International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127774L · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690851

Optoelectronics parts NewSpace qualification aboard FOLC2 optical modem mission

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ABSTRACT

Since the advent of the so-called "Newspace" approach, new actors of the space industry have replaced prudent space qualification by spectacular trial and error approaches. While such disruptive method generates emulation to reduce qualification, it remains that space industry face very challenging environmental stresses such as high mechanical requirements, operation in vacuum and radiations. The purpose of this paper is to give an overview of the application of Newspace methodology that has been applied for the demonstrator FOLC2.

Keywords: NewSpace, Qualification, Optolectronics components, Optical passive components.

1. INTRODUCTION

According to forecast, global internet traffic will grow quickly in the next few years, driven mainly by the relentless increasing number of customers across the world and the streaming of high-definition videos. Satellites will play a role for answering to this internet traffic demand in particular for underserved nations and individuals who reside in rural locations. In particular, Optical feeders for geostationary High Throughput Satellites (HTS) systems based on 1.55µm wavelength technology are expected to enable to transmit up to several terabits over one active link, and therefore surpass the classical and limited RF- technology for the GEO feeder link.

To achieve the target of implementing such Optical Communications-based feeder links, in 2018, Airbus Defence and Space, decided, with partners of the consortium (iXBlue and CILAS), through the FOLC (Feeder Optical Links for Constellations) project, supported by ESA ARTES 4.0 programs, to develop, manufacture and test in laboratory environment a breadboard of the optical communication chain, composed of the optical transmitter (Tx), the optical receiver (Rx), and the optical booster. It consisted in the evaluation of the basic technologies of 1550nm wavelength required by optical modems and optical amplifiers, as well as the assessment of their associated modulation concepts [1].

In 2020, FOLC2, as a continuation of FOLC, addressed the space qualification of a generic optical modem and amplifier, to be embedded onto TELEO, a new-generation optical communications payload demonstrator, which will enable very high capacity optical feeder link communication. This IOD (In Orbit Demonstrator) will be on-board ArabSat BADR-8 satellite in 2023. This qualification should also include the Dense Wavelength Division Multiplexing (DWDM) technology known from terrestrial fiber communications, to aggregate the whole throughput of one GEO spacecraft through one feeder link.

This paper describes the New Space approach applied to the qualification of the optoelectronics parts of FOLC2. The New Space is seen here as a way to accelerate the pace of new space technology development. It is a movement towards eliminating excess capability and taking on risk with an end goal to develop space systems that are "good enough" for the mission. Final goal is to develop space satellites with extreme speed and incredible innovation.

2. JUSTIFICATION OF THE NEW SPACE APPROACH FOR FOLC2

2.1 Parts list

The optical communication chain is subdivided into several equipments: Transmission module (Tx) including the Optical Channel Emitter (OCE); Reception module including the Low Noise Optical Amplifier (LNOA) and the High Power Optical Amplifier (HPOA).

Those equipments are composed of several Commercial Off-The-Shelf (COTS) optoelectronics parts and optical passive parts, corresponding to approximately 20 different references.

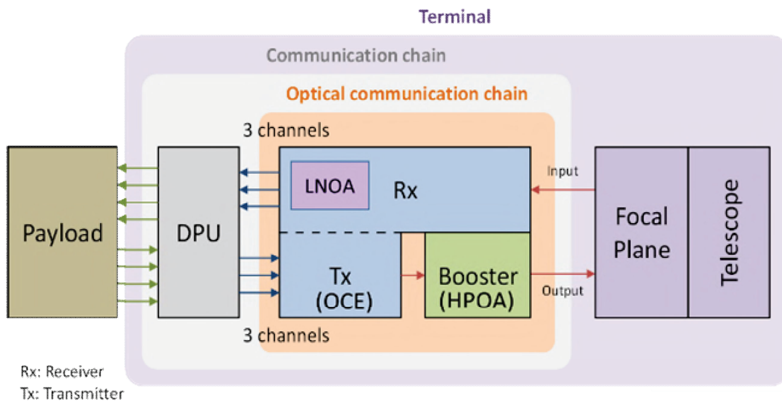

Figure 1: FOLC2 System Architecture overview

The COTS are all listed in *Table 1* and classified according to ESA family: 18 –Opto Electronics; 27 –Fiber Optics components.

Table 1 : Parts list and legacy of FOLC2 optical modem

ESA Family	Part type	Description
18-5 : Laser diode	SingleMode Pump Diode	97 nm 460mW
18-5 : Laser diode	DFB Laser	1550nm 40mW
18-4 Photodiode	Monitoring Photodiode	High efficiency 1550nm
18-4 Photodiode	High Speed Photodiode	1250-1650nm 30GHz
18-99 Miscellaneous	Mach-Zender Modulator:	1550 nm 25GHz
27-1 Optical Fiber	Optical Fiber	SM 1550 nm PM 1550 nm
27-1 Optical Fiber	Rad Er Doped fiber	1530/980nm
27-1 Optical Fiber	Rad Er/Yb doped fiber	1530/980nm
27-3 Isolators	Isolator	SM 1550nm PM 1550 nm
27-3 Isolators	Circulator	1550 nm
27-99 Miscellaneous	WDM	SM 980/1550nm PM 975/1560nm
27-99 Miscellaneous	Coupler	PM 99/1 SM 2x2 70/30 SM 2x2 99/1 PM High Power 99.9/0.01
27-99 Miscellaneous	Combiner	PM (6+1) High power 960/1560 nm
27-99 Miscellaneous	Bragg Filter	1550nm
27-2 Connector	Mini-Avim	

2.2 ECSS standard versus NewSpace

Commercial parts are eligible to the ESA standard ECSS-Q-ST-60-13C [2] which describes the generic approach for space qualification to apply. The lot acceptance test performed for each reference is described in *Figure 2*.

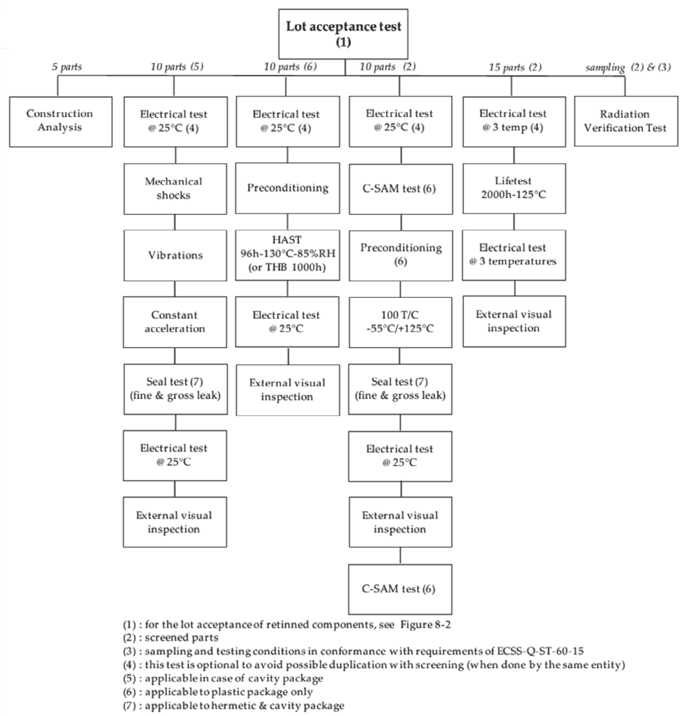

Figure 2: Lot Acceptance Test standard for ECSS-Q-ST-60-13C

According to this standard, a minimum of 50 samples are required per reference to engage a qualification. This is not really adapted to optoelectronic parts that are known to be very expensive (due to the complexity of their packaging -optical feedthrough, pigtailed devices, hermeticity constraints, high optical coupling stability requirements). In addition, the ECSS-Q-ST-60-13C does not explicitly address optoelectronics components as photodiodes and laser diodes. It does not mention optical passive components as isolators or couplers neither.
Thus, for this demonstrator project, the usual space qualification was replaced by the NewSpace approach.

The objective is to reduce the cost of spatial programs by looking to alternatives in term of selection, procurement and usage of components in order to have access to performing components not available in hirel quality level. Airbus Defence and Space has developed an internal standard [3] to define the EEE components requirements for NewSpace programs. It aims to take advantage of high volume manufacturing and associated statistical approach to address identified risks inherent to each technology and eventually to reduce the costs. Risk assessment is supported by heritage consisting both in technology know how and knowledge of the manufacturer. A majority of selected parts should be COTS to follow the NewSpace approach, and propose a cost effective solution.

3. APPLICATION OF THE NEWSPACE APPROACH

3.1 NewSpace approach

As mentioned before, the NewSpace approach relies on component legacy. The goal is to limit the cost of the qualification and upscreening. It is not required to perform tests or activities already done by the supplier or during former studies.
If the approach consists in reducing the amount of qualification tests, it is possible only because there is a strong legacy on the components, to ensure the safety of the mission.
First of all, the manufacturer/part selection is based on previous project or R&T. The awareness on the supplier is required to be confident on the tests results and data provided. The relation/knowledge with the manufacturer is the keystone of the development of the NewSpace.

Once the reference of component selected, an analysis of the information provided is required: qualification report, screening report, process flow, thermal analysis, reliability analysis etc. The data can be at component or chip level.
Every traceability information from the manufacturer is needed in order to compare the devices tested and the devices supplied for the mission.

The study of the information requires an analysis on the following points:

- The tested components shall be fully representative of the device supplied for the mission.
  If there is any impacting change on the component, it shall be covered by a new qualification. Every modification is analysed in order to identify the delta qualification required, such as a change of the epoxy of the die, it is mandatory to, at least, retest on vibrations, shocks and thermal cycling. However, radiation test is not required because it does not impact the robustness of the epoxy.
  Sometimes, the qualification is based on similar components but not 100% representative of the reference selected like, the package of the device tested during the qualification is different than the package of component for the mission. Or radiation have be performed on a different chip. In all these cases, a delta qualification is also required. The level of acceptable similarity is also function of specific failure mechanisms activated in space environment, which is different for each optoelectronic part subgroup and that can lead to specific additional qualification tests.
- The level of the tests shall cover the environment on the mission.
- The acceptance criteria for electro-optical performance shall be compliant to the mission requirement.

At the end of this analysis, the risks for each parts is identified and delta qualification tests are anticipated.
This study needs to be carry out for each mission, even if the same reference of component is selected.
In case of a replenishment of a device for an identical mission, it is required to verify that there is no change on the component. The impacting changes are the following:

- Change of Bill of Material (BOM)
- Change of Process
- Change of Design
- Change of WaferFab
- Change of Assembly Line
- Change of Screening flow

All these changes shall usually be reported in a Product Change Notification (PCN) by the manufacturer. As any modification from the list above might lead to a delta qualification, a comprehensive PCN management by the manufacturers is key to follow the New Space approach.
A construction analysis is mandatory at the first supply and when relevant, at each procurement to ensure there is no change of process on the component.

Though, all this work of data analysed is possible if and only if, there is enough information on the qualification report and if traceability on the components is available. If the data is not sufficient, or the representativeness with the supplied device cannot be demonstrated, the NewSpace approach cannot be applied.

3.2 Mitigation and derisking activities

As described before, qualification tests might be strongly reduced, if sufficient data and information on the parts are available.

They can be provided by mitigation activities that can have different origins:

- Legacy from former space projects. The component reference has already been qualified for a space mission. It is then 'only' required to compare mission's profiles and also verify the part reference dossier has remained unchanged.
  As an example here, the DFB laser and the LNOA isolators from FOLC2 were already tested for previous space project. The qualification legacy on the references allows to have a good knowledge of the robustness on these components.
  The connector Mini-AVIM is space qualified according to ECSS Generic Specification No.3420 [4].

- R&T activities carried out in advance to assess a potential risk that could call into question its eligibility for space missions. Those R&T often represent a strong interest to improve the knowledge on innovative technologies and allow to study several references and manufacturers.
  For instance here, the MultiMode Pump Diode (MMPD) reference was chosen after an R&T from CNES and Airbus Defence and Space [5]. Several references were tested: hermeticity, thermal cycling and mechanical tests were conducted.
  Similarly, dark current sensitivity under radiation of different monitoring photodiodes was studied and compared during an R&T with CNES [6].
  These former activities enable to anticipate the risk of spatialization of these technologies.

- Legacy from qualification performed by the part manufacturer.
  Most of the optoelectronics components in FOLC2 are qualified according to Bellcore/Telcordia standard.

Bellcore was a telecommunications research and development company that provided joint R&D and standards setting for the telecommunications company AT&T and its co-owners. Because of dissatisfaction with military handbook methods for their commercial products, Bellcore designed its own reliability prediction standard for commercial telecommunication products. In 1997, the company was acquired by Science Applications International Corporation (SAIC) and the company's name was changed to Telcordia. Telcordia continues to revise and update the standards. Those ones can address specific products or types of components, like optoelectronics devices with the Telcordia GR-468-CORE [8] or passive optical components with the Telcordia GR-1221-CORE [7]. The table below describes the tests required by Telcordia standards compared to the classical ECSS-Q-ST-60-13C approach.

Table 2: Comparison of test qualification required between ECSS-Q-ST-60-13C and Telcordia standards.

Test	ECSS-Q-ST-60-13C	Telcordia GR-468-CORE[8]	Telcordia GR-1221-CORE[7]
Construction analysis	X	X	
Mechanical Shock	X	X	X
Vibrations	X	X	X
Thermal Shock		X	X
Fiber Pull		X	
Ageing	X	X	
High Temp. Storage		X	X
Low Temp. Storage		X	X
Temperature Cycling	X	X	X
Damp Heat	X	X	X
Radiation	X		
Outgassing	X (in ECSS-Q-70-02A)		

As Telcordia's are not dealing with space applications, radiation and vacuum tests are not part of their requirements, and should be addressed apart.

However, most of the other tests, like environmental and endurance ones, are well covered, even if some caution shall be taken of the applied qualification levels (for instance space mechanical levels might be quite higher due to launching conditions).
Advantage of the Telcordia, compared to the classical space standard ECSS-Q-ST-60-13C, is to focus on the photonics components technologies: for instance and at the contrary to the space standard that applies a normative upper value of 125°C by default for all temperature tests, Telcordia clamps to 85°C, considering the temperature maximum rating of the optical pigtail.
Generally speaking, operating conditions offered by Telcordia are often safer for optoelectronics devices, while the generic EEE qualification approach is only partly relevant because of the diversity of materials used and the specificity of optical properties and failure mechanisms of optoelectronics parts.

As Telcordia reliability requirements were and still are quite extremes, especially due to the submarine fiber optic cable deployment, where repairs or reworks are not an option, those norms are considered today as the major stepping stone or a must-have towards the space grade qualification level of any photonic component. It represents a pertinent alternative to the perfectible ECSS for the study of optoelectronics components in the frame of NewSpace approach.

The table below describes the legacy available for each opto parts on the optical communication chain of TELEO. It shall be seen as a necessary risk mitigation exercise to be carried out before any New Space qualification approach. The next step is to identify the delta activity necessary to ensure the safety of the mission, this part is developed in the next section.

Table 3 : Legacy of FOLC2 opto-parts
**Manufacturer: No legacy on the reference of the device. Legacy of the manufacturer or component from the same manufacturer*

Description	Telcordia qualified	R&T heritage	Space heritage
MultideMode Pump Diode	Y	Y	N
SingleMode Pump Diode	Y	Y	N
DFB Laser	Y	Y	Y
Monitoring Photodiode	Y	Partial	Manufacturer*
High Speed Photodiode	N (custom qualification for space)	N	N
Mach-Zender Modulator:	N	Partial	Manufacturer*
Optical Fiber	Y	Y	Manufacturer*
Rad Er Doped fiber	Y	Y	Y
Rad Er/Yb doped fiber	Y	N	Manufacturer*
Isolator SM **Isolator PM**	Y Y	Y N	Y N
Circulator	Y	N	Manufacturer*
WDM SM **WDM PM**	Y Y	N N	Manufacturer* N
Coupler PM/SM **Coupleur High power**	Y Y	N N	Manufacturer* N
Combiner	Y	N	N
Bragg Filter	N	N	Manufacturer*
Mini-Avim	N	N	Y

4. ACTIVITIES PERFORMED FOR TELEO

The table below summarizes for each test, the legacy on each devices and the delta qualification performed to cover the mission.

Table 4 : Manufacturer legacy and delta qualification for each opto parts
C qual: Complementary qualification
Legacy: Qualification covered by legacy from manufacturer or R&T and project.
N/A: Not applicable or not relevant

<table>
<tr><th></th><th>Random vibrations</th><th>Shocks</th><th>Thermal cycling</th><th>Ageing</th><th>Damp Heat</th><th>Vacuum</th><th>TID</th><th>TNID</th><th>SEE</th><th>Construction Analysis</th></tr>
<tr><td>MultideMode Pump Diode</td><td>C Qual</td><td>C qual.</td><td colspan="3">Legacy</td><td>N/A</td><td colspan="2">C qual.</td><td>N/A</td><td>C qual.</td></tr>
<tr><td>SingleMode Pump Diode</td><td colspan="2">C qual</td><td>Legacy</td><td colspan="2">C qual</td><td>N/A</td><td colspan="2">C qual</td><td>N/A</td><td>C qual</td></tr>
<tr><td>DFB Laser</td><td colspan="2">C qual</td><td>Legacy</td><td>C qual</td><td>Legacy</td><td>N/A</td><td colspan="2">C qual</td><td>N/A</td><td>C qual</td></tr>
<tr><td>Monitoring Photodiode:</td><td colspan="2">C qual</td><td>Legacy</td><td>Legacy</td><td>Legacy</td><td>N/A</td><td colspan="2">C qual</td><td>N/A</td><td>C qual</td></tr>
<tr><td>High Speed Photodiode:</td><td colspan="2">C qual</td><td>Legacy</td><td>C qual</td><td>Legacy</td><td>N/A</td><td colspan="2">C qual</td><td>C qual</td><td>C qual</td></tr>
<tr><td>Mach-Zender Modulator:</td><td colspan="2">C qual</td><td colspan="3">Legacy</td><td>C qual</td><td colspan="2">C qual</td><td>N/A</td><td>C qual</td></tr>
<tr><td>Optical Fiber PM and SM</td><td>N/A</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>N/A</td><td>C qual</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Rad Er Doped fiber</td><td>N/A</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Rad Er/Yb doped fiber</td><td>N/A</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Isolator SM</td><td colspan="2">Legacy</td><td>Legacy</td><td>Legacy</td><td>Legacy</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>C qual.</td></tr>
<tr><td>Isolator PM</td><td colspan="2">C qual.</td><td colspan="3">Legacy</td><td>N/A</td><td>C qual.</td><td>N/A</td><td>N/A</td><td>C qual.</td></tr>
<tr><td>Circulator</td><td colspan="2">Legacy</td><td colspan="3">Legacy</td><td>C qual</td><td>C qual.</td><td>N/A</td><td>N/A</td><td>C qual.</td></tr>
<tr><td>WDM SM</td><td colspan="2">Legacy</td><td colspan="3">Legacy</td><td>N/A</td><td>C qual.</td><td>N/A</td><td>N/A</td><td>C qual</td></tr>
<tr><td>WDM PM</td><td colspan="2">C qual.</td><td colspan="3">Legacy</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>C qual.</td></tr>
<tr><td>Coupleur SM</td><td colspan="2">Legacy</td><td colspan="3">Legacy</td><td>C qual</td><td>C qual.</td><td>N/A</td><td>N/A</td><td>C qual</td></tr>
<tr><td>Coupleur PM</td><td colspan="2">C qual.</td><td colspan="3">Legacy</td><td>N/A</td><td>Legacy</td><td>N/A</td><td>N/A</td><td>C qual.</td></tr>
<tr><td>Combiner</td><td colspan="2">C qual.</td><td colspan="3">Legacy</td><td>N/A</td><td>C qual.</td><td>N/A</td><td>N/A</td><td>C qual.</td></tr>
<tr><td>Bragg Filter</td><td colspan="2">Legacy</td><td colspan="3">C qual.</td><td>N/A</td><td>C qual.</td><td>N/A</td><td>N/A</td><td>C qual</td></tr>
<tr><td>Mini-Avim</td><td colspan="5">Legacy</td><td colspan="5">N/A</td></tr>
</table>

Construction analysis was done on every reference. Either to verify no change occurred on already known components, or to validate assembly, robustness and global eligibility criteria of new products for space.

On several parts, especially for active ones, vibrations and shocks tests were carried out again, at higher levels than Telcordia's ones, to cover the mission profiles.
The tests were done at component level, except for the MMPD. For the vibrations, the test was performed directly on a bread board which is a model of the 2nd stage of the Booster. The bread board includes several MMPD, and others passive components.
For thermal cycling, ageing and damp tests, the levels shall be compliant to the profile mission. The analysis was done using Arrhenius, Coffin-Manson [11] and Hallberg-Peck [10] laws. For almost every component the thermal cycling and damp heat of the Telcordia standard were covering the mission. Only the Bragg Filter required to be qualified again due to a lack of representativeness of the devices already tested.
Only 4 references out of 20 were tested in ageing for the delta qualification. Ageing represents an important cost during qualification due to the number of piece required and the duration of test (around 2000h).

The manufacturer of optical passive components (WDM, coupler, isolator, circulator and combiner) performed qualification according to Telcordia GR-1221-CORE. There is not active ageing test required for passive components, indeed no wear out mechanisms are activated at the optical power level considered for TELEO mission. The standard includes a High Temperature Storage (HTS) of 2000h at 85°C. The Telcordia standard applies for passive components covering submarine telecom use cases where the optical fibers are not changed or fixed for equivalent duration as space missions. We conclude that the HTS test from Telcordia is covering the integrity of passive components for the mission.

As Telcordia standard are not directly for space applications, test under vacuum is not included in the specification. However, vacuum can represent a challenge for the robustness of components. Like diode laser which requires hermetic sealed package with specific atmosphere. Indeed, organic contamination can interact with high intensity light to form solid deposits over the emitting regions of the laser, causing heating of the laser [9]. For this reason the hermitic level of diode laser is a critical characteristics to control during qualification and screening.
For, non-hermetic package sensitive to vacuum as Mach-Zender modulator it was performed Thermal Vacuum Cycling Test (TVAC). TVAC was also tested on passive components as circulator and LNOA coupler, in order to check the evolution of glue under vacuum.

Every active optoelectronics components were tested in radiation at least in TID and TNID. SEE testing was required only on the High Speed photodiode which is copackaged with a transimpedance amplifier theoretically sensitive to heavy ions.
The optical fiber PM and SM were tested by Airbus Defence and Space. The test was performed at different optical powers, temperatures and up to 15 Mrad. The Radiation Induced attenuation (RIA) was measured in situ during the test, in order to characterize the RIA increase with the deposited dose.
The Booster WDM, Coupler and Isolator were produced with the same reference of fiber than the one tested by Airbus. Based on the results of the radiation campaign of the optical fiber, for the dose calculated for the mission (50 krad), the attenuation expected was ≤ 0.018 dB/m.
The WDM and coupler are composed of 1,5m of optical fiber. The fiber is the only part sensitive to radiation. Thus, for this component the expected radiation induced absorption is way below the optical losses measurement sensitivity and no further radiation test were performed, as the fiber was completely characterized under TID.
However, radiation test needs to be performed for each preform of optical fiber. This approach is acceptable for demonstrator model, but shall be more investigated to be applied for NewSpace approach.
Every passive components composed of others radiation sensitive part (Isolator, Circulator …), or composed of non-tested fiber were tested under TID which was also the case for all passive parts used in the LCE.

The analysis of legacy from manufacturer and the delta qualification performed ensures the integrity and robustness of each parts for the TELEO mission.

This approach is relevant for recurring manufacturing. If there is no PCN, or change of the reference with an identical profile mission only the construction analysis shall be required. On this case only few components would be needed, and the cost of the qualification will be highly reduced compared to standard space approach, despite the extra engineering effort required for this analysis

The same methodology was used for the upscreening, it is based on the screening already performed at the manufacturer level.
The electro-optical performance of the component was measured at reception only if some characteristics are missing. For example, if a parameter was not measured by the manufacturer, or if measurements at different temperatures are required. For instance, the MMPD were specifically tested at 50°C to complement the characterization data provided by the manufacturer.
Complementarity upscreening including X-Ray, leak test (for hermetic components), external visual inspection and PIND test were performed on active optoelectronics components due to lack of information from the manufacturer.

To conclude, the delta qualification of the 20 references of optoelectronics parts for FOLC2 requires 45 environmental tests and 15 construction analysis, which is a reduction of more than 50% of tests. The total represents a qualification with around 170 parts. The standard qualification according to ECSS-Q-ST-60-13C requires at least 50 pieces per reference, which represents 1000 components for FOLC2. The NewSpace approach allows to reduce the number of tests, and consequently the number of components needed. In this case 830 components were saved for a qualification.

5. CONCLUSION

The NewSpace approach allows to replace currently established space qualification. This methodology is based on technology and manufacturer heritage. The cost of optoelectronics parts qualification is highly reduced.
However, this is possible only with a thorough analysis on project legacy and supplier information. This study has to be performed for each procurement, and delta qualification is required in case of any change or lack of information.
If NewSpace proposes a relevant alternative to standard qualification, it shall be applied carefully and with an analysis of each technology, components and mission.

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