

How Radiation Affects Crystals and Oscillators in Space Applications

The “spacescape” exposes crystal oscillators used in space applications to the hazards of radiation. This article focuses on the effects of different types of radiation on these devices employed in satellites.

Quartz-crystal resonators and crystal oscillators used in space must withstand the damaging effects of radiation. Radiation comes in many varieties, and it requires detailed and complex analysis to determine whether a given component will weather any specific space environment and application. This article provides a big-picture, bird’s-eye view of what’s involved and the types of radiation events to watch out for concerning crystal oscillators.

The Basics of Radiation

What do we mean by radiation? For our purposes, radiation is the transmission of energy through space in the form of either subatomic particles or electromagnetic (EM) waves.

Subatomic particles include electrons, neutrons, protons, and ions. Electrons are sometimes referred to as beta particles and helium ions as alpha particles. Electromagnetic waves, in ascending order of frequency and descending order of wavelength, include radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma radiation.

The kind of radiation we’re concerned with is called ionizing radiation, because it carries sufficient energy to damage electronic components. This radiation ionizes atoms or molecules by detaching electrons from them, thereby making the atom or molecule in question electrically charged.

For instance, the energy carried by electromagnetic waves increases as the EM wave’s frequency increases (or as its wavelength decreases). Lower-frequency waves, such as visible light, microwaves, and radio waves, don’t normally carry enough energy to damage electronic circuits (or living beings). But as their frequency goes up, X-rays and (especially) gamma rays can and do cause damage.

Keep in mind that electromagnetic waves can also be described as consisting of particles called photons. A photon of visible light carries a certain amount of energy that doesn’t cause problems. However, a gamma-ray photon carries a much higher — and problematic — energy level. Any radiated particles with actual mass (photons are massless), such as electrons, protons, neutrons, and ions, all carry enough energy to cause potential damage.

Given the importance of the amount of energy involved in exposure to radiation, we need to know how it is characterized and quantified. We commonly use two scales and units of measurement. First, the energy fluence used to characterize the amount of exposure over a period is measured simply in MeV (million electron volts) or in units of MeV/cm². The other measurement is the total ionizing dose (TID) of radiation absorbed by a material, which is in units of kRads (kilorads).

Defining the “Spacescape”

Crystal oscillators are required to operate reliably in the “spacescape,” which includes deep-space orbit, geosynchronous orbit (GEO), medium-altitude orbit (MEO), and low-earth orbit (LEO). As discussed in a 2020 Q-Tech [white paper](#), the following key parameters should be considered when selecting the optimum crystal oscillator for spacescape applications: phase noise/jitter; size, weight, and power (SWaP); stability; and radiation tolerance.

We’re primarily concerned with the radiation tolerance of crystal oscillators used in satellite applications in the GEO, MEO, and LEO spacescape regions. The *table* defines, to industry standard, the TID of radiation allowed for each environment and application.

GEO orbits, which are about 36,000 kilometers above

Environment or Orbit	Application	Industry-Standard TID
Deep Space	Inter-planetary missions	300 kRad+
GEO	Com, Mil, Scientific (Full Space)	100 kRad
MEO	Com, Nav	100 kRad
LEO	Low-cost megaconstellations	30-50 kRad

Total ionizing dose of radiation allowed in space environment and applications.

ground level, are high enough to allow a satellite to be positioned in an almost stationary state over an exact earth surface location. These satellites, each costing millions of dollars, use only the very best, most reliable components considered “rad hard” in every way. We commonly call these types of applications “Full Space.”

MEO satellite applications operate between 2,000 and 35,000 kilometers above the Earth’s surface. The radiation requirements for electronics used in MEO orbits aren’t much different than those for GEO.

LEO satellites are located only about 100 to 2,000 kilometers above the Earth’s surface. Much smaller and lower cost than Full Space satellites, they’re commonly used in what are called megaconstellations. Each megaconstellation is composed of a fleet of dozens, hundreds, or even thousands of satellites. The mission life of a LEO satellite might be only a few years, as opposed to 20 years or more for Full Space satellites.

Electronic components used in LEO satellites are expected to be lower cost, smaller in size, and lower in power consumption, and yet they must still survive in their intended application. This niche is a booming growth business often referred to as “New Space.”

Radiation Effects on the Quartz Crystal

The good news is that, unlike many electronic components, the quartz-crystal resonator won’t die, meaning it will not cease to operate due to radiation under any reasonably foreseeable circumstances.

What *can* happen, however, is that certain kinds and amounts of radiation can change the frequency of the quartz resonator. The amount of frequency change is normally not excessive, but it’s subject to many variables, including the crystal’s frequency, the quality of its factor (Q), the type of its cut, and the type and amount of radiation present.

Small frequency changes are primarily caused by very small levels of impurities embedded within the silicon-diox-

ide quartz-crystal lattice. These various possible impurities can be dislodged and moved within the quartz.

Quartz used for electronic purposes is grown synthetically under very high temperature and pressure conditions. Today, vast improvements have been made in the growing of such quartz, to the extent that frequency changes due to radiation are much reduced.

Beyond that, quartz for use in resonators intended for space goes through a special process called “sweeping.” Sweeping quartz bars involves subjecting them to a very high unidirectional

DC-electrostatic field of 1000 V/cm (400 V/inch), while simultaneously exposing them to a very high temperature of about 500°C and monitoring the current flow.

The sweeping process causes many impurities to migrate through the quartz bars to their edges. These edges are then cut off with a saw, leaving pure quartz bars known as swept quartz. The resulting purified quartz bar has improved radiation insensitivity. Therefore, nearly all space-level specifications for crystals specify use of swept quartz.

Radiation Effects on the Complete Oscillator

Unlike the crystal itself, the electronic components making up the entire oscillator are much more susceptible to radiation in space applications. This is a complicated subject because all of the oscillator’s active devices (semiconductors, transistors, digital electronic devices, and so on) are subject to degradation due to several types of radiation:

Total ionizing dose (TID)

TID, as mentioned above, is the cumulative absorbed dose resulting from the energy of ionizing radiation at a dose rate between 50 and 300 rad(Si)/s. For electronic components, TID is a possible long-term failure mechanism. Typically, space applications have required components to be certified reliable for at least 100 kRads. For use in LEO New Space applications, 30- or 50-kRad compliance is commonly accepted.

On the other hand, some applications require 300 kRad or even 1 MRad. To be certified as such, components must come from a representative sample lot that has survived at least twice the TID level in question, or 200 kRads, to certify 100-kRad compliance for that lot. This testing is reported in what’s called an RLAT (Radiation Lot Acceptance Test report).

Enhanced low dose rate sensitivity (ELDRS)

ELDRS is like TID, but the total radiation is required. For example, 100 kRads, is administered at a much lower dose rate, usually 0.01 to 0.1 rad(Si)/s, thus requiring the radia-

tion testing to take a much longer period (up to 120 days). This is because, paradoxically, some components are more affected by slower rates of radiation than by faster rates. Fortunately, the primary components susceptible to ELDRS are bipolar semiconductors, and if they're not used, it's not necessary to test ELDRS.

Single-event effect (SEE)

SEE is a very important type of radiation that comes in several forms. Single events are caused by any singular impact of either a particle (usually a heavy ion), and the magnitude of the event is measured in MeV.

A key difference between the effects of TID and SEE is that TID is a cumulative effect that builds up over time, from all types of ambient radiation, while SEE damage happens almost instantaneously from a highly energetic particle impacting a semiconductor device. Because the line spacing of integrated circuits keeps shrinking, a particle impact can cause a short between two lines. The short, or other catastrophic damage, could result in a dead device.

SEE events are broken up into at least three major types of transients, which are, in increasing order of severity, as follows:

- Single-event transient (SET)
- Single-event upset (SEU)
- Single-event latch-up (SEL)

An **SET** happens when the charge collected from an ionization event discharges in the form of a spurious signal traveling through the circuit. It is, de facto, the effect of an electrostatic-discharge (ESD) event. Many modern components have some form of SET. Although it is a "soft" error and is reversible, it is important to carefully characterize each SET.

If it's a very short distortion of a wave cycle, perhaps of only a few nanoseconds, it may be perfectly acceptable in some applications. SET events that completely self-recover are the least disastrous SEE events, but they're still certainly important because they can sometimes disqualify a part from being used in its intended application.

An **SEU** is the next most serious type of single-event transient. SEU events are state changes of memory or register bits caused by a single ion interacting with the chip. Although they don't cause lasting damage to the device, they can lead to lasting problems when a system isn't able to recover from such an error.

Like SETs, SEUs are soft errors and are reversible. But in very sensitive devices, a single ion can cause a multiple-bit upset (MBU) in several adjacent memory cells. SEUs can become single-event functional interrupts (SEFIs) when they upset control circuits, such as state machines, placing the device into an undefined state, a test mode, or a halt. The affected system would then need a reset or put into a power

cycle to recover.

SELs are the worst SEE of all. SEL events result in a semiconductor "latching up" or dying. Unlike SETs and SEUs, SELs won't self-recover. The event can occur when a heavy ion or a high-energy proton passes through a semiconductor, causing a short (an effect known as latch-up) at least until the device is power-cycled back on. Because the effect can happen between the power source and substrate, destructively high current can be involved and may cause other problems in the circuit.

Bulk CMOS devices are particularly susceptible to SELs. Because this is a hard and irreversible error, a SEL is never acceptable for any space application.

Conclusion

There are many other kinds of radiation. Each type mentioned above has many layers of important details and nuances not covered in this discussion. It's hoped that this article provides some understanding of the scope involved when dealing with the effects of radiation on crystal oscillators used in space applications.



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