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Towards Generic Planning of Optical Links

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Abstract

The paper at hand presents our concept for upcoming space-ground optical Mission Planning systems at DLR GSOC. In cooperation with TESAT we have more than 15 years of operational experience for optical links. We have thoroughly discussed challenges and needs of optical mission planning systems to enable potential customers for deployment of full end-to-end systems. While earlier systems such as TDP-1 (Technical Demonstration Project) or EDRS (European Data Relay System) had individual requirements and interfaces, the new system is capable to consider ad-hoc additional requirements and generic interfaces. This flexibility is a big step towards our goal of a fully interoperable control center infrastructure. We show in the paper at hand how the new concept will be implemented and validated. The developed architecture is based upon the "Program for INteractive Timeline Analysis" (PINTA). PINTA enables the User in this specific use case to manually schedule links from a set of pre-calculated visibilities and trigger an automated link export for both optical terminals (on ground and in orbit) for their execution. At first, PINTA will be used offline for scheduling the links of the new DLR optical ground station Almería; in the frame of the Global Optical Ground Station Network (GlobeON). The subsequent development step will result in embedding these functionalities in another architecture which builds upon the new generic interfaces, replacing PINTA with the GSOC's generic Reactive Planning framework and its frontend PintaOnWeb for visual support, modification and analysis. This tool suite will allow for automatically triggered incremental planning runs immediately upon reception of new input (e.g. orbit updates, spacecraft and ground station unavailability) instead of manually initiated runs or semi-automated planning at fixed intervals. Finally, more elaborated interactions with the spacecraft and ground station operations and the prediction as well as real-time information about local weather conditions are aimed to be included into the automated planning process.

Keywords: Mission Planning and Scheduling, Optical Inter-Satellite Communication, Optical Space-To-Ground Communication, Link Management, Direct-To-Earth Scheduling, Reactive Planning

Acronyms/Abbreviations

Coarse Pointing Assembly (CPA)
Consolidated Prediction Format (CPF)
Consultative Committee for Space Data Systems (CCSDS)
European Data Relay System (EDRS)
European Space Agency (ESA)
Flight Dynamics System (FDS)
Flight Operations System (FOS)
Geostationary Orbiting (GEO)
Global Optical Ground Station Network (GlobeON)
German Space Operations Center (GSOC)
Global Navigation Satellite System (GNSS)
International Space Station (ISS)
Inter-Satellite Links (ISL)
Kongsberg Satellite Services (KSAT)
Laser Communication Terminal (LCT)
Low-Earth Orbiting (LEO)

Mission Operations Center (MOC)
Mission Planning System (MPS)
Network Operations Center (NOC)
Optical Ground Station (OGS)
Orbit Ephemeris Message (OEM)
Photo Images Cross Laser (PIXL)
PintaOnWeb (PoW)
Program for Interactive Timeline Analysis (PINTA)
Satellite Control Center (SCC)
Service Management Utilization Request Format (SMURF)
Space-To-Ground (Optical) Link (SGL)
Technical Demonstration Project (TDP)
Telecommand (TC)
Telemetry/Telecommand (TM/TC)

1. Introduction

Laser communication links have become an important operational alternative for experimental [1] and commercial programs [2, 3]. After an initial phase of technology demonstration, laser links are an operational alternative to radio frequencies for inter-satellite [4, 5] as well as for space-to-ground communication [6, 7, 8]. While the onboard hardware develops further and fits missions down to CubeSat size [9], so do ground systems evolving to implement the special features of optical communication. Space-to-ground optical links (SGLs) for commercial application demands, as RF also does, reliability. This can be achieved using a flexible link planning system which enables users and operators to modify the planning and the corresponding operational products as responsive as possible. Furthermore, the ground system as a whole, Mission Operations Systems for planning and scheduling of optical links are gradually evolving from "first of their kind" to more generic tools that may be used for multiple missions. The TDP-1 program is a clear success of the demanded evolution. The TDP-1 operational planning system has been the footprint for the Inter-Satellite Link (ISL) commercial applications and recently also for the SGLs, since its Mission Planning system has recently been replaced completely to make use of our most recent generic Reactive Planning framework [10]. This has been the result of combining experience and heritage with the mission operations, planning engineers and customers support of several projects. The new planning system is built upon several missions with Laser Communication Terminals operated at DLR GSOC such as TerraSAR-X, EDRS, or TDP-1 [11].

Moreover, the concept is fully applicable to future missions with LCTs on LEO/MEO satellites. For example, CubeSAT missions for in-orbit test, verification and demonstration or the project Compasso, one of the upcoming customers of the Bartolomeo platform onboard the ISS. On top of that it will be also applicable to the fully operational work horses for the data transmission to ground of upcoming Earth observation satellites.

On ground, DLR/GSOC (in cooperation with DLR's Responsive Space Cluster Competence Center) currently brings a number of LCTs serving as ground stations for satellite data up- and downlink into operation. The first terminal of GlobeON is built for final deployment in Almería, Spain. Further extensions are planned to be located in South Africa in collaboration with the DLR Institute for Communication and Navigation (IKN; as the principal developers at DLR for LCTs), and through mobile and immobile terminals in Oberpfaffenhofen, Germany [12]. In addition, DLR is part of the European Optical Nucleus Network [13] together with ESA and the KSAT network. The overall goal of such joint activities is a network of laser terminals which provide a standardized link service from geographically distributed sites which could in particular decrease unavailability phases due to cloud coverage significantly [14].

2. Current Link Planning Solutions at GSOC with Operational Experiences

The GSOC experience for operating and especially planning and commanding the links of Laser Communication Terminals (LCTs) builds upon a variety of several spacecraft missions. The different roles of DLR/GSOC were already discussed in [11]. The involvement of the Mission Planning team and our tool suite in these processes varies: In low-earth orbit, the first LCT that was served was the secondary payload onboard TerraSAR-X for inter-satellite experiments with the NFIRE satellite and SGLs [15]. Here, the planning and commanding of the terminal payload was done non-automated by the designated subsystem experts. The same, at least at the current stage, applies for the Photo Images Cross Laser (PIXL) CubeSat terminal [16] for which the Mission Planning team serves by providing the general planning and scheduling software component within the ground segment, but the experimental terminal operations are conducted by the operations experts of GSOC and IKN in the first stages before thinking about involving more automated processes there.

Completely different is the scenario for two geostationary communication missions: For the TDP-1 mission onboard of Alphasat I-XL, the Mission Planning team at GSOC established the planning system to support the mission with the full range of serving the relevant interfaces to an automated planning algorithm deconflicting the timeline of laser communication links, up to commanding the terminal operations with the correct parametrization. Here, already a second generation of the planning system is in action since August 2021 based on our novel generic planning framework, while the original versions based on former generic core components were operational beginning from 2013. Both systems and the transition are discussed in [10]. The main focus of TDP-1 was demonstrating the feasibility of inter-satellite and geo-to-ground laser communication and data forwarding, as well as evaluating the instrument capabilities and other technical aspects in space. It still serves as a testbed for testing novel operations modes and system operations scenarios of the involved GEO and LEO LCTs, with e.g. geo-to-plane communication on the plan for next year, and for gathering long-term experience.

Building on the first in-orbit experience of TDP-1, a non-experimental geostationary data relay mission was established which makes use of optical communication: EDRS, the European Data Relay System of Airbus and ESA, until now mainly used by the EU within the Copernicus program. It currently consists of EDRS-A as one of the payloads of the EUTELSAT-9B satellite, and EDRS-C on its proprietary satellite. For both combined, the Mission Planning team at GSOC developed and maintains the highly reactive Link Management System (LMS), embedded within the missions DPCC (Devolved Payload Control Center, EDRS-A), resp. SCC (Spacecraft Control Center, EDRS-C) [17]. Here, pre-planned links from the Mission Operations Center (MOC) at Airbus Ottobrunn are checked for conflict-freeness relative to certain constraints, value-added with invoked flight dynamics information regarding the visibilities and trajectories for the instrument orientation during the links, and planned together with the necessary surrounding regular spacecraft tasks, incl. the cross-check and alignment for mutual feasibility. The mission is characterized by an extensive number of different interfaces to be served for reporting. The planned links serve inter-satellite LEO-to-GEO and also GEO-to-LEO communication allowing for data transmission and satellite tasking via the "Space Data Highway".

All of the involved space-borne LCTs currently in operations were built by TESAT [2, 7, 18, 19, 20]. For TDP-1, TESAT even directly is our customer for supporting their operations, see above. Throughout the years of the lifetimes of the different projects a good mutual understanding and valuation of each other's competences was developed. This also led to cooperation for researching and developing future fields of applications, e.g. in the area of responsive space capabilities, and the technologies needed for reliable laser communication services. Together we have consolidated our common vision about the ground operations systems for larger constellations of ground and space assets of LCTs should behave and which services such a generic Link Planning System should be provided – to serve best ground segment entities, optical ground station providers as well as the mission operation segments of the customer space- or aircraft.

3. Challenges and Needs of Optical Link Planning Systems

For developing a „Generic Link Planning" system apart from the existing rather mission-specific heritage systems, we have identified the challenges and specified top-level functional requirements of such a system, for which an outline can be found already in [21].

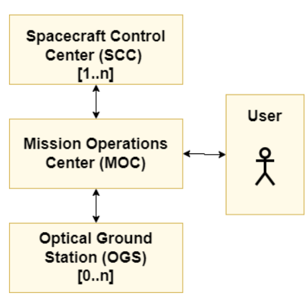

Fig. 1. The MOC as the central entity between the "User", one or more SCC(s), and, optionally the OGS(s).

In principle, one can distinguish between two types of optical links: ISLs (LEO-to-LEO and LEO-to-GEO) and SGLs. The link planning system should be capable of both types of link planning scenarios. A simplified architecture of the link planning system can be seen in Figure 1. The mission operations center (MOC) is the central entity of the link planning. It hosts the link planning tool which is designed to be the single contact point between the user, the space segment control center(s) and the ground station(s). Users in this context in general are coordinating entities, or can either be end users, i.e. "customers" of the complete service, as well. In an ISL scenario the MOC in general interacts with more than one SCC. In a SGL scenario, the MOC interacts with at least one SCC and at least one OGS.

The following section analyzes the main challenges of Optical Link Planning and derives the resulting requirements to such a system from a user's point of view, merely concentrating on the planning of SGLs.

3.1 Special challenges of Optical Link Planning

For each link planning system, independently of the used communication technology (optical or radio frequency) the users need to be offered possible link opportunities (calculated based on visibility and the mission's specific capabilities), and it has to be ensured that the two terminals being involved get the necessary information to perform a link.

In comparison to RF communication, for which a correct orientation of the transmitting and receiving antenna can be established relatively easy (depending on the bandwidth and spacecraft capabilities of course), for optical links a more detailed knowledge and more exact calculations are necessary. For instance, the beam width of the TESAT LCT-135 optical terminal is only 7µrad, while the one of the TESAT CubeLCT is 97µrad. The receive field of views are in the order of 2.5 mrad (LCT-135) and 1° (CubeLCT). To achieve sufficient open loop pointing knowledge, of 1mrad, the LCTs need to know not only the host orbit and attitude, but also the counter orbit within a small position error. Therefore, the requested orbit knowledge accuracy, especially for LEO orbits, is not possible within one- or two-weeks planning cycles but requires up-to-date information of at most one to two days in advance of the link.

Another special challenge for SGLs is the impact of the atmosphere, in particular the weather condition. In the case of RF links, very hard weather conditions (e.g. heavy rain and thunderstorms, or snow on the antenna) can already interrupt the communication, especially when using high bandwidths. The optical links are even more sensitive, due to the fact that an optical link through the atmosphere needs more than 3dB margin for achieving a successful communication. Since weather conditions cannot be known weeks in advance, this constraint shall be mitigated via short-term reactiveness of the planning system, the inclusion of weather forecast data and using ground station clusters with a high site diversity, i.e. to have the OGSs located such that the probability that at least one at a time has a cloud-free sky above is increased. Regarding the weather forecast, the current recommendation is not to use predictions extended over more than one day [7, 18].

3.2 Requirements for Optical Link Planning Systems

Based on these two main challenges, orbit/pointing accuracy (for ISLs and SGLs) and weather forecast incl. side diversity (for SGLs), the following top-level requirements have been identified regarding the interfaces and the information to be exchanged between the different entities. (In addition, there also exists a necessary interface between the spacecraft and the laser communication terminal onboard which also provides information regarding host attitude and timing and the corresponding accuracy, but which is out of scope here.)

The overall context shall be the following:

From the SCCs and the OGSs (resp. their control centers again, of course) the planning tool receives the orbit information and specific satellite or station constraints, and it delivers them the information about scheduled links incl. necessary parameters. Additionally, the local OGS (or the collocated weather forecast station) provides weather information for the assessment of potential upcoming weather constraints. For the interface to the Users, the link planning tool processes the information provided by the other interfaces and generates the link opportunities list. The Users can select the links that suit them best and send link requests accordingly. As long as not automated itself and being covered by respective planning rules within the Link Planning system, this interaction (and the follow-up automated other interfaces) need(s) to be repeatable as often as necessary in order to ensure that the Users have the best-possible knowledge of the OGSs´ visibility. Current planning systems (e.g. in-between TDP-1 or EDRS and the Sentinels' SCCs) are based on weekly schedulers and thus are not flexible enough to cope with the necessities of SGL planning or other novel conceptual ideas of new optical constellations.

Then these major technical requirements for a demonstration of the Generic Link Planning can be formulated:

- Interfaces: The MOC/tool shall enable a direct interface to each satellite SCC, optical ground station terminal (or OGS CC) and User for exchanging the corresponding information.
- Non-regular information exchanged between interface partners:

  - The MOC/tool shall receive from the SCC the following information: orbit information incl. its accuracy.
  - The MOC/tool shall receive from the SCC the following information: spacecraft non-operational zones at least on a weekly basis.
  - The MOC/tool shall receive from the OGS the following information: position and accuracy, data rate from/to spacecraft.
- Regular information exchanged between interface partners:
  - The MOC shall receive from the OGS the following information: connectivity, buffer size and storage duration, availability and weather status.
- Operational products that shall be generated by the MOC:
  - Templates for the user link request and Sequences of Events (SoEs) for internal and external activities and users.
  - These planning products provided by the MOC/tool for the ground and space terminals shall be symmetric for the space and ground segment as far as possible.
  - A timeline definition for the feedback to the customer and for the provision of the internal products shall be agreed upon.
- Functionality of the MOC/tool itself when information to be updated:
  - Pre-planning: The MOC/tool shall be able to generate a weekly (TBC) pre-planning which allows the internal user to consolidate/verify the availability of the optical terminals according to all the constraints. This pre-planning shall only be available for internal use for getting an insight into the terminals' general availability.
  - Final planning: The MOC/tool shall provide a final planning on a daily basis. The final planning contains all the final planning products.
  - Re-planning: The MOC/tool shall allow a re-planning of the activities, i.e. after the pre-planning or the final plan generation until up to one hour prior to the execution of the links.
  - Update of the slot list: The MOC/tool shall update the slot lists on an appropriate time scale, including the short-term availability of the OGS, actual weather status, and, optionally/envisaged for future upgrades of the tool, weather forecast. Both, the weather status and the forecast might either come from meteorological 'third parties', or from the OGS directly.
- Furthermore, the MOC/tool shall be independent of the project or users, i.e. a standalone concept/equipment is envisaged.

4. The new Mission Planning Concept to Plan Optical Links

The following subchapters illustrate the system architecture and give an overview about the main interfaces.

4.1 Architecture of the Link Planning System

The architecture of our Link Planning Prototype can be seen in Figure 2. It has evolved from the „Generic Link Planning" overall set-up as outlined in chapter 3. Here, one SCC and at least one OGS is intended to be involved. The link planning system is the core part of the MOC. There, the central Mission Planning component is connected to the Flight Dynamics services. Thus, necessary automated interfaces can be found both within the MOC and in-between the Mission Planning component and the SCC as well as the Mission Planning component and the OGS. These are described in the following section. In addition, there are the manual interaction possibilities of the user, however these were already described sufficiently within the requirements and their realization will be shown in chapters 5 and 6 again.

4.2 Interfaces of the Link Planning System

As visualized in Figure 2, the idea is to implement generic interfaces as far as possible. Furthermore, the MOC is designed in a way, that all users interact only via one interface with the link planning system. Over that interface user requests are sent. The new link planning system then deals with several interfaces which are described in the following subchapters. Via these interfaces, information e.g. about LCTs and OGSs are exchanged and processed, and the Flight Dynamics services are included. It is foreseen that the user gets all results and/or feedback about link execution as described in chapter 3.

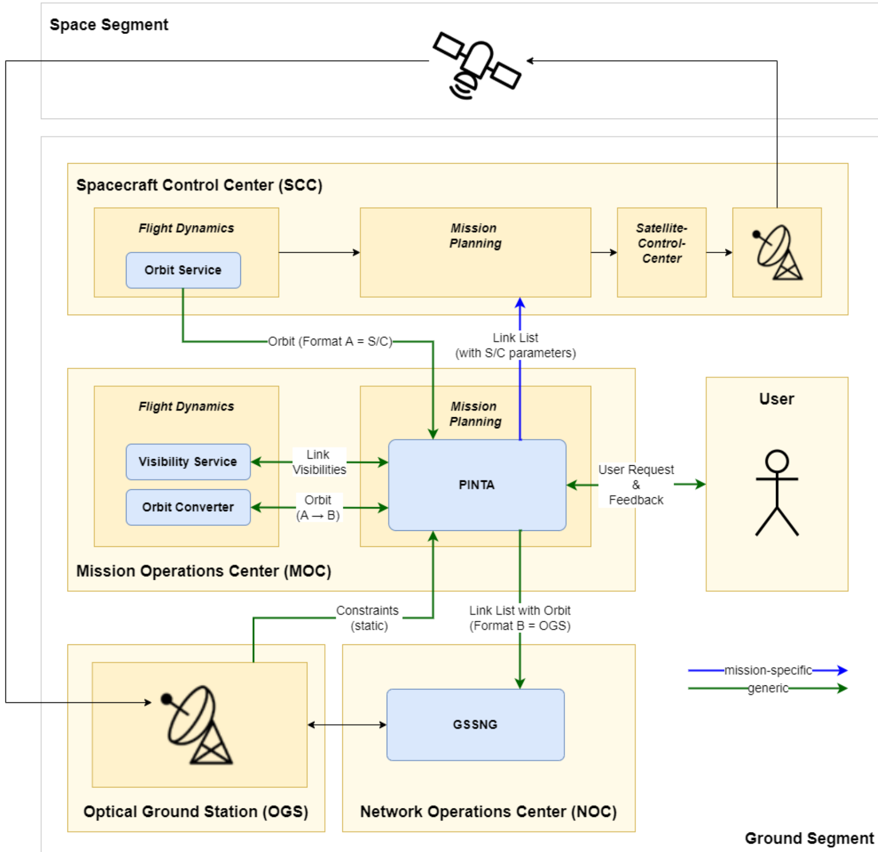

Fig. 2. Architecture and interfaces of the Link Planning Prototype, with a central Mission Planning component and Flight Dynamics services forming the MOC.

4.2.1 Interfaces within the MOC: The "new" Flight Dynamic Visibility and Link Support Services

Within the framework of the optical link planning development at Mission Planning, the Flight Dynamics group kicked off the development of a generic Flight Dynamics service, to support Mission Planning with the link planning and execution. For this, a Message Queue Telemetry Transport (MQTT)-based microservice is under development, which is generic since it is applicable to all SGLs and ISLs in GEO and LEO, but also since the in- and output of the service allow many degrees of freedom for the user, e.g. different orbit and attitude data types.

The Flight Dynamics service consists of two sub-services: the visibility service and the link-support service, as depicted in Figure 3. The first service, the visibility service, covers the link planning. The user requests the visibility opportunities for a certain time window (e.g. two weeks), based on a configuration and constraints (e.g. laser communication terminal-specific constraints) together with orbit and/or attitude input for both LCTs. The response of the service gives a set of visibility windows, providing start and stop times of each window and, optionally, the Coarse Pointing Assembly (CPA) angles and additional flight dynamics support information (e.g. distance between terminals, azimuth and elevation angles). The second service, the link-support service, covers the link realization and provides products for the link initialization and the LCT commanding process. The user requests orbit data (e.g. Consolidated Prediction Format (CPF), Orbit Ephemeris Message (OEM), Chebyshev polynomials) for (a) specific visibility window(s), based on the same inputs as for the visibility service with the addition of a list of the selected links to be realized. The response of the service is the orbit data for both LCTs as ephemeris or Chebyshev polynomials, and, optionally, an updated CPA angles list.

At this stage, a prototype of the visibility service is developed. This prototype is based on the visibility calculation between the PIXL-1/CubeL satellite and a ground station, with the possible input orbit data type restricted to Two-Line Element (TLE) information. This prototype contains the full logic chain of the visibility service from request to response, although the input options, such as orbit and attitude data of the spacecraft, are restricted.

For the future, the first goal is to extend the existing visibility service by allowing the full range of input and output options, e.g. OEM and CPF data as input to the visibility service. The second goal is to implement the link-support service, which should primarily provide CPF or TLE data to the user. The next step is then to introduce a test campaign where the Flight Dynamics services are stress-tested, where operational links can be performed between PIXL-1/CubeL and an optical ground station at DLR.

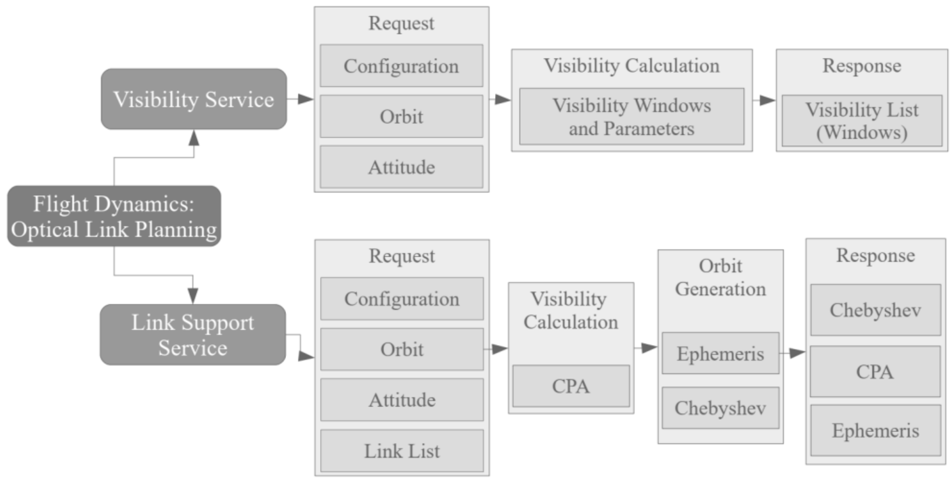

Fig. 3. Architecture of the Flight Dynamics Services.

4.2.2 Interfaces from the MOC to external entities: The Interfaces to the Optical Ground Station (OGS) and to the Spacecraft Control Center (SCC)

As already mentioned in [21], the interfaces to the OGS will be based on the Consultative Committee for Space Data Systems (CCSDS) Service Management Utilization Request Format (SMURF) and we will have the chance to extend former specifications for radio frequency communications with the special needs of optical communications like e.g. the exchange of atmospheric condition information.

It is intended to have a regular exchange between the MOC and the OGS in both directions. The needed inputs of the MOC are on the one hand e.g. the OGS position and accuracy, its connectivity and availability. On the other hand, there should be external weather forecasts and the OGS weather status updated as often as possible, if feasible, at least every hour.

As well as the interface between the OGS and the MOC, the interface between the SCC and the MOC will be based on a CCSDS format, here the Mission Planning & Scheduling Service Specification, for communicating e.g. non-operational times or other constraints via planning requests, and link lists via plan distribution. Furthermore, the SCC provides the orbit and attitude information via the CCSDS Navigation Working Group products. While the manual interaction is using the Mission Planning component's graphical UI's native functionalities of course, the automated part of the interaction between the User(s) and the MOC will also be covered by CCSDS Mission Planning & Scheduling Service operations.

5. The Link Planning Prototype for GlobeON

The new mission planning concept for a link planning tool has the goal of processing all data exchanged over all considered interfaces discussed in the previous chapter.

To demonstrate the link planning concept, we designed a link planning prototype based on the generic planning tool PINTA [22], which has been developed at DLR/GSOC and is applied for a large variety of planning projects. It is already used for solving planning and scheduling problems incl. the scheduling of the space- as well as ground-based entities needed for the missions operated at GSOC and beyond (see applications explained in [22]). With our experience about different link planning solutions on the one hand, and about ground station scheduling on the other hand, it was decided to use PINTA as the basis of the first generic link planning tool developed by DLR/GSOC.

The concept is set up for the PIXL-1 mission, which has the goal to demonstrate a data transmission from a CubeLCT to an Optical Ground Station (OGS), here the Global Optical Ground Station Network (GlobeON) [21]. The detailed architecture of the prototype for the GlobeON link planning system could already be seen in Figure 2.

The prototype uses PINTA as the generic planning tool and single point of contact between the user and the rest of the planning system.

5.1 Setup and Integration of the FDS Visibility Service in PINTA

The link planning prototype is set up as a PINTA planning model. In a first step we implemented a project specific plugin, with which one can configure necessary inputs like ground stations (specified preferably via latitude, longitude and altitude), insert latest spacecraft orbit information e.g. TLEs and additional constraints to generate a link visibility request. A possible setup scenario is shown in Figure 4.

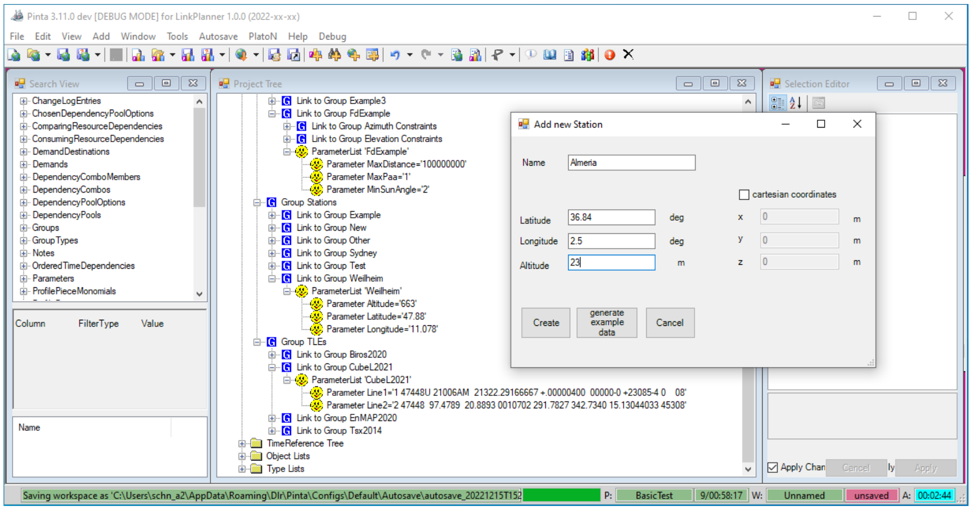

Fig. 4. Setup of the Link Planning Prototype using PINTA.

With the data set up in the scenario, the FDS Visibility Service can be called within PINTA. The link visibility request follows the visibility service schema. It is containing generic setup data as well as constraints and the orbit information of source and target. Note, that here the source and target may be space- as well as ground-based LCTs. PINTA gives the user an interface to choose between different sources and targets as well as the time window. To keep the setup generic, we implemented the possibility to switch between a SGL and an ISL.

The user can trigger the calculation of the visibilities on demand. The process takes place using the latest orbit and attitude information of the satellites resp. terminals, the static information for the terminals (e.g. mounting matrix, …) and the static configuration of the individual ground station (e.g. location, capability, …). After receiving the request, the FDS visibility service calculates all possible visibilities between the two LCTs. These visibilities are then inserted into the model and can be displayed on the PINTA timeline.

5.2 Scheduling and Request of Optical Links

After insertion of the visibilities into the PINTA timeline, the users can choose from the calculated visibilities the ones they want to request. Figure 5 shows the visibility list for PIXL-1 with two OGSs, one in Weilheim and one in Almería. In this example, the user requested two consecutive visibilities on Dec 20th 2022 with a start time around 9 pm.

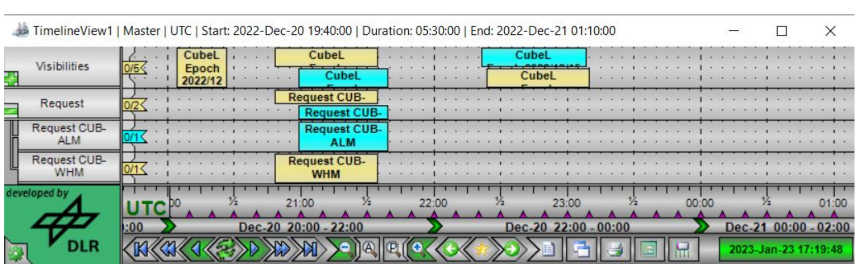

Fig. 5. PINTA timeline showing the visibility list of the satellite PIXL-1 (CUB) with (and the requests of) the two OGS Weilheim (WHM) and Almería (ALM).

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By using the existing PINTA Ground Station Schedule Request Exporter, the information about the acquisition of signal (AOS) and loss of signal (LOS) of all selected pre-calculated visibilities is exported. This request is then sent to the Network Operations Center (NOC), here GSOC's Ground Station Scheduling Next Generation (GSSNG) which exchanges information with the OGS. The OGS collects all user requests and gives feedback about the feasibility of the link request. When the link can be established, it will be added to the link timeline of the spacecraft. The schedule for the individual satellites/terminals and ground stations thereafter are sent to the SCC which considers the information within its own planning and finally transmits the information, i.e. commanding for the link, to the spacecraft. In the end both optical terminals have the information about the link to be established, may initialize their systems at the link time and establish the link at the given time.

6. Generic Link Planning Concept for the Future

The prototype concept presented in the chapters before is already kept as generic as possible, to allow for a wide applicability. However, it only forms our first step towards real "generic link planning". As a follow-up to the successful validation of the concept and its functionalities as described in the previous chapter, the goal is to integrate them into our Integrated Terminal and Antenna Scheduling tool suite, InTAS. This implies for example, that PINTA as the basic tool will be replaced by GSOC's new generic mission planning software PintaOnWeb [23], and that the functionalities for optical communication will be shared with our other generic contact and operations planning and scheduling.

Here, only a short overview of InTAS shall be given, and we show how the whole concept will be applied in another future project:

6.1 Integration of the Link Planning Concepts in the InTAS System

InTAS is a software currently developed by the GSOC Mission Planning team. Its goal is to have only one generic tool which handles the complete communication scheduling/unscheduling process and related interfaces of the commanding and data transmission contacts for all missions operated at GSOC. For now, this only includes ground station contacts in the radio frequency bands. However, since in the backend our Reactive Planning framework with the underlying Plains library is used, constraints concerning optical links (e.g. for cloud avoidance) can easily be modeled and considered for the planning of ground station contacts, too. Furthermore, as the related interfaces to the FDS are established then as well, not only SGLs will be served, but planning the whole range of communication contacts of spacecraft missions and the ground stations of the different types is envisaged with finally also covering ISLs. For the user interface the PINTA successor PintaOnWeb is utilized to provide a web-based solution for inspection and manual interaction with the planning model. Short term off-nominal changes are expected to happen in the ground station contact plan for the missions which profit from the visual, interactive interface for the users and might afford manual adaptations.

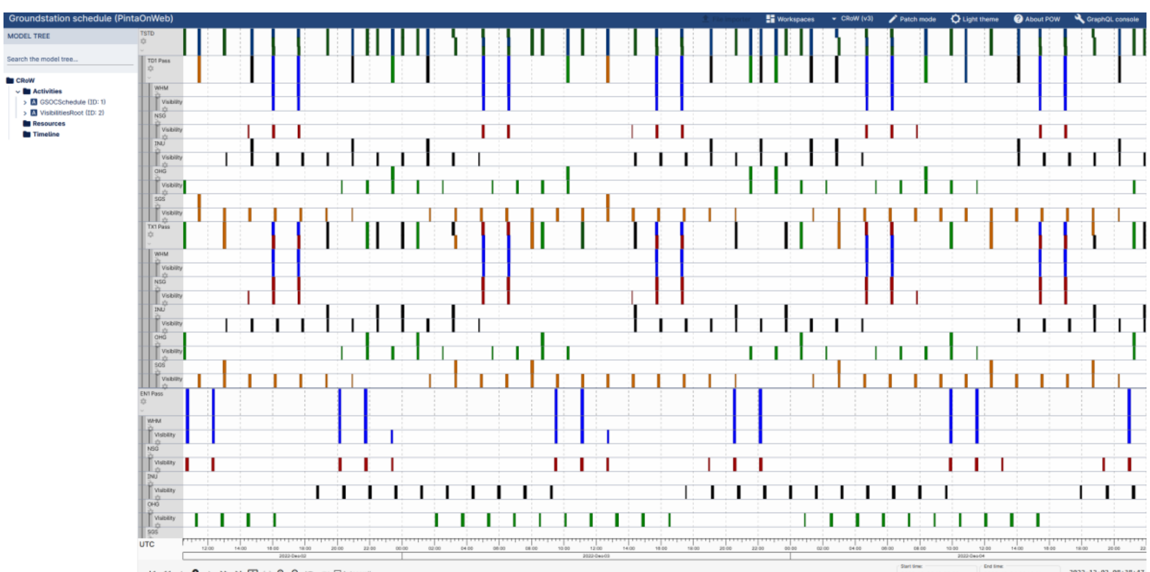

Fig. 6. PintaOnWeb Website displaying the scheduled passes and satellite visibilities for a set of missions flown in GSOC.

Figure 6 shows the PintaOnWeb "graphical view" of InTAS which displays the visibilities and scheduled contacts of different missions. In its current state, the user can easily see the upcoming passes of every mission and the visibilities between each satellite and each of its potential ground stations. This information can then be used to request additional passes, for instance to handle contingencies for a specific mission. In the nominal case, PintaOnWeb is only used as an "inspection window" for the fully automatic planning system running in the background. Reactive Planning handles the interface and the scheduling of the passes required for the daily operation of the satellite missions and automatically requests the passes from the ground station providers via a defined machine interface. The missions are notified about the scheduled and confirmed passes and can plan according to that schedule. The same applies for notifications about unavailabilities.

6.2 The Link Planning System for Compasso

One of the first missions that will use the new generic optical link planning tool as its core will be Compasso. Compasso is a payload that will be mounted on the outside of the International Space Station (ISS) on the Airbus Bartolomeo platform in order to demonstrate new optical technologies for future GNSS constellations in space [24, 25]. Its launch is scheduled for the end of 2025. The main goal of the mission is to demonstrate that precise time signals from novel optical clocks can be transferred from space to ground via optical links. The OGS is located at the DLR site in Oberpfaffenhofen, Germany.

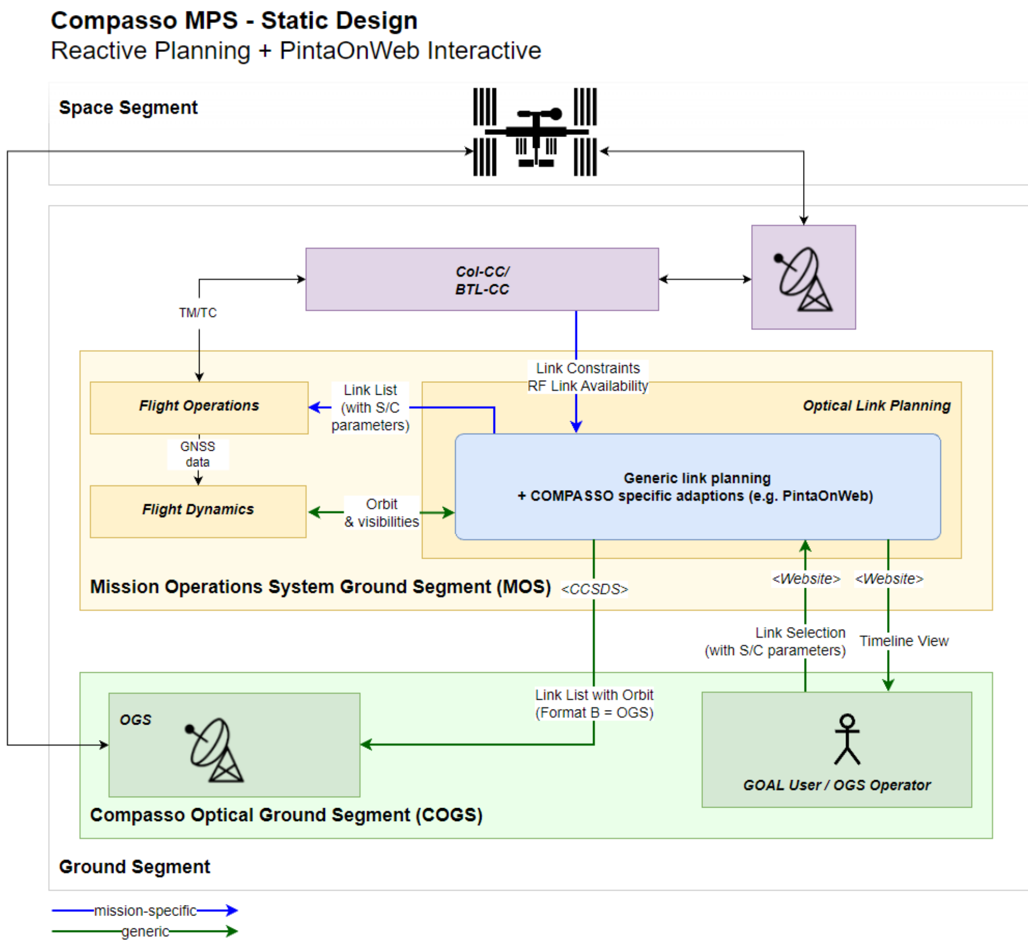

Fig. 7. The Compasso link planning system architecture.

Besides the challenges that were already mentioned, such as short reaction times due to changing weather conditions and the precise pointing requirements, Compasso adds another level of complexity to the mission planning system: Since human spaceflight demands to ensure crew safety at all times, any radiation emitting activity is prohibited when e.g. extra-vehicular activities are scheduled or during vehicle docking maneuvers. To not jeopardize ISS safety, the link planning system has to interface with the Bartolomeo Control Center for ISS planning information and updates. The planning information exchanged contains a timeline with timeslots where laser activity is strictly forbidden and thus the LCT has to be switched off via command. Furthermore, the interface is used to retrieve communication outages of the RF SGL. Figure 7 shows the overall architecture of the Compasso MPS, which is based on the generic planning tool tailored to the Compasso needs and interfaces.

The Compasso MPS will use PintaOnWeb as the ordering interface for the OGS team, which also represents the end users of the Compasso experiments. With PintaOnWeb, the OGS team can select the presented link opportunities, schedule and cancel time slots, and set all telecommand (TC) parameters for the desired link configuration.

Since Compasso has a high telemetry/telecommand (TM/TC) link availability, the Reactive Planning service in the backend of PintaOnWeb 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.

7. Conclusion and Outlook

In this paper, we illustrated the generic challenges of optical link planning for constellations especially in the planning of SGL missions, listed the main requirements, described the prototype of our generic Link Planning tool and outlined the way forward. We expect that the prototype gathers initial results with the PIXL-1 mission, before further extending and integrating the functionalities within InTAS. As the link planning concept is set up very generic, the tool can be easily adapted to other optical missions as we have shown here for Compasso.

The Generic Link Planning service is applicable to all different types of optical communication such as LEO-LEO, LEO-GEO and SGL. It will be integrated with the new generation of scheduling "conventional" RF links in the generic GSOC Mission Planning application InTAS. Within InTAS as well as for Compasso, instead of PINTA its follow-up PintaOnWeb and the use of the Reactive Planning framework in its backend will form the basis of the future generic planning for optical links. This further fosters the automation of the planning and interaction processes in addition to all the specific functionality and already existing usability advantages of the presented concept. We are looking forward to the advancing implementation stages and all the upcoming applications within GSOC missions and projects and beyond.

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