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Concept for generic agile, reactive optical link planning

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Abstract

The paper presents our concept of a generic, flexible, highly responsive, evolvable end-to-end link planning system, which enables its users to modify the planning and corresponding operational products even on late notice. The main challenges of optical communication, the orbit and pointing accuracy, and the influence of atmospheric weather conditions result in the need for having an automatically triggered reactive incremental planning immediately upon reception of new input (e.g., orbit or cloud prediction updates) instead of planning runs at fixed points in time following a predefined pattern. For direct-to-Earth communication, the local weather conditions are a major challenge which may lead to ground station link outages. This is where ground station clusters with a high site diversity come into play. To address the risk of data loss as well as increase the availability and resilience, the automated ingestion of information from the ground terminals with an ad-hoc, reactive re-planning is one possible solution. In this sense, cloud forecasts and statistics can be considered and integrated into the planning model and processes. We outline how we aim to integrate atmospheric condition monitoring concepts, that we already have implemented for Earth observation acquisition planning purposes, into our generic link planning tool suite. Our tool can be used for different types of missions. It shall evolve to an automated link planning system based on the Reactive Planning Framework combined with PintaOnWeb, a frontend for visual support, modifications, and analysis.

Keywords Mission planning and scheduling · Free-space optical communication · Space-to-ground communication · Cloud coverage handling · Site diversity · Reactive planning

1 Introduction

Satellites play a crucial role in providing real-time information for applications, such as weather monitoring, disaster response, remote sensing, and global communications. While the amount of data transmitted from space to ground is increasing exponentially over the past decades [1], low data latencies in satellite downlinks are vital to ensuring timely access to critical information. For instance, during natural disasters, such as hurricanes or earthquakes, rapid access to satellite imagery and telemetry can enable faster decision-making for emergency response teams.

Laser links are an important operational alternative to radio-frequency (RF) technologies for satellite communication. The main advantages of optical against RF communication are a larger variety of possible bandwidths resulting in higher data rates and less interferences, and a secure data transmission, i.e., higher security against interception, due to the narrow transmission cone [2, 3].

For satellites in low-Earth orbit, the data latency can either be improved using a geostationary relay network such as the European Data Relay System (EDRS), or by utilizing several ground stations at locations carefully selected to match the specific service-level requirements. Depending on the size, geographical distribution and whether RF and/or laser communication is used, such networks can typically achieve a throughput in the order of some 100 GB/day [4]. In addition, inter-satellite links may decrease the time between the satellite payload's measurement and the arrival of the relevant information at the customer further [5].

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DLR GSOC, in cooperation with TESAT, has more than 15 years of operational experience in optical communication, with missions like TerraSAR-X, EDRS [6], PIXL-1 (Photo Images Cross Laser), and TDP-1 (Technical Demonstration Project) which carry laser communication terminals (LCTs) operated at GSOC [7]. For the specific involvement of GSOC's Mission Planning team tool suite in recent laser communication projects, see [8].

Our goal is to implement a generic, flexible, highly responsive, evolvable end-to-end link planning system (LPS), which enables the users' resp. operators to modify the planning and corresponding operational products even on late notice. We describe the actions already taken and the path toward the overall goal in this paper: In Sect. 2, we first show the optical link planning challenges, followed by Sect. 3 with a description of our consequent generic link planning approach. In Sect. 4, we present the implementations we have already made and address adaptations to them. As an important example there, we outline a new, agile approach of direct-to-earth (DTE) link operations for TDP-1. The planning system of TDP-1 is built on our Reactive Planning framework [9] and could become a blueprint for commercial link planning applications for inter-satellite links (ISL) as well as DTE laser communication. Section 5 concludes with a summary and outlook toward our goal of a fully generic link planning system.

2 Special challenges of optical link planning

A detailed analysis of general challenges in space-based optical communication can be found in [2]. In the following, we will focus on the specific link planning challenges, namely, the orbit accuracy, atmospheric weather conditions, and the impact of real-time predictions.

Orbit accuracy: For RF communication, a correct orientation of the transmitting and receiving antenna can be established relatively easily (depending on the bandwidth and spacecraft capabilities). In comparison, establishing optical links requires more detailed information and calculations with higher precision. For instance, LCTs need to know not only their host orbit and attitude, but also the counter orbit within a small position error. Furthermore, a better orbit accuracy can also lead to less conservative planning margins (see, e.g., for the grazing altitude in GEO-LEO links [10]), which in turn increase the mission yield.

Weather conditions: In the case of RF links, very hard weather conditions (e.g., heavy rain and thunderstorms, or snow on the antenna) can interrupt the communication, especially when using high bandwidths. Optical transmissions are more sensitive to weather conditions: In particular, clouds practically render links impossible, but also optical turbulences may degrade the communication.

Real-time predictions: Optical link operations strongly depend on short-term information about appropriate terminals and atmospheric conditions. Most importantly, the following timing constraints apply:

- The required orbit knowledge accuracy (see above), especially for LEO orbits, requires up-to-date information of at most 1–2 days in advance of the link.
- The quality of weather forecasts decreases quickly with forecast time. For instance, forecasts for local cloud coverage only yield an improvement over statistical climatology data for lead times of 2 days or less (see, e.g., [11] for the European Centre for Medium-Range Weather Forecasts (ECMWF) model). Reliable forecasts thus require even shorter forecast periods, optimally in the order of only a few hours.
- Additional, 'short-term' predictions refer up to 1 h in the sense of the Consultative Committee for Space Data Systems (CCSDS) recommendations for atmospheric characterization and forecasting [12].

Altogether, these constraints are not achievable within 1- or 2-week planning cycles, but selecting the best OGS for a link requires a highly reactive planning system.

2.1 Cloud coverage handling: forecasts and statistics

Latest weather forecasts of the ground station sites play a crucial role in the management and optimization of space links shortly before a planned start of track. Studies from [13], with focus on deep-space data downlink, estimated already for Ka- and X-Band a data return increase for weather forecast-based link configuration of up to 25%.

For more realistic planning prior to the availability of local measurements, weather forecasts and/or statistical data can also be considered. For example, the "Gloria" telescope network [14] used 3–72 h forecasts of cloud coverage and atmospheric seeing from the Global Forecast System (GFS) [15] to schedule astronomical observations to the site with the most favorable expected conditions [16, 17].

For the GSOC Mission Planning systems, we use the ICOsahedral Nonhydrostatic (ICON) model of DWD (Deutscher Wetterdienst) and Max-Planck Institute for Meteorology, a global and regional numerical weather prediction model for short- and medium-range weather forecasts. It has a geographical resolution of approximately 13 km. Atmospheric analysis, which also includes cloud (ice) mixing ratio fields, is computed every 3 h, starting at 0 h UTC. There exist different cloud products, e.g., (high/low/mid-level) clouds in %, total cloud cover in % or cloud mixing ratio in kg/kg. For more information, see [18].

Furthermore, since the end of the 1970s, meteorological satellites construct global cloud climatologies of our planet. Several international efforts regularly improve and extend those more than 40 years of data to a comprehensive suite of cloud properties. One example is the ESAs Cloud Climate Change Initiative (Cloud CCI). The existing datasets use passive-imager satellite measurements. The one with the longest baseline (covering 1982–2016) comes from Advanced Very High Resolution Radiometer (AVHRR). All cloud properties data are collected on two processing levels (see also [19]):

1. Level-3U with a global equal-angle, latitude–longitude grid with 0.05° resolution on daily composites and
2. Level-3C on monthly averages and histograms with a 0.5° grid resolution.

Based on the aforementioned archived and forecast cloud coverage datasets, we have implemented a "Cloud Handler" tool that makes these readily accessible to Mission Planning systems. It uses the following cloud coverage products:

1. For cloud coverage statistics, the Level-3U cloud mask data of the AVHRR-PM/V002 [20] dataset provided by DWD within ESA's Cloud CCI are used. For each day of the year and each location on Earth (resolution 0.25°), it provides a probability distribution of the expected cloud coverage.
2. For cloud forecast, the ICON Forecasting System is used [18]. It runs four times daily and yields hourly sampled predictions within a forecast horizon of three days.

The Cloud Handler is already integrated into the mission planning system (MPS) of the satellite mission EnMAP (Environmental Mapping and Analysis Program) which has an optical instrument on board. The idea here is to save downlink resources and reject orders with cloud covered areas due to the fact of making optical images. More information can be found in [21].

2.2 Ground station clusters with site diversity

For each space mission, the ground station network plays a major role. For optical missions, the attenuation due to clouds has to be considered in addition; it can be minimized by spatial and temporal diversity [2]: The usage of clusters with optical ground stations (OGSs) sophisticatedly distributed geographically may decrease unavailability times due to cloud coverage significantly. The goal is to design an OGS network, so that at least one OGS at each time period is available with high probability.

On the other side, redundant ground stations produce cost. Thus, many optimization approaches exist that minimize the number of required (optical) ground stations. The studies range from global to local optimal selection [22–24] and deal with needs of GEO, MEO, and LEO satellites [25–27]. The authors of [27] found that regions like the Andes, Namibia, or the Arabian Peninsula seem to be the most popular sites, and even the Sahara or the center of Greenland as harsh-environmental regions show less cloud probabilities. In [28], the focus is set on the selection of the OGS with the best channel conditions; they also consider a constellation scenario in which the best satellite should communicate with the best OGS.

DLR/GSOC (in cooperation with DLR's Responsive Space Cluster Competence Center) currently brings a number of LCTs serving as OGSs for satellite data up- and downlink into operation. The first terminal of the Global Optical Ground Station Network (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 [29].

In addition, DLR is part of the European Optical Nucleus Network [30] together with European Space Agency (ESA) and the Kongsberg Satellite Services (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 [31].

3 Generic link planning approach

3.1 Concept

In [8], we introduced our generic link planning system (GLPS) with all its interfaces (Fig. 1): The mission operations center (MOC) acts as a central link planning entity. It is designed to be the single contact point between the user, one or more spacecraft control centers (SCCs), and optionally the OGSs. It is designed to be used for both the ISL and DTE scenario; nonetheless, the concept can be easily transferred to airborne platforms as well.

For the DTE case, our next-generation LPS should include cloud statistics and forecasts and be able to cope with a redundant OGS network with site diversity.

3.2 From naive to realistic link planning

As depicted in [32], due to the highly dynamic environment, a data instead of a pass-centric solution is envisioned. This results in a focus on total data delivery at network level and not per individual station. Compared to RF planning, it

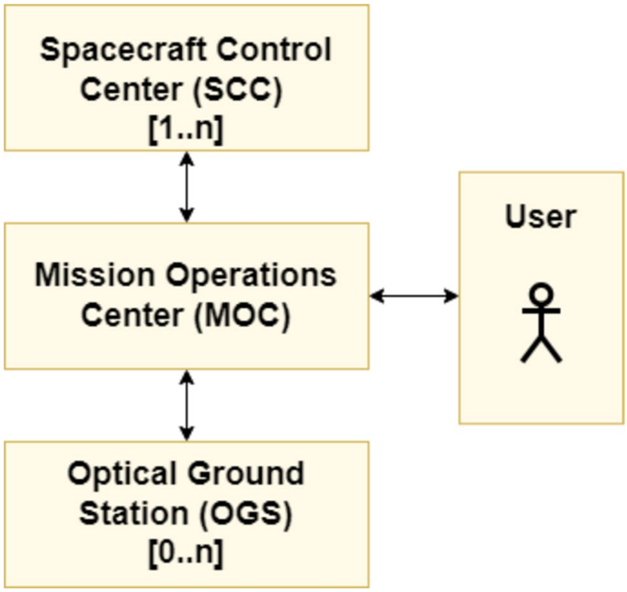

Fig. 1 Simplified architecture of the link planning system (see also [8])

needs a different mindset to imagine that data may be available only up to a certain amount in a specific time horizon (e.g., 90% of data are likely to be available within 24 h).

To treat unsuccessful data transmissions as a normal case rather than a contingency, our concept includes scenarios with different levels of complexity:

- *Statistical* forecast with a constant success assumption.
- *Statistical* forecast with a more realistic success assumption based on historical weather data. (The data vary with location and seasonally, but are static.)
- *Realistic* forecast based on the probability for a cloud-free link for the respective station and date.

In Fig. 2, we compare these with the *classical* RF approach of assuming each data downlink to be successful. As expected, all three scenarios that model outages lead to a longer latency. Under the assumption that the parameters of the statistical forecasts (scenario B and C in Fig. 2) model the reality appropriately, the latency of these simpler models is even expected to match the actually observed latencies on a global *average*. Compared to that, using historical data instead of a constant success rate for planning will get a much better estimate of the link budget for a *specific* ground station and can thus be useful, e.g., for long-term planning. The actual choice which ground station to schedule, however, shall preferably be made on real-time weather conditions, since these can vary widely from the long-term forecast [33].

Using these additional constraints, the LPS may also be used to minimize the time interval until when 100% of customer data will be available on ground. Depending on the requirements of a specific mission, the LPS can be configured to use either the statistical approach with simple constant or historical data, or true weather forecasts (from models or the OGS itself) when they become available, or a combination thereof for long- and short-term planning.

3.3 Reactive link planning for multiple satellites and OGSs

The scheduling system should be highly agile both prior and during link execution. Prior link execution, the idea is to determine an optimal timeline via algorithms. For instance, if more than one OGS is visible at a time, the one with less probability for clouds should be chosen. Furthermore, the planning is intended to be an ongoing process and changes to the plan have to be possible also on short-notice up to as close as possible to the point of link execution. For example, if a scheduled pass ends up partly or not utilized, a next opportunity for data transfer has to be found, also in consideration of contemporary passes of any missions by any customers (like depicted in [32]). This can be done via on-board or on-ground planning and short-term updates via, e.g., a redundant RF transfer.

Note that a similar optimization problem is encountered for scheduling astronomical observations on telescope networks. Depending on the use case (e.g., sky survey, dedicated scientific proposals, or space object tracking), the specific requirements differ. However, such networks often also involve instrumentation with different technical constraints, observations prefer low airmasses and require cloud-free skies, and reacting on local conditions and fast transient phenomena requires near-real-time responsiveness of the scheduling process (see, e.g., [33]). For a recent overview of approaches to the telescope observation scheduling problem, see [34].

Our generic link planning concept is intended to take a variable number of spacecraft and OGSs into consideration. The simplest case is to plan contact times for a single satellite, but future planning systems have to deal with constellations of satellites and satellites competing for OGS resources as well.

In the scenario that the network contains a sufficiently large number of OGSs, the spacecraft competition is assumed to be small. Moreover, the probability that a spacecraft has a choice between different OGSs is assumed to be high. Then, the LPS should act as in the case of a single spacecraft and use the OGS with the lowest probability for clouds first. Meanwhile, the amount of successfully downlinked data per spacecraft and OGS can be estimated (see again the example in Fig. 2). On the time of link execution, the terminal in orbit tries to establish links with its planned counter terminals on ground, one after the other, switching

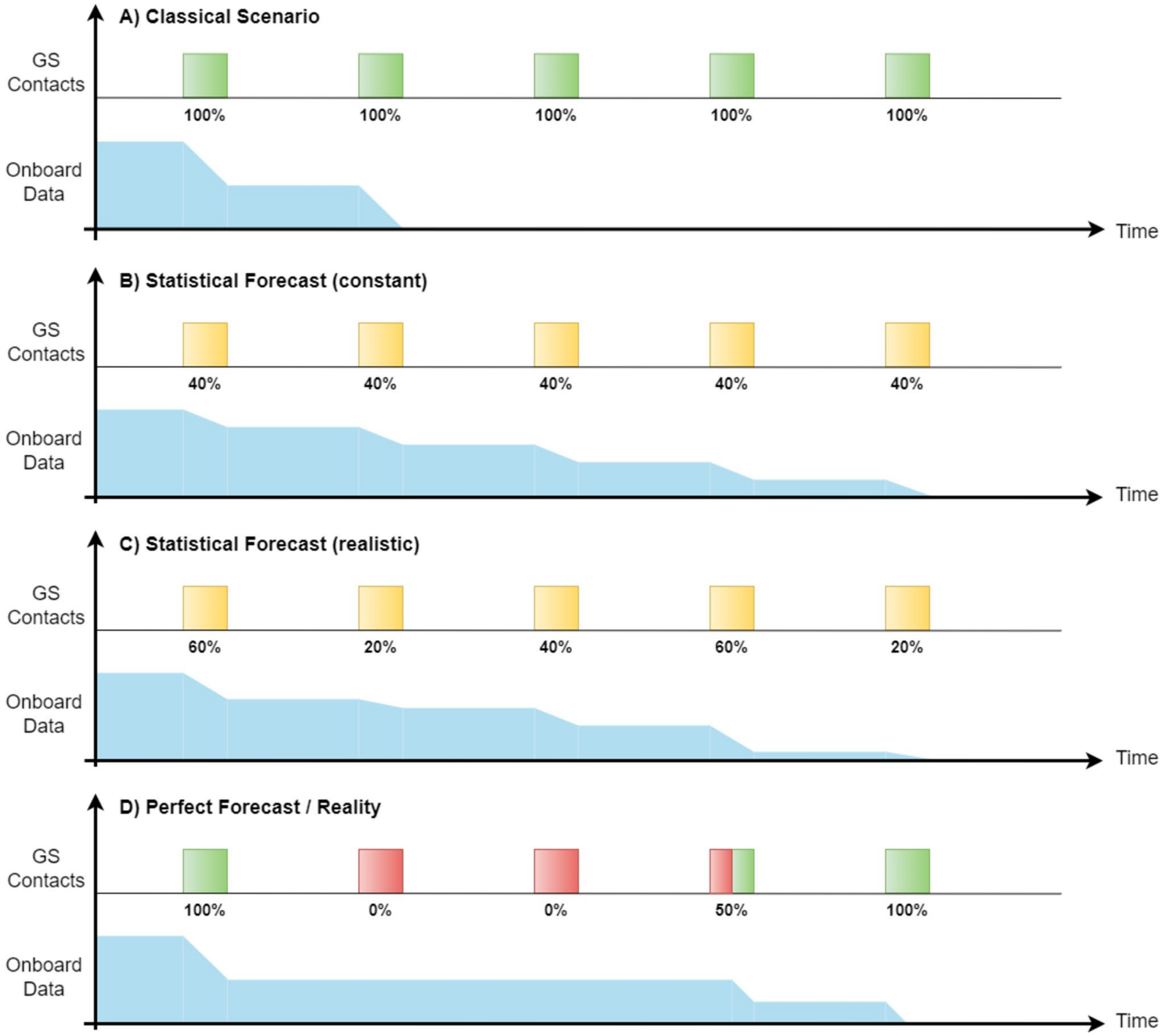

Fig. 2 Comparison of the four different downlink approaches: **A** classical, **B** statistical forecast with constant success rate, **C** statistical forecast with realistic success rate (e.g., from a weather model), and **D** describing reality or a perfect forecast. The upper lines in each scenario show possible ground station contacts together with the modeled success rate. Note that while scenarios **A** and **D** model contacts to be (partly) successful (green) or not (red), scenarios **B** and **C** model the average success rate (yellow). The lower lines show the modeled on-board data level decreasing due to the ground station contacts, with the data rate scaled down according to the modeled success rate

to the next one if establishing fails. Here (and in the following), we assume a laser terminal on a spacecraft to have at least beam alignment and on-board autonomy as it is standard, e.g., for the TESAT OSIRISv3 laser terminal [35].

In the other scenario, many spacecrafts compete about the OGS resource as there are less ground stations compared to spacecraft available. Without further guidelines (like cost, etc.), we consider fairness as a factor, similar to the solution presented in [36] for deep-space operations. Thus, we first approach to overbook the OGSs and analyze in a next step, how much data can be transferred successfully. In the end, we decide on short-notice either to take the best OGS-spacecraft-pair due to calculated probability, or to book percentages of the full available time for each spacecraft. For the latter case, the planning algorithm may additionally be configured to prefer higher elevation angles [24, 37].[1]

[1] Even if the researchers focus mainly on X- and Ka-band, the results can be applied on laser communication: As the distance increases, the received power decreases quadratically, and the longer path through the atmosphere results in higher intensity fluctuations.

4 Implementations

4.1 Link planning prototype

To demonstrate the link planning and scheduling concept, we designed a link planning prototype based on the generic planning tool PINTA [38], which has been developed at DLR/GSOC and is applied for a large variety of planning projects. The LPS prototype was set up for the PIXL-1 mission, which has the goal to demonstrate a data transmission between its CubeLCT terminal and the OGS network GlobeON [39].

The prototype architecture can be seen in Fig. 3. It has evolved from the overall concept shown in Sect. 3.1. Here, one SCC and one or more OGSs, controlled by an NOC, are intended to be involved. The LPS is the core part of the MOC. There, the central mission planning component is connected to the flight dynamics visibility and link support (orbit converter) service. Necessary automated interfaces can be found both within the MOC and in-between the mission planning component and the SCC as well as the

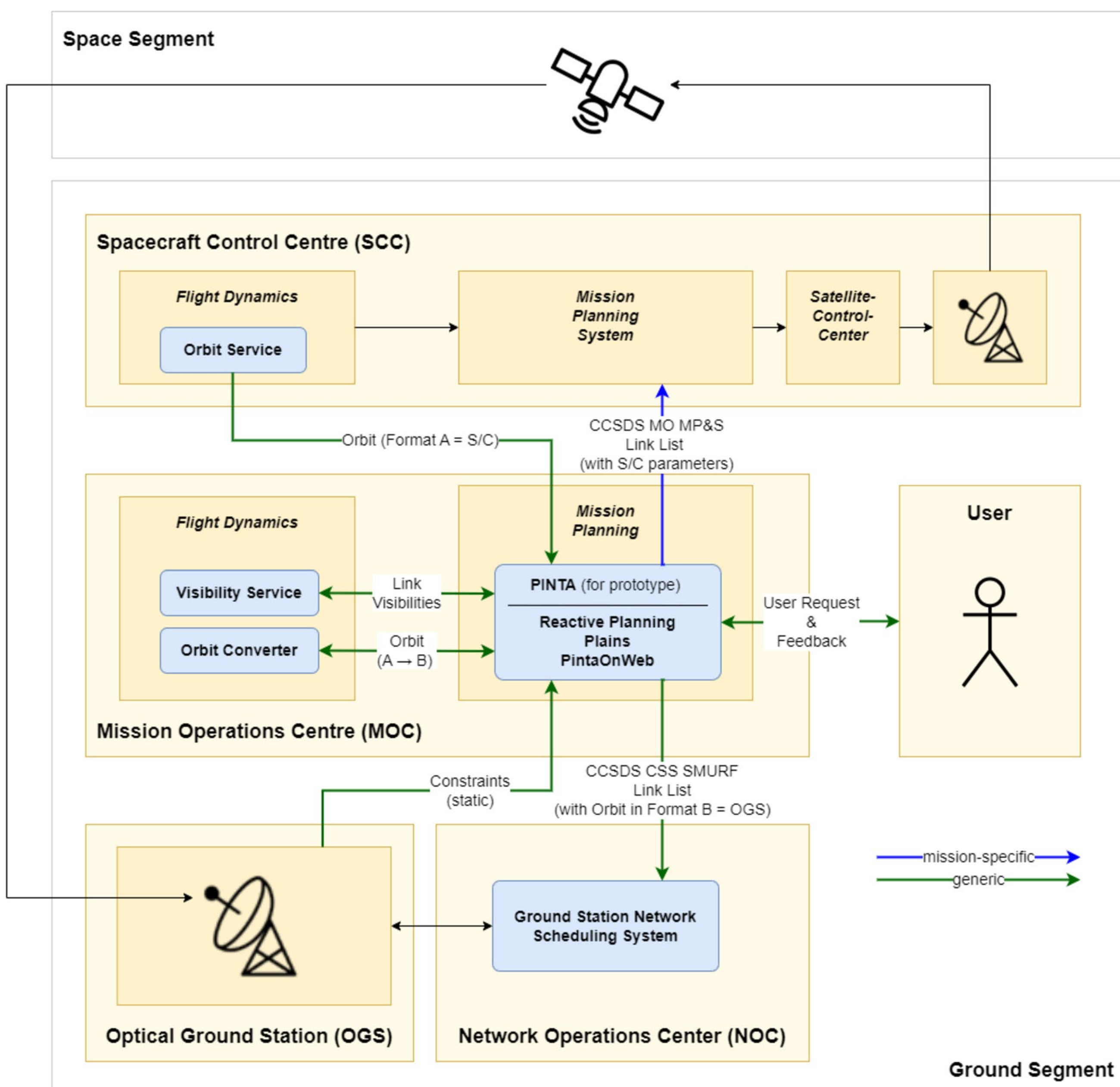

Fig. 3 Architecture of the link planning system (LPS)

network operations center (NOC) and the OGSs. All interfaces from the MOC to the external entities shall be based on CCSDS standards. The LPS is designed to enable the user resp. operator to modify the planning and corresponding operational products even on late notice. Therefore, we integrated a generic interface for feedback and user requests into our GLPS. A detailed description of the system with all its interfaces can be found in [8].

Unfortunately, until now, the concept could not be demonstrated with PIXL-1. Nevertheless, we hope to gather operational results in the frame of GlobeON.

4.2 ToUCAnS

Using the experiences gained so far with the LPS prototype, we started to integrate the concept and its functionalities in our "Tool for Unified Control Room, Antenna and Link Scheduling" (ToUCAnS), formerly known as "Integrated Terminal and Antenna Scheduling" (InTAS).

The user frontend of ToUCAnS can be seen in Fig. 4: it displays the visibilities and scheduled contacts of different missions. In its current state, the user can 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, change, or cancel passes, for instance to handle contingencies or short-time updates for a specific mission.

The GLPS architecture (Fig. 3) will be based on the same tools. This implies the replacement of PINTA as the basic mission planning component by GSOC's new generic web-based mission planning software PintaOnWeb (PoW) [40] together with Reactive Planning [41] and Plains [42, 43]. Furthermore, the NOC is intended to be an arbitrary "Ground Station Network Scheduling System" compared to the GSOC-specific "Ground Station Scheduling Next Generation" (GSSNG; [44]) used for the GlobeON prototype. The whole system follows the CCSDS exchange interface formats and standards that were already discussed in [8].

Since our Reactive Planning framework with the underlying Plains library is used as a backend, constraints concerning optical links (e.g., for cloud avoidance) can easily be modeled and considered for the planning of ground station contacts. This means in effect to enable the LPS for automatically triggered reactive incremental planning immediately upon reception of new input instead of planning runs at fixed points in time following a predefined pattern. This does, however, make the implementation of planning algorithms more complex, since they have to handle incremental re-planning instead of the traditional full planning run.

4.3 4.3 Adjustment of the LPS for TDP-1: specific use case for OGS diversity

Besides the integration of the LPS into our generic mission planning and scheduling tool suite, we aim to extend also existing specific mission planning systems like the one for TDP-1. The TDP-1 MPS is designed to plan optical links for the ISL and DTE scenario, respectively, with a planning

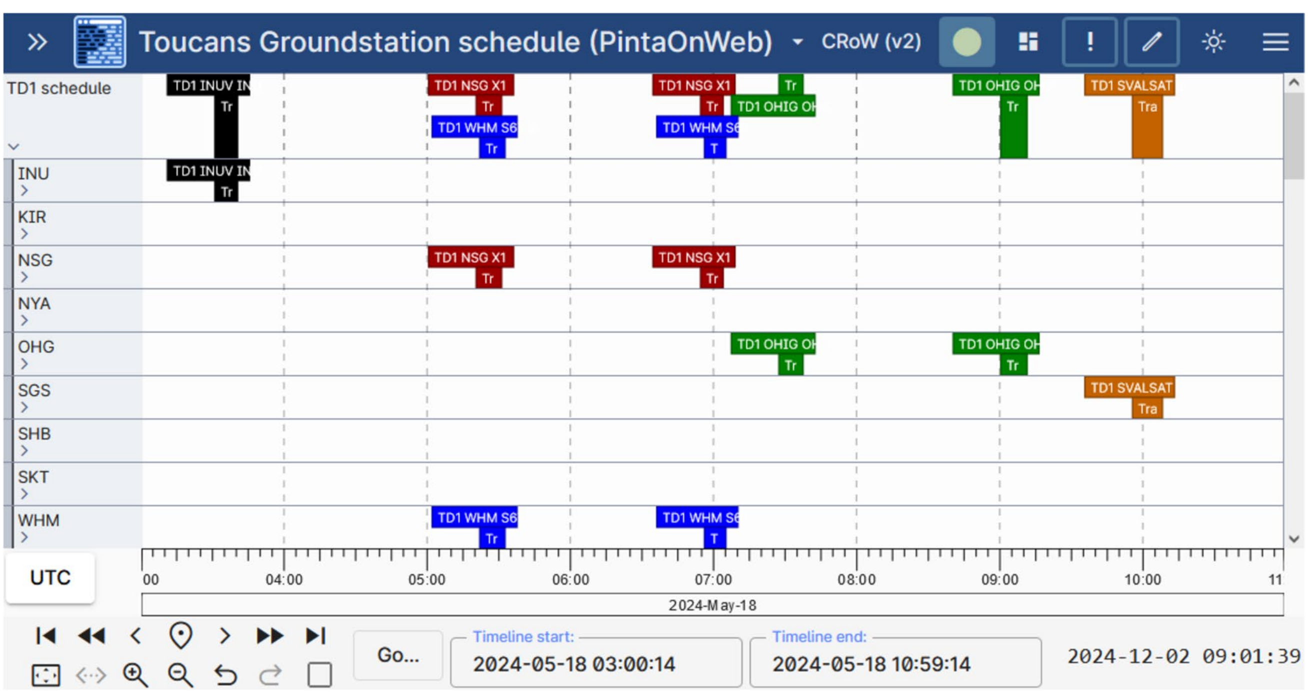

Fig. 4 PoW website displaying scheduled passes for a mission operated by GSOC. Passes of different stations are shown in different colors

horizon of one week starting each Saturday. The generated timeline is then fixed for the upcoming week each Friday [9]. During the execution week, a TESAT mission planner is able to change certain link parameters manually. However, a re-planning of a target OGS is not possible in the course of this procedure [9]. To address this issue, we aim to expand the current planning process together with TESAT. While keeping the existing MPS almost unchanged, we want to add our GLPS in between the MPS and the network operation center (NOC; see again Fig. 3), which enables short-term updates of the TDP-1-counter-terminals, at least until 2 h before the link execution. We want to utilize PoW to provide a user interface for manual terminal switches as well as the Reactive Planning and Plains backend for implementing algorithms for automatic decision-making regarding which OGS to use. Decisive criteria are, e.g., the terminal availability, weather information, and a prioritization regarding all involved OGSs. Also, manual interaction of TESAT and the OGS operators is foreseen.

The exact design is currently under development. Figure 5 shows a draft PoW timeline with planned links between TDP-1 and exemplary OGSs. Ground stations can specify possible link times and unavailabilities. If a planned link coincides with an unavailability, the link is marked in red. More information about the TDP-1 optical LPS and planned adaptations can be found in [45].

5 Conclusion and outlook toward our fully generic link planning system

Based on the main challenges of optical link planning, the orbit and pointing accuracy, the influence of atmospheric weather conditions, and the resulting need for real-time system-updates, we presented our concept of a generic, flexible, highly responsive, evolvable end-to-end LPS. As shown, the first steps toward the development of a generic link planning system are already done. We gained experiences by implementing a prototype based on our generic mission planning tool suite. To enable reactive incremental planning, we currently replace the PINTA-based prototype with a system based on PintaOnWeb and the Reactive Planning framework. As a first use case, this will be applied for the TDP-1 mission planning add-on for agile, interactive as well as automated re-planning of target OGS prior to their link execution, however still not in its final generic design form.

As a next step, we aim to integrate our Cloud Handler tool. Here, we want to add weather information of the OGS sites with increasing level of timeliness and thus reliability and in an automated way. Still, we are searching for more precise data in the sense of local propagators which provide solid near real-time forecasts for the exact areas where the ground stations are located. Furthermore, the interface between the OGSs and the mission operations center shall be extended to allow for an automated ingestion of latest weather information from the OGS sites in the LPS.

From a general mission planning point of view, on the other hand, we want to do a detailed case study about constellations of optical satellites and satellites competing about OGS resources, and identify their planning and scheduling needs. This shall then result in addressing their requirements with the implementation of different optimization approaches like solving global objective functions as well as applying solutions from game theory.

We hope to gather initial operational results then with PIXL-1 or another optical demonstrator within the frame of the European Optical Nucleus Network.

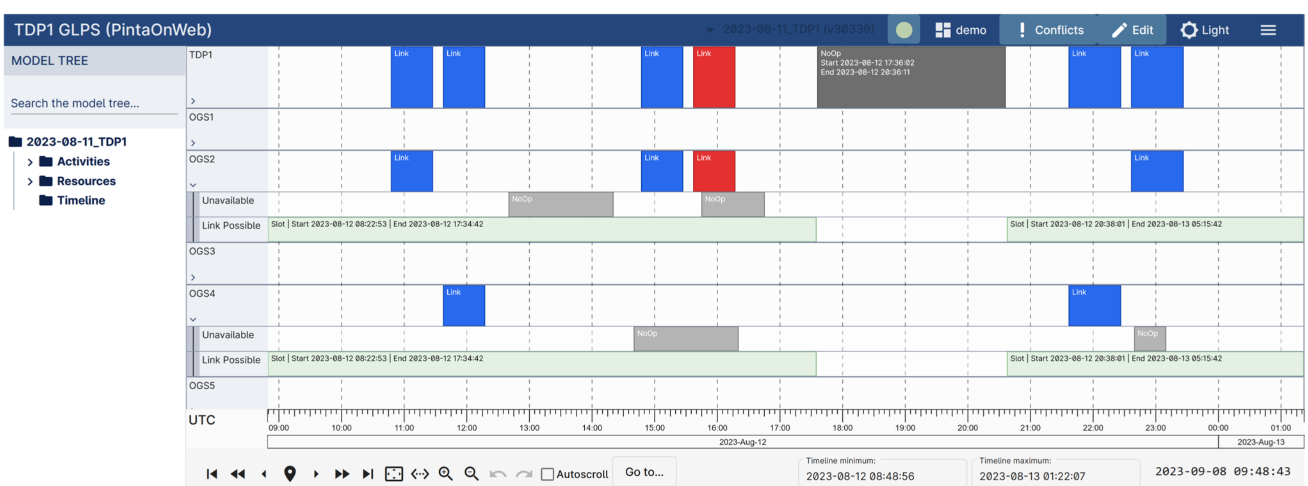

Fig. 5 PoW website displaying planned links between TDP-1 and different OGSs. Planned links are marked in blue. If a planned link coincides with an unavailability, the link is marked in red

Due to the pursued very generic setup and extensive configuration capabilities, however, the tool can be easily adapted to other optical missions like TDP-1 or Compasso [46] or other future missions to come, too.

Finally, we look forward to the integration with ToUCAnS, already on the way using the same tool base, to serve ground stations and missions in the future with a combined solution for planning all their satellite communication needs, let them be space-to-ground or inter-satellite, let them be RF or optical, or a combination of all within constellations.

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Author contribution All authors contributed to the study conception and design. The first draft of the manuscript was written by A.F. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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