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# Innovative Signal Processing Architectures & Signal Design for GNSS


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## Research context and motivation

- An increasing number of current and envisioned applications demands a **precise and reliable navigation system**. In the framework of Global Navigation Satellite Systems (GNSSs), several approaches are exploited or have been proposed to fulfill this requirement, either on the signal design side or through innovative processing architectures. Among these solutions, the availability of synchronous channels can be exploited at the receiver (RX) to increase the precision and the robustness of the position estimate through a **multichannel (MC)** approach. The coherency among these signals can be used to improve the quality of the information that is going to be extracted from them. An idea that has its theoretical foundation on the well-known Cramer Rao bound (CRB) for time-delay estimation:

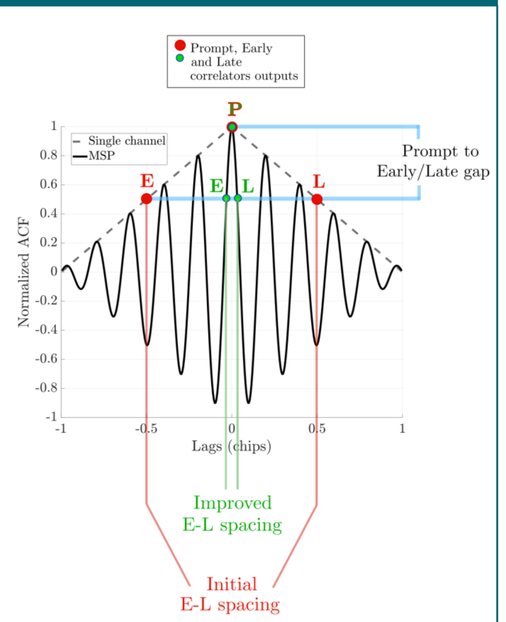
$$\sigma^2_{CRB} = \frac{B_n}{\frac{C}{N_0} 4\pi^2 \frac{1}{2\pi} \int_{-\infty}^{+\infty} f^2 G_s(f) df}$$

- However, signals' low power and limited bandwidth are intrinsic characteristics of current GNSSs that bound the achievable accuracy. To meet future demands and overcome limitations, Positioning, Navigation, and Timing (PNT) based on Low Earth Orbit (LEO) constellations have been investigated as a radical system change.
- To empower the potential of **LEO PNT** while achieving an improved position estimation, we developed an innovative MC RX architecture resilient to the large Doppler that characterizes LEO signals and effective in terms of available bandwidth exploitation.

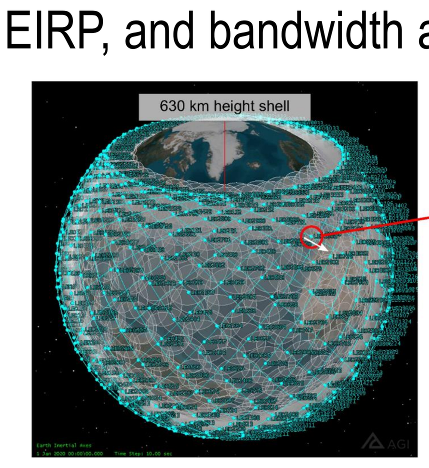
*5 min. video summarizing research context and contributions:*

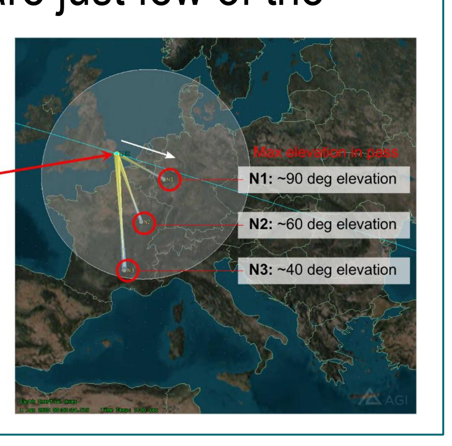
## Addressed research questions/problems

- In this context it is then straightforward to wonder (*i*) how to get closer to the CRB with existing signals while (*ii*) complying with the upcoming LEO PNT scenario and constraints.
- (*i*) To close the gap with the theoretical performance, multiple channels can be coherently processed at the RX, but a set of **design choices** must be done to address implementation problems. The **tracking stage** is the core of signal delay estimation in a GNSS RX. It is based on a pair of **codependent DLL and PLL**. To innovate such processing block implies the re-design of a closed-loop architecture which needs to be tested for potential instability phenomena. Indeed, besides such **closed-loop validation**, the proposed receiver architecture must involve a strategy to solve the **inherent peak ambiguity** that affects correlators' output in a MC architecture. Such ambiguity might lead to false locking of DLL, especially in presence of **multipath**.




- (*ii*) Nonetheless, the unexplored LEO PNT scenario opens many possibilities and challenges. Orbital altitude, carrier frequency, EIRP, and bandwidth are just few of the many design choices investigated. A parametrical analysis of the limits and performance of the technique is of utmost importance to understand the technique's **domain of application** with special attention to robustness to harsh Doppler.



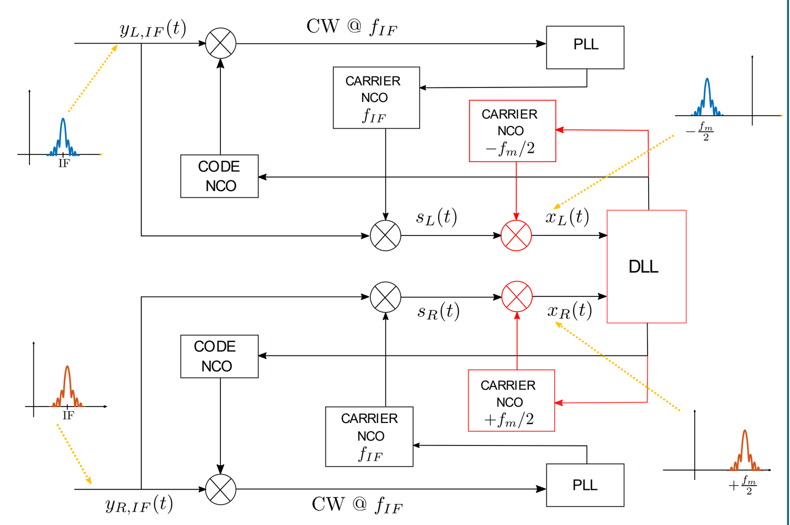




## Submitted and published works


- Nardin, A., Minetto, A., Vouch, O., Mariani, M., Dovis, F., "*Snapshot Acquisition of GNSS Signals in Space: a Case Study at Lunar Distances"* Proceedings of the 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022) , Denver, Colorado (USA), 2022.
- Nardin, A., Fraire, J., Dovis, F., "*Contact Plan Design for GNSS Constellations: A Case Study with Optical Inter-Satellite Links"* IEEE Transactions On Aerospace And Electronic Systems, vol. 58, no. 3, 2022, pp. 1981-1995.
- Nardin, A., Dovis, F., Fraire, J., "*Empowering the Tracking Performance of LEO-Based Positioning By Means of Meta-Signals"* IEEE Journal Of Radio Frequency Identification., vol. 5, num. 3, 2021, pp. 244-253.
- Nardin, A., Dovis, F., Motella, B., "*Impact of non-idealities on GNSS meta-signals processing"*, European Navigation Conference (ENC), Dresden, 2020, pp. 1-8.
- Nardin, A., Dovis, F., Fraire, J., "*Empowering the Tracking Performance of LEO PNT by Means of Meta-Signals"*, IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE), Vicenza, 2020, pp. 153-158.
- Minetto, A., Dovis, F., Nardin, A., Vouch, O., Impresario, G., Musmeci, M., "*Analysis of GNSS data at the Moon for the LuGRE project"*, IEEE 9th International Workshop on Metrology for AeroSpace (MetroAeroSpace), Pisa, 2022, pp. 134-139.
- Minetto, A., Nardin, A., Dovis, F., "*Modelling and Experimental Assessment of Inter-Personal Distancing Based on Shared GNSS Observables"*, Sensors, vol. 21, num. 8, 2021.
- Minetto, A., Nardin, A., Dovis, F., "*GNSS-only Collaborative Positioning Among Connected Vehicles"*, MobiHoc Mobile and Ad Hoc Networking and Computing, Catania, 2019, pp. 37-42.
- Dovis, F., Minetto, A., Nardin, A., Falletti, E., Margaria, D., Nicola, M., Vannucchi, M., "*Analysis of the Signal Outage"*, GPS World., vol. 30, num. 8, 2019, pp. 10-12.
- Minetto, A., Nardin, A., Dovis, F., "*Tight Integration of GNSS Measurements and GNSS-based Collaborative Virtual Ranging"*, proceedings of 31th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2018), Miami, FL, 2018, pp. 2399 – 2413.

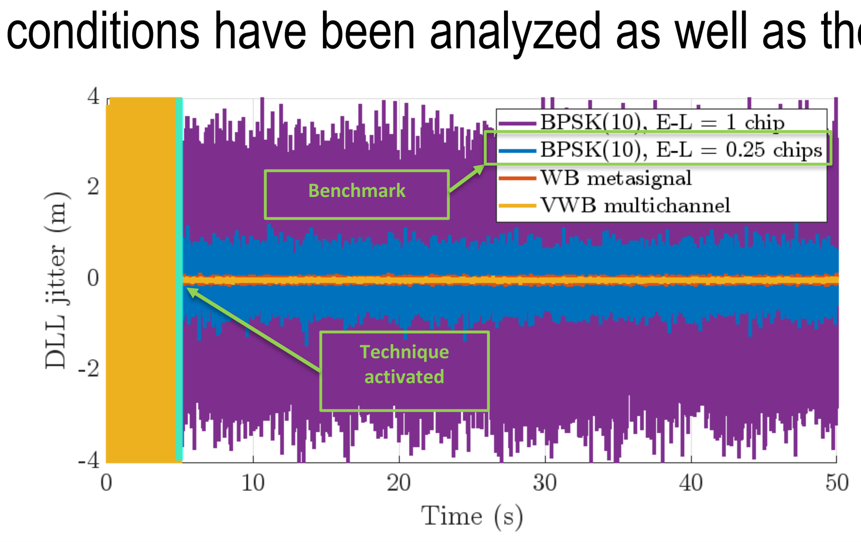

## Novel contributions

- To coherently process multiple channels at an early stage of the signal processing chain, a **re-design** of the tracking stage of a GNSS receiver is needed. To attain a lower estimation variance, a **MC DLL** has been designed to process an equivalent wideband signal obtained by introducing a **subcarrier generation** module.
- The coherence of the subcarrier with the incoming signal, is enabled by the closed-loop architecture and reached after a converging process, whose robustness has been addressed through the definition of a **two-stage tracking**.
- An initial tracking stage provides a **coarse estimation** which is twofold: (*i*) it overcomes the correlator's peak ambiguity and (*ii*) it enables a subcarrier generation whose phase error is small enough to ensure convergence in the subsequent **MC stage**, triggered to achieve a **finer estimation** and thus better positioning. A sequential two-stages approach involved the definition of a tracking lock condition, whose robustness with respect **to non-zero mean errors** such as multipath have been investigated.



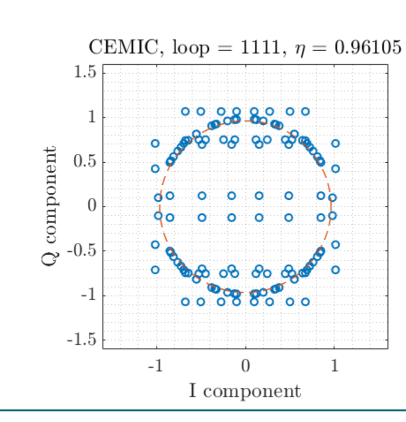

## Adopted methodologies

- To investigate the closed-loop performance in ideal conditions we simulated existing and envisioned GNSS signals in collaboration with *Thales Alenia Space*. First, through an ideal transmission chain, then through a **digital replica** of an operative **satellite payload**.
- After initial validation, a deeper investigation of the technique's domain of applicability has been carried out within the LEO PNT scenario in the framework of a project funded by the *European Space Agency* (ESA). Existing MC solutions have been implemented for comparison, completing the analysis with a wideband channel for **benchmarking**. A **characterization** of the LEO PNT domain has been carried out with **constellation simulators**, digital signal generators and software receivers. Different EIRP, bandwidth, carrier frequency, Doppler, and Line-of-Sight conditions have been analyzed as well as the architecture robustness to tracking noise, multipath, and false locking conditions. A case study based on the upcoming *Amazon*'s **megaconstellation** has been addressed and simulated completely: from constellation dynamics to signal propagation.




## Future work

- The use of the proposed MC architecture at the receiver side would allow to limit the bandwidth occupation of the transmitted signal, without compromising on the achievable accuracy. Nonetheless, performance improvement can be obtained also acting at the transmission level, thus balancing the complexity between system and user side. Indeed, **complex waveforms** can be used to further improve accuracy.
- Any change however, should take the **multiplexing** scheme into account to keep ensuring a **constant envelope (CE)** input to the satellite's HPA. A **joint design** of the transmission side and the multiplexing strategy should be addressed. An IQ diagram approaching CE is shown in figure as a preliminary result.




## List of attended classes

- 02LCPRV – Experimental modeling: costruzione di modelli da dati sperimentali (24/08/2022, 7 ECTS)
- 01SFURV – Programmazione scientifica avanzata in matlab (25/5/2020, 6 ECTS)
- 01QRPRV – Satellite Navigation signal exploitation for atmospheric and environmental monitoring (9/11/2020, 3 ECTS)
- 01UKBRV – Space Networking (didattica di eccellenza) (14/05/2020, 4 ECTS)
- 01TUFRP – All you need to know about research data management and open access publishing (4/6/2020, 3 ECTS)
- 01TTJRV – The Hitchhiker's Guide to the Academic Galaxy (13/4/2021, 3 ECTS)
- 08IXTRV – Project management (18/6/2021, 1 ECTS)
- 01SYBRV – Research integrity (3/4/2020, 1 ECTS)

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