High-Sensitivity GNSS Acquisition and Integrity Monitoring for Deep Space Navigation

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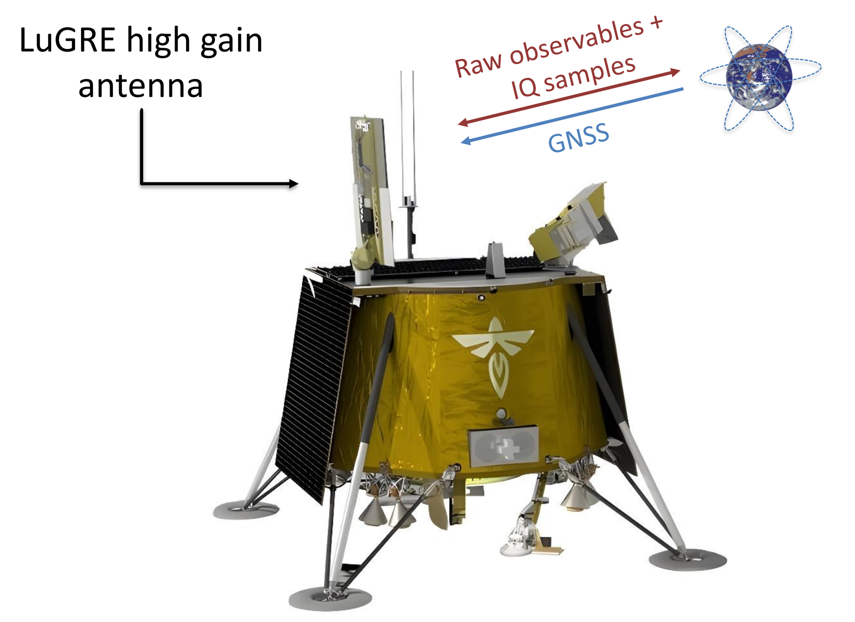
Introduction

GNSS signals are emerging as a candidate valuable resource for navigation in cis-lunar space, reducing reliance on ground station networks and enabling greater spacecraft autonomy. At lunar distances, however, these signals are extremely weak, making advanced receiver architectures and signal processing techniques essential for reliable acquisition, tracking, and robust navigation beyond Earth orbit. The Lunar GNSS Receiver Experiment (LuGRE) demonstrated the use of GNSS at lunar distances and provides a case study for evaluating receiver performance in cis-Lunar conditions and on the lunar surface.



The Blue Ghost Lander. Credits: Firefly Aerospace.

The Blue Ghost Lander on the Moon. Credits: Firefly Aerospace.

Research Questions and Goals

- What are the main impairments affecting acquisition?
  - Clock drift, large Doppler shift, low Carrier to Noise density ratio (C/N_0)?
- Is it feasible to acquire signals using only short batches of samples?
  - LuGRE collected batches of signal samples of a few hundred milliseconds.
- How can the integrity of such samples be evaluated?
  - How it is possible to detect missing samples or anomalies in the sample batches?

The Earth-Moon distance to scale.

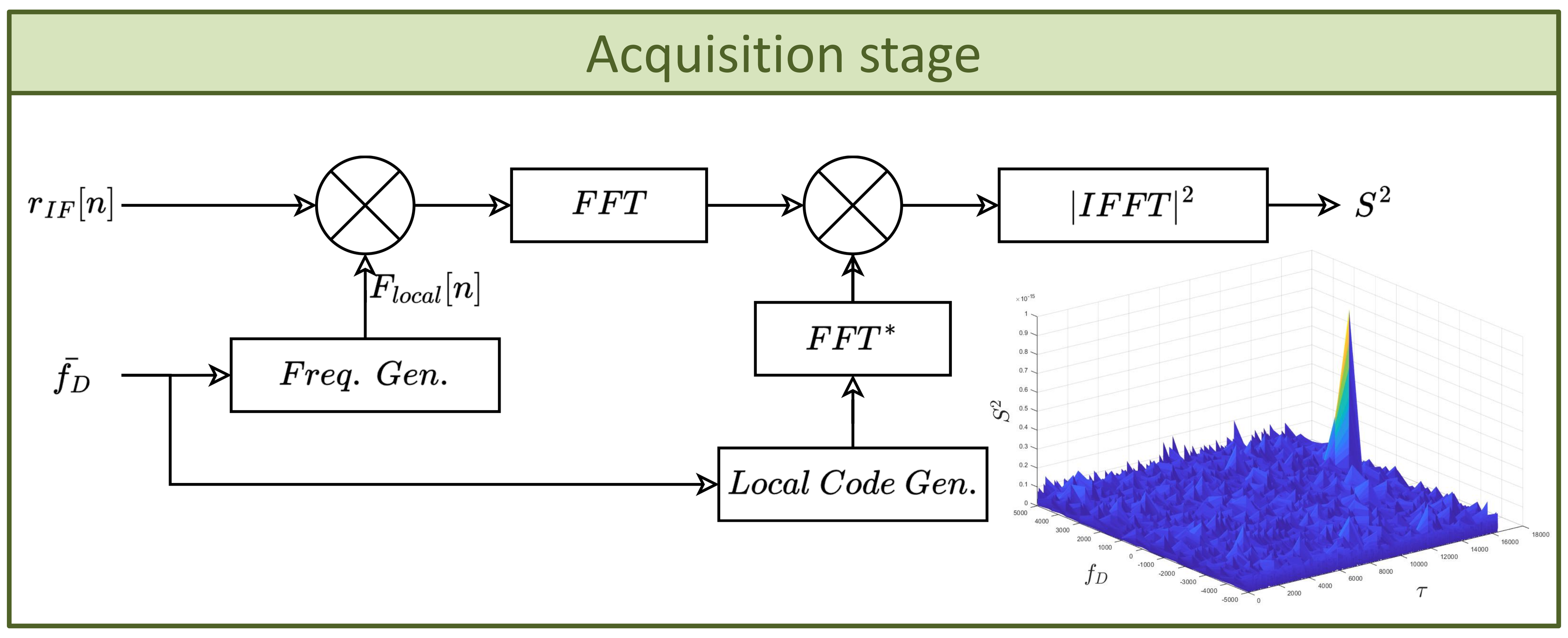
Background

The GNSS constellations transmits Pseudo Ransom Codes (PRN) that allow the receiver to acquire the received signal, which is completely buried into the noise, by correlating it with a local code replica. The acquisition search space is composed by the code phase τ and by the frequency offset f_D.

Novelties

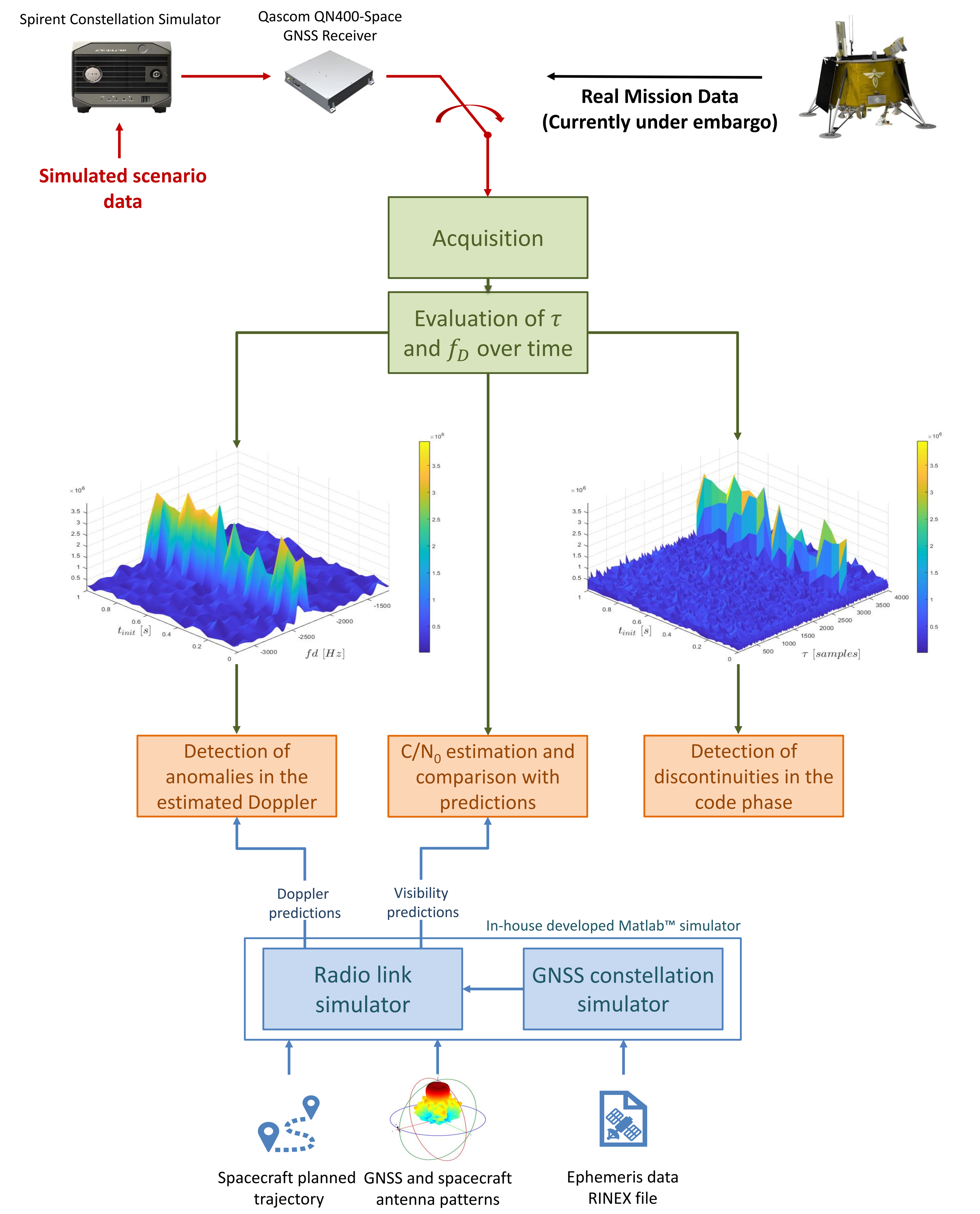
This work introduces the following novelties:

- Quantification of **code Doppler** effects on acquisition during transit to the Moon and on its surface;
- Implementation of an **integrity monitoring process** for short signal batches;
- Evaluation of GNSS **signal visibility** in cis-Lunar space and on the lunar surface through the acquisition of short signal batches.



The role of the local code Doppler compensation is analyzed in [1].

Methodology



Acquisition

The acquisition process can be repeated over multiple segments of the received signal across time. Afterwards, the carrier-to-noise density ratio (C/N_0) is evaluated. Here, the compensation of the time dilation allows to get about 3 dB of gain in the C/N_0.

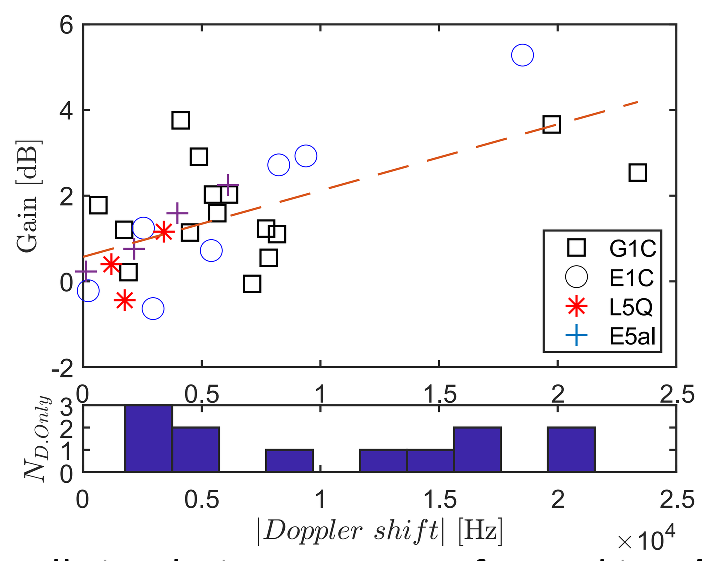
Anomalies detection comparison with simulations

Anomalies in f_D and code phase jumps are detected trough a comparison with simulated data. The evaluation of discontinuities in the assessmentcode phase enables an of the integrity of the received I/Q sample batches.

Simulation

The scenario is simulated using the planned spacecraft trajectory and satellite ephemerides, accounting for the receiver antenna and GNSS satellites' radiation patterns. Two simulators are used: Spirent for the signal-level simulation and a MATLAB-based simulator for the observables.

Results



- The code Doppler compensation can provide a gain of about **2 – 3 dB** in C/N_0 and it enables to acquire signals **that otherwise cannot be acquired** ($N_{D.only}$).
- The proposed integrity assessment scheme allowed to test of the integrity of the sample batches.
- More than **50 different GNSS signals** were acquired over **5 different simulated scenarios** considering both L1 and L5 bands.

All simulations were performed in a **hardware-in-the-loop** setup. All results shown are from simulations; **mission data will be released in October 2025.**

Publications

[1] Sciacca, L. et al. Acquiring GNSS Signals in Cislunar Space: A Hardware-in-the-Loop Investigation for LuGRE Mission Data. Proceedings of the 2025 IEEE/ION Position, Location and Navigation Symposium(PLANS), pp. 1036–1045, IEEE, 2025.

[2] Sciacca, L. et al. GNSS Signals from Cislunar Space: What You Get in the Blink of an Eye through In-Phase and Quadrature Signal Batches. Journal, manuscript in preparation.

Acknowledgments

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