Debris Tracking Laser Network

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ABSTRACT

Tracking debris with ground lasers is becoming a mature technology these days. Hence, ESA has recently launched an activity within its Space Safety program, called ESA S2P S1-SC-06: "Laser ranging - Evolution towards active sensor networking for debris observation and remediation", to develop the so-called Debris Tracking Laser Network (DLTN), designed with two main components, a sensor network composed of participating laser stations, and an on-line platform allowing users to interact with the sensor network for various use cases. This paper will present the main results of the activity with special focus on the capabilities of the system and accessible through its on-line platform developed by GMV as well as on the observation campaigns to take place end of Summer 2024. In terms of the capabilities of the on-line platform, the expected interaction of the user with the platform for the various use cases will be described, as well as the required inputs and expected outputs of such interactions. In terms of the observation campaigns, a description will be given for the different sub-campaigns designed to validate each of the use cases of the DLTN.

1. INTRODUCTION

The current increase on the number of resident space objects demands the parallel development of new ground sensor technologies able to provide the coverage and accuracy required in order to maintain the sustainability of space operations. One of the sensor technologies being evolved nowadays for space debris monitoring is the laser ranging technology.

Tracking debris with ground lasers is becoming a mature technology these days. Hence, ESA has recently launched an activity within its Space Safety program [1] to develop the so-called Debris Tracking Laser Network (DLTN), designed with two main components, a sensor network composed of participating laser stations, and an on-line platform allowing users to interact with the sensor network for various use cases. The activity has various main objectives as listed next: 1) extension of the ESA robotic optical ground station, Izaña-1 (IZN-1), to allow for daylight space debris tracking, 2) development of an on-line platform for end-users to support various use cases (sensor calibration, object observation, catalogue maintenance, collision risk refinement, re-entry prediction refinement, stare and chase), supported by a business case analysis, and 3) validation of the entire system through observation campaigns for each of the identified use cases involving various laser stations via different service level agreements.

This paper will present the main results of the activity with special focus on the capabilities of the system accessible through its on-line platform developed by GMV as well as on the observation campaigns to take place end of Summer 2024. In terms of the capabilities of the on-line platform, the expected interaction of the user with the platform for the various use cases will be described, as well as the required inputs and expected outputs of such interactions. For example, in the collision risk refinement, a user can provide a Conjunction Data Message (CDM) to the system and request observations from the DLTN until the covariance of the secondary object reaches a specified covariance reduction factor. Based on this request, the platform analyzes which lasers in the network are available and have observation opportunities, prepares a plan optimizing the observation requests to the lasers during the time interval up to the event deadline, and tasks them to gather the required observations. As the observations are produced by the lasers, and submitted back to the on-line platform, an orbit determination update is performed together with a reassessment of the collision risk posed by the event. Once the covariance reduction factor is achieved, no more observations are requested from the network and the user request is considered fulfilled. A similar case is the re-entry use case, where instead of a CDM, the user provides a Re-entry Data Message (RDM).

Regarding the observation campaigns, a description will be given for the different sub-campaigns performed to validate each of the use cases of the DLTN, describing both the objectives and the participating stations.

2. DEBRIS TRACKING LASER NETWORK CONCEPT

The **Debris Tracking Laser Network** (DLTN) is a system conceived by ESA to support Space Surveillance and Tracking operations, as well as satellite and Space Traffic Management operations, through the use of **Space Debris Laser Ranging** (SDLR), as an extension to the well known Satellite Laser Ranging (SLR) technology, used for decades now with cooperative satellites (i.e with retro-reflectors).

The following functions are identified in the DLTN system:

- **DLTN stations network** (DLTN-SN): laser stations within the network participating in observations.
- **DLTN online platform** (DLTN-OP): an online platform for near real-time requesting, scheduling, analysis, display and provision of space safety related data products to the end user based on observational data generated by the DLTN-SN and products derived from that data.

The DLTN system oversees the fulfilment of the different requests performed by external users. It takes the original data provided by the user, as well as some other external data, and requests observations to the network of laser ranging sensors for the objects involved in the request in order to fulfil the user requirements.

The following figure shows a Data Flow Diagram of the DLTN system, with the flows of information among the functions of the system. Blue boxes correspond to the above listed functions and red boxes correspond to the above listed actors. The figure shows the main flows of information between the DLTN-OP and DLTN-SN, which correspond to observation requests from the DLTN-OP to the DLTN-SN based on CPF-formatted orbital information, format commonly used by SLR stations, as well as observational data from the DLTN-SN to the DLTN-OP based on TDM/CRD-formatted observations. The figure also shows the flows of information between the DLTN-OP and the user for the different use cases supported by the DLTN and described further below.

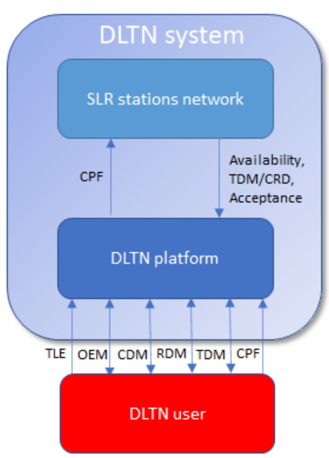

Figure 1: Data flow diagram of the DLTN system functions

The main use cases offered by the DLTN system to users are:

- **Observation request**, in which the user provides orbital information of an object, chooses one or more SLR sensors and requests tracks for the object.
- **Orbit refinement request**, in which the user provides orbital information of an object, chooses one or more SLR sensors and requests the refinement of the orbital information, while the DLTN provides as products the tracks obtained by the stations, and the refined orbital information generated with those tracks.
- **CDM refinement request**, in which the user provides a CDM (Conjunction Data Message), chooses one or more SLR sensors and requests the refinement of the CDM, while the DLTN provides as products the tracks obtained by the stations, the refined orbital information generated with those tracks and an updated CDM.
- **RDM refinement request**, in which the user provides an RDM (Re-entry Data Message), chooses one or more SLR sensors and requests the refinement of the RDM, while the DLTN provides as products the tracks obtained by the stations, the refined orbital information generated with those tracks and an updated RDM.
- **Catalogue maintenance request**, in which the user provides orbital information for several objects, chooses the end date of the catalogue maintenance and requests the reiterative refinement of the orbital information when needed until the chosen date, in order to maintain the covariance of the objects below specific limits.
- **Calibration**, in which the user requests a calibration of a SLR station analyzing observational data generated by the SLR station for objects with precise orbits available, usually in SP3 format.
- **Stare & chase request**, in which the user provides a TLE file, chooses an optical sensor and one or more SLR sensors and requests the refinement of the orbital information through the stare & chase technique, while the DLTN provides as products the tracks obtained by the stare and chase sensors, and the refined orbital information generated with those tracks. It is important to note that in this scenario the sensor may need a specific stare & chase software to be run locally in order to estimate the orbit of the object based on the stare observations so that the chase sensor can track the object afterwards.

The general behaviour of the DLTN may be seen in the figure below and is as follows:

- The user provides some initial orbital data to the software and defines some other configuration parameters in order to perform one of the mentioned requests through the web interface.
- Periodically, the software performs the computation of the observation opportunities for all the objects involved in active user requests, generates an optimized planning for all the SLR sensors in the network and sends the corresponding observation requests to the sensors through an FTP, interface between the DLTN-OP and the sensors. In the generation of the optimized planning the DLTN distributes the tracking requests considering the capabilities of the stations, in terms of power, object properties, urgengy of requests, etc
- Eventually, the sensors upload tracks for some of the requested objects through the FTP. In that moment, the software processes the tracks and performs the necessary computations to provide the expected outputs (track files, refined ephemerides, refined CDMs, refined RDMs…)
- The products are offered to the user through the web interface.

It is important to remark that, in order to perform these analyses, the software uses some external data such as the Earth Orientation Parameters and leap seconds from IERS, solar activity parameters, object properties from ESA's DISCOS, orbital information from space-track.org, etc.

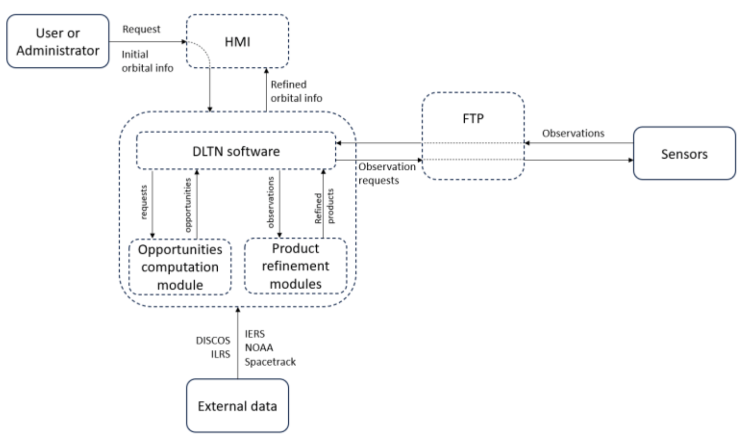

Figure 2: General software diagram

The modes of user interactions are represented in the 7 use cases presented above. Some of them are presented more in detail below as examples.

a) Request for orbit refinement of a space object

- The user will indicate the basic configuration (request type, time period) and the request specific configuration (orbit improvement in terms of orbit covariance reduction factor or intended number of tracks), provide the orbital information for the considered object to the system (TLE,OEM, CPF or OPM) and select the stations to be used among the available ones.
- The DLTN system will store the user inputs and take them into account to achieve the required orbit improvement. Those parameters will be used in the observation opportunities calculation of the considered objects from the considered stations assigning the corresponding priorities to generate the CPF files.
- The SLR stations of the DLTN system will receive a notification with the new CPF. Once the SLR station accepts the request and the observations are acquired, they will be uploaded to the system in the format previously agreed, usually CRD or TDM.
- The DLTN system will store the acquired observations and use them for orbit determination. This updated orbital information (OEM) will be stored in the DLTN system and the user will obtain the results from the system: observations (TDM) and updated orbital information (OEM).

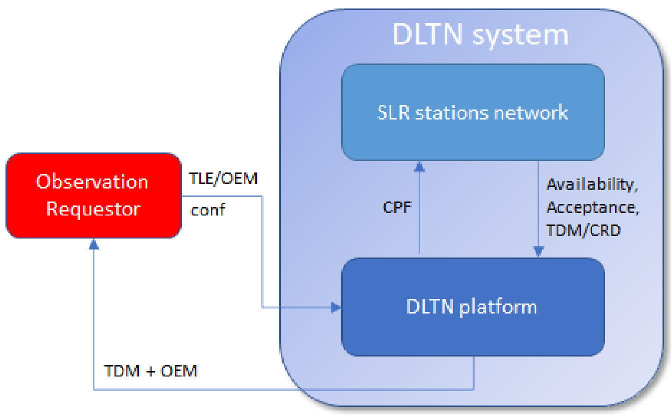

Figure 3: Request for orbit refinement of a space object

b) Request to refine a Conjunction Data Message

- The user will indicate the basic configuration (request type, time period) and the request specific configuration (objects to be re-evaluated - only secondary or both- and orbit improvement in terms of orbit covariance reduction factor or intended number of tracks), provide the Conjunction Data Message (CDM) and select the stations to be used among the available ones.
- The DLTN system will store the user inputs and take them into account to achieve the required orbit improvement. The DLTN system will propagate the state vector of the considered objects included in the CDM and will calculate, using the parameters introduced, the observation opportunities of the considered objects from the considered stations assigning the corresponding priorities to generate the CPF files.
- The SLR stations of the DLTN will receive a notification with the new CPF. Once the SLR station accepts the request and the observations are acquired, they will be uploaded to the system, usually in CRD or TDM.
- The DLTN system will store the acquired observations and use them for the orbit determination. This updated orbital information (OEM) will be stored in the DLTN and used to generate an updated CDM. It is important to mention that the orbital information will be updated as soon a new track is available and the newly generated OEM is shared also with the stations as updated prediction for further observations.
- The user will obtain the results from the DLTN system: observations (TDM/CRD), updated orbital information (OEM) and updated CDM.

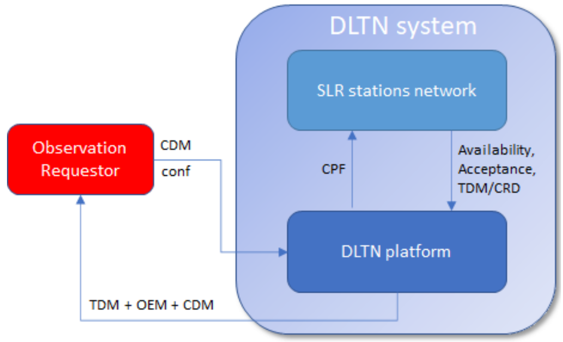

Figure 4: Request to refine a Conjunction Data Message

c) Perform stare and chase operations

It is assumed that stare and chase operations in the DLTN system are done to known objects with coarse a-priori orbital information.

- The user will indicate the basic configuration (request type, time period), provide the approximate orbital information for the considered object to the system and select the supporting passive optical sensor to be considered for the stare observations as well as the chasing SLR sensor.
- The DLTN system will store the user inputs and calculate the observation opportunities of the considered objects from the considered supporting passive optical sensor.
- The supporting passive optical sensor will receive a notification with the rough orbital information to be followed.
- Once the optical observations are acquired by the supporting passive optical sensor, the observations will be uploaded to the system in TDM format. Besides, in case a co-located SLR sensor was selected, an internal communication within the site is expected so that the SLR sensor follows the object based on the original orbital information improved with the passive optical observations. Then the laser observations may be uploaded to the DLTN.
- The DLTN system will store the acquired observations and will perform an orbit improvement using the observations. This refined improved orbit will be used to calculate the observation opportunities of this object from the additional chasing SLR stations, if any. The generated CPF file will be sent to them.
- The SLR station of the DLTN system will receive a notification with the new CPF. Once the SLR station accepts the request and the observations are acquired, they will be uploaded to the system.
- The DLTN system will store the acquired observations and use them for the orbit determination. This updated orbital information (OEM) will be stored in the DLTN system and the user will obtain the results from the system: passive optical and laser observations (TDM) and updated orbital information (OEM).

The main goal of this use case is to carry out stare and chase in a site with co-located sensors (stare and chase observations are done at the same site). Nevertheless, the proposed solution for stare and chase gives the opportunity to be applied also to non-co-located sensors, even though the accuracy of the refined orbit with stare observations degrades very rapidly and this can make difficult scheduling chasing operations in a different site.

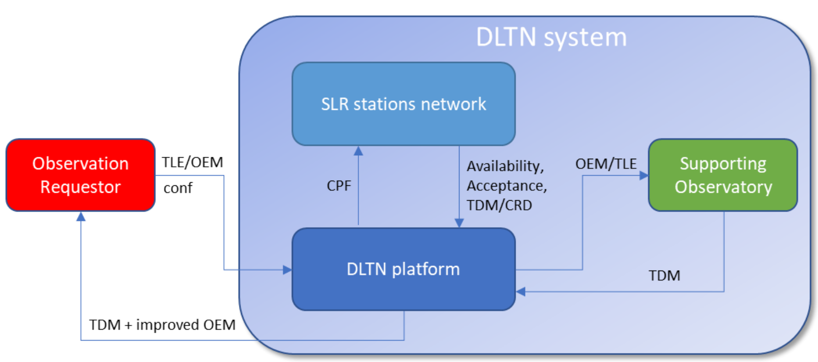

Figure 5: Request for stare and chase operations

3. DLTN OPERATIONAL PLATFORM

The figure below depicts the main components of the DLTN operational platform. It is worth to identify the two most important components: the frontend, which is a Web application providing a User Interface to the two types of users (final users, and administrators); and the backend, which provides the necessary business logic through a well-defined REST API. The backend relies, in turn, on a relational database to persist any kind of data associated to the implemented functionality, like for instance the user requests, the observation data coming from the SLR stations, or the orbits generated from them.

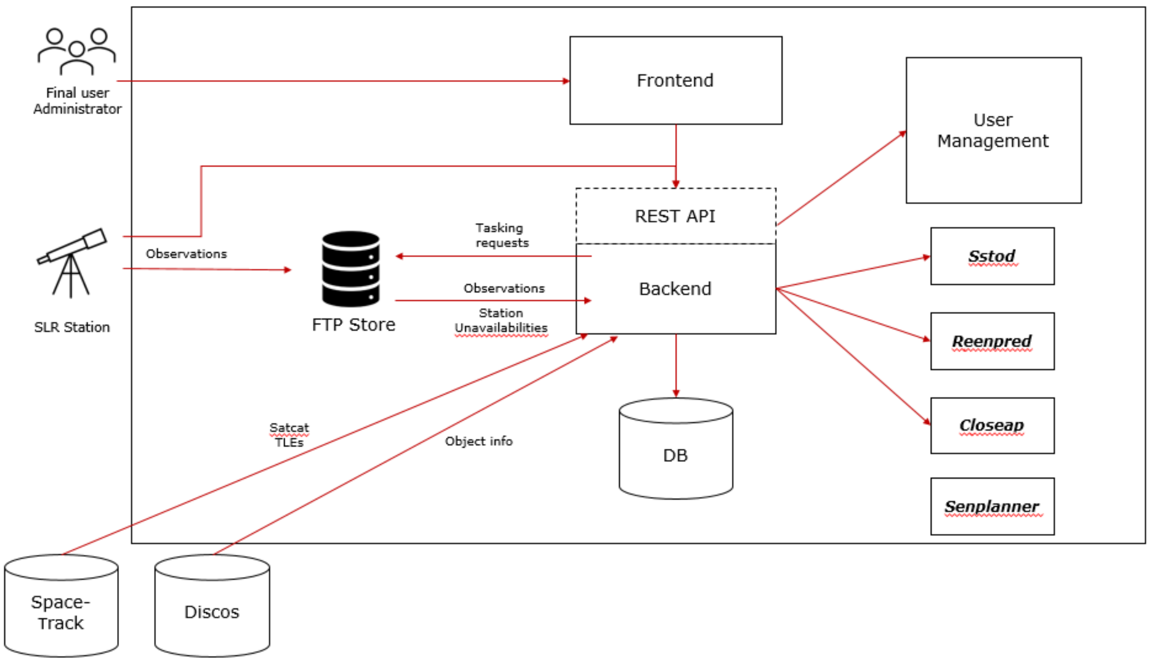

Figure 6: Overall architecture of the DLTN-OP

The SLR stations can provide their observations by uploading the observation data files to an FTP store exposed by the DTLN-OP. This store is constantly monitored by the system to get and ingest the observations as soon as they are made available by the stations. This interface is also used to command the stations with the tasking requests calculated by the system. The SLR stations are requested to get the tasking requests from there as well.

The SATCAT and TLEs catalogue are routinely downloaded from Space-Track (https://www.space-track.org) to get an updated catalogue of objects in the system. This information will be complemented with data coming from ESA's DISCOS database (https://discosweb.esoc.esa.int/) to get more accurate information about the mass, area and other properties of every object of interest. Although not depicted in the figure for the sake of clarity, solar activity, earth orientation parameters and leap seconds are routinely downloaded from external sources.

The User Management is a functional component in charge of maintaining the users database and of implementing the necessary logic to guarantee that any access to the REST API is properly authenticated and authorised depending on the user role. It has been identified as a separate module and not within the Backend to implement it through an open-source solution, named Keycloack.

Sstod, ***Reenpred***, ***Closeap*** and ***Senplanner*** are GMV COTS software components in charge of implementing the computational layer in every use case. ***Closeap*** provides conjunction analysis capabilities and is used for CDM refinement. ***Reenpred*** is intended to be used for re-entry refinement. ***Senplanner*** is to be used to, from one side, perform an initial calculation of visibilities of an object and, on the other side, calculate the plans to task the sensors network. Finally, ***Sstod*** is used in the other use cases for orbit determination and sensor calibration.

Every component is deployed in a separate container. In particular, ***Sstod***, ***Reenpred***, ***Closeap*** and ***Senplanner*** are volatile containers, meaning that the container is run when the COTS is called and disposed when the call ends and the result is returned via the corresponding outputs. The other containers are never stopped, and they are always running as services.

The following figure depicts the home page of the DLTN operational platform, which contains a world-map with the different stations configured and a left menu with all functionalities available in the platform.

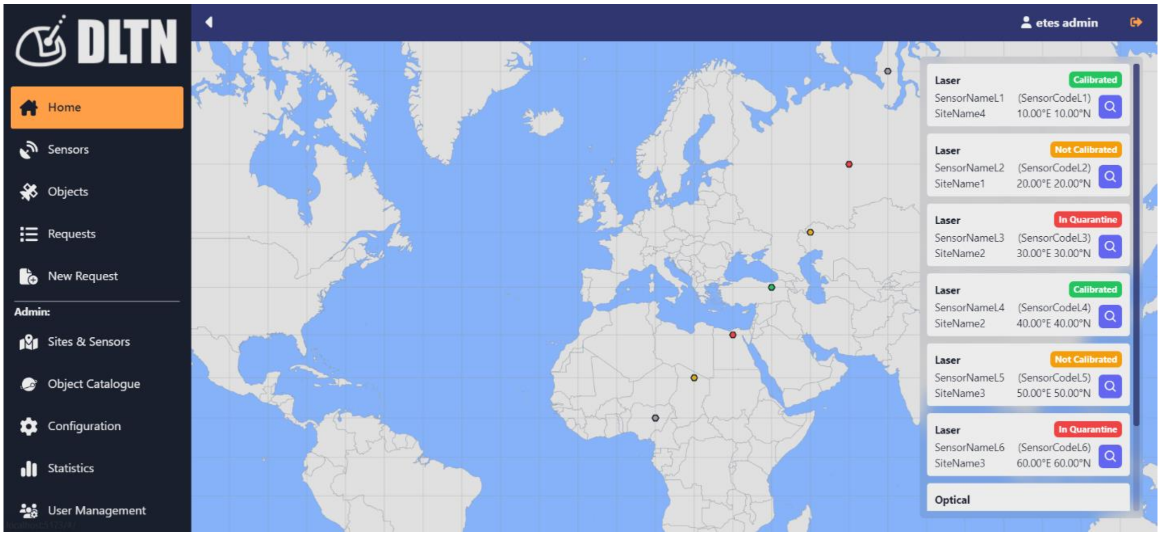

Figure 7: Home page of the DLTN operational platform

The left menu of the home page contains the following links:

- **Home**: it shows a map with all the available sensors.
- **Sensors**: it contains detailed information about the sensors.
- **Objects**: it contains detailed information about the objects and allows to create catalogue maintenance requests (see figure below).
- **Requests**: it contains detailed information about the past and present requests of a given user.
- **New Request**: it allows to generate a new request of any type.
- **Sites & Sensors**: it allows the administrator to visualize and manage all the sites and sensors in the database.
- **Object Catalogue**: it allows the administrator to visualize and manage all the objects in the database.
- **Configuration**: it allows the administrator to configure different parameters related to automatic processes and internal behaviour of the platform.
- **Statistics**: it allows the administrator to visualize some statistics about the user requests and the sensors integrating the network.
- **User Management**: it allows the administrator to manage the different user accounts and permissions.

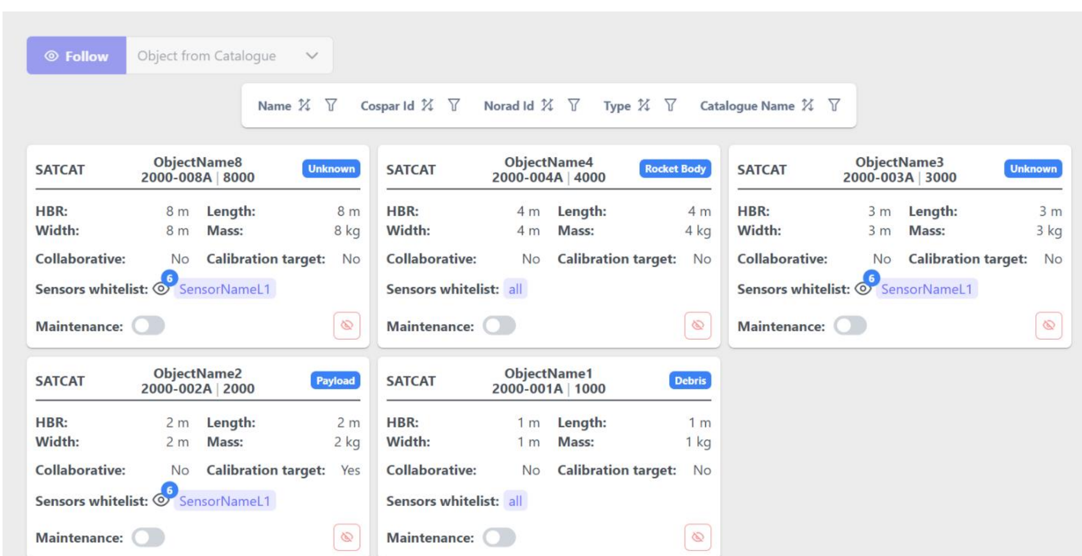

Figure 8: Objects selected in a request with context information (dummy values)

4. DLTN OBSERVATION CAMPAIGNS

An observation campaign has been designed in order to validate the developed DLTN system. The observation campaign is divided in 6 sub-campaigns intended to validate different requirements of the DLTN system, starting with a calibration campaign to test the DLTN interfaces of the platform with all the participating sensors. Table 1 below provides an overview of the different sub-campaigns. It is to be noted that each of the sub-campaigns has slightly different objectives. The details are described in the table below.

Table 1: Use case campaign list

Campaign ID	Use Case	Show case requirements
DLTN-OC-00	Calibration	a) Calibration of stations before rest of use cases in campaign
DLTN-OC-01	Collision avoidance scenario	a) Given a CDM, 7 days before the event b) Process it, improve it by a factor of 10 in terms of covariance c) Produce an improved CDM 24 hours before the event
DLTN-OC-02	Collision avoidance Scenario	a) Given a CDM from Agency operator b) Process it, improve it by a factor of 10 in terms of covariance c) Produce an improved CDM 24 hours before the event
DLTN-OC-03	LEO space debris catalogue	a) Given 5 objects with a size as low as 10 cm. b) Keep a 10 m accuracy orbit for e.g. 2 weeks c) Provide at least an observation of the object every 8 hours
DLTN-OC-04	Re-entry	a) Given a list of predicted re-entries in agreement with ESA b) Plan, schedule, and coordinate observations campaign within the DLTN with the aim of improving orbit accuracy, improving accuracy of re-entry prediction, process the acquired data, provide data to operators
DLTN-OC-05	Daytime and night-time non cooperative laser tracking	a) Given a list of cooperative and non-cooperative space debris objects, for the validation of daytime observation capability, the Izaña station shall track it with both passive and active optical system during day-light b) Given a list of cooperative and non-cooperative space debris objects, for the validation of night-time observation capability the Izaña station shall track with passive and active optical system with a maximum Sun elevation of -10 degree c) the Izaña station shall deliver range, angular, and photometric measurements
DLTN-OC-06	Stare and Chase	a) Given an a priori prediction provided by a DLTN station, the Izaña station shall be able to track the object within minutes from the reception of the message and to chase it with laser within seconds from beginning of tracking. b) The Izaña station shall improve and distribute to DLTN the orbit prediction of an observed object within minutes from the end of the stare. c) The Izaña station shall calculate an orbit of an unknown LEO object crossing its FoV and be able to chase it with the SLR system within the same pass of the observed object d) The Izaña station shall improve in real time the prediction of a LEO object and chase it with SLR system within the same pass of the observed object

The following provides the observation campaigns duration and schedule.

- DLTN-OC-00: 1 day in August 2024
- DLTN-OC-01: 3 – 7 days in September-October 2024
- DLTN-OC-02: 3 – 7 days in September-October 2024
- DLTN-OC-03: 3 days in September-October 2024
- DLTN-OC-04: 1 – 3 days September-October 2024
- DLTN-OC-05: 1 – 3 days in October – November 2024
- DLTN-OC-06: 1 – 3 days in October – November 2024

The following SLR stations, given by name, country and ILRS code, the are expected to participate:

- Graz, Austria (GRZL)
- Borowiec, Poland (BORL)
- San Fernando, Spain (SFEL)
- Mt Stromlo, Australia (STL3)
- Tsukuba, Japan (TKBL)
- Herstmonceux, United Kingdom (HERL)
- Wetzell, Germany (WETL)
- Izaña, Spain (IZ1L)

The overall campaign will be optimised such that all the use case sub-campaigns will be overlapped to optimize the stations availabilities. The campaigns are set to start in end of Summer 2024. A minimum number of 5 participant SLR stations shall be selected for each observation campaign (DLTN-OC-01 – DLTN-OC-04) considering different selection criteria. The schedule also accounts for the required flexibility in case of adverse weather and/or technical issues with the sensors.

In order to maximize the efficiency of observation campaigns, the campaigns DLTN-OC-01, DLTN-OC-02, DLTN-OC-03 and DLTN-OC-04 will be combined and performed in September-October 2024. The campaign is planned to have a balance among the different stations, maximizing the overall observation time for the overall network. During the execution of the campaign, the detailed planning will tackle the goals of the different sub-campaigns, scheduling the sensors to refine the re-entry and collision scenarios with the high priority while using the cataloguing as a low priority request, given the subset of objects visible from the stations at execution period of the campaign. Once the re-entry and collision scenarios have been considered completed, the overall resources will be dedicated to the cataloguing.

In October and November 2024, the second round of campaigns will take place. The focus will be only on non-collaborative targets, and the Stations GRZL, SFEL, BORL, STL3, TKBL are expected to participate. All scenarios DLTN-OC-01, DLTN-OC-02, DLTN-OC-03, DLTN-OC-04 will be followed up with the Izaña Station, main station of the DLTN, which is being developed by Digos in parallel to the DLTN-OP. The DLTN-OC-05 campaign, dedicated to day- and night-time non cooperative targets, will be handled by Izaña with the participation of other 5 stations. The Stare and Chase campaign will be managed by the Izaña Station with a new mount of the space debris laser ranging system. The overall aim is to get enough tracks for each object to trigger refinement of orbital information which is a last step of DLTN-OP requests.

5. CONCLUSIONS

This paper has presented the Debris Laser Tracking Network (DLTN), a system conceived by the European Space Agency to track objects using Space Debris Laser Tracking, and composed of two main elements: the DLTN Sensor Network (DLTN-SN) and the DLTN operational platform (DLTN-OP), developed by GMV. The platform and main use cases supported have been presented, together with the observation campaigns being performed to validate the entire DLTN.

ACKNOWLEDGMENTS

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