# Exploiting the synergy between optical two-way and microwave one-way ranging in a GNSS constellation

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## Abstract

New technical developments increase the capabilities for ranging and time transfer. The MicroWave Link (MWL) for the ACES (Atomic Clock Ensemble in Space) mission, or the operation of optical phase modulated data transfer between space and ground or between satellites are examples. To optimize the use of such new technology for geodesy, simulation studies are necessary. In this paper, we discuss the important steps in setting-up a simulation study to evaluate the expected improvements when introducing new observation techniques and optimizing the synergy with the existing techniques. Finally, we summarize the outcome of our simulation studies on the combination of optical two-way and microwave one-way ranging. Our focus lays on precise orbit determination as well as clocks synchronization in a MEO (Mean Earth Orbit) satellite constellation with and without integrated geosynchronous satellites. As also inter-satellite links are simulated, we work with a small ground station network of only 16 stations.

## 1. Introduction

The integration of new technologies into existing infrastructure and ranging techniques require dedicated simulation studies to exploit the synergy of the combination of observation techniques. Many developments happened in the last years: optical communication links with high data rate, and therefore high modulation frequency on optical carriers (Hemmati 2020), were tested between different satellites and between ground and satellites. Geogi et al. (2019) discussed developments with respect to clocks synchronization. In the microwave domain, ESA initiated the construction of the MWL (MicroWave Link) for the ACES (Atomic Clock Ensemble in Space) mission (Cacciapuoti et al. 20220). Inter-satellite ranging was used in the optical and microwave domain for gravity field missions, like GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO (Follow-on mission of GRACE) (Abich et al. 2019) as well as in LISA Pathfinder (McNamara et al. 2008). Satellite Laser Ranging (SLR) is a well-established two-way ranging technique measuring the time of flight of very short laser pulses to satellites equipped with retroreflectors. The combination of SLR with one-way ranging, as done for instance in the T2L2 (Time Transfer by Laser Link) or LTT (Laser Time Transfer) projects and will be further evolved in the ELT (European Laser Timing), have the possibility to combine ranging and time transfer. An overview of these techniques can be found in Exertier et al. 2019.

This paper summarises the studies done by Schlicht et al. (2019) and Marz et al. (2021, 2023a, 2023b). In these studies, we combine Galileo L-band measurements with optical phase modulated ranging between the MEO satellites (Optical Inter-Satellite Links;

OISL) and between ground stations and the MEO satellites (Optical two-Way Link; OTWL). The ground network consists of 16 stations, comparable to the Galileo sensor station network. In our simulations, every station is not only equipped with a GNSS L-band antenna, but has an OTWL terminal as well.

The paper is organized as follows: First, we present the idea behind the study. Second, we explain the focus of each step. Third, we discuss more deeply how a simulation study should be analysed. We conclude this paper with a short summary of the outcome of our performed analysis.

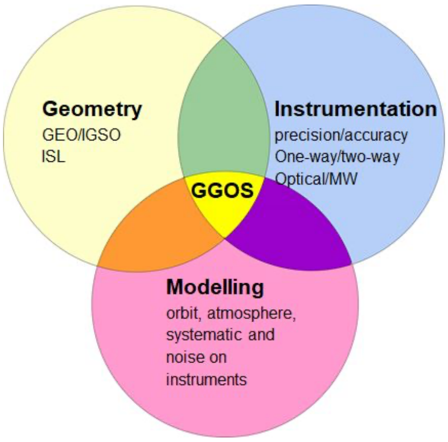

**Figure1:** The three pillars of orbit determination in the view of GGOS.

## 2. Rational of the simulation study

Precise orbit determination (POD) is based on three pillars: The combination of techniques and their accuracy and precision, the geometry of the measurements as well as the models used for the forces acting on the satellite, like delays of the signals and correction of systematic errors in the measurement (Figure 1). In fact, a measurement with mm precision will not automatically lead to mm orbit accuracy. The other aspects have to be analysed as well. For instance, is it possible to optimize the orbit modelling by estimating more empirical parameters for adjusting the orbit? Is it better to collocate the different techniques to extract systematic errors or is it more important to enhance the geometry of the tracking? The improvements on all three pillars are important to address in the study.

In any case, the expected synergies between the discussed techniques shall be analysed. The additional precise links, we want to discuss, can be one-way or two-way links and the carrier can have an optical or a microwave frequency. The basis is a microwave one-way link, the common GNSS L-band measurements. Figure 2 tries to work out the pros and cons of the different aspects of the links. Thus, we can find the best synergetic observation type to complement the GNSS L-band measurements. The advantage of a one-way technique, namely the high connectivity between transmitters and receivers, allows a high number of observations at the same epoch: One receiver on the ground can track all visible satellites at the same time and many receivers can track the same satellite. This not only connects one ground clock to many satellite clocks to synchronize the ground clock, but also allows a broad diversity of ranging geometries at one epoch. For instance, one benefit is an epoch-wise clocks synchronization. The enhanced geometry comes along with some systematic errors: multipath and phase centre variations.

The atmosphere affects the different frequency domains - microwave and optical - differently. The ionosphere causes a delay only for microwave frequencies. The wet part of the troposphere only affects microwave signals as well. This is an important disadvantage as modelling of this part of the troposphere is very difficult. The high variability of the water vapour in the atmosphere is the reason for the modelling deficiencies. On the other hand, optical signals suffer from liquid water in the atmosphere. In cloudy weather conditions, ranging from ground to space is not possible. A big advantage of technologies working with optical frequencies is the possibility to calibrate them regularly on short distances. For microwave frequencies, the distance would be much larger until you reach the far field, necessary for meaningful calibrations.

When comparing the advantages and disadvantages of the different ranging techniques, the combination of an optical space-ground two-way link with the existing L-band MEO measurements more synergies arise than in any other combination, if used in colocation: regular calibrations of L-band receivers, improvements in wet troposphere modelling, and elimination of instrumental systematics.

Inter- satellite ranging would, to a great extent, improve the geometry of Galileo satellite tracking. In such a geometrical configuration, a one-way technique would bring no benefit. Hence, we only discuss tow-way techniques. For orbit determination, a connection of all satellites in the constellation in a short time would lead to the greatest improvements. This leads again to optical tracking methods.
Therefore, for our simulation study we take optical two-way ISL measurements and optical two-way OTWL measurements into account.

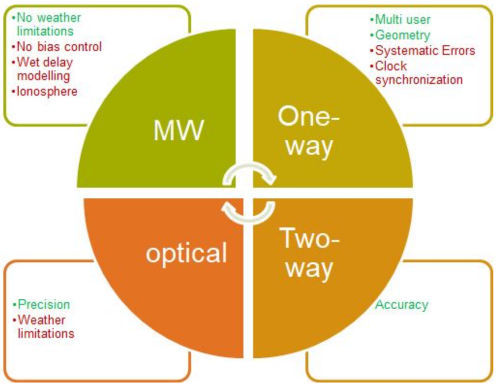

**Figure 2:** Advantages and disadvantages of different aspects of tracking techniques.

## 3. How to read an orbit simulation study

One purpose of simulation studies is an exact representation of a measurement scenario, in a sense of an end-to-end simulation. The outcome should be a numerical value of how accurate an aspired measurement scenario can be evaluated. This can be done, if all the instruments are studied in detail with all their systematic errors and noise contributions as well as a dedicated measurement scenario is agreed on. Such a study we would call a technical study at the end of an analysis process, and it is not what we want to discuss here.

A simulation study, which evaluates and optimizes the use and combination of different measurement techniques, focuses on different aspects of the measurement scenario: evaluating different empirical or semi-empirical models or testing the ranging precision of instruments necessary for achieving an aimed target. Such studies we would call scientific. Their outcome is not a numerical value, but an analysis of which aspects of the complex measurement system would lead to which improvements or degradations of the result. It is a relative analysis.

In our work, we want to analyse the combination of different ranging techniques for precise orbit determination. Hence, our relative analysis will compare different orbits and different contributions from the three pillars of orbit determination. The difficulty lays in the selection of the main influences affecting the measurements: systematic effects and different noise contributions, main contributions of orbit modelling, and ideas for improving the geometry.

On the modelling side, we first looked on the forces acting on the satellites of our used constellations and to which extend they physically can be modelled. For MEO and geosynchronous (GSO) satellites, the Solar Radiation Pressure (SRP) is not known very precisely. The box-wing model for the satellites is a good approximation for the satellite shape, but the optical properties of the satellite surfaces are not determined with the necessary precision and may be subject for changes in the orbit. The discussed errors are at about 10%. As a consequence, we took a 10% error in the optical parameters of a box-wing model as our a-priori knowledge of the SRP force. We then analysed for each satellite type which empirical parameter set would increase the orbit modelling. A quantification of the modelling error can be achieved if *true* orbit positions, representing the simulation truth with the exact optical parameters, are fitted with the models we want to represent, namely the wrong optical parameters of the box-wing model with additional empirical parameters. The outcome is the so-called *best possible* orbit. It represents the orbit we can achieve with perfect measurements, perfect geometry and no further modelling errors than the SRP mismodelling.

The orbits, which reflect the modelling error due to the 10% degradation of the optical parameters, are called *mismodelled*. The difference between *mismodelled* and *best possible* orbits reflect the improvement when additional empirical parameters are estimated on orbit positions. In the least-squares adjustment of the simulated measurements, we investigate to which degree we can improve the orbit when estimating an increased number of empirical parameters. The resulting *adjusted* orbits are compared to the *true* orbit. It is useful to estimate more parameters in the adjustment if the orbit gets closer to the truth.

We further studied the modelling of systematic errors of the measurements. Are special scenarios more adequate for estimating range and clock synchronization biases of the optical techniques?

We would expect a benefit from the collocation of an optical two-way link (OTWL) and the one-way microwave link of GNSS L-band. Estimating common troposphere parameters for the optical and microwave delays should be possible, but this is not done up to now and is left for further parts of the study.

Optical inter-satellite links (OISL) enhance the ranging geometry to MEO satellites. In our study, we analyse the different scenarios, which can be imagined for POD.

Permanent links within the orbital plane would be perfect for data exchange, but how much is the degradation of the orbit in comparison to a scenario where each satellite measures each other satellite, when they are in the field of view? In a ring scenario, the measurement would degrade to range rate observations, as the bias of the terminals cannot be estimated. How much would the orbit improve by range measurements with preferential geometry? The influence of the geometry is best analysed by comparing the formal orbit errors with the *best possible* orbit errors. Beneath the geometry, only white noise of the measurements influences this error type.

The integration of GSO satellites into a GNSS system enhances the geometry of the MEO satellites, too. Even so orbit accuracies of the GSO satellites limit the benefit. The reason why we integrated these types of satellites into the constellation is motivated by our interest in GEO (geostationary) and IGSO (inclined geosynchronous orbit) satellites POD. These types of satellites fulfil several tasks. First, they enhance the number of visible satellites in urban environments, supporting tracking of vehicles with limited visibility of the sky. Second, from our perspective, the future potential of these high orbiting satellites lay in ranging and time transfer capabilities to moon missions. They could be used as intermediate stations for connecting Earth and Moon.

We up to now did not analysis different ranging accuracies for the optical techniques for comparison. We fixed it to an expectable value of about 1.5 mm with contributions from range dependent white noise and flicker noise. By comparing the *adjusted* orbit with the *best possible* orbit, we study the influence of systematic errors, non-white noise and further modelling errors.

## 4. Main Results

In four papers we have different foci on the study. The first paper (Schlicht et al. 2019) analysed different ISL scenarios. For geodesy and navigation the most important outcome is, that a scenario where each satellite tracks subsequently all other satellites, is by far the most appropriate one. The scenario is called ‘any-to-any’ and benefits from estimating the range bias of the OISL measurements. In general, OISL observations enhance the geometry and allow the estimation of more empirical parameters.

The second paper (Marz et al. 2021) studied an optical two-way link from ground. All 16 ground stations were equipped with OTWL terminals. L-band receivers and OTWL use a common clock in space and on ground. This analysis is more complex due to the fact, that the number of optical ground-space observations are limited by cloud coverage. The benefit from OTWL depends on the number of available ground stations. If seven or more stations are available, the benefit for orbit determination in a one-day arc is slightly higher than for L-band and OISL. Such a scenario allows estimating more empirical parameters than L-band only. Even having less than seven stations, the orbit accuracy increases with respect to L-band only. The separation of clock and range by OTWL is the essential point. The best scenario is the combination of OISL and OTWL with L-band.

In a further part of the study, we integrated GSO satellites into the MEO constellation (Marz et al. 2023a). We inserted GEO and IGSO satellites homogenously distributed on the globe. As we wanted to keep the same ground station network, a consequence is, that the GSO satellites have not the same number of ground station to observe them. This leads to a broad scattering of the accuracy of POD, when only ground observations are taken into account. These differences disappear, when integrating these satellites into the OISL tracking network. Optical tracking allows estimating more empirical parameters for these orbit types, too. The achievable orbit accuracies are comparable to the MEO satellites.

The clocks will be analysed in a further publication (Marz et al. 2023b). Here we analysed two different clock types on the satellites: a passive hydrogen maser (PHM) and a clock ensemble like the one in ACES, an active hydrogen maser and a Caesium clock with cold atoms. The Allan deviation shows that PHM noise is reached at 1 day for each observation scenario. For the ACES clock, only the L-band + OISL + OTWL scenario reaches the clock noise at 1 day. We show that the benefit of a more stable clock lays in the clock prediction, whereas with an epoch-wise clock estimation the clock has no influence on the orbit estimation.

## 6. Conclusion

With the possibility to get better modelled orbits, the geodetic parameters will not contain signals with a draconitic period anymore. The GGOS (Global Geodetic Observing System; Plag and Pearlman 2009) goals of a precise terrestrial reference frame with 1 mm accuracy and a stability of 0.1 mm/year as well as improving the precision of the societal and scientific applications of GNSS (Global Navigation Satellite System) (Johnston et al. 2017) come into reach. Furthermore, the combination of different observation techniques is one of the next important steps in improving satellite orbits as well as space geodesy in total. A general advantage of the OTWL concept is the tight tie to the terrestrial reference frame. This is not the case for OISL. Compared to OISL we would than expect an improved estimation of Earth Rotation Parameters (ERPs) as well as the possibility to optimize the ITRF (International Terrestrial Reference Frame) with optical two-way ground links. Hence, the influence of L-band + OTWL on the ERPs as well as the ITRF is a very interesting question.

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