The Compasso Mission: Operational Strategies for Validating Optical Technologies On-Board the ISS

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Abstract

Compasso is an in-orbit validation mission to demonstrate new optical technologies for future GNSS constellations. It is hosted on the Airbus Bartolomeo platform on the International Space Station with a launch scheduled for December 2025. The paper illustrates the main design choices with regards to Compasso operations and the ground segment that where made in the current preliminary design phase of the mission. One of the primary mission goals of Compasso, which drives the operations design the most, is the demonstration of bi-directional time transfer via optical links from space to ground. The paper illustrates the general challenges for the optical links, specifically the ones that come with human spaceflight. Under any circumstances it is strictly prohibited that the crew safety is jeopardised by radiation emitting activities, which is why the current link planning strategy and architecture is designed to ensure that no laser activity is planned and executed during any safety critical activities on board the ISS via a fourfold redundant inhibit concept. Since Compasso is dependent on the Bartolomeo, Columbus and ISS infrastructure in general, the paper also shows how Compasso will be integrated in all these programs. An example for this is the TM/TC data routing via the ISS assets. Besides that, the operations concept shows how a payload on the ISS can be operated safely and how the in-orbit validation will be coordinated and conducted.

Keywords
Optical Link Planning, In-Orbit Validation, Mission Planning, Human Spaceflight, Ground Segment Design, Operations Concept

Abbreviations
International Space Station (ISS); Global Navigation Satellite Systems (GNSS); German Space Operations Center (GSOC), Optical Ground Station (OGS); Laser Communication and Ranging Terminal (LCRT); Extra Vehicular Activity (EVA); Bartolomeo (BTL); Bartolomeo Control Center (BTL-CC); Columbus Control Center (Col-CC); Mission Operations System (MOS); Facility and Communications System (FCS); Mission Data System (MDS); Facility and Communications System (FCS); Flight Dynamics System (FDS); Link Planning System (LPS); Telemetry (TM); Telecommand (TC); Data Handling System (DHS); Interconnection Ground Subnetwork (IGS); Flight Operations Team (FOT); On-Board Computer (OBC); Tracking and Data Relay Satellite System (TDRS); Packet Utilization Standard (PUS); Multi Purpose Communication Computer Service (MPCC): Mission Control System (MCS). Low Earth Orbit (LEO); Geostationary Orbit (GEO); Flight Operations Procedure (FOP)

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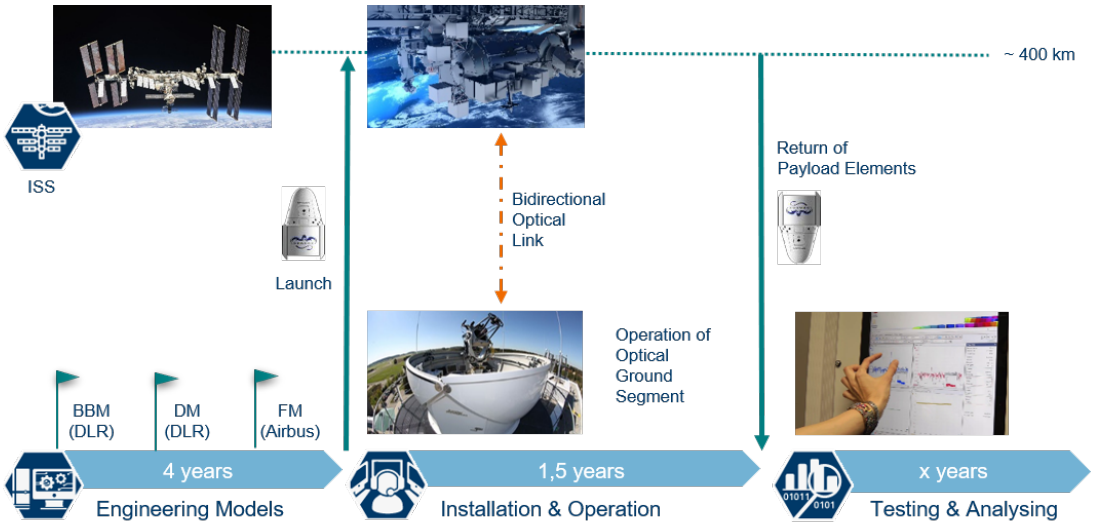

Fig. 1 High level schedule of the Compasso mission

I. Mission Overview

Global Navigation Satellite Systems (GNSS) are indispensable for virtually every aspect in our modern world. Like other established GNSS, the European Union funded Galileo GNSS is exposed to increasing user demands and precision requirements. A transition from classical microwave to optical based technology can help to meet these new market needs in a number of ways and to elevate Galileo to the next step of its evolution [1–3]. Optical systems stand out, for instance, because of their improved frequency stability. A clock based on this technology can improve the precision of the position signal. Optical laser terminals are another optical technology, which can be used to achieve higher ranging accuracy via bi-directional laser links for orbit determination combined with a very high downlink data rate [4]. The Compasso mission [5], led by the Galileo Competence Center, is dedicated to perform the In-Orbit validation of the optical core technologies. The main mission goals of Compasso demonstrate:

- the feasibility of operating (long-term, robust) optical iodine clocks and frequency comb in space (ISS) for future GNSS application
- optical data transfer via a bi-directional optical link
- demonstrate optical frequency transfer via a bi-directional optical link
- time transfer via a bi-directional optical link
- ranging via a bi-directional optical link
- characterize the influence of the atmospheric turbulence on the optical frequency and time transfer as well as on ranging via a bi-directional optical link

Compasso will be hosted on the Airbus Bartolomeo (BTL) platform that is attached to the Columbus Module of the International Space Station (ISS). The payload of the mission comprises several optical key technologies, i.e. two absolute optical frequency reference systems based on molecular iodine, one optical frequency comb and one bi-directional laser communication and ranging terminal (LCRT). A reference laser unit, a positioning, velocity, attitude and time system as well as an onboard computing and data storage system completes the core elements of the overall payload.

COMPASSO's optical frequency references are based on Doppler-free spectroscopy of molecular iodine. Both references are using lasers operating at 1064nm that can be stabilized on the same or on different (nearby) hyperfine transitions of molecular iodine. The optical frequency comb, the first to ever fly in space, transfers the frequency stability of the two references from the optical to the radio frequency domain. In addition, the frequency comb can be referenced to an on-board microwave reference consisting of a high-performance GNSS disciplined oven-controlled crystal oscillator, thereby allowing multiple comparative measurements to assess the frequency stability in different frequency regimes and in the relevant time periods of the references/clocks. A bi-directional LCRT enables time and frequency transfer between the stable frequency references and clock signals on the ISS and on Earth - together with high-precision ranging (distance measurement) and data communications. By comparing the absolute frequency of the iodine reference operated in orbit with the corresponding value on the ground, an analysis of the gravitational red shift can even be used as a test of the general relativity theory. The core components listed above will be integrated and installed on the Bartolomeo ArgUS Multi-Payload Carrier. The Compasso flight software, which runs on the ArgUS operating system, is provided by the DLR institute for software technology. To ease command and control and to employ standardized ground systems, the flight software implements the Packet Utilization Standard (PUS).

Fig. 2 Bartolomeo platform attached to the Columbus Module on the ISS. Courtesy NASA/Airbus.

Figure 1 illustrates the high-level mission schedule. Currently, the project is in phase B for which we are working on the preliminary operations concept and design of the grounds systems. The ongoing payload development will have three models that have increasing capability and maturity (a breadboard, a development and a (proto) flight model). From an operation perspective, the development model will mark the kick-off for the operational product development such as flight procedures etc. The majority of the operational product will however be created with the proto flight model. The launch of Compasso is scheduled for December 2025. The payload will be launched pressurized onboard an ISS visiting vehicle, transferred to the outside through the Bishop airlock and installed with the ISS robotic manipulator system. After preparation of Compasso on the ISS, we expect a six month long in-orbit commissioning phase for the payloads, ground systems and specifically the optical links. There will be two nominal operations phases. Mission Phase I is dedicated to conducting the optical links between the LCRT and the optical ground station (OGS) located at the German Aerospace Center site in Oberpfaffenhofen, Germany. Mission Phase II will demonstrate the long-term stability of the optical clocks. The reason for having two separate nominal mission phases lies in the high safety requirements for human space flight. Any radiation emitting device that is potentially hazardous to the ISS crew safety has to be switched off during e.g. extra vehicular activities (EVAs) or capsule dockings. As the LCRT and the optical clocks are connected to the same power line, which in addition acts as the laser safety inhibit, each LCRT switch off immediately results in a switch of the optical clock. To guarantee that the optical clock can run for three months consecutively, the LCRT will be physically disconnected from Compasso so that it is not a safety concern anymore. In contrast to any satellite mission, the ISS setup opens up the possibility to return Compasso back to Earth so that e.g. degradation of the payloads can be assessed on ground. Since Compasso will be mounted on the Airbus Bartolomeo platform (see Figure 2), located on the outside of the ISS Columbus module, a tight integration of the Compasso mission within all of these programs is essential for its success. The German Space Operation Center (GSOC) will be responsible for coordinating and conducting Compasso operations. A prime example that demonstrates the necessity of a close collaboration is the scheduling and execution of the optical space to ground links, where interfaces between the different parties need to be established to exchange e.g. the ISS planning information, resources allocations (power, data link bandwidth) and the coordination of the laser safety inhibits. Similar to the planning coordination, the routing of telemetry (TM) and telecommands (TC) between the mission control center and the Compasso space segment relies on the infrastructure and coordination of several parties: TM/TC and administrative status messages are routed via the ISS and BTL assets to the GSOC mission control systems, where the communication path includes, for instance, the BTL and Columbus onboard systems, then NASA's Tracking and Data Relay Satellite System (TDRS) for the space to ground radio frequency link, the ESA Ground Segment with Columbus Control Center (COL-CC) and the BTL Control Center (BTL-CC). Section IV gives an in-depth discussion of the full TM/TC data link, which is also depicted in 6. In the following chapters we will illustrate the challenges and our current solutions for the ground segment architecture, the planning of the optical links and the general operations concept in detail.

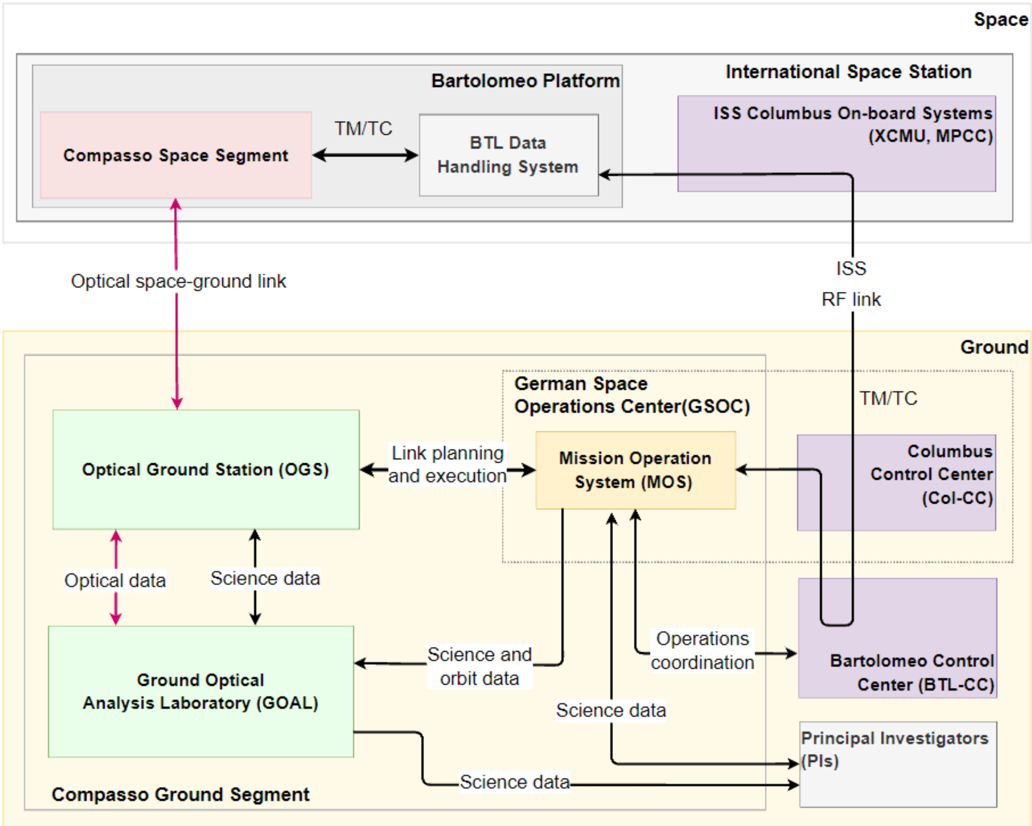

Fig. 3 High level system overview

II. System Architecture and Ground Segment Overview

Considering all the parties of the Compasso project, its no surprise that the overall system architecture is rather involved. To break it down, we -as usual- distinguish first between the space and ground segment, as depicted in Fig. 3. To clearly define the DLR Compasso system boundaries, we further separate the architecture into the DLR Compasso elements and the subsystems under the responsibility of third parties such as the BTL platform or all infrastructure related to Columbus and the ISS. BTL and ISS components provide the communication line used for the space to ground communication and resources such as power to Compasso. On the space segment side, the data stream goes through the Columbus on-board systems and terminates at the data handling system (DHS) of the BTL platform (BTL-DHS). The BTL-DHS receives and manages the data-streams of all payloads connected to the BTL platform, i.e. it also routes the Compasso data to the Compasso DHS. On the ground segment side, the Col-CC is special in this setup as it is collocated with the Compasso operations site at GSOC but is only indirectly involved in the Compasso project. The Col-CC operations [6, 7] manage and provide resources to the BTL platform, provides the basic communication infrastructure on ground and the mission planning information. Yet, the Compasso Mission Operation System (MOS) does not interface with Col-CC directly. In our setup, BTL-CC acts as a proxy for planning information and operations coordination between the ISS entities and the user payloads. BTL-CC also manages and distributes resources provided to the BTL platform and the user payloads.

On the Compasso ground segment side, there is the Ground Optical Analysis Laboratory (GOAL), which is primarily responsible for the science evaluation. The GOAL hosts and operates the ground counterparts of the optical clocks and the feed lasers for the OGS. The OGS itself is installed on the roof of the DLR institute for Communication and Navigation at the DLR site in Oberpfaffenhofen. Executing an optical laser link requires considerable effort, not only technically, but also in terms of coordination between different parties, especially regarding safety. The primary interface for the OGS to get, for instance, planning information, the ISS trajectory for pointing the OGS laser towards its target and for the link scheduling is the Mission Operations System (MOS).

The MOS (orange box in Fig. 3) also located at the DLR's Oberpfaffenhofen site is set up and operated at GSOC. Its primary task is the command and control of Compasso. It is comprised of the following five distinct subsystems that cover all necessary functionality for operating Compasso:

Flight Operations System (FOS)

FOS covers all technical and organizational aspects related to Mission Operations, e.g. flight operations team planning, flight operations team training, operations planning, operations organization, console design and organization, flight procedure development and testing.

Mission Data System (MDS)

MDS is responsible for telemetry and telecommand processing, distribution and archiving during mission operations. The MDS is thus closely related to FOS by providing the tools required for conducting operations. Here, we strongly build on the GSOC heritage systems that cater the needs of Compasso with only minor project specific adaptions such as a TM/TC data stream adapter. The TM/TC system is comprised of the GECOOS MCS [8] (itself a derivative of SCOS 2000) in conjunction with Satmon for monitoring telemetry in real-time. Protos [9] serves as a frontend for GECCOS. It provides an automation capability (especially with respect to automated processing of optical link requests) and serves as a tool for flight operations procedure development and execution. Next to the software mentioned, a multitude of other tools are maintained at GSOC and are employed as part of the MOS subsystems and to support mission operations.

Facility and Communications System (FCS)

All facility, network, and IT infrastructure activities fall into the domain of the FCS. Specifically custom implementation of the Compasso TM/TC stream endpoints and handover of the data to the multi-mission operational networks are tasks of the FDS. Being integrated into the GSOC multi-mission environment allows the project to use the flight proven network infrastructure that is maintained for all flying missions.

Flight Dynamics System (FDS)

While FDS is usually responsible for the calculation of a spacecraft's orbital motion, for Compasso it will perform all computations required for optical links. For this it considers the LCRT's position and orientation aboard the ISS (via the GNSS and attitude data from Compasso) and the position and orientation of the OGS. Furthermore, the FDS generates precise orbit products for evaluating, for instance, the precision of the optical ranging measurements.

Link Planning System (LPS)

The Compasso LPS benefits from various optical communication missions that are successfully operated at GSOC [10–12]. The LPS software maintains the mission timeline with respect to planned optical links and processing of incoming requests for new optical link sessions. It relies on calculations from FDS for providing the command system with the data required for instantiating the FOPs for optical link execution.

III. Optical Link Planning and Execution

One of the main challenges for operations and the ground segment architecture is the optical link planning for the space to ground links. The overall design is based on the generic optical link planning system [13] which is tailored to the project specific needs of Compasso. Figure 4 illustrates the architecture for Compasso including the major internal and external interfaces. In contrast to the traditional planning of radio frequency links, optical links are severely impacted by weather conditions that cannot be predicted well in advance. Therefore, the planning system has to be able to react on last minute changes that can either be ingested by the user or by an automatic weather forecast. At its core Compasso uses the Reactive Planning framework [11, 14] which is specifically designed for such a use case. Every input update triggers an immediate planning model update that gets checked against all constraints and then communicated to the users. Since Compasso has a high TM/TC link availability, Reactive Planning can play at its full strength and allow input and model updates until very shortly before the actual execution of the optical link. Currently, the input deadline is set to one hour before the on-board execution of the first link TC. The deadline also serves as a trigger for the automated export and upload of the link TC.

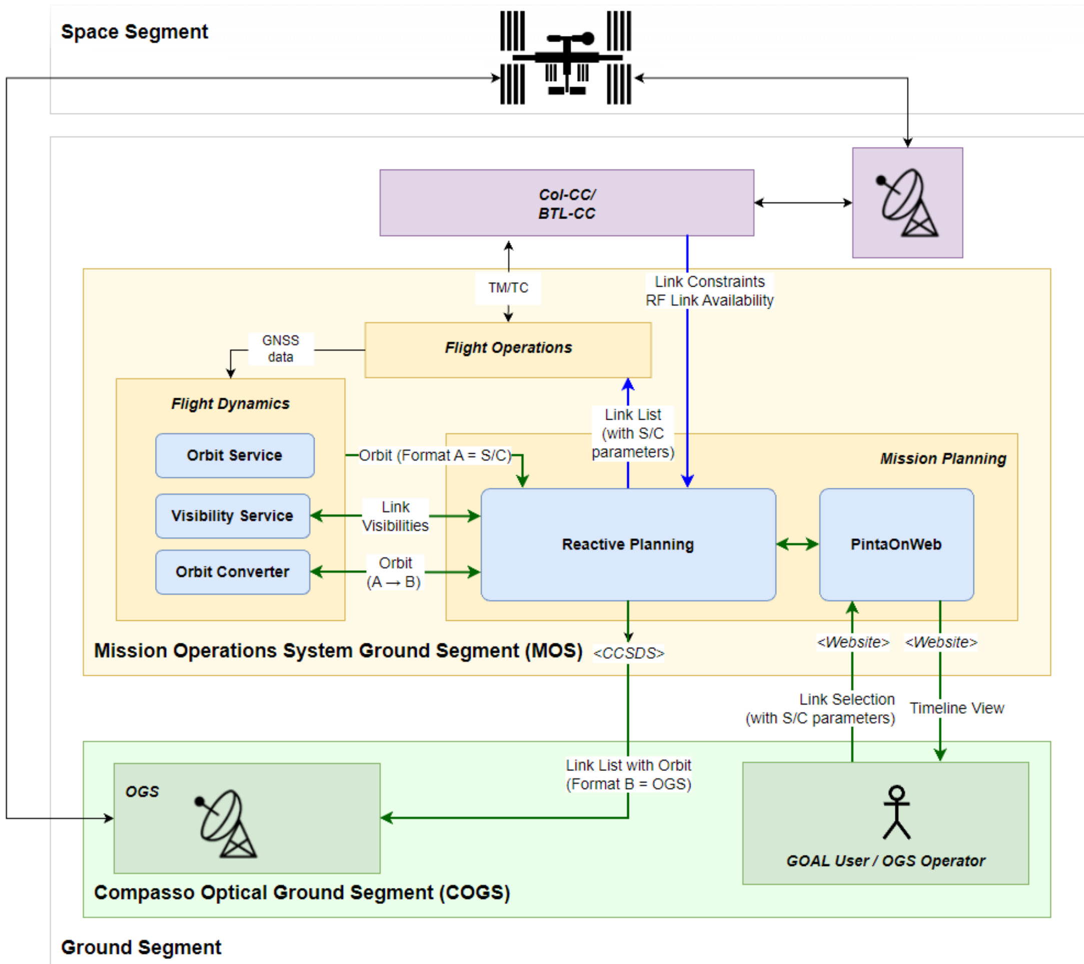

Fig. 4 Compasso optical link planning overview. The green arrows represent the generic link planning interfaces. All Compasso specific interfaces are depicted as blue arrows.

Another complexity of optical links is the precise knowledge of the trajectory for the visibility prediction of the LCRT from the OGS, which must be way more precise than for RF links as the laser beam is much narrower. In the special case of Compasso the pointing gets even more complex since the LCRT is mounted comparably far away from the center of gravity of the ISS. Even small attitude deviations might make a significant impact for the required pointing precision. On the space segment side this is achieved by carrying a star sensor and a GNSS receiver that forward the position and attitude information to the laser terminal which calculates the pointing autonomously. On ground the Compasso orbit (ISS orbit including the displacement of the LCRT) is predicted by the GSOC flight dynamics system from Compasso's GNSS data considering NASA maneuver information. The orbit is then provided to the OGS for the pointing.

Another major design driver are the ISS safety rules imposed on radiation emitting activities, for which Compasso can build on experience gained from ColKA [15, 16]. To ensure crew and ISS safety in general, laser activities are strictly prohibited, for instance, when visiting vehicles are approaching, the robotic arm on the ISS is maneuvering or EVAs are performed. Although the Compasso laser will be shielded by a baffle to largely reduce time restrictions (sparing out docked vehicles), each activity has to be coordinated. To do so, BTL-CC filters and provides the required ISS planning information to GSOC's link planning system. The filtering will be done according to flight rules, which have to be established in the next mission phases. Only a condensed timeline with safety inhibit activation and deactivation times is forwarded to the GSOC link planning system. In addition, the radio frequency link availabilities are exchanged via the interface because real-time TM is required at least for the commissioning phase of the optical links. To guarantee that no laser activity jeopardizes safety, three redundant hardware-based safety inhibits, which will be controlled by

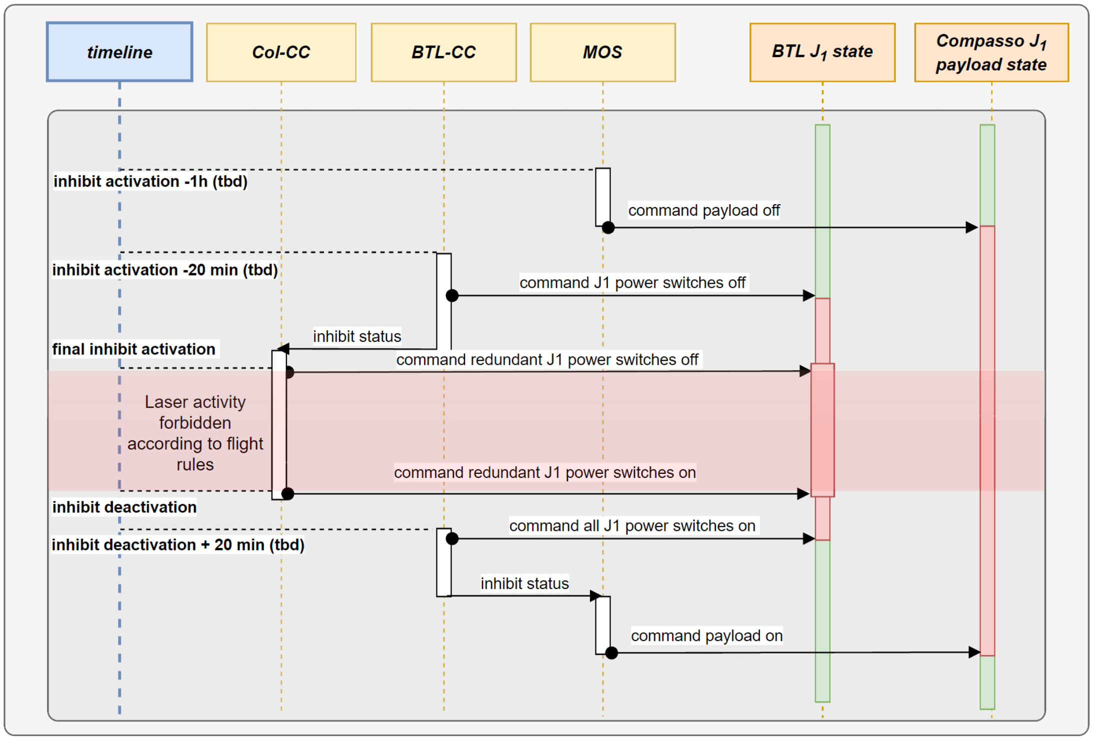

Fig. 5 Workflow for the safety inhibit activations and deactivations, illustrating at which time the involved parties change the state of their inhibit.

BTL-CC and COL-CC, are in place to de-activate the LCRT during inhibit times. Since only two powerlines supply Compasso, one for the onboard computer and essential units and one for the majority of the payloads, each inhibit activation mandates a commanded, graceful shutdown of basically all payloads. To efficiently re-activate the payloads, the whole on-board configuration will be tracked on ground to automatically power-up the systems in the desired state. Figure 5 illustrates the nominal workflow for activating and deactivating the safety inhibits.

To summarize the overall planning workflow, the first step is the prediction of Compasso's trajectory by the GSOC FDS. Based on the orbit, the FDS computes or updates visibilities between the space-borne LCRT and the OGS. The link planning system matches the visibilities with all ISS constraints and produces a list of actual link opportunities that satisfy all constraints. To allow the OGS team to allocate their resources well in advance and resolve operational conflicts early on, the list of opportunities always covers a planning horizon of 20 days. Since changes in the planning input are likely to happen within the planning horizon (updates in ISS constraints, new and more precise orbit prediction), the link planning system always updates the planning timeline when new information is available. Based on the link opportunities, researchers can request time slots, select the type of link experiment, parametrize the links TC parameters and even cancel scheduled links. The OGS team can interact with the Compasso Link Planning System via the Pinta On Web web application [17]. Finally, the commands are exported and sent to space at least one hour before the actual link.

IV. TM/TC Data Routing

As the overall setup already indicated, the space to ground connection follows a complex path through the systems of the parties involved. TM/TC data from the Bartolomeo platform hosting the Compasso payload is routed via Columbus/ISS assets through a VPN tunnel on the Interconnection Ground Subnetwork (IGS) to the IGS access point in Bremen and the BTL-CC located there (the orange Compasso TM/TC communication channel in Fig. 6). The IGS was set up and is operated by Col-CC. The Multi-Purpose Communication Computer Service (MPCC) provided by the ESA Ground Segment exposes a virtual ethernet extension from Bartolomeo systems aboard the ISS to network clients connected to the IGS. Utilizing the MPCC, Airbus as the owner and operator of the Bartolomeo platform provides a

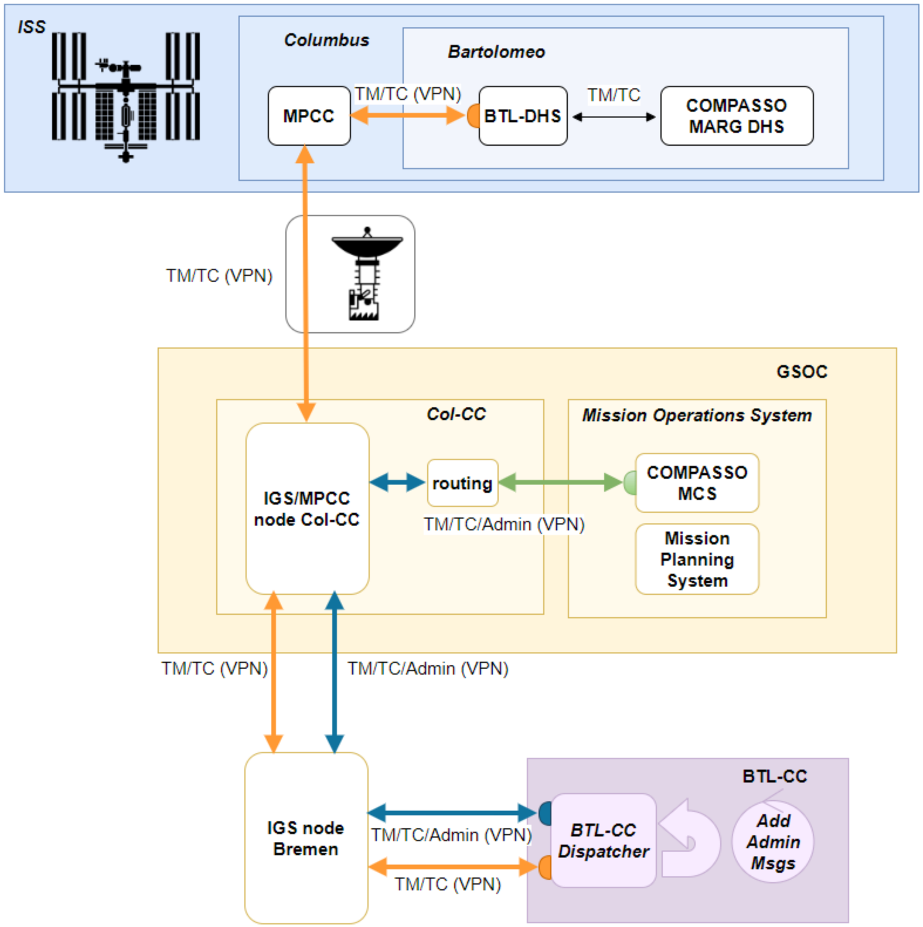

Fig. 6 TM/TC data routing through Col-CC, BTL-CC and the ISS assets. The orange connections represent the standard VPN MPCC connection for BTL payloads. All Compasso specific data connections are depicted as blue arrows.

direct tunnelled connection to the Compasso on-board computer (OBC). As the blue communication channels in Fig. 6 show, data for Compasso is again routed from BTL-CC TM/TC through the IGS to the IGS access point at Col-CC in Oberpfaffenhofen. Through their partially shared local area network, Col-CC routes the VPN tunnel from its IGS node directly to the Compasso MCS at GSOC. Thus, for TM/TC on-ground data routing, Compasso relies on the Airbus BTL-CC and Col-CC.

V. TM/TC Data Stream

The TM/TC UDP data stream provided by the Compasso OBC is spread over two separate connections, a bidirectional one for telecommands and their acknowledgments and one for telemetry. In the latter two virtual channels are available, one for real-time telemetry and one for dump data. The Bartolomeo platform transmits telemetry from all its hosted experiments bundled in one stream, i.e. addressed to one port, until the stream is split after reception at BTL-CC. At the BTL-CC Dispatcher the complete Compasso TM data stream is assembled by injecting into the TM/TC stream from the Compasso OBC UDP packages containing NCTRS administrative messages on a separate channel. The messages are compliant with [18] and inform Compasso MCS about TM/TC link health and TC uplink status, information only available at the first end point of the VPN tunnel at BTL-CC. Thus, BTL-CC provides information that in conventional satellite missions is provided by ground stations. Compasso MCS employs a new UDP adapter to the GECCOS NCTRS interface tailored to the specific three-channel structure of the Compasso data stream.

The Compasso OBC expects incoming TC transfer frames compliant to ECSS standard [19] and generates TM transfer frames with a primary header and data field according to ECSS standard [20] with a communication link control word (CLCW) attached to each enclosed downlinked package. Communications Operation Procedure-1 (COP-1) from [19] is employed with the AD service and the expedited BD service to ensure a sequence-controlled data interface and safe TC uplink or to forego sequence control if needed. TM packages are generated compliant to PUS-A [21]. PUS services supported include (with service numbers in brackets) Telecommand Verification (1), Device Command Distribution (2), Housekeeping and Diagnostic Data Reporting (3), Event Reporting (5), Memory Management (6), Function Management (8), Time Management (9), On-Board Operations Scheduling (11), On-Board Storage and Retrieval (15), Test (17), Event-Action (19), and mission-specific services.

VI. Operations Concept

Despite flying in a low earth orbit (LEO), Compasso has a high availability for telemetry and telecommand because of the almost continuous TDRS connectivity of the ISS. The operation concept is therefore more comparable to the operations of a geostationary (GEO) satellite. To cater for this, a multidisciplinary operations team, with experts from GEO and LEO missions, as well as Columbus, has been assembled and it is foreseen to integrate the operations into GSOC's multi-mission operations for GEO satellites. The proven automated concept of operations for the European Data Relay System (EDRS) [22], established and in use since more than seven years, provides the heritage the Compasso operations will be based on.

Once Compasso is launched and connected to the Bartolomeo platform, which is coordinated by Airbus, the GSOC operations team will conduct the first operational "activation and startup" phase to check out the Compasso system. The system will be monitored by the control center's automated health checking and a spacecraft controller on a 24/7 basis. However, being part of the GEO multi-mission environment, the controller is shared with other missions and will not actively monitor Compasso. He/she will be alerted by the automated checks on spacecraft events and telemetry limit checks via an audible alarm and will react according to pre-defined procedures. During this phase, a Flight Operations Team (FOT) will be conducting the startup of Compasso during their shifts. The team will be composed out of GSOC's spacecraft operations and ground operations teams as well as of experts from the space components' manufacturers. One member of the FOT will be available outside of the shifts as an on-call to be reachable by the spacecraft controller in case of unforeseen events. Before transitioning to routine operations with regular optical links, the commissioning of the payloads and the ground systems required for conducting the experiments will be performed. During this phase a fluid transition from mainly manual operations to the automated operations of the routine phase will be performed.

During routine operations the Compasso payload will be operated by an automated system, with human interaction only necessary following an anomaly either in the ground processing or the space segment. Spacecraft operations are based on Flight Operations Procedures (FOP). These FOPs include all telecommands necessary to command the spacecraft, all telemetry parameters to be verified and additional information such as expected behavior, optional breakpoints and operational criteria. ProToS [9], a ground segment component developed at GSOC, will be used to automatically execute the FOPs developed by the FOT. ProToS is capable of executing FOPs either requested by the as well automated link planning system described earlier, or triggered manually by the spacecraft controller. This semi automatically execution enables the controller to perform other tasks after triggering the FOP's execution while the tool follows the procedure's instructions and alerts in case of issues in the procedure [23].

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