

Development of a Universal RF Front-End for Next-Generation LEO-PNT Systems

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Abstract

Modern society's dependence on GNSS, combined with increasingly frequent disruption caused by geopolitical crises, has accelerated the search for alternative Positioning, Navigation and Timing (PNT) technologies. Many candidate solutions exploit Low Earth Orbit (LEO) constellations and Signals of Opportunity (SoOP), which offer higher received power, favorable geometry and improved interference resilience. The EULERIAN project develops a compact, low-power software-defined radio platform able to acquire and digitize heterogeneous LEO signals over a broad frequency range. The system combines a modular multi-band RF front-end, a coherent multi-channel digitizer and a deterministic gigabit interface for real-time streaming to external baseband processors. This paper presents the architecture, principal design choices and implementation status of a scalable acquisition platform for present and emerging LEO-PNT constellations. While similar RFFE hardware and DSP platforms may already exist separately on the market, this project serves as a key enabler for companies and research institutes developing baseband algorithms and complete LEO-PNT solutions, accelerating development time and fast prototyping while providing direct access to the underlying ECLEXYS developers to optimize, extend, and adapt the overall platform with maximum flexibility.

Keywords

LEO-PNT, resilient PNT, signals of opportunity, software-defined radio, RF front-end, deterministic data interface

1. Introduction

Modern societies increasingly rely on satellite-based Positioning, Navigation and Timing (PNT) services [1]. These services and the infrastructure of Global Navigation Satellite Systems (GNSS) are essential for transportation, telecommunications, finance, vital utilities, emergency response and defense. However, GNSS signals are transmitted from Medium Earth Orbit at extremely low received power levels, leaving this infrastructure intrinsically vulnerable.

Jamming, spoofing, signal masking in urban areas and deliberate denial of service are no longer exotic laboratory scenarios, but actual realities [2]. This has fostered worldwide interest in complementing or replacing GNSS PNT with alternative resilient capabilities.

This process started a decade ago in the United States, where Satelles demonstrated the viability of the Iridium commercial communication constellation as an alternative source of positioning and timing. The stronger power of LEO signals compared with GNSS in urban canyons provided an early real-world confirmation of LEO-based navigation [3, 4]. Europe subsequently pursued similar initiatives, the latest being ESA's CELESTE project.

In recent years LEO-PNT has acquired much higher priority. The conflicts in Ukraine and the Middle East have shown that GNSS-denied operations are no longer a niche condition. Wide regional disturbances, jamming and spoofing have affected military and civilian aircraft, maritime navigation, unmanned vehicles, critical infrastructure and emergency services. Complementary PNT solutions are consequently attracting major public investment and industrial development.

LEO-PNT receivers are widely seen as enabling technologies for platforms and services that cannot tolerate navigation interruptions. Two main approaches are being developed:

1. By leveraging existing commercial LEO constellations, such as OneWeb, Globalstar and Iridium,

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Table 1

Potential sources of LEO-PNT positioning signals.

Constellation	Satellites (2026)	Type	Primary purpose	Typical operating bands
Starlink (SpaceX)	> 8,000	SoOP	Broadband communications	Ku (10.7–12.7 GHz DL), Ka (17.8–30 GHz), E-band gateways
OneWeb (Eutelsat OneWeb)	~ 650	SoOP	Broadband communications	Ku (10.7–12.7 GHz DL, 14 GHz UL)
Iridium NEXT	66 (+ spares)	SoOP	Mobile satellite communications	L-band (1616–1626.5 MHz)
Globalstar	~ 48	SoOP	Mobile satellite communications / IoT	L-band (1610–1618.725 MHz), S-band (2483–2500 MHz)
AST SpaceMobile	< 50	SoOP	Direct-to-cell communications	Cellular bands (700 MHz–2.6 GHz)
Amazon Kuiper	Deployment started	SoOP	Broadband communications	Ku- and Ka-band
Telesat Lightspeed	Initial deployment planned	SoOP	Broadband communications	Ku- and Ka-band
Guowang (China)	Initial deployment	SoOP	Broadband communications	Ku- and Ka-band
Qianfan / G60 (China)	Initial deployment	SoOP	Broadband communications	Ku- and Ka-band
ESA CELESTE	IOD (planned)	IOD	Dedicated LEO-PNT	TBD (navigation-optimized bands)
Xona Pulsar	IOD / early deployment	IOD	Commercial dedicated LEO-PNT	L-band (planned)

PNT information can be extracted from their transmissions as Signals of Opportunity (SoOP) [5]. This exploits deployed infrastructure and can offer global coverage at limited cost.

2. By using a dedicated LEO constellation designed for navigation. In Europe, ESA’s CELESTE In-Orbit Demonstration will use orbital, communication and timing characteristics optimized for high-performance positioning and integrity services.

Table 1 lists the main signal sources that could, at least in principle, be exploited for LEO-PNT.

To support both approaches, EULERIAN targets a flexible, high-performance SDR front-end for acquiring and digitally sampling large bandwidths and connecting to independent digital baseband processors designed for different navigation tasks.

2. EULERIAN Project Vision and Rationale

The EULERIAN project’s goal is to overcome a key obstacle limiting the wider use of LEO-based PNT systems: the lack of a high-performance receiver front-end adaptable to the heterogeneity of present and future LEO constellations. Unlike conventional GNSS receivers, LEO-PNT signals originate from diverse communication constellations with different frequency bands, bandwidths, modulation formats and protocols. Acquisition hardware must therefore be flexible and reconfigurable.

EULERIAN implements a universal software-defined radio RF front-end that is as independent as possible of the system in use. Rather than creating dedicated hardware for each constellation, it uses a modular design in which only limited RF adaptations, such as an external downconverter or band filters, are required over a frequency range extending from L-band to Ku- and Ka-band. Digitized samples are transmitted through a standard high-speed serial interface to off-board FPGA hardware or a dedicated processor implementing navigation algorithms.

The design separates signal acquisition from navigation processing and concentrates on:

- a flexible wide-range RF front-end with coherent receiver channels;
- deterministic transport of high-rate digital samples to navigation-processing entities.

The hardware can therefore be connected to different SDR- or FPGA-based navigation algorithms without system modifications, supporting real-time navigation, offline analysis and hardware-in-the-loop verification. It is also intended to support future European LEO-PNT systems such as CELESTE, minimizing redesign as services evolve.

3. Overall System Architecture

EULERIAN is a generic and modular acquisition platform designed to accommodate present and future LEO-PNT applications while maintaining flexibility regarding signals and algorithms. It does not

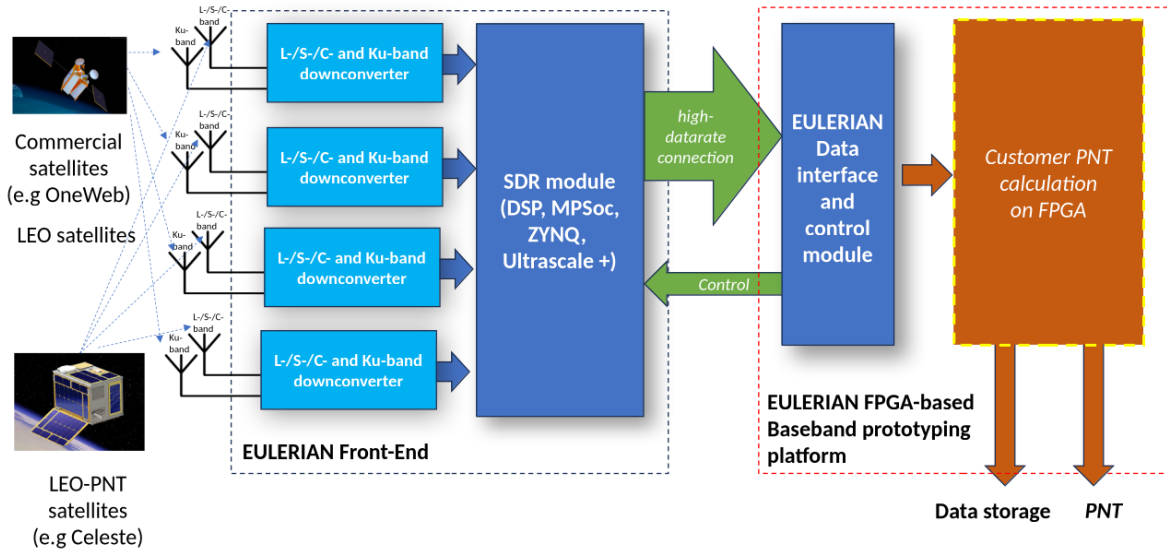


Figure 1: General block diagram of the unified EULERIAN front-end and digitizer.

initially implement a complete navigation receiver; instead, it provides high-performance acquisition, digitization and deterministic transfer to downstream processing units, as shown in Figure 1.

After optional frequency down-conversion from Ku or Ka band to an intermediate frequency within the baseline hardware range, the Radio Frequency Front-End (RFFE) performs amplification, filtering and conversion. A multi-channel SDR then coherently digitizes the signals using a common platform clock.

The resulting raw I/Q data are transmitted to a general-purpose processor or real-time hardware through a high-speed digital interface. The interface maintains ordered and deterministic sequencing across simultaneous channels and sustains throughput of several gigabits per second. This preserves coherence from the antenna input to the navigation algorithm and keeps the acquisition hardware agnostic with respect to downstream processing. If the user supplies an SDR baseband processor, the onboard FPGA can later be reprogrammed to host PNT software and transform the board into a complete LEO-PNT receiver.

4. RF Front-End

The RFFE bridges the heterogeneous radio-frequency environment of present and future LEO constellations with a standardized digital platform. It is designed as a universal acquisition subsystem operating, with minimal modification, from VHF to Ku and Ka band while preserving a common downstream architecture.

Unlike conventional GNSS front-ends optimized around narrow L-band allocations, the baseline architecture directly supports UHF, L-, S- and C-bands through a common multi-channel board with low-noise amplification, programmable gain, selectable filtering and conversion to a common intermediate frequency. All four channels share a low-phase-noise local oscillator, ensuring inter-channel phase coherence and enabling future applications such as antenna arrays, beamforming and Direction of Arrival estimation.

A common IF is adopted independently of the input band, so that the digitizer and digital chain always operate under the same conditions. Ku- and Ka-band signals, including those from OneWeb and possible future navigation systems, are handled by an external low-noise downconverter ahead of

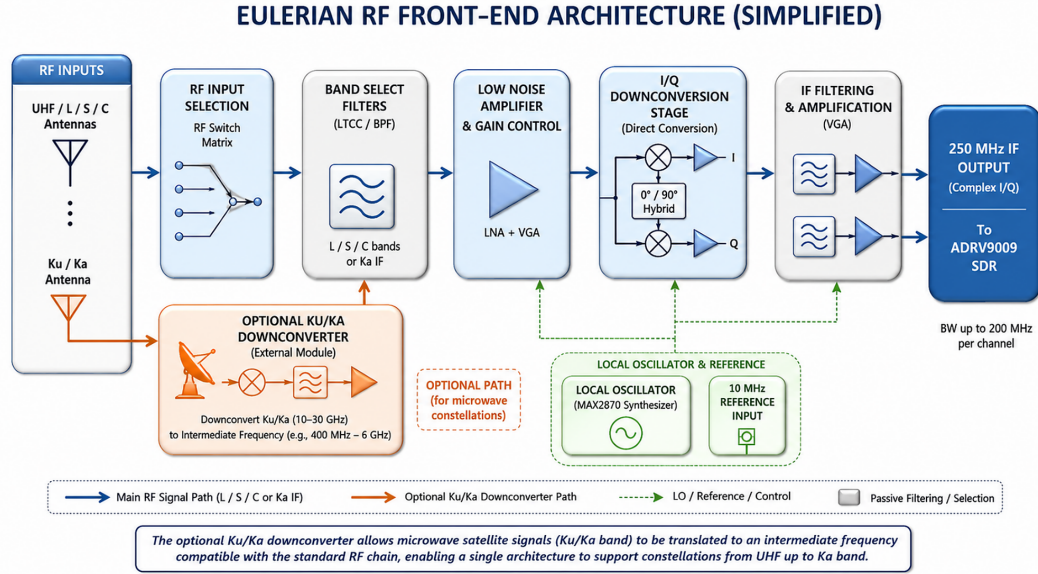


Figure 2: Block diagram of the EULERIAN RFFE.

the standard RFFE. This module translates approximately 10–30 GHz signals to about 2.4 GHz, placing them within the S-band range of the baseline front-end.

This two-stage conversion isolates microwave-specific circuitry in a compact external module while retaining the same internal mixers, oscillator, filters and calibration procedures. Once translated to S-band, the signals follow the same chain as lower-frequency inputs. The architecture therefore supports new constellations through limited RF adaptations rather than complete receiver redesign.

5. SDR and Digitization

The analog-to-digital transition is handled by an SDR architecture. Since future LEO-PNT signal bandwidths, modulations and processing requirements are still evolving, software and firmware reconfiguration is preferable to dedicated acquisition hardware.

The reference architecture supports an instantaneous bandwidth of up to 200 MHz. A trade study selected the Analog Devices ADRV9009 as the baseline SDR [6]. Developed for wideband telecommunications, it provides high instantaneous bandwidth, dynamic range, phase-noise performance, mature software support and affordable evaluation hardware. It is a dual-channel device capable of coherent simultaneous digitization of up to 200 MHz per channel.

Both receive channels use a common internal synthesizer. EULERIAN exploits this constraint by presenting identically centered signals to both channels before digitization, thereby supporting tight phase coherence. The associated FPGA initializes and controls acquisition, sample rate and gain, performs buffering and sample formatting, and establishes repeatable command sequencing.

Although the ADRV9009 is the high-performance baseline, the architecture is not tied to it and can also accommodate narrower-band, lower-cost SDR devices. System complexity is concentrated in an adaptable acquisition platform while signal processing and navigation intelligence remain in software or modifiable FPGA code.

6. High-Speed Digital Interface

A four-channel receiver digitizing bandwidths approaching 200 MHz generates several gigabits per second of I/Q data. These data must reach the navigation processor without loss, excessive latency or loss of synchronization. The high-speed interface shown in Figure 3 is therefore a key enabling feature.

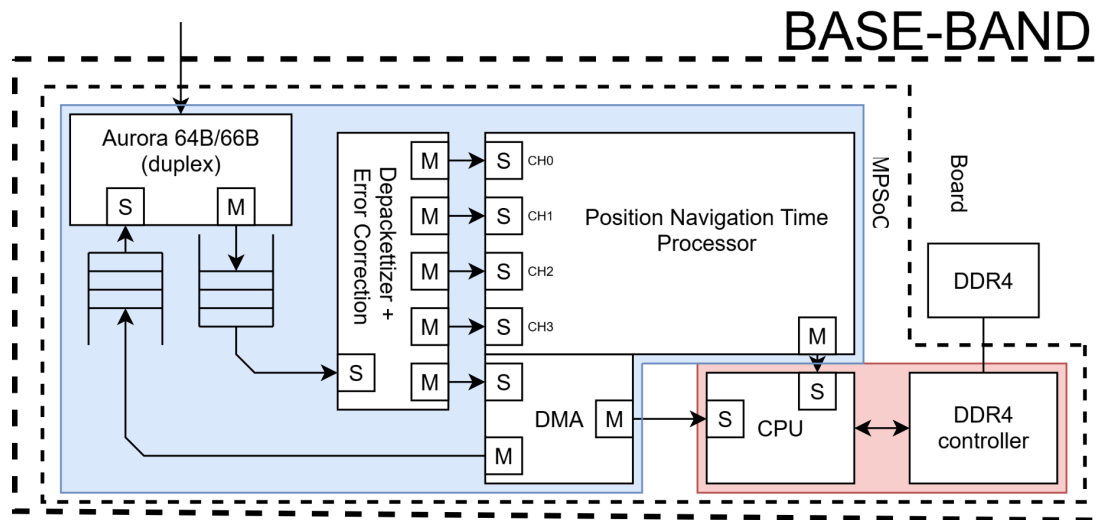


Figure 3: EULERIAN high-speed deterministic digital interface.

The architecture uses multi-gigabit Aurora 64B/66B serial transport with FEC, packet resynchronization, continuous sequence checking, hardware DMA and high-speed buffers. It monitors packet integrity and ordering while sustaining the streaming data rate. The result is an ordered, integrity-verified sequence of I/Q samples delivered to an external navigation processor.

EULERIAN deliberately separates RF acquisition and digitization from navigation processing, which is generally moved to an external FPGA- or processor-based platform. This allows users to select their own baseband processor or algorithms and also permits recording large raw-I/Q datasets for offline analysis. The adopted QSFP+/QSFP28 point-to-point architecture provides sufficient margin for four channels and is scalable to larger systems.

Standard SDR protocols such as VITA-49, DIFI and eCPRI were evaluated. Because both ends of the link are controlled within EULERIAN, a minimal proprietary protocol was selected to prioritize throughput, simplicity and deterministic operation. The FPGA can progressively host more baseband processing, allowing the platform to evolve from a universal acquisition unit into a complete LEO-PNT receiver without fundamental architectural changes.

7. Verification Strategy

Verification extends beyond demonstrating the required data rate: it must show that deterministic behavior is maintained. Hardware and software tests address integrity, synchronization, latency, phase coherence and RF performance, while environmental resilience is assessed by inspection and system analysis. Components are validated first, followed by end-to-end acquisition under representative conditions.

FPGA verification cores generate pseudo-random sequences across multiple acquisition channels and drive the Aurora 64B/66B interface. Each received packet is checked for header integrity, packet-counter progression and payload validity. Additional tests inject continuous-wave signals into multiple RF channels to evaluate cross-correlation, interference and coherent response.

8. Applications and Future Developments

EULERIAN is a generic acquisition platform rather than a receiver dedicated to one constellation. It can support present commercial signals and future dedicated LEO-PNT systems without changing the basic RF acquisition hardware.

A particularly promising field is Assured PNT for defense, where GNSS jamming and spoofing have created an operational need for complementary navigation. Maritime navigation, critical infrastructure, aviation, railway signalling, road transport, emergency response, autonomous vehicles and network time dissemination can likewise benefit from hybrid LEO-PNT receivers.

The evaluation platform uses commercial SDR products and FPGA development boards to reduce development time. Future work will progressively miniaturize and integrate the design, moving from evaluation hardware to dedicated FPGA and eventually ASIC implementations to reduce size, weight, power and cost.

9. Conclusions

The rapid emergence of LEO-PNT as a complement to conventional GNSS creates a need for receiver architectures combining flexibility, performance and long-term adaptability. EULERIAN addresses this need through a standardized RF front-end and digitization platform supporting a broad range of present and future LEO constellations. By separating acquisition from navigation processing, the architecture promotes interoperability, accelerates algorithm development and reduces the effort required to adapt receivers to new constellations and signal formats.

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Declaration on Generative AI

During the preparation of this work, the authors used generative AI tools (mainly Chat GPT, occasionally Claude) for English language refinement, drawings improvement and support in converting the manuscript to the CEUR-ART LaTeX format. The authors reviewed and edited all output, and take full responsibility for the content of the publication.

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