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INTER-SATELLITE LINKS :
IMPROVING GNSS NAVIGATION MESSAGE PERFORMANCE

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ISL CONTEXT

/// Navigation services highly depend on ground segment's components such as :

- Worldwide network of ground stations performing observables.
- Ground segment hosting Orbit Determination and Time Synchronization (ODTS) and producing navigation data to broadcast.
- Ground uplink stations to upload these navigation data to space segment.

/// Contingencies affecting these components could lead to critical loss of service accuracy/availability.

- Local at station level.
- Global level (network, mission segment…).

/// Inter-Satellite Links (ISL) between platforms in orbit could allow :

- Data exchange = improved and more frequent data dissemination.
- Inter-Satellite Ranging as additional observables for the ground Orbit Determination and Time Synchronization (ODTS).
- On-board autonomous ODTS algorithm using ISR as main observables.

ISL TECHNOLOGY

/// ISL establishes a communication link between orbiting platforms.

/// ISL can be established both in radio frequency (RF) or optical bands.

- Optical link, while providing more accurate measures, increases the platform's complexity. Optical links require a more precise attitude control system, as well as more power and a longer acquisition time.
- RF link consumes less power than the optical link, has a weaker data rate and is less robust against interference and signal jamming.

/// PRN code can be modulated on the carrier and then used from the receiving satellite to compute time of arrival, providing a pseudorange measurement. Carrier-phase measurements can be performed by using a frequency locked loop (FLL).

/// This link allows the distribution of data, telecommands and telemetry.

/// Steerable antennas make it possible to establish an ISL either in plane or out of plane.

/// **The main advantages of ISR:**

1. A more favorable geometry of measures for better observability of cross track and along-track components.
2. Quasi-absence of atmosphere induced delays (constraining the minimum distance of the line-of-sight satellite-to-satellite to the Earth surface).
3. Dual one-way ranges can be computed if measures are shared between couples of satellites.
4. High-quality measurements due to high carrier over noise ratio C/N_0.

ISL CONTACT PLAN

/// ISL architecture defines how often measures can be acquired and at which epoch, considering many options :

- Full-duplex or half-duplex communication
- Frequency
- Communication schemes
- Number of ISL interfaces per satellite

/// ISL contact plan envisaged for this experiment is a point-to-point (“unicast”) type and “sequential,” enabling communication between pairs of satellites, in half-duplex mode either intra-plane or inter-plane during repetitive cycles.

/// In a Sequential Contact Plan, a given satellite tries to establish ISL communication to all satellites one after the other. This is done following a fixed matrix, independently of the distance or other parameters that might affect the link itself.

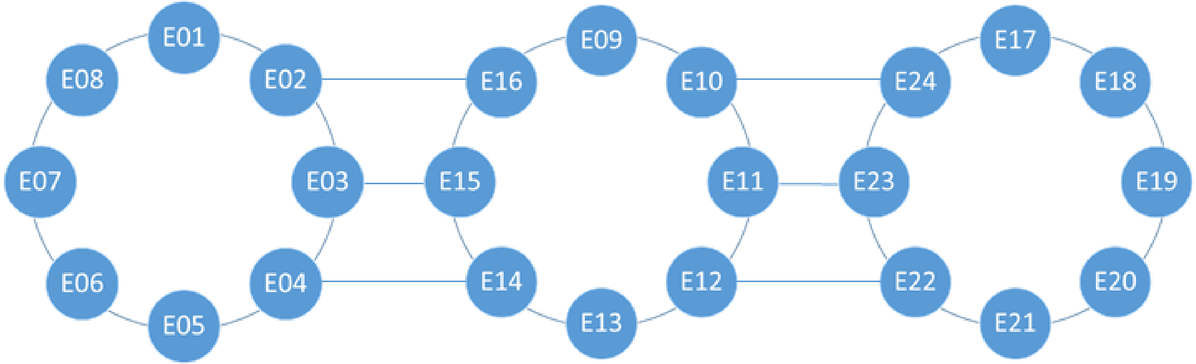
/// In order to optimize the benefits at ODTS level, ISL must be established across planes (geometry, global network).

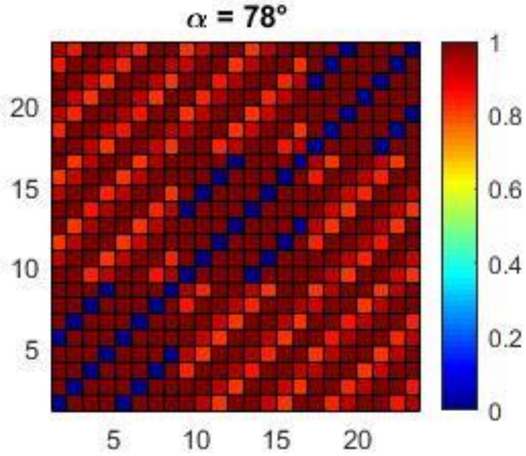
/// For an exhaustive contact plan definition, the time slot, pointing delay and communication cycle must be defined:

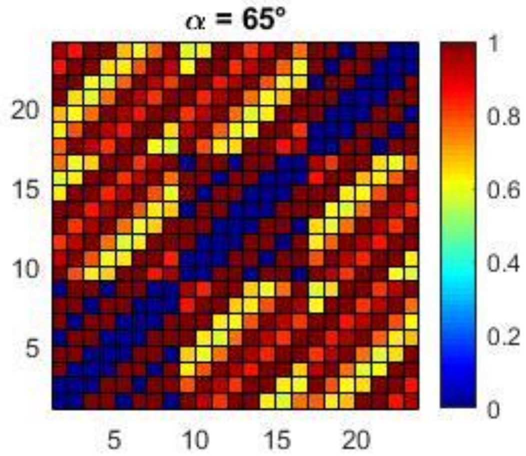
- **Time slot:** The duration of a communication interval between two satellites, which includes two sub-slots of equal duration. During the first sub-slot, Satellite A transmits to Satellite B and vice versa during the second sub-slot. The transmitted signal is used by the receiving satellite to make measurements and receive data.
- **Pointing delay:** The delay between one time slot and the next, necessary to point the antenna toward the next satellite. It also includes other additional delays due to the acknowledgment messages necessary to begin transmission.
- **Communication cycle:** The time needed to communicate with all the constellation’s satellites. At the end of a single communication cycle, all possible couples of satellites have established an ISL and exchanged data/ranging.

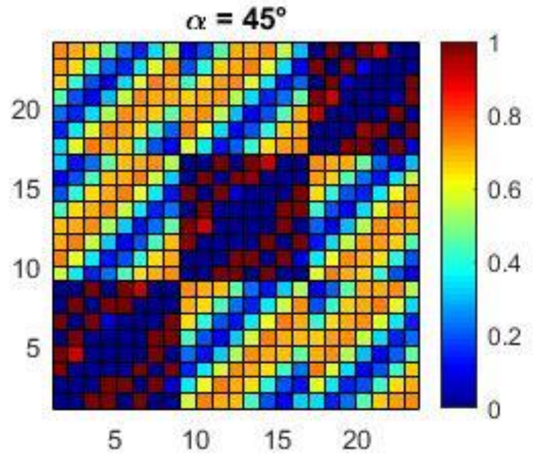
ISL CONTACT PLAN EXAMPLE

- Walker 24/3/1 constellation
- Intra-Plane Links
- Inter-Plane Links
- Different visibility cone

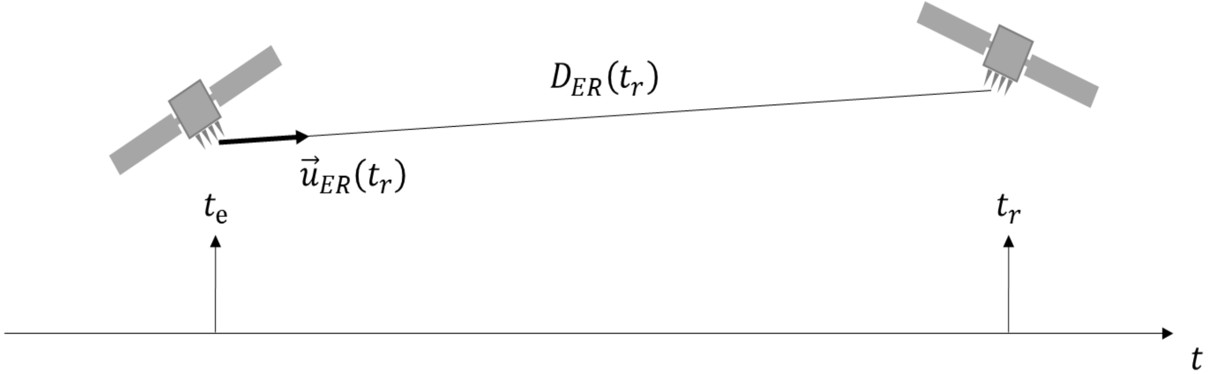








ISL : ONE-WAY RANGING

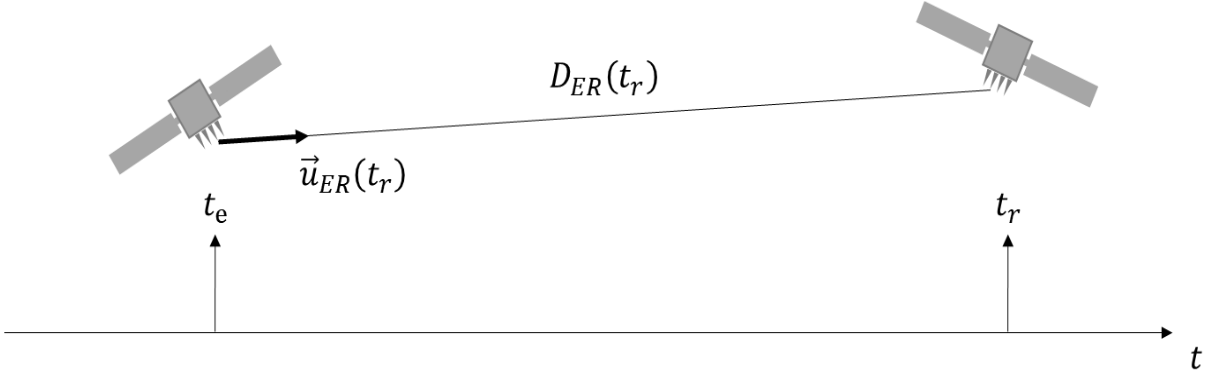


$$\rho_{ER}(t_r) = D_{ER} + c\,[\delta t_R(t_r) - \delta t_E(t_e)] + c\left[\Delta t_R^{rel} - \Delta t_E^{rel} + \Delta t_{saphiro}\right] + B_R + B_E + PCO_{ISL} + \varepsilon_M$$

Where :

- D_{ER} stands for the geometric distance between emitter and receiver center of mass.
- δt_R **and** δt_E stand for the apparent satellite clock bias (containing hardware bias) with respect to system time reference.
- Δt_R^{rel} **and** Δt_E^{rel} stand for the eccentric relativistic effect affecting both receiver and emitter satellites.
- $\Delta t_{saphiro}$ stands for the Shapiro effect, being the effect on the signal propagation due to Earth gravitational field.
- B_R **and** B_E stand for the instrumental delays (in meter) relative to the ISL antenna on the receiving and the transmitting chain.
- stands for
- PCO_{ISL} stands for the phase center offset relating to the emitter and receiver satellites.
- ε_M stands for the measurement noise.

ISL : DOPPLER



$$\frac{f_R - f_E}{f_E} = \frac{1}{c}\frac{\partial \rho_{ER}(t_r)}{\partial t_r} = \frac{1}{c}\left(\dot{D}_{ER}(t_r) + c\left[\delta \dot{t}_R(t_r) - \delta \dot{t}_E(t_e)\right] + c\left[\Delta \dot{t}_R^{rel} - \Delta \dot{t}_E^{rel}\right]\right) + \varepsilon_d$$

Where :

- $\boldsymbol{f_R}$ **and** $\boldsymbol{f_E}$ stand respectively for the received signal frequency and the original transmitted frequency.

Note : Considering relatively short time slots, Doppler is preferred to phase measurements, since they won't import additional ambiguity parameters to solve in the system.

ISL IN GROUND GNSS ODTS

Main challenge of processing ISL measurements is inserting them in a classical GNSS ODTS process.

Ground GNSS stations produce continuous and high rate ranging measurements, permitting periodic snapshot estimation for clock biases.

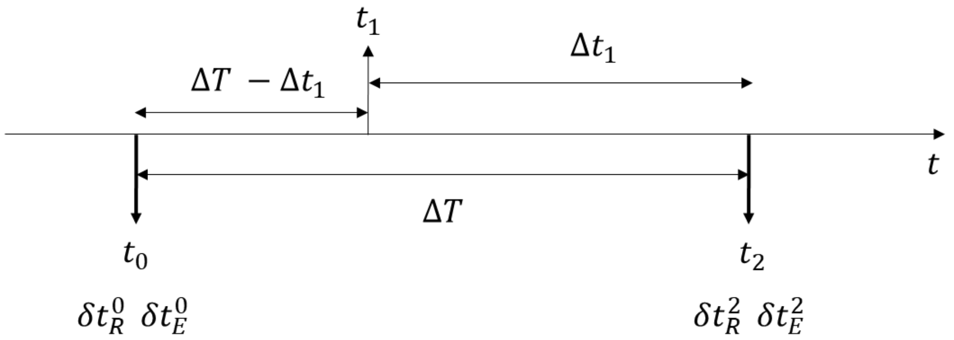
ISL measurements are only available during effective time slots of the communication cycle.

If satellite R has measured at epoch t_1 the cross-pseudorange $\rho_{RE}(t_1)$ with satellite E, while the nearest snapshot resolution occur in t_0 and t_2 → 2 additional snapshot clock biases should be added to the state vector for each ISR measurement.

Solution : Assuming the time dynamic of the satellite's clock evolves slowly on short intervals (a few minutes), δt_R (t_r) and δt_E (t_e) can be linked to the closest snapshot resolutions.
Clock bias at time t_1 can be expressed as the satellite's clock offset at system epochs t_0 and t_2 (ex : linear interpolation).

$$\boldsymbol{\delta t_R^1 = f(\Delta T - \Delta t_1)\delta t_R^0 + f(\Delta t_1)\,\delta t_R^2}$$
$$\boldsymbol{\delta t_E^1 = f(\Delta T - \Delta t_1)\delta t_E^0 + f(\Delta t_1)\,\delta t_E^2}$$

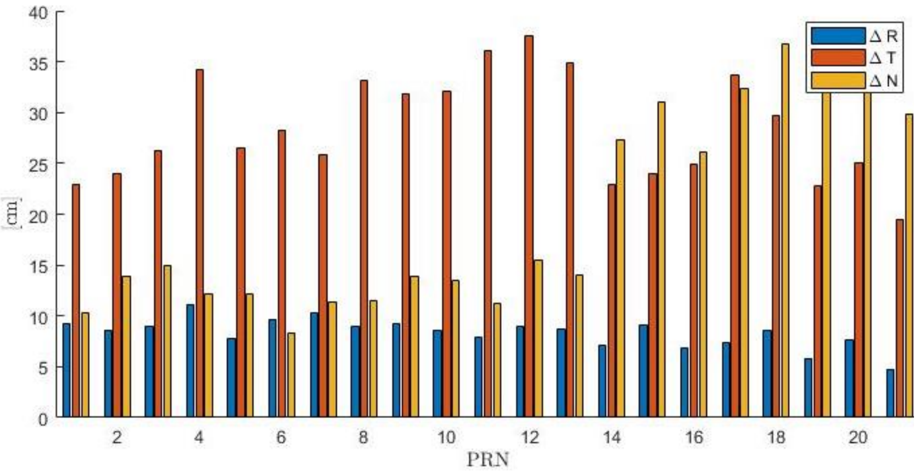
Where *f(t)* depends on the specific interpolation method selected (this can be extended to include more interpolation points).



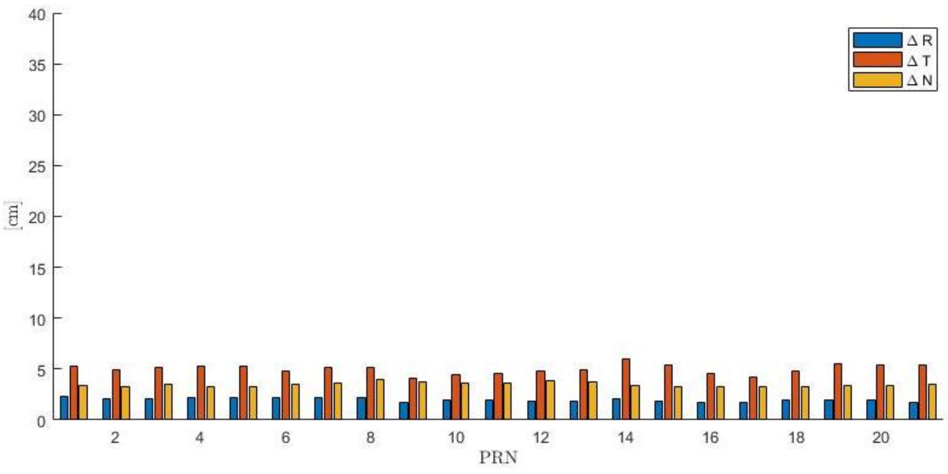
EXPERIMENTATION RESULTS

/// RTN Errors RMS [cm] over estimation arc (10 days)

“GNSS Only”



“GNSS + ISL”



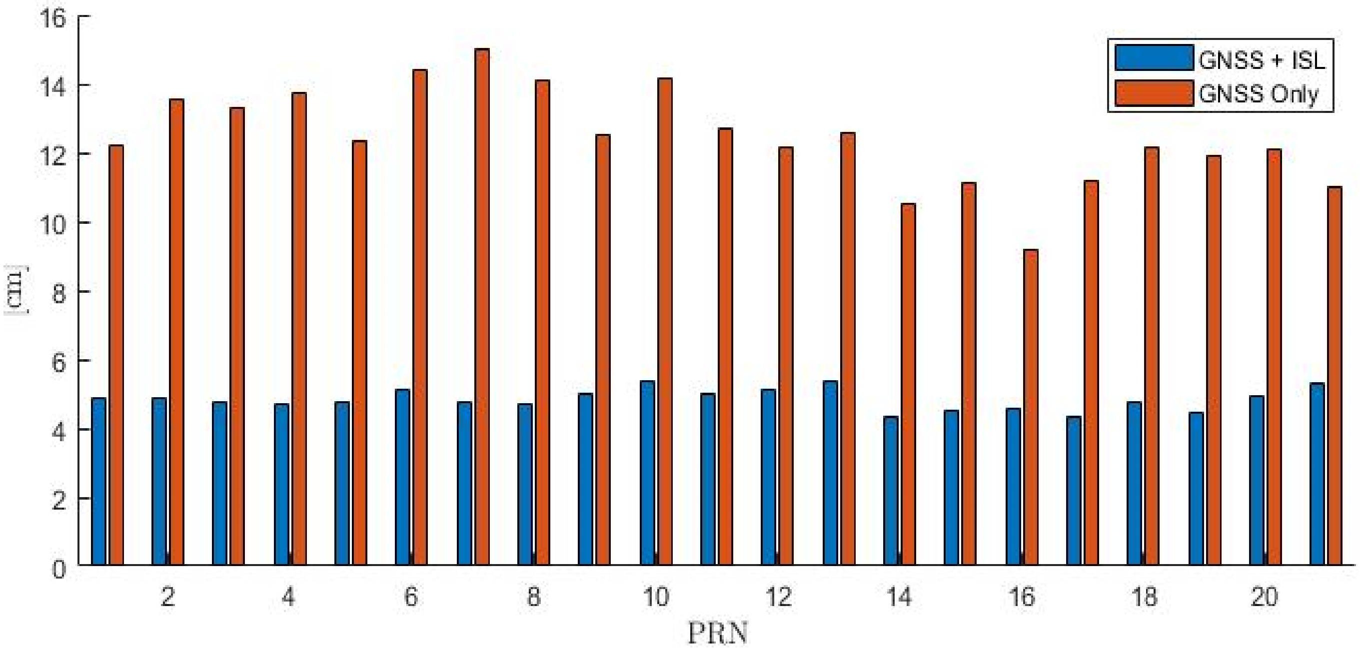
Date: 20/01/2025

Ref: Not referenced

Template: 83230347-DOC-TAS-EN-011

EXPERIMENTATION RESULTS

/// Clock Errors RMS [cm] over estimation arc (10 days)



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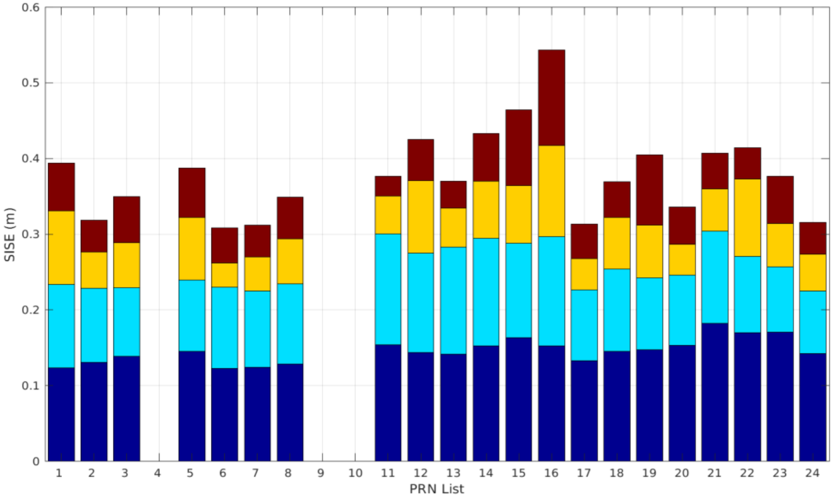
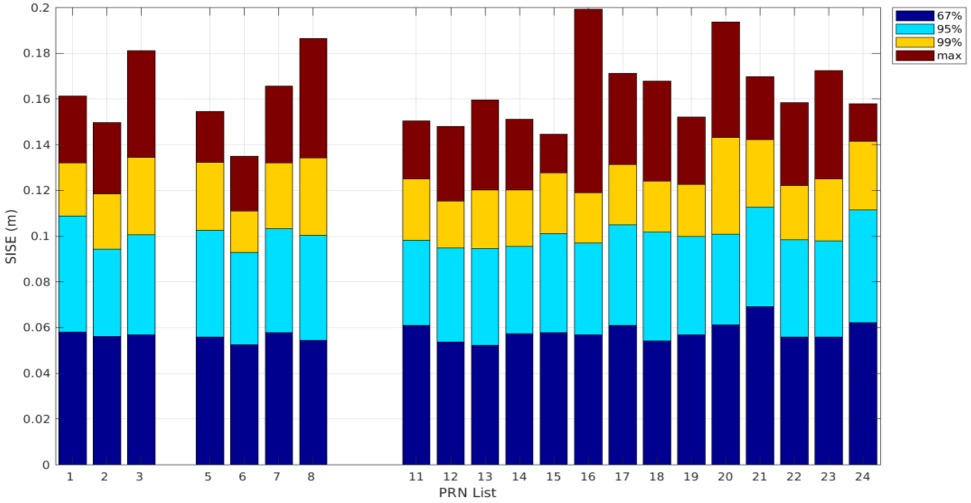
EXPERIMENTATION RESULTS

/// WUL SISE Statistics comparison between "GNSS Only" and "GNSS + ISL' at 20 minutes. NEODIS Package Software

Data	Worst Satellite WUL SISE@95% at 20 min	Worst Satellite, WUL SISE@95% at 100 min
GNSS	30.3 cm	38.8 cm
GNSS + ISL	11.2 cm	21.3 cm





ISL IN ON-BOARD AUTONOMOUS ODTS

/// Whenever contact with ground is lost, GNSS constellation can continue performing its own ODTS exploiting only ISL observations. Here is two possible approaches :

- **Distributed:** Each satellite performs its own state using ISR to other satellites, navigation messages and associated covariance.
- **Centralized:** ISR and state vectors are shared and centralized in one constellation ODTS filter that estimates all satellites' states at the same time.

/// Broadcast navigation message shall be computed with respect to a common timescale and Terrestrial Reference Frame.

- **Time Synchronization**
  - Different alternatives are possible:
    - **1. Satellite master clock:** A given satellite takes the master clock role. Clock biases are computed with respect to this specific SV. The performance is limited by the clock's stability and has the major drawback of having a single point of failure.
    - **2. Composite clock:** A common timescale is built using all or a selected sub-set of SV clocks.
  - Composite clock solution is expected to provide better long-term stability and also be more robust to individual satellite feared event.
  - Constraints of relative difference between the constellation reference time and UTC cannot be directly controlled until ground contact is establish.
- **Earth Orientation Parameters**
  - Earth orientation parameters become unobservable once ground contact is lost.
  - Orbits are propagated in an inertial frame.
  - Errors due to mis-orientation of Earth-bound force fields during orbit propagation have limited impact on performances.
  - Errors due to mis-orientation of Terrestrial Reference Frame during navigation data computation impact critically the performances.
  - A long-term EOP prediction model available on board is highly recommended. This model can be easily updated and uploaded to the space segment during nominal operations.

ISL : DUAL ONE-WAY RANGING IN ON-BOARD AUTONOMOUS ODTS

At epoch t_1 in the proper time of satellite A, satellite A performs with the satellite B a pseudo-range measurement ρ_{AB} (t_1). During the next sub-slot, satellite B measures the pseudo-range ρ_{BA} (t_2) with the satellite A at epoch t_2 of its proper time.

$$\boldsymbol{\rho_{AB}(t_1) = \|\vec{r}_A(t_1) - \vec{r}_B(t_1 - \tau_{AB})\| + c[\delta h_A(t_1) - \delta h_B(t_1 - \tau_{AB})] + \gamma_1 + \varepsilon_m}$$

$$\boldsymbol{\rho_{BA}(t_2) = \|\vec{r}_B(t_2) - \vec{r}_A(t_2 - \tau_{BA})\| + c[\delta h_B(t_2) - \delta h_A(t_2 - \tau_{BA})] + \gamma_2 + \varepsilon_m}$$

With : $\gamma = c\left[\Delta t_A^{rel} - \Delta t_B^{rel} + \Delta t_{saphiro}\right] + B_A + B_B + PCO_{ISL}$

These measurements can be corrected in order to project them at a common epoch.
Correction is computed as the difference of theoretical between actual and common epoch.

$$d\rho_{AB} = \tilde{\rho}(t_0) - \tilde{\rho}_{AB}(t_1) = (\vec{v}_A \Delta t_{1A} - \vec{v}_B \Delta t_{1B}) \cdot \vec{u}_{AB} + c\left(\delta \dot{h}_A \Delta t_{1A} - \delta \dot{h}_B \Delta t_{1B}\right)$$

$$d\rho_{BA} = \tilde{\rho}(t_0) - \tilde{\rho}_{BA}(t_2) = (\vec{v}_B \Delta t_{2B} - \vec{v}_A \Delta t_{2A}) \cdot \vec{u}_{BA} + c\left(\delta \dot{h}_B \Delta t_{2B} - \delta \dot{h}_A \Delta t_{2A}\right)$$

With : $\Delta t_{1A} = [t_0 - (t_1 - \delta h_A)]$, $\Delta t_{1B} = [t_0 - (t_1 - \delta h_A - \tau_{AB})]$, $\Delta t_{2B} = [t_0 - (t_2 - \delta h_B)]$ *and* $\Delta t_{2A} = [t_0 - (t_2 - \delta h_B - \tau_{BA})]$

New formulation at t_0

$$\boldsymbol{\begin{cases} \rho_{AB}(t_0) = \rho_{AB}(t_1) + d\rho_{AB} \\ \rho_{BA}(t_0) = \rho_{BA}(t_2) + d\rho_{BA} \end{cases}}$$

And

$$\boldsymbol{\begin{cases} \tilde{\rho}_{AB}(t_0) = \|\vec{r}_A(t_0) - \vec{r}_B(t_0)\| + c[\delta h_A(t_0) - \delta h_B(t_0)] + \gamma_0 + \varepsilon_m \\ \tilde{\rho}_{BA}(t_0) = \|\vec{r}_B(t_0) - \vec{r}_A(t_0)\| + c[\delta h_B(t_0) - \delta h_A(t_0)] + \gamma_0 + \varepsilon_m \end{cases}}$$

We can build a Clock-free and a Geometry-free set of equations in order to separate the orbit and clock problems to solve.

$$\boldsymbol{P = \frac{\tilde{\rho}_{AB}(t_0) + \tilde{\rho}_{BA}(t_0)}{2} = \|\vec{r}_B(t_0) - \vec{r}_A(t_0)\| + \varepsilon_P}$$

$$\boldsymbol{H = \frac{\tilde{\rho}_{AB}(t_0) - \tilde{\rho}_{BA}(t_0)}{2c} = \delta h_A(t_0) - \delta h_B(t_0) + \varepsilon_H}$$

LINK TO PUBLICATION

- Marco Laurenti et Al., ISL: Improving GNSS Navigation Message Performance, 31 May 2024
  https://insidegnss.com/isl-improving-gnss-navigationmessage-performance/

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THANK YOU!
ANY QUESTION?

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