Challenges in Electronics Design and Qualification for Earth Observation Pulse Tube Space Cryocoolers

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ABSTRACT

For more than 10 years, Air Liquide Advanced Technologies has developed a broad range of cryocooler systems to address diverse applications by translating into different performance ranges of cooling power, thermal stability, and mechanical vibration. In collaboration with SITAEL, the first cryocooler drive electronics unit was developed.

For Earth Observation applications, the critical performance metrics of a cryocooler system are the cooling efficiency, the temperature stability, and the ability to minimize the levels of exported vibration. Such performance requirements induce many challenges for electronics driving and controlling the cryocooler. These challenges cover domains such as power electronics, small signal acquisitions and digital logic design.

This paper will show the importance of associating the electronics design at the highest level of system design. One major contributor to system wall-plug efficiency is the electrical power factor of the cryocooler, which drives directly the maximum output of power supply and hence power components performance. Another major contributor on the digital side is the choice of the communications bus, and the control loop drive. The choice of technology to use to implement the control logic directly the impacts the overall system efficiency.

Eventually, the selection of electrical parts is mainly driven by two factors. Some of the critical components are either under ITAR or EAR99 restriction or are not qualified according to appropriate standards. The former concerns mainly FPGA, SRAM, 16-bits ADC, a ndPWM controllers. For the latter several components generally need a qualification program to be used on satellites, such as thermal sensors, hermetic connectors and force sensors.

INTRODUCTION

Air Liquide began its space activities in the 1960s with cryogenic propellant tanks for launch vehicles. In the late 1990s, orbital space cryogenics project were started and led to three big successes; MELFI turbo Brayton cooler for ISS, HERSCHEL cryostat and PLANCK dilution cooler. All those projects focused only on the thermo-mechanical, and gas management parts. It was only with the start of CRYOSYSTEM project that Air Liquide extended its involvement to driving electronics for space cryocoolers.

Unfortunately, CRYOSYSYTEM project was terminated after a successful PDR and did not lead to a full system development. It was only with the development of space coolers for earth

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observation that Air Liquide pursued the development of a full cryocooler system. Today, LPTC coolers have successfully passed qualification campaign for the first French government application. Several orders have been placed making this product a great success in Europe. The development of the driving electronics of these coolers was one of the new challenges posed by this ambitious program.

CRYOCOOLER ELECTRONICS FUNCTIONS AND ARCHITECTURE

LPTC is a cooler aimed at a wide range of applications. Current orders already cover earth observation and weather observation, low orbit and geostationary orbit, imagers and interferometers. The diversity of the applications and users makes it difficult to settle on a limited functionality for the electronics. Instead, we made sure to incorporate the maximum number of functions and to provide for full user control for most of the system parameters. This was also deemed necessary as a risk reduction for the system development.

The main system functions to be implemented in the electronics are the following:

- Provide cold power to the cold tip.
- Ensure temperature regulation at the cold tip.
- Ensure exported micro vibration reduction.
- Report operating data.
- Sustain launch mechanical loads.
- Perform health check and report health check data.

Figure 1 shows LPTC system including mechanical cooler, driving electronics and vibration sensors. Figure 2 shows a block diagram of the cooler system with adjacent instrument environment.

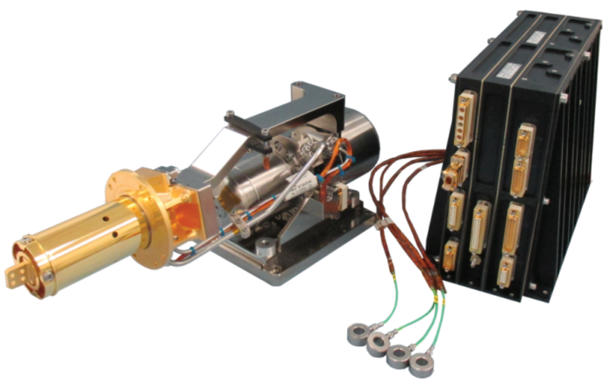

Figure 1. LPTC system overview

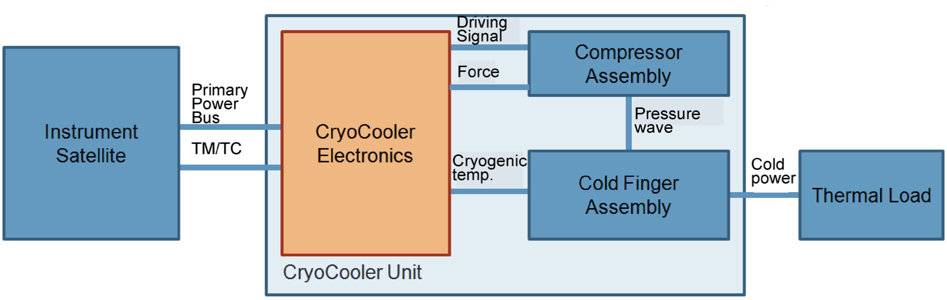

Figure 2. System block diagram

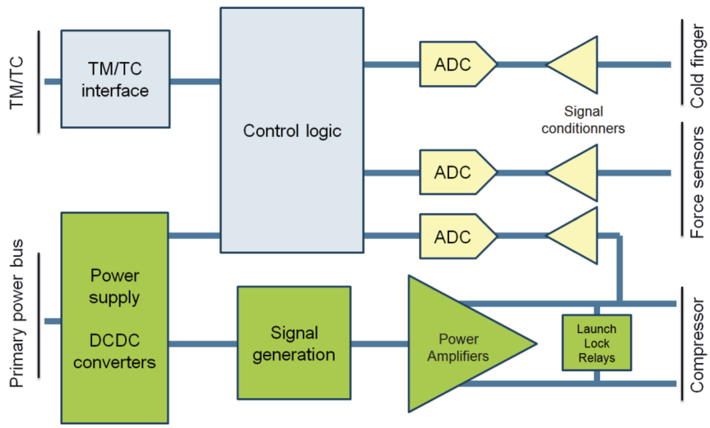

Figure 3. Driving electronics architecture

Fulfilling all of these functions and providing an interface with the instrument power bus and communication bus lead to an architecture incorporating several main blocks:

- Power conversion.
- Signal generation and amplification.
- TM/TC interface.
- Control logic.
- Sensor acquisition.

Figure 3 illustrates this architecture.

CHALLENGES FROM REQUIREMENTS

LPTC was designed and developed to provide a high level of reliability and performance. This strains the design of most parts of the system, and the electronics is no exception.

Performance requirements

The two main challenges of performance requirements are the temperature stability and the micro vibration reduction. These two functions have to be ensured for changing environmental conditions. Moreover, vibration reduction has to be ensured during cool down phase, to avoid perturbation on other satellite payload instruments.

Ensuring precise temperature and force regulation conditions the resolution of sensor acquisition chains. In our case, we seek a temperature stability better than 20mK. This requires temperature acquisition to have a resolution much better than a few mK over the whole user temperature required range. For exported forces, the target is to be able to reduce them below 50mN at operating frequency and harmonics below 500Hz. This again requires a high resolution of the sensor acquisition chain, below 10mN. On top of resolutions, accuracy and precision of the acquisition chains need also to be very good. For instance, a precision better than 1 Ω at 3 kΩ is necessary for temperature measurement.

Launch locking

A launch lock is necessary to protect compressor pistons from hitting endstops during launch. Customers require this function to be ensured with driving electronics OFF or ON. Passive (OFF) is achieved by shorting compressor coils on a resistance or RC circuit. Active locking involves an amplification circuit generating a counter motor force.

In both cases, energy is dissipated in the driving electronics but the satellite cooling system is not operating. Extra care must then be taken for the thermal control in this mode.

In the case of passive locking, the function needs to be triggered by relays operated once before launch. For reliability purpose, a series parallel combination of relays is implemented, which adds a considerable mass to the electronics. The challenge is also on relay qualification for the launch vibration environment.

Electrical interface

Depending e tsatellite, the electrical bus can be different. In the case of LPTC, we had up to 50% voltage difference between minimum and maximum supplied voltage to electronics. This, combined with requirements on low conducted emissions (CE) in common and differential modes, represents another challenge on the design, related to customer requirement. Besides the CE at high frequency, the challenge was how to reduce the CE at low frequency (mainly around 100 Hz) without impacting the mass. An active low pass filter, inside the CDE, was conceived, realized and successfully tested.

CHALLENGES FOR DESIGN

Designing a driving electronics for a cooler is always a challenge. In the case of electronics for the LPTC, two parts were a particular focus.

Power part

The main challenge on the power part comes from the fact that the cooler has a non optimal and varying power factor. The penalty of the low power factor on the efficiency is double. Parts with higher voltage rating are required, and these parts dissipate more. Moreover, reflected power needs to be absorbed. This requires filtering circuit to be added, but this cannot be done with a perfect efficiency. Table 1 illustrates the effect of voltage rating on MOSFET choice, showing the influence on dissipation.

Analog part

Temperature stability requirements are demanding to the design of the acquisition chain. Temperature sensors used in the LPTC are Cernox. An additional requirement is put on the maximum drift of the acquisition chain, which requires auto calibration to be implemented. Typical electrical requirements on the acquisition chain is 1Ω resistance resolution on a 3000Ω value. This translates into typical current probes of 100 µA and measurements of 100µV differences. To achieve this, 4 wire measurement is mandatory, but also high precision reference resistors for chain auto calibration. Design of instrumentation amplifier requires extra care.

For exported forces acquisition, we use piezo electric load washers. Typical sensitivity of the used sensor is 4 pC/N. The required resolution of force translates into measurement of currents as low as 1 pA. Achievement of this can be done only using low noise charge amplifiers. Downstream the charge amplifier, voltage measurement needs to be as low as 1mV.

Table 1. Effect of voltage rating on MOSFET dissipation

IRF P/N	Max voltage	RDSon	Max current
IRHMS57163SE	130	0.0145	45
IRHMS57160	100	0.0130	45
IRHMS57064	60	0.0060	45
IRHMS57Z60	30	0.0045	45

Force signal treatment is also a big task for the digital section. The LPTC is equipped with 4 load washers used to reconstruct 3 axis forces acting at the centre of the compressor. Induced vibration is encountered at driving frequencies and at its harmonics. This requires force signal to be transformed from time to frequency using pseudo FFT techniques. Such treatment occupies a large part of digital resources of the electronics.

EEE COMPONENTS

Several challenges come from the EEE components, technical and programmatic.

Technical challenges are related to components not in a qualified parts lists. Components such as temperature sensors, force transducers, hermetic connector and plug, coaxial connector for force transducers, are not part of European qualified parts lists. For those components, a qualification program had to be agreed and conducted. Although we did not fear any component not being suitable for application, agreement on the qualification program, formal conducting and discussion on potential test failures represents a long and not straight path. Qualification standards are often inspired from US MIL standards, requiring all environment test needed to use components in the field. Tests such as moisture, corrosion, cable pull strength are sometimes hard to fulfill. The question comes then to keep on trying to pass them, or to negotiate skipping them. In case of non skipping and failure, the subject comes again, when discussing deviation.

An additional difficulty comes from the fact that sometimes, the suppliers of the components are not familiar with space standards, which adds a product assurance additional burden to the work to be done for the qualification.

One interesting case was the piezo load washer. We went successfully through a complete qualification program for this component. It was only when reviewing the results with the customer that the question of the EEE category of the component was raised. After discussions, we concluded that the part being purely passive and not subjected to any external voltage or current, it could actually be non-EEE classified.

Some components such as relays required delta qualification because the applied environments were out of the qualification domains of the component. In our case random vibrations and shocks had to be played again at high levels to check the suitability of relays. This was actually a big risk of ending up with no technical solution. Test required to monitor micro openings of the relay during vibration. Figure 4 shows a test mounting for relay vibration qualification.

ENVIRONMENT AND QUALIFICATION CHALLENGES

Radiation

Radiation can be a problem for system availability because of SEU, SET, LET. The temperature and force regulation chains are complex and both involve a large number of parts. Studies were done to evaluate SEE scenarios and potential outages at system level.

Figure 4. Relay mounting on vibration jig

Final demonstration was done through a test simulating an outage of temperature acquisition chain. For this test, we equipped the system with a special temperature harness and disconnected the sensor manually for al limited time. This was finally the simplest way to determine the effect of acquisition chain outage on the system and demonstrate how the system could handle it successfully.

Launch lock

Qualification of the launch lock at electronics level requires closing the loop of the launch locking function on a representative device by simulating the compressor. In order to assess actual dissipations in the system in a more representative way, it was asked also to perform qualification with a real mechanical cooler, applying vibration to the complete system. This of course adds to the difficulty and programmatic aspects because it requires:

- A large shaker to accommodate a much heavier load to be vibrated
- Adapted jig for the complete system
- Monitoring of compressor voltage and currents during vibration

Figure 5 illustrates the test set up used for launch lock qualification.

Test means

Qualification tests, environment or functional require a considerable amount of test means to be designed and manufactured. Most of them are not standard devices and require a lot of engineering to ensure adequate performance in the verification task:

- Passive cooler simulators (equivalent resistor circuits)
- Active cooler simulators (reactive circuits, representing potential values of cooler electrical properties, including variable power factor)
- Force sensor simulators (considering EMC)
- Temperature sensors simulators
- EGSE for system functional testing

PROGRAMMATIC CHALLENGES

Although first electronics developments occurred early in the LPTC technological maturity development program, the launch of several flight models qualification program, concurrent to the developments of electronics represents a very big challenge.

The complete system responsibility was a premiere for Air Liquide and we had to deal with early choices in the orientation of electronics fundamental design. One big challenge on the schedule is the lead time of components. Class 1 components were required for LPTC programs, due to reli-

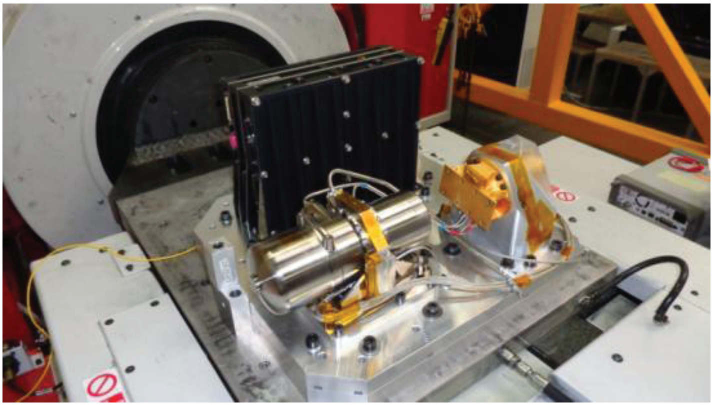

Figure 5. Launch lock vibration qualification test

ability requirements. The downside is that lead time is one year for the most critical components, meaning that design choices gave to be made very early compared to qualification tests. This leaves no margin for design modification.

Other features such as VHDL code freezing need to be done very early, and any modification of the code takes several months to be validated. Again, having to handle a code modification late in the program is extremely difficult.

CONCLUSIONS AND PERSPECTIVE

Although electronics development had been started as early as mechanical cooler technology maturation, concurrent development and qualification of electronics and mechanical cooler is a challenging task. Technically, because cryocooler electronics package the power, analog and digital functionalities in the same box, the design and qualification engineering activities have to be run in parallel.

Air Liquide was responsible for the complete development of a cryocooler system for the first time. In collaboration with SITAEL, the Cooler Drive Electronics was developed. The first and complete demonstration model was designed and manufactured six years ago. Very high level requirements, combined with a high standard ESA qualification frame put a lot of pressure on the development and qualification activities, both technically and programmatically. Some conservative choices on system functionalities and their implementations had to be made. The same for component qualifications.

Future electronics developments will benefit quite a lot from this first experience. Electronics design fundamental choices cannot be easily disconnected from cooler requirements and satellite interfaces. The emphasis of future developments will be put on efficiency, cost and development and MAIT schedule.