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The SODI Diffusion Soret Coefficient Experiment onboard ISS: a flexible and modular approach to operations in orbit

Marcello Lappa, Chiara Piccolo, Gennaro Esposito, Salvatore La Gala, Domenico Sorrentino, Domenico Giordano, Giuseppe De Chiara, Giuseppe Di Costanzo, Raimondo Fortezza, Carlo Albanese

sodi@marscenter.it

Telespazio – Science Systems & Applications –
Vai E. Gianturco 31 – 80146 – Naples (Italy)
Ph: +39 – 081 – 6042 591/485
Fax: +39 – 081 6042 100

Abstract

The Selectable Optical Diagnostics Instrument (SODI) is a Class-2 Payload for scientific experiments in the field of fluids on board the International Space Station. Being equipped with various optical diagnostics, such as Mach-Zehnder Interferometer, Particle Image Velocimetry and Near Field Scattering, this design has been expressly conceived to study several phenomena and, among them, diffusion processes and Soret effects in liquids (SODI DSC). Telespazio (located in Naples, Italy) has played the role of SODI FRC (Facility Responsible Center) and European USOC (User Support Operation Center), receiving the full range of SODI telemetry (H&S and Scientific telemetry), issuing commands to the Payload and providing console positions during on orbit active phases (07-Nov to 16-Jan-2012). The NASA interface to Telespazio Operators has been represented by the Payload Operations Integration Center (POIC) at MSFC (located in Huntsville), that also includes the MSG Ops Team (that was in charge of coordinating all MSG operations, MSG being the Class-1 facility hosting the SODI hardware and providing the required interfaces to the ISS data and power systems). In a position of FRC, Telespazio has conceived the mission scenario (Mission Operation Implementation Concept), implemented the Ground Segment and related ground data services, developed all the necessary payload products and executed the SODI DSC experiment (55 scientific runs) onboard by interacting directly with NASA on behalf of the European Space agency (ESA).

I. SODI Payload Overview

The Selectable Optical Diagnostics Instrument (SODI) is a Class-2 Payload for scientific experiments in the field of fluids on board the International Space Station. The payload is equipped with various optical diagnostics, such as Mach-Zehnder Interferometer, Particle Image Velocimetry and Near Field Scattering [1].
This design has been expressly conceived to study diffusion phenomena and Soret effects in liquids (SODI DSC and related continuation SODI DCMIX), to discern the influence of vibration stimuli on these phenomena (SODI IVIDIL), and to study the aggregation of colloidal solutions (SODI COLLOID). Flexibility for investigating such a large spectrum of subjects has been achieved by resorting to an original modular architecture (several subsystems which can be installed or not depending on the category of phenomena to be investigated).
SODI also makes use of the potentialities offered by the Microgravity Science Glovebox (MSG) [2].
Developed by the European Space Agency (ESA) and integrated by NASA Marshall Space Flight Center (MSFC), the MSG (Figure 1) is a Class-1 Facility currently located in the ISS US-Lab module (formerly in the Columbus module, close to the FSL).

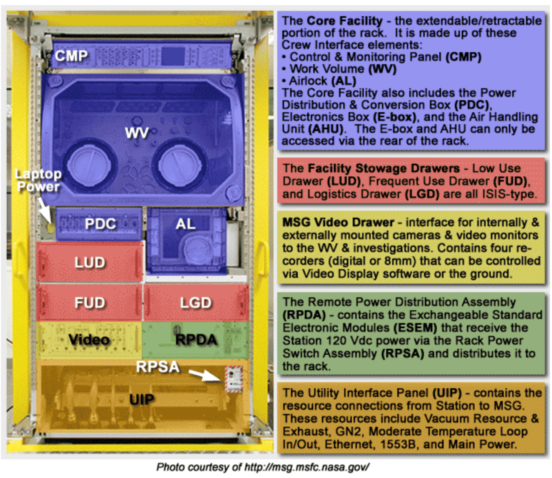

Figure 1: MSG and its subsystems (Courtesy of NASA)

A.. SODI Hardware

The different hardware components (Table I) have to be installed inside the Work Volume of MSG and connected to related power and data lines (Figure 2).

Module	Assembly ID	DSC Setup	IVIDIL Setup	COLLOID Setup
IPU Electronics Box (Including Flash Disk)	SODI-01-1420-0000-000-VE	X	X	X
Bottom Plate Assembly (containing FCU, Translation Motor, and Fixed Opt. Bracket)	SODI-01-1410-0000-000-VE	X	X	X
DSC Cell Array	SODI-01-1200-0000-000-VE	X		
IVIDIL Cell Array	SODI-01-1100-0000-000-VE		X	
COLLOID Exp. Container	SODI-01-1300-0000-000-VE			X
Fixed Optical Module	SODI-01-1910-0000-000-VE	X	X	
Moving Optical Module	SODI-01-1920-0000-000-VE	X	X	
Vibration Mechanism	SODI-01-1120-0000-000-VE		X	

Table I: SODI Modular Concept

Figure 2: Example of crew on orbit involved in assembling SODI inside the MSG Work Volume.

B. Software

The SODI "software" can be split into three fundamental components\categories:

1) Operating System Software
2) SODI Application Software
3) Experiment timeline scripts

In it's most basic form of operation the SODI instrument is autonomous and, upon applying power to the instrument:

- Automatically starts the SODI Application Software, which, in turn:
  - Starts the transmission of status data
  - Detects the hardware ID tag of the cell array installed

Given this basic scenario, the SODI ASW accepts ground commands to

- Manipulate the timeline state
- Manipulate files on the SODI file-system
- Exchange files with over the SODI external interfaces
- Manipulate individual actuators in the system (off-nominal operations)

In the basic configuration SODI *scripts* are started via ground commanding: The experiment is started and executed according to an execution table contained in the script. The execution table of the experiment describes all actions that need to be executed for the experiment. It contains information such as temperature set points, duration of each step, acquisition rate of images and other data (temperatures, Peltier-power), configuration of the optical diagnostics (laser diodes, shutters, mirrors), activation of vibration mechanism or stirrer. All this information is stored in a set of files located in the memory on the program-flashdrive of the Image Processing Unit (IPU).

II. Scientific Rationale

The acronym DSC stands for *Diffusion and Soret Coefficients*.

Diffusive processes are ubiquitous in daily life and in natural processes, and play a key role in the transformation and mixing of fluid mixtures. In this context, the term "diffusion" is used to describe the relative motion of a species with respect to the others (which can be caused by gradients of concentration and/or temperature or by sedimentation induced by gravity).

Main purpose of SODI DSC was the measurement of diffusion coefficients of selected ternary mixtures taking advantage of the reduced gravity environment available on board the ISS. Albeit the socalled thermal diffusion, or Soret effect, was discovered more than 100 years ago, its physical mechanisms are not fully understood, and while several models exist, no unified theory is able to predict the value and sign of coefficients for multi-component liquid mixtures or suspensions of particles. This lack of knowledge is partially due to unavailability of experimental data, especially for ternary and higher component mixtures (measurement of thermal diffusion coefficients requires a convection free environment [3] that is difficult to obtain on the ground for binary mixtures and often impossible for ternary ones since any convective flows of buoyancy origin result in a substantial modification of the mass transport processes [4]).

Nevertheless, a proper knowledge of the coefficients for multi-component liquid mixtures is of a crucial importance for several applications of industrial relevance. A relevant example along these lines is represented by oil reservoirs (where all the aforementioned effects contribute to the distribution of the component of the mixture that forms crude oils). Oil companies are extremely interested in reliable thermodynamical models potentially allowing the characterisation of an entire reservoir using a reduced number of exploratory wells. It is in such a context that the SODI DSC experiment and related scientific outcomes should be considered.

III. SODI DSC Experiment Protocol

A sketch of the experimental setup related to the SODI DSC experiment is depicted in Figure 3. The sample is contained in a cell 10 x 10 x 5 mm^3 (w,l,h) and is visualized by means of a Mach-Zehnder interferometer at two wavelengths. A set of interferograms ("fringe images") is acquired. Each fringe image is acquired after changing the source wavelength by a fraction of nanometre around the main wavelength. An image processing algorithm allows to calculate the final phase and amplitude image from the set of fringe images. A temperature gradient perpendicular to the optical path (normal to the page in Figure 3) is applied to the cell.

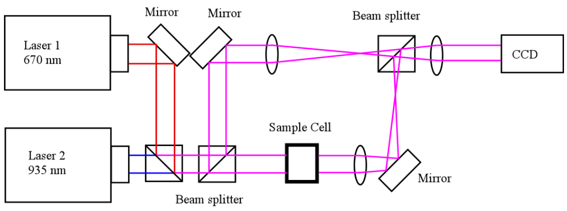

Figure 3: Sketch of the optical set-up. The cell is probed by means of two –wavelength intereferometry in a Mach Zehnder scheme. A temperature gradient perpendicular to the light beam is applied to the cell.

The experiment scheme [5] is based on the well marked difference between the thermal characteristic time τ_α=L^2/α and the diffusion one τ_D=L^2/D, where *L* is the side of the cell, α the thermal diffusivity and *D* the smallest eigenvalue of the diffusion matrix. The experimental procedure can be summarized as follows (see Figure 4):

- **Step 1:** The cell is kept at a constant initial temperature for a thermalisation time.
- **Step 2:** A temperature difference is applied across the sample. After a time comparable with the thermal time τ_α, a linear thermal profile is established throughout the liquid, perturbed by some residual convection due to the residual steady gravity acceleration. During this "thermal" phase, the concentration of the mixture remains approximately unperturbed in the bulk due to the high value of the diffusion time τ_D .
- **Step 3:** After a time comparable with the diffusion time τ_D (~10^5 s), a concentration

gradient is established across the sample. In the case depicted in Figure 4, the largest Soret coefficient is negative so that the concentration C of the denser component is higher in hot regions of the fluid.

– **Step 4:** The thermal gradient is switched off so that the fluid gets back to isothermal conditions in a short time τ_α. Then, the concentration gradient relaxes due to Fick's backdiffusion on much longer times τ_D allowing the study of diffusion alone.

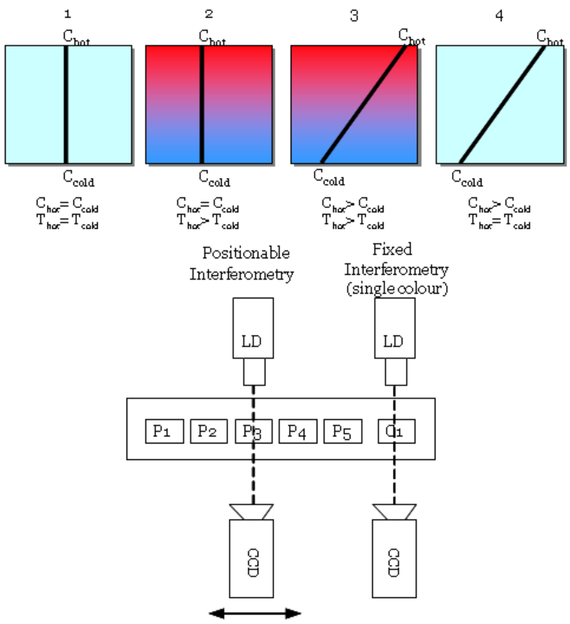

Figure 4 Top: Experimental steps for SODI DSC: thermalisation phase (1), thermal gradient establishment (2), Soret separation (3), isothermal diffusion (4). Bottom: cell array, composed of 5 primary cells and one companion cell.

After the completion of the fourth step, the system is brought to the initial isothermal and isoconcentration condition. If needed, the run can be repeated at a different temperature difference. Then, the positionable optics is moved to another sample and the entire cycle is repeated.
The samples are arranged in cell arrays with 6 cells each, of which one is "companion" (reference) cell and 5 "primary" (experiment) cells (see again Figure 4). Each of the 5 primary cells in the array is sequentially probed by a movable MZI based on the scheme of Figure 3, while the companion cell is filled with a corresponding binary mixture probed by a single-colour MZI as depicted in Figure 3.

IV. The Operational Scenario

The strong NASA-ESA interplay in the definition and implementation of SODI typical operational concepts, together with the related involvement of several centres and entities on both NASA and ESA sides with different functions and responsibilities, has led to a very complex operational scenario (as discussed in detail in the SODI Mission Operations Implementation Concept [6]), and substantial differences with respect to other Class-1 and/or Class-2 facilities (traditionally operated under the supervision of a single Space Agency, e.g., [7-10]).
In such a complex framework MARS-Telespazio has taken care of many aspects: Definition of the staffing concept and console coverage schemes, JOIP (Joint Operation Interface Procedures) for USOC/POIC Interactions, JOIP for USOC/MSG FOT Interactions, Payload Regulations, PES (Payload Developer Engineering Support) concept, crew PODFs (Payload Operations Data File), ground PODFs for troubleshooting and facility recovery, etc.
The following text provides a focused synthesis of the involved Payload Operations Teams (real-time and off-line), their locations and the support they provided (console or off-line) during the different phases of the launch, in-flight and return operations. Furthermore it includes a description of the ground segment services configuration and data flow implemented in support of the in-flight operations.

A. Telespazio (MARS)

Telespazio (located in Naples, Italy, call sign MARS) is the FRC assigned by ESA for the SODI experiments. As such MARS has taken care of crew activities, received the full range of SODI telemetry (health & status data, scientific telemetry), commanded the SODI Payloads, provided SODI console positions during SODI active on-orbit phases, monitored system characteristic parameters, and played a leading role in anomaly resolution processes. For the DSC experiment MARS has also served in a position of USOC, taking care of all scientific operational aspects and providing support as required to the science team.

B. CREW

Trained crew members participated to operations essentially installing the SODI hardware inside MSG, and replacing periodically (on the basis of MARS requests/plans) the flash disks on which scientific data were stored.

C. PI/UHBs

The SODI science team was actively involved during the SODI active on-orbit phases. They iteratively interacted with MARS during the initial on-board optical checkout (image quality optimization campaign); then, they examined on a daily basis the outputs of the scientific runs (set of representative images periodically downlinked by MARS) during nominal operations execution. The PI was finally provided with the full set of telemetry data and images as soon as the flash disks were returned to ground (28S and 30S).

D. POIC

During SODI onboard operations, the Payload Operations Integration Center (POIC) at MSFC provided real-time support operations functions. Among them, MARS interacted essentially with the POD (Payload Operations Director) for real-time coordination, the OC (Operations Controller) for planning matters, PRO (Payload Rack Officer) for command and downlink windows activation/deactivation, LIS (Lead Increment Science Representative) for science related matters. Occasional interactions was also required with the PAYCOM (Payload Communications Manager) for crew-related communications, DMC (Data Management Coordinator) for video downlink and Marshall Data (RPI-OPS) for telemetry anomaly resolution.

E. MSG Flight Operations Team (FOT)

The main interface for SODI operations to the POIC cadre was the MSG Ops Team, who coordinated all MSG operations. The MSG Ops was contacted by MARS during SODI active on-orbit phases essentially for SODI payload activation or deactivation and especially for requests of image file transfer (from the MSG to ground).

F. SODI Engineering Support Function

SODI Engineering Support has been provided by the support teams from the Payload Developer at QinetiQ. During SODI on-orbit active phases, the SODI Engineering model (EM, see Figure 5) was available at MARS premises for troubleshooting activities and the validation of products modified on the basis of real-time request of the science team.

Figure 5: SODI EM and related EGSE located in the MARS Clean room.

G. ESA PAC and MSO

Responsibilities of ESA PAC (Payload Activity Coordinator) and MSO (Mission Science Office) during operations included the following aspects:

- Science and Payload Operations Coordination / Management,
- Planning and re-planning assessment in case of major changes,
- Conflict resolution in payload operations and science requirements,
- Acquisition, distribution and report of Payload Operations and Science achievement,
- Mission Status,
- Coordination of specific science requirements / P/L Operations issues directly with MARS.

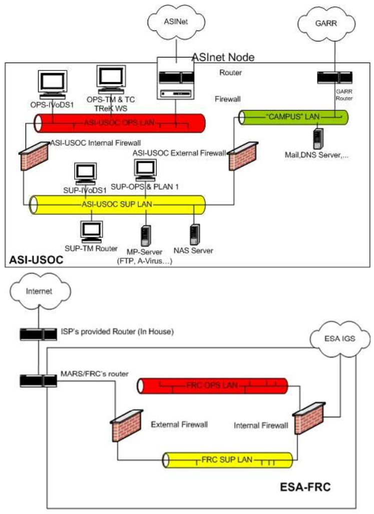

Figure 6: Sketch of Telemetry Processing and Visualization Systems at MARS.

Communications infrastructure related to telemetry receiving, file transfer and services like IVoDS (Internet Voice Distribution System) have been provided by NASA (Huntsville Operation Control Center, HOSC).
Moreover, MARS has resorted to the TReK (Telescience Resource Kit) Telemetry Processing application of the NASA TReK suite for reception of SODI scientific and Health & Status cyclic telemetry, and any other relevant station data from the POIC (Figure 6).
The nominal communication path for TReK data exchange between MARS and POIC is via Internet using UDP protocol.
In addition, MARS developed the SMCD (Science Monitoring Control & Distribution software, Figure 7), a graphical application (Human Computer Interface) for monitoring relevant payload data (this software receives telemetry data directly from the TReK TM Processing application installed at MARS site).

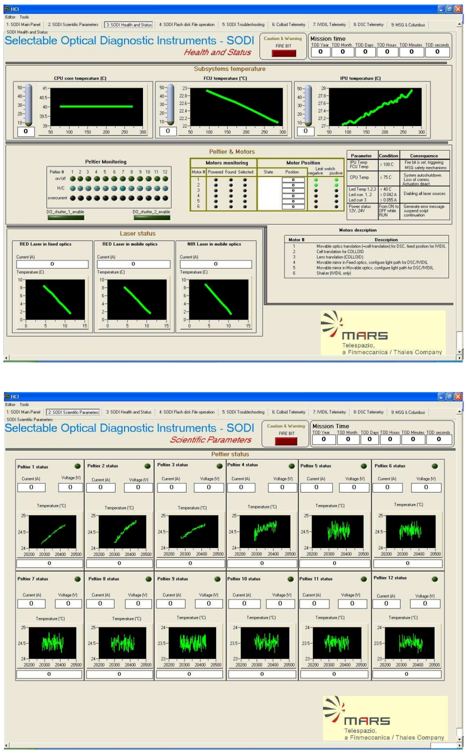

Figure 7: SMCD HCI: Top: SODI Health & Status Display, bottom: Scientific Parameters Display.

Figure 8 finally shows the SODI console set configuration in the MARS control room and related console operators chairs.

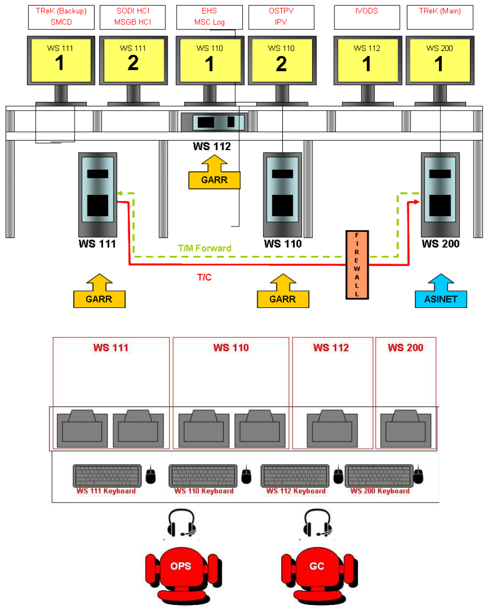

Figure 8: SODI console set in the MARS control room.

In particular, during operations, the MARS Operations Lead (see Figure 8) has:

- holded the overall lead/responsibility for the USOC real-time operations;
- interfaced to the POIC cadres;
- monitored the incoming PL telemetry and relevant ancillary data;
- informed timely the MSG Ops Lead about irregularities/anomalies;
- issued commands to the PL at planned timeslots;
- issued recovery commands as required;
- initiated file transfers to/from payload.

The used call sign of the USOC Ops whose functions have been described above was "SODI".
In parallel, the MARS Ground Operations Controller (GC, see Figure 8) has taken care of:

- the coordination, maintenance and configuration of the USOC operations infrastructure (computer systems and networks);
- the operability of the USOC external connections (towards POIC and UHB);
- all the interfaces to the POIC Ground Controller.

V. Achievements and Lessons Learned

The complex fully implemented operational scenario, whose principal aspects have been illustrated in the earlier sections (together with a short description of the ground infrastructure), has proven to be effective in the management of typical operational aspects of the SODI payload/experiments.

The hybrid mission operation concept elaborated by MARS, with an eye on the standard NASA approach on one side and an eye on typical ESA concepts and processes on the other side, has proven to be exhaustive and also sufficiently flexible to accommodate the management of off-nominal situations and on-orbit troubleshooting.

A total of 55 scientific runs were executed onboard (51 days of operations).

A total of ≅600 Gigabytes of data were stored onboard on the SODI flash disks. Approximately 50 Gigabytes were downlinked (one Gigabyte per day, a sample image as downlinked by MARS and provided to the science team is shown in Figure 9).

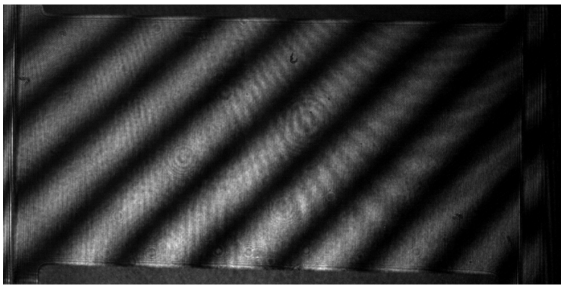

Figure 9: Example of downlinked images showing fringe distribution in microgravity condition (Courtesy of SODI Science Team and ESA).

Most of the efforts spent by MARS to develop the complex SODI operational scenario as well as to bridge the gap between typical NASA and ESA concepts/processes, has led to the identification of some "lessons learned" and suggestions to both agencies with regard to in-flight operations. Some detailed indications along these lines are given in the remainder of this final section (the reader being referred to [8] for some earlier lessons learned with the SODI IVIDIL and COLLOID experiments).

A. Crew activities with payloads based on a modular concept.

The possibility of having crew errors during on-board mechanical operations is relatively high for payloads, which, as SODI, are based on an extreme modular concept (many parts to be assembled together with many cables and connectors). A possible way to mitigate such a risk is to avoid a fragmentation of the activity (in other words, we suggest to allocate a single time slot to complete the overall installation/mechanical setup of the payload).

Furthermore, it is recommended not to schedule crew (hardware-related) operations as "voluntary science".

B. Interaction with NASA Management

During experiment execution, continuous offline interaction was required with NASA POMs (to keep them updated on the payload status, successful run execution, way forward, etc.).

As per agreed concepts reported in [6], however, such a task was not under USOC responsibility.

After the suppression of the Team of ESA POMs on November 2011, it is highly suggested (for future operations with the SODI payload, e.g., the DCMIX future campaign) to identify a new position on the ESA side to expressly cover such interactions (during the DSC experiment this function was temporarily covered by ESA MSO).

C. On the ground Science Campaign and Optical Checkout

Most of time spent for contingencies was related to the execution of a relatively long (10 days) and "unscheduled" optical checkout, expressly requested by the science team as a *mandatory* activity needed for optimizing the quality of images generated by the SODI instrument (prior to starting nominal scientific runs).

The science team (and ESA MSO) are highly recommended for future operations (DCMIX) to define "a priori" (before the experiment start, preferably at the ESR definition stage) well-defined criteria to be used to assess/improve the quality of images, and provide precise indications *on the time required to finalize such a process*. The USOC should be provided with specific procedures for image quality assessment/optimization at least two months in advance with respect to the experiment start date.

D. Engineering Support Function

SODI DSC was operated on the basis of a 24/7 coverage scheme due to the limited extension of the availability window of the MSG facility (which forced all the involved teams to extend operations over weekends, thereby forcing the nominal 24/5 coverage scheme as per MOIC[6] to 24/7). ESA/PD agreement for the engineering support function however was based on the 24/5 nominal coverage scheme. This caused a lack of PD support to MARS for all anomalies occurring during weekends. ESA is highly recommended for future operations to match exactly the console coverage scheme requested to the USOC with the engineering support function agreed with the PD.

E. Payload Integration Agreement (PIA) and Responsibility Sharing

The high complexity of the scenario related to the SODI experiment (ESA payload hosted in NASA facility, European console team interacting directly with equivalent NASA console teams, ESA MSO playing the role of supervisor in USOC/Science team interactions and covering ad interim the function formerly covered by ESA POMs) has produced some unavoidable "holes" in the assignment/coverage of responsibilities/tasks. Among them the issue illustrated in Sect. V.B. Another missing definition of responsibilities has been identified with regard to the development of crew PODFs (procedures) involving SODI specific hardware outside the MSG facility (i.e. parts of SODI to be operated by the crew outside the Work Volume of MSG).

A similar concept applies to the closure of NASA PARs (Payload Anomaly Reports). According to the classical ESA concept, the USOC is in charge of opening SPRs (System Problem Report) in the IOT database and support the PD in the anomaly resolution process (SPR closure). During the execution of the SODI DSC experiment, MARS continuously informed NASA about the outcomes of SPR telecons/meetings and related information was inserted by NASA into their PAR database. PARs, however, were not closed immediately by NASA upon notification by MARS of the closure of the equivalent SPRs.

It is highly recommended to expressly cover these cases in future releases of the SODI Inter-Agency Payload Integration Agreement (PIA).

Acknowledgments

We thank ESA for the financial and operational support in the ISS operation preparation and execution.

Moreover, we would like to express our appreciation to all POIC positions for the excellent support provided during operations. We wish also to give our special thanks to the MSG Team (MSG Ops and Investigation Leads) for all the patience they had in downlinking files and monitoring the experiment during the Orbit 3 shift. Most of all, we indebted to Charlie Scott for his friendly approach and positive team spirit, without whom this experiment would not have been possible.

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