63rd International Astronautical Congress, Naples, Italy.

IAC-12-B6.2.9

PREPARATION, HANDOVER, AND CONDUCTION OF PRISMA MISSION OPERATIONS AT GSOC

Ralf Faller
German Space Operations Center, DLR Oberpfaffenhofen, Germany, ralf.faller@dlr.de

Andreas Ohndorf, Benjamin Schlepp, Sabrina Eberle
German Space Operations Center, DLR Oberpfaffenhofen, Germany
andreas.ohndorf@dlr.de, benjamin.schlepp@dlr.de, sabrina.eberle@dlr.de

The experimental satellite project PRISMA was initiated in 2005 by Sweden, France, Denmark, and Germany, with the Swedish Space Cooperation (SSC) as the project lead. The purpose was the demonstration of necessary techniques and the validation of the respective sensor technology for future missions that involve close formation flight and rendezvous in space. At that time, the German Aerospace Center DLR was not only involved in providing satellite GPS hardware and navigation software components but also as one of the experimenters for GPS-based navigation and autonomous formation flight. The idea of also conduction a part of the flight operations phase from Germany came into discussion at the end of 2009, with the purpose of sharing mission operations cost. This was agreed by Sweden and Germany shortly before launch of the two PRISMA satellites, which took place in June 2010. Nine months later, mission operations were handed over from SSC's control center in Solna, Stockholm, to the German Space Operations Center (GSOC) in Oberpfaffenhofen, Germany. After successful operations by GSOC, the re-hand over of the mission back to Solna was performed in August 2011.

The baseline concept for the German PRISMA ground segment foresaw cloning of the Swedish ground segment developed by SSC at GSOC to minimize the development and test effort, but specific adaptations were needed to integrate PRISMA into GSOC's multimission environment. Furthermore, the original station network, which consisted only of the Kiruna ground station in North Sweden, was extended by two additional DLR ground stations in Weilheim, Germany, and in Inuvik, Canada. That extension proved especially beneficial to the shift concept.

Another important aspect was the training of the German operations personnel in a short time. This was realized by training on the job concept, which kept the additional workload for teaching and training on acceptable levels and at the same time supported the Swedish flight operations team during their operations phase.

This paper gives an overview of the GSOC ground segment and the flight operations activities. It reflects the challenges with regard to personnel and to the technical implementation of PRISMA flight operations at GSOC with limited available time. It also summarizes the lessons learned after five months of successful flight operations.

I. INTRODUCTION

With the launch of the first satellites more than 50 years ago, utilization of near-Earth space for scientific, commercial and military purposes began. During the following decades, aspects like orbit pollution by space debris and potential collisions between these objects, whose count is steadily increasing, were not considered. Nowadays, these objects more and more endanger current and future manned and unmanned space missions. This is especially true for certain valuable orbit families. As a consequence of that fact, sustainability topics like on-orbit servicing/maintenance or active space debris removal came into focus of involved organizations. The realization of these ambitious objectives is challenging and requires development and in-space validation of new enabling key technologies, namely telepresence, telerobotics, autonomous formation flight (AFF), and autonomous rendezvous and docking (AR&D).

I.I PRISMA Project Concept

In 2005, the Swedish National Space Board (SNSB) and the Swedish Space Cooperation (SSC) initiated the satellite project Prototype Research Instruments and Space Mission technology Advancement (PRISMA) to demonstrate these key technologies. The responsible SSC Space Systems Division was bought by German OHB AG and renamed to OHB Sweden AB in July 2011, and the notation OHB-SE is used in this paper from here on. PRISMA was a two-satellite mission to demonstrate close formation flying, proximity and rendezvous activities with a high level of on-board autonomy in the areas of guidance, navigation and control (GNC). Following the low-cost concept of PRISMA, some European partners joined the attractive project and helped realizing it by providing hardware and software, or both. Additionally, a few also took part as experimenters, defining and executing own experiments. OHB-SE was responsible for the project and mission management, for the design and manufacturing of the space segment, for the implementation and validation of the ground segment, and the conduction of mission operations. The German Aerospace Center DLR provided a GPS navigation system, the Centre National d'Études Spatiales (CNES) provided a formation flying radio frequency sensor (FFRF), the Technical University of Denmark (DTU) a star tracker camera-based, so-called Vision Based Sensor (VBS), and Techno Systems Developments, Naples, Italy, provided a Digital Video System (DVS).

I.II Space Segment

PRISMA's space segment comprised two satellites. The bigger main satellite, called Mango, was equipped with sensors and cameras for the relative navigation as well as a propulsion system for active orbit alteration. The smaller satellite, called Tango, acted as the target for the rendezvous and formation flying experiments and featured no propulsion system. It also had only a simple attitude control system (ACS) based on magnetometer, sun sensor and magnetic torquer rods. The primary task of Tangos's ACS was an uninterrupted electrical power supply by continuously maintaining a Sun-pointing attitude. Tango was operated remotely via Mango via an UHF inter-satellite link (ISL).

On 15th June 2010, both satellites were put into a 720/780 km sun-synchronous dawn-dusk orbit with a Dnepr rocket from Yasni in southern Russia. The two spacecraft were launched in a combined configuration, i.e. Tango firmly attached to Mango, and separated after a few weeks of commissioning. Figure 1 shows an artist view of both satellites being very small proximity.

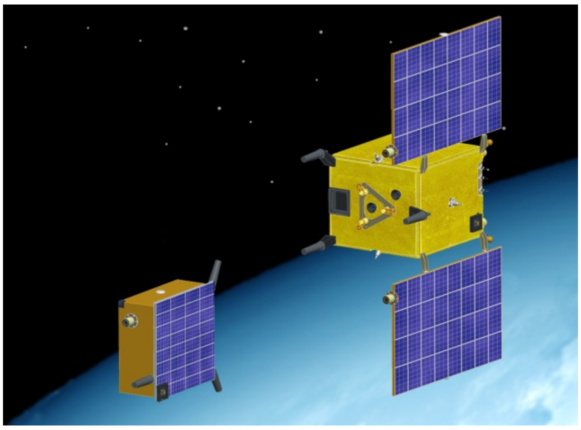

Fig. 1: PRISMA satellites Mango (right) and Tango

A main aspect of PRISMA was the high level of onboard autonomy, which allowed execution of most experiments without ground visibility. Safety measures, to avoid collisions between the two spacecraft, for example, were completely covered by the space segment.

I.III Ground Segment

The initial concept for the PRISMA ground segment foresaw a mission control center (MCC) in Solna, Stockholm, an operator control center (OCC) at the European Space and Sounding Rocket Range (ESRANGE) in Kiruna, northern Sweden, and a ground station, also at ESRANGE. The MCC should be responsible for the overall mission control, flight procedure development, test, validation and simulations. The OCC was designed for the actual execution of the flight operations. This concept had to be adapted a few times before the mission started in 2010 (see chapter III).

The key ground segment element was the monitoring and control (M&C) software suite called Rocket and Multi-Satellite EGSE System (RAMSES) [2]. RAMSES covers all main monitoring and control functions, such as telecommand script execution and logging, telemetry processing and display, and alarm and event monitoring. It is fully compatible to the ECSS Packet Utilization Standard (PUS) and other CCSDS standards and formats such as the Communications Operation Procedure-1 (COP-1). For PRISMA, RAMSES was supplemented with mission specific MATLAB tools, e.g. special navigation and attitude data displays. Mission planning was done with the commercial project management software HANSOFT[*], and storage and exchange of raw TM data and processed data products among the different project parties was facilitated by an archive system hosted by the Parallel Data Center (PDC) at the Royal Institute of Technology, Stockholm.

I.IV Operations Concept

In spite of having a high autonomy level of the space segment, the mission concept was designed to have at most 10 ground station passes per day in total, up to 6 passes for active flight operations and up to additional 4 passes for download of recorded data. The dump passes were needed to have both, sufficient monitoring periods for the experimenters during their experiments, if required, and the necessary contact duration to download all the data. Download-only passes were planned to run with only a command operator for monitoring of spacecraft health. The other operations team members should be on call during that time. Thus, the active flight operations basically required only a one-shift operations day and 5-7 days per week depending on the experiment. However, due to the experimental character of the payloads, it turned out that actively managed contacts past the end of a shift became necessary more often and the operations

[*] Hansoft AB,SE-753 20 Uppsala, Sweden, www.hansoft.se

concept needed to be altered to an overlapping two-shift concept.

An operations shift was manned by a mission responsible flight director (MCC), an operator (OCC) and a Guidance, Navigation and Control engineer (GNC). MCC prepared the passes, conducted them and also did the post-pass reporting. He also monitored the satellites' functions, took care of the data dump management, and coordinated all activities in case of anomalies. By orders of the MCC, the operator executed the respective flight procedures. The OCC was also responsible for monitoring of ground system functions and software. He monitored and confirmed execution of sent real-time and time-tagged commands and checked incoming events and warnings. The third position in the control team was the GNC engineer. He monitored the GNC related functions of the satellite, such as attitude and relative navigation data, functioning of the GPS system, and execution of attitude and orbit maneuvers. During a pass, GNC assisted MCC and initiated recommendations in case of anomalies. For the experiment preparation, GNC was in close contact with the experimenter. During critical experiment phases, the experimenter (EXP) was also present in the control room and therefore available in case of questions. This has been the case, for example, for all experiments involving the High Performance Green Propellant (HPGP) propulsion subsystem.

II. ADDITIONAL GROUND SEGMENT FOR PRISMA

II.I Mission Concept Needed to be Revised

After start of the project in 2005, the preparation of the PRISMA space and ground segment made good progress. Hardware and software was developed and validated, and an experiment timeline was generated and agreed with the respective experimenters. Availability of financial and personnel resources made it however necessary to modify the initial ground segment concept. The first change was the concentration of mission and operator control functions in Solna, whilst only a backup control capability remained at the station in Kiruna. This design change improved the financial situation, but in 2009 it became clear that the mission could not be executed within the planned financial budget. All project partners therefore checked their options to intensify their engagements. In that way, DLR offered to perform at least a part of the mission from the German Space Operations Center (GSOC). With respect to the few months left until mission launch, the new and revised concept for mission preparation and execution comprised three phases.

In the first phase, the project team should proceed with the preparation for the launch. The first 5-9 months of the mission should be performed by the mission control center in Solna with personnel reinforcement by GSOC engineers. In parallel, a second control center should be established at GSOC and an operations team needed to be trained and qualified to take over the mission. During this first phase, GSOC also included with Weilheim ground station in Weilheim, southern Germany, a second station into the PRISMA ground station network. Primary ground station was however still Kiruna ground station. The phases are illustrated in figure 2.

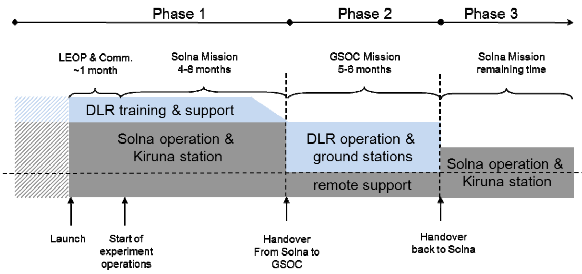

Fig. 2: Agreed concept of activities and operational responsibilities after launch; DLR contributions in blue and OHB-SE in grey

The second phase comprised the handover of the satellites from Solna to GSOC and the following five to six months of mission operations by the GSOC team. During this phase, GSOC operations team should be supported by Solna specialists, partly on site but most of the time remotely, e.g., on-call engineering support during office hours. During that phase, GSOC also planned to validate Inuvik ground station, Canada, for operations with PRISMA. The re-handover of the space segment from GSOC back to Solna marked the end of the second mission operations phase.

In the third and last phase, Solna should resume the mission operations and operate PRISMA until end of life.

The updated concept with two mission control centers and the timeline were discussed and agreed by all parties in spring 2010, shortly before the launch.

II.II Motivation

The motivation for GSOC to take charge of the mission operations for a short period of five to six months was driven by the unexpected opportunity to get additional experience in operating a close-formation-flight space segment and also to conduct rendezvous and proximity operations. With the mission TanDEM-X [1], GSOC had already gathered experience in formation flight with satellites having a spatial separation of >150 m. PRISMA, however, planned to decrease that distance even further, down to less than 10 m.

GSOC was already involved in PRISMA and had prepared some experiments concerning autonomous formation flight and autonomous orbit keeping. With the deeper involvement in PRISMA, some additional experiments concerning optical navigation could be envisaged. Furthermore, performing the flight operations from GSOC was now the opportunity to get directly into the driver's seat.

All in all, these new opportunities could be a direct benefit for upcoming on-orbit servicing (OOS) missions like DEOS [3]. This German On-Orbit Servicing Mission, which is planned to be launched in 2017, will demonstrate rendezvous and robotic capturing of another satellite, maintenance activities and controlled reentry of captured objects. GSOC will be in charge of the mission operations for DEOS, so with PRISMA, relevant key technologies could be developed and exercised beforehand in order to reduce the risk for DEOS.

II.III Challenges and Risks

Beside the positive aspects of the project, the challenges and risks need to be mentioned here. The main constraint for the implementation of ground segment for PRISMA at GSOC was the time. The discussions between the involved parties in Sweden and Germany started in October 2009, which was at that time 4 months before launch. In spite of starting immediately with the preparations and taking into account the launch delay until June 2010, the time frame was quite ambitious to accomplish both, the implementation of the control facility and network and the training of corresponding operations personnel.

Another constraint to be respected was the limitation of available documentation and personnel resources for education and training needs. According to the initial mission concept, it was planned to operate the mission by the same personnel, who developed and tested the satellites and the ground segment components. The project documentation was well prepared for the external experimenters, but less-suited for external flight operations. Thus, a main part of the operational knowledge needed to be found out in direct contact with the specialists in Solna. Unfortunately, the Swedish resources for training of the GSOC personnel were limited as well. Right from the start of the cooperation it was clear, that class room lessons or dedicated training sessions could not be provided.

II.IV Agreed Approach

Taking all available information and analysis results at that time into account, the details were discussed between OHB-SE, SNSB, and DLR and it took some intense negotiations before a corresponding Memorandum of Understanding (MoU) could be agreed upon and signed. Key element of that MoU was mutual support on reasonable endeavor basis without any liability.

The agreed technical approach thereby was:

- Implementation of a second control facility at GSOC.

  The basic concept was to use the proven control software suite RAMSES and mission specific tools to minimize the effort for development, test, and validation. GSOC additionally planned to use a few components and processes of their own multimission environment for the purpose of both, keeping the costs on adequate levels and ensuring maximum mission safety by reusing reliable and mission proven processes.
- Presence of GSOC personnel at OHB-SE's control center in Solna during the final mission preparation, including the simulations

  This became necessary due to the limited documentation and personnel resources.
- Personnel support by GSOC operators during the first operations phase controlled by Solna control center

  This support was mainly intended to preserve Swedish resources but had also positive effect on the training of designated GSOC personnel.
- Five to six months of PRISMA mission operations by GSOC

  This was the main topic, comprising the execution of different experiments. It was foreseen to hand over PRISMA mission operations responsibility to GSOC for that period. Remote support by OHB-SE specialists for experiment planning and validation and in case of anomalies was agreed.
- Return of the control for the space segment back to Solna

  Initial planning foresaw that GSOC's final activity was the depletion of the remaining fuel of Mango, which practically terminates the satellite formation, and the re-handover of Mango to Solna control center. This planning was however revised during the first months of the mission because the better-than-expected propellant consumption allowed to keep the formation longer and provided options for additional experiments.
- Implementation of a station network including the DLR stations in Weilheim and Inuvik

  GSOC's baseline was to use its own antennas in Weilheim as prime station supplemented by contacts via the DLR station in Inuvik, Canada, and the SSC station in Kiruna.

Beside these technical aspects, organizing the required, additional funding for this project was another topic to be addressed. With the interesting perspective of running the mission from GSOC (see chapter II.II), the German Federal Ministry of Economics and Technology provided funding, which covered a part of the total costs for facilities, stations, and personnel. The remaining part was financed by GSOC itself.

III. GSOC PREPARATIONS IN DETAIL

As the available time for mission operations preparation for GSOC was short, respective activities started shortly after the first contractual negotiations between SNSB, OHB-SE, and DLR/GSOC, i.e. preparation work was already ongoing a few months before MoU signature. Figure 3 gives an overview of the relevant milestones of the preparation phase until handover.

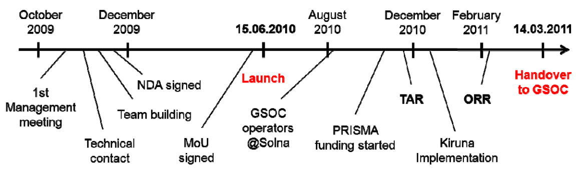

Fig. 3: GSOC ground segment preparation timeline

As described in chapter II, the preparation of an additional ground segment for PRISMA at GSOC technically concentrated on three major topics: the implementation of respective control center hard- and software, the preparation of the additional stations plus corresponding network, and education and training of operations personnel. This is described in the following subchapters.

III.I Mission Control Center

Following the baseline approach of cloning the Solna control software and tools, the installation of the M&C software RAMSES on corresponding PCs could be done straight forward. Different to mission operations at Solna control center, which were conducted out of a single computer network with access to the Internet, security requirements of the multimission environment at GSOC required two LANs for this task. The direct satellite operations, e.g. reception, processing, and archiving of TM and the release of commands, were performed from the so called Ops LAN, which is connected to the respective ground station. Other mission activities took place in an office LAN, e.g. storing and retrieving data via the external data storage PDC, mission planning with HANSOFT via the Internet, or training and rehearsals with the spacecraft simulator, located in Solna. Thus, RAMSES and other operational software tools (Ops tools) were available in both network environments. A controlled and secure data exchange between both LANs was realized by an automated file distribution system (AFD†). Figure 4 illustrates the LAN concept and connections to external entities.

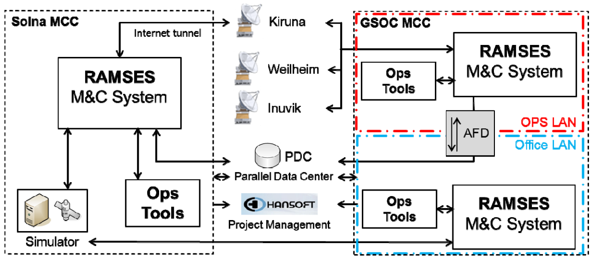

Fig. 4: Different ground segment architecture in Solna and GSOC; two separated LANs were needed at GSOC, an operations network for satellite control and one for the access of the simulator and external entities

In addition to the provided Swedish operations support tools, GSOC flight operations personnel also used existing generic GSOC multimission tools and newly developed GNC related software modules for their operations, e.g., for maneuver planning, analysis, and visualization.

Workspace for the PRISMA flight operations team was allocated in one of GSOC's multimission control rooms. Figure 5 shows the layout of the control room K9, which was at that time also used by two other missions (GRACE and CHAMP).

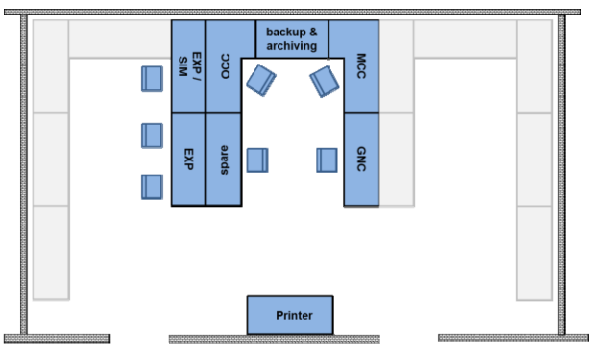

Fig. 5: Workspace within control room K9 showing the PRISMA consoles (blue) and positions of other projects (light grey)

III.II Ground Stations and Network

The PRISMA specific configuration of the ground station in Weilheim, which is 30 km southwest of Oberpfaffenhofen, could be done in short time. As the existing leased line between that ground station and the control center was shared with other missions supported

† AFD (Automatic File Distributor) developed by DWD, http://www.dwd.de/AFD

by GSOC, its bandwidth capacity was increased to four Mbit/s to avoid potential bottlenecks. This was necessary because of PRISMA's peculiar downlink characteristic of having housekeeping and payload TM together in one single TM stream of approx. 1 Mbit/s and using a RAMSES component for archiving directly in the OPS LAN. This policy differs significantly from the often employed scheme of routing only low-bandwidth housekeeping TM to the control center and archiving the high-bandwidth, raw payload TM directly at the ground station for later retrieval and offline processing.

The ground station in Kiruna, originally planned to be the one and only PRISMA ground station, was configured to rely on a single link to OHB-SE's control center in Solna. In a first step to support the necessary qualification tests of GSOC's planned new ground segment, this configuration was successfully altered for dual control center support. This allowed routing of TM to both control centers simultaneously and eased development activities without influencing concurrently ongoing mission support by OHB-SE.

First TM reception test passes via Kiruna revealed an unacceptably high systematic frame loss rate of 10-15%. Analysis of the link between Kiruna and GSOC identified the employed connection type between Stockholm and Germany as the bottleneck. The data were routed through a public Internet link, whose nominal bandwidth was sufficient, but, depending on the current bandwidth usage by other Internet traffic, some TM packets arrived delayed at GSOC and were dropped by the network system due a setting that preferred on-time data over complete data. A change of that SLE protocol setting from “timely complete” to “online complete”, and a following optimization of buffer size-controlling parameter to support continuous data flow, finally ensured that all packets were routed to the RAMSES system without losses. However, during some passes, the fluctuating available bandwidth still caused TM backlogs of up to 30 seconds. This was considered inacceptable, especially during potential contingency or time critical situations, and an exclusive connection was finally rent to mitigate that problem.

The implementation of the Inuvik station was not mandatory for GSOC's operations phase, but it promised a higher flexibility for operations planning. This station of the DLR Remote Sensing Data Center (Deutscher Fernerkundungsdienst, DFD) was already in use for the TanDEM-X mission and allowed contacts with PRISMA in orbits outside Kiruna's visibility. Inuvik passes allowed GSOC running active flight operations during normal working hours instead of during night shifts. In context with the remote support by OHB-SE's specialists during office hours, this option also improved mission safety. The visibilities of the PRISMA space segment from the employed ground stations during one day are shown in figure 6.

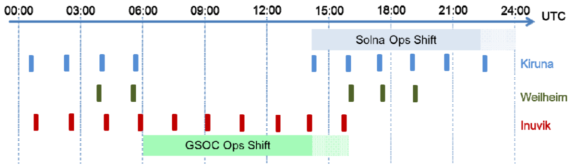

Figure 6: Typical ground station visibilities during 24 hours over ground stations Kiruna, Weilheim, and Inuvik

First tests with Inuvik also showed TM gaps, which was solved with the described modified SLE protocol setting. The inevitable few TM delays were accepted and taken into account for the operations.

Tests and qualification of the stations took place concurrently to ongoing OHB-SE mission operations. TM tests with Weilheim and Kiruna were possible without any additional preparations by Solna due to the overlapping visibility of these two ground stations. For TM testes with Inuvik, however, mission planning in Solna needed include upload of additional transmitter-on commands for theses passes. Uplink tests were closely coordinated with ongoing mission activities, and we therefore used spare passes without any other activities foreseen by OHB-SE for these tests. Only dummy commands authorized by OHB-SE were sent during these TC test contacts by GSOC and potentially running experiments therefore not disturbed.

III.III Operations Team

Besides implementing GSOC's PRISMA ground segment in a challengingly short time frame, building and training of the GSOC flight operations team was another major concern. The first idea was to use the personnel already involved in the DEOS mission, which was at that time in preparation of the system requirements review (SRR), plus experienced engineers form other projects, who could get familiar with the PRISMA specific environment in a short time. Unfortunately, both strategies did not result in the required number of flight engineers, as the DEOS team members alone were too few and most of the experienced engineers were busy with critical mission phases of their projects. Most of the final PRISMA flight operations team therefore had less experience in mission operations than desired, but they compensated this with ambitious engagement.

The MCC position was manned by personnel of GSOC's Mission Operations department. Specialists from GSOC's Spaceflight Technology department covered the GNC position. OCC was manned by personnel of GSOC's multimission support team, who were also responsible for the operator function in other missions. At begin of the GSOC mission phase, the flight operations team thus consisted of five MCC engineers, three GNC specialists, and 16 OCC operators. The latter were so many because the whole multimission operator team needed to be familiarized with PRISMA OCC tasks to fully integrate PRISMA into the existing multimission environment, which saved cost.

The training of MCC and GNC engineers started with MoU signature a few weeks before launch of Mango and Tango. Due to their limited resources and the soon-to-come launch, OHB-SE could not support dedicated training for GSOC's foreseen MCC and GNC personnel. The chosen alternative was therefore to send these colleagues to Solna, to follow the final simulations, rehearsals, and also the first weeks of PRISMA mission operations. By watching and interviewing OHB-SE's operation team members they learned the ground segment's functionality and how to operate the space segment. In the next step, after certification through OHB-SE flight operation team and mission management, GSOC personnel started covering the OCC position, turning the flight operations team into a joint one consisting of GSOC and OHB-SE engineers. This support lasted from mid August 2010 until end of February 2011.

In parallel to the training and shift work at Solna, the GSOC team conducted an own training program in Oberpfaffenhofen by means of class room lectures and simulations. Team members returning from Solna informed their colleagues during these lessons about gained know-how. Two months before handover of PRISMA space segment to GSOC, the multimission operators were instructed in the OCC tasks and duties.

III.IV Ground Segment Qualification

The qualification of GSOC's PRISMA ground segment was an essential milestone for the clearance to handover from Solna to Oberpfaffenhofen, and two reviews were conducted to prove technical and operational readiness. With the GSOC-internal technical acceptance review (TAR) in November 2010, correct technical implementation of control room equipment and software, the operational status of the ground stations, and the corresponding network were confirmed. Although being an internal review, representatives from OHB-SE and from the DLR Spaceflight Management were present as well. In February 2011, the official operational readiness review (ORR) finally confirmed the readiness of all technical and personnel elements for the mission. This time, the review was chaired by the DLR Spaceflight Management. The proper functioning of the TM and TC-chain via the stations in Weilheim and Kiruna could be confirmed as well as the adequate training level of the operations personnel. The result of the ORR was the formal "Go" for handover although the implementation of Inuvik station support was not finished at that time. This was however not mandatory, because WHM was planned as prime station with supporting contacts over KIR.

IV. HANDOVER AND MISSION EXECUTION

The handover of a mission from one control center to the other is a highly critical operation. It is not only the moment when the responsibility for a satellite changes; it is also a complex process with many essential activities for preparation of the handover, the handover itself and post-handover activities. It comprises both, the handover of responsibilities and the exchange of latest information between the control centers to ensure a smooth progress without unwanted delays or anomalies. Typical examples for such information are the latest status of the space segment, formation parameter, violations of TM limits during the last contact, and the onboard time-tagged commands. The handover and related activities are treated in more detail in the following subchapters.

IV.I Handover Preparation

In order to ensure a safe and controlled handover of the PRISMA formation to GSOC and vice versa, the preparations for it started several months before the planned event [5]. A corresponding handover plan was created and agreed by both parties beforehand. This plan comprised the following main aspects:

- Handover criteria
- Handover activities and timeline
- Responsibilities

Handover criteria were a set of conditions and requirements to be fulfilled before the handover could take place. For PRISMA, the primary criterion was the readiness of the new ground segment, confirmed through a passed ORR. Another requirement was the availability of a mutually agreed emergency procedure to be used in any case of emergency during PRISMA operations at GSOC. The procedure contained principal rules, basic guidelines for immediate actions, and phone numbers of on-call OHB-SE specialists. Another requirement was the availability of an agreement of kind and support by the OHB-SE support team during the GSOC operations phase. This agreement included on-site support by support engineers during handover and the first operation days at GSOC and an office-hour, on-call support for all remaining mission operation days until re-handover.

All activities of the handover process and their timing were covered by a dedicated handover procedure. This procedure started two months before the planned handover day with the availability of the handover plan and the official announcement of the handover day. A few days before handover and during a preparatory handover teleconference, both parties discussed and confirmed last activities and the planned timing. This teleconference also served for the discussion of open issues, identified problems, and questions. In conjunction with the teleconference, the control center that hands over control responsibility provides the second, control-receiving control center with a first set of data and information. This so-called handover data package 1 comprised the current set of flight procedures, data bases, and the mid-term experiment plan. Another crucial aspect was the coordination of the Kiruna station scheduling, because both control centers had to use that station during consecutive passes. Then, on handover day, a data package 2 should be exchanged in the same way as the first one, containing the latest available information about the satellites, occurred anomalies, or TM-limit violations. During the handover teleconference this latest data should be discussed, if required, and the completion of handover confirmed by GSOC and OHB-SE. Table 1 lists the main handover activities and their schedule.

The handover plan also described responsibilities for each respective activity. This comprised both, the support by Solna specialists during the critical handover days and an on-call support during the GSOC mission phase. It was agreed that two specialists from OHB-SE are present from handover day on for some days in order to provide support in case of anomalies, problems with ground segment components, or with the satellites. For the entire GSOC operations phase, an on-call support for trouble shooting and in case of anomalies was arranged. This support was only available during office hours, which was conflicting with the original shift concept that foresaw night time operations. This problem was automatically mitigated with the change to daytime operations when Inuvik ground station support became available later

IV.II Handover to GSOC

The actual execution of the handover from Solna to GSOC closely followed the planned and agreed procedure, with only minor deviations. The handover date and time, which was planned for the afternoon on 14th March 2011, could remain unchanged since no relevant problems were detected during the preparatory handover teleconference. The latest flight procedures were implemented at GSOC as soon the first handover data package arrived from Solna. The only deviation from the planned procedure occurred when the scheduling of the Kiruna station passes shifted from Solna to GSOC. When GSOC sent their passage plan, beginning with the first pass *after* the handover, to the automated scheduling system in Kiruna, previous scheduling requests were automatically deleted. This unfortunately included the passes planned for Solna PRISMA support *until* handover. This behavior was quickly detected, the station scheduling corrected and special consideration to this topic given for the planning of the re-handover from GSOC to Solna.

Time	Item / Activity
H/O – 2 month	Handover plan and procedure available
H/O – 2 weeks	Handover date/time announcement
H/O – 4 days	Preparatory handover teleconference
	• H/O procedure and timeline agreed by both parties
	• H/O data package 1 provided
H/O – 2 days	Final coordination and scheduling of Kiruna station
Last pass before H/O	Kiruna pass
	Last operations by Solna
	GSOC was monitoring TM
	Handover data package 2 provided after the pass
Handover	Handover teleconference
	• Discussion of data package 2
	• Space segment and GSOC ground segment were stated green for H/O
	• Handover execution was confirmed by both sides
First pass after H/O	Satellites were operated by GSOC successfully via Kiruna
	Solna was monitoring TM
	Start of on-site support by Solna specialists at GSOC
	Start of Solna MCC stand-by phase
H/O + 1 day	Start of experiment operations
H/O + 3 days	End of Solna MCC stand-by phase
H/O + 1 week	End of on-site support by Solna specialists
	Start of Swedish on-call support
	End of handover process

Table 1: Handover major milestones and activities

The last experiments of Solna mission control were completed as planned and both satellites configured for handover. During Solna's last pass via Kiruna in the afternoon, GSOC was already monitoring TM. After that passage, the second handover data package was generated, transferred to GSOC, and discussed during the handover teleconference before the next passage, this time controlled from GSOC. The "Go" for the handover could be agreed by both sides and the next Kiruna pass was successfully operated by GSOC, with Solna monitoring TM this time. Routine checks during that passage and first commands confirmed successful handover by GSOC. As agreed before, the Solna control center remained in hot stand-by for the next three days, and two engineers from Solna were present at GSOC during the first week of their operations, which turned out very helpful.

With the end of that on-site support and start of an on-call service by Solna, the handover process was completed and documented with a handover report. One lesson learnt from that first handover was to foresee more time between the two actual handover contacts. This way, handover package preparation, transfer, implementation, and discussion in the handover teleconference could be achieved in a more relaxed manner and also if not all actions function as planned.

IV.III Mission Execution

After the successful handover, flight operations at GSOC were started directly on the next day with the upload of new AOCS software, which was typically done at the beginning of a new experiment with navigation topic. The first experiment conducted under GSOC control was from DLR and called Autonomous Formation Control 2 (AFC-2), which was running for 19 days. Table 2 lists this and all other PRISMA experiments executed during GSOC mission operations phase.

Experiment	Duration	Experimenter
Autonomous Formation Control 2 (AFC-2)	19 days	DLR, GSOC
Autonomous Formation Flight (AFF)	9 days	OHB-SE
Autonomous Rendezvous (ARV-2)	2 days	OHB-SE
(PROX-FARM)	12 days	OHB-SE
High Performance Green Propellant Experiment (HPGP-3)	21 days	ECAPS, SE
PRISMA Mass Analyzer (PRIMA)	In parallel to others	Swedish Institute of Space Physics (IRF)
Autonomous Orbit Keeping 2 (AOK)	30 days	DLR, GSOC
Formation Flight Re-Acquisition (FFReAc)	5 days	DLR, GSOC / OHB-SE

Table 2: Experiment timeline

The typical activities for an experiment preparation and execution were as follows:

- Experiment preparation
- Onboard software update (if necessary)
- Validation of Experiment procedures
- Experiment Readiness Review (ERR)
- Transfer to the initial formation/conditions
- Experiment execution & monitoring

The preparation of an experiment was the longest phase starting with the first definition, planning of fuel budgets, development of onboard software and corresponding flight procedures, and adaptations with respect to the overall mission timeline. Close to the start of the experiment, the experimenter was doing the final preparations together with a GNC engineer who took care of all experiment and GNC related aspects during its execution. During an experiment readiness review (ERR), the upcoming experiment was explained to the flight operations team, detailed activities, constraints and critical phases, including hold points with go/nogo decisions, were discussed and agreed between the respective experimenter and the flight operations team. The ERR was thus a key element of every experiment preparation.

Some experiments were using dedicated onboard software components that needed to be uploaded and activated beforehand. This was normally done by the flight operations team in preparation of the experiment without presence of the experimenter.

It was not always possible, that an experiment could be directly started with the configuration in which the previous experiment ended. The satellites therefore often needed to be reconfigured correctly, and sometimes also an orbit transfer was necessary to bring the satellites into the required initial formation. In order to minimize the propellant consumption for the transfers, the general experiment timeline was optimized beforehand in a way that the final formation of one experiment is as close as possible to the next experiment's initial conditions.

The validation of the prepared experiment procedures was done in two stages. The first validation was performed with a software simulation, where the complete experiment, including the dynamic behavior of both satellites, was simulated. Fuel consumption and safety distances were checked with this. Due to access limitations, this could be performed only at OHB-SE and so GNC engineers in Solna were always involved in the experiment preparation process. The second validation was done by GSOC MCC via remote access to the hybrid satellite simulator. The prepared flight procedures were therefore loaded into the simulator to check the correctness of the generated commands (real-time and time-tagged).

The experiment execution started with the upload of the experiment's commands by running the corresponding flight procedures. The satellites' behavior was monitored in real-time during the passes and also offline after a contact through analysis of downloaded and recorded TM. Most experiment parts ran without ground visibility, but sometimes, ground actions, such as enabling or disabling the next experiment sequence; mode changes; or experiment abort commands needed to be done during a contact.

In parallel to the experiment related activities, MCC took care of the routine tasks of the mission. These activities were mainly the management of the onboard data storage and the corresponding dump of data to ground, regular TM checks on daily basis, updates of GPS related data (YUMA GPS Almanac) on weekly basis, or loading of transmitter on/off commands for the upcoming passes.

IV-IV Re-handover from GSOC to Solna

The re-handover of Mango and Tango back to the OHB-SE control center in Solna was performed on 23rd August 2011. The handover was prepared in basically the same way as the first handover, taking into account the lessons learned. This time, the scheduling of station could be arranged smoothly. On the handover day, GSOC performed its last active pass at around noon and three hours were available for the compilation of the second handover data package and for the handover teleconference. A TM-only contact with Inuvik in between was used to for additional monitoring. Solna control center then successfully resumed mission operations again with the first contact over Kiruna in the afternoon.

For the re-handover, neither on-site support nor a longer stand-by phase by GSOC after handover was needed. GSOC monitored the first two Kiruna passes but was then released from operations.

Since the re-handover the PRISMA formation was operated by OHB-SE again, who continued experimental activities. Additional experiments were acquired and also GSOC provided an additional experiment, the Advanced Rendezvous demonstration using GPS and Optical Navigation (ARGON) [6] in April 2012, but this time, PRISMA was operated by Solna.

V. EXPERIENCES AND LESSONS LEARNED

With the re-handover of the fully functional PRISMA satellites back to Solna control center, a main requirement of this ambitious endeavor could be met. Beside the main task of running the PRISMA mission for a certain period, valuable experiences could be gathered and are described in this chapter.

V.I Control Center Implementation in Short Time

The implementation and qualification of an additional control center plus station network within less than one year was never done or tried at GSOC before. In spite of following the approach to install a clone of an already developed control center concept, much effort was necessary until all elements were validated and ready for handover. Some changes of the initial concept, e.g., the implementation of a dual LAN concept for the mission operations workspace, needed to be realized. A general lesson learned in this context was therefore, that the implementation of an external mission control center requires adaptations, even when complete systems were provided.

The default M&C system at GSOC is SCOS2K. Integration and usage of the external Swedish M&C system RAMSES gave GSOC the opportunity to use and learn from an alternative concept for satellite monitoring and control by running it during a real mission. Getting this experience is considered as a convenient side effect.

V.II Data Connection Experiences

As described in chapter III.II, the loss of TM frames after first implementation of the network due to communication link bottlenecks led to a solution which has not been used before. The new approach has become another option in the repertoire of GSOC's ground data system.

V.III Successful Mission Operations

Running the PRISMA mission operations for five months was a valuable experience for GSOC, whose engineers had the opportunity of running such an interesting mission from the "driver's seat". Some lessons, how to operate highly automated very close formations, rendezvous and proximity activities could be learned.

Of course, not all operations processes went smooth from the beginning on. Some glitches occurred and adaptations were implemented on-the-fly. One contingency situation occurred when in the preparation process of one experiment a transfer to the entry formation failed due to a combined software and operator failure. This caused an unexpectedly high propellant consumption, and some time was needed for investigations before the experiment activities could be resumed, but such situations or occurrences could not be completely avoided. Respecting the limited preparation time, the mission went quite smooth.

V.IV Additional GSOC Experiments

With the deeper involvement in the PRISMA project, GSOC gained additional rendezvous and optical navigation experience. This was one of the main motivations to perform the mission operations at GSOC. Camera raw data recorded during the relative navigation experiments could be received and will be input for new developments.

V.V Evaluation of Long Contact Phases

Running LEO missions with consecutive or overlapping ground station passes and the required switch from one station to the next is a standard task of control centers and has been exercised often before. The handover were coordinated by the control center and the flight operations paused for the time span that is necessary for the change of the TM and TC links. Rough orders of magnitude for the switching time spans were already available, but in view of upcoming missions with robotic activities, requirements to minimize the TM and TC link outages are expected. Thus, consecutive passes with PRISMA were used to measure these times. It was also tried to investigate, how a training of the involved personnel could reduce these outage times. Several test passes were run and the times were measured. The results indicated that the telemetry link could be switched without losing any TM frames. For the change of the TC link, outages of 20-30 seconds were measured and it is not expected, that this could be significantly reduced by special drill of the involved personnel. Any further, reliable reduction of the TC outage duration is only possible through automated handover procedures for which the M&C systems of involved ground stations must be prepared. This is an interesting, and in the perspective of future OOS missions, promising future task. Figure 7 shows an orbit with overlapping contacts over Weilheim, Kiruna, and Inuvik, which allowed a cumulative contact time of 30 minutes.

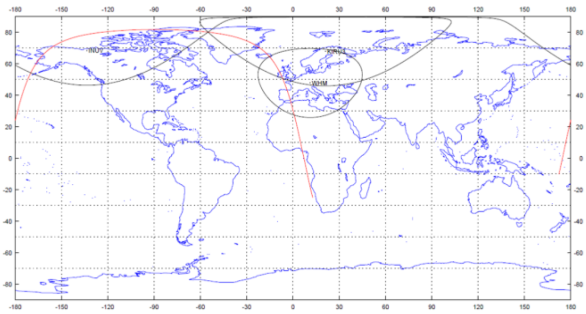

Figure 7: Consecutive Weilheim-Kiruna-Inuvik pass

VI. CONCLUSION

Execution of PRISMA mission operations by GSOC were successfully conducted in compliance with deadlines and budget limitations. A second PRISMA ground segment was implemented in Oberpfaffenhofen, comprising control facilities, an extended ground station network, and a mission operation team. This allowed the handover of control from Solna to GSOC for five months of mission operations from Germany. After this time, control over the two fully functional satellites Mango and Tango was successfully returned to Solna control center again.

The two main goals of this ambitious endeavor could be met. First, with the new operational scenario, it was possible to compensate budget shortages. The mission was run completely and all initially planned experiments could be performed. Second, GSOC had the opportunity to operate a mission with close formation, rendezvous, and proximity aspects, and was also able to run some additional own experiments. Finally, valuable experiences w.r.t. upcoming OOS tasks could be gained.

ACKNOWLEDGEMENTS

We thank all involved personnel on Swedish and German side for teaming up successfully under such unusual circumstances. It was only their joint commitment that made this success possible.

The PRISMA mission operations at GSOC were funded by the German Federal Ministry for Economics and Technology (Förderkennzeichen 50 RA 1020).

REFERENCES

[1] S. D'Amico, J.-S. Ardaens, S. De Florio, and O. Montenbruck, "Autonomous Formation Flying - TanDEM-X, PRISMA and Beyond." 5th International Workshop on Satellite Constellations & Formation Flying, 2008, Evpatoria, Ukraine

[2] M. Battelino, C. Svärd, A. Carlsson, T. Carlstedt-Duke, M. Törnqvist, "The Architecture and Application of RAMSES, a CCSDS and ECSS PUS compliant Test and Control System", DASIA 2010

[3] D. Reintsema, J. Thaeter, A. Rathke, W. Naumann, P. Rank, and J. Sommer, "DEOS – The German Robotics Approach to Secure and De-Orbit Malfunctioned Satellites from Low Earth Orbits." i-SAIRAS 2010, Sapporo., Japan

[4] C. Furtuna, C. Garcia, W. Kruse, „SLE experience over unreliable network links", SpaceOps 2012, Stockholm, Sweden

[5] T. Karlsson, N. Ahlgren, R. Faller, B. Schlepp, "PRISMA Mission Control: Transferring Satellite Control Between Organizations", SpaceOps 2012, Stockholm, Sweden

[6] D'Amico S., Ardaens J.-S., Gaias G., Schlepp B., Benninghoff H., Tzschichholz T., Karlsson T., Jørgensen J. L.c "Flight Demonstration of Non-Cooperative Rendezvous using Optical Navigation", 23th International Symposium on Space Flight Dynamics, 2012, Pasadena, CA, USA