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EXPOSE-E: Application of a decentralized payload operations concept for European Payloads on the ISS

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ABSTRACT

EXPOSE-E (EXPOSE-EuTEF) is an ESA payload dedicated to the study of exobiology. EXPOSE-E, located with other European payloads on the EuTEF pallet, has been successfully installed outside the Columbus laboratory on the International Space Station, commissioned and put in its nominal operation status. It contains samples of interdisciplinary astrobiological experiments exposed to the space environment for the sake of increasing the knowledge of the origin and of the evolution of life within a planetary context.

The operational tasks for the EXPOSE-E payload are performed within the European Ground Segment, and mainly shared by two User Support and Operation Centers (USOCs): MUSC and ERASMUS. The MUSC (Microgravity User Support Centre) located in Cologne/Germany acts as EXPOSE-E Facility Support Center. In this role, MUSC is responsible for EXPOSE-E Monitoring and Commanding, telemetry analysis, data archiving and data distribution to the EXPOSE-E Principal Investigators (PIs). ERASMUS, located at ESTEC in the Netherlands, is the Facility Responsible Centre (FRC) for EuTEF platform. ERASMUS holds the overall responsibility for the operation of the EuTEF class-1 payload and the nine experiments it accommodates. ERASMUS has a direct telemetry and command interface to the Columbus Control Center (Col-CC) and provides the TM/TC interface between MUSC and Col-CC. This paper will present the applied operational scenario and first experience gained during the beginning of EXPOSE two years mission.

FULL TEXT

Introduction

The successful installation of the European module Columbus onboard the International Space Station (ISS) has commenced a new route for the European access to space and to the resources provided by the ISS.
Columbus is completely devoted to research in the field of microgravity and, in general, in the space environment. Experiments conducted inside Columbus concern various research areas such as biology, fluid dynamics, human physiology and protein crystallization. They all are conducted in highly automated facilities such as BIOLAB, the Fluid Science Laboratory (FSL), the European Physiology Module (EPM) and the European Drawer Rack (EDR). Besides these payloads, Columbus presently hosts two external payloads: SOLAR that investigates solar and stellar physics and EuTEF.
EuTEF (European Technology Exposure Facility) is a fully automated programmable facility with modular and flexible accommodation for a suite of nine payloads. All EuTEF payloads carry experiments that need to be exposed to the space environment. One of these payloads is EXPOSE-E: the only contribution of the ISS to photobiology and exobiology. Actually, it contains samples of fungi, lichens and other primordial forms of life, which generally survive in extreme conditions, in order to study their behavior in space.

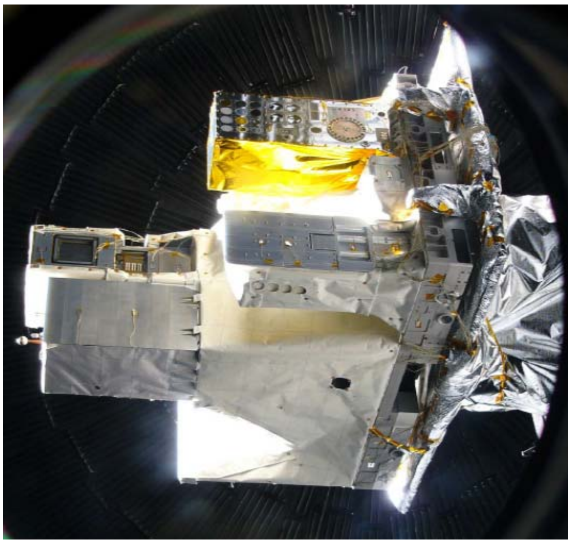


Figure 1: *EuTEF*

EXPOSE-E and EuTEF Payload

The German Aerospace Center has a long history and a strong background in the field of Astrobiology as demonstrated by several successful mission contributions such as EURECA (EUropean Retrievable Carrier) that flew since August 1992 to June 1993 [1], LDEF (Long Duration Exposure Facility) in orbit since April 1984 to January 1990 and SpaceLab 1 and 2 that flew in 1983 and in 1993 respectively. This allowed DLR to successfully respond in 1997 to ESA Announcement of Opportunity (AO) for the 'Externally Mounted Payloads for first utilization phase in 2002' with EXPOSE [2].
EXPOSE scientific objectives were related to exobiology experiments requiring exposure to the space environment and UV radiation. Originally, EXPOSE was constituted of six biological experiments and it had to be installed on SEBA (Space Exposure Biology Assembly), located on the Truss segment of the ISS. The accidents occurred to the STS Space Shuttle procrastinated the start of all the European activities onboard the ISS and gave time enough to issue a call for a second batch of EXPOSE. EXPOSE

payloads are developed by Kayser-Threde under ESA contract.
The first batch, named EXPOSE-R, will be presumably installed in November 2008 on the Russian segment of the space station and will contain the experiments originally foreseen and new additional Russian ones.
The second batch, EXPOSE-E, contains eight experiments and, during its operational period of 18 months, it will support both long-term studies of microbes and microbial communities from special ecological niches, such as endolithic and endoevaporitic ecosystems, in space and simulated Martian environmental conditions. These experiments include the study of photo-biological processes in simulated radiation climates of planets as well as studies of the probabilities and limitations for life to be distributed among the bodies of our solar system. In addition, EXPOSE-E experiments will valuably contribute to the study of the potential pathways of the appearance of life on planets and the distribution of life beyond its planet of origin. To conclude, results from EXPOSE-E experiments will provide a better understanding of the processes regulating the interactions of life with the environment on Earth.
EXPOSE-E accommodates the experiment samples in a variety of sample compartments piled in the experiment pockets. Each experiment pocket is equipped with entrance optics and filters. In addition to these experiment pockets, the payload is also equipped with an active experiment: the Radiation Risk Radiometer Dosimeter (R3D) that makes detailed measurements of the solar radiation. Both the experiment pockets and R3D are installed in three removable trays and each tray is equipped with one valve. Two valves were opened during commissioning in order to release the air contained in the trays. The third valve remains closed as its tray contains a gas mixture that simulates the Martian atmosphere.

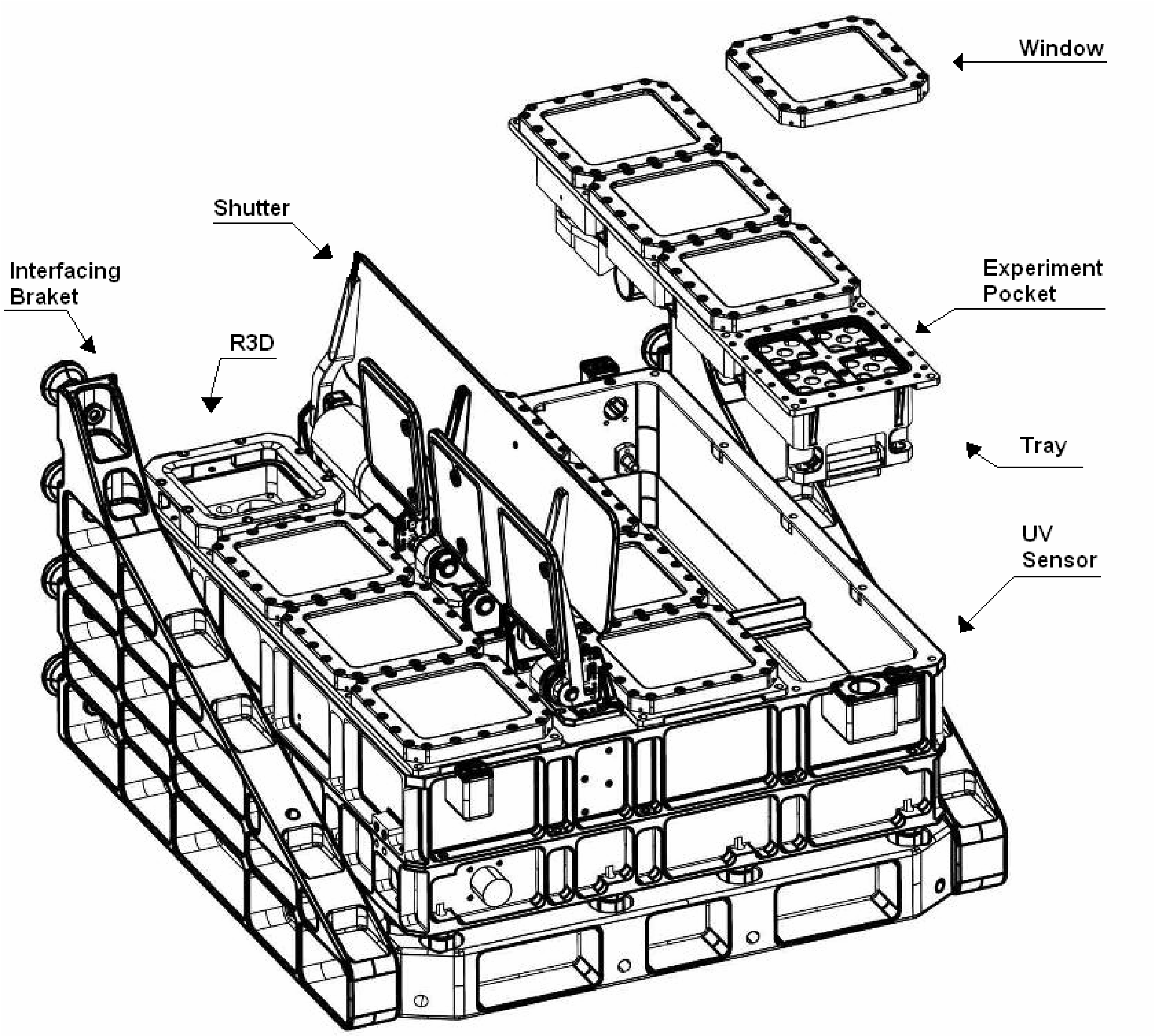


Figure 2: *EXPOSE-E*

Temperature in trays is actively controlled using some heaters and, in addition, two of the three trays are equipped with white shutters that can be automatically closed in case the temperature rises above a predefined value.

Since its successful commissioning on 20 February 2008, besides the housekeeping telemetry of the payload, EXPOSE-E control unit collects every ten seconds temperature measured in eight representative positions, the UV radiation measured by five solar sensors and gathers data generated by R3D.

Data collected are used not only to analyze samples once they will be brought back on Earth at the end of the mission but are also used to feed the PSI (Planetary and Space sImulation) facilities, where the same samples as those installed on EXPOSE-E are exposed to similar UV radiation conditions and to the same temperatures as detected by EXPOSE-E sensors.

EXPOSE-E interfaces with the ISS through EuTEF payload. As EXPOSE-E is not directly connected to the Station, it is classified as class-2 payload; EuTEF, instead, is considered a class-1 payload.

EuTEF is a platform containing data handling, power, mechanical and thermal control infrastructures to allow easy access to space environment for nine payloads, like EXPOSE-E. Actually, EuTEF provides EXPOSE-E with mechanical connection via an interfacing bracket, with electrical connections, both through a 28V Operational Feeder and a 120V Survival Feeder, and with data connection through a RS422 serial interface.

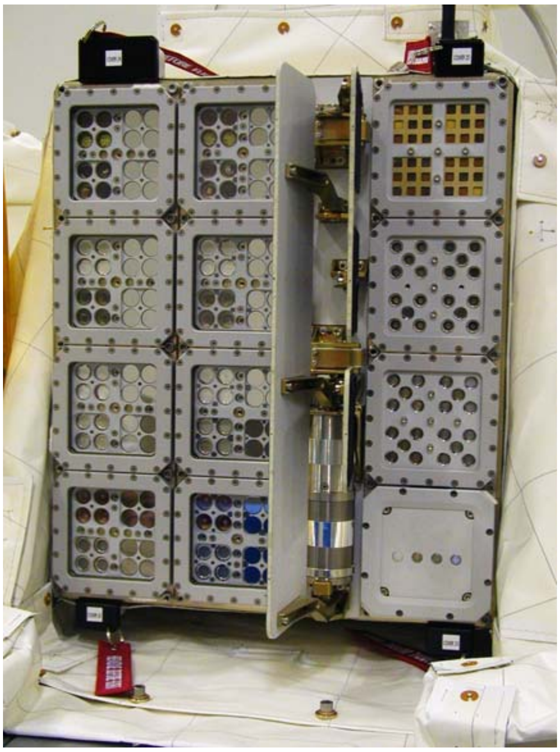


Figure 3: *EXPOSE-E Flight Model*

Decentralized Approach for ISS Payload Operations

Under the overall management of ESA, the European User Support and Operations Centers carry out the majority of tasks related to the preparation and in-flight operations of European multi-user facilities. This approach makes the USOCs instrumental for the implementation of the ISS ground segment for payloads operations preparation, real-time data dissemination and provision of instantaneous experiment command processing [3].
Depending on the scope of the task assigned to a USOC, there exist two basic levels of responsibility: Facility Responsible Centre (FRC) and Facility Support Centre (FSC). A FRC is delegated the overall responsibility for a specific multi-user level payload. Its functions focus on payload system aspects and are related to all the phases of payload operations since pre-flight activities to post-flight ones. A FSC, instead, supporting a FRC, is both in charge of one of more subsystems constituting a payload and holds the responsibility for experiments conducted in a facility focusing also on experiment operational matters.
The interface between the payloads and the ISS, meant as system providing resources to the facilities it hosts, is granted by the interaction between FRCs and Columbus Control Centre (Col-CC) located in Oberpfaffenhofen (Germany).
The decentralized approach relies on the interactions between Col-CC, FRCs and FSCs since the early pre-flight phases until the deployment of the payload. This is meaningfully embodied by Erasmus USOC, located at ESTEC in the Netherlands, and MUSC (Microgravity User Support Centre), located in Cologne, Germany. Actually, Erasmus USOC is in charge of EuTEF as FRC while MUSC acts as FSC for EXPOSE-E. In this role MUSC is taking the point of contact both with the Principal Investigators (PIs) of EXPOSE-E and with the Payload Developer (PD).

Payload Operations for EXPOSE-E

Signing the EXPOSE EuTEF Instrument Operations Interface Description (EXPOSE EuTEF IOID), the collaboration between MUSC and Erasmus USOC to operate jointly EXPOSE-E and EuTEF was officially initiated.

The most demanding phase for MUSC and Erasmus USOC was the preparation to the flight. Actually, pre-flight tasks mainly concerned:

- Installing at MUSC the biological samples in EXPOSE-E with the help of the PD and of PIs
- Preparing and validating facilities and experiments operations, in close collaboration with the PIs
- Studying operations feasibility and science samples bread-boarding

with the use of the Engineering Model (EM)

- Determining ground rules and constraints attaining EXPOSE and EuTEF
- Creating a Science Program for EXPOSE-E and making it operative providing inputs both to the overall mission and to the increment planning
- Consolidating operations scenarios with the help of PIs and PDs
- Creating a consolidated planning in collaboration with Carlo Gavazzi Space (EuTEF PD) and Kayser Threde (EXPOSE-E PD) for increment preparation
- Writing the Payloads Operations Data Files (PODFs)
- Setting connections between MUSC and Erasmus USOC
- Providing experiment qualification and validation tests
- Experiment ground and launch site processing.

Results obtained during the pre-flight operations were widely proven and certified through *Stand Alone Simulations* (SAS) between MUSC and Erasmus USOC. EXPOSE-E operations were also tested both within the frame of Columbus operations, through *European Simulations* (ES) that involved all USOCs and Col-CC, and in the frame of ISS operations, though *Integrated Simulations* performed with the supervision NASA officers. During simulations, both nominal and off-nominal contingencies were reproduced with the help of EuTEF and EXPOSE-E EMs and of the Columbus Emulator in use at ESA.

One month before the launch, flight preparation operations were concluded and a new phase of EXPOSE-E started: the *operational* one. This phase is mainly characterized by the following tasks:

- Managing real time operations, re-planning for payload and experiment execution if necessary
- Processing payload data and reporting eventual flight anomalies
- Distributing scientific data to all involved PIs.
- Collecting science requirements for experiment and payload upgrade

For payload operations ESA has established the European ISS Ground Segment with the necessary support tools. Among the flight operation tools, like the CEFN (Columbus Electronic Flight Note) System, aimed to report Columbus and payload anomalies, the Console Log, aimed to keep a log of all the activities performed by operators on console, the International Procedure Viewer (IPV), to share PODFs online, the OSTPV (Onboard Short Term Plain Viewer), designed to give a quick graphical report about activities taking place onboard the ISS, and the Voice Loop System, the main part is devoted to the payload command and data distribution system. The architecture of the ground segment is schematically shown in fig.4.

Col-CC receives all Columbus data and routes them to the FRCs. FRCs share the data with their supporting FSCs. Therefore, EXPOSE-E data reach MUSC through the Erasmus USOC. In addition, MUSC receives some EuTEF data in order to perform a more efficient data analysis and to improve the overall comprehension both of the system and of the environment surrounding the payload. In its central role, MUSC holds EXPOSE-E data for payload status analyses and distributes both scientific data and some elaborated payload data to the PD and the PIs. The network to distribute the Columbus data is the Interconnecting Ground System (IGS). Payload data monitoring and payload commanding is performed by the *Columbus Decentralized Mission Control Subsystem* (CD-MCS).

The close collaboration between MUSC and Erasmus USOC also led to the development of some solutions aimed to enhance the data exchange both with the Erasmus USOC and with the EXPOSE-E PIs. EXPOSE-E real time and dump data are also distributed from the Erasmus USOC via a *Virtual Private Network* (VPN) established between the USOCs: a dedicated UHB (User Home Base) terminal is installed at MUSC and, with the help of a software tool provided by Erasmus, it is possible to collect and store the EXPOSE data at MUSC. The subsequent data distribution to the PI sites is described in the next chapter.

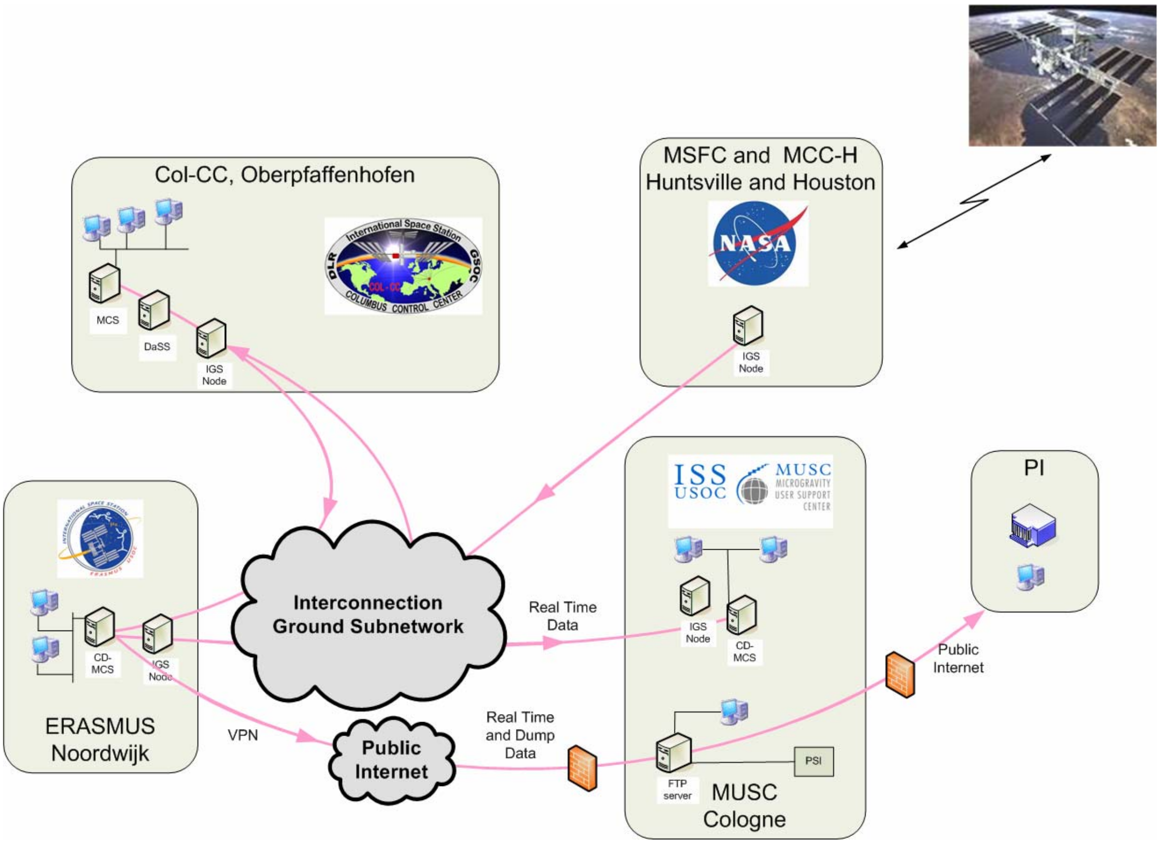


Figure 4: *Data Distribution for EXPOSE-E in the ISS Ground Segment*

At the end of EXPOSE-E mission, post-flight activities for MUSC and Erasmus USOC will mainly concern:

- Supporting the deployment of the payload
- Supporting the transportation of the payload at MUSC where it will be disassembled and all the samples will be restituted to PIs
- Supporting PIs in post-flight data interpretation
- Reconstructing the story of EXPOSE-E in order to obtain and consolidate lessons learned
- Storing EXPOSE-E data for ten years

EXPOSE-E Data Retrieval via MUSC Virtual Control Room and FTP Server

In its role of FSC, MUSC is in charge of storing EXPOSE-E data and to distribute them to the PIs, according to their requests.

In order to give continuous access to EXPOSE-E telemetry, MUSC put at PIs' disposal an FTP server (see figure 4) where relevant data are stored. Furthermore, this server also provides relevant information such as the current and the past attitudes of the station and a list of foreseen activities of the ISS that might affect EXPOSE-E performances.

EXPOSE-E can also be constantly monitored through the so-called 'Virtual

Control Room' (http://www.dlr.de/expose/): a website where EXPOSE-E temperatures and detected UV radiation are displayed with an immediate graphical interface (figure 5).

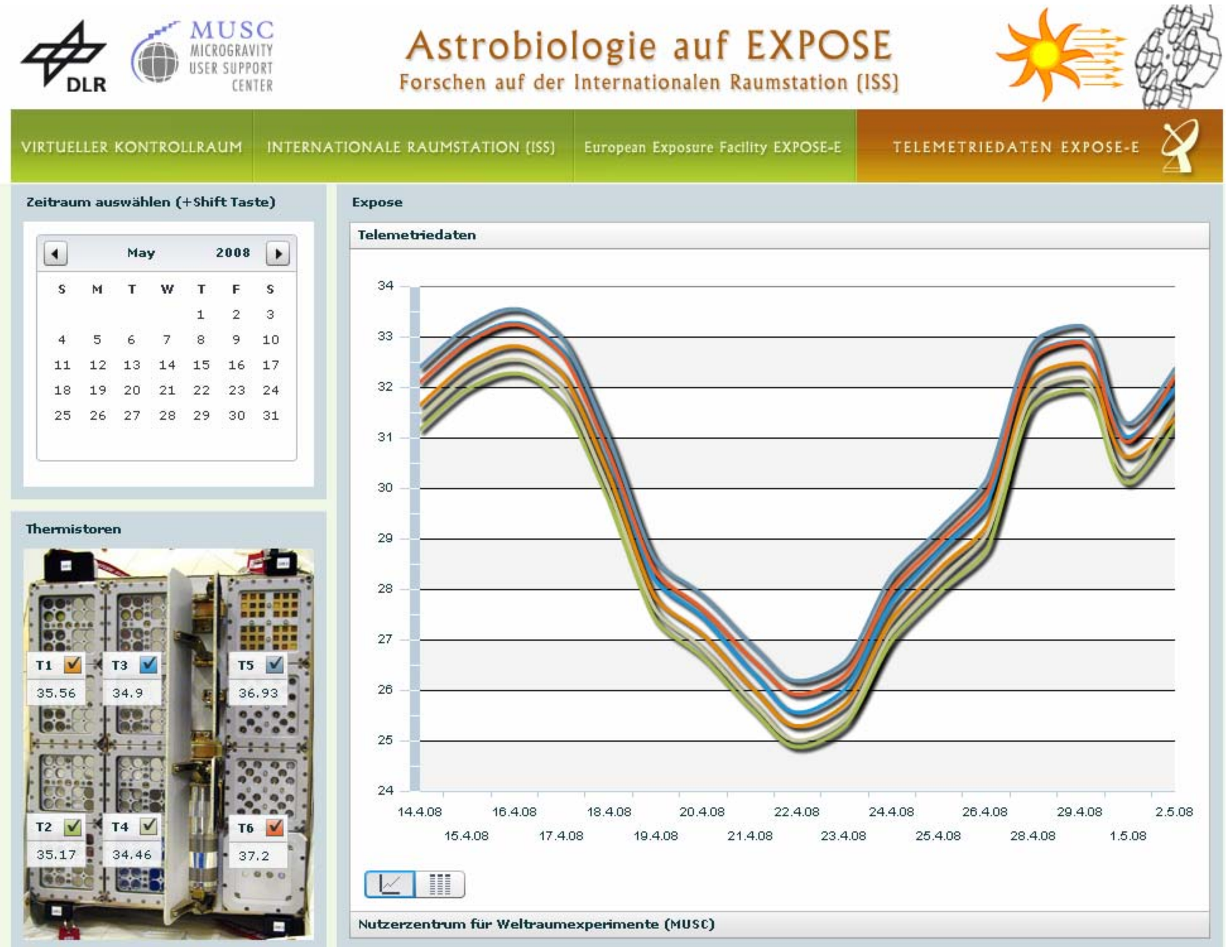


Figure 5: *EXPOSE-E Virtual Control Room Graphical Interface*

EXPOSE-E First Operational Data

All EXPOSE-E experiments except R3D are passive. The biological and chemical experiments on EXPOSE-E will be analyzed after return to the laboratories of the investigators that provided them. Therefore, further and more detailed experiment results will be available only after the mission and published by the PIs.
Environmental and housekeeping data of EXPOSE-E are investigated continuously as they are downloaded. Some examples for the first weeks of mission are briefly reported here.
Both temperature and solar irradiation oscillate with a period comparable with the orbital period of the ISS: approximately 1.5 hours. It is worth to mention that temperatures show stronger variations when decreasing than when increasing (Fig 8). Therefore, the heating of the EXPOSE-E trays due to solar radiation is faster than the cooling when the facility is in Earth's umbra. In the graph below, UV curves and corresponding temperature curves are plotted with the same time axis in the time frame ranging since March 10th, 2008 01:40 to 07:20. The graph shows clearly the correlation between solar irradiation and temperature progression.
For this time frame, it can also be shown how UV sensor 3 detects the irradiation earlier than UV sensor 4, while 1 and 2 seem to be irradiated during the whole

period of time in spite of the other two. Considering the geometry of EXPOSE-E with respect to EuTEF (Fig 7) and the plots of the four UV sensors (Fig 6), it is reasonable assuming that the UV sensors 3 and 4, located at the 'bottom' of EXPOSE-E, are shadowed by EuTEF platform, by other experiments installed on EuTEF and by Columbus, in spite of UV sensors 1 and 2, located on the top.

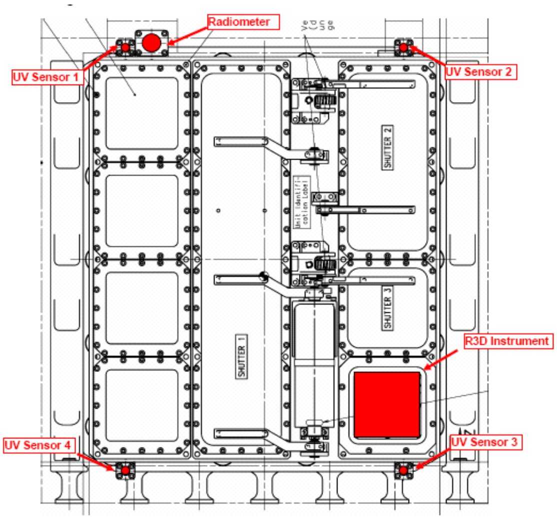


Figure 6: *Drawing of positions of UV sensors 1 to 4 on EXPOSE-E (EXP-MN-KT-005 Issue: 2, Fig 3-4)*

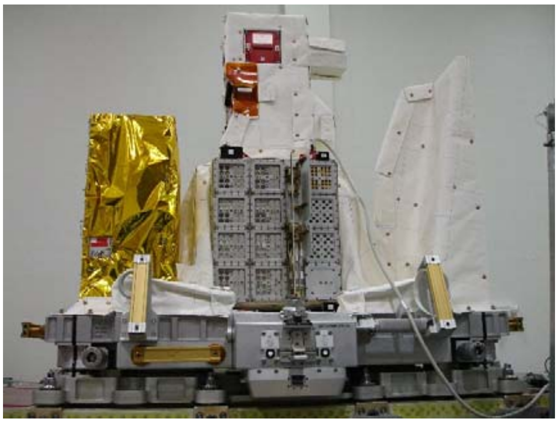


Figure 7: *Picture of EXPOSE-E integrated onto EuTEF with other instruments at KSC, courtesy of ESA.*

In fact, UV sensors 3 and 4 are near the bracket that attach EXPOSE-E to EuTEF, and where most shadow is expected form the proximity to Columbus and the other experiments on EuTEF. Nevertheless, the highest UV radiation measured during the report period was measured by UV-Sensor 3 (see UV irradiation), suggesting no higher shading effect.

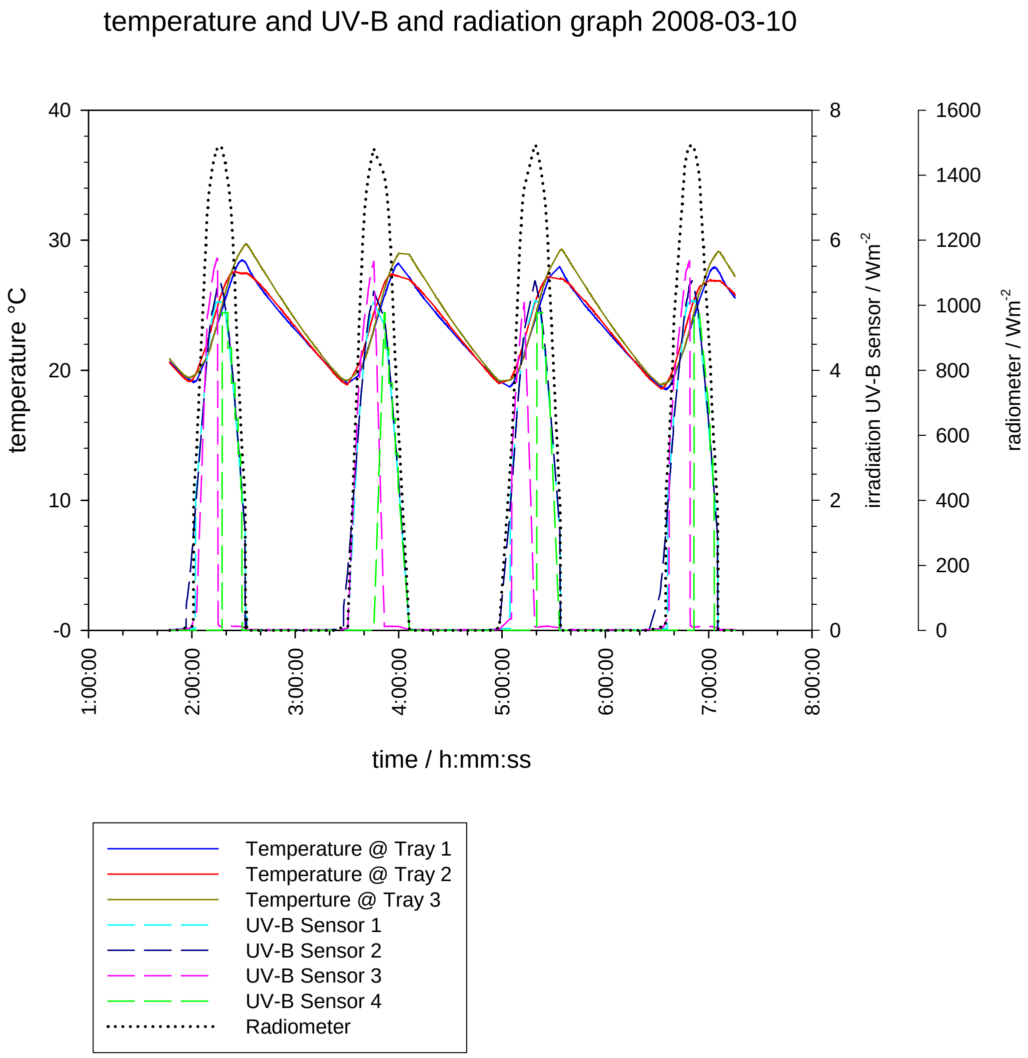
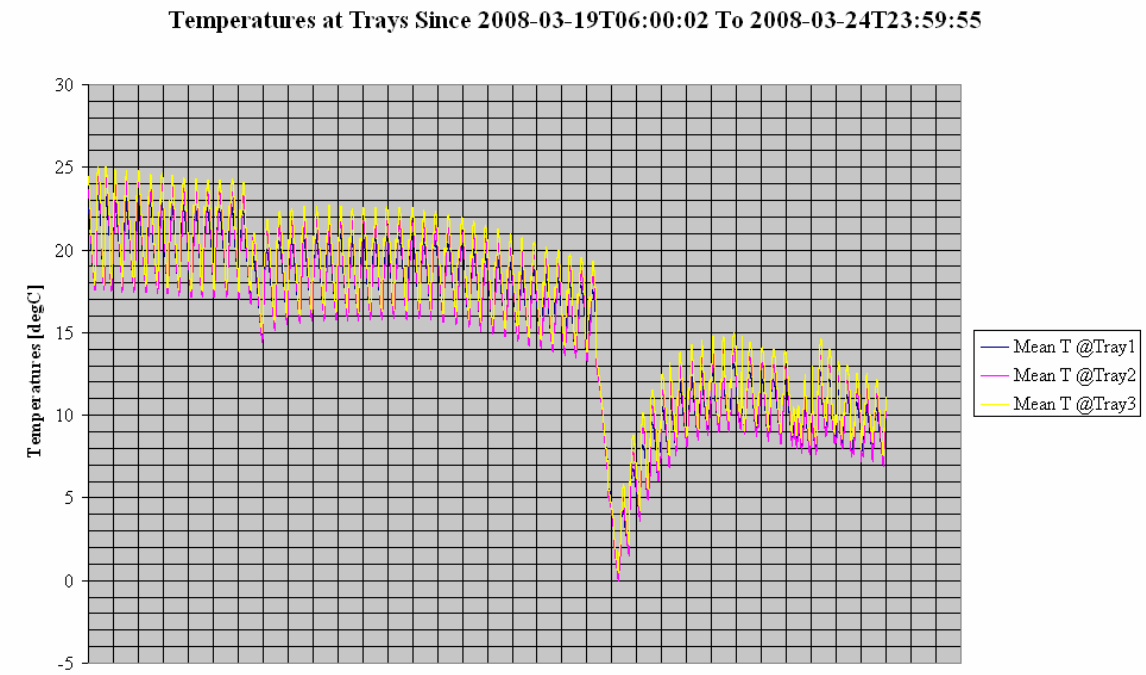


Figure 8: *Temperatures and solar irradiation as measured by the EXPOSE-E sensors between 01:00 and 08:00 on March 10, 2008. The graphs nicely show the illumination rhythm (periodicity: around 90 min = 1 orbit) and the corresponding temperature oscillations. Solar light is measured by the radiometer (dotted line) and four UV sensors (dashed lines).*

Temperature

Temperature data of all six sensors are in general similar. Tray 3 seems to be slightly warmer in average than trays 2 and 1, but this has to be confirmed considering data from the entire course of the mission. Temperatures measured until 01.04.2008 ranged between +39 °C to -22 °C. Alternating periods of sunlight and shadow within the 92 minute orbital period result in average temperature oscillations spanning between 10 and 15 °C, and are more or less similar and regular. Larger temperature variations have been recorded during ISS maneuvers: ISS attitude changes lead to temperature variations up to 30 °C in 1 h (25.03.2008, 00:00 to 01:00, Fig 9). On 25 March 2008, for instance, at 01:40 the attitude of the ISS, measured in terms of yaw, pitch and roll angles, passed from (+175.0°, +17.9°, +354.2°) to (+2.2, +354.7, +357.7) due to the reconfiguration of the moment gyros. Attitude changes also result in a change both of the temperature range and of the orbit temperature oscillation.



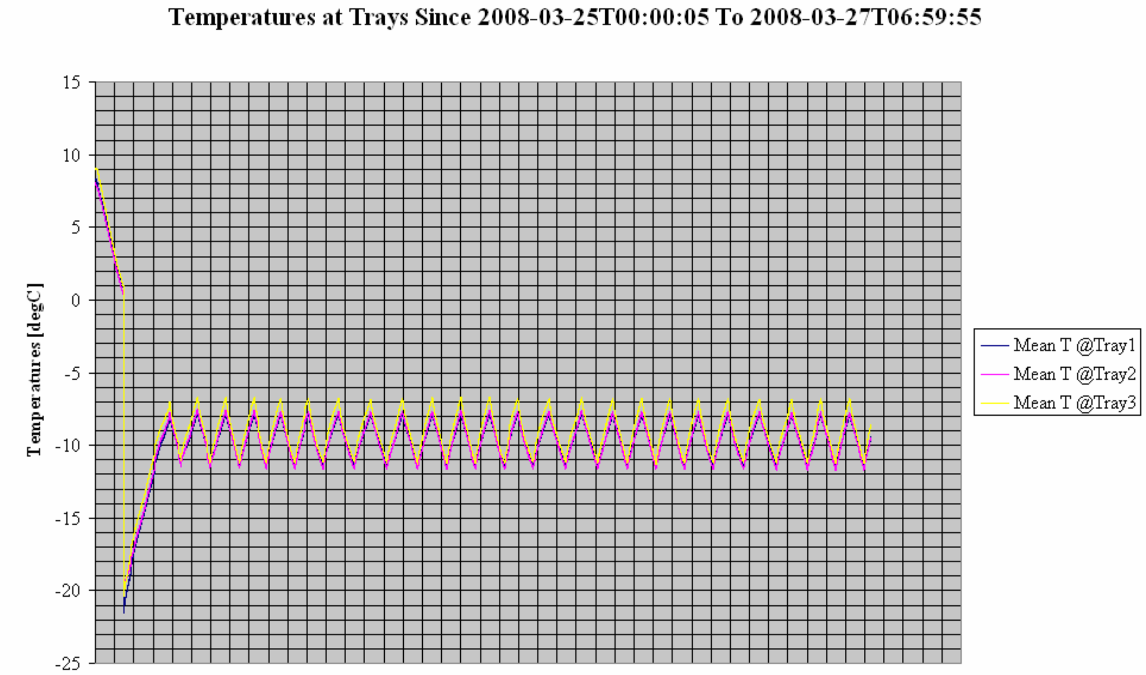


Figure 9: *Steep decline of temperature for approximately 30 °C, most probably caused by attitude changes of the ISS (right diagram, beginning. The left diagram 19.03.2008-24.03.2008 is shown to underline the correctness of the first measurement point of the right diagram, starting 25.03.2008 at 00:00:05).*

UV irradiation

The four UV sensors of EXPOSE-E measure the UV-B irradiation of 5.1 Wm-2, oscillating in correspondence with the temperature oscillations, which confirms that temperature variations are mainly due to solar radiation, rather than Earth albedo

and heating from other instruments mounted on EuTEF. An example is given in Fig 10 for UV-irradiation and in Fig 11 for the corresponding temperature for the period March 12 - 17, 2008.
Current interpretation of these data indicate different and varying shading, at least partly due to the attitude of ISS, as can be seen in Fig 10 and 11. This correlation between ISS behavior, incident irradiation and temperature changes was expected.

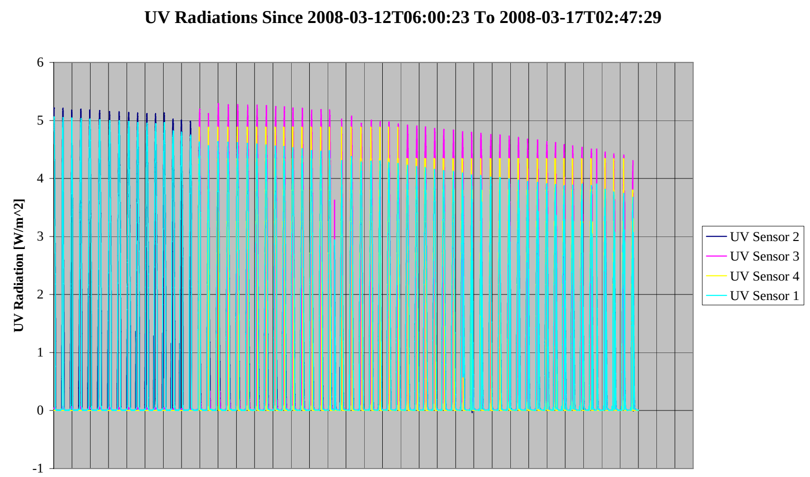


Figure 10: *Average UV radiation at the 3 trays in the time period March 12-17, 2008*

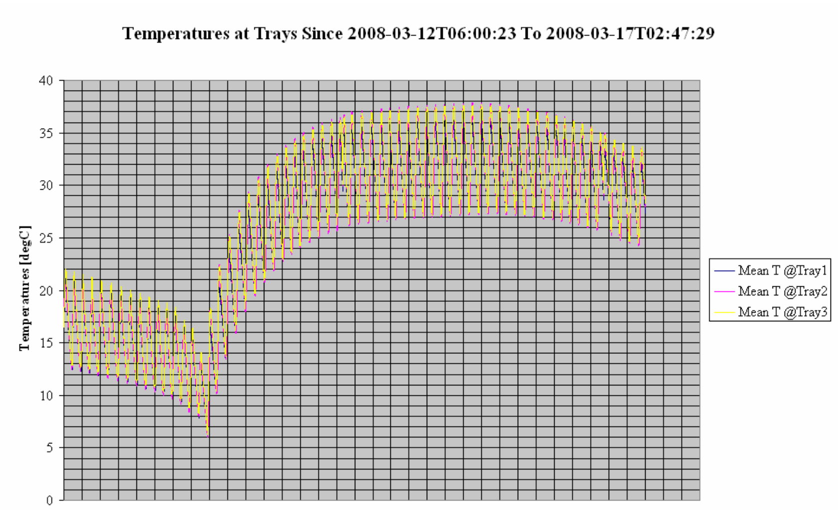


Figure 11: *Average temperature at the 3 trays in the time period March 12-17, 2008. Temperature minimum was measured on March 13, 2008 at 06:06:09.*

The maximum UV value of 5,9885 Wm-2 reached during the report period was measured with UV-B sensor 3 on Tray 3 on March 08, 2008, at 22:50 hours.

Radiometer

The Radiometer readings are in good accordance with the data of the UV-B sensors (Fig. 8). The radiometer measures solar irradiation over a wide range of wavelengths from 150 to 4800 nm, whereas the UV-B sensors are confined to 220-380 nm. Hence, in terms of energy, the radiometer detects much more light than the UV-B sensors. Therefore, in Fig. 8 a different scale along the y-axis are presented for the radiometer and the UV-B sensors. Concerning the analysis of the biological effect induced by the UV radiation, the total flux of the UV over the whole mission, corrected for each optical filter and window set accommodated on top of the experiments, will be derived from the EXPOSE-E data of the UV sensors and provided to the scientists.

Conclusions

This paper presents the first successful operation results received from the EXPOSE-E payload onboard the International Space Station. EXPOSE-E is operated in the frame of the activities of EuTEF, the European Technology Exposure Facility installed in February 2008 outside the European module of the ISS.
The first eight months of payload operations resulted to be highly successful both from the scientific and from the operational point of view. Concerning the scientific objectives, although most of the studies are still in progress, the valuable data collected by EXPOSE-E match with many of the predictions made. In addition, the operational results of the mission prove the effectiveness of the decentralised ground segment concept established by ESA for the European ISS payload operations.

Acknowledgements

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