PHOTONIC TECHNOLOGIES IN SPACE APPLICATIONS: SELECTION AND ACCEPTANCE TEST CRITERIA

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1. ABSTRACT

Photonic technologies have changed the world of communications in the form of fibre optics, integrated optics, electro-optical components and micro-photonics. They offer some compelling advantages compared with their traditional RF counterparts when considered for use in space applications. Therefore, research and development of photonics technologies for space applications in areas of communications, sensing and signal processing has been a major theme for several years.

The use of photonic technologies for space applications has risen the problem related to the ability of optoelectronic and optic components to withstand space environment as all optoelectronic and optic components come from terrestrial applications. Therefore, the development of photonic technologies for space applications has made the selection and acceptance test criteria of all optoelectronic and optic components that are part of the photonic system imperative.

The paper presents a summary of the experience of Alter Technology Group on the mechanical, thermal, radiation and endurance testing on several photonics technologies. In addition the paper describes an assessment related to the reliability of these parts to be used in space applications together with the critical requirements to be considered for associated environmental testing.

2. INTRODUCTION

The use of photonics technologies for space application presents significant advantages due to its specific properties as follows

- Almost unlimited bandwidth (i.e. 1550nm fiber can go to several THz.)
- Reduced propagation losses at spacecraft level (due to short communication distances).
- Supports any modulation or coding format
- Immunity against electromagnetic interferences,
- Optimum mechanical properties (light weight, mechanically flexible, reduced volume, resistant against corrosion of contamination).
- Reduced noise generation and Electromagnetic immunity are clear advantages in cases where satellite operation works close to the sensors sensitivity bandwidth (i.e. natural Earth microwave emissions).
- Mechanical flexibility and low weigh of FO compared with standard hardness are an advantage when articulated systems are used or many meters of cabling are required.
- Mass reduction possibilities in case of using photonic systems may result in important cost reduction during handling and launching of the S/C.
- Huge bandwidth and multiplexing properties makes FO systems is a clear advantage for signal processing. and thermal and structure monitoring applications.

- Optical the use of optical wireless technologies will reduce cost and time in the Assembly and Test (AIT) phase.

The selection and evaluation procedures of COTS optoelectronic components for its use in space application need to be established due to the fact that no qualified components exists and that no standards are available that define the procedures to be applied for optoelectronic devices to be used in space qualifications. The following paragraphs propose a generic procedure for the selection and acceptance test criteria for optoelectronic devices, and also includes analysis related to the Specification Performance Requirements and Environment Constraints related to space applications.

Summary results of a large number of parts which has been tested by Alter are also presented to demonstrate current status of most promising technologies. Finally, one case example is presented related to optical amplifiers.

3. SELECTION AND ACCEPTANCE TEST CRITERIA

When COTS components have to be used in space applications because qualified components are not available, then the selection of the right component has to be made in such a way that risk mitigation techniques are applied at the time that the technical requirements of the application are met.

The following steps have to be followed:

1. Specification Performance requirements:
    a. Definition of the basic technical requirements of the application (opto-electronic parameters) with the identification of the critical parameters and their limits.
    b. Definition of specific quality and reliability requirements applicable to the application.

2. Survey of the available commercial candidates that meet the critical parameters.

3. Definition of the environmental constrains (related to the space application).

4. Trade-off through the data available for all the candidates identified in the survey, attending to the following aspects (some of them may require of visits to the manufacturers):
    a. Manufacturer experience in space application technologies.
    b. Manufacturer willingness to provide technology and reliability data and support (i.e. PCN s notices).
    c. Availability of TELCORDIA qualified devices and or TELCORDIA qualification of the manufacturer.
    d. Technology maturity.
    e. Availability of reliability data.
    f. Previous space heritage (if any).
    g. Available technology data (this information can be used, for instance, for the prediction of the sensitivity of the device to radiation effects).
    h. Availability of “single lot date code”.
    i. Availability of non pure-tin components.

5. Pre-selection of two or three candidates that are supposed to meet the minimum requirements.

6. To perform SELECTION TEST: Definition of the preliminary TESTS that will allow the selection of the best candidates. These SELECTION TESTS have to be designed in such a way that they provide enough data to :
   a. Obtain relevant data concerning the performance of the devices when this data is not available from the trade off.
   b. Determine which of the candidates presents better performance for the application, by comparison of the results of the test performed on the candidates.

7. To decide which is the best candidate for the application. This candidate will be submitted to full evaluation.

8. Evaluation of the best candidate.- The device identified as the best candidate for the application will be submitted to a full evaluation with the purpose of:
   a. Fully characterize the performance of the device when used in the final application in terms of:
      i. Quality of package and assembly.
      ii. Reliability
      iii. Stability of the Electro-optical parameters in the full real operating temperature range.
      iv. Stability and performance under space radiation environment
      v. Stability under extreme mechanical efforts (shocks, vibration, acceleration)
      vi. Performance and stability under vacuum and thermal variations.
   b. Identify potential failure modes.
   c. Determine the potential limits in the application or use of the device.

9. Visits the manufacturer may be necessary in order to analyze the results of the evaluation, check the manufacturer willingness to collaborate in technical issues and to prepare the procurement of the flight lot.

   In case the result of this evaluation indicates one or more problems that discourage its use for the application, then other candidate has to be evaluated.

10. Procurement of the flight lot.

11. Lot Acceptance Test.- In case a new lot, different from the one subjected to evaluation, has to be procured for flight purposes, then LOT ACCEPTANCE TEST have to be performed to identify any potential deviation from the performance of the evaluated lot. Note that, in case that the flight lot has not been submitted to screening, or the screening reported by the manufacturer is not considered enough to ensure the screen out of the enfant mortality elements, then a complete screening in accordance with chart III of ESCC 5000 has to be performed

Schematic flow for optoelectronic parts selection, evaluation and acceptance procedure is provided in Chart I.

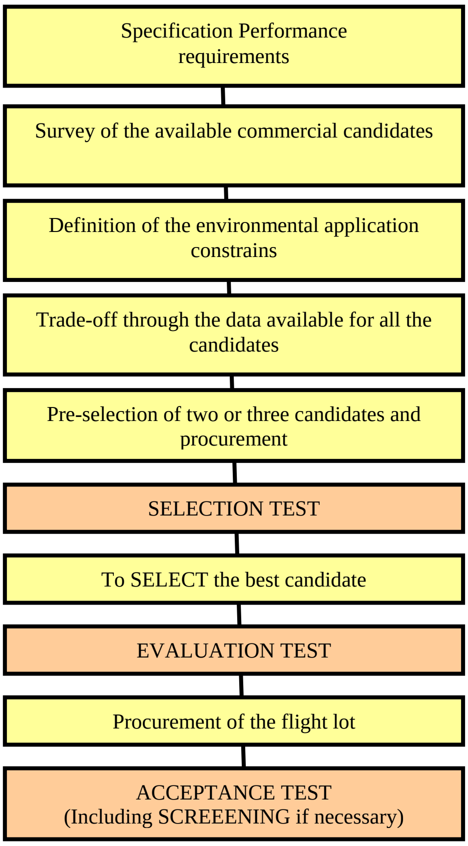


CHART 1- PARTS SELECTION, EVALUATION AND ACCEPTANCE FLOW FOR COTS OPTOELECTRONICS COMPONENTS

3.1 SPECIFICATION PERFORMANCE REQUIREMENTS

3.1.1 Electro-optical requirements

The first step in the parts selection process is the exact definition of the electro-optical performance required for the application. This implies the clear identification of:

- Key parameters.
- Acceptable limits to the range of variation of these parameters during the mission, taken into account:
    - Operating temperature range.
    - Environmental conditions (radiation).
    - Expected mission lifetime.

The key parameters have to be selected in such a way that they allow a wide margin of potential commercial candidates at the time that the performance of the mission is not jeopardized. Some aspects will require the maximum possible flexibility. To make that flexibility possible it is necessary that the selection process is initiated at the first steps of the design, to reduce as much as possible the design related constrictions.

3.1.2 Quality requirements

Quality requirements are determined by the type of mission and application; nevertheless, it is strongly recommended to apply the quality requirements established in ECSS-Q-60A. These quality requirements have to be followed to the maximum extent as possible in terms of:

- Procurement policy
- Screening
- Package and assembly quality and testing.
- Acceptance test criteria

3.1.3 Reliability requirements.

Reliability is one of the main concerns when using commercial components in space applications. This asseveration does not mean that the commercial components are not reliable enough for their application in space, but its real reliability has to be verified. This verification can be performed by means either of the analysis of the reliability data provided by the manufacturer (if available) or by testing, in order to warranty a minimum of 10 years (typical value) of operation in space environment.

3.2 ENVIRONMENTAL CONSTRAINS

The environmental constrains imposed by the space missions are mainly driven by the conditions stress during launching and by the operation in free space. The following elements constitute the main constrains compared with the majority of the commercial applications:

- Operating temperature range
- Thermal variations
- Vibration
- Accelerations
- Vacuum
- Harsh radiation environment

3.2.1 Operating Temperature range

Typical operating temperature range warranted by the manufacturer for commercial parts goes from 0 to 40 º, while space application requires in general parameters and functional stability in the range from -55 to +125ºC (although some specific missions / applications may require ranges from -185ºC to +300ºC). The selected parts need to remain functional and parametrically stables in the specified temperature range.

3.2.2 Vibration

The capability of the optoelectronic components to survive strong vibration conditions during launch is a requirement to be taken into account. Specific requirements need to be defined on a case by case mission.

3.2.3 Thermal cycles

Space hardware has to be able to survive extreme temperature cycles produced during operations due to the continuous travelling of the satellite from exposition to solar radiation to shadow during its rotation around the Earth. The mechanical stress produced by these temperature cycles may induce degradation in the mechanical parts of the component. It has to be verified that the components can withstand the thermal cycles test designed for these purposes.

3.2.4 Accelerations

Optoelectronic parts should be able to survive hard accelerations during launch, as per the conditions given in the following requirements. Requirements must be defined on a case by case basis although the following figure may be used as baseline.

Frequency (Hz)	***Acceleration (g)***
100	40g
2000	1000g
10000	1000g

3.2.5 Vacuum

Space operation requires stable performance under vacuum conditions. The main concern related to vacuum conditions operations is related to the risk for certain materials to outgass, with two negative effects:

- Deposition of out-gassing materials on optical parts;
- Material degradation due to chemical reaction or de-composition.

As a general test requirement, Any part must be designed to withstand a depressurisation rate of 26 Torr/s from ambient pressure down to 10-10 Torr in free space at full operating conditions..

3.2.6 Space radiation environment

Four sources of radiation can be distinguished:

- Cosmic rays: all kind of ions, but primarily protons (85%) and helium (14%).
- Radiation belts (Van Allen belts), protons and electrons trapped in the earth's magnetic field
- Solar particles (mainly protons)
- Atmospheric secondary (possible influence on low orbit spacecraft)

As a general baseline, the following requirements apply for optoelectronics parts:

- Total ionization dose (gamma rays).- Optoelectronic parts should be able to withstand the total mission cumulated dose of gamma rays. Reference dose: 100 Krad(Si).
- Proton induced displacement damage.- Optoelectronic parts should be able to withstand a fluence of protons with an energy between 10 to 65 MeV (depending on the application) Protons and a typical fluence of 5x1010 protons/cm2.

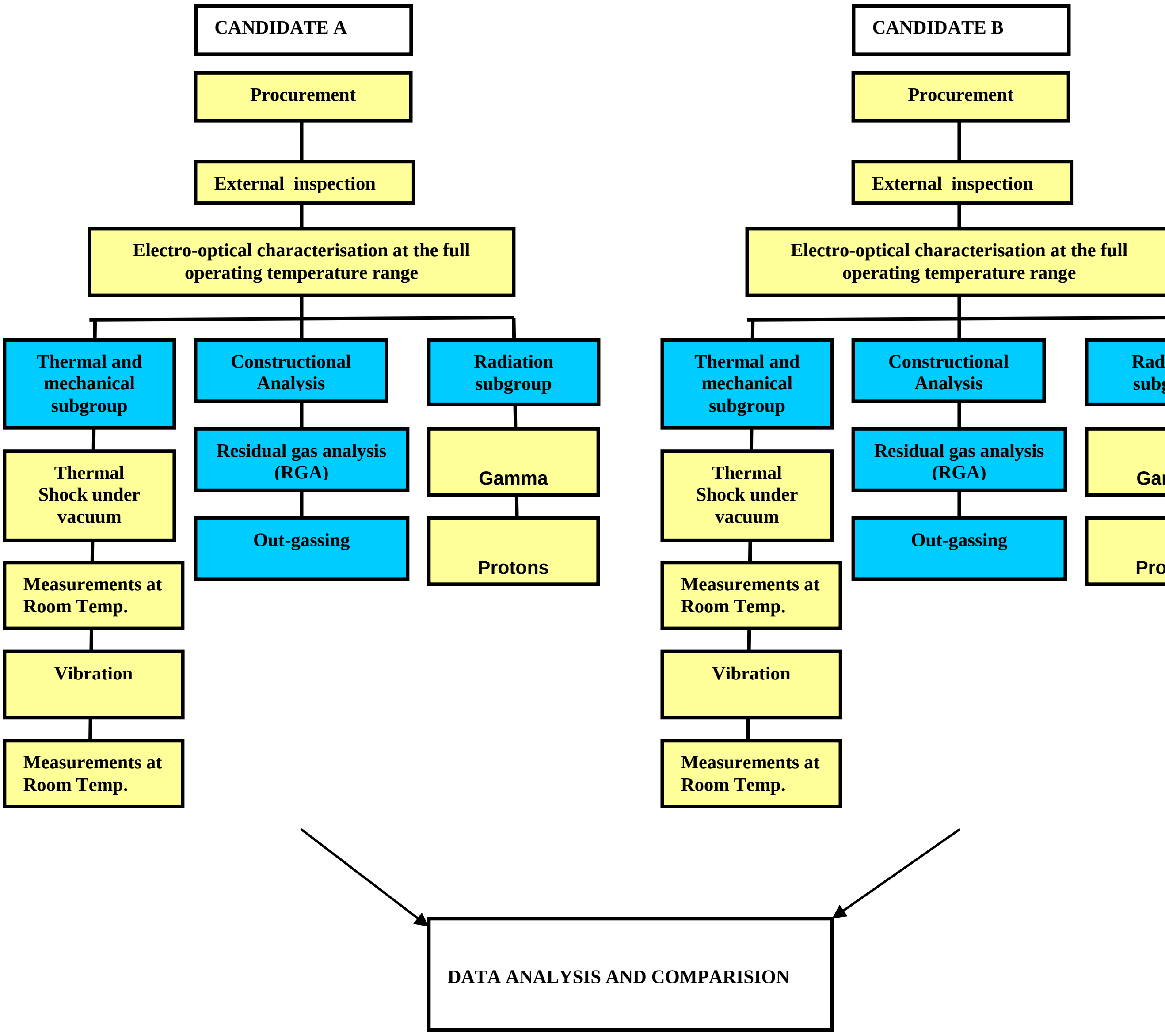
3.2 SELECTION TEST

The SELECTION TESTS have to be designed to provide enough data to:

a. Obtain relevant data concerning the performance of the devices when this data is not available from the trade off.
b. Determine which of the candidates presents better performance for the application, by comparison of the results of the test performed on the candidates.
c. Check de candidate devices behavior against the most critical requirements of the space application, for which the components have not been designed.

For these purposes, the selection activities shown in the next chart have to be performed as a minimum.

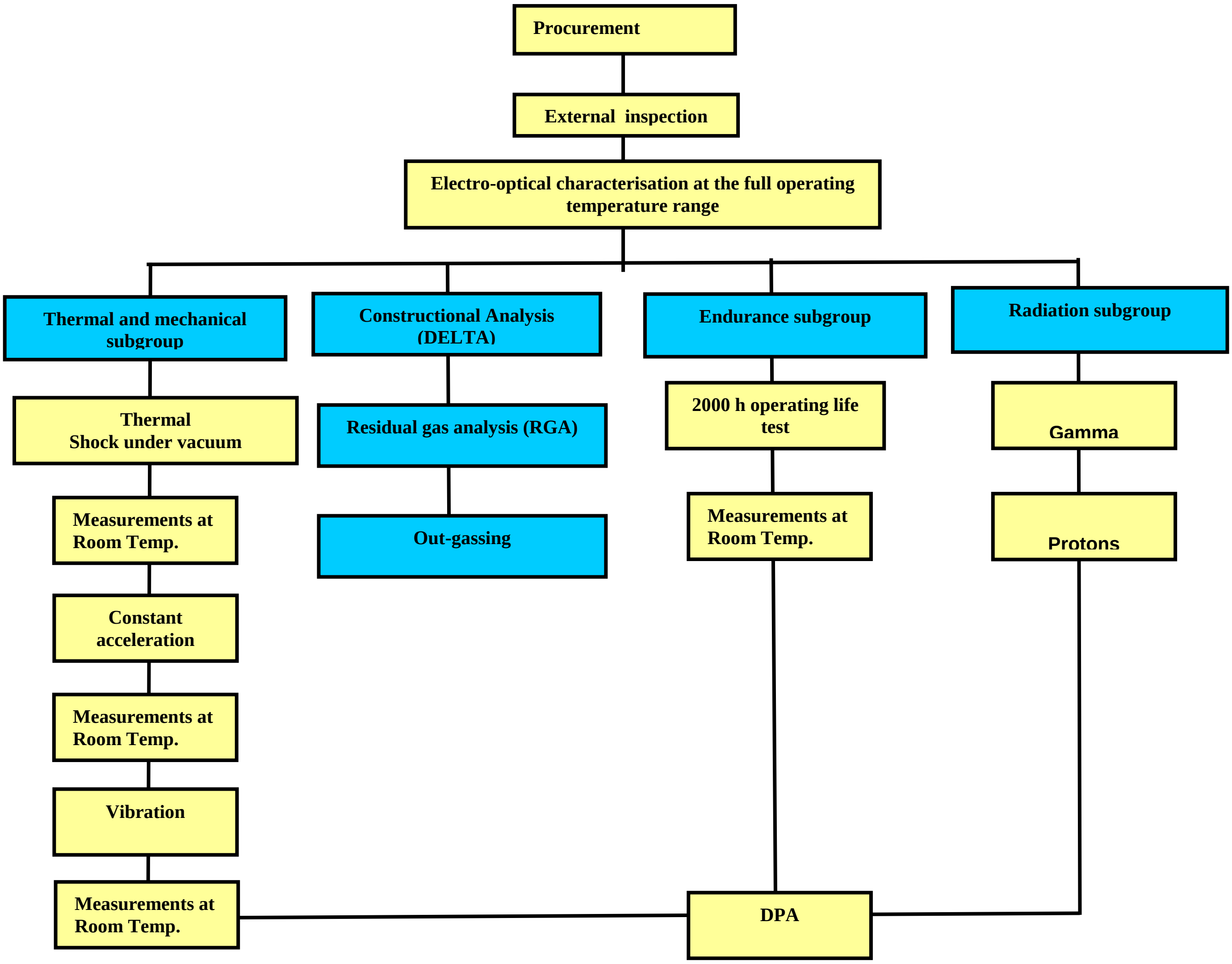
CHART II.- SELECTION FLOW FOR COTS OPTOELECTRONIC COMPONENTS



3.4 EVALUATION

Next chart describes the evaluation test flow in the general case. This test flow will need to be adapted to the specific technology of the devices and shall take into account the data available from the manufacturer and the results from the Selection Test. Some of the test defined in the next chart may be omitted in case the results from the Selection Test are considered enough and not additional knowledge is expected to be gained if they are repeated during the evaluation (in special if the same lots is used for type selection and evaluation purposes).

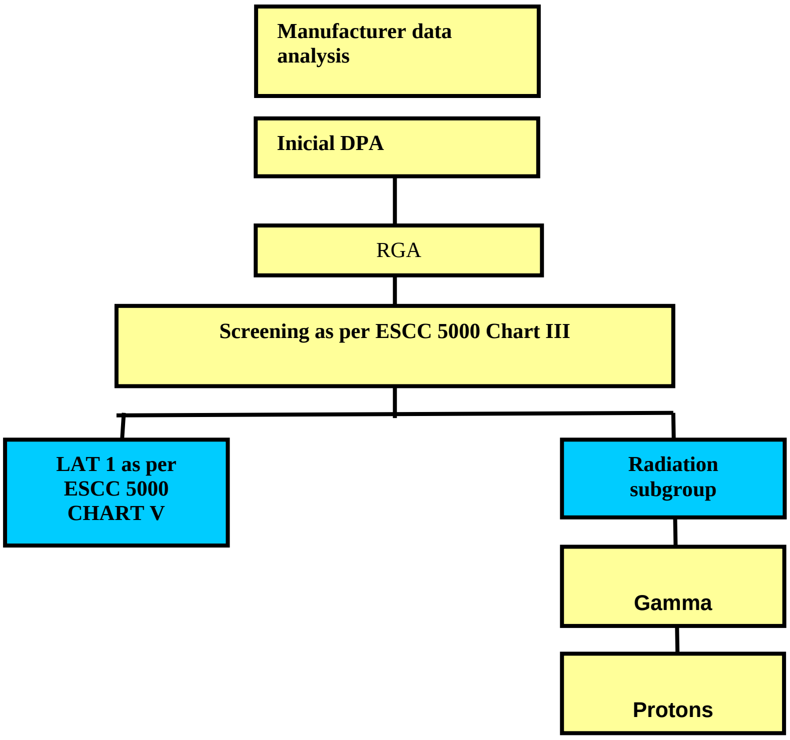
CHART III.- EVALUATION FLOW FOR COTS OPTOELECTRONIC COMPONENTS



3.5 ACCEPTANCE TEST

In case that the procurement of the flight lot implies the use of a new lot of components with lot date code(s) different from the one(s) used for selection and/or evaluation purposes, then a Lot Acceptance Test procedure has to be applied as per Chart IV.

CHART IV.- ACCEPTANCE FLOW FOR COTS OPTOELECTRONIC COMPONENTS



4. ALTER TECHNOLOGY EXPERIENCE ON OPTOELECTRONICS PARTS.

ATGSP is a company with more than 20 years of experience in testing of EEE parts for space. In addition to that experience, in the last years, ATGSP is putting an important effort in the development of new capabilities to validate new technologies (i.e. optoelectronics and MEMS) for space applications and to extend these testing capabilities from the part level to instrument or system level.

Based on above, Alter Technology group provides a large experience on optoelectronics parts testing with specific capabilities on optoelectronics measurements as well as mechanical, thermal, radiation and constructional analysis tests.

In addition, the experience of ATSP in the management of space projects together with the commitment of the company with the research and development activities is been reflected in the participation of the company in a large number of projects as coordinator of other research and/or development groups.

The following table provides a summary of most significant projects participated by Alter in the frame of photonics technologies.

Project	***Devices under evaluation***
SMOS Satellite – MOHA (Mira Optical Harness) Qualification of optical components	FO laser diode FO detector Optical fibre FO splitters
OWLS (Optical Wireless Link Systems for intra-satellite communications).	IR LEDs IR Photodiodes
Multigigahertz Optical Modulators of very low RF driving power (Testing of selected Optical modulators)	Optical modulators 1550nm
High Efficiency Optical Amplifiers for FO on board applications. (Testing of selected optical amplifiers; project management).	Optical amplifiers 1550nm
Qualification of Photodiodes & Thermopiles for Space application in Mars environment	Photodiodes Thermopiles
POE (Programmable optoelectronic adaptative element) Design & Qualification of POE elements for space application	Liquid crystal
FOD (SpaceFibre) Development of an EM model of a high speed optic transceiver for use onbard telecom satellites	Optical transceiver 10 Gbits (1550 nm)
PHT (Photonic Transceiver for Secure Space Applications) Design & Qualification of PHT element	Pump Lasers (450nm) FO lasers (840nm) Beam splitters Optical amplifiers NL crystals
ELECTRO-PHOTONIC ADC	Optical modulators
SWIR (Short wave Infra red laser diodes)	Short wave Infra red laser diodes
(Others)	Photodiodes InGaAs 800-1600 nm
(Other)	LED IR 770 LED Red, green & blue

For all cases, parts were submitted to specific environmental tests to check suitability to meet space environmental requirements. The following table shows the list of test performed by part and an indication of failures encountered.

Device type	Radiation Gamma	Radiation Protons	Thermal Vacuum	Vibration	Life test	Construc. Analysis
FO laser 1310 nm	√	√	√	√	√	√
FO detector 1310 nm	√	√	√	√	√	√
Optical fibre	√	√	√	√	√	√
FO splitter	√	√	√	√	√	√
LEDs 670 nm	√ •	√ •	√ •	√ •	√ •	√ •

Device type	Radiation Gamma	Radiation Protons	Thermal Vacuum	Vibration	Life test	Construc. Analysis
PIN Photodiodes 400-1000 nm	√ •	√ •	√ •	√ •	√ •	√ •
Optical modulators (1550 nm)	√ •	√ •	√ •	√ •	√ •	√
Optical amplifiers (1550 nm)	•	√	√	√ •	√	√
Photodiodes UV 200-400 nm	√	√	√	√	√	√
Thermopiles IR (up to 20 µm)	√	√	√	√	√	√
AOM Free space Acousto-optical modulator 1064 nm	-	-	√	√	√	√
BAM Laser diode (850nm)	√	√	√	•	•	•
SLED (820nm)	√	√	√	√	√	√
Liquid Crystal	-	-	***On going***	-	-	***On going***
Optical transceiver 10 Gbits (1550 nm)	•	•	***On going***	***On going***	***On going***	***On going***
Pump Lasers (450nm)	√	√	√	√	***On going***	√
FO lasers (840nm)	√	√	√	√	•	•
FO lasers (840nm)	√	√	√	√	•	•
FO lasers (840nm)	√	√	√	√	√	√
Beam splitters	√	√	√	√	√	√
Optical amplifiers (840nm)	√	√	***On going***	***On going***	***On going***	***On going***

√ Pass the test // • Fail // - Test not performed // √• Type selection

5. CASE STUDY

5.1 Assessment on commercial amplifiers for potential use in space applications

Optical amplifiers play a key role in terrestrial telecommunications including WDM transmission systems, CATV and Radio Over Fibre applications. They have been considered in space applications such as LIDARs or space-borne laser altimeter for Earth observation and deep space missions, and Optical Inter-Satellite communication links (OISL). Together with other optical technologies, they are expected to bring significant improvements and/or constitute one of the enablers of advanced payload concepts. They may offer major benefits in the development of future telecom payloads with broad bandwidth, wide connectivity, and enhanced flexibility at low mass and small size. These applications include the generation and distribution of local oscillators in the microwave frequency range, the photonic RF frequency conversion, as well as the combinations of these functions into more complex sub-systems such as analogue repeaters with optical switching, or antenna sub-systems and beam-forming networks.

5.1.1 Selection of components

Taking into account the previous reviews and analysis of the current status of optical amplifier products, technologies and R&D trends, the intention of testing the most promising devices and devices from the main technologies, and also the limited budget, optical amplifier products were selected and proposed for procurement and further evaluation through testing.

The selection of optical amplifiers was as follows:

- +17dBm output power uncooled EDFA for intensive testing (6 units),
- +17dBm output power uncooled EDFA for comparison (1 unit),
- +24dBm output power uncooled EDFA with cladding-pumped fiber for intensive testing (6 units) ,
- +13dBm output power EDWA on glass for comparison (1 unit),
- +11dBm output power EDWA on Silica-on-Silicon for comparison (1 unit),
- +14dBm output power SOA for comparison (1 unit).

5.1.2 Test Plan

The test plan was defined considering the test related to space environmental mainly. Note that all the selected amplifiers were commercial devices not designed for space applications but with Telcordia qualification.

The following group of tests was proposed:

- Constructional analysis. One of the EDFAs with 6 devices available was used for initial constructional analysis in order to get a deep understanding of the technologies used.
- Electro-optical characterization at room, maximum and minimum operational temperature.
- Mechanical tests. Space level vibration (both sine and random) and SRS (Shock Response Spectrum) to simulate vibrations during launch and pyrotechnic shocks.
- Thermal vacuum cycling
- Radiation test. Both protons and gamma radiation campaigns.
- Final DPA (Destructive Physical Analysis)

5.1.3 Test results

The main results of the tests were the following:

+17dBm output power uncooled EDFA for intensive testing (6 units):

- Mechanical tests: Low degradation was observed, probably related to repeatability of the measurements.
- Thermal vacuum: No degradation.
- Proton radiation: Very little degradation.
- Gamma radiation: The test results show about 3dB optical gain degradation of each piece of Erbium-Doped Fibre used in the amplifiers, and no degradation for all other optical and electro-optical components.

+24dBm output power uncooled EDFA with cladding-pumped fiber (6 units):

- Mechanical tests: Low degradation, probably related to the variation of the geometry of the amplifier fiber which was not well fixed internally in the package.
- Thermal vacuum: No degradation.
- Proton radiation: Maximum degradation of 6 dB approximately in gain.
- Gamma radiation: Very high degradation leading to non-working samples. Fig. 6 below shows the gain spectra after gamma radiation steps of 0, 10, 20, 30, 60 and 100 Krads.

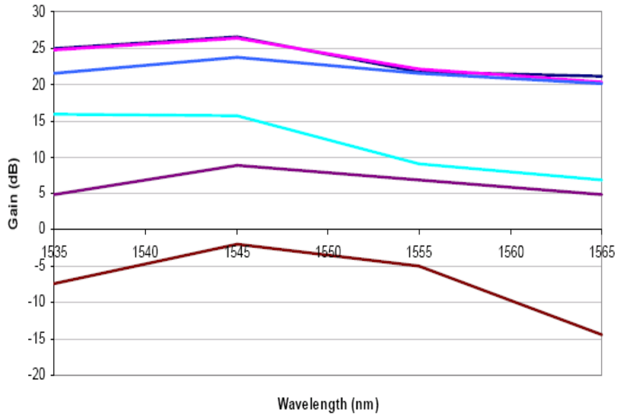


Figure 6: Gamma radiation-induced degradation of spectral gain

+17dBm output power uncooled EDFA for comparison (1 unit):

The component failed after vibration tests (only initial measurements at room, min and max temperatures had been previously performed). The internal visual inspection performed after the failure showed that the device had not been designed for supporting any mechanical tests.

+13dBm output power EDWA on glass for comparison (1 unit)

- Mechanical tests: Very low degradation of less than 1 dB in gain and noise figure.
- Thermal vacuum: Degradation of 1.4 dB in gain and no degradation in NF.
- Proton radiation: Degradation of 2.4 dB in gain and no degradation in NF.
- Gamma radiation: Degradation of around 7 dB in gain and no degradation in NF.

+11dBm output power EDWA on silicon insolator for comparison (1 unit):

Only one sample was tested and it failed during the initial measurements at 70ºC, therefore, no information about the behavior after mechanical tests, thermal vacuum or radiation has been obtained.

+14dBm output power SOA for comparison (1 unit)

The SOA was extensively tested in terms of linearity, in the RF and optical domain. As expected, the SOA does not provide fully linear amplification, and generates unwanted frequency-compounds through cross-gain saturation and Four-Wave Mixing processes. First, such frequency compounds were observed in the optical domain with LO-type signals. These non-linear effects increase as the input power increases and as the frequency separation decreases. Then, we observed non-linear effects in the RF domain with telecom-type signals.

These effects increase as the optical input power increases, and as the RF signal modulation index increases. The sample was damaged at the end of these tests when higher optical power inputs were being tested.

6. CONCLUSIONS AND RECOMMENDATIONS

- Very few optical components are qualified for space applications. This means that COTS are necessary most of the times. A cost effective approach for selection and acceptance criteria of these COTS has been presented in this paper.

- Detailed construction analysis, endurance, radiation and environmental test performed before the complete qualification flow can be very useful for increasing the reliability of the devices and reducing both the price of the selection and project qualification. It is recommended to do this prior to any project qualification activity.

- Specific test setup conditions must be considered when working with photonics parts to ensure test bench is suitable to provide electro-optical characteristics while parts are being submitted to environmental test in operating conditions.

- Alter Technology Group has a large experience on EEE parts procurement as well as extensive testing on most significant photonics technologies for space applications. Reliability data are available for main parts to help on the final selection of the product for the intented application.

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