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OPTICAL FIBER TECHNOLOGY FOR SPACE: CHALLENGES OF DEVELOPMENT AND QUALIFICATION

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I. INTRODUCTION

Using fiber optical components and assemblies for space flight applications brings several challenges for the design and the qualification process. Good knowledge of the system and environmental requirements is needed to derive design decisions and select suitable components for the fiber optical subsystem. Furthermore, the manufacturing process and integration limitations are providing additional constraints, which have to be considered at the beginning of the design phase. Besides Commercial off the shelf (COTS) components, custom made parts are often necessary.

The lack of generic qualification standards for fiber optical assemblies is leading to challenges for technology validation. Therefore, understanding the technology and its failure modes is essential for the design and development process of a fiber optical subsystem, and to derive an appropriate validation and qualification approach.

For the Raman Laser Spectrometer (RLS) of the ExoMars Rover, a dedicated fiber optical harness had to be developed. This project gives an example of the challenges of the design and validation process of this technology. A combination of COTS and custom made components are used to fulfill the instrument needs on the fiber optical harness.

II. DEVELOPMENT CHALLENGES

A. Development Constraints

Fiber optical subsystem are becoming more common in space flight projects. Either for communication, fiber optical sensor systems, or as simple waveguide for instruments. Before starting the design and development process, all requirements and constraints have to be identified. The performance, environmental and mission requirements are given by system, instrument or mission level. Furthermore, constraints from integration, tests and manufacturing have to be identified.

Integration constraints are very often not considered by the system design in early stages of the project. Fiber optical components and assembly have to be handled with more care than electronic cables and connectors. More space for integration accessibility for tooling is required. The ferrules of fiber connectors have to be inspected and cleaned before integration. Sometimes it is necessary, to perform the visual inspection and cleaning on already integrated assemblies. The integration needs have to be considered on system design in early project stages.

B. Design

The goal of the design activities is to translate the requirements into a working and reliable design. All requirements have to be analyzed and evaluated carefully. The design and development flow is illustrated in Fig. 1. Especially environmental requirements, like the thermal, mechanical and radiation load levels are driving the design. Typical temperature environments are ranging from -55°C to $+85^{\circ}\text{C}$, however for some applications the lower limit could extend down to -135°C for exposed positions. For planetary missions, the upper (survival) temperature limits can be as high as $+135^{\circ}\text{C}$ due to the necessary sterilization required by planetary protection guidelines. These conditions have to be considered for the selection of materials for fibers and coatings, as well as for selection of adhesives used for connector termination.

The radiation environment is driving, together with the performance requirements, the selection of the fiber material, type and composition. Ionizing radiation levels usually range from a few krad up to several Mrads for exposed, unshielded positions and long mission durations. Ionizing radiation results in the creation of color centers in the optical fiber which leads to signal degradation. The selection process considering radiation effects for optical fibers is explained more detailed in the one of the following sections.

Design and performance requirements are defining the optical properties of the fibers. The type of fiber (single mode, multimode or PM), wavelength range, core diameter and numerical aperture are the key optical parameters of an optical fiber.

A main driver of a space project is cost and schedule. Commercial off the shelf (COTS) components are used to save money and to accelerate procurement. However, the availability of COTS components for harsh environments is often very limited. For some applications, non-standard fiber optical components are needed, as no comparable COTS items are available. For most COTS and all special items, qualification and evaluation tests have to be planned.

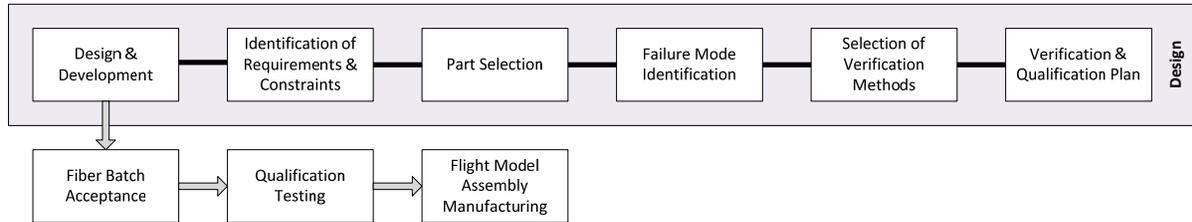


Fig. 1. Design and Development Approach

C. Design Verification

As mentioned before, all requirements and constraints have to be analyzed and evaluated carefully. For every requirement, a verification or validation method has to be selected. This task should be performed in an early project phase, in order to establish the verification and qualification plan. Quite often, difficulties arise with the selection of the verification method:

For some components it is not possible or representative to be tested as stand-alone part; but it is required to test them in an assembled or terminated status. For example, most tests on fiber connectors are performed in a mated condition as a connector pair and a mating adapter, terminated with an optical fiber. Sometimes requirements are badly written and cannot be verified in any way. In such cases, clarifications with system or customer level is required. Other requirements cannot be verified or tested on component or assembly level. This means, that for these requirements, tests have to be foreseen on higher system level, in order to be verified in representative way. For some tests of fiber optic assemblies, it is necessary, to perform in-situ monitoring of the optical transmission.

Critical components have to be identified and dedicated tests developed. If not already included in the requirements, the allowable deviation from the performance parameters have to be defined. For components, especially non-standard custom designed components, a dedicated failure-mode analysis has to be carried out. But it is also necessary, to identify failure modes on assembly level: an assembly of different components has different failure modes, as individual, stand-alone components. Therefore it is necessary, to perform a failure mode analysis of the assembly construction. If helpful, additional tests can be conducted in the development phase or a destructive physical analysis can support the identification of failure modes for components and assemblies. Besides the analysis of the part or assembly construction and materials, it is also often necessary to have knowledge about the manufacturing and assembly processes and their parameters. An example is the connector termination process: some process parameters, like curing temperatures, can cause additional stresses in the component, and lead to catastrophic failures.

These activities should result in a qualification program, which covers as many failure modes as possible.

III. RADIATION TESTING OF OPTICAL FIBERS

A. Background

As mentioned before, optical fibers exposed to a radiation requirement are creating color centers which is leading to signal degradation. The rate and number of color centers is influenced by several parameters, like temperature, dose rate, total dose, doping substances and the manufacturing process.

Supplier of optical fibers sometimes are changing the manufacturing processes. As the radiation hardness of an optical fiber depends, among other factors, a lot on the fiber drawing process, there is a danger, that the environmental behavior, in this case the radiation hardness, of an optical fiber changes. This can lead to the situation, that there are differences in the radiation response between two different batches of optical fibers. This means, every batch of optical fibers has to be tested, if the similarity of the preforms and the drawing process cannot be guaranteed.

B. Radiation Qualification and Workmanship Testing

In order to perform the radiation qualification tests properly, representative radiation parameters have to be defined, including a clear visibility on the margin philosophy. A radiation safety factor of 2 is normally used for test applications and calculation of the mission radiation load. However, it should be verified, if margin factors were already used for the definition of the radiation environment requirements. Applying multiple margins has the danger that the test radiation level is for a worst case several factors above the realistic radiation level, and as a consequence the components would fail the qualification test.

At the beginning of a project, it is sometimes not clearly defined, which fiber type from which supplier will be used. Data of the radiation behavior are rarely available and often incomplete. A trade-off and test campaign with different fibers from different suppliers might be needed, in order to select the best optical fiber. As project

budgets are especially in early phases very limited, it is not possible to procure optical fibers from each type with the needed quantity for all development and flight models.

It might be helpful to ask vendors to reserve sufficient quantities of the same batches. However, if in later phases the same batch of the selected fiber is not available from the vendor, a radiation workmanship test is required. A TID Cobalt-60 test would be the preferred test method due to the low. The results are then compared to the initial qualification test to confirm that the fiber has the same, or a better radiation hardness.

IV. QUALIFICATION AND FLIGHT EVALUATION APPROACH

A. Introduction and Prerequisites

The general problem when faced with the qualification of fiber optical components, is the lack of standards. There are several standards on component level, but no generic standard for assemblies is present. The purpose of the qualification is to cover failure modes of the design. Furthermore, additional acceptance tests are needed to test for workmanship. Only a few qualified fiber optical components are existing. As an example, the ESA qualification of the MiniAVIM connector was completed recently. It happened several times in the past that the production of fiber optical components, which were qualified and flown, was ceased. Even for qualified parts, additional tests are needed even, in case the original qualification did not fully cover the required test conditions or the information is not available.

When planning qualification activities, it is important to know, that a combination of qualified components used in an assembly, does not mean that the assembly is qualified. As an assembly of components has different or additional failure modes, the qualification tests have to be performed on assemblies in a representative configuration, with additional attention focused on the manufacturing process.

B. Qualification Approach

A generic qualification flow for optical fiber subsystems is presented here. The approach follows the development flow of the project, so that the tests are performed with the actual flight fiber cable. This qualification approach is a combination of batch acceptance testing and qualification testing. It is similar to qualification approaches presented for other missions [1]. The flow is shown in Fig. 2.

The activities after the design and development phase are beginning with the procurement of the optical fiber and, if used, the fiber cable. The radiation qualification is performed with the optical fiber at the beginning. After successful qualification of the fiber and cable, the qualification tests on the cable assemblies are performed.

Environmental tests are conducted with mission representative parameters for the assemblies. It is important for all qualification tests, to wisely set the parameters in order to avoid excessive test margins and overtesting. There are some standards existing, most prominently the ECSS standards, which are giving guidelines for margin philosophy, test parameter and test cycle selection.

Tests shall be performed with the complete, representative assemblies, e.g. fiber cables terminated with connectors, in a mated condition, to allow in-situ monitoring, as far as possible. One exception, for example, is the shock test, as an in-situ monitoring of the optical transmission is not possible. Besides measurement of the transmission (or insertion loss), components shall be visually inspected before and after tests.

All processes, like the thermal precondition of the fiber cable, and including the connector termination process, have to be performed for the test sample manufacturing in the same way as later on the flight hardware.

The qualification approach can be tailored with tests skipped or tests added, depending on specific mission requirements. Additional test might also be called for from the use of special components. These tests can include packaging tests, lifetime tests (especially for active components), or additional optical performance tests, which are required by some applications.

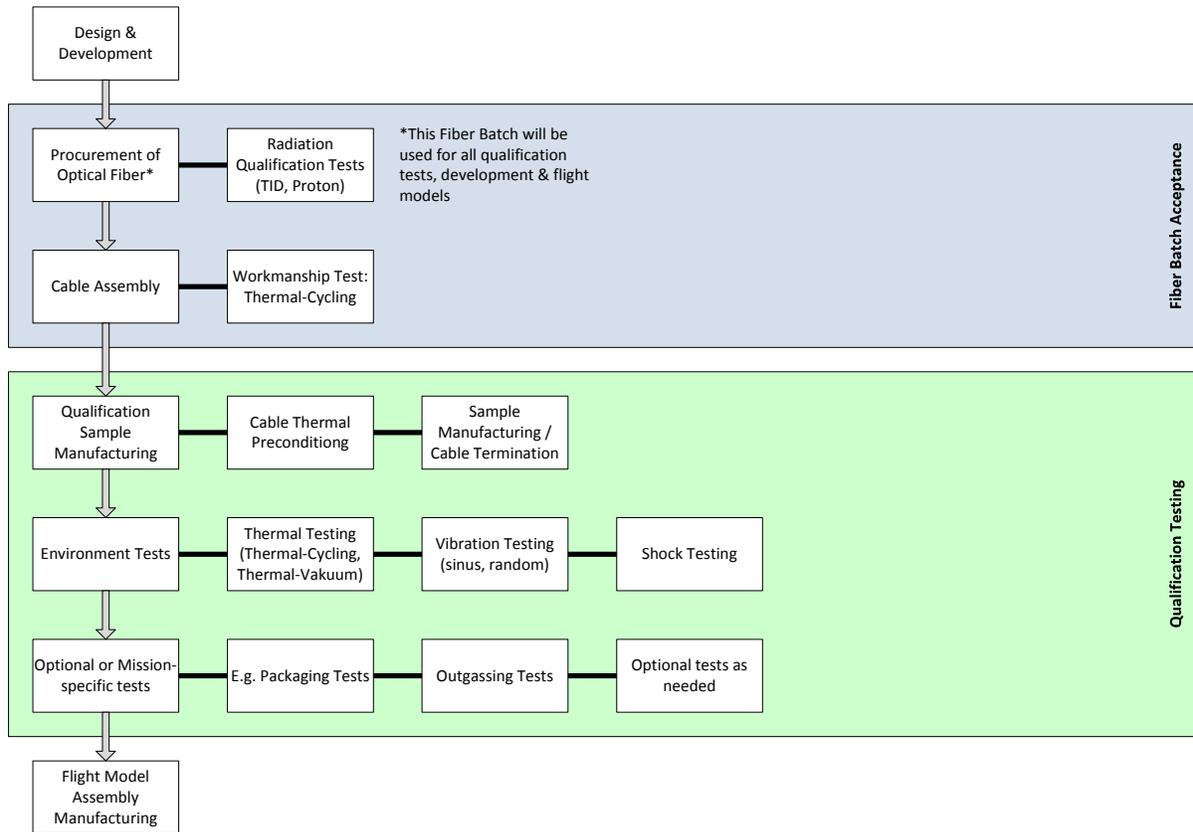


Fig. 2. Qualification Sequence

C. Flight Hardware Acceptance Testing

After completion of the qualification tests, the procurement of the flight components (if not already procured for the qualification tests, like in the case of the fiber cable), and acceptance testing are performed. The manufacturing and acceptance flow is shown in Fig. 3. The purpose of the acceptance testing is to verify the workmanship of manufacturing.

Acceptance tests are conducted for thermal-cycling tests and vibration tests in the same configuration as the qualification tests. However, for the thermal-cycling test is performed a reduced number of cycles compared to the qualification test. The vibration test parameters with realistic load levels.

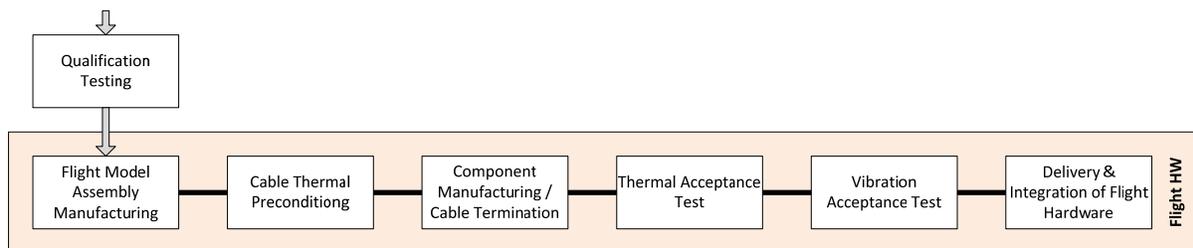


Fig. 3. Manufacturing & Acceptance Testing of Flight Hardware

After completion of the acceptance testing, the fiber optical assemblies are ready for integration into the flight instrument.

V. FIBER OPTICAL HARNESS FOR THE EXOMARS RLS INSTRUMENT

A. Design Process and Part Selection

For the ExoMars Raman Laser Spectrometer (RLS), a fiber optical harness subsystem had to be developed. The purpose of the optical harness is to connect the excitation laser and the spectrometer to the optical sensor head. The configuration of the fiber optical harness is illustrated in Fig. 4. It has to be noted, that the project underwent a long development process, with several changes of the instrument design baseline, so the design of

the optical harness had to be adjusted accordingly. The first design included two optical sensor heads – one externally mounted on a robotic arm, which was later removed (accommodating also the later removed LIBS (Laser induced breakdown spectroscopy) functionality), the second optical head inside of the rover, accommodated above the sample distribution system. The current baseline design includes only the internal Raman optical sensor head, positioned over the sample distribution system, one spectrometer and one redundant laser assembly. The system is described more detailed in [2].

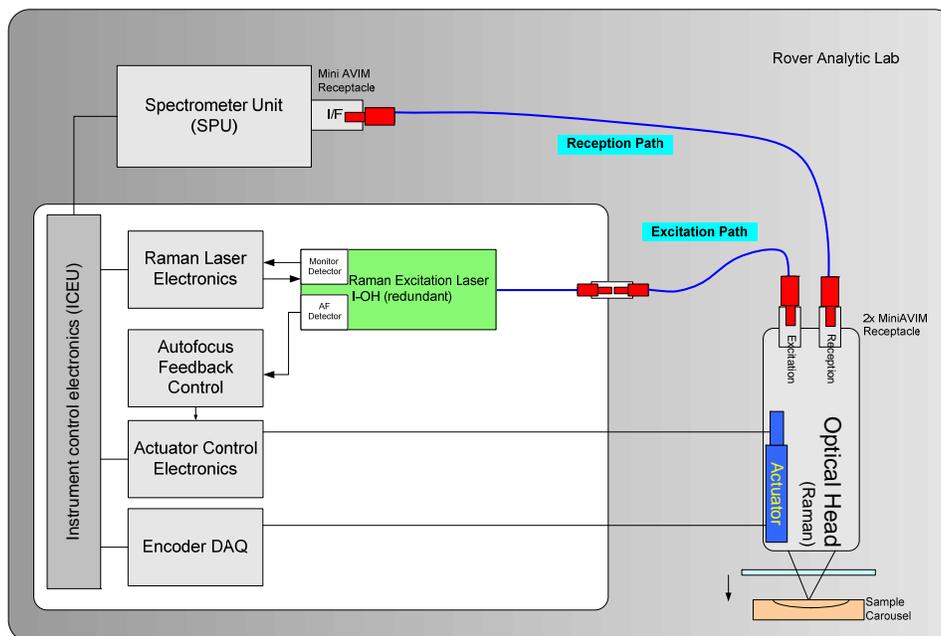


Fig. 4. Configuration of the optical harness inside the RLS instrument

Two design drivers for the fiber optical harness are the thermal environment and, initially, the mass limitations. The initial design required that the system to be used in a thermal environment from -130°C up to $+30^{\circ}\text{C}$, and in addition to withstand the dry heat sterilization at $+135^{\circ}\text{C}$. With the changing instrument design changes (removal of the external optical sensor head), this design driving requirement was changed to -40°C to -10°C (while still requiring the dry heat sterilization).

As the first baseline design called for a larger number of optical interconnects, the development of a light-weight fiber optical connector was pushed. Diamond developed the MiniAVIM connector for this project initially. In comparison to the already space-qualified AVIM connector, the mass of the MiniAVIM connector is about $1/4^{\text{th}}$.

The Gore 1.2mm simplex cable was selected due to its high flight heritage and robustness for large thermal ranges. As the fiber core diameter and numerical aperture were given through the optical design, the exact fiber type and supplier had to be chosen. The market offers a wide range of the required $50\mu\text{m}$ NA0.22 multimode, step-index optical fibers. The driving requirement for the fiber selection was the required radiation hardness of 20 krad. The selection and test approach is described in the following section. After completion of the evaluation tests, the Ceramoptec WF50/125P polyimide coated optical fiber was chosen.

The design of the optical head and spectrometer called for high precision alignment of the fiber connector ferrules. As the use of standard free-space mating adapters was not possible, a high-precision fiber optical receptacle was developed. The receptacle is an all-Titanium part with high precision inner and outer manufacturing tolerances, in order to position the fiber with the required accuracy. Fig. 5 shows the used components for the Raman Laser Spectrometer on ExoMars.

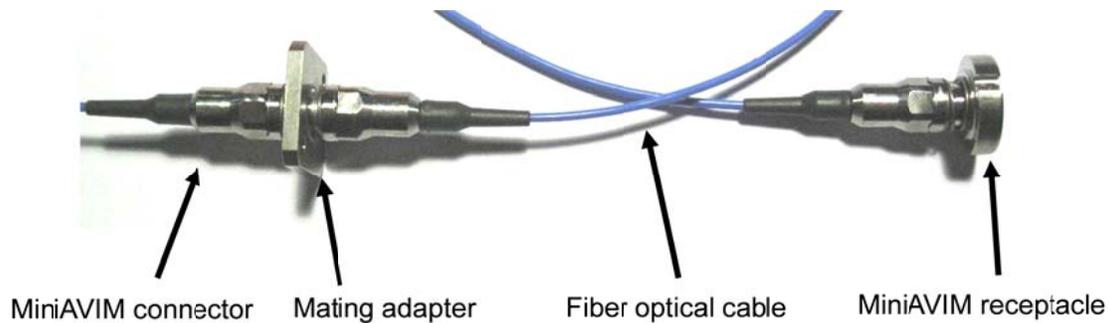


Fig. 5. Component Configuration of the RLS Optical Harness Subsystem

B. Radiation Testing

During the design phase of the RLS instrument, a trade-off between four different types of optical fibers with same optical properties (core diameter, index-type, numerical aperture) was performed. Besides the fiber coating, the main difference between the fiber types was the OH content of the fiber core: two fiber types with a high OH content (>1000 ppm) and two types with low OH content (<1 ppm). As the OH absorption bands are not within the wavelength range of the instrument, the absorption has not a negative impact on the instrument performance. It was observed, that fiber with higher OH content have a higher radiation hardness.

A 50 MeV Proton and a TID gamma test were performed to support the trade-off decisions. The previously connection between the OH content and the radiation hardness could be confirmed [3]. For the instrument, the high-OH fiber from Ceramoptec WF50/125P was chosen. As the fiber batch used for this test was not available afterwards, a new batch of the same type was procured and a TID Gamma test conducted as workmanship test. The results showed, that the radiation induced attenuation for both tests were the same within the test and measurement accuracies.

C. Qualification Approach

The qualification approach was planned as described in section IV. As the radiation testing (TID Gamma and Proton test) of the optical fiber was performed already on another batch of the same type of optical fiber, a TID Gamma workmanship test was foreseen for the flight batch of the optical fiber. All tests were planned to be performed in a mated condition with in-situ monitoring, and to be performed on system level if possible.

The custom-made fiber receptacle will be subjected to a tailored testing. As it is not possible, to test this component as a stand-alone component, the performance requirements cannot be verified. Therefore, the qualification tests have to be carried out within the assembled system.

VI. CONCLUSION

Today, fiber optical systems are used for many applications in space flight. For the design and development, it is important to identify critical requirements and constraints early in the project. Failure modes have to be identified as early as possible to select the appropriate verification methods and plan the qualification tests.

The outlined qualification approach covers most failure modes for passive fiber optical subsystems. Tests shall be performed on assembly level, rather than component level, as assemblies have different failure modes as components. The proposed approach can be used for future projects to plan an efficient qualification program. If needed the test program can be tailored if required.

For the optical harness of the ExoMars Raman Laser Spectrometer, the qualification program is based on the laid out approach. Some qualification tests were already performed in an earlier phase, to support trade-off decisions between different design options. An example is the radiation qualification: the TID Gamma and the Proton test were performed using several different fiber types. As the qualified fiber batch was not available later, a TID Gamma test was successfully conducted as workmanship test on a new batch of optical foreseen to be used for the flight models.

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