The application of inter-satellite links connectivity schemes in various satellite navigation systems for orbit and clock corrections determination: simulation study

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Abstract

Inter-Satellite Links (ISLs) are intended to improve precision of orbit determination and satellite clock estimation. The ISLs provide a precise pseudorange measurements between satellites in a specific constellation. The study is a preparatory assessment of exploitation of seven connectivity schemes in the terms of the precise orbit determination for three types of constellations—Galileo-like with 24 satellites on three orbital planes, GPS-like with 24 satellites on six orbital planes, and GPS with real positions. The first part of the study focused on detailed analysis of the various ISL connectivity schemes, considering the geometry of ISL observations. The selected results of ranging were examined in the context of the precise orbit determination based on weighted least squares adjustment. The second part of the analysis was based on simulated measurements with two approaches. First approach focuses on geometrical dependencies and the second is performed with ISL measurement biases estimation. It was found that the use of the ISL technique with GNSS measurements in orbit determination improves the results by reducing the RMS error in the along-track and cross-track components. Choice of connectivity schemes does not have a significant impact on the total results of orbit determination, but give different contribution to particular components. Introducing constant bias in ISL measurements occurs in slightly worse estimation results. However, the relations between connectivity schemes is very similar to approach without simulation of ISL bias, the differences are at the level of 10%. Satellite and station clock estimation errors are almost equal for all used connectivity schemes. Results of clocks are also not influenced by ISL bias. This study showed that the ISL technique is a highly promising addition for future generations of satellite navigation systems and that sequential and ring connectivity schemes can be recommended for use in future navigation constellations.

Keywords Inter-satellite links · Orbit determination · Connectivity schemes · Clock estimation

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1 Introduction

Inter-Satellite Links (ISLs) are considered to be a fundamental component of future Global Navigation Satellite Systems (GNSS) to improve the positioning accuracy and orbit determination. ISLs provide precise pseudorange measurements between satellites in a specific constellation. The combination of ISL and GNSS measurements is one of the key requirements for improving orbit determination. Connections between satellites can be used to transfer information, which might shorten the ephemeris update interval and improve navigation (Gong et al. 2019). One of the advantages of the ISL system is the potential to establish links outside of the atmosphere, and thus the ISL measurements are not affected by atmospheric delays and they are also less impacted by multipath and interference than GNSS measurements (Rodríguez-Pérez et al. 2011). It has also been suggested that satellites could determine their orbit autonomously by processing ISL measurements (Xu et al. 2012). Therefore, ISLs could make a great contribution to onboard processing and represent a step towards fully autonomous constellations in the future (Yang et al. 2017b).

ISLs have been already assessed in simulations in a few initial studies (Fernández 2011; Xu et al. 2012). The concept of ISL exploitation was first proposed to support autonomous satellite navigation in Global Positioning System (GPS). It provided a possibility for satellites to self-navigate by using data exchanged with other satellites (Ananda et al. 1990; Huang et al. 2019; Sun et al. 2018; Tang et al. 2018; Xu et al. 2012; Zhou et al. 2018). GPS started introducing technology similar to ISLs in 1997 and used an ultra-high frequency (UHF) with Time Division Multiple Access (TDMA) scheme in Block IIR series. The current plans about the ISLs in next-generation GPS blocks are not publicly known.

At present, the BeiDou Navigation Satellite System (BDS) is the most advanced system to introduce ISLs. Since March 2015, new generation satellites have been launched to validate, among others, the ISL system. All in-orbit BDS-3 operational satellites are equipped with ISLs (Gong et al. 2019). The ISL payload enables observation of other satellites and ground stations with Ka-band single frequency pseudorange measurements (Pan et al. 2018; Ren et al. 2019; Tang et al. 2018; Zhou et al. 2018). Each satellite operates within a 1.5 s timeslot with another satellite, creating a link pair (Pan et al. 2018; Zhou et al. 2018). However, even with additional ISL measurements, the constellation is still affected by external environmental and technological effects (Ren et al. 2019; Tang et al. 2018). Observations to anchor stations, described as Ground-Satellite Links (GSLs), use the same communication and measurement system as ISLs. However, unlike the ISL observations, they need to be corrected for tropospheric delays (Ren et al. 2019).

The European Space Agency (ESA) has conducted projects in the frame of the General Studies Programme (GSP) to assess the capability of introducing inter-satellite ranging and communication links and their influence on GNSS orbit determination. They intend to analyse potential improvements in orbit determination brought by introducing the ISLs. The first project, “GNSS+”, indicated technological difficulties in on-board implementation of the ISL hardware due to the increase of payload mass and power consumption (Fernández 2011). The investigation was continued in the second project, labelled “ADVISE” for further simplification of the technology and the system architecture. Both projects assumed the adaptation of the orbit and clock determination algorithms with respect to classical implementations (Fernández 2011; Han et al.

2013). According to a statement published on the ESA webpage (https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Optical_inter-satellite_links_are_best_tech_for_Galileo), demonstration flight and verification of the ISLs on board a Galileo 2nd Generation spacecraft is planned in 2021.

In this research, we focused on the possible consequences of introducing ISLs in the orbit determination process. We aimed to investigate the behaviour of three constellation types (1) Galileo-like with 24 satellites on three orbital planes, (2) GPS-like with 24 satellites on six orbital planes, and (3) GPS-real with real satellite positions (Table 1). We simulated the ISL measurements and included them in the orbit and clock estimation process to fully assess their impact on the orbit, with consideration of the different constellation geometries. There are many ways to select satellite pairs and assign specific measurement epochs and thus these need to be studied in more detail. This ranging schedule is called a connectivity scheme in our research. The differences among these schemes are likely to lead to various different influences on the orbit determination, which can be revealed by analysis of the orbit in position components (radial, along-track, and cross-track). It is also essential to maximize efficiency of the connections within the scheme to meet data-exchange requirements (Shi et al. 2011). The role of the connectivity scheme becomes even more important in the case of mixed constellation configurations of geostationary orbit (GEO), inclined geostationary orbit (IGSO), and medium earth orbit (MEO) satellites. Such a configuration already exists in BDS (Han et al. 2013); however, the long transmission distance between GEO and MEO or IGSO and MEO might cause some difficulties (Yi et al. 2013). To solve this problem, sub-constellations are usually created, e.g. links are established between 3 GEO satellites + 3 IGSO satellites (Han et al. 2013). We believe that results of this research can be used to help select the appropriate connectivity scheme for operational ISL hardware in future generations of navigation constellations.

2 Connectivity schemes

There are many possibilities to establish potential satellite pairs, which potentially can change the performance of the combined orbit determination. In the case of the ISL topology, connectivity schemes are mostly defined including geometrical information about satellites, the distances between them, and the pointing angles of the ISL system (Werner et al. 1997). In more advanced procedures, such topology is then optimized in terms of

Table 1 Galileo-like, GPS-like and GPS-real (status on 25 May 2014) constellation parameters

Constellation parameters			
Parameters	Galileo-like	GPS-like	GPS-real
Walker definition	24/3/1	24/6/1	–
Number of satellites	24	24	31
Number of orbital planes	3 (A, B, C)	6 (A, B, C, D, E, F)	6 (A, B, C, D, E, F)
Satellites per plane	8	4	4–6 (uneven placement)
Node spacing	120°	60°	60° (nominal)
Inclination	56°	55°	55° (nominal)
Orbit radius	29,600 km	26,560 km	26,560 km (nominal)

efficiency or erroneous connections. Alongside purely geometric or sequential links, algorithms have already been studied to maximize network connectivity and augment the overall network performance (Shi et al. 2011; Yi et al. 2013). The criteria of link establishment and their properties must be investigated to create valuable connections for orbit determination purposes (Han et al. 2013). Shi et al. (2011) proposed establishing ISLs in the frame of topology processing. In this case, the input is a constant topology that refers to the visibility in each ranging interval. Another method for establishing ISLs is the condition of minimum value of PDOP (position dilution of precision)—the configuration of satellites impacts the quality of measurements and PDOP might be used to verify the performance of satellite geometry (Han et al. 2014). The adjacency matrix in graph theory can also be used under the defined parameters (i.e. optimal perspective of the azimuth angle, elevation angle, or distance) to generate connectivity schemes (Han et al. 2011).

Chosen pairs of satellite in the connectivity scheme can be repeatable in subsequent epochs (e.g. during one orbit arc) or associated with single epochs and then the new pair is created. Permanent links are realized between satellites in the same orbital plane, when both satellites are constantly visible to each other. Such links can reduce complexity of switching procedures. Links for specific periods are realized mostly between satellites in adjacent orbital planes. These ISLs cannot be maintained permanently during the whole system period, mostly as a result of temporary losses of visibility (Werner et al. 1997). Restrictions put on the measurements (e.g. distance, azimuth, and elevation) then become the main limitations and are most likely to affect the ISLs (Han et al. 2014).

Mutual visibility is very important for connection establishment between satellites in each of the measurement epochs. The main obstructions are the Earth and atmosphere, for which the height that affects the satellite links is defined as 1000 km (Tang et al. 2016; Xu et al. 2012). In our approach, links from pairs of satellites that cross the atmosphere are automatically rejected. We do not define a maximum distance for which the connection can be established, but only satellites with a propagation time over 50 ms are considered because of the technological restrictions mentioned in Fernández (2011). Three constellations—Galileo-like, GPS-like, and GPS-real—were tested for orbit determination supported with ISL observations. The GPS-real initial conditions (satellite positions and velocities in cartesian coordinates) were taken from files with precise ephemeris distributed by U.S. National Geospatial—Intelligence Agency (NGA). GPS-real is characterized by irregular satellite placement in the orbital planes (Table 2). Orbit simulations were performed on 25 May 2014 according to the settings

Table 2 Specifics of GPS-real constellation (25 May 2014) used to check the performance of connectivity schemes with uneven placement of satellites in orbital planes

Slot	PRN	Slot	PRN	Slot	PRN	Slot	PRN	Slot	PRN	Slot	PRN
A1	24	B1	16	C1	29	D1	2	E1	20	F1	14
A2	31	B2	25	C2	27	D2	1	E2	22	F2	15
A3	8	B3	28	C3	19	D3	21	E3	5	F3	13
A4	7	B4	12	C4	17	D4	4	E4	18	F4	23
A5	9			C5	3	D5	11	E5	32	F5	26
A6	30					D6	6	E6	10		

Satellite 6 was not usable on the given date and was therefore excluded from the GPS-real orbit determination

Table 3 Parameters of the orbit simulation

Data time span	1 day
Earth gravity field	EGM2008 16 × 16 (Pavlis et al. 2012)
Gravitational perturbation	Sun, moon and planets Relativistic perturbations (Petit and Luzum 2010)
<i>Non-gravitational perturbations</i>	
Solar flux	Constant
Earth's albedo	Analytical (Rodríguez-Solano 2009)
Satellite surface properties	Box-wing model (GSA metadata— https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata))
Numerical integrator	Runge–Kutta 4th order

presented in Table 3. The satellite with PRN 6 was not usable on this date and was therefore removed from the GPS-real orbit determination. PRNs are the pseudo-random noise sequences, that each satellite transmits to be recognized in the active constellation. Here, PRN are used only to differentiate satellites and their placement in orbital planes.

The mechanical properties of the transmitting antenna (i.e. range of motion for directional antennas or maximum angle of visibility determined by antenna placement) and potential obstacles of satellite elements (e.g. part of the satellite box or communication antennas) limit the number of possible satellite pairs. To correctly realize the scheme, antennas should be able to point to most of the visible satellites (Huang et al. 2017, 2018). Figure 1 shows the possible influence of hardware mechanical limitations in the tested constellations. Two antenna angles of view (α) were tested, which are defined as the opening angle of the cone placed in the centre of satellite and directed towards the centre of the Earth. In each case, the highest percentage of visibility of the satellites is noted for a single satellite from the same orbital plane. However, more satellites on adjacent orbits are visible in GPS-like constellations. With GPS-real the situation is complicated because of the irregular placement of the satellites, even with an 180° angle there are many limitations due to shadowing. In general, for Walker-defined constellation types, Galileo-like and GPS-like the highest visibility is noted for satellites on the same orbital planes. The satellites from adjacent planes are visible at least several times in one day. Considering the number of possible connections, satellites from adjacent orbital planes are generally preferred to avoid or minimize Earth shadowing.

We considered two types of possible connection between two satellites (Fig. 2):

1. One-way—satellite i sends a signal and satellite j receives it—only one measurement at one time.
2. Dual one-way—satellite i sends a signal to satellite j and satellite j simultaneously sends a signal to satellite i —two measurements in one epoch.

In our research, the emission time is given by the clock of the satellite that transmits a signal in the current epoch and the reception time is given by the clock of the receiving satellite. The ISL measurements contain the clock offset and the receiving and transmitting time delays of the ISL equipment. However, for the purpose of this research,

Fig. 1 Visibility of the satellites within the three types of constellation and different values of antenna angle of view α for 25 May 2014 for 2880 epochs (every 30 s): **a** Galileo-like and $\alpha=180^\circ$, **b** Galileo-like and $\alpha=90^\circ$, **c** GPS-like and $\alpha=180^\circ$, **d** GPS-like and $\alpha=90^\circ$, **e** GPS-real and $\alpha=180^\circ$, and **f** GPS-real and $\alpha=90^\circ$. Satellite 6 was not usable on the given date and was therefore excluded from the GPS-real orbit determination

Fig. 2 Connection type: **a** one-way and **b** dual one-way

delay values were set to zero to simplify the solutions. The reduced ISL pseudorange can be written as follows:

$$\rho_{ij}(t_1) = \left| \vec{R}_j(t_1) - \vec{R}_i(t_1 - \Delta t_1) \right| + c * \delta t_j(t_1) - c * \delta t_i(t_1 - \Delta t_1) + \varepsilon_{ij} \quad (1)$$

where $\vec{R}_i$ and $\vec{R}_j$ relate to the three-dimensional position of the satellites i and j in Cartesian coordinates, δt_i and δt_j refer to satellite clock errors, c is the speed of light, Δt_1 is the light travel time, and ε is a measurement noise of a link. We also assumed that bias terms, e.g. associated with transmitting and receiving delays, are compensated by calibration and we did not include them in the simulations.

Equation (1) represents the one-way measurement type, for which satellite clock error estimation is required. In the dual one-way type, two satellites send signals to each other in turn and thus create a link pair (Tang et al. 2018; Yang et al. 2017a). In this connection type, satellite j receives a measurement $\rho_{ij}(t_1)$ from satellite i at time t_1 , when satellite i measures a pseudorange $\rho_{ji}(t_2)$ from satellite j at time t_2 . The observation equation is written as follows:

$$\rho_{ji}(t_2) = \left| \vec{R}_i(t_2) - \vec{R}_j(t_2 - \Delta t_2) \right| + c * \delta t_i(t_2) - c * \delta t_j(t_2 - \Delta t_2) + \varepsilon_{ji} \quad (2)$$

The dual one-way observations need to be transformed to a common epoch for the satellite orbit determination. This means that the distance between two satellites is reduced to the same observation time (Yang et al. 2017a). The mean value of the measurements $\rho_{ij}(t_1)$ and $\rho_{ji}(t_2)$ eliminates satellite clock error and contains only orbit parameters (Eq. 3). The difference of the dual one-way measurements is free of orbital estimation errors and might be used to determine the satellite clock offsets (Guo et al. 2010; Liu et al. 2009; Pan et al. 2018).

$$\frac{\rho_{ij}(t_0) + \rho_{ji}(t_0)}{2} = \frac{\left| \vec{R}_j(t_0) - \vec{R}_i(t_0) \right| + \left| \vec{R}_i(t_0) - \vec{R}_j(t_0) \right|}{2} + \frac{\varepsilon_{ij} + \varepsilon_{ji}}{2} \quad (3)$$

Connectivity schemes tested in this research can be divided into four groups which contain schemes based on particular features or rules for creating satellite pairs (Table 4). The schemes are presented in Fig. 3 and for each plot they are referenced to the same epoch. Each scheme varies in the number of total ISL measurements in 24 h period (Table 5). We do not make specific assumptions about hardware possibilities to establish connection except simultaneous receiving and transmitting ISL signal to evaluate possible methods of

Table 4 Groups of connectivity schemes with their establishment basis

Group	Name of the connectivity scheme	Establishment basis
1st group	Intra-plane closed	Link between adjacent satellites in the single orbital plane
	Intra-plane open	
2nd group	Nearest (general, dual one-way)	Link based on the smallest distance between accessible satellites
	Nearest (general, one-way)	
3rd group	Nearest (inter-plane, dual one-way)	Link based on the smallest distance between accessible satellites only from adjacent orbital planes
4th group	Sequential (dual one-way)	A priori defined repeated sequence of links
	Sequential (one-way)

Fig. 3 Representation of connectivity schemes: **a** intra-plane closed (ring), **b** intra-plane open (open-ring), **c** nearest (general), **d** nearest (inter-plane), and **e** sequential (specifics in Table 4)

Table 5 Connectivity scheme characteristics

Scenario name	Connection type	Total number of established ISLs with 30 s interval in 24 h in the Galileo-like scenario
Sequential	One-way	31,033
Sequential	Dual one-way	62,070
Intra-plane closed	One-way	69,120
Intra-plane open	One-way	60,480
Nearest (general)	One-way	34,416
Nearest (general)	Dual one-way	68,820
Nearest (inter-plane)	Dual one-way	68,592

links establishment and check their potential impact on different constellation geometry. For next studies, we plan to prepare advanced simulations with e.g. use of doubled ISL hardware or allow only for consecutive links for dual-one way connection type.

The first group is based on the orbital planes and the satellite slot. These schemes are strongly associated with the geometry of the constellation. In our research, these schemes were represented as intra-plane closed (ring) and intra-plane open (open-ring). They describe ISLs as a connection between consecutive satellites in the same orbital plane (Fig. 3a, b). In the open-ring scheme, the last satellite does not establish connection with the first satellite. In terms of the possible application of the Doppler effect, the ring schemes are not desired as they experience insufficient Doppler wavelength shift (Yang et al. 2009). The second group is associated with the distance between the satellites and it is realized by nearest (general) scheme with both one-way and dual one-way connection types, where each satellite is linked to the nearest accessible satellite (Fig. 3c). The third group is a combination of the conditions and is represented by the nearest (inter-plane) with dual one-way connection type, in which connections are established to the nearest satellite from the adjacent orbital plane only (Fig. 3d). The fourth group consists of observation scenarios based on the a priori defined sequence of pairs (Fernández 2011; Rodríguez-Pérez et al. 2011). It was modified for application to a constellation with an even number of satellites (Monika Stetter, Technical University of Munich, personal communication). This was realized with both sequential one-way and sequential dual one-way schemes. Both sequential schemes are presented in Fig. 3e.

3 Analysis of connectivity schemes

In this section, we address the question of how different connectivity schemes with the chosen error terms may influence the accuracy of orbit determination including GNSS and ISL techniques together. Orbit determination with sub-centimetre accuracy remains difficult to obtain in current technological and computation opportunities. Many subtle and non-trivial issues e.g. nongravitational perturbations and technological issues should be taken into account to achieve this level of accuracy. In this section, our goal is to assess the potential influence of different geometry of the observations on the orbit estimation errors. The performed analyses are based on simulations using software currently being developed at Space Research Centre of the Polish Academy of Sciences (Centrum Badań Kosmicznych Polskiej Akademii Nauk—CBK PAN). The software includes a precise orbit

propagator with specific support for navigation satellites, simulator of the GNSS and the ISL observations and an orbit estimator.

Simulations for research presented in this section were conducted with 44 ground stations, and the ISL and GNSS measurements were simulated at a 30 s sampling rate each for 1-day arc. In this section, the ISL observation noise was simulated as white noise with standard deviation set to 0, 2, 5, and 10 cm to consider possible solution variations, and GNSS measurements were simulated with an observation noise equal to 2 cm. Ambiguities are assumed to be fixed to the integer. We investigated two situations: Test 1, in which only ISL and GNSS measurement errors were simulated and only orbits (satellite positions) were estimated; and Test 2, in which satellite and station clock errors (as white noise with standard deviation equal to 1 ns) were simulated simultaneously with ISL and GNSS measurement errors, then orbits, satellites, and station clocks were estimated. Both tests were performed for a Galileo-like constellation with no environmental effects—the models used for simulation of reference orbit (i.e. solar radiation pressure) were identical as used in the orbit estimation procedure. Thus, we aimed to assess the relation between possible contributions of the various connectivity schemes, as well as their behaviour with applied measurement errors. Outcomes are not impacted by differences between the box-wing model used in simulation and the Empirical CODE Orbit Model (ECOM) of the Center for Orbit Determination in Europe (CODE) (Arnold et al. 2015) used in estimation during simulation performed in Sect. 4.

The Test 1 results (Fig. 4) revealed the geometric properties of each connectivity scheme. For all chosen schemes, the radial component was least affected by the ISL as the estimation errors did not exceed 0.5 cm for the ISLs with 10 cm measurement error. Along-track and cross-track components were the most prone to change and therefore we now focus on these. In the case of intra-plane schemes (Fig. 4a, b), which strongly support the along-track component, the choice of an open or closed approach does not affect the results. These schemes were characterized by lower error in the along-track component compared with sequential schemes and the nearest with one-way connection type. In the simulation conditions when only GNSS and ISL errors are taken into account, the cross-track component was better estimated than the along-track component. The ISL errors in the intra-plane schemes indirectly impacts on the cross-track position component. Sequential schemes (Fig. 4c, d) were the most variable. Along-track and cross-track components were equally estimated, but the error was higher by about 0.5–0.7 cm for the one-way connection type. However, comparison of these results to the nearest (general) scheme with both connection types used (Fig. 4e, f) reveals that they were almost equivalent. The findings suggest that sequential schemes are not well suited to orbit determination because they vary according to the connection type, when the nearest (general) scheme is more stable in orbit determination contribution. As the number of ISL measurements in the dual one-way connection type is twice as high as in the one-way connection type, this may not be the main reason for such results while considering lack of other errors, such as clock errors. The final scheme, nearest (inter-plane, dual one-way) (Fig. 4g) bears the burden of the dual one-way connection type effect, which minimizes the total results about 10% than in the nearest (general, one-way) scheme. The suggested approach of connecting satellites from adjacent planes seems to have no impact on the outcomes of the orbit determination errors.

Introduction of additional errors to the simulation process in Test 2 was conducted to verify the performance of the connectivity schemes in terms of their exploitation and geometry dependencies under imperfect conditions. One of the main differences compared with Test 1 was the more variable and less accurate results for the radial component (Fig. 5). However, according to the orbit determination results, we can generally

Fig. 4 Result of the sensitivity test only with GNSS and ISL measurement errors included for **a** intra-plane closed, **b** intra-plane open, **c** sequential (dual one-way), **d** sequential (one-way), **e** nearest (general, dual one-way), **f** nearest (general, one-way), and **g** nearest (inter-plane, dual one-way) schemes

distinguish: (1) ring schemes with the lowest error in the radial component, (2) schemes with one-way connection type (total error about 0.5 cm higher than in (1)), and (3) schemes with dual one-way (total error 1–1.5 cm higher than in (1)). Orbit determination results with ring schemes were the lowest and both of the included schemes behaved almost identically for the cross-track component (Fig. 5a, b). The orbit error for the along-track components in the open-ring scheme was about 0.5 cm higher than that in the intra-plane closed scheme. For sequential schemes (Fig. 5c, d) and for the nearest (general) scheme

Fig. 5 Result of the sensitivity test with GNSS and ISL measurement errors together with clock errors included for the **a** intra-plane closed, **b** intra-plane open, **c** sequential (dual one-way), **d** sequential (one-way), **e** nearest (general, dual one-way), **f** nearest (general, one-way), and **g** nearest (inter-plane, dual one-way) schemes

(Fig. 5e, f), along-track and cross-track components were estimated with errors at level of 4–5 cm. Both components were determined with almost the same error, consistently with sequential schemes and schemes based on the smallest distance (nearest) with a maximum difference equal to 0.2 cm. The last scheme, nearest (inter-plane) (Fig. 5g) had a better estimated cross-track component (by about 0.5 cm) because of the connections established only between orbital planes.

The clock estimation error results (Fig. 6) show that higher ISL measurement errors caused poorer satellite clock solutions, but the station clocks were not directly affected. Figure 6a shows that station clocks errors were higher than satellite clock estimates, as only GNSS measurement error was simulated and ISLs can potentially help to reduce also satellite clock errors. However, introducing the ISL measurement errors in Test 2 led to poorer satellite clock estimation (Fig. 6b–d). The least resistant to this error were ring schemes, followed by schemes based on the one-way connection type. The orbit was not much better determined with dual connection, despite the doubled number of connections and promising observation geometry; however, dual one-way connection provided an improvement to clock estimation. Clock estimation errors were decreased by 40% (Fig. 6b) to 60% (Fig. 6d) for satellite clocks and 50% (Fig. 6c) to 70% (Fig. 6d) for station clocks compared with all other connectivity schemes. Dual one-way connectivity schemes provided consistent

Fig. 6 Mean satellite and station clock estimation error when the ISL measurement error is **a** 0, **b** 2 cm, **c** 5 cm, and **d** 10 cm. Simulated satellite and station clock errors were equal to 0.1 ns each

results and different strategies of observation did not influence the estimation in the tested case.

Tests performed in limited simulation conditions should be considered separately for the geometry of observation and clock estimation. Tests 1 and 2 showed that ring schemes were very resistant to applied measurement error, even if the scheme geometry is not complicated and does not support the cross-track component. The sequential and nearest approaches led to very similar orbits and the difference between schemes can be neglected. At the same time, ring schemes and schemes based on the one-way connection type had little contribution to the clock estimation, contrary to dual one-way.

4 Connectivity schemes performance in orbit estimation

4.1 Simplified simulation approach

In this section, the connectivity schemes described in Sect. 2 and initially tested in Sect. 3 are used in three constellation geometry types (Galileo-like, GPS-like, and GPS-real) to test the performance of the combined orbit determination. Reference orbits for all constellations were propagated with the Galileo FOC box wing model with optical parameters announced by European GNSS Agency (GSA) for direct comparison purposes (<https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata>). Simulation and estimation methodology are presented in Table 6. Each simulation scenario was repeated 15 times, imitating the Monte-Carlo approach for reliable error assessment and mean estimation errors are shown on the plots together with their standard deviation as error bars (Figs. 7, 8, 9, 10, 12, 13, 14, 15).

The results presented in this section are obtained with simplified approach to the simulation i.e. no ISL measurements biases are included. We want to focus on pure geometric impact of the ISLs on the constellation. Outcomes are not disturbed with ISL systematic effects, what potentially can help to identify more resistant connectivity schemes.

Table 6 Research methodology summary

Orbit simulation

GNSS constellation
Galileo FOC box-wing model
Gravitational and non-gravitational perturbations

GNSS observations

44 GNSS stations
30 s sampling
Observation noise with standard deviation equal to 1 cm
Zenith wet delays
Ambiguities assumed to fixed to integer

Orbit estimation—weighted least squares algorithm

Satellite positions
ECOM2—9 parameters
Epoch-wise satellite clocks
Epoch-wise station clocks
Zenith wet delay—piecewise linear model

ISL observations

Seven connectivity schemes
30 s sampling
Observation noise with standard deviation equal to 0.5 cm

Fig. 7 Orbit estimation mean RMS errors for the **a** radial, **b** along-track, and **c** cross-track components, and **d** the total 3D RMS value

First, we would like to present the results of simulations performed for different days to check the impact of potential variabilities with the constellations. We have tested two cases: when we used five consecutive days and second case when we used additional two random dates: 20.02.2014 and 28.08.2014. In the first case orbit estimation was done separately for each day and in Table 7 are presented mean results for 3D orbit errors together with standard deviations of the results based on the outcomes from five consecutive days. These values show small impact of constellation geometry and chosen day of simulation as the standard deviations are usually smaller than 2 mm.

Fig. 8 Satellite and station clock estimation mean RMS error for the Galileo-like constellation

In Table 8 are presented results of 3D RMS orbit errors computed for three different days to check potential influence of constellation variability. Standard deviations of the results obtained for Galileo-like, GPS-like and GPS-real equal to about 2 mm. In Galileo-like, the largest differences between days are observed for intra-plane open and nearest (inter-plane, dual one-way), when for other connectivity schemes differences between days can be neglected. For GPS-type constellations the situation is opposite—results are more variable between particular days except sequential (one-way). Considering results for each type of the constellation the general conclusions about connectivity schemes seem to be invariable between days. For further preliminary analysis of exploitation of the ISLs presented in Sect. 4 we will focus on one day only—25.05.2014.

The radial component (Fig. 7a) was sensitive to connectivity scheme choice and it was particularly affected by GNSS measurements, more than other directions. Assuming millimetre orbit accuracy, both GPS constellations behaved similarly. In general, considering the behaviour of each scheme in the radial component, Galileo-like performed better for the nearest (general, dual one way) and sequential (dual one-way) schemes, and ring schemes showed better contribution in GPS constellations by reducing error by 25%. The worst results were found for sequential (one-way) and the best for nearest (inter-plane, dual one-way) in each constellation. Figure 7b shows that the along-track component is the most supported of all tested connectivity schemes. The mean difference between schemes is ~1 mm, except intra-plane open, for which the error is 2 mm larger than other scenarios. For all tested cases, orbit estimation errors are stable and there is no impact of constellation

Fig. 9 Satellite and station clock estimation mean RMS error for the GPS-like constellation

type. Considering the cross-track component (Fig. 7c), the accuracy of the results are on the level obtained for the along-track component, except in the ring schemes—intra-plane open and intra-plane closed. As ring connectivity schemes are based on measurements in each orbital plane between satellites on adjacent orbital planes, the cross-track component is not supported by the ISLs. The 3D RMS total errors (Fig. 7d) show minor differences between connectivity schemes used in Galileo-like, GPS-like, and GPS-real constellations. Ring schemes performed worse than other schemes at the level of 30%.

Clock estimation errors are presented in Fig. 8 for the Galileo-like constellation, Fig. 9 for the GPS-like constellation, and Fig. 10 for the GPS-real constellation. In general, clock estimation errors were stable for the tested connectivity schemes. The schemes based on one-way connection type did not show worse results than the dual one-way connection types. Advantages of dual one-way connection type are associated with removing satellite clock errors from the observations; however, it seems to be less necessary when ISL accuracy is higher than GNSS, as was assumed in this section. No particular connectivity scheme stands out in the adopted simulation conditions.

For the GPS-like constellation, performance of clock estimation (Fig. 9) is very similar to that of the Galileo-like constellation. The impact of connectivity schemes on the estimation was <0.007 ns (<2 mm) for satellite clocks and <0.004 ns (<1 mm) for station clocks. Very characteristic for the results was the smaller precision of the satellite clock estimation compared with the results for the Galileo-like constellation. We distinguished three groups: (1) ring schemes, (2) schemes with one-way connection, and (3) schemes with dual

Fig. 10 Satellite and station clock estimation mean RMS error for the GPS-real constellation

Table 7 Mean values of 3D RMS orbit errors with standard deviations calculated from 5 day-results

Connectivity scheme	Galileo-like		GPS-like		GPS-real	
	Mean (cm)	Std (cm)	Mean (cm)	Std (cm)	Mean (cm)	Std (cm)
Intra-plane closed	1.35	0.14	1.24	0.09	1.39	0.15
Intra-plane open	1.36	0.10	1.28	0.08	1.35	0.12
Nearest (general, dual one-way)	1.03	0.22	1.01	0.08	1.03	0.11
Nearest (general, one-way)	0.91	0.06	0.81	0.04	0.86	0.09
Nearest (inter-plane, dual one-way)	1.02	0.17	0.99	0.05	0.98	0.09
Sequential (dual one-way)	0.93	0.24	1.02	0.15	0.92	0.08
Sequential (one-way)	0.85	0.12	0.81	0.05	0.83	0.07

one-way connection. Ring schemes also use one-way measurements; however, according to geometry of the observation (only in one orbital plane), they should not be associated with the second group. In the GPS-like constellation, the satellite clocks estimation precision was lower with use of dual one-way connection. In contrast, estimation precision with one-way is the best among all schemes. This indicates that the advantage of deleting clock errors from ISL measurements in the GPS-like constellation does not have a major impact on the results and it is therefore better to employ the one-way connection type.

Table 8 3D RMS orbit errors for three random days: Day 1—20.02.2014; Day 2—25.05.2014; Day 3—28.08.2014

Connectivity scheme	Galileo-like			GPS-like			GPS-real		
	Day 1 (cm)	Day 2 (cm)	Day 3 (cm)	Day 1 (cm)	Day 2 (cm)	Day 3 (cm)	Day 1 (cm)	Day 2 (cm)	Day 3 (cm)
Intra-plane closed	1.31	1.35	1.35	1.16	1.27	1.41	1.45	1.37	1.33
Intra-plane open	1.25	1.21	1.45	1.27	1.23	1.47	1.54	1.45	1.41
Nearest (general, dual one-way)	0.84	0.99	0.93	0.94	1.01	0.78	1.19	0.91	1.02
Nearest (general, one-way)	0.78	0.71	0.76	0.71	0.91	1.03	1.10	0.93	0.93
Nearest (inter-plane, dual one-way)	0.77	0.92	0.95	0.92	1.08	0.84	1.18	1.23	1.01
Sequential (dual one-way)	0.82	0.81	0.83	0.63	0.89	0.73	1.13	0.89	1.01
Sequential (one-way)	0.84	0.79	0.82	0.79	0.79	0.64	0.86	0.76	0.81

A similar conclusion can also be applied to the GPS-real constellation—schemes with the dual one-way connection type are characterized by 3–4 times higher standard deviations of the estimation results than those in one-way connection (Fig. 10). This might be associated with the number of the orbital planes and satellite placement. In general, the clock estimation results are characterized by slightly lower values of satellite clock estimation errors, especially for intra-plane closed and sequential (dual one-way), but in fact these differences between GPS-like and GPS-real can be neglected. None connectivity scheme is prominent, and thus each of the schemes can be used for satellite and station clock estimation. Given the result for both GPS constellations and the fact that the outcome varies substantially in comparison with the Galileo-like constellation, it might be concluded that geometry of the constellation, i.e. number of orbital planes, is more important than the number of satellites.

The choice of the proper connectivity in case of the clock estimation seems not to be the vital issue, as the maximum difference between them is ~ 2 mm. However, in our opinion, both sequential and ring schemes can be recommended for processing GNSS and ISL data together. The dual one-way scheme is sensitive to the constellation geometry; however, the advantage of eliminating of satellite clock error probably will be vital in more advanced analysis with consideration of more extreme measurement conditions. Simultaneously, the strength of intra-plane closed and intra-plane open schemes is that clock estimation under these schemes is not sensitive to the constellation geometry.

4.2 Impact of ISL measurement biases on orbit determination

In the second approach described in this section we included additional systematic errors in the simulation step. We introduced ISL measurement biases in the simulations conducted with the same settings as described in the beginning of previous subsection (Table 6). ISL biases are simulated as a constant for the satellite for a day—in our test case biases are equal to 0.5 cm. Biases are estimated as a constant value for satellite per day. It must be emphasized that both GNSS and ISL measurements are combined in the orbit estimation, so ISL bias estimation is supported with sufficient number of GNSS observations. It is especially important in case of rings schemes. Due to their repeatable satellite pairs and connections in only one orbital plane bias values can flow between the satellites when only or mostly ISL measurements will be considered (with no usage of ground stations or, per chance, there will be not enough GNSS measurements). In this research, we would like to note above developments and address it as complementary tasks in the potential future investigations.

Table 9 presents mean values of estimated biases for all satellites and RMS values of the differences between simulated and estimated biases are shown. The mean values demonstrate that bias is well determined for most of the connectivity schemes. The worst results are obtained for intra-plane open, which are 20% lower than reference values. RMS values prove that each of the connectivity schemes differently participate in bias estimation because of divergent satellite pairs and thus different number of observations for particular satellites. Differences between tested constellations can be mostly negligible. Connectivity schemes based on the closest distance and repeatable sequence of pairs perform equally. Ring schemes with the constant pair allocation result in more variable result and thus twice higher RMS than in other schemes. In Fig. 11 are presented mean results of bias estimation for the satellites.

Fig. 11 Mean estimated ISL measurement biases of each satellite for the tested constellations: **a** Galileo-like, **b** GPS-like, and **c** GPS-real

In Fig. 12 are shown results of orbit estimation errors for Galileo-like, GPS-like and GPS-real constellations. The outcomes are very similar to those obtain in subsection 4.1, when no bias was included in the simulations. The highest difference is noticed for the ring schemes and Galileo-like constellation and it equals to about 25% of the outcomes. Results of estimation in Fig. 12d show that bias slightly worsen the total 3D errors, but do not change the dependencies mentioned in subsection 4.1, that sequential and schemes based on the distance between satellites are equivalent. However, the standard deviation of the mean solution change, mostly for ring schemes in each component (especially for Galileo-like) and for radial component in nearest (inter-plane, dual one-way) scheme for GPS-real.

Table 9 Estimated mean values of biases and their RMS values—constant value of bias equal to 0.5 cm for each satellite for one day was simulated

Connectivity scheme	Galileo-like		GPS-like		GPS-real	
	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)
Intra-plane closed	0.48	0.24	0.45	0.18	0.48	0.17
Intra-plane open	0.43	0.28	0.39	0.25	0.41	0.21
Nearest (general, dual one-way)	0.52	0.11	0.45	0.13	0.51	0.14
Nearest (general, one-way)	0.52	0.13	0.47	0.14	0.51	0.19
Nearest (inter-plane, dual one-way)	0.48	0.17	0.47	0.16	0.49	0.15
Sequential (dual one-way)	0.50	0.11	0.50	0.11	0.51	0.08
Sequential (one-way)	0.48	0.10	0.49	0.17	0.48	0.12

It means that these connectivity schemes potentially do not ensure repeatable estimation of biases which then impact on the orbit determination accuracy.

Figures 13, 14 and 15 present results of satellite and station clock estimation errors for Galileo-like, GPS-like, and GPS-real, respectively. The comparison between results for Galileo-like shown in Figs. 8 and 13 reveals that station clocks were less affected by introducing biases than satellite clocks. The differences are mostly negligible. For satellite clocks, it seems that estimation of additional parameters help in case of ring schemes and these based on one-way connection type. For intra-plane closed the satellite clock estimation error is smaller about 1.5 mm. For schemes using dual one-way connection type the results are very similar to respective values in Fig. 8. The same conclusions can be made for results shown in Fig. 14 for GPS-like and Fig. 15 for GPS-real and compared to Figs. 9 and 10, respectively. Results are better for ring schemes and one-way connection type. Schemes using dual one-way connections are comparable with results shown in Figs. 9 and 10, for GPS-like, and GPS-real, respectively.

In general, introducing ISL measurement bias estimation does not have a significant impact on the clock estimation. Dual one-way connection type is more resistant to biases according to elimination of clock errors from ISL measurements. For one-way connection type, which requires satellite clock estimation, it performs slightly better for presented approach. In opposite to satellite clock which seems to be fragile on the chosen connection type, estimated ISL biases are not associated with chosen type of connection in the connectivity schemes.

5 Conclusions

In this study, we aimed to explore the possible behaviour of the estimation process based on GNSS observations combined with ISL measurements. Attention was paid to three different constellation types (Galileo-like, GPS-like, and GPS-real) and seven different ISL connectivity schemes: (1) intra-plane closed, (2) intra-plane open, (3) nearest (inter-plane, dual one-way), (4) nearest (general, dual one-way), (5) nearest (general, one-way), (6) sequential (dual one-way), and (7) sequential (one-way). The outcome for each of the schemes varies in accordance with scheduled satellite pairs and exploitation of the two

Fig. 12 Orbit estimation mean RMS errors for the **a** radial, **b** along-track, and **c** cross-track components, and **d** the total 3D RMS value in approach with ISL measurement biases estimation

connection types. In general, ISLs strongly contribute to minimization of the orbit errors (especially in along-track and cross-track components), and help to minimize mainly satellite clock estimation errors.

Ring schemes are less sensitive to the geometry of the constellation and the larger number of planes and variable number of the satellites in the orbital planes marginally improve orbit estimation and improve clock estimation. Results obtained with schemes based on the distance to the satellite are not dependent on the settings of the connection type or the constellation geometry. Schemes based on a predefined sequence of satellite pairs seem to be the most versatile; however, the maximum benefit from using the dual

Fig. 13 Satellite and station clock estimation mean RMS errors for the Galileo-like constellation in approach with ISL measurement biases estimation

one-way connection type may not be realized. These schemes perform equally among the tested constellation types. Sequential schemes appear to be the best choice when high efficiency in orbit and clock determination common with simplicity of creating ISL pairs are considered.

We have also tested the simplified scenario with constant bias in the ISL measurements. Biases were introduced to check potential impact on the orbit determination including the ISL connectivity schemes. For tested cases, when ISL measurements are outnumbered by GNSS observations, the influence of the bias is not significant for this case. In the further research we will focus on alternative methods and scenarios, e.g. with limited ground stations. Bias estimation with less GNSS measurements might result in much worse values for ring schemes or it might require changes in the estimation approach.

Fig. 14 Satellite and station clock estimation mean RMS errors for the GPS-like constellation in approach with ISL measurement biases estimation

The choice of connectivity scheme for the ISL measurements used further in orbit determination is not essential in reducing estimation errors. For performed simulations, the proposed schemes sufficiently contribute to the orbit computation. However, while 1-cm accuracy (or even better) orbit will be possible, the connectivity scheme will potentially play a vital role in the navigation constellation equipped with the ISL payload. Ring schemes and sequential schemes are the most promising of the studied schemes because of their easiness in pair assignment, probable long-term stability, and low computational burden. In future research, we will focus on exploitation of the ISLs with chosen connectivity schemes considering possible observation conditions and limitations e.g. hardware issues or a variable number of ground stations.

Fig. 15 Satellite and station clock estimation mean RMS errors for the GPS-real constellation in approach with ISL measurement biases estimation

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References

- Ananda MP, Bernstein H, Cunningham KE, Feess WA, Stroud EG (1990) Global positioning system (GPS) autonomous navigation. In: IEEE symposium on position location and navigation. A decade of excellence in the navigation sciences, pp 497–508
- Arnold D, Meindl M, Beutler G, Dach R, Schaer S, Lutz S, Prange L, Sošnica K, Mervart L, Jäggi A (2015) CODE's new solar radiation pressure model for GNSS orbit determination. *J Geod* 89:775–791. <https://doi.org/10.1007/s00190-015-0814-4>
- Fernández FA (2011) Inter-satellite ranging and inter-satellite communication links for enhancing GNSS satellite broadcast navigation data. *Adv Sp Res* 47:786–801. <https://doi.org/10.1016/j.asr.2010.10.002>
- Gong X, Huang D, Cai S, Zhou L, Yuan L, Feng W (2019) Parameter decomposition filter of BDS-3 combined orbit determination using inter-satellite link observations. *Adv Sp Res* 64:88–103. <https://doi.org/10.1016/j.asr.2019.03.017>
- Guo R, Hu XG, Tang B, Huang Y, Liu L, Cheng LC, He F (2010) Precise orbit determination for geostationary satellites with multiple tracking techniques. *Chin Sci Bull* 55:687–692
- Han S, Gui Q, Li G, Du Y (2014) Minimum of PDOP and its applications in inter-satellite links (ISL) establishment of Walker- δ constellation. *Adv Sp Res* 54:726–733. <https://doi.org/10.1016/j.asr.2014.04.020>
- Han S, Gui Q, Li J (2013) Establishment criteria, routing algorithms and probability of use of inter-satellite links in mixed navigation constellations. *Adv Sp Res* 51:2084–2092. <https://doi.org/10.1016/j.asr.2012.12.020>
- Han S, Gui Q, Li J (2011) Analysis of the connectivity and robustness of inter-satellite links in a constellation. *Sci Chin Phys Mech Astron* 54:991–995. <https://doi.org/10.1007/s11433-011-4339-4>
- Huang G, Cui B, Zhang Q, Li P, Xie W (2019) Switching and performance variations of on-orbit BDS satellite clocks. *Adv Sp Res* 63:1681–1696. <https://doi.org/10.1016/j.asr.2018.10.047>
- Huang J, Liu W, Su Y, Wang F (2018) Cascade optimization design of inter-satellite link enhanced with adaptability in future GNSS satellite networks. *GPS Solut*. <https://doi.org/10.1007/s10291-018-0707-0>
- Huang J, Su Y, Liu W, Wang F (2017) Optimization design of inter-satellite link (ISL) assignment parameters in GNSS based on genetic algorithm. *Adv Sp Res* 60:2574–2580. <https://doi.org/10.1016/j.asr.2016.12.027>
- Liu L, Zhu LF, Han CH, Liu XP, Li C (2009) The model of radio two-way time comparison between satellite and station and experimental analysis. *Chin Astron Astrophys* 33:431–439. <https://doi.org/10.1016/j.chinastron.2009.09.009>
- Pan J, Hu X, Zhou S, Tang C, Guo R, Zhu L, Tang G, Hu G (2018) Time synchronization of new-generation BDS satellites using inter-satellite link measurements. *Adv Sp Res* 61:145–153. <https://doi.org/10.1016/j.asr.2017.10.004>
- Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the earth gravitational model 2008 (EGM2008). *J Geophys Res Solid Earth* 117:1–38. <https://doi.org/10.1029/2011JB008916>
- Petit G, Luzum B (2010) IERS conventions (2010). *Bur Int Des Poids Mes Sevres*. <https://doi.org/10.1109/28.273627>
- Ren X, Yang Y, Zhu J, Xu T (2019) Comparing satellite orbit determination by batch processing and extended Kalman filtering using inter-satellite link measurements of the next-generation BeiDou satellites. *GPS Solut*. <https://doi.org/10.1007/s10291-018-0816-9>
- Rodríguez-Pérez I, García-Serrano C, Catalán Catalán C, García AM, Tavella P, Galleani L, Amarillo F (2011) Inter-satellite links for satellite autonomous integrity monitoring. *Adv Sp Res* 47:197–212. <https://doi.org/10.1016/j.asr.2010.07.019>
- Rodríguez-Solano JC (2009) Impact of albedo modelling on GPS orbits. Master's Thesis. Technische Universität München
- Shi LY, Xiang W, Tang XM (2011) A link assignment algorithm for GNSS with crosslink ranging. In: 2011 int conf localization GNSS, ICL-GNSS 2011 13–18. <https://doi.org/10.1109/ICL-GNSS.2011.5955268>
- Sun L, Wang Y, Huang W, Yang J, Zhou Y, Yang D (2018) Inter-satellite communication and ranging link assignment for navigation satellite systems. *GPS Solut*. <https://doi.org/10.1007/s10291-018-0704-3>
- Tang C, Hu X, Zhou S, Liu L, Pan J, Chen L, Guo R, Zhu L, Hu G, Li X, He F, Chang Z (2018) Initial results of centralized autonomous orbit determination of the new-generation BDS satellites with inter-satellite link measurements. *J Geod* 92:1155–1169. <https://doi.org/10.1007/s00190-018-1113-7>
- Tang Y, Wang Y, Chen J (2016) The availability of space service for inter-satellite links in navigation constellations. *Sens Switz*. <https://doi.org/10.3390/s16081327>

- Werner M, Delucchi C, Vögel HJ, Maral G, De Ridder JJ (1997) ATM-based routing in LEO/MEO satellite networks with intersatellite links. *IEEE J Sel Areas Commun* 15:69–82. <https://doi.org/10.1109/49.553679>
- Xu H, Wang J, Zhan X (2012) Autonomous broadcast ephemeris improvement for GNSS using inter-satellite ranging measurements. *Adv Sp Res* 49:1034–1044. <https://doi.org/10.1016/j.asr.2012.01.001>
- Yang D, Yang J, Li G, Zhou Y, Tang CP (2017a) Globalization highlight: orbit determination using BeiDou inter-satellite ranging measurements. *GPS Solut* 21:1395–1404. <https://doi.org/10.1007/s10291-017-0626-5>
- Yang D, Yang J, Xu P (2017b) Timeslot scheduling of inter-satellite links based on a system of a narrow beam with time division. *GPS Solut* 21:999–1011. <https://doi.org/10.1007/s10291-016-0587-0>
- Yang Q, Tan L, Ma J (2009) Doppler characterization of laser inter-satellite links for optical LEO satellite constellations. *Opt Commun* 282:3547–3552. <https://doi.org/10.1016/j.optcom.2009.05.058>
- Yi X, Sun Z, Yao F, Miao Y (2013) Satellite constellation of MEO and IGSO network routing with dynamic grouping. *Int J Satell Commun Netw* 31:277–302. <https://doi.org/10.1002/sat.1032>
- Zhou Y, Wang Y, Huang W, Yang J, Sun L (2018) In-orbit performance assessment of BeiDou intersatellite link ranging. *GPS Solut*. <https://doi.org/10.1007/s10291-018-0784-0>