(almost) everything you wanted to know about...

Components in Space

Interview with **Jaime Estela**, Spectrum Aerospace Group

Now that small companies and even start-ups can afford their own satellites, it's good to know more about components in space.

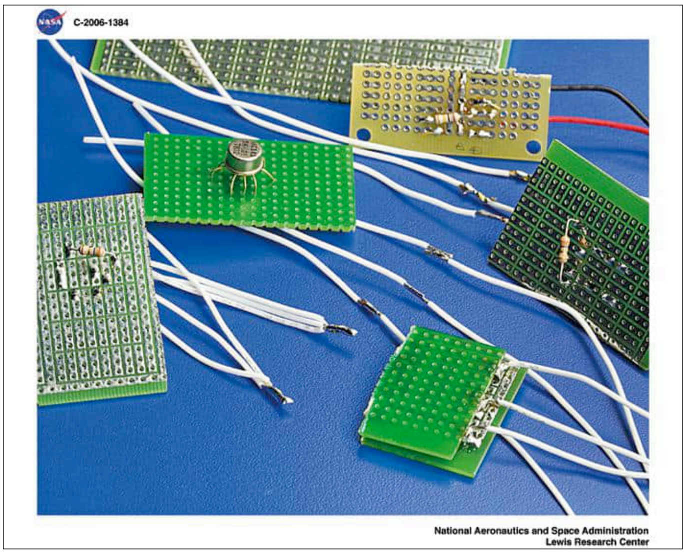

Figure 1. ISS astronauts practicing repair tasks for electronic components (photo: NASA).

Q *Are electronic components in space degraded by radiation?*

A All electronic components in space are degraded by radiation. The robustness of components depends on many factors. Some components only have a short life in space, while others can operate in space for many years. Components specifically designed for military use can function in space for a very long time. Commercial parts vary. Even if they are not made for use in space, many components can function in space for several years with only minor degradation.

Q *What are the effects of radiation in space?*

A **Displacement damage (displacements in the crystal structure):** Particles (neutrons, protons, alpha particles and heavy ions) and high-energy gamma photons alter the structure of the crystal lattice and affect the properties of semiconductor devices.

Accelerated aging (ionizing radiation): Charges are induced and accumulated. These charges increase the leakage currents of the components, causing higher power dissipation which ultimately causes failure of the components.

Single event effect: Highly ionized particles induce strong transient discharges (noise pulses) in semiconductor devices, which interfere with device behavior and cause data corruption.

Q *How are components tested for radiation resistance?*

A There are two main types of radiation test in practice:

Total ionizing dose (TID) test: For this test a cobalt-60 cell is used as a gamma source. Similar sources are used in medical equipment, but there they are much weaker. The radiation exposure simulates several years of deployment in space in a very short time. The radiation-induced charges affect the properties of semiconductor devices in various ways.

Single event effect (SEE) test: In this test a particle accelerator is used to bombard the component with protons or heavy ions. The most serious result is data corruption due to short noise pulses induced in the circuit. This effect is highly relevant for digital circuits.

Q *Are there differences with regard to the satellite orbit?*

A Yes – the higher the orbit, the higher the radiation dose. Low earth orbit (LEO) satellites are exposed to the least radiation doses. Passengers in aircraft flying at an altitude of 10 kilometers (33,000 feet) also receive higher radiation doses, and the active flying hours of crews are limited to avoid endangering their health. The ISS space station orbits at a height of 350 to 450 km. This orbit was chosen to minimize the radiation dose received by the astronauts.
The Van Allen Belt provides additional protection. Objects inside the Van Allen Belt are protected by its magnetic field. The highly charged particles are captured by the magnetic field and diverted to the polar regions.
Telecommunications satellites are positioned in geostationary Earth orbit (GEO). Satellites in this orbit appear to hover over the same spot on the surface of the Earth. The height of the geostationary orbit is nearly 36,000 km, putting it well outside the Van Allen Belt. This orbit is more demanding on electronic

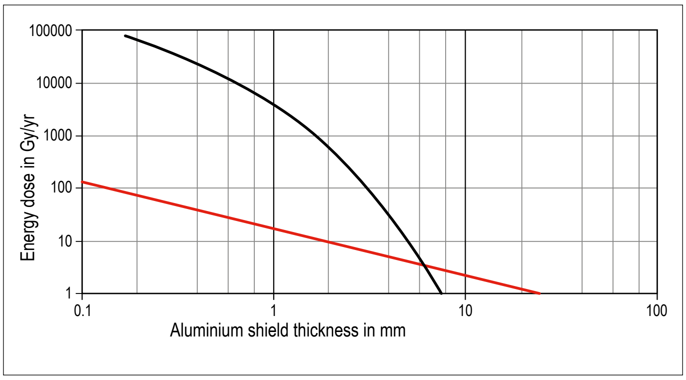

Figure 2. Radiation protection by aluminum shielding in geostationary orbit (black curve: energy dose due to electrons) (source: Wikipedia, public domain).

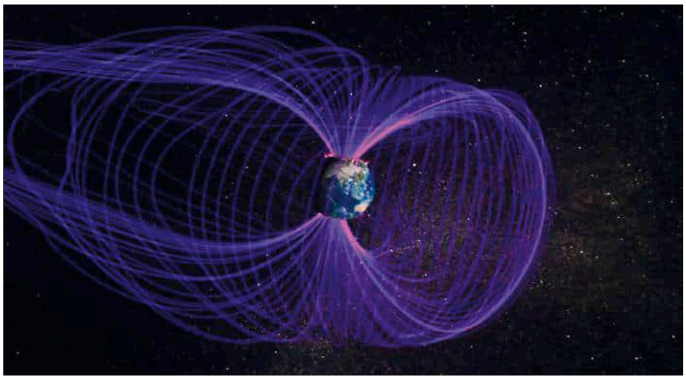

Figure 3. The first US satellite mission in 1958, Explorer 1, discovered a belt of electrically charged particles surrounding the Earth (graphic: NASA).

devices because they must operate under higher radiation levels. Deep space missions are even more difficult. Most of the electronic devices are located inside the protective structure of the satellite.

Q *What types of components are used in space missions?*

A The longer and higher the mission, the more protective measures are necessary. The design must fulfill the requirements – no less, but also not too much more. Components classified as "International Traffic in Arms Regulations" (**ITAR**) can easily function for 100 years in LEO, but if the planned mission lifetime is relatively short — for example, only five years – these components are unnecessarily expensive. For this reason, commercial off-the-shelf (**COTS**) components are being used more and more.
Geostationary satellites need to be able to operate reliably for 15 years in a distinctly harsher environment. Using ITAR components is therefore worthwhile. It often happens that the electronics of these satellites still function reliably even after the end of their planned lifetime.
Another situation is high-altitude research rockets, which are airborne for only a short while (at most 15 minutes). Here there is no need for special components; COTS components are fully sufficient.

Q *Which protection mechanisms are the most effective or most reasonable in various situations?*

A Almost all satellites are built with **redundancy**. Pico satellites and small nano satellites, which do not have enough room for redundant hardware, form an exception. Redundancy helps to increase the useful operating time. In the early days of space flight, all systems had multiple redundant modules. For example, up to eightfold redundancy was employed for the on-board computer. Especially for manned missions, the electronics must work flawlessly. Although redundancy increases the complexity, power consumption, weight and size of the space vehicle, it is still one of the most important ways to increase the reliability of aerospace systems.

Fault tolerance: It is always advisable to design the electronics with robust components. You can even take the known degradation of the components into consideration in the design, so that the electronic functions are always inside the operational envelope. On the data sheet of a commercial component you cannot see how it will behave under the conditions of a space mission. Even the manufacturer does not know. However, these properties are very important for deployment in space, so they must be determined empirically.

Shielding: It is common practice to protect electronic devices by placing them inside the satellite structure. Increasing the thickness of the shielding improves the protection, but it also increases the size of the structure and, worse yet, the weight of the satellite. These two factors raise the launch costs. It is also possible to use other materials, but most of them are heavier than aluminum. For this reason, special shielding is only used where it is absolutely necessary.

Q *Which components are especially vulnerable, which are less vulnerable, and which are not vulnerable?*

A The key difference is between passive and active components. Resistors and other passive components are very robust, but semiconductors are strongly degraded by radiation. Bipolar technology is generally more resistant to radiation than CMOS technology. However, that depends on many factors, including the layer geometry, the materials, the packaging and so on.

Diodes, transistors, all ICs, crystals and optoelectronic components are sensitive to **ionizing radiation**, while FETs, CCDs, CMOS active pixel sensors, other optoelectronic components, and all ICs are sensitive to **single event effects**.

ESA and NASA now promote the use of FPGAs because programmable hardware can be repaired remotely. In addition, FPGAs pack a lot of functions in a single component, making the electronics more compact. ESA also has a processor called LEON, which is a soft IP core that can be implemented on an FPGA [1].

Q *What are the effects of degradation or damage?*

A One effect of degradation is that the electronics can consume more power. Progressive degradation ultimately leads to functional failure of components.

If you know how a component behaves in space, you can take this into account in the design. For example, if you have an amplifier with a gain of 5 and you know from simulation or a qualification test that the gain will drop to 3 by the end of the mission, you can incorporate this information into the circuit design so that the circuit will function properly over the entire mission lifetime. That way you can counter the degradation of the component.

If you use components in aerospace electronic designs without knowing how they behave in space, you are taking unnecessary risks. The most professional approach, but also the most expensive, is qualification of individual components. Nowadays there are satellite operators who want to save time and money by performing very short tests on fully assembled boards. If a board fails the test, you have no idea which component actually failed. The robustness of the board is only as good as the weakest component. If on the other hand you know the behavior of every component, you are in a good position to make the board more robust.

A TID test takes about two weeks and follows ESA recommendations. Sometimes people want to have a test performed in just six hours. That is like baking a cake: if the package says “bake 30 minutes at 200°C” and you instead decide to bake it for only 10 minutes in an oven at 600°C, you will not obtain the same result. You cannot fool physical processes. ◄

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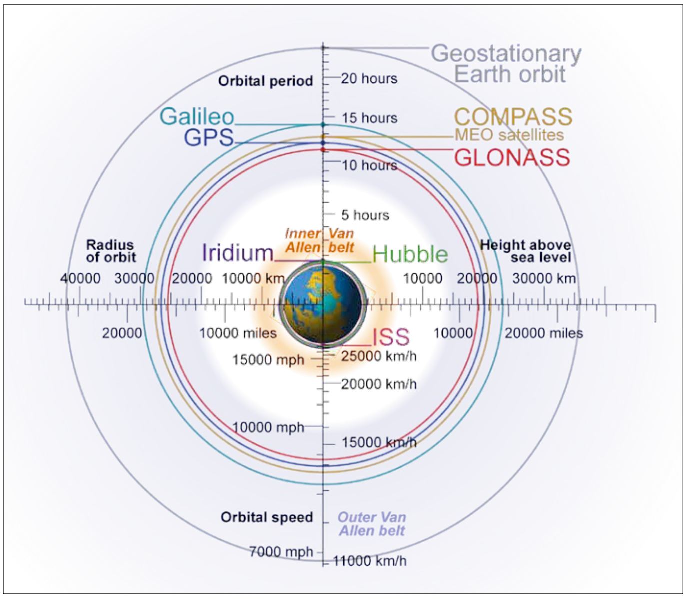

Figure 4. Orbital positions of satellites and the ISS in the Van Allen Belt as seen from the North Pole (graphic: Geo Swan, CC BY-SA 3.0).

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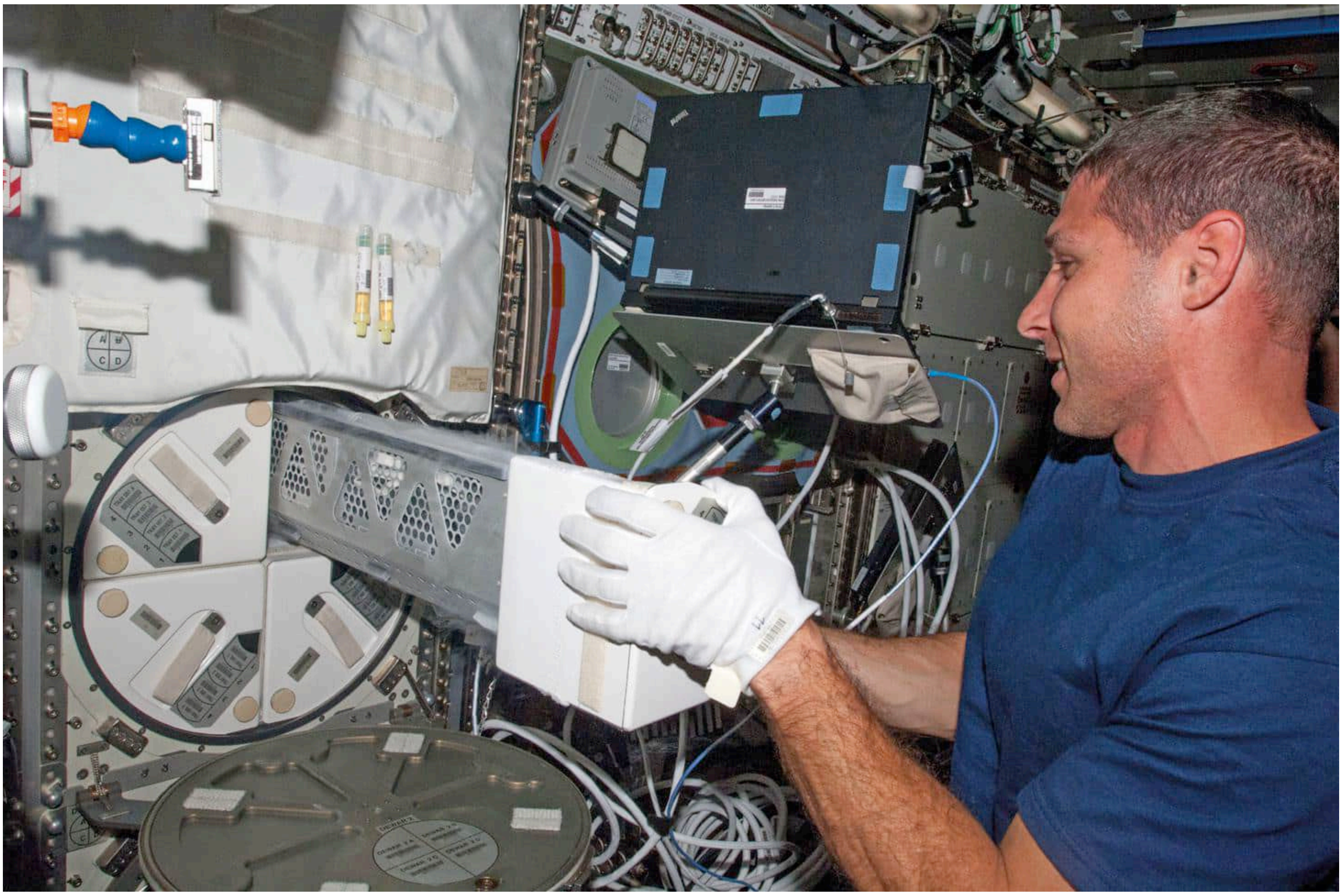
Electronics in Orbit

Space science for all of us

By **Jaime Estela** (Spectrum Aerospace Research)

Satellites are constructed from robust materials, simply because they have to perform flawlessly under extreme environmental conditions. Their electronics require the use of specially manufactured — and therefore extremely expensive — components. For small satellites (smallsats) regular commercial components offer a cost-effective alternative, although their behavior must first be qualified in simulation tests to international standards before deployment.



NASA astronaut Mike Hopkins removes a Dewar flask from the freezer to begin biological tests (photo: NASA).

In space there's a variety of physical phenomena that affect the performance of electronic components and materials. For satellite missions it's vital to know this environment extremely well in order to minimize any damage and/or disruption to the electronics. The precise behavior of the components under such adverse conditions depends on the orbit of the satellite and can be simulated using software tools. The outcome of these simulations then assists satellite developers to design their systems accordingly.

Figure 1 sets out the phenomena that determine the service life and dependability of electronic components:

- **Atomic oxygen**: UV light breaks up O_2 molecules into individual atoms of oxygen. This atomic oxygen is highly reactive and will consequently erode the outer surface of the satellite's structure. This 'space rust' affects the thermal behavior of the structure and the satellite. This is a very important issue, as it affects the satellite's thermal system.

- **Plasma**: Ionized gases produce electrostatic charges that stress the surface of the satellite electrically. Discharging these can interfere with the operation of the satellite and the instruments inside it.

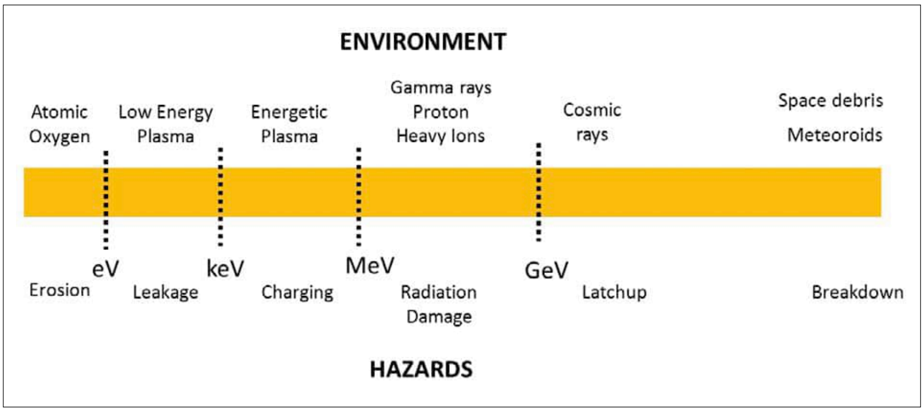


Figure 1. Environmental conditions in space and their potential hazards (source: Spectrum Aerospace)

- **Radiation**: A multitude of effects result from this phenomenon. Gamma rays degrade the electronic components. Protons and heavy ions can at best falsify digital data or at worst physically destroy the electronics aboard the satellite.

- **Micrometeorites and space junk**: The deadliest events in space are caused by small artificial or natural matter. The effects of micrometeorites or space junk should not be underestimated; they can damage or destroy satellites. This very thing has already happened, resulting in the loss of spacecraft.

Degradation in electronics

In the early days of space flight history, electronics designed especially for spacecraft did not exist. Instead electronic components designed for military purposes were upgraded for deployment in space. In this upscreening process various supplementary tests were conducted, with the best-performing components selected.

In 1973 military-grade components were again used in the hardware for the Skylab space station. In the qualification test the hardware had to be upgraded several times over on account of malfunctions that arose. These improvements resulted in the need for more than $3 million of additional investment in procuring new electronic components required and on additional qualification exercises.

Electronics in the first Skylab mission (1981) once more employed military-specification components. In order to raise the dependability of the system, most elements were installed with six-fold redundancy. Valid data was checked using a statistical method (voting algorithm). However, this inclusion of redundant systems also enforced an increase in weight and power consumption as well as other challenges to hardware and software design.

As military-grade electronics did not really lend themselves to space flight applications and the upscreening produced no improvement of the components, work began in the 1960s on the systematic development of dedicated space electronics, which demanded qualitatively high-end production techniques. As a basis for this new generation of components in the USA military components were selected, with complementary tests defined for their qualification. This strategy made possible a reduction in production costs for space flight missions, at the same time achieving a high level of ruggedness in the components. However, because the demand for components of this kind was obviously very small, their price remained high.

Nowadays the qualification process for just one component to European Space Agency (ESA) or U.S. National Aeronautics and Space Administration (NASA) standards requires an investment of a million dollars or more. The time taken for certification is around two years [1]. Of course the entire test process can turn out to be complex or simple, according to the type of component. By way of example, testing a diode is less cost-intensive and protracted than checking out a microcontroller.

Qualification tests

The experience gained over the last sixty years during numerous space missions and using various technologies enabled institutions like ESA and NASA to devise guidelines for developing qualifications and standards. These guidelines underpin the professional qualification of electronic components for space flight missions. The standards laid down by ESA can be found on the ESCIES (European Space Components Information Exchange System) portal [2]. A database of qualified integrated circuits together with their test results is available on the ESCIES website [3].

For a qualification test the components under examination (Devices Under Test, DUTs) are made ready and the measurement environment configured. First the precise number of components is determined and depending on the type of test, either a small number or the entire quantity of the components is nominated. This means that sometimes just a few components will suffice for the qualification (for example during radiation testing), whereas for an outgassing text (for instance) all of the components must be tested. During testing the DUTs are characterized.

An important requirement in qualifying components is that all of the components for qualification must be identical (in geometry, size, materials and so on) and must also come from the same production batch.

The test results are collated in a test report. Following qualification a test report will describe the behavior of the relevant component parameters under space flight conditions. A complete, highly extensive qualification is known as a 'screening test'. A process of this kind takes a couple of years and requires a high level of financial investment. In the screening test the following individ-

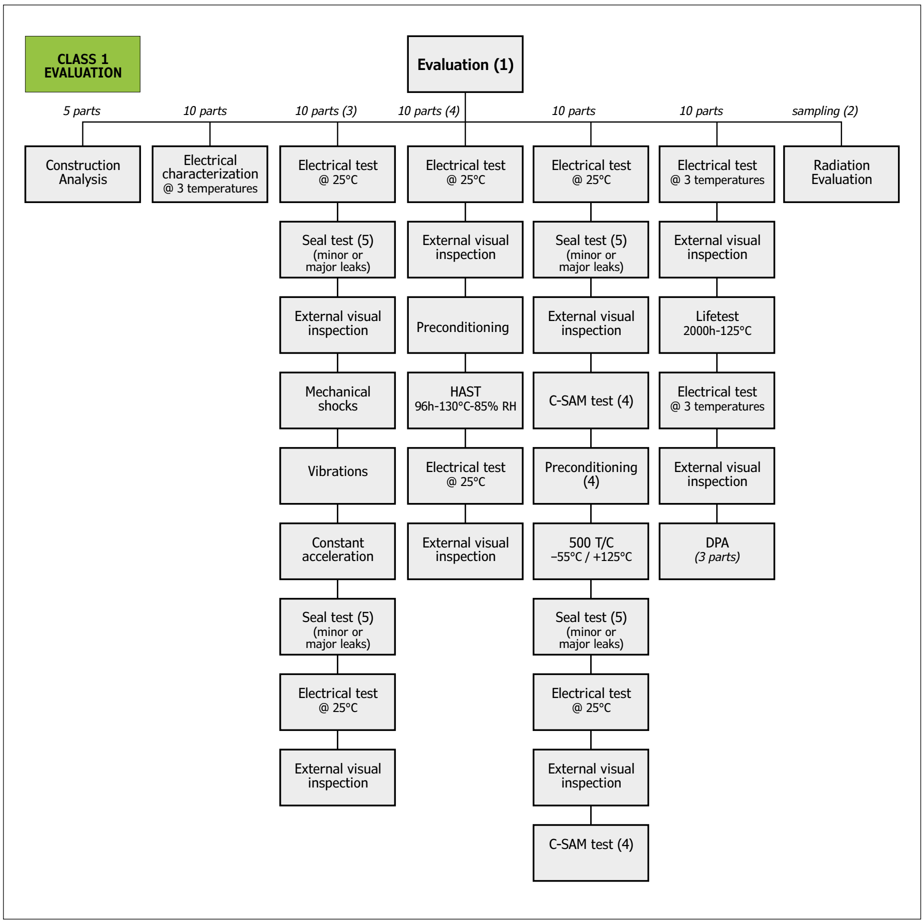


Figure 2. Evaluations tests carried out in Class 1 (ECSS-Q-ST-60-13C Evaluation tests flow chart Class 1, source: ESA).

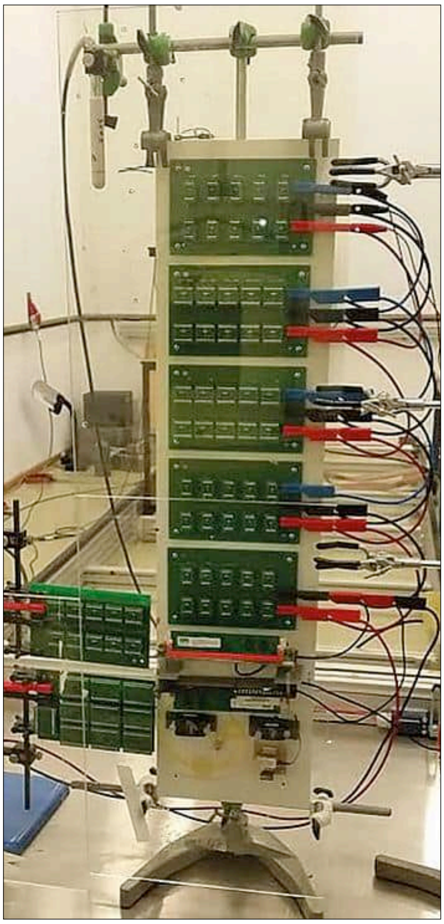


Figure 3. Array of devices under test ready for radiation testing (source: Spectrum Aerospace).

ual tests are undertaken:

- Electrical test
- Impermeability testing
- Visual inspection
- Mechanical shock
- Vibration test
- Constant acceleration
- Thermal test
- Radiation test
- Outgassing
- Stress test
- Thermal shock
- Solderability

ESA document *ECSS-Q-ST-60-13C_ Space Product Assurance* describes the various quality classes [4]. The differences between these classes lie in the depths of the qualification processes. Class 1 is concerned with complete qualification (**Figure 2**), whereas Class 3 requires only a short qualification process (mainly radiation tests).

Characterization

The way in which these qualification processes are carried out can be seen in a brief description of the TID (total ionizing dose) testing of an LTC2052 drift-free operational amplifier. Firstly, a rack is prepared which contains circuit boards with the components to be inspected (**Figure 3**). In this case, the two configurations (bias condition) shown in **Figure 4** are of importance: an 'off mode' in which all pins are connected to system ground and an 'on mode', in which the device is configured for a specific operating point but the component is not processing a signal (that is, in a kind of standby state).

Figure 5 shows the test setup. Cobalt-60 is used as the radiation source. The two test configurations are subjected to irradiation. During irradiation, the test specimens are measured from time to time by means of automatic test equipment (ATE). These characterization results show the degradation of the components at ever-increasing levels of radiation dose. The reduction in performance depends on the technology of the device and the accumulated radiation dose. For example, rising current consumption can be observed with increasing radiation dosage (**Figure 6**). At the end of the test changes in electrical parameters are detected; in some cases components have even been completely destroyed.

The smallsat marketplace

The market for small satellites is showing fairly rapid growth. New products and functionalities are sought to match the growing requirement. For manufacturing smallsat hardware military ITAR (International Traffic in Arms Regulations) components are not the right solution; qualified COTS (Commercial Off-The-Shelf) mass-produced products) are.

Market research carried out by analysts Northern Sky Research indicates clearly that in the next ten years more than 2,500 small satellites (weighing up to 100 kg) will be launched into space [5]. Another market study, by the firm Spacework, forecasts 3,000 smallsats up to 50 kg in the period 2014 to 2020 [6]. Both forecasts envisage future constellations of satellites (effectively mass-pro-

Q & A, by Jaime Estela

- *A competition was planned to win a place for a circuit board on board a StarLab flight. What has become of it?*

Yes, this is still live. However, delays have arisen because a firm that wanted to co-sponsor the prize competition and had experience in events of this kind has dropped out. We are in discussion with other firms but this will definitely take a bit longer.

- *When will the first flight take place?*

The first flight should take place in December, although while some uncertainties remain, we don't yet have a fixed date. In principle flights should then be made in a three-month cycle.

Can you give a ballpark idea of your charges?
The price depends on the size of the PCB. For a small board (5x3 cm2) you can reckon on around €3000 / £2500 / $3260 upwards.

- *How will the experiments be monitored?*

Electronics in space are observed using telemetry data. Sensors measure specific parameters and the test results are then transmitted to Earth. This way you always know exactly how your space electronics are functioning. Developers need to concentrate on their own experiments nevertheless, for which reason a StarLab development kit is provided. This electronic support package assists developers to prepare experiments involving telemetry electronics quickly and straightforwardly.

- *Can you test only components or also complete assemblies?*

Both. Although testing individual components takes up more time and the costs are higher, the results are very precise. With complete PCBs the costs and time to test are lower, but the inaccuracy is greater. The problem with complete assemblies or entire PCBs is that in the case of a malfunction it may not be possible to localize the error precisely.
Not all components are equally robust. Consequently you need to determine the ruggedness of the components first before you can develop a system for deployment in space. If you do this in the opposite way order, a single component may end up significantly degrading the viability of the entire assembly.
I have devised a new concept that lies between component and PCB level. In this way complete PCBs can be qualified more accurately.

- *Who can I ask if I have any questions or a specific interest?*

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duced and thus relatively low-priced swarms of satellites, like GPS for example). Increased production-line manufacturing of satellites will create an even greater requirement for qualified electronic parts.

Space-COTS

For the NewSpace [7] movement of multiple (U.S.) startup companies aiming to make space travel cheaper and more accessible, space-qualified COTS devices provide the means of getting commercial components qualified for use in space. The term and concept of 'space COTS' arose from work using commercial electronics in smallsat operations and also out of long-term involvement with ESA standards for qualifying electronic components. Space-COTS is a compromise between non-qualified components (for example, in CubeSats) and fully qualified ITAR components. From the experience gained with small satellite missions it is known that many commercial components can definitely function in space for several years, despite not having been conceived for space applications. Space-COTS parts are tested at various levels and defined, by qualification level,

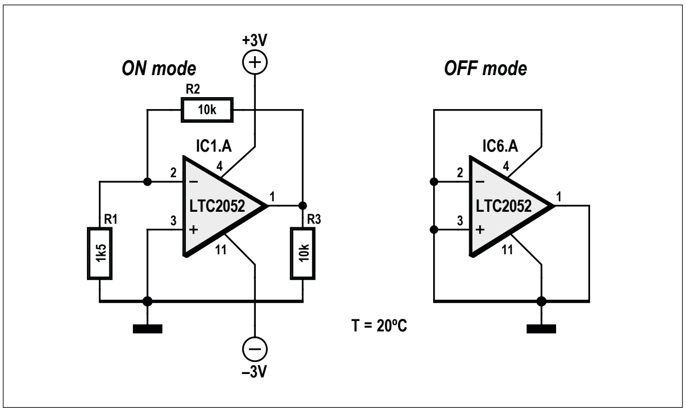

Figure 4. Two configurations of an LTC2052 for TID testing (source: Spectrum Aerospace).

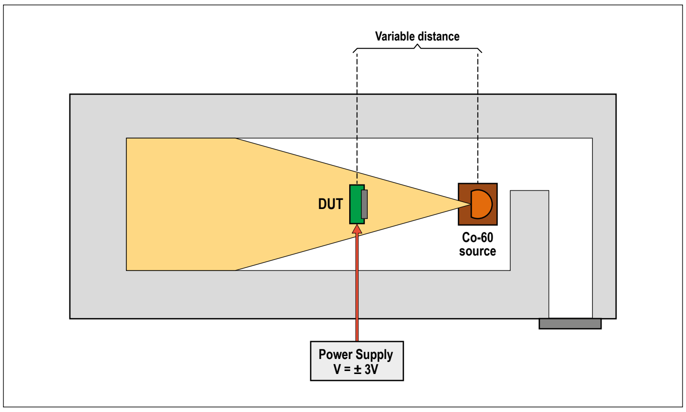

Figure 5. Test setup using a Cobalt-60 radiation source (source: Spectrum Aerospace).

in the following classes:

- Class A: Full screening test
- Class B: TID and SEE test (SEE = Single Event Effect)
- Class C: TID test

These classes accord with ESA and NASA specifications and also with the new ISO (International Organization for Standardization) standards.

StarLab

Many firms are developing new products for space flight. These products do not have any flight experience ('flight heritage'). To test a product in space, you need to invest at least €250,000 / £212,000 / $274,000 (covering satellite plus flight but excluding the cost of test procedures). What's more, as well as the financial wherewithal, you must have the patience to resign yourself for a flight delay of at least 18 months. There are indeed dedicated satellites for technology proving trials but these launches take place very infrequently and are reserved for a very small number of privileged companies [8].

However, moves are now afoot to make the International Space Station (ISS) usable by a wider user base, enabling small private payloads to be installed on this platform. One of these initiatives is the StarLab project. One container can include multiple experiments; power and data connections are available for each experiment, with test data transmitted to Earth virtually in real time. The StarLab project, with its innovative qualification, provides regular access into space for everyman – and at moderate prices.

Good electronics can definitely arise in the Maker community too. Their developments can also be of interest for space flight, even if the theme of space electronics is largely unknown in Maker circles. The StarLab project gives new electronics wings to pass tests in space. Testing your own designs in space is certainly still a big ask, but the StarLab project makes this elaborate and expensive exercise simple and advantageous. An entirely new field of activity opens up to developers and the space flight sector can profit from innovative, qualified products.

Is your curiosity aroused? Are you game for making experiments in space? Check out the answers to your burning questions about the StarLab project in the panel. The gateway to space stands wide open! ◄

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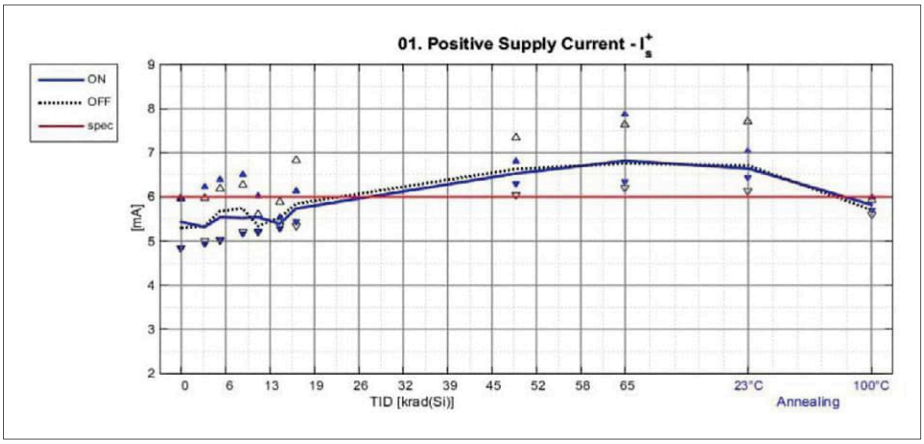

Figure 6. A test result: current consumption increases with increasing radiation dose (source: Spectrum Aerospace).

Space electronics: the bad old days

I guess the question I'm asked the most often is: "When you were sitting in that capsule listening to the countdown, how did you feel?" Well, the answer to that one is easy. I felt exactly how you would feel if you were getting ready to launch and knew you were sitting on top of two million parts — all built by the lowest bidder on a government contract.

— Astronaut John Glenn, the first American in orbit (1962), spoken in 1997.

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