# Agile Optical Satellite-to-Ground-Link Operation With The Current TDP1 Optical Link Planning System

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**Abstract**

The Technology Demonstration Payload No.1 (TDP1) on board the geostationary communication satellite Alphasat I-XL is successfully in operation since 2014. It consists of a Laser Communication terminal (TDP1-LCT) and a Ka-band payload. The TDP1-LCT regularly performs Satellite-to-Ground-Links (SGLs) with various optical ground stations, e.g. with the Transportable Adaptive Optical Ground Station (TAOGS, currently located on Tenerife, Spain) and the OGS-OP from the Institut für Kommunikation und Navigation (IKN, located in Oberpfaffenhofen, Germany). Different restrictions and challenges are to be taken into account, especially when executing optical links through the Earth atmosphere. One major challenge is the weather conditions, which may lead to a considerable link outage depending on the location of the optical ground station. The link planning for the TPD1-LCT is done by the TDP1 Mission Control Center (MCC) at the German Space Operations Center (GSOC) and it is currently based on a weekly planning cycle. In practice, this means that the decision to which optical ground station an optical link is planned to has to be made at least one week in advance. Weather conditions, on the other hand, may change within hours and the longer the forecast time is, the more inaccurate the forecast gets, especially regarding the aspect of cloud coverage. Thus, the system in place is not agile enough to respond to such short term changes. The current planning system has been originally designed to enable a demonstration, for which the requirements were conservative from today's perspective. The demonstration of the system and the weekly planning cycle was successful and the following ongoing performance surpassed expectations resulting in multiple extensions of the TDP1 Program. To cope with the requirements for increased agility this contribution shows how fast re-planning of Satellite-to-Ground-Links (SGLs) can be realized, in order to support site diversity taking into account weather conditions.

**Keywords**

Laser communication terminal; optical link planning; Mission planning; site diversity; optical Satellite-to-Ground communication; Generic Link Planning System; Reactive Planning;

## 1. ABBREVIATIONS/ ACRONYMS

- Consultative Committee for Space Data Systems (CCSDS)
- European Data Relay System (EDRS)
- Flight Dynamics System (FDS)
- Flight Operations System (FOS)
- Generic Link Planning System (GLPS)
- Geostationary (satellite) (GEO)
- German Space Operations Center (GSOC)
- Input Operations Request (IOR)
- Institut für Kommunikation und Navigation (IKN)
- Inter-Satellite-Links (ISLs)
- Laser Communication terminal (LCT)
- Low-Earth Orbiting (Satellite) (LEO)
- Mission Control Center (MCC)
- Mission Planning System (MPS)
- Non-operational zones (NOOPs)
- Optical Ground Station (OGS)
- procedure parameter files (ppf)
- Program for Interactive Timeline Analysis (PINTA)
- Satellite-to-Ground-Links (SGLs)
- Sequence of events (SOE)
- Technology Demonstration Payload No.1 (TDP1)



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- Technology Demonstration Payload - ESA Coordination Office (TECO)
- Tesat-Spacecom GmbH & Co. KG (TESAT)
- Transportable Adaptive Optical Ground Station (TAOGS)

## 2. INTRODUCTION

The Technology Demonstration Payload No.1 (TDP1) is one of the four Technology Demonstration Payloads on-board the geostationary communication satellite Alphasat I-XL and it consists of a Laser Communication terminal (TDP1-LCT) and a Ka-band payload. The TDP1-LCT was developed and build by Tesat-Spacecom GmbH & Co. KG (TESAT) and originally served as a demonstration mission for the EDRS Space Data Highway. It is an LCT-135 with an outer telescope diameter of 135 mm, it comprises a space qualified 1064 nm laser source and uses homodyne Binary Phase Key Shifting (BPKS) modulation. The TDP1-LCT is able to transfer up to 1.8 Gbps and is designed for a range of 45 000 km. Apart from the bi-weekly performed Inter-Satellite-Links (ISLs) with the Sentinel-1 and Sentinel-2 Satellites, the TDP1-LCT regularly performs Satellite-to-Ground-Link (SGL) campaigns with various optical ground stations. These include e.g. the Transportable Adaptive Optical Ground Station (TAOGS, fully operated by TESAT personnel and currently located on Tenerife, Spain), the OGS-OP from the Institut für Kommunikation und Navigation (IKN, located in Oberpfaffenhofen, Germany) and the Greek OGS in Chelmos (Greece). Additionally the T-AOGS has been and will be relocated to the Observatory in Zimmerwald (Switzerland). When operating ISLs the geometrical limitations dominate. However, the major challenge when executing optical links through the Earth's atmosphere, from a GEO to ground, are the rather dynamical weather conditions; especially cloud formation may lead to a considerable link outage. The optical link planning for the TPD1-LCT is done by the TDP1 Mission Control Center (MCC) at the German Space Operations Center (GSOC) and it is currently based on a weekly planning cycle. This is a rather inert process, as practically this means that the decision to which optical ground station an optical link is planned to has to be made at least one week in advance. Local weather conditions, like e.g. cloud coverage, wind, dust or humidity, which may restrict the successful performance of an optical link with a certain OGS, on the other hand, may change within hours. For details on weather prediction please refer to [9]. The longer the weather forecast time is, the more inaccurate the forecast gets, especially regarding the aspect of cloud coverage. One possibility to achieve a higher rate of successfully executed SGLs would be to use site diversity [4]. For this, several OGS at different locations need to be able to perform the links and by using fast re-planning of the target OGS it is decided which OGS shall be the active one and thus where the LCT in space shall point to. It is obvious that the link planning system in place is not agile enough to respond to such short-term changes. The current TDP1 link planning system has been originally designed to enable a demonstration and it was very successful in this scope. However, since the requirements for the demonstration were rather conservative from today's perspective, the TDP1 link planning system has to evolve in order to cope with the requirement of increased reactiveness in the link planning process. Recently a very agile Generic Link Planning System (GLPS) has been developed at the Mission Technology Department of GSOC [2]. The GLPS is a highly reactive system, which could offer the possibility of fast target OGS re-planning during the execution of SGLs. A combination of the current TDP1 planning system with the advantages of the GLPS could make a more agile optical Satellite-to-Ground-Link (SGL) operation with the TDP1-LCT possible. In Chapter 3 of this paper, the current link planning process for TDP1 is described and Chapter 4 discusses the challenges of SGL operation. Chapter 5 gives a short overview of the advantages of the GLPS, whereas the process for the target re-planning itself, leading to the agility needed to support site diversity, is presented in Chapter 6.

## 3. THE CURRENT OPTICAL LINK PLANNING PROCESS FOR TDP1

The optical link planning for TDP1 is done by the TDP1 Mission Control Center (MCC) at the German Space Operations Center (GSOC). Figure 1 displays the present status of the TPD1 optical link planning process, with emphasis on the file flow between the TDP1 Mission Planning System (MPS), the TDP1 FDS (Flight Dynamics System) and the TDP1 FOS (Flight Operations System). The TDP1 MPS is based on the generic Reactive Planning framework, which has been developed at GSOC to support fully automated and interactive mission planning systems. The Reactive Planning framework contains different components, especially a File- and a MessageIngestor, which may receive inputs from various sources, as well as the MasterProcessor. The latter is responsible for the optical link planning itself. There are different interfaces from and to the TDP1 MPS in place, most importantly to TDP1 FDS and to the TDP1 FOS. TDP1 FDS is responsible for the calculation of the time frames in which the involved LCTs have visibility and of the generation of the Chebyshev parameters, describing the position of the target terminal. TDP1 FOS collects the information when the satellites are unavailable for TDP1 operation (these times are called non-operational zones (NOOPs) and is in charge of creating the sequence of events (SOE) as well as of the creation of the so-called slotlists. The slotslists are the combination of the calculated visibility time frames and the NOOPs. Regarding GEO links, which is the case for the TDP1-LCT, the pure visibility is always given, but the restriction here is the sun avoidance angle. The flow of the input/output files is as follows: The TESAT mission planner delivers the link requests and Procedure Execution Requests (PERs) as input to the TDP1 MCC. The other important inputs for the link planning at the TDP1 MPS are the slotlists provided by TDP1 FOS. The TDP1 MPS then performs the planning of the links and PERs based on these inputs and exports the linklist to TDP1 FDS and TDP1 FOS. On the basis of the linklist, the needed Chebyshev parameters are calculated by TDP1 FDS and they are then provided to TDP1 FOS, where they are filled into the corresponding link procedure parameter files (ppfs), which have been created by TDP1 FOS. TDP1 FOS exports the ppfs and the Input Operations Request (IOR) to the Technology Demonstration Payload - ESA Coordination Office (TECO) [7]. The IOR is a list of all tasks (from all TDPs) to be executed and additionally contains information necessary for plausibility checks and de-confliction of the different tasks. TDP1 FOS creates the SOE, also on the basis of the linklist, and forwards this to TESAT. The SOE is a list including all links and PERs planned by the TDP1 MPS. For more detailed information on the TDP1 MPS itself please refer to [1] and [3].

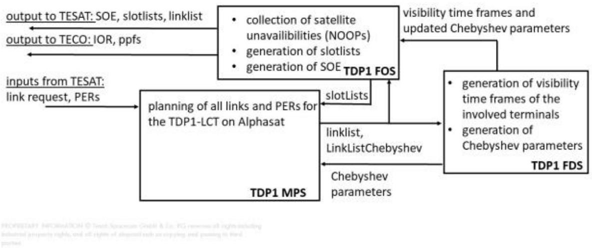


Figure 1. The current TDP1 MPS with interfaces to TDP1 FDS and TDP1 FOS

The link planning process for TDP1 is based on link execution weeks starting on Saturdays. The TDP1 mission planner at TESAT delivers the planning products such as link requests and PERs as planning inputs to GSOC. The link requests contain link parameters, which are differentiated between link configuration parameters (e.g. the link ID) and link planning parameters (e.g. phase 1 duration of the link). The PERs contain configuration parameters for the LCT itself, e.g. the optical power amplifier (OPA) output at a specific range. All planning products needed for an execution week have to be delivered until 16:00 o'clock UTC on the Thursday before the execution week starting on Saturday. As a result, the planning for an execution week usually starts on the Monday before the execution week. This means that all decisions about the optical links to be planned, especially the target OGS, have to be made at least one week in advance. Certain parameters, such as LCT configurations parameters and link planning parameters (contained in the link request) may still be changed during the execution week via the so-called PER-update process. In this process the content of an already planned PER may be changed and the updated PER may be reintroduced to the TDP1 MCC by the TESAT mission planner. The updated PERs are then processed by the TDP1 FOS, new ppfs are created by TDP1 FOS and these are afterwards exported to TECO. The TESAT mission planner may trigger this PER-update process until about two hours prior to the execution time of the PER. This PER-update process also applies for changing link parameters, as link requests are processed by the TDP1 MCC in such a way that the output are also PERs. However, during this process target re-planning is not possible. The information on the position of the target terminal is introduced into the ppf via a set of Chebyshev coefficients, provided by TDP1 FDS. At the moment, the update of these Chebyshev coefficients, is performed once a day at midnight and it covers all links for the next 48 hours. This process is triggered by TDP1 FDS and cannot be initiated or controlled by TESAT.

As the current planning system has originally been designed to enable a demonstration, for which the requirements were conservative from today's perspective, this rather inert link planning process was sufficient. However, performing optical links through the Earth's atmosphere involves challenges and restrictions, which can be reduced significantly by applying site diversity. As using site diversity requires the possibility to change target OGSs ad hoc, in order to perform the optical link to an OGS with clear sky conditions, a more agile link planning system is needed.

## 4. CHALLENGES OF OPTICAL SATELLITE-TO-GROUND-LINK OPERATION

An important part of the TDP1-LCT operations are the regularly performed SGL campaigns. When executing optical links through the Earth atmosphere, several constrains and challenges are to be taken into account. One major challenge are the weather conditions. Depending on the location of the OGS, unfavourable weather conditions lead to considerable link outage. Even at the current location of the T-AOGS in Tenerife, more than 25 % of the optical links are lost due to weather issues [6]. While wind, dust and humidity also play a role, especially cloud coverage has a very high impact on the performance of optical links through the Earth' atmosphere. Our experience for the site in Oberpfaffenhofen was, collected in eight campaign weeks (196 optical links in total) in different seasons, 73 % link outage due to clouds. As described in Chapter 3, currently a re-planning of the target of an optical link is not possible during the execution week. Thus, in case an OGS cannot perform an optical link, e.g. due to considerable cloud coverage, this link is simply lost, even if another OGS would have clear sky conditions. Weather conditions may change within hours and the longer the forecast time is, the more inaccurate the forecast gets, especially regarding the aspect of cloud coverage. It is obvious that the planning system in place is not agile enough to respond to such short term changes in the weather conditions. To achieve a higher rate of successfully performed SGLs a more agile planning system, with the possibility to perform a fast re-planning of the target terminal, is needed. This, in combination with a real time weather forecast for each of the involved OGSs, would lead to more SGLs being successfully executed. Usually during SGL campaigns, several optical links per day are planned to one OGS, but in certain weeks, campaigns to various OGSs are planned in parallel as well. As described in Chapter 3, there is the possibility to change several settings for the TDP1-LCT, leading to a variety of different link types. These are especially used when OGSs perform dedicated experiments. However, even currently optical links with the TDP1-LCT may also run by themselves using the default parameter settings. This is the way ISLs are performed at the moment. Although different OGS campaigns have different objectives and thus different link types may be required, there are basic link types, which can be used by more than one OGS. The long-term goal of the more agile optical link planning is to ensure a correct and robust data transmission via SGLs and in this case only one standard link type is needed. Site diversity is the key to this goal, as it offers the possibility to change the target OGSs ad hoc, in case conditions on one or the other OGS change on short notice. Thus correct data transmission to Earth is enabled via a successfully executed SGL to an available OGS. For more detailed information on site diversity, please refer to [4].

## 5. THE GENERIC LINK PLANNING SYSTEM AND ITS ADVANTAGES

One solution for the challenges of optical SGL operation described in the previous Chapter is the combination of the current TDP1 MCC and certain parts of the existing Generic Link Planning System (GLPS). This system has been developed by GSOC recently and it is able to immediately react on any modified input information such as a modification of the target terminal, by automatically starting another planning run. This is in contrast to the weekly planning runs currently used in the TDP1 MPS. Another advantage of the GLPS is that it supports generic interfaces rather than individual interfaces like in the TDP1 MCC. The GLPS is based on GSOC's Reactive Planning Framework and also provides a GUI called "PintaOnWeb". Figure 2 shows the GLPS and its different interfaces, which are differentiated between generic (green arrows) and mission specific (blue arrows). One of the generic interfaces is the "Manual Interaction" between the GLPS and the User, also indicated by a green arrow in Figure 2. This is the interaction via the GUI "PintaOnWeb".

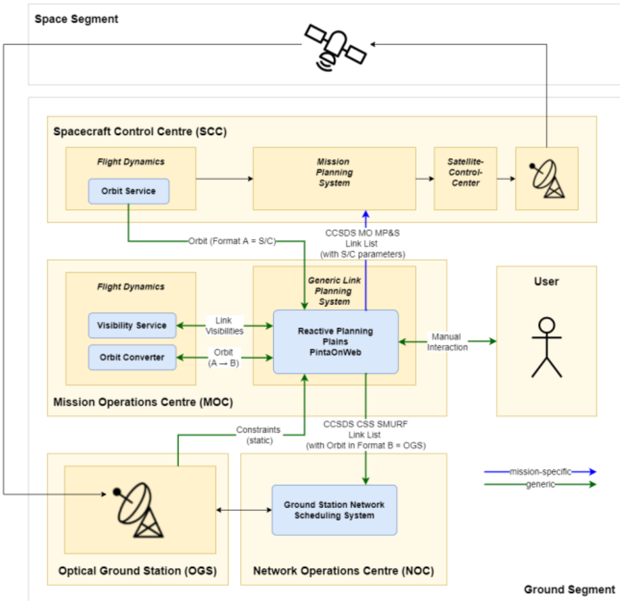


Figure 2. The GLPS and its interfaces (taken from [5], used with permission)

Other interfaces of the GLPS are standardized according to CCSDS (Consultative Committee for Space Data Systems) as indicated in Figure 2. More detailed information on the generic link planning system can be found in [2] and in [5]. Especially the web interface, "PintaOnWeb", as a feature of the GLPS, could be used to achieve more agility in the optical link planning, as this interface could offer the possibility for the user to modify the planning according to his needs. Specifically this means a change the target OGS depending on its availability and the local weather conditions. The following Chapter discusses the combination of the TDP1 MPS and particular parts of the GLPS.

## 6. ACHIEVING MORE AGILE OPTICAL LINK PLANNING WITH THE TDP1 MPS USING THE GLPS

This Chapter discusses the implementation of specific parts of the GLPS into the TDP1 MPS in order to achieve a more agile optical link planning system. The main aspect aimed at here is the possibility of fast re-planning of the target OGS, leading to the demonstration of site diversity. The intended combination of the TDP1 MCC and the GLPS is displayed in Figure 3 with special focus on the flow of files. The baseline is that the TDP1 MCC and its functionalities shall remain largely unchanged; meaning the weekly planning of the links with the link starting times, link durations and default OGSs is still done as described in Chapter 3. Thus the flow of files between the TDP1 MPS, the TDP1 FOS and the TDP1 FDS remains the same (compare with Figure 1). The actual re-planning of the target OGS shall be done by the specific parts of the GLPS. Once the TDP1 MPS has performed the link planning, as described in Chapter 3, the following files are exported to the GLPS: SOEs, slotLists and LinkListChebyshev. With this, all planned activities as well as the available slots of the different counter terminals are known to the GLPS.

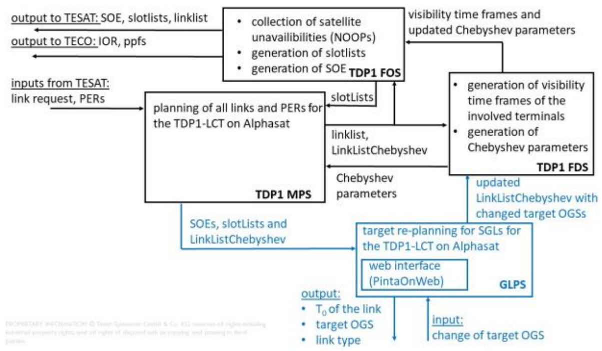


Figure 3. Intended combination of the TDP1 MPS and the GLPS

The information about the optical links planned for the TDP1-LCT, including the starting time of the link ($T_0$), the link length, the link type and target OGS, is then made available to the user (TESAT but also the operators of the OGSs) via the web interface PintaOnWeb. Utilising this web interface the user shall be able to change the target terminal only; the link planning parameters as well as the TDP1-LCT configuration parameters will remain unchanged. To be precise, especially the link type but also the starting time and duration of the link cannot be modified. The layout of the envisioned GUI for the fast re-planning, based on PintaOnWeb is shown in Figure 4. There is a Gantt chart representing the present status of the planned links as well as the unavailabilities of all the different OGSs. The first line of the Gantt chart is reserved for the information on TDP1. In the time range shown here TDP1 has NOOPs and after that four links have been planned to different OGSs. Further down there are two lines allocated to each of the OGSs. The upper lines contain the links planned to that OGS and the second line may be used by the OGS operators to indicate their unavailability. The colour code for the links is the following: links marked in green are planned and confirmed, meaning that the OGS where the link was planned to is available and can execute the link. The links marked in red are the ones where the target OGS is not available anymore. Links marked in orange are request by a certain OGS. In the example shown in Figure 4, link 1 and 2 were planned to OGS1 (marked in green, OGS1 is available) and link 3 and 4 have initially been planned to OGS2. Link 3 is marked in green, as the OGS2 is available during that time, but link 4 is marked in red because in the meantime OGS2 is not available anymore and thus cannot perform this link. For link 4 the target OGS may be changed now and in the example shown here, OGS1 requests to have this link (marked in orange).

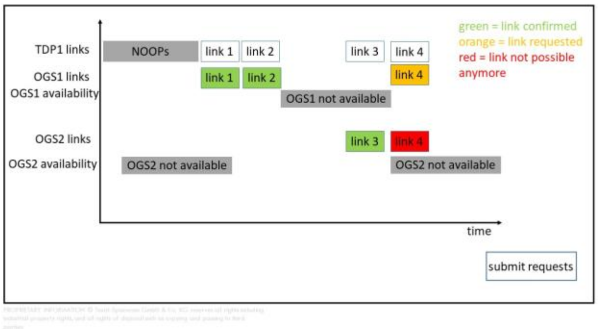


Figure 4. Preliminary layout of the GUI

For the first version, it is envisaged to have a two-step process for the change of the target terminal. In the first step links may be preselected by one or the other OGS and are then marked in orange as describes above. This shall be possible until two hours prior to the starting time of the link and the OGS operators have the right to preselect different links. Only in the second step the requested re-planning of the OGSs is confirmed by a super-user (e.g. TESAT personnel) and the request will be submitted (symbolized by the "submit requests" button); then the re-planning will be processed by the GLPS, including the necessary file transfers and exports. In case one or several target OGSs have been changed via PintaOnWeb, the GLPS modifies the corresponding target terminals in the LinkListChebyshev and exports the updated LinkListChebyshev to TDP1 FDS, where the new file is detected immediately. TDP1 FDS then processes the new counter terminal by generating the corresponding Chebyshev parameters and sending them to TDP1 FOS. There the updated file is again detected immediately. TDP1 FOS identifies the modified link using the link ID and generates a new SOE, reflecting the modification of the target OGS(s). The updated SOE is forwarded to TESAT (the user). Additionally and even more importantly, the ppfs are updated by TDP1 FOS and afterwards transferred to TECO (refer to the process described in Chapter 3). In the second step, when the requested re-planning is confirmed, it shall be selectable, whether the re-planning (and thus the file transfers and exports) is triggered only for the next link or for the next 24 hours. This depends, of course, on which links have actually been changed in the GUI and it shall reduce the amount of file transfers. The flow of files just described is displayed in Figure 3. For a more detailed description of the implementation of the GLPS into the TDP1 MPS please refer to [5].

## 7. CONCLUSION AND OUTLOOK

When the above-described solution for the challenges in optical link operation through the Earth's atmosphere is successfully demonstrated, an important milestone has been reached to support site diversity at the TDP1 system. The goal is to have the system ready-to-use in 2024 to demonstrate the concepts of site diversity on the one hand but also to achieve a significantly higher rate of successfully performed SGLs in weeks when different SGL campaign are running in parallel. With the process discussed in this paper, fast re-planning of optical links is possible but it still requires the user's intervention. On the one hand, the user (e.g. the OGS operator) needs to observe the local conditions, decide which links may be executed and then requests changes of target OGSs accordingly via the web interface. On the other hand, there needs to be an entity (e.g. TESAT personnel) who takes a decision in case one optical link is requested by more than one OGS. An additional and more far-reaching approach in achieving site diversity is that the fast re-planning will be automatically triggered based on the output of a decision matrix, rather than on the manual input from a user via the web interface. This automated decision-making shall be implemented in the GLPS, making use of its generic interfaces. The most important input to this decision matrix is the latest weather forecasts from the different OGSs. Another important aspect is the prioritization of the OGSs, meaning as soon as a link could potentially be executed by the OGS with the highest priority, this OGS automatically gets the link. Finally yet importantly, the information on the availability of the OGS is another input to the decision matrix. The later includes the information whether the terminal is technically functional and whether the operator is available. Based on these three input parameters the GLPS shall automatically decide if a re-planning of the optical links is needed in order to achieve a higher rate of successfully executed SGLs.

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