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Herwig Zech

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Optical Intersatellite Links for Navigation Constellations

Herwig Zech, Philipp Biller, Frank Heine, Matthias Motzigemba

Tesat Spacecom, Gerberstrasse 49, 71522 Backnang

ABSTRACT

Satellite constellations are used for navigation purposes since long. Connecting the satellites in a constellation by intersatellite links (ISLs) offers a full range of new possibilities. Ranging and time synchronization information can be exchanged between the satellites to improve the in orbit SC positioning knowledge. Besides ranging and time synchronization, ISLs can be used for service channel purposes or to distribute SW updates for the spacecrafts in a short period of time. ISLs improve the navigation constellations autonomy properties being less vulnerable to ground station unavailabilities.

For ISLs, radio frequency (RF) and optical technologies have been investigated. Due to the shorter wavelength, a better ranging resolution can be achieved with optical than with RF ISL solutions. Optical ISLs (OISLs) offer a very attractive solution for intersatellite links in terms of size, weight and power while providing multi gigabit per second data rate capabilities. In addition, optical communication links offer high operational security and immunity to interference sources while benefitting from a non-regulated optical frequency spectrum. For those reasons, optical intersatellite links for navigation constellations have been investigated in several studies supported by DLR and ESA. TESAT with partners have investigated the benefit of OISLs for navigation systems and on the Galileo OISL Terminal design.

In this paper, the results of these studies will be presented. Various OISL connection schemes in a navigation constellation are compared. The key design parameters of a Laser Communication Terminal for navigation systems will be given. Furthermore, the results of a lab demonstration showing the parallel distribution of ranging and communication data will be summarized. The focus of the investigation is on the Galileo navigation constellation.

Keywords: Optical Intersatellite Links, Navigation systems, Galileo, Laser communication in space

1. INTRODUCTION

Several missions demonstrating LEO-LEO [1], LEO – Ground [2] and Moon-Ground [3] laser communication in the Gbps range have shown that space based laser communication is a very useful high bandwidth point to point communication method for space. LEO-GEO connections were successfully demonstrated a decade ago by the Artemis – Spot 4 mission, with data rates of 50 Mbps [4].

Based on the successful demonstrations of optical link capabilities, the European Space Agency has decided to implement a high data rate (1.8 Gbps) laser communication system between earth observation LEO S/C that are deployed in the Copernicus program of the European Union and dedicated GEO nodes with visibility of central Europe for minimum latency, quasi real-time delivery of earth observation data to the customers [5].

Today, optical communication in space is a reality and is taken into account in current and future space programs. Starting from LEO to LEO ISLs demonstrated in 2008, TESAT has built a broad portfolio of optical communication solutions ranging from powerful GEO to GEO long distance ISLs to small, low complex DTE solutions for cubesat missions. Since end of 2016, the European Data relay service is operational relying on optical intersatellite links from LEO to GEO orbits.

Optical ISLs offer a very attractive solution for intersatellite links in terms of size, weight and power while providing multi gigabit per second data rate capabilities. In addition, optical communication links offer high operational security and immunity to interference sources while benefitting of a non-regulated optical frequency spectrum.

The paper is organized as follows. A crucial point for the introduction of optical communication in any kind of new application is the question of the maturity of the technology. Therefore, in chapter 2, the first operational application of optical communication in space will be described. Chapter 3 summarizes the benefits of OISLs for a navigation constellation with various connection schemes. The parallel transmission of data and ranging signals is given in chapter 4. An outlook for navigation constellations by making use of the full potential of OISLs is described in chapter 5, followed by a summary in chapter 6.

2. OPERATIONAL LASER COMMUNICATION SYSTEM: EDRS

Laser Communication Terminals (LCTs) suitable for link distances between LEO and GEO orbits were developed and manufactured by TESAT with the support of DLR and ESA. This second-generation LCTv2.2 design is derived from the first generation LCT concept, which was foreseen for LEO constellation applications end of the 1990s. The first LCT of the second generation was launched in 2013 on board of Alphasat. Further LCTv2.2 terminals were installed on Sentinel-1A/-1B/-2A/-2B and on EDRS-A satellites, forming together the European Data Relay Satellite System EDRS [5].

The LCTv2.2 is designed for a data relay scheme, as depicted in Figure 1. A user terminal mounted on a LEO satellite or on a UAV is transmitting the data optically to an LCT mounted on a GEO satellite. The data is then transmitted via a Ka-band downlink to a Ka-band ground station. The main advantages of the data relay scheme is its ability to bring the data directly to the processing center in near real time. This is because for more than half of the user satellites orbit, visibility to the GEO is given. In addition, the Ka-band ground stations can be placed close to the data processing center rather than close to the poles.

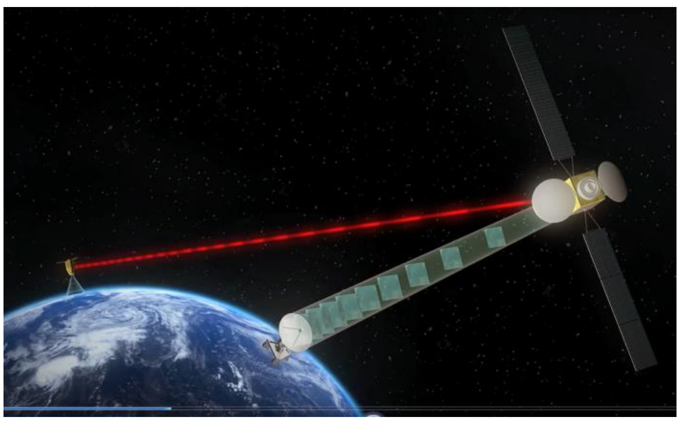

Figure 1 Data relay scheme. A LEO satellite or a UAV is sending optically a data stream (shown in red) towards the GEO satellite, shown on the right. From the GEO satellite, a Ka-Band RF transmission to a ground station follows

The Alphasat LCT was the first build of the second generation LCTv2.2. Figure 2 shows the LCT shortly before integration into the Spacecraft.

Figure 2 Alphasat LCT with Coarse Pointer opened; radiator interface is located on the left side.

Since the end of 2016, EDRS is operational, serving about 40 optical LEO to GEO links per day [6] [7].

3. BENEFITS FOR NAVIGATION CONSTELLATIONS

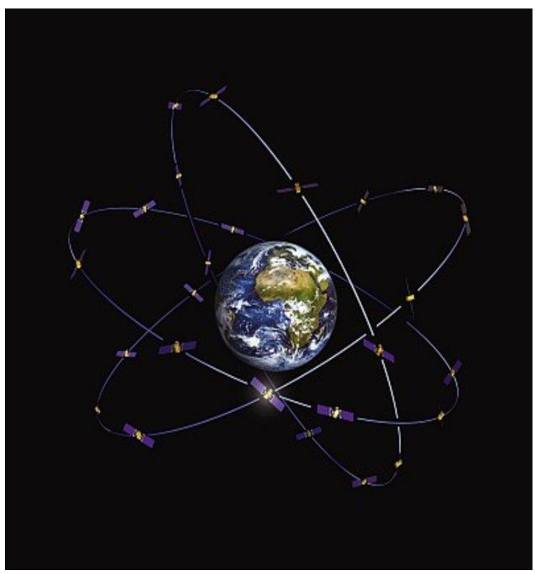

Figure 3 Galileo satellite constellation with 24 active satellites in a Walker constellation.

An overview of the Galileo constellation can be found in [8]. When fully deployed, Galileo will have 24 satellites organized in 3 planes with 8 active satellites each. The constellation operates at 23.222 km above sea level, following a so-called 27/3/1 Walker constellation (including three spare satellites), see Figure 3.

3.1 Benefits for Galileo by using OISLs

Optical Intersatellite links bring potential benefits for Galileo in the following areas:

Operational benefits
- Virtual ground station for all S/C (add, drop and transmit capability)
- Longer communication window for S/C operators
- No ITU regulations required
- Robustness against ground station unavailability

Security improvements
- No Interference
- No Jamming
- Robust against eavesdropping
- Key distribution (quantum keys)
- Shorter time to Integrity Alert (SOL)

Performance benefits
- Highly accurate orbit determination
- High bandwidth commercial service
- Higher data update rates
- Higher Ephemeris / Clock update rates
- Improved constellation geometry measurement (ring topology)
- Ability for swarm intelligence (S/C cluster)
- Ability of hardware savings (clock redundancy)
- Immediate clock dissemination and synchronization of all S/C (close to real time)
- Immediate TC/TM for all S/C
- Latency reduction:Urgent S/C information can be sent around the ring and reaches ground within seconds
- One groundstation can serve all SCs at the same time.
- Information flow around the ring possible in clock-wise and counter clock-wise direction

3.2 OISLs vs RF ISLs

In this section, the main differences between OISLs and RF ISLs are explained.

Due to the shorter wavelength in the optical domain, a much better ranging resolution than can be achieved with optical than with classical RF solutions.

The higher carrier frequency in the optical domain opens up a larger spectrum. Therefore, OISLs do have the capability for higher data rate throughput.

As the optical beams are much narrower than RF beams, no interference with other potential optical communication systems will occur. Therefore, the optical frequency spectrum is not regulated, which makes the planning and operation of a navigation constellation much easier.

Due to the narrower beams, OISLs are more robust to jamming and interception compared to RF ISLs.

Due to the narrower beams in the optical domain, it takes more time to reposition the beam pointing mechanisms to the starting position. In an “Any-to-Any” scenario, see below, RF links can be established faster than optical links. Due to the bidirectional nature of the OISL and the capability to transfer data and ranging signals in parallel, this disadvantage can be compensated, refer to chapter 4.

OISLs do have higher requirements for the SC platform in terms of platform stability and open loop pointing accuracy. As previous SC accommodations have shown, the requirements for the OISLs are well within the range of typical SC platform properties.

3.3 OISL connection schemes

Intersatellite links can be applied in different ways in the Galileo constellation. In Figure 4, the most promising connection schemes are shown.

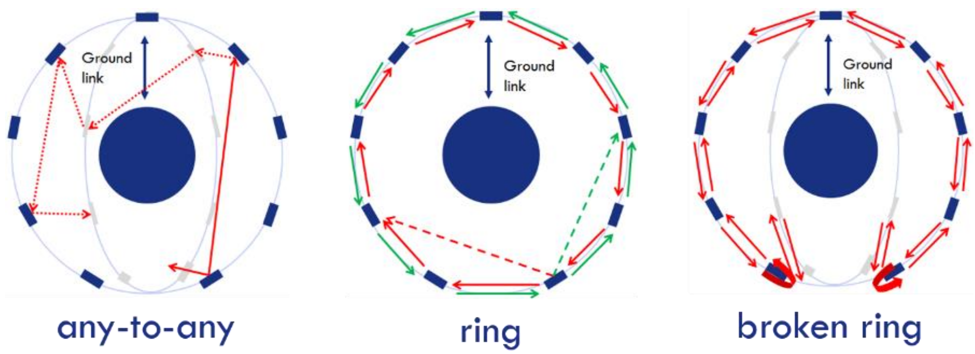

Figure 4 Intersatellite connection schemes

In the „Any-to-Any“ configuration, the SCs are setting up a link to another SC, exchanging data and ranging information. Afterwards the link is broken and the connection with a third SC will be established. Then, connection is made to a fourth SC and so forth. Typically, the time slot per link connection is in the 30 seconds range. Not taking into account visibility constraints and distance limitations, in principle, data and ranging exchange between any pair of satellites in the constellation is possible. As ranging information between any pairs of satellites can be utilized, this offers the best basis for SC positioning calculations. Only one ISL terminal per SC would be necessary. Distribution of information across the constellation is possible, but due to the time division scheme, it takes quite a while to distribute information like eg a SW update across the constellation. So, a near real time information dissemination is not possible. For a full Any-to-Any scenario, the maximum distance exceeds 55000km, which would be a design driver for the OISL terminals. Limiting the distance leads to a reduced connectivity scheme.

The “Ring” configuration has the advantage of a permanent standing connection along the ring, allowing the information distribution to all satellites in the ring in nearly realtime. This improves the capability of the constellation to cope with groundstation unavailabilities. To achieve a ring configuration, two terminals are necessary per satellite. As information is only exchanged in one plane of the constellation, the positional accuracy can only be improved along the SC trajectories.

The “Broken Ring” scenario overcomes this drawback by breaking the communication links inside one plane from time to time and setting up links to one of the neighbouring planes. Please note that due to the bidirectional nature of OISLs, the communication flow in the original planes can still be maintained. Both the Ring and the Broken Ring scenarios can be achieved with a reduced distance requirement compared to the any to any scenario. Even with the requirement to reach the over next neighbour in a plane, the distance stays below 42000km.

The three scenarios were analysed by TU Munich and compared to a GNSS constellation without ISLs. For a GNSS16 station solution, the additional ISL observations bring no significant improvement in orbit accuracy. However, in a GNSS 7 station solution, the formal orbit errors could be improved by a factor of three and differences to "true" orbit by a factor of 10 using additional ISL data. The best orbit accuracy could be achieved in an Any-to-Any scenario, whereas the orbit accuracy is not significantly worse for the other scenarios. For Any-to-Any and Broken Ring scenarios, in orbit-calibration of the ISL-instrument range biases is possible.

Optical ISLs allow for a high precision ranging and clock synchronization between satellites. Ranging allows for precise orbit determination with reduced sensor station network and thus precise orbit prediction. Precise clock synchronization provides the user a single constellation clock with short term stability corresponding to the individual clocks and long term stability corresponding to the clock ensemble. The availability of a single constellation clock and consistent clock and orbit prediction are the basis for precise navigation.

4. LASER TERMINAL FOR GALILEO

The SMART LCT is currently under development at TESAT. It was designed as a LEO user terminal for the data relay scheme. The SMART LCT will be compatible to the existing GEO LCTs in orbit, while reducing complexity, size, weight and power. The SMART LCT development is running with the support from DLR. The first flight model of the SMART LCT will be delivered in 2020.

The key functional requirements for the Galileo Laser Terminal are summarized below:

- 5 cm ranging accuracy
- Data transmission of 120kbps
- Link distance of 45000km.
- fit to a 30s time grid in an "Any-to-Any" scenario, incl repositioning of the optical beams

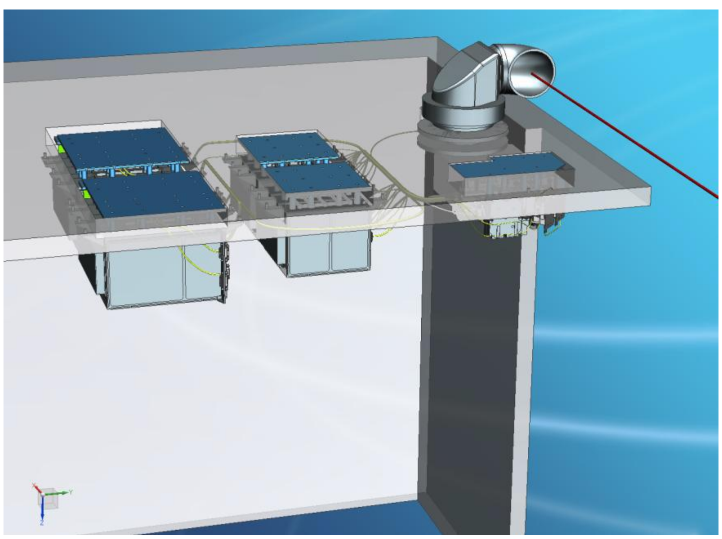

Figure 5 SMART LCT shown with the Optical Head on the right and the Communication Unit and the PAT Control electronics in a redundant scheme.

Our investigations showed that the SMART LCT operated at 1064nm fulfils the set of requirements. With 70mm of aperture and 5W of optical transmit power the link budgets for communication, acquisition and tracking are positive with significant margin.
As shown in Figure 5, the SMART LCT consists of an optical head supported by two electronic units, the PAT control electronics and the communication unit. Both electronic units can be duplicated for redundancy purposes as shown in Figure 5.

Modifications of the current SMART LCT design are necessary mostly in the communication subsystem, while the rest of the SMART LCT design can be reused. The SMART LCT design is a solid basis for the Galileo Optical Intersatellite Link (GOISL) terminal. Table 1 summarizes the key parameters for the SMART LCT adapted to the Galileo requirements.

Tab. 1 SMART LCT for Galileo: technical parameters

Item	Value
Aperture	70mm
Transmit power	5W
Operating wavelength	1064nm
Pointing range	hemispherical
Mass	45kg (Version with redundant electronics)
Power consumption	135W

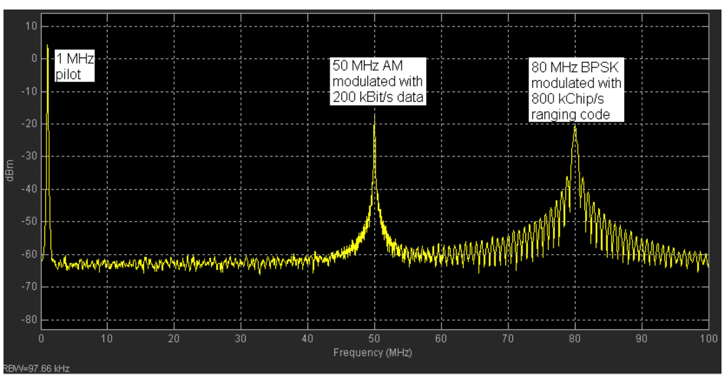

Figure 6 Transmission scheme for parallel data and ranging signal transmission.

One of the key properties of the GOISL is the simultaneous transmission of data and ranging signals. Together with the bidirectional data transfer capability, this allows to stick to the 30s time slot scheme currently under discussion in an any to any scenario, even taking into account worst case time durations for the repositioning of the optical beams.

A demonstration of data transmission and ranging in parallel fulfilling the requirements above was performed in a lab environment. Ranging and timing signals were spectrally separated from the data transmission. The ranging / timing processing equipment was provided by Timetech and is based on Timetechs huge heritage in ranging and timing systems [9]. An 80 MHz IF subcarrier was used for the ranging and timing signal, while the carrier for the data transmission was in the range of 50MHz, see Figure 6. This allowed to transmit both signals simultaneously. The data requirement was 120kbps, derived from the actual boundary conditions of the navigation constellation. With an increased data rate of 1

Mbps, which can easily achieved in the optical domain, the total time necessary for the data exchange between the two communicating SC can be reduced significantly.
With the transmission of data and ranging signals in parallel and in both directions at the same time, the LCT can support a 30 seconds time slot even under worst-case angular travel conditions for the optical beam from the end point of a previous link to the starting point of the following link. Therefore, it could be demonstrated that the LCT can support an Any-to-Any link scenario based on a 30 seconds time interval with the given requirements for data transfer and ranging accuracy.

5. OUTLOOK

Besides the benefits as mentioned in the previous sections, OISLs can provide additional opportunities for the Galileo constellation:

- Optical communication offers a high bandwidth. Therefore, higher data rate applications could be implemented to add additional communication services
- The SMART terminal at 1064nm is originally designed for LEO to GEO links in the EDRS data relay system. With core elements of the SMART terminal being available in the Galileo OISL terminal, only moderate add-ons would be necessary to establish connections from Galileo satellites to EDRS GEO satellites. In that scheme, EDRS would act as a virtual ground station for Galileo.
- The laser terminal could be used for a secure key exchange between satellites by applying quantum key distribution technologies.
- Scientific investigations to characterize the earth's atmosphere
- Precise ranging measurements to better characterize the earth's gravity field
- Clock redundancy concepts across satellites

6. CONCLUSION

Optical Intersatellite Links (OISLs) show a great potential for navigation constellations. A significant advantage is the non-regulation of the optical spectrum and the robustness of OISLs against jamming and interference due to the narrow beam width. In this paper, it was described that the underlying technology is mature and that, with moderate modifications, the SMART LCT currently in development fulfills the requirements for Galileo OISLs. Due to the bidirectional nature of the optical link and the capability of transmitting ranging and data signals in parallel, the SMART LCT would fit into the time scheme of the time-slotted any to any connection scenario currently envisioned in Galileo. The simultaneous transmission of ranging signals and data was demonstrated in a lab environment. OISLs offer a full range of new possibilities for a navigation constellation, by eg expanding the OISLs to rings with less dependability on ground stations and adding communication channels as additional services. Clock synchronization techniques between satellites will increase the robustness of the navigation constellation in the clock domain.

Acknowledgment

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