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SPECTROModule: A modular *in-situ* spectroscopy platform for Exobiology and Space Sciences

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The evolution of the solar system and the origin of life remain some of the most intriguing questions for humankind. Addressing these questions experimentally is challenging due to the difficulty of mimicking environmental conditions representative for Early Earth and/or space conditions in general in ground-based laboratories. Performing experiments directly in space offers the great chance to overcome some of these obstacles and to possibly find answers to these questions. Exposure platforms in Low Earth Orbit (LEO) with the possibility for long-duration solar exposure are ideal for investigating the effects of solar and cosmic radiation on various biological and non-biological samples. Up to now, the Exobiology and space science research community has successfully made use of the International Space Station (ISS) via the EXPOSE facility to expose samples to the space environment with subsequent analyses after return to Earth. The emerging small and nanosatellite market represents another opportunity for astrobiology research as proven by the robotic O/OREOS mission, where samples were monitored *in-situ*, i.e. in Earth orbit. In this framework, the European Space Agency is developing a novel Exobiology facility outside the ISS. The new platform, which can host up to four different experiments, will combine the advantages of the ISS (long-term exposure, sample return capability) with near-real-time *in-situ* monitoring of the chemical/biological evolution in space. In particular, ultraviolet-visible (UV-Vis) and infrared (IR) spectroscopy were considered as key non-invasive methods to analyse the samples *in situ*. Changes in the absorption spectra of the samples developing over time will reveal the chemical consequences of exposure to solar radiation. Simultaneously, spectroscopy provides information on the growth rate or metabolic activities of biological cultures. The first quartet of experiments to be performed on-board consists of IceCold, OREOcube and Exocube (dual payload consisting of ExocubeChem and ExocubeBio). To prepare for the development of the Exobiology facility, ground units of the UV-Vis and IR spectrometers were studied, manufactured and tested as precursors of the flight units. The activity led to a modular *in-situ* spectroscopy platform able to perform different measurements (e.g. absorbance, optical density, fluorescence measurements) at the same time on different samples. We describe here the main features of the ground model platform, the verification steps, results and approach followed in the customization of commercial–off-the-shelf (COTS) modules to make them suitable for the space environment. The environmental tests included random and shock vibration, thermal vacuum cycles in the range −20°C to +40°C and irradiation of the components with a total dose of 1800 rad (18 Gy). The results of the test campaign consolidated the selection of the optical devices for the Exobiology Facility. The spectroscopic performance of the optical layout was tested and benchmarked in comparison with state-of-the-art laboratory equipment and calibration standards showing good correlation. This includes spectra of samples sets relevant for the flight experiments and a performance comparison between the SPECTROModule ground model and state-of-the-art laboratory spectrometers. Considering the large number of samples and different types of optical measurements planned on-board the ISS, the main outcome was the implementation of an LED-photodiode layout for the optical density and fluorescence measurements of IceCold (42 samples) and ExocubeBio (111 samples); while the UV-Vis spectrometer will be mainly focused on the change of the absorption spectra of the 48 samples of OREOcube .The ExocubeChem samples (in total 48) will be analysed by infrared spectroscopy. The ground platform supports the establishment of analogue research capabilities able to address the long-term objectives beyond the current application.

Keywords: Exobiology, Astrobiology, Spectroscopy, *In-situ* monitoring, Low Earth Orbit, International Space Station, UV/VIS, IR

Acronyms/Abbreviations

International Space Station (ISS), commercial off-the-shelf (COTS), Commercial Resupply Service (CRS), ultraviolet-visible (UV-Vis), infrared (IR), low Earth Orbit (LEO), Fourier-transform infrared spectroscopy (FTIR), European Programme for Life and Physical Sciences in Space (ELIPS). International Life Sciences Research Announcement (ILSRA), Ground Model

(GM), Ground Support Equipment (GSE), European Space Agency (ESA), Planetary and Space SImulation (PSI), Optical Density (OD), Light-Emitting Diode (LED), Scientific Module (SM). Fourier Transform InfraRed Spectrometer (FTIR), Manufacturing, Assembly, Integration and Testing (MAIT), Cargo Transportation Bag (CTB), Total Ionizing Dose (TID), Multi-Layer Insulation (MLI), German Aerospace Centre (DLR), Helmholtz Zentrum München (HZM)

1. Introduction

Since the early 1990's there is a long heritage of ESA astrobiology experiments in LEO, initially using the free-flying EURECA facility, deployed and retrieved by the Space Shuttle, followed by six short-duration BIOPAN missions on unmanned Foton capsules and three long-duration EXPOSE missions on the ISS [1], Figure 1.

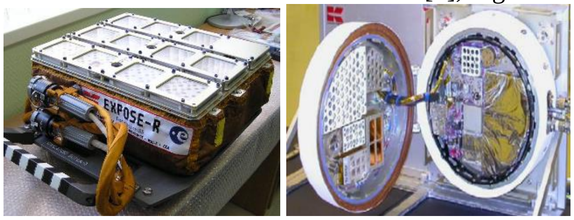

Figure 1: EXPOSE-R Facility (on the left) and BIOPAN Faciliy (on the right), credit :ESA

The earlier BIOPAN and EXPOSE facilities exposed a variety of microorganisms (amongst other samples) to investigate the effect of LEO environmental parameters, namely short wavelength solar UV, ionizing radiation and temperature oscillation in addition to the desiccating effect of space vacuum or a simulated Mars atmosphere consisting of a Mars gas at 600-1000 Pa pressure. Due to these atmospheric conditions, the samples were exposed dry, resulting in a metabolically inactive state of the microorganisms. The inactivity of the biological samples allowed the passive accumulation of damage to be analyzed post-flight on the ground.

The facilities were designed to support the investigation of the survival of microorganisms of harsh space and Mars conditions, and of the possibility of viable organisms to travel in space or to Mars, accidentally as blind passengers on a spaceship (planetary protection relevance) or naturally ((litho)panspermia).

These missions have provided a unique set of data to understand the influence of UV, cosmic radiation, vacuum, microgravity and thermal excursions on a wide variety of organic compounds and life forms. In all cases, the scientists were only able to compare the pre-flight results with the post-flight results, without having the possibility to understand how the chemical and biological changes developed over time during the orbital flight, [14, 15, 16, 17, 18, and 19].

With our increasing knowledge of our solar system, celestial bodies with subsurface oceans are now also considered as possible habitable worlds. With the possible availability of liquid water, for example on some of the icy moons, the question on the survival of microorganisms in harsh desiccating environments of other planets is now extended to the question of active life e.g. in the icy moons' oceans.

Consequently, a new generation of space experiments intends to investigate the response of metabolically active organisms capable of repairing damage induced by space conditions, like short wavelength UV and radiation. Since these active cultures may develop and grow during the mission, in contrast to the passively exposed organisms, the investigation after the mission on the ground is no longer sufficient to understand the effects of these extreme environments. Only active *in-situ* measurements to be performed during the mission and therefore during the interplay of exposure and reaction of the organisms allow further insights into the effects of space on living systems.

The advantage of long-term exposure and mainly sample return, is fostering the development of new platforms (commercial and institutional) to provide more locations and opportunities for accommodation of exposed payloads. Examples for the ISS are:

- Nano Racks External Platform NREP [2]
- IVA-replaceable Small Exposed Experiment Platform i-SEEP [2]
- Materials International Space Station Experiment MISSE-X [3]
- Bartolomeo, new commercial exposed platform on Columbus Module [5]

The emerging small and nanosatellite market represents another opportunity for astrobiology research as proven by the O/OREOS mission [4], where samples were analysed *in situ*; but with the limitation in sample number and no option to return the samples to Earth.

In this framework, the European Space Agency is developing a novel Exobiology facility to be installed on the outside of the ISS. As an outcome of the ILSRA 2014 call, eight individual experiments, namely Biosign, MEXEM, IceCold, Rotifer, GENESISS, ExocubeBio, ExocubeChem and OREOcube, were selected for implementation on this facility. Therefore, the platform design is based on a modular approach to accommodate the needs of all experiments, and it will be equipped with an array of instruments to fulfil their different requirements.

Specifically the experiments GENESISS, ExocubeBio, ExocubeChem, IceCold and OREOcube will require *in-situ* measurement. In particular, IceCold, OREOcube and ExocubeBio would require the use of a UV-Vis spectrometer, while ExocubeChem will require the use of an IR-spectrometer.

1.1 SPECTROModule Project Objectives

To prepare for the development of the Exobiology facility, ground units of the UV-Vis and of the IR spectrometer were studied, manufactured and tested as precursor of the flight units. The spectrometers represent the core instrumentation for the *in-situ* measurements. To accomplish spectroscopic measurements, the instruments are coupled with a “samples handling mechanism”, which describes the system/subsystem that moves the various samples in and out of the optical path and therefore allows monitoring of several samples with one spectrometer unit. The built spectrometer and the sample acquisition system (called SPECTROModule GM) was used as input to define the interfaces and specification of the new facility as well as the software specification to fulfil the experiment’s execution and scientific data handling.

The Ground Model (GM) has a double purpose:

a) The spectrometer and sample acquisition system (SPECTROModule) have to be a proof of concept of the proposed technical solution for the flight unit. Hence, it has to be representative of the flight design solution. The system has to be validated and tested to assess the compliance with the ISS environment and assure it performs as planned.

b) SPECTROModule and the Ground Support Equipment (GSE) delivered in the frame of the project shall be also used as a Science Reference Module (SRM) by the scientists to test the system performance and the experiment protocols. Therefore, the GM system has to be flexible and reconfigurable to serve different setups and support the scientific teams in identifying the suitable experimental protocols and potential improvement areas.

This paper reports the main outcomes of the SPECTROModule project, focused on the activities performed on the ground models of the UV-Vis spectrometer, sample acquisition system and FTIR spectrometers.

2. Experiments Definition for the First Mission

2.1 First Mission Overview

The Exobiology facility will be a multi-user platform. Therefore, the utilization concept is based on the development of a “Common Module”, which will represent a fixed interface to two exchangeable Scientific Modules (SM1 & SM2), each one hosting a different quartet of experiments. Considering the scientific requirements of the experiments and of the necessary instruments, the first group accommodated on SM1 will consist of OREOcube, IceCold, ExocubeBio and ExocubeChem. It is envisaged that the facility will first be deployed for about 1 year to perform the mentioned 4 experiments, then recovered into the ISS for reconfiguration for the other 4 experiments, and then redeployed outside the ISS for about 1 year. The currently planned flight date of the Exobiology Facility with SM1 is in the middle of 2022. The Exobiology Facility will be accommodated outside the Columbus module (currently on the upcoming Bartolomeo Platform, its launch scheduled with Space X CRS-20 in March 2020 [5]).

The operational scenario is based on the following phases:

1) Samples will be uploaded to ISS in a passive, temperature controlled bag
2) The common module and the SM1 will be launched in a soft stowed configuration to ISS
3) The crew will perform the integration of the samples into the SM1 inside ISS,
4) The assembled Exobiology Facility will be transferred outside ISS via the NanoRacks Airlock Module (Bishop), scheduled for launch with Space X CRS-21 in August 2020
5) The Facility will be installed on the Bartolomeo platform via robotic arm installation, assuring continuous power during all the transfer phases to keep the samples in the required temperature range.
6) After the experiment run of SM1, the robotic arm will retrieve, via the NanoRacks Airlock, the complete Facility; allowing the removal of SM1 and consequent download of the samples to Earth in a cold stowage configuration.
7) SM2 will then be installed and the second set of experiments will be exposed as per the aforementioned procedure.

2.2 IceCold

The icy moons of the outer solar system, Europa and Enceladus in particular, are part of the few possibly habitable places in our solar system. Though the moon´s surfaces are too hostile to expect any life, the liquid water oceans beneath the water ice surfaces may provide the necessary environment to support life similar to Earth´s deep oceans. Recent evidence of possible very-near surface water (brine) together with the geological youthfulness of the linear features and observed plumes support the idea of a possible extant habitat. Life existing near the surface – even if transient - may interact with surface electromagnetic and particle radiation. Short wavelength solar UV and – in the case of Europa - Jupiter´s radiation might penetrate into the ice shield and brines, challenging possible life to evolve protection mechanisms. The extremophile microorganisms selected for IceCold represent the 3 domains of life on Earth (Archaea, Bacteria, Eukarya). The experiment aims to test the hypothesis that they survive and multiply in a periodically cold (below 0°C), salty, liquid environment, even when exposed to low extra-terrestrial short wavelength UV and ionizing radiation, in space on an outside exposure platform of the ISS. The candidate test organisms *Halorubrum lacusprofundi* (archaeon), *Rhodococcus JG-3* (bacterium) and *Rhodotorula JG-1b* (eukaryon) isolated from Antarctica grow at low temperatures in salty liquid media. They are complemented by the bacteria *Deinococcus radiodurans*, *Bacillus subtilis* and the archaeon *Halobacterium salinarum*. The set of microorganisms will be uploaded in a metabolically passive, dried form. When installed on the expected destination Bartolomeo outside of the ISS, the metabolism and growth of the cultures are started by the addition of medium, marking also the start of the experiment. The cultures growth will be monitored by automated repeated measurements of the optical density (OD). Increasing OD of the cultures indicates the growth of the microorganisms while no OD increase indicates microorganisms that are not multiplying. The in-flight control set of samples will remain in the dark during the whole mission while the test set is covered with MgF_2 windows and shutters for defined irradiations with extra-terrestrial short wavelength solar radiation. The cell growth of 36 samples (18 sun irradiated, 18 in the dark) is monitored via OD measurement. Considering that the culturing medium by itself can contribute to the OD and to change thereof, three sun-exposed and three dark culture-free cuvettes will be accommodated and optically measured. The following optical measurements will be performed, using the setups shown in the diagrams in Figure 2:

- OD of each culture (Sun irradiated and in the dark)
- OD measurements of the cuvette filled by medium only will provide the light absorption caused by the medium itself that has to be subtracted. This value is understood to be the reference measurement (blank)
- Measurement of the solar spectrum behind the optical window (attenuated) to give information about the transmissivity of the window.
- Solar spectrum not attenuated by any window.
- Measurement of the dark spectrum, which should be subtracted from both sample and reference spectra.

IceCold will not be temperature controlled and hence oscillates with the LEO temperature at the exposure platform. Incident extra-terrestrial solar UV will be measured by the experiment's common spectro-radiometer. All obtained science (OD) and environmental (temperature, UV spectra) data will be transmitted to Earth for analysis regularly together with housekeeping/health data. The overall mission exposure time is expected to be approximately six months. After exposure, the samples will be returned to Earth for additional investigations. A flight identical ground reference experiment will be performed in parallel to the mission according to the mission data in the Planetary and Space Simulation facilities at DLR Cologne as far as possible.

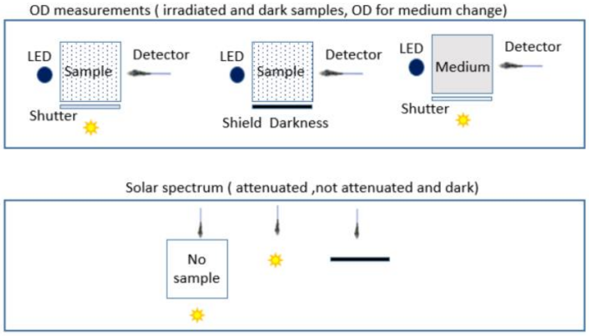

Figure 2: IceCold optical density (OD) and spectral measurements.

The psychrophilic organisms proposed for the space experiment here are representatives of very important groups of microorganisms on Earth. The experiment will increase our knowledge of the limits of life and serve as a demonstrator for free-flying experiments in higher radiation orbits.

2.3 OREOcube

Current and upcoming planetary exploration missions such as Curiosity [6] from NASA or ExoMars [7] from ESA fuel our pursuit of tracing life's origin on Earth and possibly beyond. The stability of molecules indicative for life, so-called biomarkers, is a prime objective of OREOcube. Studying the stability of astrochemically relevant organic molecules when exposed to photons, electrons and heavier particles has a long history in ground-based experiments [8]. Numerous facilities and laboratories worldwide are capable of exposing samples to selected or extended parts of the electromagnetic spectrum, electrons and/or heavier particles such as atoms or ions. However, to date, it is technically and experimentally extremely challenging, and economically unfeasible, to reproduce solar radiation levels faithfully in ground-based laboratories [9]. In the last decades, experiments on the ISS provided valuable data on the effect of the outer space environment in low Earth orbit on organic and biological samples [10]. A major disadvantage of previous studies, where measurements were only possible before and after the space exposure period, was the lack of *in-situ* data. However, to gain real kinetic information *in-situ* and time-resolved measurements are required. Attempts to equip space exposure platforms with *in-situ* measurement capabilities have been successfully accomplished by NASA in the form of free-flying nanosatellites. A recent example is the O/OREOS satellite [11]. Similarly, with its *in-situ* spectroscopic capability, OREOcube will measure changes in organic samples when in contact with inorganic surfaces and provide insights into the kinetic details of photochemical reactions in order to study radiation-induced modifications of astrochemically relevant organics and inorganics. In addition to the *in-situ* capabilities, OREOcube samples will be returned to

Earth to allow further sophisticated analysis in ground-based laboratories. Potential candidates of organic compounds and inorganic substrates for the OREOcube project were selected based on recent findings and observations in the fields of astronomy, astrophysics, meteoritics and planetary sciences.

The OREOcube experiment requires the acquisition of UV-Vis absorbance spectra of thin films of organic compounds and organic/inorganic dual layers. Their photochemical changes, when exposed to solar and cosmic radiation, will be acquired by the onboard UV-Vis spectrometer. OREOcube samples are contained in hermetically sealed sample cells. Four different measurements are performed *in-situ*, as illustrated in Figure 3:

- UV-Vis spectra of each individual sample cell
- UV-Vis spectra of a limited amount of blank cells (no samples inside) to normalize the above measurements
- Dark spectra with the Sun blocked off, and without sample cells to determine signal level changes and to correct for baseline offset and fixed pattern noise
- Direct Solar Spectrum

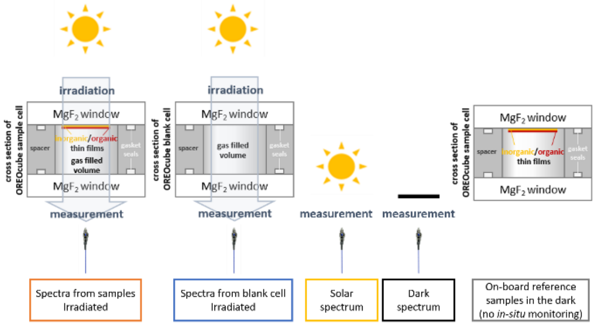

Figure 3: OREOcube samples measurements' set.

2.4 Exocube (ExocubeBio and ExocubeChem)

The interaction of solar and cosmic radiation with organic molecules and biological systems is of great importance in space science and in particular for astrobiology [12] and astrochemistry [13]. How does life at different stages of complexity respond to, and evolve in, space and planetary conditions? During such processes, what biomolecular mechanisms come into play at the interfaces between biology, chemistry, and physics? ExocubeBio and ExocubeChem are aiming to address these questions with far-reaching implications for the interpretation of the results of past and upcoming planetary exploration missions.

With its heritage from the NASA O/OREOS mission [4], the two Exocube experiments represent a new generation of space exposure platforms based on miniaturized in-situ analytical instrumentation. Infrared spectroscopy as well as fluorescence and colorimetric measurements, will allow monitoring radiation effects on biological molecules and organisms. According to the type of samples, a short name was assigned: ExocubeChem ('chemistry', i.e. non-living samples) and ExocubeBio ('biology', i.e. (mostly) living samples). Exocube will couple the capability of in-situ online monitoring of organism responses to the spaceflight environment with detailed post-flight sample analyses on the ground. Using a UV-Vis spectrometer, the ExocubeBio experiment, measures the OD and fluorescence signal as an indication of biological and metabolic activities. ExocubeBio will expose protocells, prokaryotes and eukaryotic cells to space radiation in low Earth orbit and microgravity and measure *in situ* their biological response via reporter dyes.

The ExocubeChem experiment requires the use of a Fourier-Transform Infrared (FTIR) spectrometer for the acquisition of different spectra of biological membranes and organic compounds, directly deposit as thin fils on the exposure window. In this way, we can investigate (i) the response of life at different stages of complexity to space conditions and (ii) the role of membranes and membrane components as the interface between life and the physical environment.

In-flight monitoring together with further sophisticated ground-based post-flight analysis, will allow us to study in detail the bio-molecular pathways triggered by radiation events and microgravity. It will also help to identify key molecules and membrane components that are involved in the adaptation of these organisms to space conditions.

3. SPECTROModule Project

The project was executed in four main phases, as illustrated in figure 4.

Phase I activities included a market survey to identify off-the-shelf (OTS) instruments, which can be used for the Exobiology Facility spectrometer and consolidate the instrument specifications considering performances as well as the environment in which the instrument will work and the need to be integrated into the Exobiology facility. Phase II led to a design and customization of the identified instruments, sample handling system and Ground Model platform. Later, in Phase III, the main Manufacturing, Assembly, Integration and Testing (MAIT) activities were performed on the Ground Models. It is worthwhile to mention that, for the UV-Vis SPECTROModule GM hardware, two models of the spectrometer and sample handling were released (GM#1 and GM#2) considering the challenging schedule over the project duration of one year. Developing two models allowed decoupling environmental tests from the scientific test campaign at the scientists' site, performed in Phase IV.

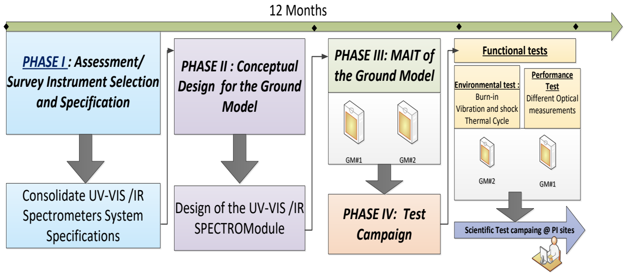

Figure 4: SPECTROModule project phases.

3.1 System Description

SPECTROModule consists of two different hardware setups. The first setup includes a UV-Vis spectrometer, which serves the experiments OREOCube, ExocubeBio, and IceCold. The second setup uses an FTIR spectrometer for the experiment ExocubeChem. The spectrometers were selected to fulfil the scientific requirements defined for each experiment, as well as technical constraints related to the operating environment (outside ISS) and available budgets. The following main points were used to screen the market for the most promising candidates:

- Spectrometer with high optical performance: wavelength range 200-1000nm, spectral resolution of 2 nm, absorbance unit accuracy of 0.03 and signal-to-noise ratio (SNR) 250:1
- Compliance with power budget (5W) and dimensions (10x10x10 cm^3)
- Independent sample/spectrometer interfaces for sample removal and exchange
- Space application heritage

The key point, mainly for the UV-Vis architectural design, was identified in the sample handling system. It represents the “method/technique” selected to bring all the samples of the three experiments to be observed by one spectrometer. In total, about 120 different sample measurements need to be performed for the flight model using one spectrometer and the minimum number of samples for ExocubeBio. The approach used is based on a trade-off analysis considering the reliability and robustness as a selection criterion. Moreover, the selected solution will have an impact on the sample removal operational concept for the return to Earth. Therefore, the sample handling represents the direct interface with the sample compartments.

Two reconfigurable ground model platforms were designed and manufactured for each optical setup based on the conceptual layout and future interfaces with the Exobiology Facility, as illustrated in Figure 5.

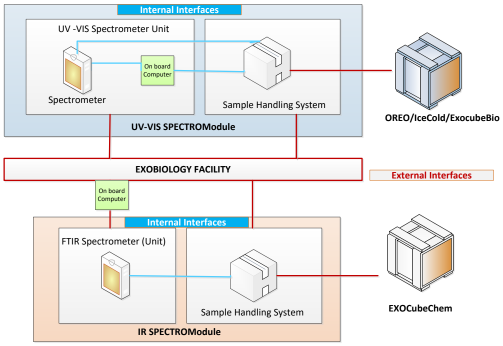

Figure 5: SPECTROModule system concept and interface.

3.2 COTS Optical Instrument: Selection, Ruggedization and Testing

The remainder of this chapter describes how the hardware was selected and how critical COTS components were ruggedized and tested for their use in space.

3.2.1 UV-Vis Spectrometer and Samples Handling

The UV-Vis spectrometer market survey provided a short list of top candidate instruments able to fulfil the requested performances. The OEM-Embed 2000 from Ocean Optics was selected as the final choice, shown in Figure 6. This spectrometer can measure spectra from 200 nm to 1000 nm with a spectral resolution better than 2 nm. The OEM version allows developing a dedicated interface for power and software implementation and allows testing of customized software code instead of the COTS software. One of the main goals of the project was to assess the possibility to use one spectrometer to serve three experiments at the same time on the future Exobiology Facility. For the ground model two possibilities to perform the acquisition selection between the different samples were presented and compared. They are called ‘cell switch’ or ’fiber switch’.

The cell switch concept is based on a mechanism similar to a carousel, which drives the sample compartments under the optical fiber tip for measurements.

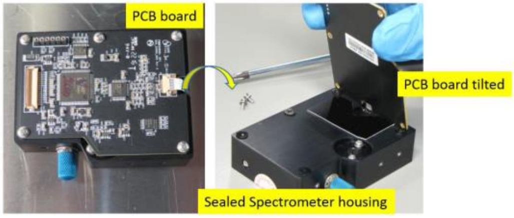

Figure 6: UV-Vis spectrometer system.

In the fibre switch concept, each cell is associated with its own dedicated multimode optical fibre. A switch unit is used to select the fibre that is measured by the spectrometer. Due to the strong differences among the experiments in terms of protocols and subsystem (e.g. pumps, reservoirs, several LEDs type), it was agreed in testing the optical fibre switch technology to allow higher flexibility in sample handling in a compact size. The spectrometer is connected via a customized 48-channel fibre switch from Agiltron (Figure 7) to the experiments' sample compartments of IceCold, to ExocubeBio and to the OREOcube cartridges. The model Light Bend Mini was the baseline option due to the large wavelength bandwidth, epoxy–free design in critical optical areas, customization for a high amount of ports, small size (4x4x10cm^3) and low power (1W).

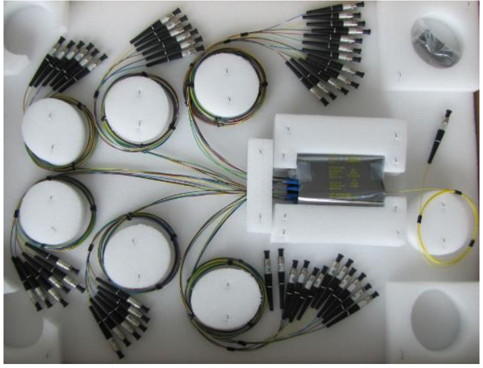

Figure 7: Optical fiber switch with 1x48 channels.

The IceCold and ExocubeBio sample compartments have several LEDs on the opposite sides of the fibres for optical density measurement and LEDs perpendicular to them to perform fluorescence measurements. LEDs with different wavelengths are used for the different biological samples of IceCold and ExocubeBio. The OREOcube samples are directly exposed on one side to a light source, which simulates the Sun. The glass fibre for measurements in the UV-Vis spectrometer collects the transmitted light from the Sun (simulator). Figure 8 shows the accommodation of all the experiments on one optical bench.

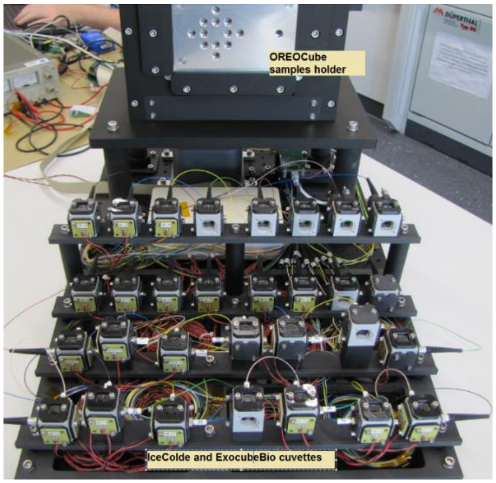

Figure 8: SPECTROModule for UV-Vis applications.

3.2.2 FTIR Spectrometer Hardware

The FTIR spectrometer hardware is required for the ExocubeChem experiment because these samples show spectral features in the wavenumber range from 1000 cm^{-1} to 4000 cm^{-1}. The FITR spectrometer has a radically different measuring concept than a grating spectrometer (used for IceCold, OREO and ExocubeBio). In the FTIR spectrometer for ExocubeChem, a collimated light beam from the light source is split via a beam splitter into two light beams. The beams are retroreflected by corner cubes that are mounted on a common pendulum axis. After reflection, the light beams combine and exit the interferometer to be measured with a detector. Due to the oscillation of the pendulum, a time-dependent interference pattern can be recorded at the detector. Following a Fourier-transformation, the interferogram is converted to a spectrum. In the infrared wavelength range, Fourier transform spectrometers have several advantages:

- Better signal-to-noise ratio
- Higher spectral resolution
- Flexibility in the spectral resolution

The disadvantage is that they are usually not so compact and require controlled thermal conditions for achieving high quality measurements. The market survey led to the selection of the original equipment manufacturer (OEM) version spectrometer from Arcoptix that consists of a light source, the actual interferometer and a Peltier-cooled detector, shown in Figure 9. High (24W) and low power (1.5W) IR lamp sources were procured for scientific tests supporting the elaboration of a trade-off assessment between the performances achieved and the thermal and power budgets.

The interferometer dimensions are 200x114x82mm^3 (LxWxH) including the infrared source; while the detector package measures 103x53x55mm^3 (LxWxH).

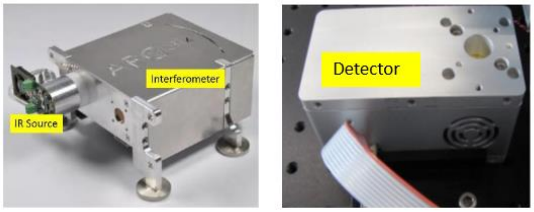

Figure 9: FTIR spectrometers components.

The ground model setup for the FTIR, shown in Figure 10, was derived from the optical design requiring to place the ExocubeChem samples under observation, using a linear stage mechanism. The platform is an optical bench allowing the adjustment of the configuration or the inclusion of future new items (e.g. second detector). In total, twelve exposed samples cartridges and twelve dark cartridges can be hosted on the GM sampling system for testing. Two different configurations were provided to the scientists as transmission and transflection configuration.

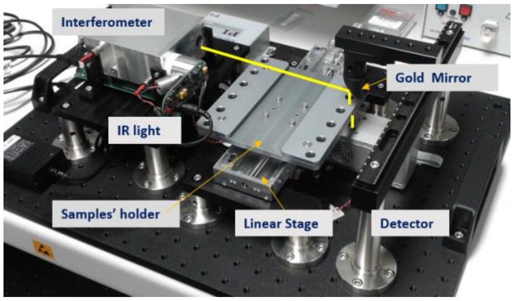

Figure 10: FTIR GM platform - transmission set-up.

In the transmission set-up, the collimated light beam leaves the spectrometer, which is then directed with a 45° flat mirror through the ExocubeChem sample to the detector, as shown in the yellow light path in Figure 10. In contrary, the idea behind the focused transflection setup is to use a mirror and lens in a cat's-eye configuration, where the sample is between mirror and lens. Thus, a small aperture of the sample does not reduce the intensity and a double pass through the sample increases the measurement sensitivity (Figure 11). However, the design becomes more complex, including more optical components and has increased alignment requirements.

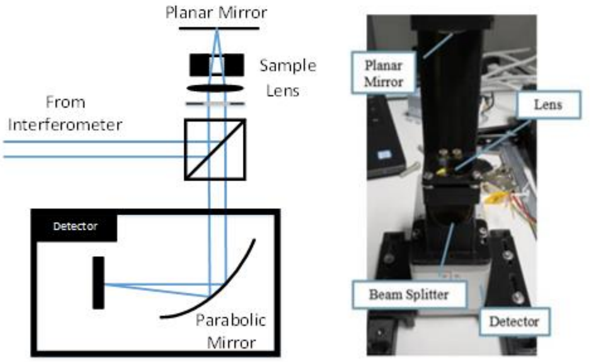

Figure 11: FTIR GM platform:transflection setup elements

3.2.3 *COTS Ruggedization and Environmental Tests*

The COTS evaluation program for SPECTROModule started with a critical initial inspection. Components were evaluated to understand their suitability for use in space outside the ISS, for example if forbidden components are used that outgas as outgassing compromises the optical components. Afterwards, an environmental test campaign was performed to evaluate whether critical components can survive the launch and the space environment. The UV-Vis spectrometer and the fiber switch underwent vibration and shock testing and a thermal-vacuum chamber test.

The UV-Vis spectrometer and the fiber switch were placed in a 0.5 Cargo Transportation Bag (CTB), which was then mounted onto the respective test benches. Figure 12 shows the layout of the fiber switch and spectrometer inside the CTB. The 48 cables were fixed in two separate layers on the foam. The UV-Vis spectrometer was placed under these layers.

Figure 12: UV-Vis and fiber switch in 0.5 CTB for vibration and shock tests.

The vibration test was successfully performed at ZARM in Bremen and the shock test at the DLR Raumfahrtsysteme in Bremen. The applied random vibration test levels, as envelope of the different ISS Cargo spacecraft, are reported in Figure 13.

Frequency [Hz]	Protoflight Envelope
20	0.040 (g^2/Hz)
20 - 50	0 (dB/oct)
50	0.040 (g^2/Hz)
50 - 120	+1.51 (dB/oct)
120	0.062 (g^2/Hz)
120 - 230	0 (dB/oct)
230	0.062 (g^2/Hz)
230 - 2000	-3.04 (dB/oct)
2000	0.007 (g^2/Hz)
OA (g_{rms})	6.50

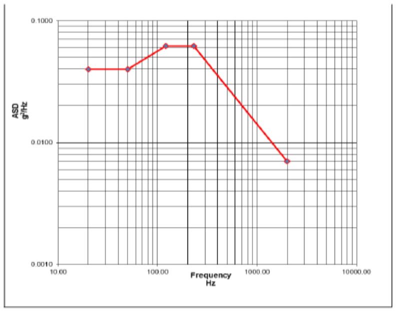

Figure 13: Protoflight random bibration spectrum all launcher for T=0-60 s in each axis.

Pyroshock tests have to be performed on the test items along each of the three axes according to the value reported in Table 1. Pre-tests have to be performed on a mass dummy, to avoid over-testing and to ensure the correct shock pulse input to the test item. Optical performance measurements were conducted before and after the tests.

Axis	Frequency	Level SRS
3 shocks in each axis	100 Hz 3000 Hz 10000 Hz	15 g 1700 g 1700 g
attenuation	D= 5% / Q=10	
resolution	1/12 Octave	

Table 1: Applied shock response spectrum.

The thermal test was performed in-house at OHB Oberpfaffenhofen. The test setup is shown in Figure 14. The fibre-switch with its fibres was directly exposed to vacuum, but the UV-Vis spectrometer was placed in an airtight nitrogen compartment, because the used version was not designed for vacuum.

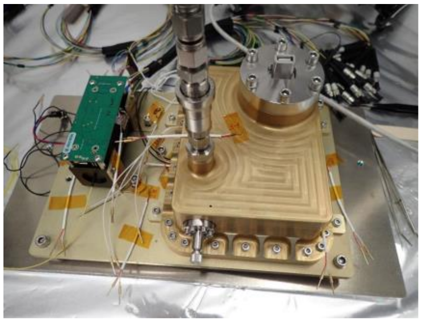

Figure 14: UV-Vis and fiber switch setup for thermal vacuum test.

The setup was connected electrically and optically to equipment outside the chamber to verify the system performance during the test. Overall, eight cycles between -25°C and 60°C were performed. The performance was measured at extreme temperatures. Interestingly, the spectrometer showed very low values, when close to the upper operational limit declared by the manufacturer. It shows that the UV-Vis spectrometer cannot operate at all beyond its operational limit. However, once the temperature falls again, the spectrometer operates normally. Therefore, a thermal control system needs to be implemented in the Exobiology Facility on the ISS.

A Total Ionizing Dose (TID) test was also performed for the fibre switch (without fibres) and the FTIR spectrometer. A Co-60 ELDORADO source, at the Helmholtz Zentrum München (HZM) Institute of Radiation Protection, was used to irradiate the components with a total dose of 1800 rad (18 Gy). The source has a mean gamma energy of 1.25MeV and 0.27Gy/min in 1 m distance, Figure 15. Both the fibre-switch and the FTIR spectrometer were operated during the test. No anomalies were detected, confirming the promising implementation for LEO applications.

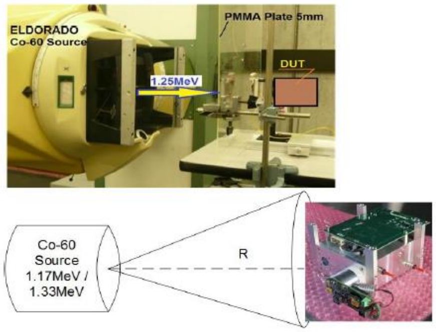

Figure 15: TID test setup at Helmholtz Zentrum München (HZM).

Finally the FTIR spectrometer underwent a thermal test, where it was successfully cycled eight times from -20°C to +40°C. The spectrometer was customised by removing the fan from the detector and then covered with ten layers of Multi-Layer Insulation (MLI) to simulate the heat exchange outside ISS. Figure 16 shows the thermal cycle test setup. During thermal cycling, the FTIR was constantly monitored and showed no degradation in performance.

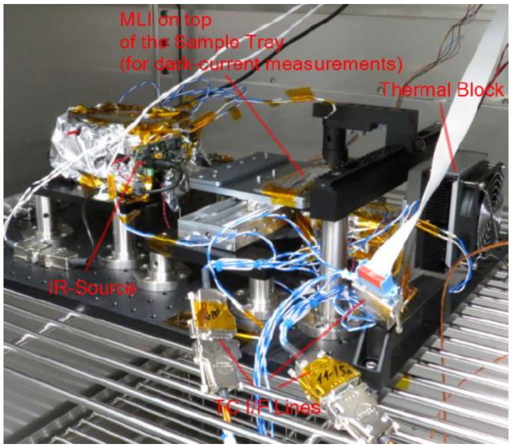

Figure 16: FTIR Set-up for thermal test.

The results of the COTS evaluation program are being used to ruggedize these components for use outside the ISS and dedicated developments are on-going with the instruments' manufacturers.

4. Results and Discussion

The performance tests were validated by using a ground model platform, mainly needed for the OREOcube and IceCold experiments that required the Sun as a source of light for their measurements. ExocubeBio and ExocubeChem, on the other hand, have built-in light sources (LEDs and an infrared light source) so that testing and measurement was possible without an external light source.

The ground model platform and the cell holder were designed to place all the scientific samples under the irradiation source at the same time for the test execution. The DLR Planetary and Space Simulation (PSI) facilities in Cologne were used and modified to accommodate the platform with all samples or only a portion of them, depending on the needs. A dedicated rack was manufactured to host the SOL2 (adapted solar simulator, Dr. Hönle AG) lamp with a shutter, while the experiment platform was mounted on a sliding table, which allows testing different irradiated positions, as shown in Figure 17.

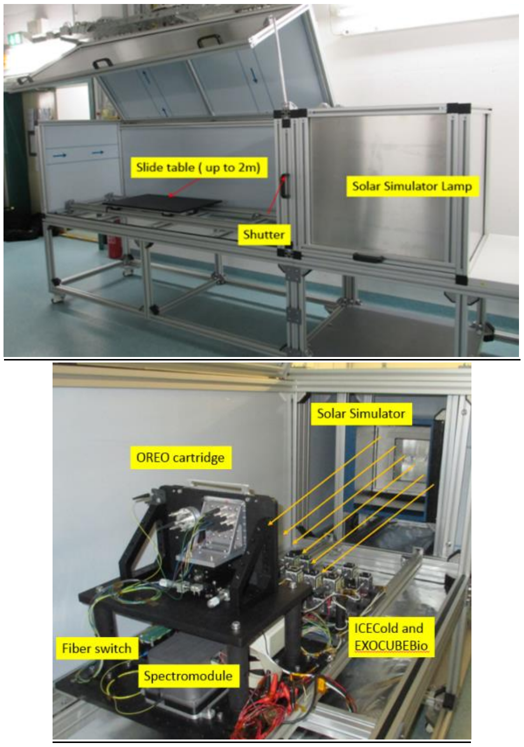

Figure 17: Ground Model Platform: Rack (top) and main plate with experiments Interfaces (bottom) at DLR Cologne.

The spectrometer with fibre switch port #43 was calibrated using a Bentham CL3 calibration lamp. The fibre tip was positioned at a specified distance of 200 mm in front of the glass window of the calibration lamp. Then a validation of the calibration curves was performed using a UVC 254 low pressure mercury lamp NN 8/15 (Heraeus) as a source and compared to the values from the Bentham DMc150 spectroradiometer and SPECTROModule with different integration times (Fig.18). Further correction measurements are necessary, in particular for the short wavelength region below 250 nm and for tor the peak irradiance measurements, but overall, GM#1 accurately follows the wavelengths distribution, with a maximum measured at 254 ± 1 nm.

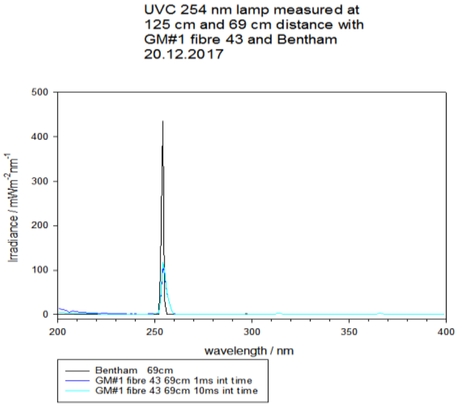

Figure 18: Comparison of Bentham and GM#1 measurements of the UVC mercury low-pressure lamp at 69 cm distance.

Tests, performed with the solar simulator at two different distance from the sources, showed a good correlation as reported in Figure 19.

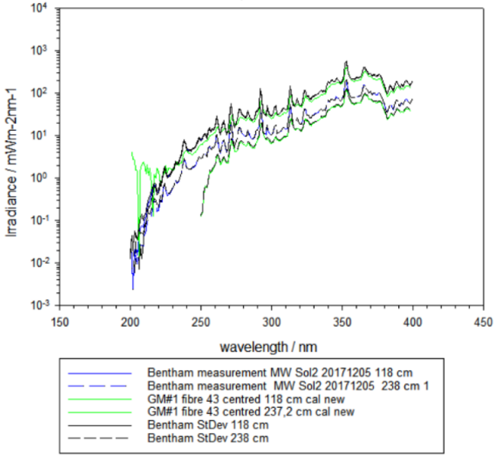

Figure 19. Comparison of Bentham and GM#1 measurements of the SOL2 at 118 cm distance, linear presentation.

Ground model testing of the OREOcube UV-Vis system showed that the selected COTS hardware is well-suited to be further developed into flight hardware. As shown in Figure 20, spectral comparison of test samples consisting of organic and inorganic thin films recorded with the above-mentioned spectrometer systems show very good agreement in the 300 - 800 nm wavelength range. Below 300 nm, the performance of the OREOcube spectrometer prototype is still in very good agreement with spectra recorded with a state-of-the-art UV-Vis spectrometer (UV-2450, Shimadzu), but indicates that the deep UV spectral region requires sufficient photons and high-sensitivity detectors for adequate spectral resolution and signal-to-noise levels. Furthermore, the test results significantly helped to discover optimization potential with respect to not only the spectrometer system and the selected optical bench but also the optical system as a whole, including light fibres and additional optical elements such as lenses and diffusers. Pre-flight testing and thin film preparation also highlight the importance of *in-situ* measurements for monitoring organic molecule and biomarker stability, when irradiated with simulated solar light. In-depth studies of the photochemical evolution of suitable organic molecules, which are accessible via UV-Vis spectroscopy, are part of the pre-flight experiment schedule and will feed into the selection process of the actual flight-sample candidates.

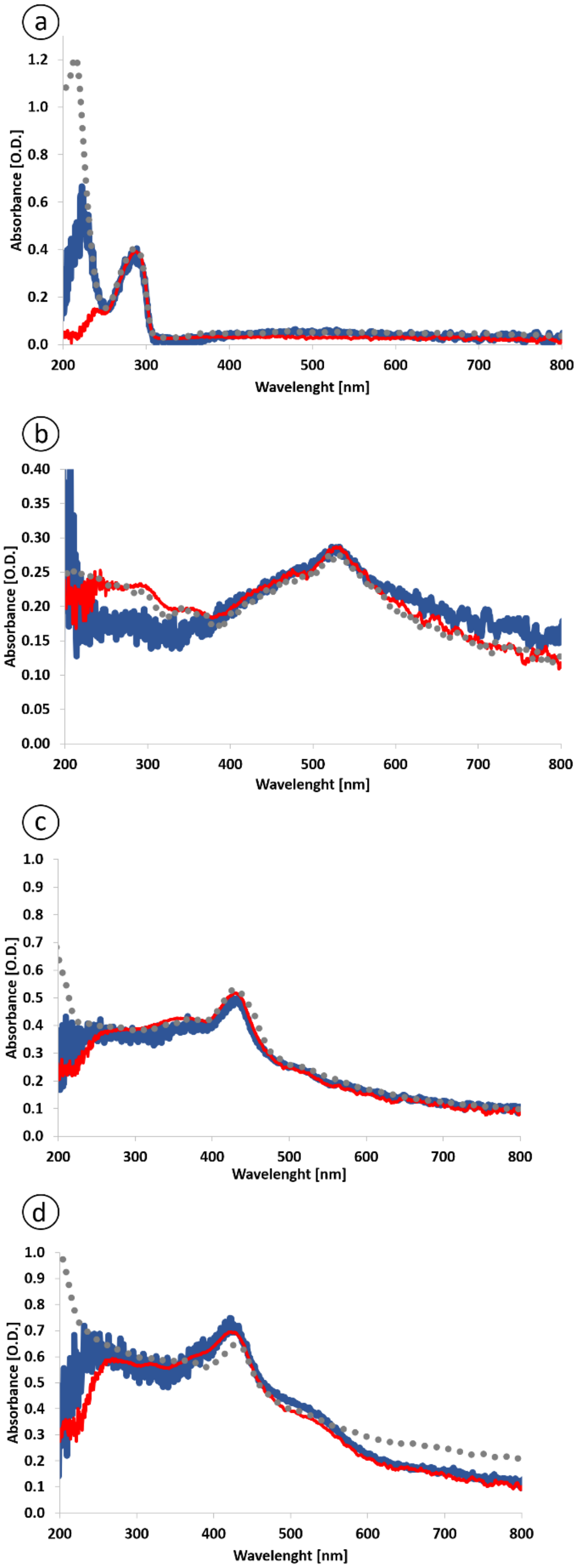

Figure 20: UV-Vis spectra of OREOcube pre-flight test samples. The blue trace was recorded with the OREOcube prototype spectrometer (Embed, OceanOptics) and a UV-Vis light source (OceanOptics DH-2000-S-DUV), in red are spectra recorded with the OREOcube prototype spectrometer and with a solar simulator (Sciencetech Inc. SF300-A) as light source whereas the grey trace was recorded with a Shimadzu state-of-the-art spectrometer (UV-2450): a) 100-nm L-tryptophan thin film, b) 30-nm beta-carotene thin film, c) 20-nm iron tetraphenyl porphyrin chloride (FeTPPCl) on magnetite, d) 20-nm FeTPPCl on hematite.

The ExocubeChem spectroscopy unit was designed to perform infrared measurements and is based on a miniaturized FTIR COTS spectrometer (FTIR "Rocket" OEM Module, Arcoptix). Its spectral performance and space suitability, including radiation and mechanical shock testing, were assessed in the frame of the SPECTROModule campaign.

ExocubeChem test samples are organic molecules of astrobiological relevance and important biomarkers for the search for life. Particular emphasis is placed on membrane molecules and membrane additives such as lipids, pigments and sterols. Organic molecules have various features in the so-called 'fingerprint' region allowing the probing of specific molecular vibrations. An example is shown in Figure 21 with the lipid molecule stearic acid and the amino acid L-alanine. Based on a selection of test samples, the infrared spectroscopic setup based on the FTIR GM was assessed and tested. A comparison with a state-of-the-art FTIR spectrometer (VERTEX 70V, Bruker) showed very good spectral agreement between the instruments used and helped to identify areas of alignment and light source optimization of the ExocubeChem future flight model.

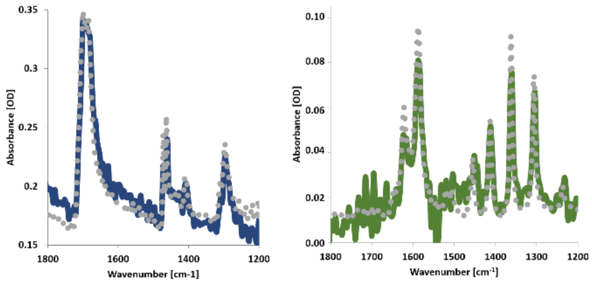

Figure 21: FTIR spectra in the infrared 'fingerprint' region: left - stearic acid; right - L-alanine; the grey trace were recorded with a bench-top FTIR spectrometer (VERTEX 70v, Bruker) whereas the blue and the green spectrum was recorded with the ExocubeChem FTIR prototype (FTIR "Rocket" OEM Module, Arcoptix).

For ExocubeBio, several tests were performed with the spectrometer configuration also for the OD and fluorescence measurements using calibrated solutions. Fluorescence reference standards (Spectral Fluorescence Standard Kit (certified by BAM), Merck) were used to benchmark SPECTROModule against a bench-top Agilent Eclipse fluorescence spectrophotometer.

Fluorescence measurements, in combination with LED excitation at 420 and 535nm, revealed a very good agreement between the systems used, as shown in figure 22.

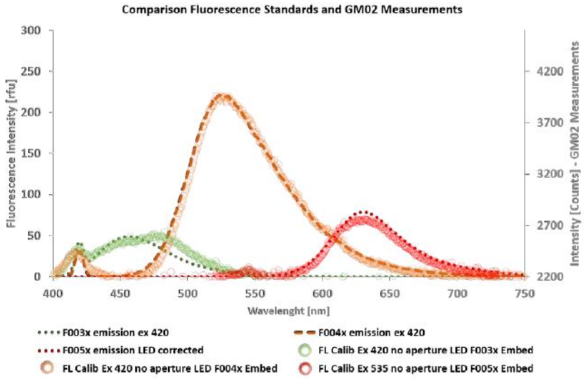

Figure 22: Fluorescent intensity comparisons with fluorescent standards by taking into account differences in LED intensity levels.

5. Conclusions

The SPECTROMoulde GM platforms demonstrated their usefulness as test-benches to verify the scientific requirements for the future Exobiology Facility in a laboratory test campaign. During the SPECTROModule project, it could be shown that the selected hardware can survive the harsh environment of space with minor modifications and that the instruments exceeded the required measurement performances. Moreover, the utilization of one spectrometer to serve three experiments in parallel proved to be challenging with the scheduled operation on board, as well as complex in case of accommodation of more samples. Therefore, another outcome of the project is the utilization of LEDs and photodiodes to measure OD and fluorescence at fixed wavelength ranges for ExocubeBio and IceCold.

The spectrometer and the optical fibre switch will be mainly used for the OREOcube experiment, allowing for a fine-tuning in the UV region of interest. The ExocubeChem infrared spectrometer and sample handling system will be further optimized in terms of alignment, light source intensity and overall optical configuration. Nevertheless, the tested FTIR prototype showed great promise for development into a space compatible flight model.

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