Addressing the Environmental and Operational Issues for Data Acquisition Systems Onboard Space Launch Vehicles

Read About

COTS data acquisition for Space applications

Environmental ruggedness

Introduction

Over recent years, the world of space flight testing has changed dramatically. This is driven firstly by an increase in the number of players in the market with the rise of private and commercially driven space vehicle development companies (e.g. SpaceX, Orbital Sciences, Scaled Composites, RocketLab) and the growth of space programs in other countries such as China, India and Japan. Secondly, these and traditional players such as NASA, ESA and Boeing are seeking to cut costs and speed development by using Commercial-Off-The-Shelf (COTS) equipment which has resulted in these companies selecting and using equipment previously only validated in commercial and military flight testing.

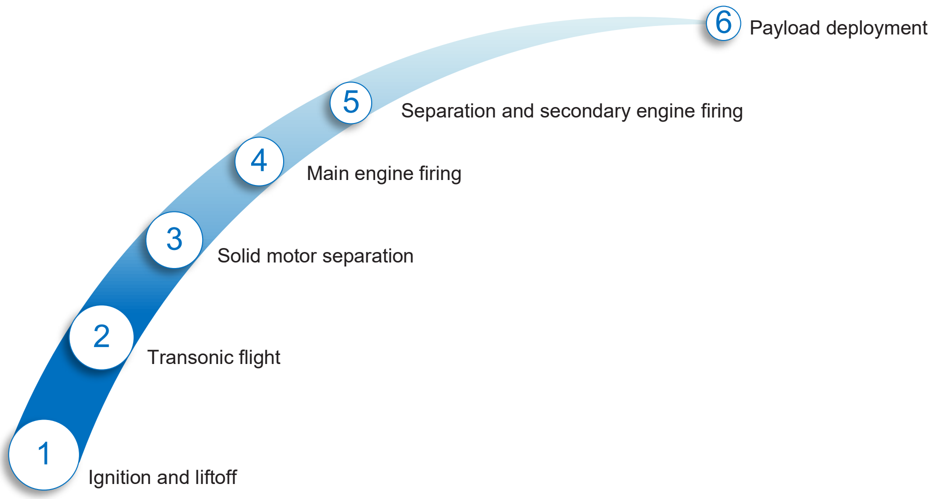

Figure 1: Key points of stress in a typical launcher profile

However, the environment experienced by equipment in space and during launch is very different from that experienced in terrestrial environments. So it is not sufficient to just take a system that has proven performance in, for example, a military jet and expect that it will operate effectively and reliably in a launch vehicle. In addition, there are peculiarities in the vehicles themselves that present special challenges to the suppliers of flight test equipment.

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These include

- Non-reusable vehicles that require all data to be telemetered from the vehicle. However, the environment during take-off prevents reliable telemetering meaning that data must be retrieved after take-off, but before destruction, during the flight path.
- Radical changes to the instrumentation topology during the mission, as sections of the vehicle detach possibly carrying sub-sections of the flight test instrumentation network with them.
- Large vehicles requiring data to be transferred over 50-100m of cabling at high speeds.
- Instrumentation on orbiting vehicles may be “out of sight” of ground receiving stations for long periods of time, requiring a capability for on-board recording and transmission on demand.

This white paper looks in more detail at the environmental and operational issues for space launch vehicles (although such applies for many other space mission types) and suggests solutions based on existing ruggedized COTS data acquisition systems (DAS).

Environmental Issues

The environmental shock and vibration experienced by equipment during launch and the journey into orbit tends to be much more extreme than that experienced by equipment during terrestrial flight. The nature of the exposure depends on the stage of flight but tends to be much harsher during the initial stages (ignition, lift-off and transonic flight) than later on. However, each of the later stages (stage separation, secondary engine firings etc.) provides brief transient shocks.

Launch

During launch the main source of dynamic loading is from acoustic noise generating vibrations within the structure and from the vibration associated with the engine and flight. The acoustic pressures range in frequency from 30 Hz to 10 kHz while the engine induced vibration are of lower frequency (10 Hz to 2 kHz typically) with peak power spectral densities reaching 1.6 g^2/Hz or more.

Separation

The main environmental effect of stage separation is the shock associated with the pyrotechnic methods for inducing the separation or with the release of structural strain. This can expose the vehicle to transient shocks of 2,000 g or more.

Orbit

During launch, but especially in orbit, the equipment is subjected to extremes of temperature change. The issue here is not so much the actual temperatures themselves, as the rate at which temperature changes can occur which affect both accuracy of sensor measurement, and creates the risk of damage due to condensation on the electronics. Another issue which needs to be taken into account is that the unit will be operating in a near complete vacuum. This has implications for the component selection and for heat dissipation in the unit.

Once in orbit the units operate in a steady (very low) thermal environment but are exposed to much higher levels of radiation than terrestrial devices. In the space environment, very high energy particles (> 10 MeV) cause single event effects (SEEs). These manifest mainly as single event upsets (SEUs) where a single bit flips in a memory cell possibly altering system configuration, or as latch-up in larger/power transistors, which can be destructive. Note that the vast majority of high energy particles are present in the Van-Allen radiation belts, which begin at altitudes above 300 km.

Selecting equipment for space vehicle instrumentation

The first step to selecting flight test instrumentation for a space vehicle is a realistic assessment of the environmental stresses that the equipment will actually experience. This includes looking at where and how the equipment will be mounted in the vehicle. Unfortunately, due to the nature of the task that instrumentation is being asked to perform, it is often mounted in hostile locations (e.g. near the engines).

When it comes to assessing system performance given the shock and vibration envelope there is no substitute for testing the unit. For example, a DAS can be put through a series of environmental tests aimed at establishing its ability to survive the launch profile. The results of this can be used to recommend non-compliance, compliance after minor modifications, such as mechanical and some component changes, or compliance. The lessons learned during those tests can also be incorporated into the COTS standard product, making them also capable of operating on a launch vehicle.

Similarly, thermal shock testing is required to validate the units for operation in space. Finally, the design of the system needs to take account of radiation effects. Avoid systems based around large microprocessors with large amounts of vulnerable data and programs stored in memory devices.

Instead look for radiation tolerant technologies (such as Actel FPGAs). Some data acquisition units (DAU) use built in state-machine architectures to refresh and reset volatile memory frequently (10s of times a second) to erase any transient errors due to SEUs and are thus more suitable to operating in an orbiting environment. The issue of latch-up is more difficult to resolve but there are options for latch-up detection and power-cycle circuits to resolve it.

Operational Issues

The behavior and actions of launch vehicles pose some interesting operational issues that are rarely encountered during terrestrial flight testing. During the vehicles mission, the shape and topology of the vehicle changes dramatically as sections separate and are discarded. It makes sense to also discard any flight test instrumentation associated with the lost sections to reduce power and weight. This presents a challenge for the flight test instrumentation network, as nodes will be lost dynamically during the test. There are two common scenarios

1. At launch, all FTI units operate synchronously and record or telemeter their data as required. When separation occurs, the slave nodes and all associated data are lost.
2. At launch, all FTI units operate synchronously as a single distributed data acquisition system in a traditional master/slave configuration. However, after separation, the expectation is that the discarded stage will be recovered. In this scenario it is not unusual to place a recorder in the discarded stage to capture all data during launch, including post-separation data from the discarded stage. So the operational requirement is for the slave nodes in the discarded stage to continue to operate as though the master was still present.

With the right instrumentation both of these scenarios can be covered using one of two possible FTI network topologies: traditional master/slave or distributed Ethernet network. In traditional master/slave one chassis is nominated the master and acts as a data aggregator and time/synchronicity controller for all FTI nodes. This unit is located in the continuing stage. During separation two things happen – the continuing stage master may (optionally) switch sampling strategies to save transmission and/or recording bandwidth, reusing spectrum formerly occupied by the data from the slaves in the discarded section.

In the discarded section, one to the slaves automatically reconfigures to be a master and continues to aggregate and record data. This can happen only if the FTI architecture is such that any chassis can be a master or a slave, its "personality" determined only by external wiring. The wiring loom is designed so that when separation occurs the "personality change" is achieved. Although this sounds complex, COTS systems exist that do this and the design has been validated in the field.

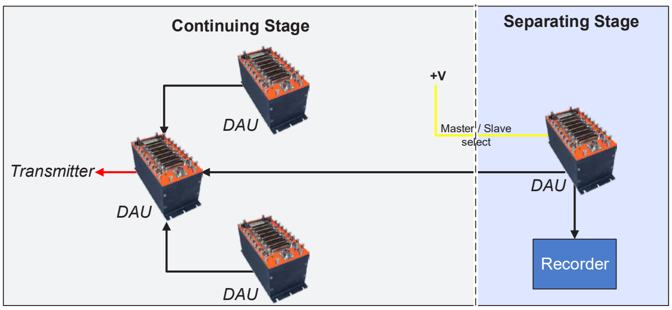

Figure 2: Conceptual view of dynamic topology

The recent advent of Ethernet based FTI equipment permits a much simpler approach to solving the same problem. In this topology, each FTI chassis is a node in an Ethernet network and there is no notion of a master or a slave. Synchronization (and isochronous sampling) is achieved via standard network techniques such as the IEEE 1588 Precision Time Protocol (PTP). When separation occurs, the effect is to lose the network packets from devices in the discarded stage. The devices in the discarded stage can continue to operate in a local network until power shut off occurs.

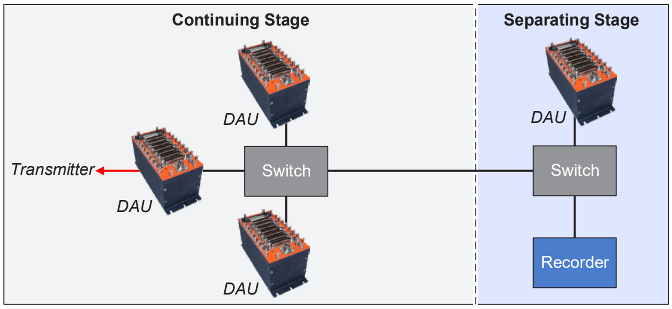

Figure 3: Conceptual view of networks data acquisition

Telemetering in a difficult environment

One of the periods of most interest during a launch is the launch instant itself. The stresses and strains on the craft and engines during ignition and take-off are about as high as they will be at any other time during the mission. Unfortunately, the nature of the launch environment is such that telemetering this data off during take-off is operationally difficult due to electromagnetic noise and interference, and limited available spectrum.

To solve this issue, some DAS can locally store the data during the take-off stage, and then begin to transmit it after a predetermined time (e.g. 30s) once stable flight has been achieved. An important element of this approach is that the transmission occurs automatically after a user set period of time – there is no requirement to send a “trigger signal” to the vehicle. Note that this solution avoids a separate recorder – the storage medium is embedded in the data acquisition unit itself and data is stored locally.

Once in orbit, a vehicle may have limited windows of opportunity to telemeter the data back to earth. Typically, an orbiting vehicle can transmit to only one or two base stations and may have a clear link to these stations for only a few hours a day.

Recorders can support a read-while-write functionality which means that the recorder acts as a traditional passive recorder for most of the time – however, when instructed (for example, through an uplink from earth) the device can start transmitting all data recorded during a specified time frame without interfering with data acquisition that is taking place concurrently. In addition, the device can accept instructions for erasure and reformatting of media to optimize media life over an extended period of time. These devices can be built around open media storage standards and protocols (SNMP and PCAP) to simplify integration into operational environments.

Utilizing this network paradigm means that the data acquisition and recording devices can be accessed and controlled using existing network links and protocols.

Long cable looms and large vehicles

Many launch vehicles consist of “interesting” areas (engines, stage junctions, instrumentation pods) separated by large chunks of not so interesting areas (fuel tanks). This results in long cable runs (anything up to 200 ft) between units in the vehicle. The issue here is that traditionally data has been transferred using CAIS or PCM (RS-422), and data rates over these kind of distances are very limited (< 1 Mbps). With these traditional approaches RS-422 repeaters are required for higher bit rates. Each repeater adds wiring complexity, weight and increases the bit error rate (BER).

However, some instrumentation available today uses state-of-the-art transceivers to transmit PCM over distances greater than 200ft at 20Mbps using RS-422. This equipment greatly simplifies the wiring and transfer of information. An alternative solution for the same problem is to use Ethernet as the data transfer medium (standard Ethernet is capable of transmitting 100 Mbps over 100 m). In such an Ethernet based network, one FTI node can be designated the PCM node and aggregate data from all other network nodes for Telemetering.

Conclusion

Space organizations are under pressure to lower the cost of launches and one way to help achieve this is through the use of lower cost COTS DAS. This paper has touched on some of the environmental and operational issues that are specific to space applications. Environmental concerns about shock, vibration and temperature can be addressed through test. Concerns about operation in a high radiation environment can be addressed by considering the design and components used in the FTI equipment, in addition to testing.

Operational concerns can be addressed at a higher level, by considering the topology and technology to use for the test instrumentation network. By focusing on simple, robust architectures and state-of-the-art technology problems with stage separation, long cabling runs and delayed telemetry can be solved. Moving to a network paradigm offers significant simplicity and re-use of existing network interfaces to access and control satellite based data acquisition units.

Although challenging, all of these problems can be solved using COTS devices available today. Curtiss-Wright has folded these considerations into our COTS DAS and provided many COTS solutions for launcher development and flight instrumentation systems. Our equipment has flown on or been selected to fly on platforms such as the Boeing CST-100, RocketLab Electron, SpaceX Falcon 9, ESA Ariane 6 and ULA Delta IV.

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