

CHAGALL: An Adaptive Distributed GNSS Architecture for Autonomous Geodetic and Environmental Monitoring

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Abstract

Long-term geodetic and environmental monitoring requires autonomous stations capable of operating for extended periods while balancing positioning accuracy, energy consumption, communication bandwidth and the ability to capture transient events. Conventional fixed-rate monitoring systems cannot efficiently satisfy these competing requirements. This paper presents CHAGALL, an adaptive distributed GNSS monitoring architecture supporting three configurable acquisition strategies—duty-cycled, continuous and adaptive event-driven—that are decoupled from the Monitoring Services consuming their observations, including geodetic positioning, dynamic event analysis and GNSS Reflectometry (GNSS-R). A common stream of GNSS measurements is transformed into application-specific Observation Products, each retaining only the information required by its downstream processing workflow. Computationally-intensive tasks, including PPK positioning and GNSS-R processing, are executed centrally, allowing remote stations to remain energy-efficient while enabling deployments to trade positioning performance, temporal resolution, communication overhead and power consumption according to application requirements. CHAGALL builds upon operational experience gained with previous-generation monitoring systems and introduces an Observation Product abstraction that decouples measurement acquisition from application-specific processing. The architecture is currently under development: individual subsystems have been validated independently, while integrated system validation remains future work.

Keywords

GNSS monitoring, distributed sensor networks, adaptive observation strategies, low-power autonomous stations, GNSS-R, geodetic positioning

1. Introduction

Continuous monitoring of natural hazards, civil infrastructure and environmental processes is increasingly important for risk mitigation, asset management and scientific research, requiring long-term observation capable of detecting both slow deformations developing over months or years and transient events lasting seconds. GNSS is well suited to this task, providing accurate absolute positioning under all weather conditions over large areas; multi-constellation, multi-frequency observations combined with advanced post-processing now enable millimetric displacement precision.

The use of mass-market GNSS receivers for this purpose, rather than only conventional geodetic-grade equipment, has been progressively validated over the past decade, from early feasibility studies for landslide monitoring [2] and controlled-precision tests [3], to multi-year operational deployments such as GIMS [1, 4].

As monitoring networks have grown denser, the primary engineering challenge has shifted from positioning performance to system autonomy: stations must operate unattended for extended periods, often battery- or solar-powered, on low-bandwidth links, capturing short-duration events without continuously operating at high observation rates. This calls for systems that adapt their sensing, observation and communication strategies to the monitored phenomenon and operational constraints, rather than relying on fixed acquisition and transmission schemes.

Designing autonomous GNSS monitoring systems requires balancing several competing application-dependent requirements. Long-term geodetic monitoring primarily targets slowly evolving phenomena and therefore does not necessarily require high observation rates. In contrast, geohazard and

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structural health monitoring must capture short-duration events, making temporal resolution more important than the precision of individual measurements. GNSS-R introduces an additional requirement, namely the continuous acquisition of high-resolution C/N_0 observations.

No single acquisition strategy satisfies all these requirements. Duty-cycling the receiver extends operational autonomy but reduces positioning performance by interrupting carrier-phase tracking. Continuous high-rate acquisition captures dynamic events and supports GNSS-R, but increases energy consumption, storage requirements and communication bandwidth. Likewise, transmitting complete raw datasets simplifies backend processing but wastes bandwidth when only a subset of the observations is required. These trade-offs become increasingly important in large-scale, resource-constrained monitoring networks, where sensing, communication and processing must be jointly optimized.

The main contributions of this work are:

- the introduction of the *Observation Product*, a hardware-independent abstraction that decouples GNSS measurement acquisition from application-specific processing;
- the separation of acquisition strategies from Monitoring Services, enabling the same hardware platform to support multiple monitoring objectives while allowing sensing and processing functions to evolve independently;
- a modular distributed architecture supporting heterogeneous GNSS receivers through a common software abstraction layer, facilitating extensibility and the integration of future Monitoring Services without requiring changes to deployed remote stations.

2. System Architecture

CHAGALL is a distributed monitoring architecture in which autonomous remote stations perform data acquisition and local observation management, while computationally-intensive processing is delegated to a centralized infrastructure. This functional partitioning supports a wide range of geodetic and environmental monitoring applications while keeping the remote stations energy-efficient and suitable for long-term autonomous deployment.

The architecture, illustrated in Fig. 1, consists of three elements: autonomous remote monitoring stations deployed in the field; a wireless communication infrastructure; and a centralized processing infrastructure providing processing, storage and user services.

2.1. Overall Architecture

The remote monitoring station is the field-deployed sensing element, responsible for sensor management, observation generation, temporary data storage and communication management. Rather than continuously transmitting raw sensor outputs, it generates application-specific Observation Products, transferred through the communication infrastructure to a centralized backend responsible for long-term storage, advanced processing and user services; computationally intensive functions such as precise positioning and environmental analysis are executed centrally, keeping the remote station energy-efficient and suitable for long-term autonomous deployment.

This separation lets the same platform be reconfigured for a wide range of deployment scenarios, from ultra-low-power to continuous and event-driven acquisition (Section 3), without changes to the underlying hardware.

2.2. Functional Partitioning

CHAGALL assigns each function to the subsystem where it can be performed most efficiently, balancing energy consumption, computational complexity and communication overhead. Time-critical and energy-sensitive tasks are executed at the remote monitoring station, while computationally-intensive processing is delegated to the centralized infrastructure.

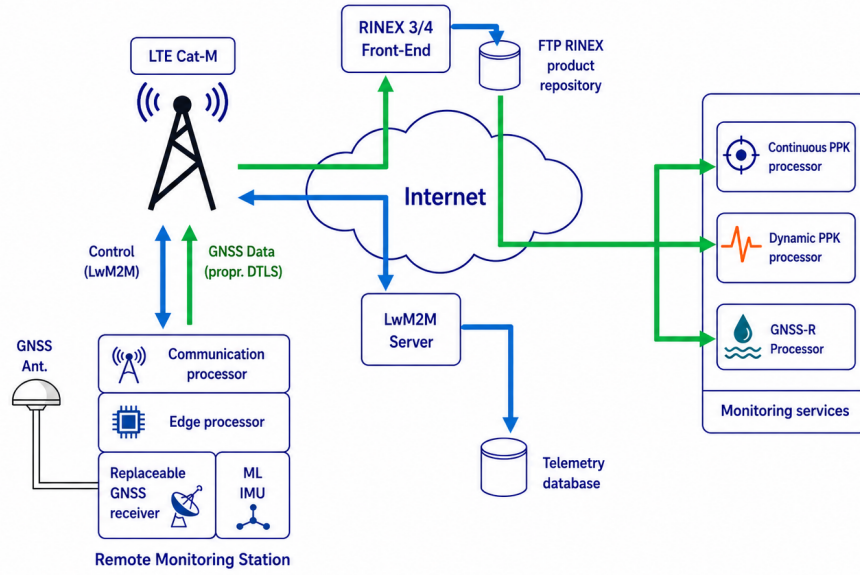


Figure 1: Overall CHAGALL architecture, comprising the distributed remote monitoring stations, the wireless communication infrastructure and the centralized processing infrastructure.

The remote monitoring station is responsible for sensor management, measurement acquisition, Observation Product generation, temporary local storage and communication scheduling. Local processing is intentionally limited to lightweight operations that organize and reduce the volume of data before transmission, minimizing both energy consumption and communication bandwidth while preserving the information required by the downstream Monitoring Services.

The centralized infrastructure performs computationally-intensive tasks, including precise positioning, GNSS-R processing, long-term data archiving, visualization and network management. By concentrating these functions centrally, CHAGALL allows processing algorithms and Monitoring Services to evolve independently of the deployed monitoring stations, extending the operational lifetime of the overall system while keeping the field hardware simple, energy-efficient and suitable for long-term autonomous deployment.

2.3. Observation Product

The *Observation Product* is the logical interface between the distributed remote monitoring stations and the centralized processing infrastructure. Rather than transmitting raw GNSS receiver outputs, each remote station transforms the acquired measurements into one or more application-specific Observation Products. Each product contains only the observations required by its corresponding Monitoring Service, reducing communication bandwidth while remaining independent of the underlying GNSS receiver implementation.

A common stream of GNSS measurements may generate different Observation Products according to the selected acquisition strategy and the requirements of the downstream applications. PPK Observation Products contain the observables required for high-accuracy positioning, whereas GNSS-R Observation Products retain only the information needed for reflectometry analysis. Consequently, multiple Monitoring Services can operate simultaneously on products derived from the same measurement stream while receiving only the information relevant to their respective processing workflows.

Once transmitted to the centralized infrastructure, Observation Products are archived and independently processed by the corresponding Monitoring Services. This separation between product generation and product exploitation allows processing algorithms and user services to evolve without requiring modifications to deployed remote stations, thereby extending the operational lifetime and flexibility of the overall monitoring platform.

Table 1

Content of the PPK and GNSS-R Product measurement sets.

Field	PPK set	GNSS-R set
Time tag (per set)	Yes	Yes
Pseudorange (per SV, per signal)	Yes	—
Carrier phase (per SV, per signal)	Yes	—
C/N ₀ (per SV, per signal)	Yes	Yes

Table 1 summarizes the information contained in the two Observation Product types currently defined. A PPK Observation Product carries a common time tag together with, for each tracked satellite and transmitted signal, the pseudorange, carrier phase and C/N₀. A GNSS-R Observation Product is intentionally lighter, carrying only the time tag together with the corresponding C/N₀ measurements.

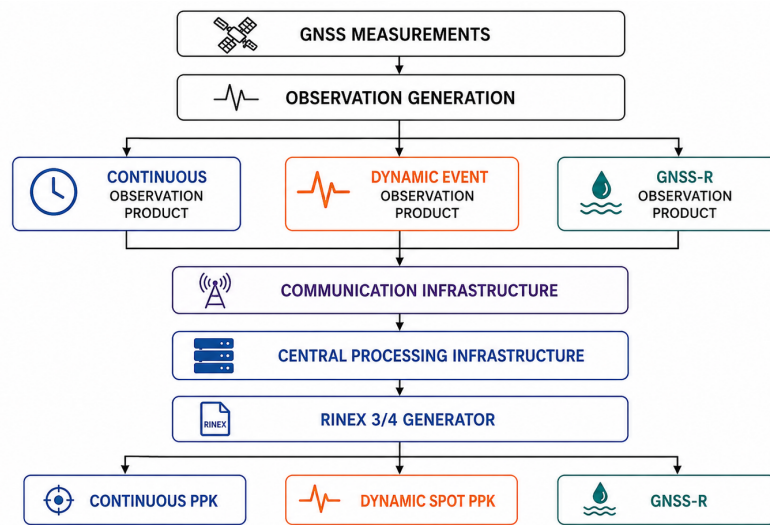


Figure 2: Generation of application-specific Observation Products from a common stream of GNSS measurements at the remote monitoring station.

2.4. GNSS Receiver Selection

The GNSS receiver is implemented as a replaceable module (Fig. 1), allowing CHAGALL to be configured with different receiver families according to the acquisition strategy and Monitoring Services required by a particular deployment. This modular approach enables the hardware platform to be optimized for different operational requirements without affecting the overall system architecture.

Three receiver families are currently supported, providing different trade-offs between positioning performance, GNSS-R capability and power consumption (Table 2).

Table 2

Candidate GNSS receivers and their suitability for each acquisition strategy and for GNSS-R.

Receiver	Duty-cycled	Continuous	Adaptive	GNSS-R (SNR res.)
u-blox NEO-10T	Preferred	Yes	Yes	Yes (1 dB-Hz)
u-blox ZED-X20P	Yes	Yes	Preferred	Yes (1 dB-Hz)
Quectel LG290P	Yes	Yes	No	Preferred (1/16 dB-Hz)

2.5. Software Abstraction Layer

The modular receiver architecture is complemented by a layered software abstraction (Fig. 3) that isolates the application software from receiver-specific implementations.

Each supported GNSS receiver is accessed through a dedicated driver that provides a common interface to the application layer. A receiver-specific observable processor converts the native receiver output into a compact binary representation shared by all supported devices. Consequently, the remainder of the software stack—including Observation Product generation, communication and centralized processing—operates independently of the selected GNSS receiver.

Receiver-specific functionality is therefore confined to the driver and observable-processing layers. Supporting an additional GNSS receiver requires only the implementation of these two components, while the application software and centralized infrastructure remain unchanged.

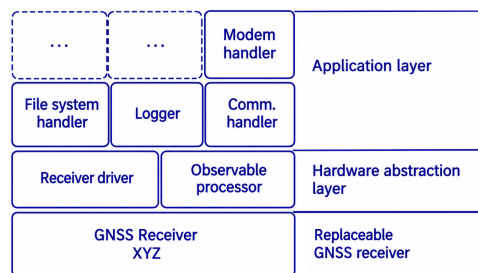


Figure 3: Software abstraction layers decoupling application software from the specific GNSS receiver in use.

2.6. Network Deployment

A CHAGALL deployment comprises two or more remote monitoring stations sharing a common centralized processing infrastructure rather than operating as isolated sensing nodes. This architecture reflects the relative positioning techniques employed for geodetic monitoring: both PPK and RTK require a reference (base) station at a known location in addition to the rover stations whose displacement is to be monitored. Consequently, a minimum of two stations is required to produce displacement estimates.

Figure 4 illustrates a typical deployment. Each remote monitoring station uploads its Observation Products through the wireless communication infrastructure to the centralized backend, which hosts the Control and Management functions together with the Monitoring Services described in Section 5.

The architecture naturally scales from a single base-rover pair to large monitoring networks. A single reference station may support multiple rover stations within its operational coverage, allowing additional monitoring nodes to be deployed without modifying the overall system architecture.

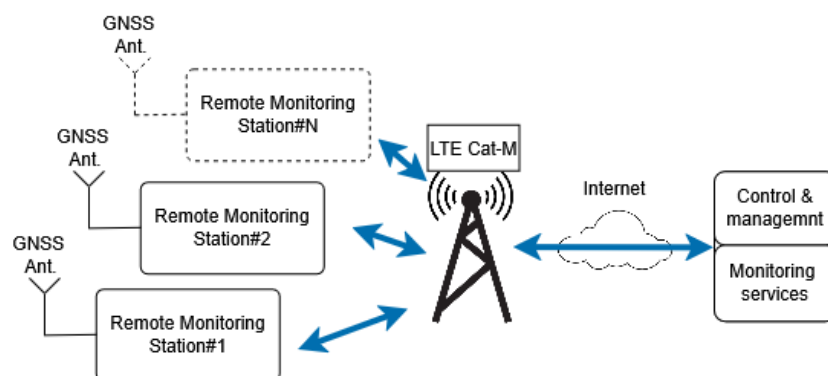


Figure 4: CHAGALL network topology, showing multiple remote monitoring stations sharing a common central infrastructure for control, management and monitoring services.

3. Monitoring Capabilities

CHAGALL supports three configurable acquisition strategies—duty-cycled, continuous and adaptive—that determine how GNSS observations are generated at the remote monitoring station. These strategies are independent of the Monitoring Services that consume the resulting Observation Products, allowing the same hardware platform to support different monitoring objectives without architectural changes.

3.1. Duty-Cycled Monitoring

Many monitoring applications target slowly evolving phenomena, where long-term autonomy is more important than maintaining a continuously high observation rate. In these scenarios, CHAGALL acquires GNSS observations at configurable intervals matched to the temporal dynamics of the monitored process while independently scheduling data communication with the centralized infrastructure. Temporary local storage decouples observation acquisition from data transmission during communication outages.

CHAGALL also supports a duty-cycled power mode in which the GNSS receiver is periodically switched off between measurement windows (e.g., 15 minutes per hour), with PPK processing applied to each snapshot; since tracking is interrupted at every power-off, ambiguities are re-resolved independently each time, introducing a tunable trade-off between duty cycle and accuracy. This typically yields centimetre-level accuracy, versus the millimetre-level accuracy of continuous acquisition (Section 3.2), but since many applications do not require millimetre precision, it lets a station run from a replaceable battery alone, without an active energy source such as a photovoltaic panel — as already demonstrated commercially by the Worldsensing GNSS Meter, which achieves multi-year autonomy from replaceable D-size cells [5].

3.2. Continuous Monitoring

Continuous monitoring is the reference acquisition strategy for applications requiring uninterrupted observation, without the receiver being duty-cycled off between measurements, such as dynamic landslide monitoring, infrastructure stability assessment and long-term deformation analysis. Because carrier-phase tracking remains continuous, carrier-phase ambiguities can generally be maintained over the observation session. If cycle slips occur, the affected ambiguities must be detected and corrected or re-estimated, preserving millimetre-level positioning performance when sufficient observations are available. This contrasts with duty-cycled acquisition, where ambiguities must be re-resolved after each receiver restart and centimetre-level accuracy is typically obtained (Section 3.1). CHAGALL acquires GNSS observations at a programmable interval and transfers them to the central infrastructure, where high-accuracy positioning is obtained through established post-processing techniques such as PPK rather than through on-station computation.

3.3. Adaptive Monitoring

Some monitoring applications—including landslide acceleration, rockfalls, structural impacts and seismic events—are characterized by long periods of stability interrupted by short-duration dynamic events. In these scenarios, capturing the event evolution is more important than maintaining a continuously high observation rate, while operating permanently at the highest rate would unnecessarily increase energy consumption, storage requirements and communication bandwidth during the much longer periods of normal operation.

CHAGALL addresses this challenge through adaptive monitoring. Under normal conditions, the remote monitoring station acquires GNSS observations at a low-power rate suitable for long-term autonomous operation. Dynamic events are detected by an embedded MEMS-based inertial measurement unit (IMU) integrating a machine-learning engine. The detection model can be remotely reconfigured

to recognize different classes of dynamic events, allowing the same hardware platform to be adapted to different monitoring applications without hardware modifications.

When an event is detected, the monitoring station automatically increases the GNSS observation rate to capture the phenomenon with higher temporal resolution. Once the event has concluded, the station returns to its nominal acquisition rate, thereby allocating energy, storage and communication resources only when required while preserving long-term autonomy.

4. Observation Product Architecture

The Observation Product abstraction forms the architectural boundary between the distributed monitoring stations and the central processing infrastructure. Rather than simply encapsulating GNSS measurements, they decouple observation generation from application-specific processing, allowing both sides of the architecture to evolve independently.

Each Observation Product contains only the information required by its corresponding Monitoring Service while remaining independent of the underlying sensing technology, communication mechanism and processing algorithms. Consequently, remote monitoring stations generate standardized Observation Products, while their interpretation is entirely delegated to the centralized infrastructure.

This stable abstraction enables Monitoring Services and processing algorithms to evolve independently of deployed monitoring stations while preserving compatibility with previously generated Observation Products. New services may reuse existing products whenever the required information is available, while additional Observation Product types can be introduced without affecting the communication architecture.

Observation Products therefore define the architectural boundary between data acquisition and information exploitation. Monitoring Capabilities determine how observations are acquired, Observation Products define how they are exchanged, and Monitoring Services transform them into application-specific information.

5. Central Monitoring Infrastructure

The Central Monitoring Infrastructure transforms Observation Products into application-specific information while providing a common framework for long-term data management, visualization and system supervision. Computationally intensive processing is centralized, keeping the remote monitoring stations simple, energy-efficient and easy to maintain while allowing new Monitoring Services and processing algorithms to be deployed without modifying the field hardware.

5.1. Monitoring Services

Four Monitoring Services are currently defined.

Geodetic Positioning computes high-accuracy displacement estimates from Observation Products generated using the duty-cycled or continuous acquisition strategies. Established post-processing techniques such as PPK are employed; because duty-cycled acquisition interrupts carrier-phase tracking, ambiguities are resolved independently for each observation interval.

Dynamic Event Analysis processes the high-rate Observation Products generated during adaptive monitoring to characterize transient geophysical events. High-temporal-resolution positioning is performed only during the detected event window, allowing detailed analysis while maintaining the energy efficiency of low-rate operation during normal conditions.

GNSS-R exploits interference between the direct satellite signal and signals reflected by the surrounding environment. The resulting variations in the received C/N_0 contain information about surface properties and are processed to estimate environmental parameters such as soil moisture, snow cover, vegetation conditions and water level. Since its introduction [6], GNSS-R has evolved from a signal-quality metric into a recognized environmental sensing observable [7, 8], with viability on

mass-market equipment confirmed by multi-constellation retrievals [9] and long-term validation of a low-cost SNR sensor [10].

Future Services can be introduced as additional Observation Products and processing algorithms become available, without requiring modifications to the deployed monitoring stations.

5.2. Data Management and Visualization

Observation Products and derived information are archived within a centralized data management framework that provides long-term storage, historical traceability and uniform access. Information from multiple monitoring stations is integrated to support visualization, trend analysis, alarm generation and reporting.

5.3. Remote System Management

The centralized infrastructure supervises and configures the distributed monitoring network throughout its operational lifetime. Monitoring strategies, observation schedules and other operational parameters can be updated remotely, simplifying the management of large-scale deployments from a single point of control.

5.4. Extensible Service Framework

The separation between Observation Products and Monitoring Services allows CHAGALL to evolve incrementally. New Monitoring Services can be introduced whenever the required Observation Products are available, preserving compatibility with existing remote stations while extending the capabilities of the centralized infrastructure.

6. Discussion and Conclusion

CHAGALL builds on several years of operational experience gained by the authors and partner organizations with previous-generation distributed GNSS monitoring systems, most notably GIMS [1]. This experience highlighted recurring architectural limitations, including the tight coupling between sensing, communication and application-specific processing, which complicated the evolution of long-lived monitoring deployments.

This paper presented CHAGALL, an adaptive distributed GNSS monitoring architecture that addresses these limitations by separating Monitoring Capabilities, Observation Products and Monitoring Services through well-defined abstraction layers. This separation enables sensing hardware, acquisition strategies and centralized processing algorithms to evolve independently while preserving compatibility with deployed monitoring stations. The resulting architecture provides a flexible foundation capable of supporting heterogeneous GNSS receivers, multiple monitoring applications and future service extensions. Comparable architectural principles are reflected in commercial services such as GReD's GeoGuard, demonstrating the practicality of centralized GNSS monitoring architectures [11].

The complete CHAGALL architecture is currently progressing through system integration. Individual hardware and software subsystems have undergone independent functional verification, while full end-to-end validation under representative operational conditions remains future work. These activities will assess the complete distributed architecture and confirm the benefits of the proposed architectural abstraction for long-term autonomous geodetic and environmental monitoring.

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Declaration on Generative AI

During the preparation of this work, the author(s) used Claude (Anthropic) in order to: check grammar and spelling, identify and remove redundant passages, verify citation details against independent sources, and in converting the manuscript to the CEUR-ART LaTeX format.

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