Proton Irradiation testing for selected P3-E/P5-A electronic components

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Introduction

For electronic components, a major difference between terrestrial operation and use in space applications is not only the missing cooling by convection of air, but in addition the increased flux of ionizing particles with high energy. These particles, which are normally captured by the earth's magnetic field and absorbed by the atmosphere can cause certain effects in semiconductor devices. In logic circuits, these effects range from a temporary faked signal to complete destruction of a device. For this reason, it is highly recommended either to use radiation hard components or to characterize commercial-off-the-shelf components for their suitability in the proposed mission.
This article describes the test results for an irradiation of selected P3-E/P5-A electronic components with protons.

Radiation induced effects in electronics

Several effects of high energy particles have to be discussed separately to understand their effects in semiconductors. These effects are:

- Single Event Effects (SEE)
- Total Ionizing Dose effects (TID)
- Displacement Damage

which will be briefly described in this section. For a more detailed discussion, see also [1].

Single Event Effects: As the name implies, single event effects have their origin in a single interaction of an ionizing particle with the semiconductor lattice. SEE are mainly caused by highly energetic solar protons, which are captured by the earth's magnetic field in the Van Allen radiation belts. While these protons don't pose a threat for LEO orbits, the elliptical Molnyia-type orbits of the Phase-3 satellites spend a significant fraction of their orbital period in these regions. As a result, commercial electronic devices, which worked well for LEO missions are not automatically qualified for use in HEO missions.
SEE can be further subdivided in three effects. *Single Event Upsets (SEU)* are the most commonly known. Here, a particle releases enough energy in a state register to alter its content and therefore corrupt the corresponding data. This can be effectively compensated for by using either triple-redundant logic or error detection and correction circuits (EDAC), as this has been the case for the IHUs of AO-13 and AO-40. A *Single Event Latchup (SEL)* is created, when the deposited energy triggers parasitic bipolar transistors, which may be present in output circuitry of a CMOS device. The sensitivity to SEL is dependent on the actual circuit layout of the device. A SEL can lead to very high supply currents and can only be cleared by disconnecting the supply voltage from the affected device. If the current density in the device

exceeds its maximum rating, this is called *Single Event Burnout (SEB)*, which characterizes an irreversibly failure of the device.
Total Ionizing Dose effects: Any ionizing particle or radiation passing matter leaves an ionized trace on its flight path (hence the name 'ionizing') which can lead to a buildup of space charge in a small volume of isolating material. The gate oxide of field effect transistors used in CMOS circuits is an example of such an isolating material. As the FET is controlled by the electric field in the drain-source channel below the gate oxide, any additional charge (and therefore field) leads to a gradual shift of the gate threshold voltage of the FET device. If this shift exceeds the design margins, the device will stop operating. It can be seen, that the TID induced failure is cumulative, different to the SEE, which can be caused by a single particle. TID can not only be caused by protons, but also by electromagnetic radiation, like gamma rays, which either directly hit the satellite or are created by protons absorbed by matter in front of the electronic device.
Displacement damage: This type of damage characterized the displacement of lattice atoms in the semiconductor bulk material, effectively changing the doping concentration of the semiconductor material. While the underlying nature of the Displacement Damage is a single interaction of a heavy particle with the lattice, only a large number of displaced atoms will cause observable effects. Therefore, it can be treated like a cumulative effect.

From the discussion of the mechanisms, it can be shown, that bipolar devices are mainly affected by displacement damage, while CMOS logic is in particular sensitive to SEE. As protons are the most abundant member of the particle flux in space and result in all three types of radiation damage, a proton irradiation is normally used to test electronic devices for their suitability in satellite applications.

Tested components and irradiation setup

Compared to commercial satellites, amateur radio satellites are full of electronic circuits. It is clear, that a complete test of all used devices in not possible. In light of the upcoming P3-E satellite mission, we restricted the scope to the digital payload, as a single event effect will not affect the operation of HF-transponders, as well as TID effects would only cause a gradual performance decrease. A single event effect in satellite critical systems however, might knock out individual subsystem or even the whole satellite with a single proton. Therefore, we tested the following components:

- <u>CAN-DO widget</u>: used for the P3-E internal CAN bus, which connects the different subsystems to the IHU
- <u>AD9834 DDS</u>: a direct digital synthesis chip used in the P5-A coherent transponder for frequency generation

Each component was exposed to protons of a kinetic energy of 60 MeV, which is identical to standard commercial tests performed by ESA and space industry. The used proton flux was 10^9 $p \cdot cm^{-2} \cdot s^{-1}$, which illuminated a circular area of 90 mm diameter. The separate test setups for each device were positioned inside this area and their operation was monitored in real-time during the irradiation, which allowed a precise determination of accumulated fluence, at which the operation of a device was affected.

Test procedures and results

For the CAN-DO module, an automatic readout script was modified by John Conner, NJ0C, to continuously read out the module once every 5 seconds. The digital outputs were connected to the inputs, which were programmed with a walkbit pattern to monitor the digital function. During the irradiation, first deviations from the written data to the read-back data were observed at an integrated flux of $3.2{\cdot}10^{11}$ $p{\cdot}cm^{-2}$ corresponding to a TID of 44 krad in Silicon. The CAN-bus communication ceased completely at an integrated dose of 61 krad, corresponding to an integrated flux of $4.5{\cdot}10^{11}$ $p{\cdot}cm^{-2}$. After accessing the sample device, it was determined, that a single event latchup caused an excessive current consumption, which was limited by the current limit of the used power supply unit. The resulting voltage drop most probably was the cause for the CAN-bus failure. An immediate power cycle restored a low current reading, similar to the value pre-irradiation, but unfortunately due to the test procedure, it was not possible to re-test the functionality of the CAN-DO module. To determine, if the module failure is permanent, a functionality test of the module is planned for the next weeks.

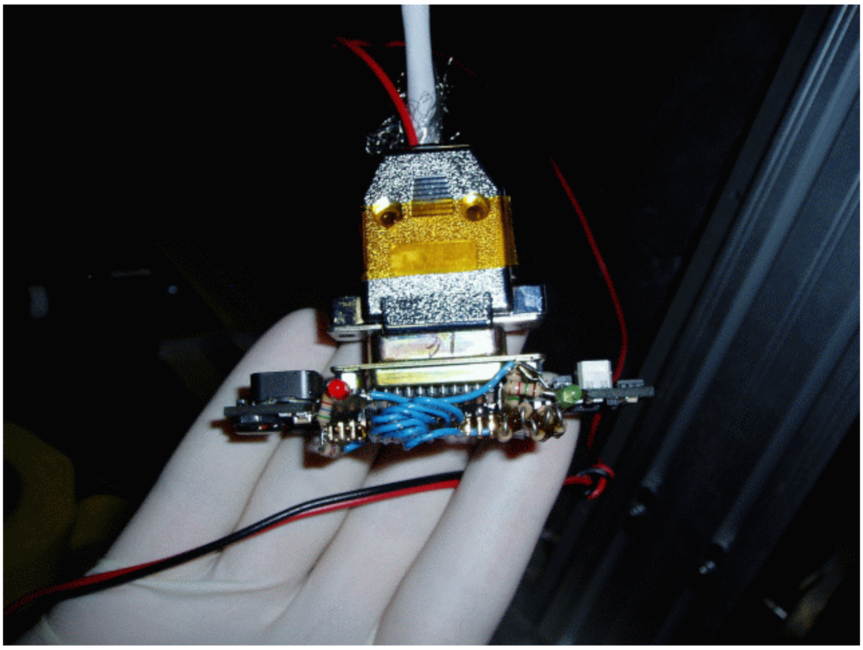

Fig.1: The CAN-DO module before installation into the test area.

For the simultaneous test of the analogue inputs, a voltage divider chain was connected to the on-board switching regulator output, which was toggled on and off for each readout cycle. When plotting the voltages, which were read back over the integrated dose, a stable operation up to approx. 57 krad can be observed (Fig. 2+3). First performance degradation can also be seen, prior to the failure of the readout itself.

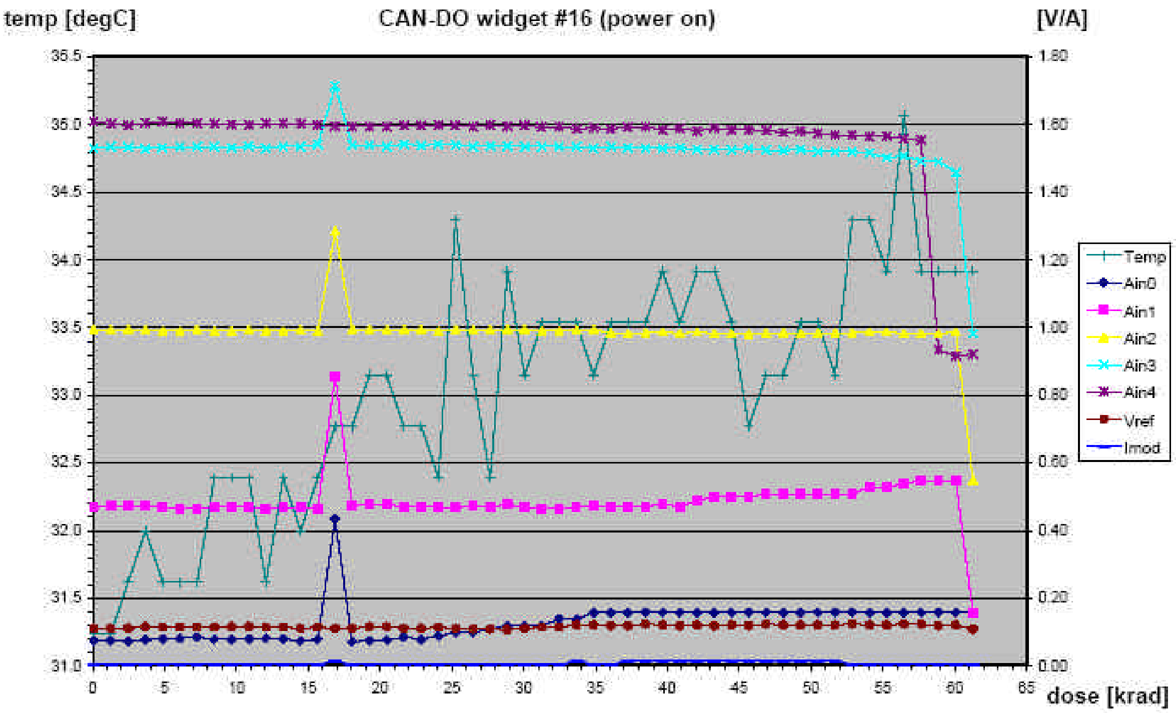

Fig. 2 read back data from the CAN-DO module, regulator OFF (see text)

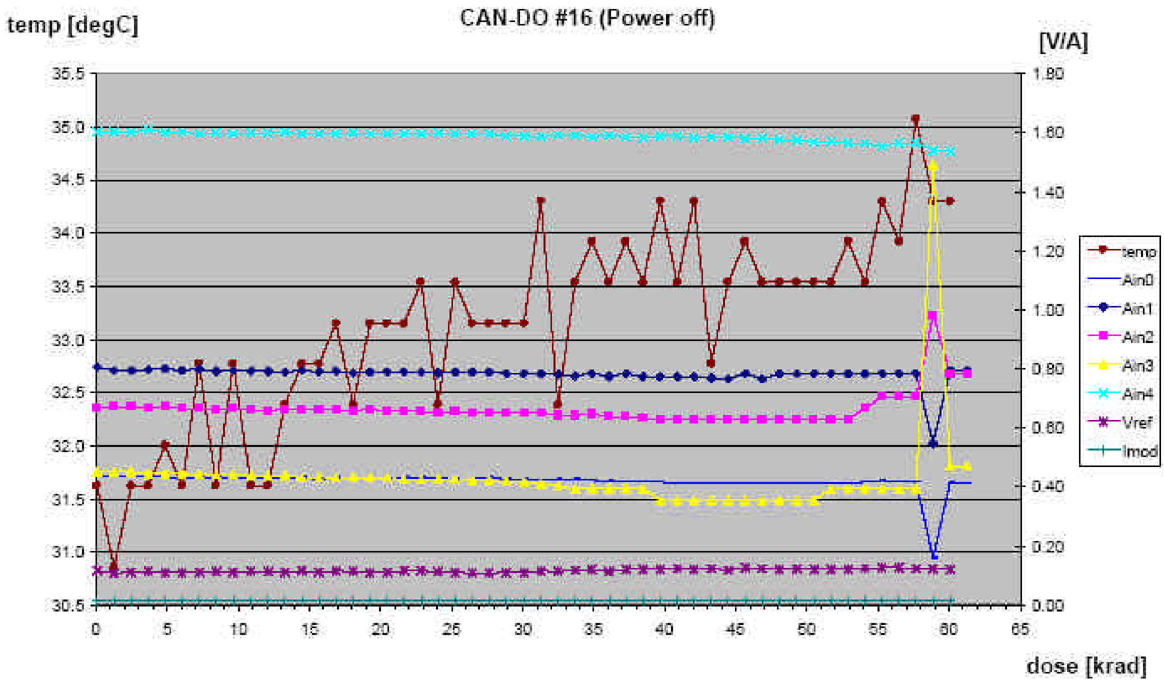

Fig. 3 read back data from the CAN-DO module, regulator ON (see text)

The AD9834 DDS circuit was located on a small board which held in addition a 40 MHz master oscillator and a PIC12F675 controller for initialization of the DDS device. The frequency output was matched to a 50 Ohms impedance and connected to a 30 m long RG-174 coaxial cable, which was connected in the control room to an oscilloscope. Only the frequency and the signal amplitude were monitored, a precise measurement of phase noise was not possible. Up to a dose of 140 krad (equivalent to

10^{12} $p \cdot cm^{-2}$), no deviation in either amplitude nor frequency were observed. After gaining access to the setup, a large current consumption was determined, which was still below the limit of the power supply unit, therefore not causing a drop of supply voltage. As the temperature of the controller was very high compared to the DDS chip itself, a single event latchup was suspected in the controller. A power cycle was able to restore the low current consumption before irradiation. Again, the test procedure did not allow to check again the functionality of the controller.

Comparison to the environment inside the satellite

The tested doses have to be compared to the expected dose levels and fluences in the interior of the satellite. For this, the natural flux in the satellite orbit has to be combined with the average shielding provided by the satellite structure itself (which consists mainly of aluminum) and some optional shields made from small tantalum sheets, which are directly glued on sensitive components. With an assumed shielding thickness of 3 $g \cdot cm^{-2}$, the remaining dose rate for the planned Molniya-type orbit is on the order of 300-500 rad/year, which sums up to a maximum of 5 krad over 10 years. While this numbers have been calculated by Amsat some 25 years ago and verified by AO-10, online tools (CREME96, [2]) exist to calculate the dose level for a given orbit. In addition to the orbital parameters, the shielding of the satellite structure is taken into account as well. For a P3-E like set of parameters(Perigee 965 km, Apogee 45260km, 48 deg inclination), an average value of 900 rad/year is calculated, which can be considered to be a good agreement with the calculations made by Amsat given the complicated nature of the data..

Conclusion

Electronic devices in space are affected by ionizing particles and radiation. When using commercial components, these have to be carefully evaluated for their sensitivity to radiation induced failure. Highly energetic protons are an ideal probe for testing as they cover all possible types of radiation induced failures.
Planned for use in the P3-E satellite, the CAN-DO module and the AD9834 DDS synthesizer were exposed to protons with an energy of 60 MeV. While the DDS synthesizer was able to operate to doses of up to 140 krad, the CAN-DO module stopped operating at 61 krad. Compared to the expected environment inside the satellite, which corresponds to a dose of 5-10 krad for a projected mission duration of 10 years, the obtained results suggest that the CAN-DO module and the DDS synthesizer of the coherent P5-A transponder should not suffer from radiation induced failure.

References

[1] F. Faccio, CERN: Radiation effects in electronics devices and circuits, http://humanresources.web.cern.ch/Humanresources/external/training/tech/special/ELEC2002/ELEC-2002_18Apr02_1_PDF.pdf
[2] CREME96 website: https://creme96.nrl.navy.mil/index.html