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Columbus Operation as Basis for Future Exploration

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ABSTRACT

In 2017 some major milestones have been set for the international human spaceflight after ISS. The ISS International Partners focus on a manned space station around the Moon as the next step for human exploration of space. It would offer a lot of new challenges and opportunities compared to the well-known ISS in Low Earth Orbit:

- The new station will be outside the radiation belt of the Earth offering a radiation environment close to deep space valuable both for system validation and new experiments
- Larger distance to Earth and more complex logistic will offer a proving ground for future mission
- Testing of new communication means and short-term communication outages give way to new crew-ground interaction
- It could be used as gateway for manned lunar excursion with additional challenges

Col-CC will use the gained experience in 10 years of Columbus operations to study new ways of interaction with the crew, new communication ways and analyse new ground and on-board software solution suitable for the new setup:

- ATHMoS: New tool for supporting flight controller in analysing onboard systems on signatures of potential future failures
- Implement, use and analyse Delay Tolerant Networks and tools which allow communications between space and ground with minimum communication breaks
- Master-Timeline with MMI (Man-Machine-Interface): Pre-configured but flexible, automated on-board command system assisting the astronauts in re-configuration and switching on/off on-board subsystems and experiments

The new opportunities and challenges of operating a manned station in the vicinity of the moon are compared to the "standard" operations of Columbus and ISS in near Earth orbit. This will include a discussion of necessary changes in operations for this new phase of space exploration.

The paper will present results of the first studies performed in-house Col-CC/GSOC and will provide an outlook on the planned next steps towards deep space operations and exploration.

Introduction

During the more than ten years of operations of the Columbus module at the ISS, the Columbus Control Center (Col-CC) has supported 10 long-duration and one short-duration mission with 9 different ESA astronauts. Paolo Nespoli and Alexander Gerst were supported twice during this timeframe. All ESA astronauts of the 2009 class have performed at least one space mission and provided high valuable results during their stay on the ISS. Based on the long experience of DLR's German Space Operations Center (GSOC) in manned space operations and the missions to ISS described below, Col-CC is supporting also the current mission “Horizons” with Alexander Gerst until December 2018. Alexander Gerst will become the first German Commander of the ISS; this will be the second ESA astronaut as commander on ISS after Frank de Winne in 2009.

In the Interim Utilization Phase, which was done in parallel to setting up Col-CC ([4] to [6]) for the later Columbus operations, the Eneide Mission in 2005 and the Astrolab mission with Thomas Reiter in 2006 (see [1] and [2]) were successfully supported. Since February 2008, when Col-CC started its Columbus operations (see [7] to [12] and [14] to [17]), all further missions and increments have been prepared and supported successfully. With this experience Col-CC will be able to operate Columbus until at least 2024, assuming that the basic setup will not change (see [13]).

European Astronauts on ISS

In the second half of 2017 ESA Astronaut Paolo Nespoli was on-board ISS for the second time after his stay in 2010/11 for expedition 26/27. Paolo Nespoli was launched in orbit in Soyuz 51 on 28 July 2017 together with his crew mates Sergey Ryazanskiy and Randy Bresnik. During his stay at ISS he performed many experiments like Energy, Subvis/Justin and MARES/Sarcolab. He was also carrying out maintenance activities, e.g. for the European Drawer Rack (EDR), and prepared the Biolab rack for the upcoming Athrospira experiment. Paolo Nespoli and his crewmates returned to Earth on 14 Dec. 2017.

Fig. 1: Expedition 56 (Photo: NASA)

The next launch of an ESA astronaut took place on 6 June 2018 when the German ESA astronaut Alexander Gerst and his two crew mates Serena Auñón-Chancellor and Sergei Prokopyev were launched in space with Soyuz-MS09 (55S). Since the docking of Soyuz 55 on 8 June there are six astronauts on ISS, see Fig. 1 from NASA:

In the front row from left are astronauts Drew Feustel of NASA and Alexander Gerst of the European Space Agency. In the rear from left are crew members Oleg Artemyev of Roscosmos, Ricky Arnold of NASA, Sergei Prokopyev of Roscosmos and Serena Auñón-Chancellor of NASA.

For ESA Alexander Gerst is onboard and will become ISS Commander from October 2018. Fig. 2 shows him during the GRIP experiment in June 2018.

Fig. 2: Alexander Gerst (Photo: NASA)

The landing of Soyuz 55 with the crew members Alexander Gerst, Serena Auñón-Chancellor and Sergei Prokopyev is planned for 10 December 2018. In the half year of his stay on board ISS Alexander Gerst will be supported by ESA teams on ground, consisting of the User Support and Operation Centers (USOCs) in 7 European countries, the Engineering teams in Bremen and Turin, the EAC team in Cologne and the Flight Control Team and Ground Control Team at the Columbus Control Center in Oberpfaffenhofen (see [19]).

Columbus Subsystem Operations

The Operations of Columbus has provided Col-CC (see Fig. 3) in-depth insight and many years of experience with the following subsystems:

- **ECLSS**:
  The Environmental Control and Life Support Subsystem (ECLSS) is integrated in the ISS Operations; the United States On-Orbit Segment (USOS) provides

Columbus with breathable air. The internal distribution and circulation of air as well as temperature and humidity control are tasks of Col-CC.

- **TCS**:
  The Columbus Thermal Control Subsystem (TCS) is connected to the USOS TCS via heat exchangers. Therefore it is operated by Col-CC in close cooperation with Mission Control Center – Houston (MCCH). The cooling water distribution in Columbus to active racks and systems is provided via individual valve control. The temperature of the TCS system is ensured by operating modulating valves.

- **DMS:**
  The Data Management System (DMS) consists of computers and data networks managed in two layers (nominal, vital DMS). Nominal DMS operations like configuration for payloads or data up-/downlinks are managed by Col-CC as well as software updates. These can have small or large operational impact, depending on the type of change. A typical software cycle would involve restart of nominal DMS impacting all connected systems and payloads.

- **COMMS:**
  The communications subsystem (COMMS) is containing video and audio equipment as well as the High Rate Multiplexer. In the near future also the Columbus Ka Antenna will be integrated in the setup. The configuration of the COMMS equipment is a daily task of Col-CC in support of crew activities or experiments.

- **EPDS:**
  The Electric Power Distribution System (EPDS) consists of Columbus PDUs which receive, convert and distribute power to the Columbus power consumers. The handling and distribution of 120V and 28V is possible. Configuration of the system for payload operations is a typical task performed by Col-CC

The technical handling of the described subsystems is granted by the STRATOS position.

The operational handling and oversight on all Columbus activities is the task of the Columbus Flight Director. He is also responsible for crew and vehicle safety in Columbus and point of contact for the Houston Flight Director.

The planning is performed by the EPIC group. A lot of technical understanding and experience is brought into the timeline by dedicated experts.

The three positions at Col-CC are in close contact with all operations entities including payload centers in Europe (USOCs) as well as with International Partners (IPs). They are ensuring proper preparation and execution of ESA activities in Columbus and elsewhere on ISS.

Fig. 3: Main Control-Room K4 at Col-CC (Photo: Zoeschinger)

The experience gained with the Columbus subsystems and payload operations will help during operations of a future habitat. It is expected to have multiple similarities for the basic subsystems. Especially the experience with long-term handling and degradation of equipment and possible workarounds will be needed for habitat operations:

- Basic system functions are provided without need for interaction
- Specific activities require individual configuration
- A certain level of Space – Ground coordination is needed for common operations according to crew needs.
- Constant data analysis can allow for predictions on degradation and failure.
- Safety of crew and vehicle have to be granted for all operations

On the other hand the operation of the habitat is expected to show differences, e.g. for:

- Communication Delays
- Crew autonomy

- Onboard and Ground Automation
- Commanding autonomy
- Radiation

These aspects are considered in the next chapter.

Communication Delays

Operating in the vicinity of the moon means increased signal delay times of ca. 1 second one way.

For this kind of far distance communication special protocols and techniques like DTN (Delay Tolerant Network) and DDS (Data Distribution Service) were developed.

GSOC/Col-CC has already participated in several studies and test beds for DTN networks in the frame of ISS operations with a test bed together with HOSC (Huntsville Operational Support Center) and together with ESA in the frame of CCSDS (Consultative Committee for Space Data Systems) standardization. This work will be continued and GSOC is planning to provide a permanent test bed. See also [21] [22] [23].

In view of delays for onboard operations activities and procedures, DLR has contributed in IAC 2016. The paper [16] shows proposed methods to make procedures tolerant to delays, and enable operations to use these procedures for deep space missions.

Crew Autonomy

The level of crew autonomy is driven by different factors:

First, the previously described communication delays increase the need for more crew autonomy. In the vicinity of the moon the delays are in the frame of single seconds which allows for realtime crew communications similar to the ISS setup. For Mars missions the delays of many minutes is involving non-realtime exchange. In this case the crew autonomy has to be increased. This will impact nominal crew procedures as well as handling of anomalies. See also [16].

Second, the onboard design is driving the possible levels of crew autonomy. For example the set of available commands is driving the crew ability to perform certain operations. For Columbus not all commands are available to crew on the onboard laptops PWS (Portable Workstation) and PCS (Portable Computer System). This design was chosen with the idea of ground teams intensively supporting the crew on ISS.

Crew time is a precious resource on ISS. Therefore the planning of activities is currently done in view of minimizing necessary crew time. With increased onboard system autonomy the savings are easier to achieve.

Third, the crew and ground interactions have to be carefully setup in procedures and timeline planning. In current operations the ground team executes all time-consuming configuration tasks for the crew. This involves coordination with ground on readiness, e.g. using the procedure step “ON COL-CC GO”. On ISS this can only be done due to the good overall communications coverage with ground. For the moon vicinity the handling during communication outages has to be different. One way is to let the crew execute all procedure steps. In order to minimize crew time the subsystem autonomy should be high. Also system reconfigurations in the onboard user interface should be simplified compared to current ISS operations.

In general the automated handling of operations has to consider context information. Examples are state of the interfacing systems or mission status and priorities. This might be implemented by automated system handling and decision making using artificial intelligence.

Onboard and Ground automation

Onboard Subsystems automation is helpful in the deep space scenario due to the possibly reduced interactions with ground. Compared to Columbus a raise of onboard automation is needed per design, e.g. to easily perform reconfigurations considering all side conditions. This would include automatic handling of operations and appropriate crew information. Possible examples from Columbus are switchovers of the active Water Pump Assembly (WPA) or reconfigurations of the Condensate Water Separator Assembly (CWSA).

Also early indications of onboard problems are helpful in a deep space scenario. From this background the following subsystem monitoring approach can help the operations teams.

ATHMoS (Automated Telemetry Health Monitoring System) was developed at GSOC using Outlier Detection and Machine Learning. The paper [18] shows results and mechanisms to get early indications of future anomalous behaviour of telemetry parameters using past telemetry data.

Commanding Autonomy

In order to understand possible scenarios on commanding autonomy a dedicated look to Columbus commanding is done. This paragraph explains the Columbus commanding setup and design which could involve autonomous commanding. The practical handing is explained in the frame of current ISS Operations.

Commanding in Columbus can be done via single commands, Automated Command Sequences (ACS), Flight Automated Procedures (FLAP) or time-tagged commands. Also commanding using the Master-Timeline (MTL) application was originally implemented in the onboard software.

Columbus ground commanding from Col-CC is done using the Monitoring and Control System (MCS). Some of the commands trigger FLAPs or ACS, which are onboard command sequences or procedures executed in the Columbus Data Management System (DMS). Whereas an ACS is a fixed set of commands in the vital DMS, a FLAP is executed in nominal DMS and can consider constraints. FLAP Telemetry pre-checks and verifi-cations are possible to ensure proper execution. Both FLAP and ACS are fixed as part of the software design; changes require a new software upload. They are used for a dedicated set of activities that have a given structure, e.g. switchover to redundant hardware.

Time tagged commanding is a capability of the Columbus DMS to send commands with time tags to the onboard system. The command is stored in an onboard computer until execution time arises.

The Master Timeline was part of the Columbus Design and implemented in the Columbus Laptop Applications. The MTL consists of a series of Activities; each Activity contains a set of Entries with onboard commands. The MTL File includes all commanding details and needs to be uplinked to the Columbus DMS. The starting and stopping of the MTL can be done via onboard laptop and via ground commanding. The usage of MTL was intended for non-critical command operations in Columbus. A dedicated MTL viewer was designed to ensure situational awareness for the crew.

In day to day operations of Columbus commanding is currently done with single commands, partly triggering FLAP or ACS. The MTL and time tagged commands are not used by the Columbus Flight Control Team (FCT). The reasons are multi-fold and laid out hereafter.

A high percentage of communications coverage for commanding and telemetry is given for ISS operations using the TDRSS (Tracking Data and Relay Satellites System) network. FLAP and ACS are triggered with direct commands by the FCT where signal delays are limited to a few seconds. The operational boundaries are covered by procedures and proper timeline planning. Therefore the execution is operationally controlled and direct commanding is preferred by FCT. Time tagged or delayed commanding is not needed due to the given good coverage.

The Execution of MTL and time tagged commands would need to be monitored with respect to ongoing operations. Changes to boundary conditions would need to be constantly analysed. They could arise from timeline changes, crew interface or failure cases. The handling via MTL or time tagged commands increases the risk of getting out of sync and interfering with other activities by crew or ground. Therefore the FCT prefers the flexibility of direct commanding.

From a practical side the MTL command file would need to be properly prepared and uplinked. The daily preparation is time-consuming and complex and would most probably be possible offline or during night shifts. Experience shows that timeline changes during the day could invalidate the MTL frequently. Re-adjusting the MTL to ongoing operations would put additional load on the FCT.

In summary, the complex ISS operations is driven by multiple control centers, payload operations users and the crew interface. The flexible handling of activities in cooperation with the crew is possible and expected. Col-CC is staffed 24/7, has good communications coverage and prefers the direct commanding for Columbus, making use of FLAPs and ACS. This approach limits the effects of commands to a manageable time horizon and ensures situational awareness for all parties. Therefore time tagged commanding or the MTL are not used by Col-CC during operations. In the meantime the MTL software functionality was removed.

For habitat operations the onboard commanding could be more autonomous if implemented in a smart way. An integrated setup reflecting timeline, procedure execution status and other context information is needed, together with a simplified user interface. With this also a MTL type function could be facilitated in day to day operations.

Radiation

Radiation has effects on crew and on equipment. Crew effects are handled by the medical group who is providing medical operations expertise for ISS. For ESA, medical experts like Flight Surgeons and Biomedical Engineers located at the European Astronaut Center in Cologne are supporting Astronauts together with their international counterparts as an integrated team. The gained expertise will help for habitat operations.

Special attention should be given to the elevated radiation level for crew members. In the vicinity of the moon they are operating long-term outside the shielding of the earth magnetic field.

For subsystems the radiation has known effects. Especially electronic components and software can suffer from bit flips. DMS has experienced failures which are likely to be triggered by radiation. Impacts can be reduced by design (e.g. shielding) or by operations (e.g. preventive reboots).

For the predictability of radiation effects on equipment see also [20].

Summary and Outlook

The Columbus Control Center at GSOC has gained more than 10 years of experience in operating Columbus. During this timeframe a lot of knowledge was built up and preserved in the Columbus Flight and Ground Control Teams. Similarities for operations of the habitat of a future manned space station can be seen in the key Columbus Subsystems (ECLSS, TCS, DMS, COMMS, EPDS). Also differences of the setup and potential operations impacts have been identified and discussed. The habitat operations will need a higher level of autonomy for crew and systems. This can be ensured by onboard design, but will be complemented by a dedicated ground setup. Intelligent setups together with gained experience from ISS are the basis for successful future habitat operations.

Despite the quite long expected lifetime of the ISS until 2024 (maybe even until 2028 or 2030) GSOC is now starting to prepare itself for future tasks in the Post-ISS phase. From the current point of view there are two major contributions GSOC could provide for any post-ISS activities either in Low Earth Orbit or in an orbit around the moon:

- Setup and operating a Ground Segment interconnecting the multiple control centers and facilities. This Ground Segment can be based on Columbus Interconnection Ground Subnetwork (IGS) experience and potentially use already existing assets. Advanced features and capabilities like DTN will be provided for simulations and testing activities. Gateways for remote users will be provided as well.
- Operations of a habitation module, e.g. in a lunar orbit as part of the Lunar Orbital Platform – Gateway (LOP-G). The operation of the habitation module is very close to the Columbus Operations. That would allow bringing the many years of experience of the ongoing operations into the new project to a maximum extent. This includes the technical experience, planning aspects and the overall operations and safety responsibility for crew and vehicle.

GSOC has already investigated since some time operations scenarios beyond Low Earth Orbit (see [3] and [16]) and is currently intensifying the effort in the view of new opportunities ahead.

Hence, GSOC has setup a forward plan to investigate operations beyond LEO and for the Post-ISS phase. The next step is – in collaboration with Technical University Munich – to analyse mainly operations related topics for a potential future LOP–G mission. The following areas will be investigated in the first phase:

- Dedicated analysis of the system setup and the logistics of a manned space station in an orbit around the moon.
- Analysis of transfer orbits and flight trajectories needed for supplying a station around the moon.
- Development of a Concept of Operations with distributed control centers focussing on dedicated tasks

The work will follow and adapt its baseline to the ongoing advancements of the design and the chosen orbit of the envisaged LOP-G space station. It is planned to perform an independent analysis of the most recent design of the space station and develop some guidelines for a possible operations scenario. Depending on the results of the first phase it is foreseen to have a more in-depth analysis of the focal points in a second phase.

References

[1] Kuch, T.; Sabath, D.; Fein J.: Columbus-CC – *A German Contribution to the European ISS Operations*, IAC-05-B4.2.08, 56th International Astronautical Congress, Fukuoka, Japan, 2005

[2] Sabath, D.; Kuch, T.; Fein J.: *Das Columbus-Kontrollzentrum in Oberpfaffenhofen*, DGLR-2005-153, DGLR Jahrestagung 2005, Friedrichshafen, Germany, 2005

[3] Sabath, D.; Nitsch, A.: *Analysis of Operational Scenarios for Moon Related Space Flight Activities*, Proceeding of DGLR International Symposium "To Moon and beyond", DGLR-Report 2005-08, ISBN 3-932182-47-2, Bremen, 2005

[4] Sabath, D.; Nitsch, A.; Hadler, H.: *Columbus Operations – Joint undertaking between DLR and Industry*, SpaceOps 2006 Conference, AIAA 2006-5807, Roma, 2006

[5] Kuch, T., Sabath, D.: *The Columbus-CC—Operating the European laboratory at ISS,* 58th International Astronautical Congress, Hyderabad, 2007

[6] Sabath, D.; Hadler, H.: *Management and shift planning of the COL-CC Flight Control Team for continuous Columbus Operations*, SpaceOps 2008 Conference, AIAA 2008-3395, Heidelberg, 2008

[7] Sabath, D.; Schulze-Varnholt, D.: *First Experience with Real-Time Operations of the Columbus Module*, 59th International Astronautical Congress, IAC-08-B3.3.3, Glasgow, 2008

[8] Sabath, D.; Schulze-Varnholt, D.: *One Year of Columbus Operations and First Experience with 6 Persons Crew*, 60th International Astronautical Congress, IAC-09.B3.3.1, Daejon, 2009

[9] Sabath, D.; Nitsch, A.; Schulze-Varnholt, D.: *Highlights in Columbus Operations and Preparation for Assembly Complete Operations Phase*, 61st International Astronautical Congress, IAC-10.B6.1.5, Prague, 2010

[10] Sabath, D.; Nitsch, A.; Schulze-Varnholt, D.: *Changes in Columbus Operations and Outlook to Long-term Operation Phase*, 62nd International Astronautical Congress, IAC-11.B3.4.-B6.6.2, Cape Town, 2011

[11] Sabath, D.; Soellner, G.; Schulze-Varnholt, D.: *Development and Implementation of a New Columbus Operations Setup*, 63rd International Astronautical Congress, IAC-12.B3.4-B6.5.1, Naples, 2012

[12] Sabath, D.; Söllner, G.; Schulze-Varnholt, D.: *First Experience with New Col-CC Console Setup*, 64th International Astronautical Congress, IAC-13.B3.4-B6.5.3, Beijing, 2013

[13] Sabath, D.; Kuch, T.; Söllner, G.; Müller, T.: *The Future of Columbus Operations*, SpaceOps 2014 Conference, AIAA 2014-1618, Pasadena, 2014

[14] Baklanenko, M.; Sabath, D.; Söllner, G.: *New Col-CC Operations Concept and New Challenges*, 65th International Astronautical Congress, IAC-14,B3.4-B6.5,4, Toronto, 2014

[15] Leuoth, K.; Sabath, D.; Söllner, G.: *Consolidating Columbus Operations and Looking for New Frontiers*, 66th International Astronautical Congress, IAC-15,B3,4-B6.5,3, Jerusalem, 2015

[16] Bach, J. M.; Sabath, D.; Söllner, G.; Bender, F.: *Adapting Columbus Operations and Providing a Basis for Future Endeavours*, 67th International Astronautical Congress, IAC-16,B3.4-B6.5,2, Guadalajara, 2016

[17] Schlerf, A.; Sabath, D.; Söllner, G.; Verzola, I.: *Implementation of an Additional Command System, Pathing the Way for New Tasks at Col-CC*, 68th International Astronautical Congress, IAC-17,B3.4-B6.5,3, Adelaide, 2017

[18] O'Meara, C.; Schlag, L.; Faltenbacher, L.; Wickler, M.: *Automated Telemetry Health Monitoring System at GSOC using Outlier Detection and Supervised Machine Learning*, SpaceOps 2016 Conference, AIAA 2016-2347, Daejeon, 2016

[19] Bach, J. M.; Sabath, D.: *horizons Mission – Challenges and Highlights*, 69th International Astronautical Congress, IAC-18,B3.4-B6.4,3, Bremen, 2018

[20] I.Verzola, I; Lagny, A.E.; Biswas, J.: *A Predictive Approach to Failure Estimation and Identification for Space Systems Operations*, SpaceOps 2014 Conference, AIAA 2014-1722, Pasadena, 2014

[21] Pierce-Mayer, J.: *Techniques for the Use of Video over Delay Tolerant Networks as a Tool for Safety and Situational Awareness*, 66th International Astronautical Congress, IAC-15,B3.9-YPVF.2, Jerusalem, 2015

[22] Pierce-Mayer J.; Peinado, O.: *DTN-O-Tron: A System for the User-Guided Semi-Autonomous Generation and Distribution of CGR Contact Plans*, IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE), Orlando, Florida, 2015

[23] Pierce-Mayer J.; Peinado, O.: *DTN Network Management,* SpaceOps 2016 Conference, AIAA 2016-2367, Daejeon, 2016