Optical Technologies for Future Global Navigation Satellite Systems

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***Abstract* — Accurate, robust and reliable positioning and timing has become crucial for a wide spectrum of applications. New technologies will further improve the services offered by Global Navigation Satellite Systems (GNSSs). Optical technologies are promising candidates to achieve significant improvements in terms of accuracy, robustness and reliability of GNSSs in near future. First and foremost, optical inter-satellite links (OISLs) and optical clock technologies show enormous potential for future applications at the core of next generation GNSS architectures. Both technologies can be implemented independently from each other in current GNSS as the development lines may differ, in particular in terms of technology readiness. We will present different tracks on how optical key technologies could potentially be integrated in next generations of GNSS, and assess the corresponding improvements.**

Keywords — Future GNSS, Optical Inter-Satellite Links, Optical Clocks, Optical Time-Transfer, Optical Ranging

I. INTRODUCTION

Global Navigation Satellite Systems (GNSSs) reached daily life usage by millions of civilian people, mostly in an unperceived manner. They provide real-time positioning, navigation and timing (PNT) solutions. Accurate, robust and reliable positioning and timing has become crucial for miscellaneous applications, in particular for safety-of-life services and in dependable applications such as autonomous driving and flying, maintenance of electrical power grids and financial infrastructures, and even in climate change measurements and corresponding research.

Thus, all GNSSs (i.e. Galileo, GPS, BeiDou, GLONASS) are permanently facing higher requirements and demands originating from user and operator sides, which lead to a continuous progress and modernization of the systems. Lately available technologies carry the potential to further improve the services offered by GNSSs. Optical technologies are promising candidates to achieve tremendous improvements in terms of accuracy, robustness and reliability of GNSSs in near future. First and foremost, optical inter-satellite links (OISLs) and optical clock technologies show enormous potential for future applications at the core of next generation GNSS architectures.

The advantages of optical technologies compared to their classical microwave counterparts are manifold, e.g. better frequency stabilities of optical clocks or higher ranging precision using optical links. Several studies of new concepts for GNSSs relying on optical technologies were already published. DLR has advanced a concept for a next generation GNSS architecture named Kepler, fully exploiting the performance of optical frequency references (OFRs) in combination with optical frequency combs (OFCs) as well as on bi-directional laser communication and ranging terminals (LCRTs) establishing inter-satellite links for precise ranging and clock synchronization [01]-[09]. With the Kepler architecture it is possible to improve the overall performance of GNSSs while simultaneously reducing the complexity and size of the required ground segment infrastructure.

It is emphasized, that a high level of improvement is already achieved by solely introducing OISL into GNSS architectures (Kepler fast-track). An advantage of this technology is that implementation in existing systems can be realized on very short time scales as the core systems of the required technology is already quite mature and exhibits reasonable heritage. Precise inter-satellite ranges enabled by OISLs would directly lead to improvements in orbit determination of the MEO (Medium Earth Orbit) satellites and, if clock synchronization capabilities are available, to clock error minimization. Moreover, the OISL can contribute to the data dissemination within systems e.g. facilitating the intra-system dissemination of constellation-keeping data, allowing new commanding and operations models with reduced ground segments, or reducing the time-to-alert if a malfunction of one satellite or several satellites is detected.

Beside optical inter-satellite links, compact, highly stable, optical clocks established by the combination of optical frequency references with optical frequency combs, show potentials to improve future generations of GNSSs by complementing or replacing current clock technologies onboard satellites.

In order to prepare the introduction of optical technologies to future GNSSs, the German Aerospace Center (DLR) together with industrial partners currently prepares an in-orbit verification (IOV) mission called COMPASSO [10]. The payload of COMPASSO comprises two optical frequency reference systems based on molecular iodine, an optical frequency comb and a bi-directional laser communication and ranging terminal (LCRT). The latter shall serve for time and frequency transfer between the orbiting payload and an optical ground station (OGS) as well as optical data dissemination and precise ranging capabilities. As a preparatory step towards operational space application, COMPASSO will be installed on the Airbus Bartolomeo platform, which is attached to the Columbus module of the International Space Station (ISS). The primary objective of COMPASSO is to validate the performance of the in-orbit operation of the mentioned optical key technologies as well as to pave the way for their long-term operations (10 to 15 years) focusing on future generations of GNSSs. Furthermore, the optical technologies tested within the COMPASSO mission, might be potential candidates for scientific space missions, such as GRACE-I/MassChange, the successor to the Gravity Recovery and Climate Experiment (GRACE) follow-on mission, the Next Generation Gravity Mission (NGGM), or the Laser Interferometer Space Antenna (LISA). Launch of COMPASSO is planned for 2026.

The following sections will show roadmaps and the advantages of introducing different optical technologies to GNSSs. We start with implementing optical inter-satellite links in GNSS architectures combined with ultra-stable quartz oscillators. This scenario is what we call “Kepler fast-track“, as the main components of the required LCRTs are already of high technology readiness level (TRL). Subsequently, we will show the potential of optical clocks complementing or replacing classical microwave clocks currently used in GNSSs. Thereafter, we will highlight the option of combining optical clocks and OISL resulting in exploiting the full potential of optical technologies. Lastly, we will depict the potential of complementing a GNSS MEO segment using OISL with an additional layer of satellites in low earth orbit (LEO) comprising optical link technologies, e.g. new LEO constellations for communication or PNT purposes.

II. INCORPORATING OPTICAL INTER-SATELLITE LINKS FOR FUTURE GNSS

Optical communication in space is a reality and considered in current and future space programs. Starting from LEO to LEO inter-satellite links (ISLs) demonstrated in 2008, by the optical terminals developed by Tesat-Spacecom, the technology has evolved providing connectivity between e.g. GEO satellites, GEO and LEO satellites and optical links from small satellites in LEO to optical ground stations. Since late 2016, the European Data Relay System (EDRS) is operational relying on optical ISLs from LEO to GEO satellites. Such technology is mature and it can be adapted to achieve precise ranging capabilities as well as time and frequency transfer between satellites (in the same or different orbits) and between satellites and ground.

A corresponding LCRT is currently developed within the COMPASSO mission by Tesat-Spacecom and DLR. Therefore, the commercially available SmartLCT (see Figure 1 and Figure 2) from Tesat-Spacecom is adapted to serve the ranging and time-transfer requirements of future GNSS applications. The LCRT is divided in four subunits with a volume of less than 35x35x20cm³ per subunit. The peak power consumption (reached during acquisition) is 130W and the mass is 30kg.

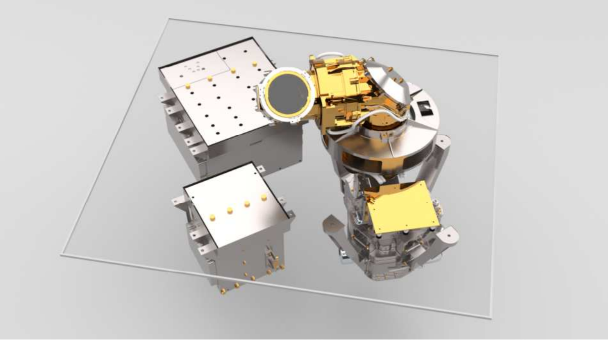

Figure 1: Sketch of the SmartLCT from Tesat-Spacecom. Copyright: Tesat-Spacecom.

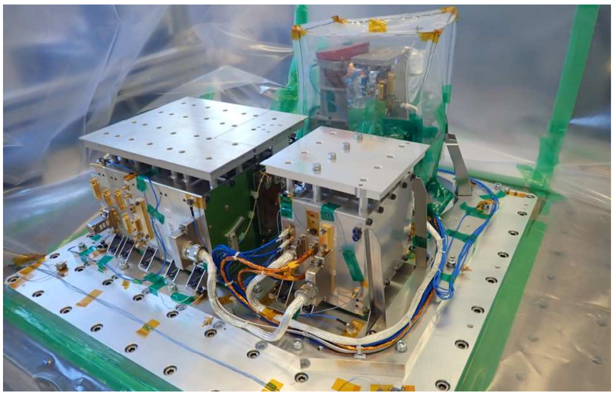

Figure 2: Picture of a flight model of a SmartLCT from Tesat-Spacecom. Copyright: Tesat-Spacecom.

The LCRT modifies the communication unit of the original SmartLCT terminal introducing an additional processing unit called OSCAR (Optical System for Communication and Ranging) which implements the required signal processing to achieve time-transfer and ranging. Additionally, an optical single mode fiber coupling is added and a coherent receiver is integrated, which allows for homodyne reception.

Currently, the clocks onboard GNSS orbiting satellites are not synchronized but are kept free-running. The GNSS ground segment, composed by many regionally or globally distributed ground stations, is used to continuously track L-band navigation signals to observe changes and deviations of the individual clocks on the satellites. They are estimated from pseudo-range and carrier phase observations in a joint Orbit Determination and Time Synchronization (ODTS) process aimed at estimating a large number of additional parameters, such as atmospheric delays, station coordinates and station clock offsets, satellite orbits, parameters of dynamical models, carrier-phase ambiguities, etcetera. Next, the satellite orbits and clocks are predicted and the information is distributed to final users via navigation messages. However, limited accuracy of the predictions results today in a 1–2 dm Signal-in-Space Range Error (SiSRE), that combines the contribution of both satellite orbit and clock errors. This error source can significantly be reduced by using OISLs for system-wide synchronization of all clocks and real range measurements between the satellites.

Each OISL enables clock comparisons between linked satellites and a constellation-wide distribution of these values in a decentralized fashion. It then becomes possible to continuously determine the clock offset of all satellite clocks by direct measurements. Due to the continuous nature of the clock measurements, it is furthermore possible to create a space-based clock ensemble for system time generation, consisting of all and only satellite clocks. This information is used to either calculate corresponding clock corrections which are distributed to navigation end-users, or to actively steer the satellite clocks towards the ensemble mean to achieve highly accurate system-wide synchronization of all on-board clocks, which is the preferred option.

It should be mentioned that in principle no long-term stable clocks are needed for this concept because satellite clocks keep synchronized and do not have to be predicted. Frequency reference systems showing excellent short-term and good medium-term (up to 100s) performance are sufficient to achieve this high level of synchronization between the satellites. Therefore, high performance oven-controlled crystal oscillators (OCXOs) can be used. They have been flown on several missions in the past and exhibit thus serious space heritage. For time distribution and reference aspects, a connection to a terrestrial time frame such as Universal Time Coordinate (UTC) is desirable. The offset of the space system time to UTC can easily be estimated from ground measurements to a timing reference station – by fixing all satellite synchronized clocks to null and estimating the station clock offset in ODTS process. Microwave atomic clocks such as RAFS (Rubidium Atomic Frequency Standards) or PHMs (Passive Hydrogen Masers) would support standard GNSS service during transition from current constellations and architectures to new concept using optical inter-satellite links. It is furthermore noted that OCXOs are typically vulnerable to extraordinary solar radiation events such as solar flares and thus additional shielding might be needed and a backup system using classical atomic clocks which show less degradation to such effects should be considered to complement the OCXOs.

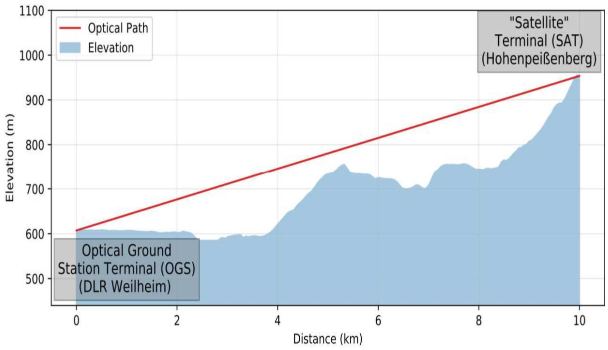

Figure 3: Sketch of the time-transfer and frequency transfer experiment via a free-space optical link over a distance of 10.45km.

In addition to highly accurate time-transfer, OISLs also provide very precise ranging measurements between linked satellites. These measurements support a precise orbit determination (POD) – which only require two terrestrial links for precise tracking of earth rotation. They also provide excellent estimates for orbits. The ranges between the satellites can be measured with sub-mm precision using the bi-directional optical free-space links and short-term stable frequency references. Simple high-performance oven-controlled crystal oscillators (OCXOs) again suffice to achieve mm-level ranging precision.

It is emphasized that in principle only two ground stations are needed to perform POD when using OISL and synchronized clocks, and can further be reduced to just one station if Earth rotation parameters are externally provided. High POD accuracy is translated into much better orbit prediction performance, autonomous and continuous clock synchronization eliminates the need of the clock prediction and reduces the clock errors to the level of synchronization errors. Simulations with perfect models show significant improvement of the prediction SiSRE – from a dm-level for Galileo to a cm-level for Kepler [07][08] which corresponds to an improvement of one order of magnitude in SiSRE. Autonomous clock synchronization and inter-satellite ranging will also significantly improve SiSRE for long-term orbit predictions which is particularly relevant in the context of GNSS AUTONAV designed for system operability (180 days) with no contact to ground.

This clearly shows the benefits of implementing OISLs between GNSS MEO satellites in very near future with moderate delta developments needed to adapt already space-proofed optical terminals with ranging and time-transfer capabilities.

First field experiments investigated the performance of optical free-space links via laser communication and ranging terminals over a link distance of 10.45 km, which corresponds to a LEO to ground link, in a terrestrial testbed (through atmospheric channel). The experiments targeted at a validation of the theoretical predictions of the precision of time and frequency transfer achievable with real hardware [28]. In these experiments, DLR successfully tested a two-way frequency transfer (TWFT) and a two-way time-transfer (TWTT), where measurement stabilities of $5 \cdot 10^{-15}$ and $2 \cdot 10^{-13}$ were achieved for the TWFT and the TWTT, respectively. It is emphasized, that the time-transfer capabilities were demonstrated by using an OCXO as frequency reference. This supports the expectation that TWTT can achieve sub-picoseconds time uncertainty and sub-mm ranging uncertainty on the optical links.

Beside the improvement of SiSRE and therewith of the overall system performance, OISL exhibit additional advantages that increases system reliability and robustness. Optical links are inherently very robust against jamming, spoofing and eavesdropping. Time-to-alert, if a malfunction within the system is detected, can be drastically reduced using a network of optical information channels between the MEO satellites. Moreover, OISL would additionally allow for quantum key encryption of information dissemination between the satellites in a further evolutionary step (not considered in very near future).

III. EXCHANGING/COMPLEMENTING CLASSICAL CLOCKS BY OPTICAL CLOCKS FOR FUTURE GNSS

On ground, optical clocks currently show the best performance in terms of both short-term and long-term frequency stability and outperform their classical counterparts by several orders of magnitude. As a result, the re-definition of the SI unit second is recently under debate [11][12].

Optical clocks mainly consist of an optical frequency reference system and an optical frequency comb, which transfers the frequency stability from the optical to the radiofrequency domain [13]-[17]. Optical frequency reference systems are stabilizing the frequency of a laser source on an electronic (or nucleus) transition of atoms or molecules comparable to the basic working principle of their classical counterparts operating in the radiofrequency or microwave regime. However, as the optical transition frequency is several orders of magnitude higher than the radiofrequencies used in classical clocks such as passive hydrogen masers or rubidium and cesium standards, and the linewidth of those optical transition is comparable low (typically below 1 Hz), much higher frequency stabilities in terms of Allan deviation can be achieved for all relevant averaging times. The most stable optical clocks show a long-term stability up to 10^{-18} [s/s], see e.g. [18]-[23]. However, the best high-performance optical frequency references are very complex and still necessitate of large hardware setups (in particular for laser cooling, beam preparation and ultra-high vacuum environments) and thus first space demonstration will not take place on very short time scales. Fortunately, there are several promising compact concepts for space applications already in the pipeline, which show better performance than classical radiofrequency references currently used. One very promising candidate is DLR's optical frequency reference based on molecular iodine.

Over the last years, DLR has developed several setups of iodine-based optical frequency references in collaboration with the Humboldt-University Berlin and the University Bremen. Those setups were developed for space applications [24]-[27] and are currently adapted for the above mentioned COMPASSO mission, c.f. Figure 5 and Figure 6. Together with an optical frequency comb developed by Menlo Systems (see Figure 4), the iodine reference serves as optical clock for the COMPASSO mission, as the stability of the iodine reference is transferred to the radiofrequency domain (here 100MHz) via the comb. For an application in Galileo, the SWaP (Size, Weight and Power) budget of the iodine reference need to be further optimized. This has been evaluated within an ESA study and several design adaptations, using e.g. a shorter iodine gas cell, are currently investigated.

It is emphasized, that for GNSS a short-term stability in the low 10^{-13} [s/s] range is sufficient to minimize clock errors when synchronizing the satellites via optical bi-direction links (i.e. OISL). Further improvement on the clock or synchronization side of the MEO GNSS satellites will not additionally contribute to increasing performance of the overall system, as other effects, such as ionospheric delays,

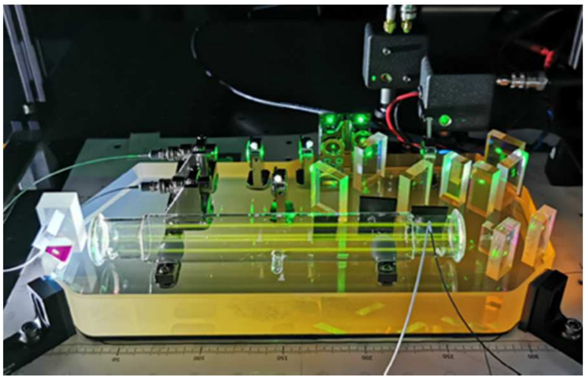

Figure 4: Picture of an iodine spectroscopy setup developed at DLR which serves as prototype for the COMPASSO mission.

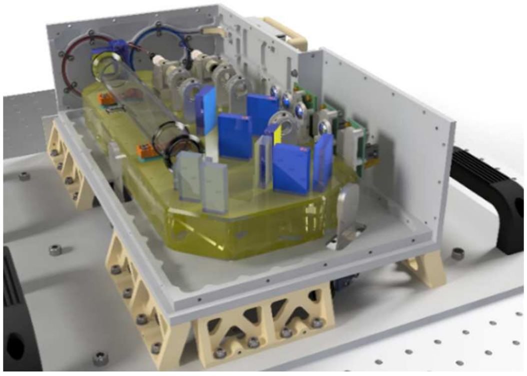

Figure 5: CAD sketch of the iodine spectroscopy placed within a thermal shield. The fiber components of the laser system are mounted to the bottom side of the shield.

Figure 6: Picture of the COMPASSO engineering model of the optical frequency comb. Copyright: Menlo Systems GmbH.

tropospheric impact, multi-path, etcetera, will dominate the errors of the positioning and timing solution for ground users in this scenario. Nevertheless, preliminary simulations without functional modelling errors reveal that the SiSRE of current GNSS architectures can be reduced up to a factor of three when POD is based on 18 ground stations, assuming that the optical clocks are extremely stable (frequency stability well below the 10^{-16} level), operate perfectly and, once estimated, are accurately predictable over long period of time without the need of re-estimation.

IV. COMBINING OPTICAL CLOCKS AND OPTICAL INTER-SATELLITE LINKS

The full potential of optical inter-satellite links is revealed if combined with optical high-performance frequency reference systems and clocks. We call this scenario the scientific or high-performance track of Kepler.

As already mentioned above, the best optical frequency reference systems on ground show outstanding frequency stability in terms of Allan deviation in both the short-term as well as in the long-term domain. Short-term stabilities down to the low 10^{-15} [s/s] or high 10^{-16} [s/s] regime are achievable by e.g. cavity-stabilized laser systems, which are furthermore typically used to pre-stabilize laser sources for optical atomic clocks. Long-term stabilities down to the 10^{-18} [s/s] regime were reported by several research institutions. It is noted that those outstanding performance measures will not be reachable for optical frequency references in space within short time frames. As already mentioned in section III, those terrestrial setups are quite complex and bulky and thus it will need extensive developments to achieve space applicable versions of the optical clocks currently showing the best performance on ground (e.g. ion traps or lattice clocks). However, the envisaged performance parameters of DLR's compact optical frequency reference based on molecular iodine vapor (see section III) are already very promising. The performance goals for this setup in the already mentioned IOV mission COMPASSO are a short-term stability in the low 10^{-12} regime and a long-term performance in the low 10^{-14} regime. Those performance parameters strongly depend on the used laser source and can dramatically be improved (1-2 orders of magnitude in the short term) by using a more stable laser to be stabilized on the iodine transitions. This could be achieved on short time scales by e.g. a pre-stabilization by a cavity, which is currently under development for space application by different institutions.

First studies of optical free-space frequency and time-transfer capabilities using bi-directional coherent laser terminals under controlled environmental conditions demonstrated that the short-term stability of such high-performance optical frequency reference systems can be transferred without substantial degradation [04]. For longer averaging times the Allan deviation of the optical transfer channel shows a $1/\tau$ decay up to several thousand seconds. This gives evidence that the optical transfer channel is showing a better stability performance than the optical reference (cavity stabilized laser) and thus that frequency transfer capabilities are limited by the frequency reference itself. This opens a wide range of additional applications far beyond the requirements of global navigation satellite systems.

However, although the approach of combining optical frequency references with bi-directional optical links may have limited interest in a very near future for the classical (ground) scope of GNSSs, it can facilitate new approaches for space applications (e.g. LEO orbit determination) for which the atmospheric errors are largely eliminated and where OISLs and clock synchronization in GNSS should significantly improve navigation performance. This can be of great relevance especially in the field of LEO-PNT with ODTS relying on GNSS constellation, geodesy, Earth observation and scientific studies and missions. Implementing this scenario would have strong impact on e.g. monitoring and determining Earth's gravity field or the provision of terrestrial reference frames. Moreover, it would allow to compare the performance of optical frequency references over far distances, in particular between continents to a very high level of accuracy. This is currently not possible due to a lacking of proper optical fiber networks connecting different continents. An optical network established via coherent bi-directional optical ISL within the MEO segment of a future GNSS constellation would allow for comparing the best optical clocks which are located all over the globe, e.g. in Japan, USA and Europe.

The combination of optical frequency reference systems, i.e. cavity stabilized lasers and optical ISL is mainly directed at science. In an initial phase of Kepler, it was considered for global navigation as well. Since the performance of the fast-track Kepler system is sufficient for all current needs, this combination is only followed for scientific interests such as testing new clock technologies in space.

V. COMPLEMENTING THE OPTICAL MEO SEGMENT WITH AN ADDITIONAL OPTICAL LEO LAYER

The European Space Agency (ESA) is currently planning a so-called LEO-PNT initiative within its future NAV program. Although the underlying concept is not yet finalized at the time this paper was prepared, the future LEO segment shall augment the current MEO segment of Galileo. Therefore, in the request for information (RFI) process of the future NAV program, DLR proposed to implement optical inter-satellite links in the LEO layer, first and foremost to support satellite clock synchronization and enable precise orbit determination without relying on the GNSS signals broadcast by the MEO segment and large global ground infrastructure. This would allow for a fully autonomous LEO layer, resulting in an enhanced robustness and resilience of the overall future Galileo system (combination of LEO and MEO segment) or in general future GNSS.

Implementing OISL in the future LEO-PNT would perfectly match with a future implementation of OISL in the MEO segment, as described in section II. Incorporating OISL in both segments and executing OISL between both, will increase the overall robustness. Due to the radial nature of the OISLs between satellites orbiting in LEO and MEO, additional ranging information is gathered and, coupled with the L-band ranges determined by the additional LEO segment, lead to very accurate and precise orbit determination of all satellites in the system [05].

Finally, when assuming that the future LEO segment will further serve as an integrity layer for the MEO GNSS signals, we match at envisioned DLR's Kepler concept architecture

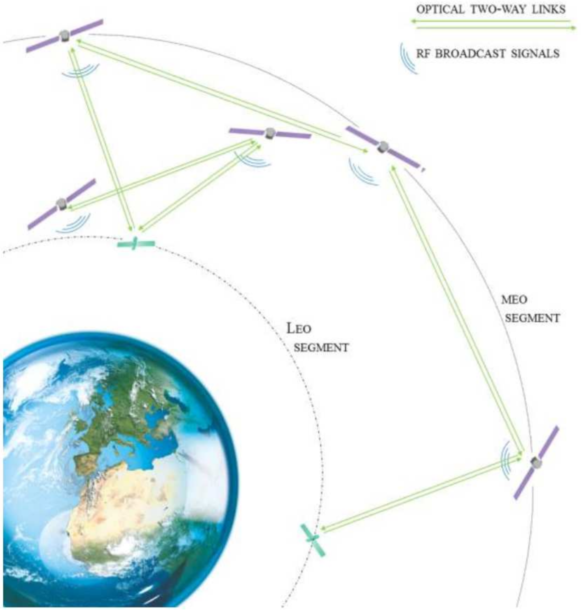

Figure 7: Sketch of DLR's Kepler architecture for a future Global Navigation Satellite System consiting of a MEO and a LEO segment comprising bi-directional link between both segements and withing the segments for synchronization, ranging and data dissimination. The LEO segment additionally provides integtrity to the braodcsted GNSS signals by the MEO satellites.

(c.f. Figure 7) which was proposed several years ago [01]. As already mentioned before, the Kepler concept is based on two important elements, namely the tight synchronization of MEO (and LEO) satellites using bi-directional optical links, which are simultaneously used for synchronization, ranging and exchange of data, as well as the in-space observation of the L-band navigation signals broadcasted by the MEO satellites by a small constellation of LEO satellites. Furthermore, the tight optical synchronization drastically reduces (and might even eliminate) clock errors from the navigation messages and serves as measurement channel for the creation of an (optical) clock ensemble in space contributing to e.g. Galileo system time.

CONCLUSION AND OUTLOOK

We presented two different types of optical technologies which will improve the performance of GNSS in the future. They are optical clocks and optical inter-satellite links for ranging, synchronization and data transfer. We emphasized the potential improvements for GNSS performance for each of the technologies separately, as well as for the combination of both technologies. We also addressed the current efforts of the European Space Agency to prepare a future LEO PNT system complementing the current MEO segment of Galileo, to highlight the advantages of implementing OISL in both segments.

Optical frequency reference systems and optical clocks show the potential to improve the robustness and the performance of GNSS. Simulations with perfect models show that the SiSRE of GNSS might be improved up to a factor of three if very stable optical clocks assure accurate predictability without the need of their re-estimation. The SiSRE improvement up to a factor of 3 was obtained for POD with 18 ground stations. In addition, high performance optical frequency references open new possibilities for scientific and geodetical missions beside their application in future GNSS and LEO-PNT. However, as maturity in space application is still lacking, their implementation in GNSS might be not as fast as e.g. optical inter-satellite links. Main challenges for future space application will be further miniaturization of the setups to decrease of the SWaP (Size, Weight and Power) budget, i.e. the development of highly stable space-proven laser sources that show the required from factors as well as corresponding spectroscopy units.

Optical inter-satellite links show enormous potential to improve the performance of existing global navigation satellite systems already in near future. The implementation of OISL between the MEO satellites of a GNSS will directly lead to an improved robustness and reliability of the overall system as optical links are inherently very robust against jamming, spoofing and eavesdropping. It is noted that OISL would additionally allow for quantum key encryption of information dissemination between the satellites in a further evolutionary step. Moreover, OISL would improve the performance of a GNSS if used for ranging measurements and clock synchronization between the MEO satellites. Simulations reveal that an improvement of one order of magnitude is possible in SiSRE by the implementation of OISL between the MEO satellites for precise ranging and clock synchronization. Simultaneously, OISL enable fast data dissemination between the satellites which can reduce the time-to-alert if malfunctions are detected within the system. Furthermore, OISL in the MEO segment will directly open the possibility to optically connect the MEO segment of a GNSS with an additional optical (communication) segment operating in LEO. As optical terminals for establishing OISL are already a mature technology for data dissemination in space, only little delta-developments are needed to enable the required ranging and synchronization capabilities for implementation in a GNSS. Ground experiments already proved the concepts and the feasibility of ranging and synchronization via optical free-space links and the COMPASSO mission will demonstrate these capabilities within the next few years in space, which will pave the way for OISL in operational GNSS in very near future.

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