The Space-COTS Dilemma

Can you have your cake and eat it too?

TELEDYNE e2V
HIREL ELECTRONICS

Overview

It's a cliché to say that cellphones are a marvel of computing power, one that is comparable to the supercomputers of only a few decades ago. However, it is astonishing the amount of leading-edge componentry available inside one for such a low price. That same cellphone is also a big driver of the need for more network system bandwidth. Satellite designers have to meet the challenge of satisfying a portion of that bandwidth and tend to look on in envy at the technology available to phone designers. So why can't satellite designers use the same parts catalog available to phone engineers at Apple and Samsung? The answer isn't simple, and how close to this ideal is possible depends upon the degree of risk that is acceptable to a satellite project. Note that the discussions that follow apply to many military applications also, particularly airborne platforms that are exposed to appreciable levels of atmospheric radiation.

The Evolution of Space Communications

As has been widely reported, there have been sizable investments in satellite constellations, along with lots of debate about their economic and performance claims. Whereas traditional satellites cost a billion dollars for one, the current vogue is to compete with these "exquisite" assets with large groups of lower flying, lower cost, small satellites. The question is how to get the cost down while still being able to get the job done?

Different Industries, Different Needs

To answer this, we'll first look at the spectrum of needs across different industries shown in Figure 1 below.

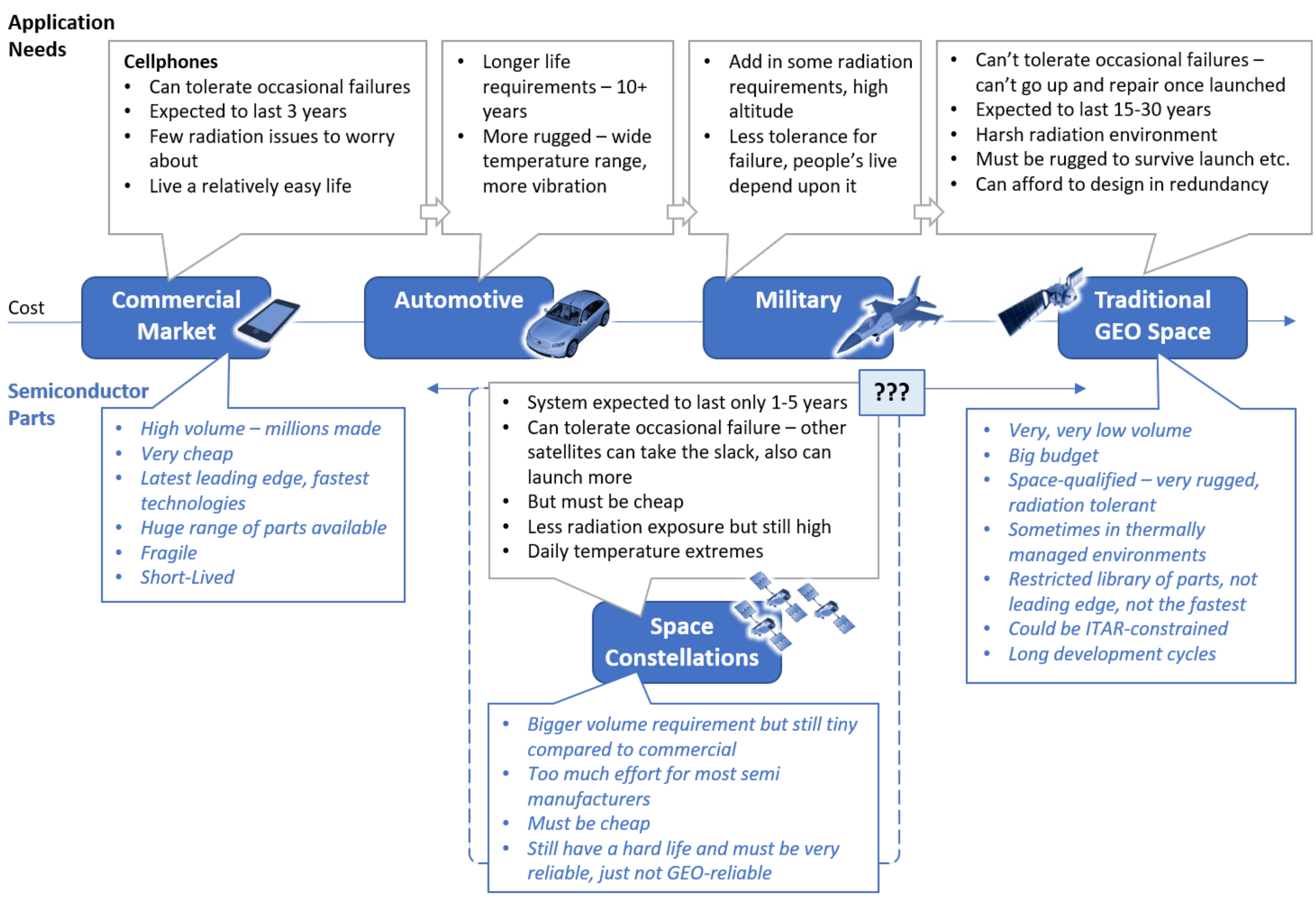


Figure 1: Comparing needs of different end markets for semiconductors

On the left, commercial semiconductors (COTS, or Commercial-off-the Shelf) are high volume and relatively cheap. They're leading edge, with a huge variety of sophisticated functionality readily available. On the downside, they don't have to last very long, they're fragile, and models come and go so they aren't purchasable for an extended period. Crucially, such parts don't have to deal with a lot of radiation exposure, and if they fail Amazon will send you a new phone. You can probably see where this is headed – at the other extreme, one-off billion-dollar exquisite satellites are the opposite on almost every measure. Careers end if satellites like these fail, and so the parts used are tested extensively and expensively.

In between these extremes are a range of applications with differing needs and methods of testing. Moving to the right in Figure 1 and, in general, the degree of resilience increases, as does the cost, but the number of component types available decreases substantially, and the parts that are qualified for use tend to be older designs. It is said that the highest level space parts often lags commercial by up to 20 years.

How Much Risk Can You Take?

Makers of constellations have some advantages over the designers of traditional satellites. These include an ability to take more risk of failure because constellations of a thousand satellites are more tolerant of a few dying, and their relatively low cost allows replacements to be launched. On the flip side, intuitively, a thousand satellites can't be allowed to cost a billion dollars each, so costs must be several orders of magnitude lower for the economics to work. However, working against this is the part quantities – whereas traditional space might want 10 or 100 of a particular part, constellations might need a thousand – many more, but tiny in the grand scheme of cellphone semiconductors, so most chip manufacturers don't want to touch all of the hassle that goes along with selling space parts.

Why is Space so Hard?

While the answer to this question has filled many PhD theses over decades, there are some examples of why space is hard on semiconductors in Figure 2 below.

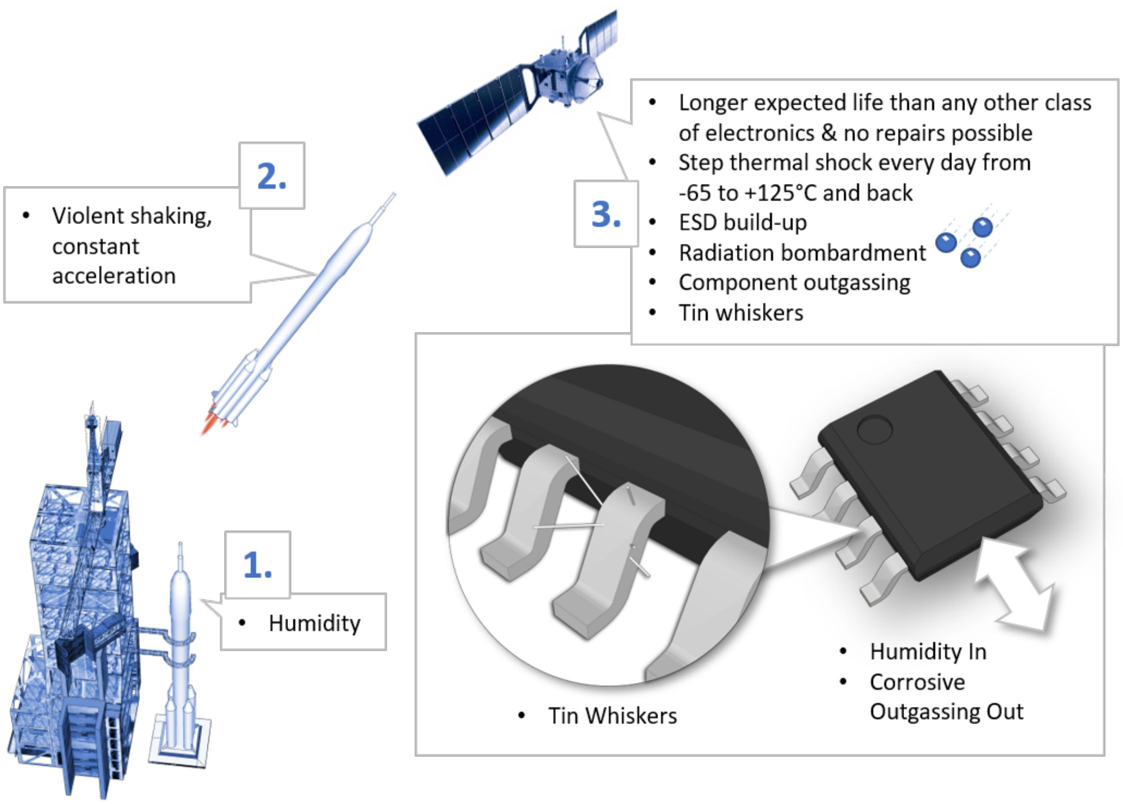


Figure 2: Examples of hostile aspects of using semiconductors in space

These include:

- Launch – while satellites float majestically in orbit, the first few minutes of their journey to space are violent, to much higher levels than expected for automotive, for example.
- Temperature extremes – space may be a near-void, but orbiting satellites typically undergo step-function changes in temperature as they go between full sun and the earth's shadow, suffering frequent and regular thermal shock from perhaps -65 to +125°C. Large and expensive satellites sometimes have heating and cooling systems on board which reduce this, but lower cost ones do not. Some orbits result in these step changes dozens of times a day.
- Radiation – a huge category which encompasses electromagnetic radiation through to subatomic particles to ions of different sizes and energies, responsible for an extensive range of issues. The amount and types of radiation a satellite will have to tolerate will vary depending upon the altitude of orbit, with Low Earth Orbit (LEO) constellations seeing less of some types than exquisite GEO, or geostationary orbit, satellites. In fact, even with shielding from radiation, most GEO satellites receive enough radiation to kill a human in just a few months[1]. Some semiconductors are more prone to these effects than others. Often logic, switch drivers, and processors are CMOS-based, and can thus suffer badly, whereas. RF circuits based on GaAs, and more recently, power circuits in GaN, can be less affected.
- It has been said that a large percentage of space failures are from ESD (Electro-Static Discharge). Frequently this comes from device package lids not being properly grounded, which allows charge to build up from showers of cosmic electrons.
- Packaging of semiconductors can have its own issues:
  - Plastic - packaged parts were replaced by hermetically sealed parts in military and space long ago because plastic can sometimes outgas, coating nearby components in chemicals that cause corrosion. The non-hermetic sealing can also allow humidity into packages, particularly on the launchpad in humid locations, ultimately leading to corrosion of the semiconductor inside.
  - The move to RoHS, or lead-free solder in commercial electronics has been good for the planet, but less helpful to space electronics. A phenomenon known as 'tin whiskers' can occur when not enough lead is present, where tiny hairs of tin grow and can eventually short between critical parts of circuits. Growth rates from 0.03 to 9 mm/year have been reported[2]. For this reason, space parts typically have leads dipped in tin-lead solder.

For these and other reasons, up to 50% of smaller satellites fail before their mission was supposed to end. While smallsats are significantly less expensive than the large GEO satellites, they are still expensive to design, assemble, test and launch. They are complex systems with multiple sub-systems all designed to work in conjunction to accomplish a given objective. In these complex systems, all it takes is one IC to fail, and the satellite malfunctions.

[1] https://www.powerelectronics.com/technologies/power-electronics-systems/article/21854012/preemptive-testing-can-mitigate-cosmic-radiation-effects

[2] https://nepp.nasa.gov/WHISKER/background/index.htm

Dying Before My Time

Everything must die eventually, including semiconductors. An old but good mental model of general reliability of electronics is the bathtub – the observation that frequently parts die in largest numbers early in their operational life (infant mortality), often due to process and workmanship variations; if the design is well understood, the failure rate settles down to a relatively modest and constant level, and the causes of failures tend to be random. Eventually wear-out mechanisms dominate, and the number of failures rise at the end of the useful life. A sketch of this is shown in Figure 3 (a). Obviously, something as complicated as a satellite is a system made up of thousands of parts and is only as good as the weakest link - the failure of individual parts can bring the whole system down.

For space there are additional issues affecting reliability to overlay, including radiation, as shown in Figure 3 (b). Broadly speaking, these effects can be cumulative, and as they accumulate they affect some kinds of semiconductors more than others as mentioned. For example, the leakage in the many transistors that make up integrated circuits can rise over time, or the threshold switching voltage can change, eventually affecting behavior. Alternatively, single events can be damaging depending on their energy, mass and where they hit; they can cause transitory events like a logic 'one' being read as a 'zero', or more serious latch-up events where a whole satellite might need to be rebooted, if it can be salvaged at all.

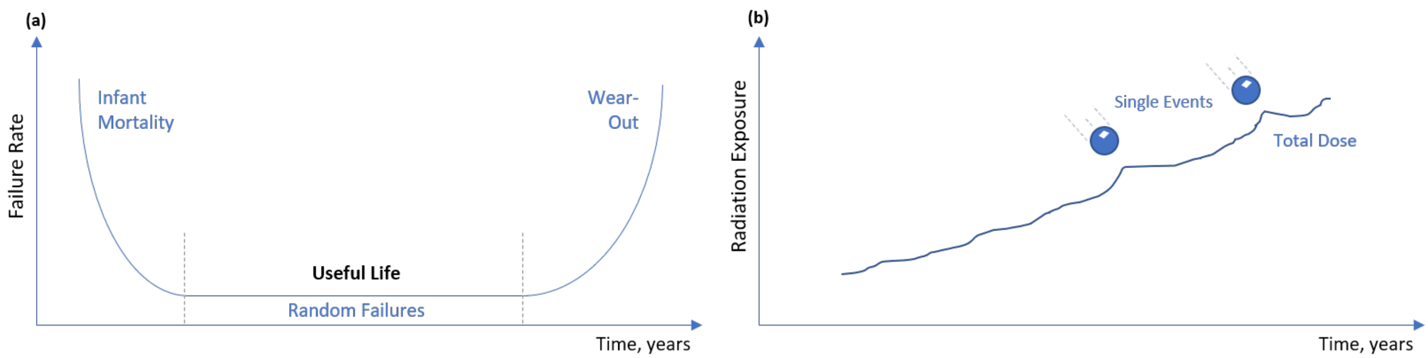


Figure 3: (a) Illustrates the bathtub model of electronic reliability performance over time. (b) shows the accumulation of radiation effects over time (Total Ionizing Dose, or TID), with occasional events of large energetic particles hitting crucial locations in circuits.

But it's So Expensive...

It's impossible to be certain that a part won't fail at any given time, so space-on-a-budget is all about balancing risk against expense. Decades of experience by engineers in traditional space have led to methods that reduce risk extensively, but the costs and time involved are very high. Examples include:

- Design a new part from the ground up for space, or pay a foundry to take an existing part and redesign it in the right way. If you can find a company to do it, this can mean $4-6M, and a risk that the part will become export controlled.
- Characterize the radiation tolerance of individual wafers and keep track of where on each wafer a particular device came from. Typically process control of wafer manufacture is most accurate in the center of a wafer, so typically for space applications, at a minimum, a percentage of devices around the edge will be thrown away, reducing yield and increasing expense. Lot traceability means tracking individual devices from when they are diced up all the way through to packaging and test, with extensive documentation to prove it. This is difficult and expensive to do, and doesn't fit with the typical process flows of high volume semiconductor suppliers. These concepts are shown in Figure 4.

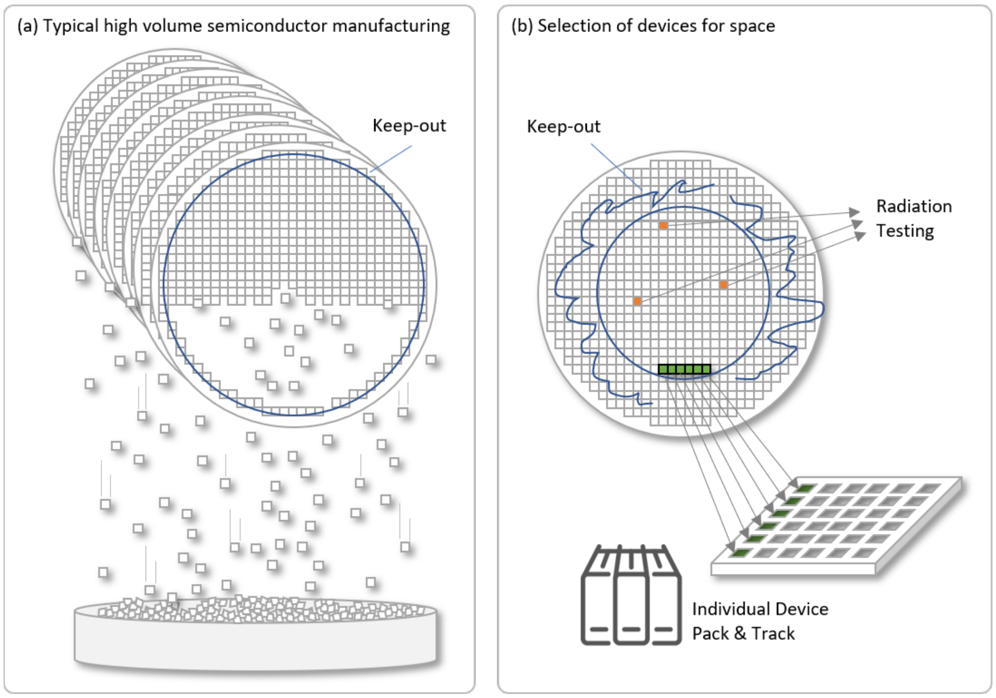


Figure 4: (a) Typical high volume semiconductor manufacturing is heavily automated, with most devices on a wafer usable for commercial applications; parts from different locations on a wafer, and from different wafers are mixed together.
(b) In space applications, radiation tolerance can vary by wafer, and by location on the wafer. The area on the wafer where devices are discarded is larger, and the precise location of devices picked is tracked carefully and documented throughout the manufacturing, packaging and test processes

- Package devices carefully in rugged ceramic packages which provide hermetic sealing.
- Perform extensive testing at all stages, from radiation testing with a variety of different radiation types to establish tolerance, through to extensive shake, rattle and roll, burn-in and electrical stress testing to weed out failures from process and workmanship issues.
- Provide as much radiation shielding as practical on the spacecraft. Shielding effectiveness can depend upon material and thickness, but even then, only provide protection from some types of radiation.
- Provide temperature-controlled environments on the spacecraft. This only works for large spacecraft with large power, cost and weight budgets.
- Replicate circuits to provide architectural redundancy. There might be two or three copies of critical circuits either running or turned off to minimize aging.
- Many of these options are simply not open to designers of smallsat constellations for reasons of cost, project timeline, size or weight constraints.

Ready for Some Excitement?

While the topic of semiconductor part qualification and screening for space is never going to count as exciting reading, it can be pretty exciting for the devices undergoing screening themselves. It is worth taking a minute to look at how this is typically done. The approach is to make sure that the underlying design is ok, then do the following:

1. Test to make sure the parts are radiation tolerant up to an acceptable level of the types of radiation expected - as much as is practical. Given that radiation tolerance of components often varies by wafer and by position on the wafer, individual devices must be tracked from before they are diced up, through all subsequent stages, and have a documentation trail to back this up. This is very important.

2. Weed out devices that would form the infant mortality part of the bathtub curve because of workmanship issues such as poor wire bonds, packaging issues etc., or process problems, such as slight mask misalignments during manufacture that can cause failures later. Testing is accomplished through electrical and temperature stress testing and burn-in. These tend to be a combination of steps applied to the whole batch, then more extreme steps applied to a smaller number of parts. The latter are tested and discarded but demonstrate that the remaining devices in the batch are likely to be robust enough.

By the end of these steps we should have reasonable confidence that we have sufficiently well made, good devices, with enough miles on the clock that they are through the infant mortality part of the bathtub curve, and individually traced and documented to be tolerant enough of radiation for the mission ahead.

Take a commercial part and put it on a rocket – What could possibly go wrong?

Going back to the questions raised at the beginning, the aim is to see whether variants of commercial parts can be used in space while keeping risk within acceptable bounds for the mission parameters and architecture, and whether this can be done at lower cost and faster than would traditionally have been done for a space program. Can space reliability be created on the cheap?
Some possibilities include:

1. One option is to buy the standard commercial plastic device, then employ a 3rd-party test facility to screen components to various additional criteria. However, once the 3rd party exercises the device beyond the commercial limits, there is no recourse upon failure; the user loses the cost of the devices plus testing.
2. Another option is to use devices that have been qualified for automotive use per AEC-Q100[3]. These devices have successfully passed very stringent automotive qualification and test criteria and are a 'cut above' standard COTS but with one glaring deficiency: the automotive market is not concerned with radiation effects. So, the satellite designers must research the technology the automotive device is fabricated with to get an indication of potential radiation tolerance. The commercial organizations supporting these devices are not always forthcoming with internal design & process information, especially for inquiries related to relatively small volumes needed for space designs.
3. The next option for the space COTS designer is to evaluate devices packaged in ceramic and qualified for military and defense applications. But, similar to the automotive choices, radiation tolerance is not part of the qualification of these devices. Therefore, the satellite designer must research the underlying technology to estimate the potential radiation tolerance. The number of device types available in ceramic packaging in this segment is also much lower, and they often lag in performance factors such as speed, CPU performance, power efficiency etc.

[3] http://aecouncil.com/AECDocuments.html

A summary is shown in Figure 5 below.

Parameter	Commercial 	Automotive 	Military 	GEO 
Thermal Extremes	No	Yes	Yes	Yes, major
Rugged	No	Yes	Yes	Yes
Radiation Tolerance	No	No	Generally not	Yes
Hermetic Packaging	No	No	Yes	Yes
RoHS	No Pb	No Pb	Pb ✓	Pb ✓

Figure 5: Comparing space-relevant parameters to different classes of semiconductor

Taking parts from non-space categories is likely to have a higher probability of success the further to the right you go in the table. In each case, the radiation performance is a missing factor that needs to be established early. For many traditional space applications, a minimum TID (Total Ionizing Dose) tolerance of 100 or 200 krad(Si) might be required, whereas for LEO constellations, 20-30 krad(Si) might be acceptable given the lower radiation exposure at these orbits and the shorter mission life. An example of some of the tradeoffs with using a plastic part for a short low orbit mission are shown in Figure 6.

	Commercial Plastic 	Full Space-Qualified Ceramic 	Space-COTS, short mission LEO 
Tin-Lead-Dipped Leads	×	✓	✓ Can be applied to plastic parts to stop tin whiskers
Thermal Shock	×	✓	✓ Still important, temperature cycling will be used in screening. (Less likely to be a problem on ceramic-packaged parts)
Radiation Tolerance	×	✓	✓ Get away with 20 or 30 instead of 100 krad(Si)?
Moisture Ingress Resistant	×	✓	✓ Assume mission duration short enough
Outgassing-free	×	✓	✓ Assume mission duration short enough

Figure 6: Example trade-offs for a plastic part in a short low orbit mission

A comparison of some process flows for Space-COTS are shown in Figure 7.

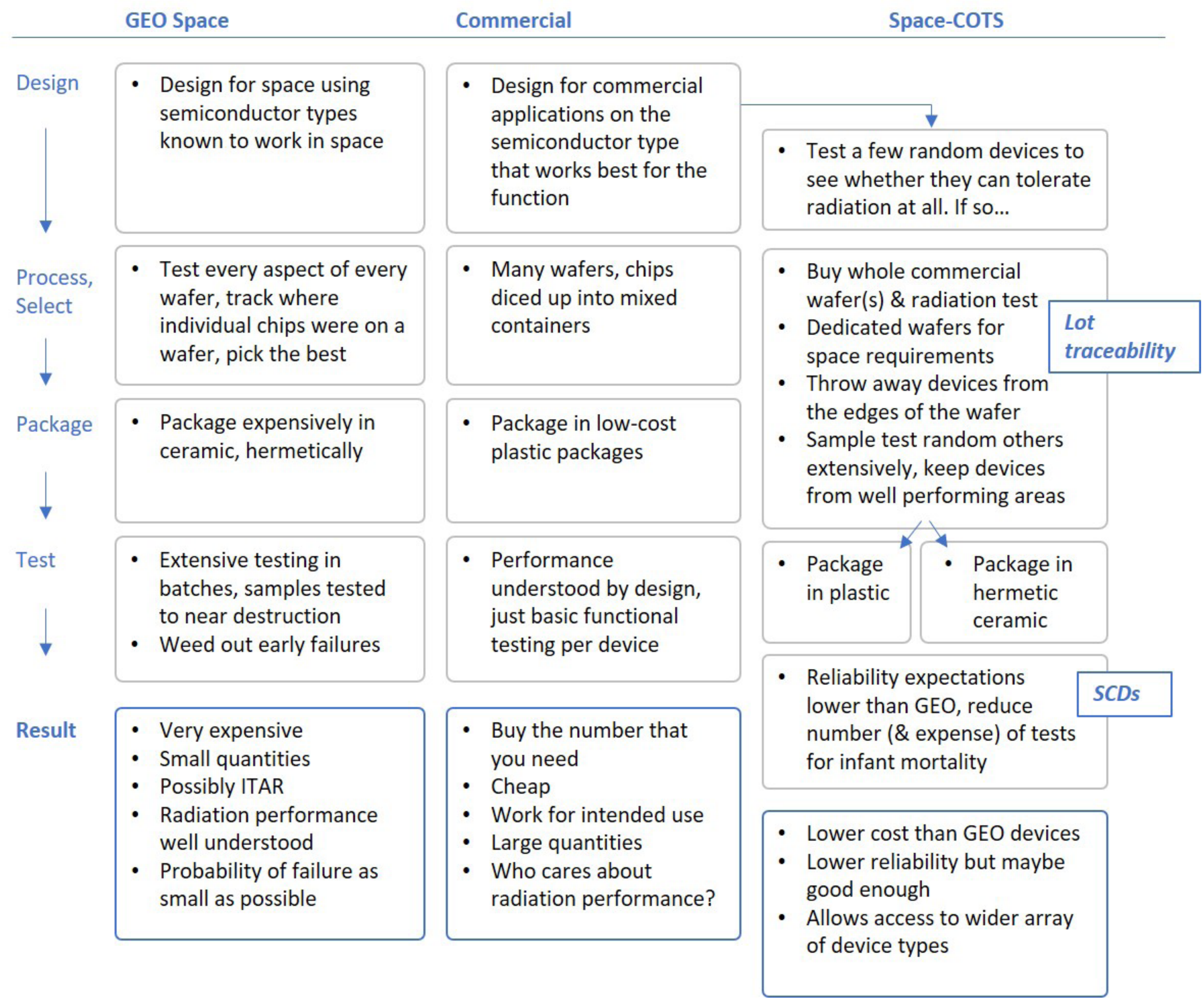


Figure 7: Comparing semiconductor part selection and screening

Here Comes the Advertising Part...

Teledyne e2v HiRel Electronics is a leader in this area, with a long history working with customers who have tried all of these options. We supply semiconductor parts qualified for the GEO market, but also tailored for the lower cost constellation and military markets. One way of keeping costs down is to offer a standard range of parts with the type and degree of testing adjusted to customer requirements ("Source Control Documents" or SCDs). Typically, we work with selected semiconductor vendors who have no interest in servicing the military or space markets, but design and manufacture leading edge devices with a high probability of passing radiation tolerance. We will buy, characterize and store whole wafers of devices, either for us, or at the direction of customers. We will then characterize to their SCD and provide surety of supply and a detailed documentation trail when requested to do so.

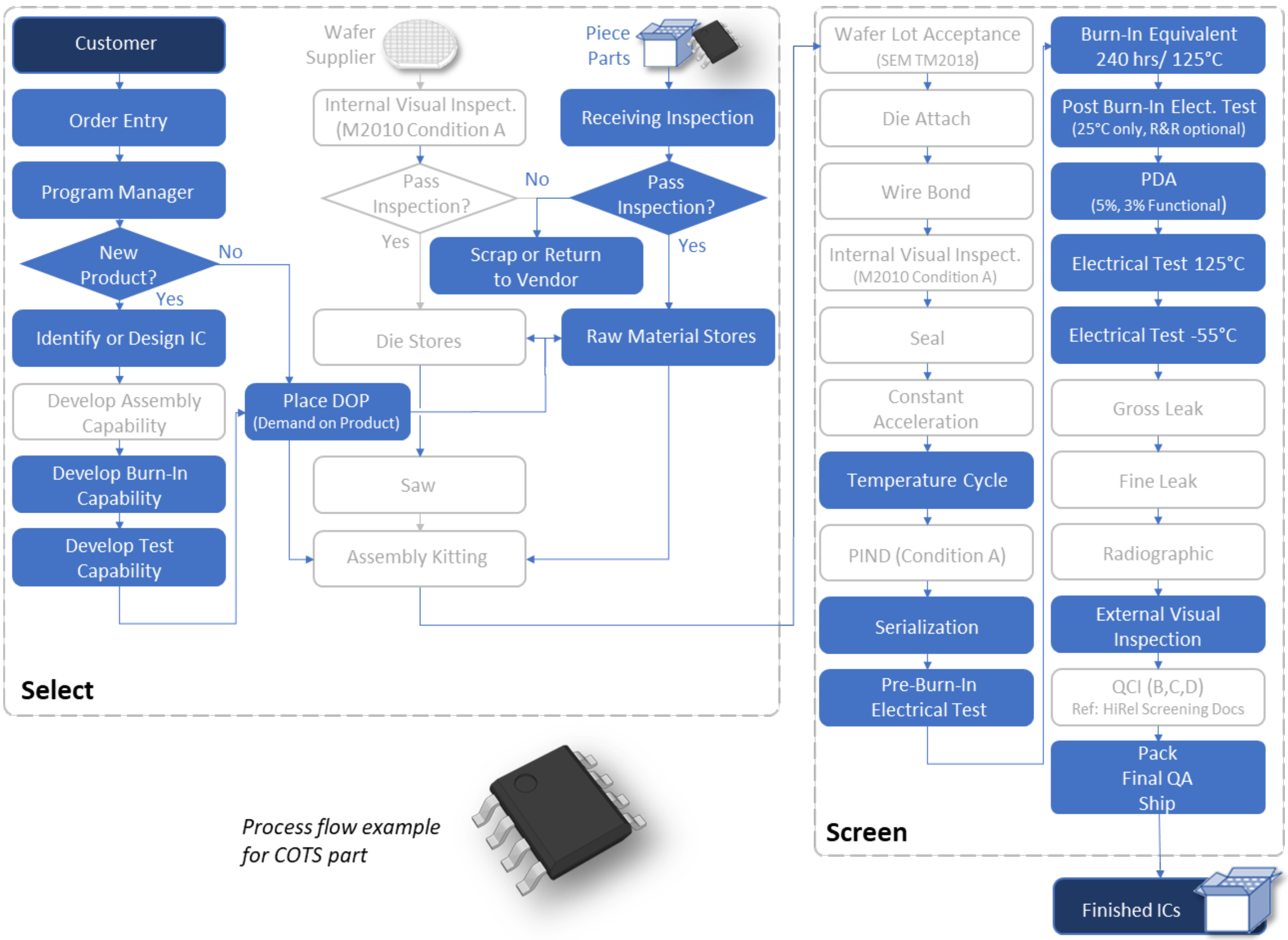


Figure 8: An example process flow for a plastic space-COTS part

Figure 8 shows a typical process flow for a part. The steps show the flow for an example GEO qualification for a part, and then shows the steps that the customer asked us to omit for their space-COTS part greyed out.

The flow is divided into two sections:

1. Selection - where we work with a customer to capture requirements, find or design parts that are either packaged or wafer-level, then buy them, prepare them and store them. This is where NRE expense is often involved, particularly in designing custom burn-in and test fixturing for a particular device.
2. Screening - This is where we've worked with a customer to decide how much testing, of which types, will fulfill their budget and risk targets. It can rely on previous radiation data for the batch, or involve additional custom testing.

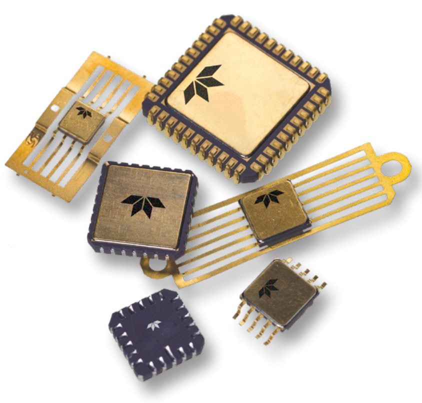
In the fuller flow, many of the steps are to verify that packaging and assembly were done correctly, (particularly if chips are packaged in ceramic packages) and potentially providing documentary evidence of this. The space-COTS flow above includes temperature cycling and some degree of burn-in. Electrical testing before and after burn-in looks for performance drift and disqualifies devices that deviate too much. In this example, the flow provides the right degree of confidence for the customer and mission.

Lessons Learned

- Most semiconductor companies have abandoned space because it is both very difficult, and also hard to make money on. Volumes are low, testing is exhaustive, and the documentation requirements are huge. The reality is that space-COTS does not change this equation greatly, and so for the economics to work for us there needs to be a combination of per-part cost and NRE that add together to make business sense.
- It is increasingly common for us to get requests for parts to be supplied in plastic packaging rather than ceramic, in the belief that this will save cost, and after all, isn't space a vacuum anyway? Often the reality is that by the time NRE has been spent on burn-in and test fixturing, not much cost has been saved. For this reason, we will often recommend repackaging critical parts in ceramic.
- Plastic parts often suffer when undergoing thermal shock. Typically, the die and lead frame inside the package are encapsulated in plastic, and repeated thermal cycling can cause breakage internally, either disconnecting bonds or allowing moisture ingress and semiconductor/bond pad delamination.
- Buying and qualifying a single dedicated wafer of devices significantly reduces concerns of process and lot-to-lot variability
- The number of standards and testing regimes is bewildering. A helpful poster/PDF comparison is available[4].

Summary

For shorter missions and lower-flying platforms that can tolerate more risk than a typical major GEO satellite, the breadth and recency of devices that are available broadens considerably. While it is unlikely that a typical smart phone chipset will have sufficient radiation tolerance to be useful, many devices that would not have been considered in earlier times become potential candidates. We have looked at the environmental challenges that face devices in space, and some screening methods to weed out infant mortality and establish some degree of radiation tolerance. The reality is that customers are putting commercial-grade semiconductors in space, and are seeing failures because of this[5], but the loss of satellites in large constellations so far are seen as acceptable given the number of and costs involved.



Teledyne e2v HiRel Electronics works with customers requiring components from constellations to the longest mission GEO satellites. We provide fully custom parts and screening flows, but also an increasing portfolio of qualified RF, power GaN and integrated products that can be customized as needed through SCDs. These range from GaN power HEMTs, drivers and POL modules, to PLLs, gain blocks, switches and more.

[4] https://www.teledyne-e2v.com/content/uploads/2018/07/Space_Flows_Comparison_Chart_TE2VSFCC_V1.pdf

[5] https://spacenews.com/starlink-failures-highlight-space-sustainability-concerns/

Global Sales Office

Teledyne e2v HiRel Electronics
765 Sycamore Drive
Milpitas, CA 95035 USA
Tel: +1 (408) 737 0992
Fax: +1 (408) 736 8708
tdemarketing@teledyne.com

TELEDYNE e2V
HIREL ELECTRONICS

www.tdehirel.com