

OpSTAR: An In-Orbit Demonstrator for Optical Time Transfer and Positioning in Future Space Networks

Sinda Mejri^{*}, David Ibanez, Daniel Blonski, Stijn Mast, Thomas Fuhrmann, Bernardino Quaranta, Lucien Canuet, Matteo Loche, Jose Angel Avila Rodriguez
ESA ESTEC (European Space Research and Technology Centre) is Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

ABSTRACT

The convergence of optical communications and high-precision timing offers new opportunities for future space-based Positioning, Navigation, and Timing (PNT) systems. The European Space Agency's Optical Synchronized-Time and Ranging (OpSTAR) mission is an in-orbit demonstrator conceived to validate optical time-transfer and ranging technologies and to assess their contribution to system- and user-level PNT performance. The system comprises two satellites in medium Earth orbit equipped with dual laser communication terminals and a ground segment including co-located optical ground stations, both adapted with PNT-specific functions enabling optical inter-satellite and space-to-ground links. This paper presents the OpSTAR system concept and, in particular, the methodology adopted for its in-orbit demonstration plan. The campaign follows a progressive and dependency-driven approach, in which experimentation areas build from the establishment and characterization of the optical links toward picosecond-level time synchronization, centimeter-level ranging, and the assessment of positioning performance. Higher-level experiments address system resilience under degraded link or clock conditions, long-term performance, and autonomous operation, while dedicated interoperability activities assess multi-vendor optical terminal compatibility. The resulting demonstration framework establishes a structured path from individual optical-link capabilities and observables to end-to-end PNT performance assessment. OpSTAR is therefore intended to provide system-level evidence on the applicability, performance, robustness, and interoperability of optical time-transfer and ranging technologies, supporting their maturation toward future operational optical PNT architectures.

Keywords: Optical PNT, optical time transfer, optical ranging, laser communication terminals, optical inter-satellite links, optical ground stations, in-orbit demonstration, interoperability, Future GNSS.

* Sinda.mejri@esa.int

1. INTRODUCTION

Future space-based PNT systems are expected to require increasingly accurate and resilient synchronization and ranging capabilities. In this context, optical technologies offer significant potential by combining high-capacity communications with precise time-transfer and ranging functions. Previous studies have investigated optical inter-satellite links as an enabling technology for future GNSS architectures, combining precise synchronization and ranging with high-capacity communications [7]. Experimental demonstrations have further shown the feasibility of combining two-way optical time and frequency transfer with data transmission over atmospheric free-space links [3]. More recently, real-time digital implementations have demonstrated how precise time-transfer observables can be integrated directly into optical communication waveforms and processing architectures [6]. The integration of these capabilities within a common optical infrastructure could enable new system architectures in which optical links contribute simultaneously to connectivity, synchronization, ranging, and ultimately navigation performance.

While individual optical communication, timing, and ranging technologies continue to mature, their integration into an operationally representative PNT system requires validation beyond individual components or links. In particular, an in-orbit system-level demonstration is required to determine how optical-link performance and derived timing and ranging observables propagate into synchronization, orbit determination, positioning, resilience, and operational performance.

Operational aspects such as link availability, degraded configurations, long-term behaviour, autonomy, and interoperability between different terminal implementations are also important considerations for future optical PNT systems.

The European Space Agency (ESA) is addressing these aspects through the Optical Synchronized-Time and Ranging (OpSTAR) in-orbit demonstrator. OpSTAR is based on two satellites in medium Earth orbit equipped with dual laser communication terminals, complemented by a ground segment including co-located optical ground stations. The architecture enables optical inter-satellite and space-to-ground links to be exploited for communication, precise time synchronization, and ranging. A central element of OpSTAR is its progressive and dependency-driven demonstration approach. The experimentation campaign builds from optical-link establishment and characterization toward precise time synchronization and ranging, before progressing to positioning performance, resilience, autonomous operation, and interoperability.

This paper presents the OpSTAR system concept and focuses particularly on the demonstration plan, its experimentation areas and their dependencies, and the methodology adopted to progress from individual optical-link capabilities toward end-to-end PNT performance assessment.

2. OPSTAR MISSION CONCEPT AND OBJECTIVES

2.1 Mission concept

OpSTAR is conceived as an in-orbit demonstrator to investigate the use of optical links for precise time transfer, ranging, and PNT. The mission provides an integrated environment in which optical communication terminals are exploited not only for data connectivity, but also for the generation of precise timing and ranging observables and their subsequent use within a PNT system. The OpSTAR space segment consists of two satellites in Medium Earth Orbit (MEO), each equipped with two laser communication and ranging terminals (LCRT). This configuration enables optical inter-satellite links (OISL) between the two spacecraft while simultaneously supporting optical space-to-ground links (OSGL). The space segment is complemented by a ground segment comprising co-located optical ground stations, providing the ground infrastructure required for the optical space-to-ground demonstrations. The resulting end-to-end OpSTAR mission architecture and its principal optical links are illustrated in Figure 1.

The combination of OISL and OSGL provides the fundamental architecture for evaluating optical time transfer and ranging in both space-to-space and space-to-ground configurations building upon concepts previously investigated for optical-link-enabled future GNSS architectures [7]. By integrating these capabilities within a common system, OpSTAR enables the resulting optical observables to be assessed beyond individual link performance and ultimately in terms of their contribution to system- and user-level PNT performance.

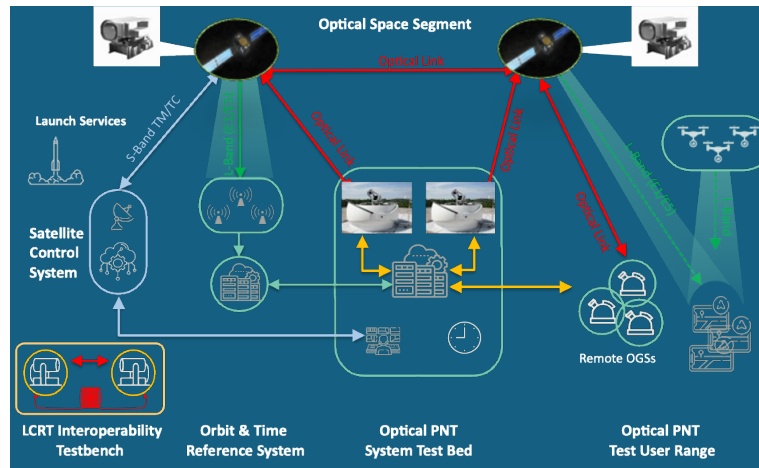


Figure 1. OpSTAR mission concept showing two MEO spacecraft, optical inter-satellite and space-to-ground links, and the co-located optical ground stations.

During simultaneous visibility of both spacecraft from the optical ground segment, the OISL and two OGSLs can additionally be operated as a closed optical measurement topology. This configuration provides a dedicated means of assessing the consistency of time-transfer observables generated across the different optical links [2].

2.2 Demonstration objectives

The main objective of OpSTAR is to demonstrate the use of optical links as an integral part of a future space-based PNT system. The demonstration objectives are therefore defined across several levels, progressing from the establishment of the optical links to the assessment of their contribution to end-to-end system and user performance.

At link level, the first objective is the establishment and characterization of optical inter-satellite links (OISL) and optical space-to-ground links (OSGL). This includes the assessment of acquisition, tracking, link continuity, and overall link robustness, providing the foundation required for all subsequent experiments.

At measurement level, the optical links are exploited for precise time synchronization and ranging. OpSTAR targets the demonstration of picosecond-level time synchronization and centimetre-level optical ranging in both space-to-space and space-to-ground configurations. These experiments provide the timing and ranging observables required for the subsequent PNT assessment. At system and user level, the objective is to determine how the optical observables translate into positioning performance. This allows the benefits and limitations of optical time transfer and ranging to be evaluated within the complete PNT chain rather than solely in terms of individual link or measurement performance.

Beyond nominal performance, OpSTAR also addresses robustness, resilience, and operational aspects. Dedicated demonstrations will investigate system behaviour under degraded conditions, including reduced link availability or clock failures, as well as long-term performance and autonomous operation.

Finally, multi-vendor interoperability forms a transversal objective of the demonstration. Interoperability activities aim to validate compatibility between different optical terminal implementations and to provide input toward open interfaces and standards for future optical PNT systems. OpSTAR is therefore conceived as a system-level demonstrator rather than an isolated optical-terminal experiment. The resulting hierarchy of demonstration objectives, progressing from optical-link establishment toward system level PNT performance, resilience, autonomy, and interoperability, is summarized in Figure 2 and forms the basis of the demonstration methodology described in section 4.

Level	Objective	Key output
1 	Establishment and characterization of OISL and OSGL	- Demonstrated optical connectivity - Link performance and availability
2 	Optical time synchronization	- Picosecond-level time synchronization - Time-transfer validation for PNT
3 	Optical ranging	- Centimeter-level ranging - Range observables for PNT
4 	Assessment of positioning performance	- Validation of positioning contribution - Contribution of optical observables to system and user level
5 	Robustness and resilience	- Resilience to degradations and failures - Availability and continuity of PNT service
6 	Operational and autonomous aspects	- Long-term performance and stability - Level of autonomy and operational readiness
7 	Multi-vendor interoperability	- Interoperable multi-vendor links - End-to-end PNT interoperability

Figure 2 OpSTAR demonstration objectives from optical-link validation to system-level PNT assessment.

3. OPTICAL PNT SYSTEM ARCHITECTURE

3.1 Space segment

The OpSTAR space segment consists of two spacecraft in MEO, each equipped with two laser communication terminals (LCTs). The dual-terminal configuration enables the establishment of OISL between the two spacecraft as well as OSGL with the optical ground segment. The optical terminals therefore constitute a key element of both the communication and PNT architecture of the demonstrator.

Within OpSTAR, the LCRTs are exploited beyond their conventional communication function. In addition to providing optical connectivity, the optical links support the generation of precise timing and ranging observables. The integration of precise time-transfer functionality within an optical communications link has also been demonstrated using digital communication waveforms and conventional coherent receiver processing, illustrating the potential for communication and timing functions to share a common optical terminal architecture [6]. The terminals consequently interface with the spacecraft timing and navigation functions, allowing the optical measurements to be related to the on-board time reference and subsequently used within the PNT processing chain.

This architecture enables communication, time synchronization, and ranging functions to be supported through a common optical infrastructure. The OISL provides the basis for exchanging information and performing time-transfer and ranging measurements between the spacecraft, while the OSGL extends these capabilities to the ground segment. The combination of both link types allows the timing and ranging relationships between the space and ground nodes to be characterized within a common system architecture.

3.2 Ground and experimental segment

The OpSTAR ground and experimental architecture comprises three main building blocks: the Ground Control Segment (GCS), the Mission Experimentation Segment (MES), and the Orbit and Time Reference System (OTRS). The Ground Control Segment provides the conventional spacecraft monitoring, control and TT&C functions required for mission operations. The MES provides the infrastructure for the preparation, execution and evaluation of the optical communication and PNT experiments, while the OTRS generates independent orbit and clock reference products used for performance verification. The resulting ground and experimental architecture, including the interfaces between the GCS, MES, OTRS and the end-to-end performance assessment, is shown in Figure 3.

The MES includes two interoperable Optical Ground Stations (OGSs) together with the experiment coordination and data-processing infrastructure. The OGSs provide the optical space-to-ground interface with the OpSTAR spacecraft and support the communication, time-transfer and ranging experiments. The experimental infrastructure coordinates the different optical-link configurations and provides the processing and synchronization capabilities required for their verification [1].

Beyond optical link establishment, a central function of the MES is to provide a controlled and traceable reference environment for the characterization of the optical observables. Common timing and frequency references, together with well-defined measurement reference points and dedicated calibration functions, enable signal-path delays and systematic biases to be characterized. This traceability is particularly important for two-way optical time transfer, where the estimated clock offset is affected by differential hardware delays, atmospheric propagation, relative endpoint dynamic, relativistic effects and clock behavior [12]. Preliminary analysis of the OpSTAR close-loop configuration identifies the characterization of hardware and atmospheric delays as particularly important picosecond level time transfer accuracy [2].

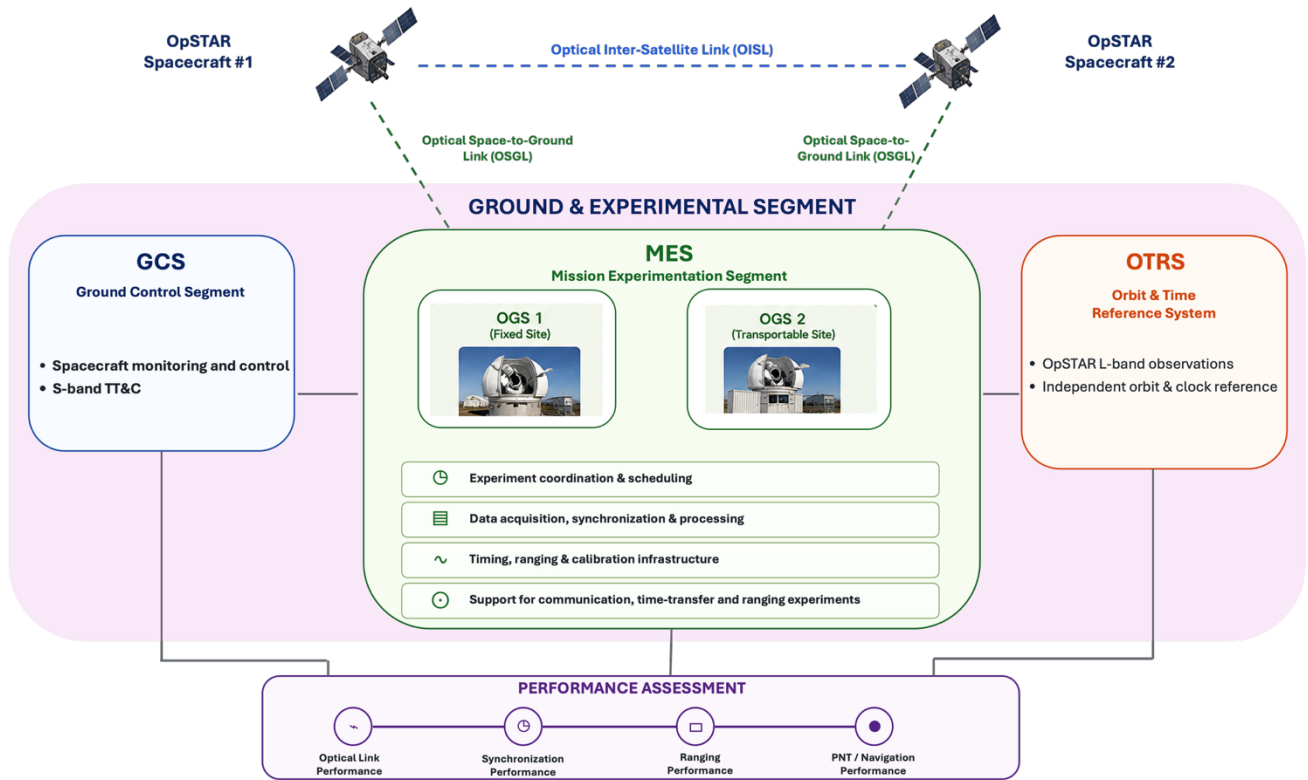


Figure 3 OpSTAR Ground and Experimental Segment architecture and its interfaces with the space segment and end-to-end PNT performance assessment.

The acquired optical-link measurements are processed and correlated with the corresponding timing, ranging and navigation observables, enabling the performance observed at link level to be propagated towards system-level PNT performance. Complementing this experimental chain, the OTRS derives independent orbit and clock reference products from OpSTAR L-band observations. These products provide an external reference against which the synchronization, ranging and navigation performance obtained from the optical measurements can be assessed.

Together, these elements provide the controlled and traceable environment required for end-to-end assessment of optical timing, ranging and PNT performance.

3.3 User segment and PNT observables

The OpSTAR user segment provides the final step in the end-to-end demonstration chain, translating measurements generated by the optical links into PNT observables and, subsequently, into user-level positioning and navigation performance. This enables the benefit of the optical links to be assessed not only in terms of their intrinsic communication or measurement performance, but also through their contribution to the resulting PNT solution.

OISL and OSGL measurements are processed and calibrated to derive time-transfer and ranging observables, which are subsequently introduced into the PNT processing chain. This establishes the functional connection between optical-link performance, measurement quality and the positioning and navigation performance ultimately available to the user, while preserving traceability across the complete demonstration chain. The experimental methodology used to establish this progression, and the subsequent system- and user-level PNT assessment, are described in Sections 4.1 and 4.4, respectively.

4. IN-ORBIT DEMONSTRATION AND EXPERIMENTATION CONCEPT

4.1 Progressive experimentation approach

The OpSTAR in-orbit demonstration is structured as a progressive and dependency-driven experimentation campaign. The campaign is conceived as an incremental verification chain, in which each experimentation level establishes not only a demonstration result, but also the performance, calibration, and operational conditions required for interpreting the subsequent levels. The objective is therefore not to execute a collection of independent experiments, but to progressively establish and validate the capabilities required to assess optical time transfer and ranging within an end-to-end PNT system.

The campaign begins with the establishment and characterization of the OISL and OSGLs, providing the validated optical infrastructure required for subsequent time-transfer and ranging experiments. Once these observables have been characterized, including their relevant calibration and uncertainty contributions, they are propagated into system- and user-level experiments to assess their contribution to positioning performance. The campaign is subsequently extended toward increasingly representative operational conditions, including degraded configurations, resilience, long-term performance, and autonomous operation.

Open-loop and closed-loop configurations complement this progression. Individual measurement paths can first be characterized independently, while closed-loop configurations combining OISL and OSGL observables provide additional means of assessing the internal consistency of independently derived measurements and identifying residual systematic contributions associated with calibration, hardware delays, and the measurement geometry across the space-ground architecture.

Calibration and measurement traceability, as well as multi-vendor interoperability, are treated as transversal aspects of the campaign. Experiment execution is additionally adapted to orbital geometry and space-ground co-visibility, allowing compatible activities to be performed in parallel where operational conditions permit.

Table 1 summarizes the resulting progressive experimentation framework and the representative assessments associated with each verification level. For each experimentation level, performance is assessed through defined observables and verification metrics, including link availability and stability, time-transfer accuracy and stability, ranging accuracy, residual calibration biases, closed-loop consistency, and the resulting positioning performance.

Table 1 Progressive OpSTAR experimentation framework.

Experimentation level	Main objective	Representative assessment
Optical link characterization	Establish and characterize OISL and OSGL	Acquisition and tracking, link performance, availability and stability
Time synchronization	Characterize optical time-transfer observables	Clock offset, synchronization accuracy and stability, systematic effects
Optical ranging	Characterize ranging observables	Ranging accuracy and stability, biases and calibration
Closed-loop verification	Assess consistency across combined OISL/OSGL measurement paths	Loop consistency, residual biases, calibration and measurement traceability
System & user PNT	Determine how optical observables contribute to the PNT solution	Positioning performance and incremental benefit of optical observables
Robustness & autonomy	Assess performance under representative and degraded conditions	Link/clock failures, resilience, long-term behaviour and autonomous operation

4.2 Optical link experiments

The establishment and characterization of the optical links constitute the first level of the OpSTAR experimentation campaign and provide the foundation for all subsequent time-transfer, ranging, and PNT experiments. Both OISL between the two OpSTAR spacecraft and OSGL between the spacecraft and the optical ground segment are considered.

The initial experiments address the complete sequence required to establish and maintain OISL and OSGL connectivity, including acquisition, transition to tracking, link stability, continuity, and recovery following loss-of-link events. The resulting measurements will characterize repeatability and operational availability under representative in-orbit conditions and, for OSGL operation, under the applicable space-to-ground geometry and optical-ground-segment constraints.

The resulting measurements will provide a characterization of the optical-link performance and operational conditions under which reliable connectivity can be achieved. These results are important not only for evaluating the communication function of the optical terminals, but also for establishing the conditions under which sufficiently stable optical links are available for precise time-transfer and ranging measurements. Selected link configurations also support optical data-relay experimentation, illustrating the multifunctional use of the common optical infrastructure for communication and PNT functions. Previous terrestrial experiments have demonstrated simultaneous optical data transmission and two-way time and frequency transfer over a 10.45-km atmospheric path, providing experimental evidence that communication and precise timing functions can coexist on a common bidirectional optical link [3]. OpSTAR extends this principle to representative MEO space-to-space and MEO space-to-ground configurations and to their evaluation within an end-to-end PNT system.

4.3 Time synchronization and ranging

Following the establishment and characterization of the optical links, the next level of the OpSTAR demonstration addresses precise time synchronization and optical ranging. These experiments exploit the validated OISL and OSGL connectivity to derive the timing and ranging observables required for subsequent PNT processing. OpSTAR targets the demonstration of picosecond-level time synchronization and centimetre-level ranging, with the objective of characterizing the achievable performance under representative in-orbit conditions. Recent laboratory demonstrations of bidirectional optical links for next-generation GNSS have experimentally verified precise two-way time-transfer and ranging concepts under representative link-power conditions [11]. OpSTAR extends this verification toward an integrated in-orbit environment combining OISL and OSGL measurements with system- and user-level PNT assessment.

For time synchronization, the optical links are used to exchange timing information between the participating nodes and to estimate their relative time offset. The experiments will assess the capability of the optical system to transfer timing information with high precision and to support synchronization between the corresponding time references. The resulting time-transfer observables will be characterized in terms of their accuracy and stability and will subsequently provide inputs to the higher-level PNT experiments.

In parallel, the optical links are exploited to derive precise ranging observables between the participating nodes. The ranging experiments aim to characterize the achievable measurement performance and its stability over the different link configurations and operational conditions. Together, the timing and ranging measurements provide complementary observables that connect the optical-link layer to the navigation and positioning functions of the demonstrator.

The combination of OISL and OSGL measurements provides complementary space-to-space and space-to-ground timing and ranging observables, relating the spacecraft measurement geometry to the ground-based timing and reference infrastructure. A specific OpSTAR experimentation configuration exploits the simultaneous operations of the OISL and the two OSGLs to establish a closed optical measurement loop between the two spacecraft and the ground segment [2]. The resulting topology provides multiple two-way timing and ranging observables linking the participating clocks and geometric paths. Comparison of independently derived observables around the loop provides a means of investigating measurement consistency, residual biases, and calibration errors that may remain hidden when individual links are considered separately. Different closed-loop topologies configuration can subsequently be exercised as the available space-ground geometry evolves, providing complementary consistent checks across the measurement architecture. The

characterized timing and ranging observables subsequently provide the inputs to the system- and user-level PNT assessment described in section 4.4.

4.4 System and user-level experiments

Following the characterization of the timing and ranging observables, the OpSTAR experimentation campaign progresses toward system- and user-level PNT assessment. The objective is to determine how the performance achieved at optical-link and observable level translates into positioning and navigation performance, thereby establishing the end-to-end relationship between the optical measurements and the resulting PNT solution.

Under nominal conditions, the experiments will evaluate the contribution of the optical time-transfer and ranging observables to positioning performance. Previous simulation studies of optical inter-satellite links in MEO navigation constellations have shown that highly precise inter-satellite ranging can contribute to improved precise orbit determination and signal-in-space range performance [5]. OpSTAR provides the opportunity to investigate this relationship using experimentally derived optical observables within an in-orbit PNT demonstration. By propagating the characterized observables through the PNT processing chain, the demonstration will assess how their accuracy, stability, and availability influence the resulting system- and user-level performance. This represents an important transition from evaluating individual optical functions to assessing their benefit within an integrated PNT architecture.

The experimentation campaign will also consider degraded configurations to investigate the robustness and resilience of the system. Scenarios involving reduced optical-link availability, link interruption, or degradation or failure of clock-related functions will be considered to assess their impact on the PNT solution and the capability of the system to maintain or recover its performance. Such experiments are intended to identify critical dependencies and provide insight into the resilience mechanisms required by future operational optical PNT systems.

Beyond individual operational scenarios, OpSTAR will investigate long-term behaviour and stability. Extended experimentation will allow the consistency of the timing, ranging, and resulting PNT performance to be assessed over longer observation periods and under changing operational conditions. This is particularly relevant for identifying performance variations or systematic effects that may not be evident during individual link or measurement experiments.

Finally, higher-level experiments will address autonomous operation, investigating the capability of the system to perform selected functions with reduced ground intervention. The use of OISLs for autonomous constellation synchronization has previously been investigated through distributed clock-steering concepts in which each spacecraft maintains a local realization of a common system time [4]. Within OpSTAR, autonomous-operation experiments provide an opportunity to investigate such concepts in conjunction with representative optical-link, timing and ranging operations. This includes the progression toward autonomous management of the optical links and associated timing and ranging functions, as well as the ability to respond to changing operational conditions.

Together, these experiments extend the OpSTAR validation from individual optical-link and measurement performance to the behaviour of the complete PNT system under nominal, degraded, and operationally representative conditions. They therefore provide an essential step in assessing the applicability of optical time-transfer and ranging technologies to future operational PNT architectures.

5. INTEROPERABILITY AND END-TO-END VALIDATION

Interoperability is an important requirement for the development of future optical space networks, particularly where space and ground elements from different suppliers are expected to operate within a common infrastructure. Existing standardization and interoperability frameworks, e.g. the Consultative Committee for Space Data Systems (CCSDS), the Space Development Agency (SDA) Optical Communications Terminal Standard, and the ESA Specifications for Terabit/s Optical Links (ESTOL), provide common specifications and interfaces intended to support capability and multi-vendor optical systems [8][9][10]. For optical PNT, communication-level interoperability is necessary but not sufficient.

Independently developed terminals may successfully establish and maintain a compatible optical communication link, while the resulting timing and ranging observables may still be affected by implementation-dependent biases. PNT interoperability therefore additionally requires consistent timing and frequency interfaces, clearly defined measurement

reference planes, and characterization and calibration of relevant signal-path delays. This is particularly important for two-way time transfer, where differential transmit and receive hardware delays enter directly into the estimation of the relative clock offset and may constitute a systematic contribution if not adequately characterized and calibrated [2].

Within this context, OpSTAR addresses interoperability as a transversal element of the demonstration, extending the concept beyond optical communication compatibility towards end-to-end PNT interoperability. For OpSTAR it's foreseen to develop a dedicated an iter-operability testbed to allow the testing of multi-vendor configurations and their associated timing, ranging and calibration interfaces to be verified under controlled conditions, while the subsequent in-orbit experiments extend this assessment to representative operational links. The objective is not only to demonstrate that terminals from different suppliers can communicate, but also that the resulting optical measurements remain consistent, calibrated and traceable when used within the complete PNT processing chain.

6. CONCLUSION AND OUTLOOK

OpSTAR is conceived as a system-level in-orbit demonstrator for optical PNT, bringing together optical communications, precise time transfer, ranging, and navigation within a common experimental framework. Rather than assessing these capabilities independently, the mission aims to establish the relationship between optical-link performance, timing and ranging observables, and the resulting system- and user-level PNT performance.

A central element of the OpSTAR concept is its progressive and dependency-driven verification approach. The experimentation campaign progresses from the establishment and characterization of OISL and OSGL, through precise synchronization and ranging, toward positioning performance, resilience, long-term operation, and autonomy. This approach ensures that higher-level PNT demonstrations build upon previously validated link and measurement capabilities and enables performance to be traced through the complete end-to-end chain.

The combination of the space, ground, experimental, interoperability, and user segments provides the infrastructure required for this end-to-end assessment. In particular, the integration of common timing and frequency references, defined measurement reference planes, calibration and delay characterization, coordinated data processing, and dedicated interoperability testing enables the demonstration to extend beyond optical-terminal performance toward meaningful system-level PNT validation.

Looking beyond the demonstration itself, OpSTAR is expected to provide evidence and operational experience supporting the definition of future European optical PNT architectures. The results will contribute to understanding the achievable performance, robustness, resilience, interoperability, and autonomy of optical PNT systems, while supporting the identification of requirements, interfaces, calibration approaches, and verification methodologies needed for future operational implementation. In this context, OpSTAR provides a bridge between the maturation of individual optical communication, timing, and ranging technologies and their integration into future operational PNT systems. The demonstration is expected to support the evolution toward interoperable optical space networks in which communication, synchronization, ranging, and navigation functions can be jointly supported by a common optical infrastructure.

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