr^{-1}\ MeV^{-1}$
E is energy in MeV.

The fitted spectrum is shown in Fig. 5 along with the orbit-average AE8 MIN [11] differential spectrum. The Merlin/SURF points plotted correspond to the energy range where SURF has its primary sensitivity. The spectrum obtained is seen to be slightly harder than the AE8 MIN prediction.

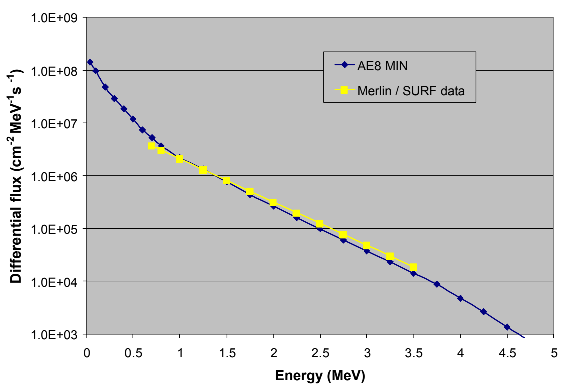


Fig. 5 Plot of the AE8 MIN differential spectrum for Giove-A orbit and the exponential electron spectrum fitted from the SURF data (averaged over the period from December 2005 to May 2008). The points plotted on the fitted line correspond to the main range of sensitivity for the three SURF plates.

D. *Total Ionising Dose and Dose Rate*

A degree of fade had become noticeable in the '3mm Al shielded' RadFET data as the mission has progressed as shown in Fig. 6 which compares 'raw' data with the 'corrected' data. Over the first 11 months no fade was seen (it would have been easily observed with the available analogue-to-digital converter resolution) but is now quite pronounced. Increased temperature could be a cause of more rapid fading but RadFET temperatures have been fairly steady in the range 25 ºC to 35 ºC with an overall mean of around 31 ºC (there was a period in March to June 2006 where temperatures were a little cooler at around 25-30 ºC). Hence temperature changes do not seem to explain the effect. Also the '6mm Al shielded' RadFET, which is an identical device with a common thermal environment, has shown negligible fade so far. Therefore the increased fade rate appears to be linked to the total dose received. For Tyndall/ESA 400nm-oxide PMOS RadFETs, room temperature fade after a 4 krad(Si) rapid dose is reported to be about 0.65% over five days [15]. However in the '3mm Al' RadFET (only) we are now seeing about 3% fade after five days (calculated from a quiet period after a rapid dose increment).

A very simple fade correction approach is used: days with readings which are lower than the previous day are clearly 'wrong' and are thus set to the same value as the previous day (i.e. zero dose increment). The 'corrected' line is however still expected to be an underestimate since, for example, a day which registers zero increase in dose (before correction) would presumably be masking an actual positive dose.

Obviously fade is highly undesirable in space dosimetry and new efforts to reduce the effect in RadFETs would be beneficial. Some types of RadFET apparently suffer a lesser degree of fade [16] than those used here.

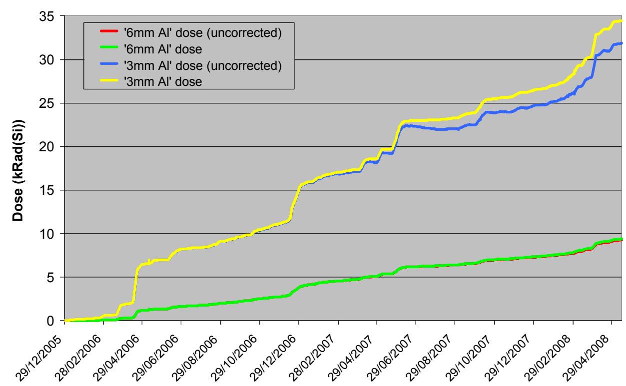
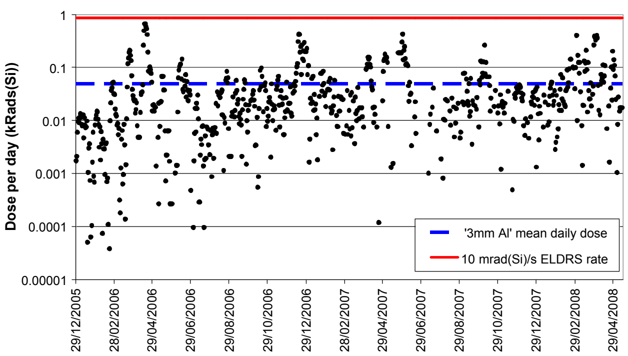


Fig. 6 Plot of the uncorrected and corrected ionizing doses measured by the two RadFETs. Significant fade is occurs only in the less shielded device in the second half of the data period. The two RadFETs are identical and operate at the same temperature.

Comparisons of the measured dose to that predicted using the AE8 environment model and sector shielding tool have previously been provided in [2] which indicated good agreement for the '3mm' RadFET but poor agreement for the '6mm' RadFET (substantially less dose was predicted than has been measured). An independent Geant4 simulation prior to the mission indicated a dose underneath the Merlin box lid (i.e. roughly the location of the '6mm' Al RadFET) of approximately 30krad(Si); however this simulation did not include the 0.25µm Kovar lid on the RadFET or the other ceramic packaging which could have a substantial effect. Further Geant4 simulations are clearly required to investigate this issue.

For some radiation effects such as enhanced low dose rate sensitivity (ELDRS), dose rate is of particular interest. Obviously the dose rate constantly changes around the orbit as the satellite passes through the radiation belts, but here we consider the dose per day as a useful practical timescale. Fig. 7(a) and Fig. 7(b) show the (corrected) dose received on each day of the mission as measured by the '3mm Al' and '6mm Al' RadFETs. The mean dose rate to date is 50.1 rad(Si)/day for the '3mm' device and 11.7 rad(Si)/day for the '6mm' device. Also shown is the 10 mrad(Si)/s (= 36 rad(Si)/hr) dose rate often used for ELDRS testing. Clearly average dose rates for these shielding configurations are much lower than the 10 mrad(Si)/hr rate, although on the peak days the rate in the '3mm' RadFET comes quite close. The 36 rad(Si)/hr rate has of course been found to represent a worst case for many devices, relative to lower dose rates, and so is thought to provide a conservative test [17].



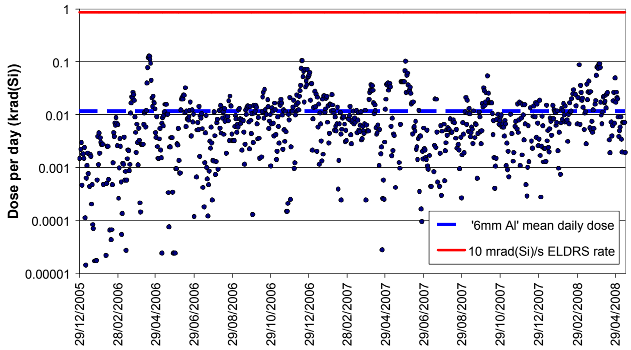


Fig. 7 Plots of dose per day derived from (a) the '3mm Al' (top) and (b) the '6mm Al' RadFETs (lower). The '6mm Al' dose rate is probably more representative for most realistic component shielding assuming a long mission in MEO. Also plotted for comparison are the mean daily dose rates over this period and the 10 mrad(Si)/s ELDRS test rate.

E. Observations of the December 2006 SPEs

As mentioned in section III, a solar energetic particle event was detected by the proton monitor on 6th December 2008 with a second, more impulsive, event following on the 13th December. In Fig. 2 we saw that there was a sharp increase in dose around the same time and also an electron/charging enhancement. The >40 MeV proton flux, total ionising dose ('3mm Al' RadFET) and SURF charging data from December 2006 are re-plotted at greater resolution in Fig. 8. The proton data is taken from orbital positions with L >7 to avoid the effects of attenuation due to geomagnetic shielding. It is seen that dose only starts to increase markedly at around 1600hrs GMT on the 15th December, after the proton flux from the second event has reduced by two orders of magnitude from the peak. At virtually the same time the charging current in the bottom plate also increased showing that the electron environment had become enhanced and it remained so for a long period thereafter. We can be quite sure that the electron enhancement is not due to contamination of the detectors by protons not only because it occurs after the proton event has subsided but because the SURF detector is highly immune to proton contamination [1]. Hence we conclude that the sharp dose increment observed by the RadFETs in December 2006 was due almost entirely to the electron enhancement which followed CME passage and not the proton event. Interestingly this CME was probably responsible for accelerating the protons close to the Sun (13th Dec) but takes some two days longer to arrive at the Earth and accelerate the outer-belt electrons.

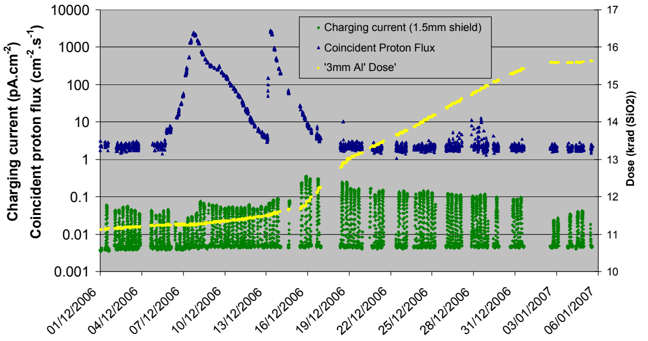


Fig. 8 December 2006 solar particle events: plot of the >40MeV proton flux outside of the belts (locations with L >7), internal charging current in the bottom SURF plate (peak sensitivity is to ~2MeV electrons) and total ionizing dose in the '3mm Al' RadFET. The majority of the 4.5 krad(Si) additional dose in December 2006 is received after the proton events have subsided. The dose increase correlates much better with an electron enhancement recorded by the SURF detector. Occasional data gaps occurred during this period due to on-board communications problems.

IV. Conclusion

A common approach to internal charging analysis is to determine the deposited current averaged over one day, for example, and to compare it to a known 'safety' threshold. Over the solar minimum period to date our measurements in MEO show that the NASA 0.1 pAcm^{-2} threshold for deposited internal charging current has been routinely exceeded for a 0.5mm Al absorber under 0.5mm Al shielding. The particular significance is that the outer honeycomb panels of spacecraft usually provide approximately this amount of shielding and hence dielectrics or isolated metallic items (0.5mm thick or greater) immediately underneath would be at risk from discharges. The DICTAT2.0/FLUMIC2.0 design tool available on Spenvis predicts that even higher currents could have been expected over the period, notably at the equinoxes. A design based on the DICTAT2.0/FLUMIC2.0 worst case current would have anticipated current levels as high as 1.4 pAcm^{-2} (compared to the observed ~0.2 pAcm^{-2}) and so a need for more shielding would have been indicated. Indeed, in our observations, the currents in the more shielded plates did not exceed the NASA threshold over this period, though once again DICTAT2.0/FLUMIC2.0 indicated that currents two or three times higher could have occurred.

At the winter solstices the DICTAT2.0/FLUMIC2.0 prediction was exceeded in all three plates but these excursions are not overly concerning because virtually all missions last at least a year and thus will necessarily include two equinoxes. Hence our data indicates that DICTAT2.0/FLUMIC2.0 gives safe (without being overly pessimistic) charging current predictions for missions lasting six months or more (i.e virtually all missions). The practical usefulness of the seasonal modulation in FLUMIC is questionable and probably causes confusion. Users should certainly be made fully aware of the need to ensure that equinox values are used for design purposes.

The percentage of days on which charging currents have exceeded a given threshold have been presented to summarise our internal charging data. Such plots may be useful to validate new models for the more extreme environments, especially those which might allow engineers to design for specific confidence levels rather than simply to a 'worst case'. The average electron environment obtained from SURF data shows that, at least over the energy range from approximately 0.5 to 3.5 MeV, the spectrum has been slightly harder than predicted by AE8.

Total ionising dose has been measured using two identical RadFETs located at '3 mm Al' and '6mm Al' shielding depths, noting that these figures are the minimum levels of shielding for each device and apply in one direction only. Of the two RadFETs, the '6mm' Al data is probably the more relevant for typical components located inside electronics boxes since significant shielding is usually needed to survive lengthy missions in this orbit. Some fading has occurred in the '3mm Al' RadFET but only in the second half of the mission while negligible fading has been seen in the other device (all other conditions are equal). Hence the increase in fading seems to be dose-related. While a basic correction procedure has been implemented, fade effects in long term space dosimetry are highly undesirable since it leads to underestimation. Hence it is recommended that efforts are made to find an ultra-low fade RadFET for realistic operating temperatures up to, say, at least 50 or 60ºC.

Ionising dose over this period (as measured by the RadFETs) has been accumulated entirely during electron enhancement events - the only solar proton event observed contributed no discernable dose increment. The mean daily dose for the '3 mm Al' and '6mm Al' RadFETs has been found to be much lower than the usual ELDRS test rate of 10 mrad(Si)/s (or 36 rad(Si)/hr) at 50.1 rad(Si)/day and 11.7 rad(Si)/day respectively. For the more lightly shielded RadFET the peak daily dose-rate observed (18th April 2006) was just less than the ELDRS test rate.

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V. Acknowledgements

Our thanks go the SSTL team, in particular Susan Jason, Elizabeth Rooney and Angela Brown, who most successfully integrated the standard version of Merlin into Giove-A. Furthermore the support of the MEORAD project in processing aspects of the Merlin data is gratefully acknowledged.