THE INTERNATIONAL CONFERENCE ON THE 120TH ANNIVERSARY OF THE BULNAY EARTHQUAKE: ADVANCES IN ASTRONOMY AND GEOPHYSICS

Earthquake Early Warning Instrumentation and System Considerations

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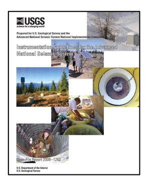
Abstract

Earthquake early warning (EEW) systems depend on the prompt, reliable arrival of seismic data at network data centers. Network operators invest significant resources into the design, installation and operation of real-time acquisition systems to ensure maximum data completeness and minimum data latency, to allow EEW processing modules to detect events and issue warnings as quickly as possible. These mission critical acquisition systems must perform before, during and after earthquakes, as main shocks are frequently preceded by foreshocks and followed by aftershocks, which are often just as dangerous.

To optimize earthquake early warning systems, much can be learned from existing and industry proven EEW solutions and how they can be efficiently deployed with high quality ground motion seismic stations capable of delivering the highest fidelity and low latency data sets to the processing data centers' detection algorithms. Specifically, public safety EEW systems require strict service level agreements (SLA) with regards to overall uptime, prompt arrival of high quality data, and issuance of accurate and timely warnings. This can only be achieved via the proper definition and selection of sensors, data loggers, power systems, and communication systems. Also, when planning EEW Networks, it is important to consider the end-to-end workflow, from system definition and roll-out, through to network operation, maintenance and ongoing validation to ensure the system continues to satisfy its mandate.

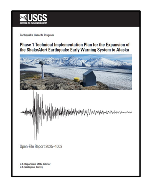
Deployment of an EEW system can represent a significant challenge to monitoring agencies, but leveraging proven implementations and technology partners can greatly reduce the associated risk and implementation timeline. This poster covers these key considerations and challenges for EEW systems, as well as fielded solutions that address them.

Requirements for Reliable EEW Systems



Instrumentation Guidelines for the Advanced National Seismic System
USGS Open-File Report 2008-1262

Revised technical implementation plan for the ShakeAlert system—An earthquake early warning system for the West Coast of the United States.
USGS Open-File Report 2018-1155



Phase 1 technical implementation plan for the expansion of the ShakeAlert earthquake early warning system to Alaska.
USGS Open-File Report 2025-1003

Robust Real-time Monitoring Network

- *Class A accelerometers* with low self noise and high dynamic range, to detect small P wave signals without clipping on large S waves
- *Broadband seismometers* to detect small, frequent events for continuous system validation
- *Real-time geodetic monitoring* to measure displacement of large events
- *Data telecommunications systems to reliably transport data from field sensors to regional alert centers with minimal latency*
- *Redundant systems* with no single point of failure

ENGINEERING PROJECT

- Instrumentation Selection
- Telemetry Selection
- Acquisition System Design
- Data Center Design

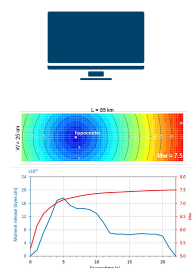
Major Capital Investment

Accurate Source Characterization

- *Sophisticated scientific software algorithms to analyze seismic and geodetic data to rapidly detect earthquakes, reject non-earthquake signals, determine earthquake characteristics, and estimate the resulting ground-motion intensities.*

SCIENCE PROJECT

- EEW Processing Modules
  - Research (Pd ⇒ M)
  - Iteration
  - Software
- Evolves with Science



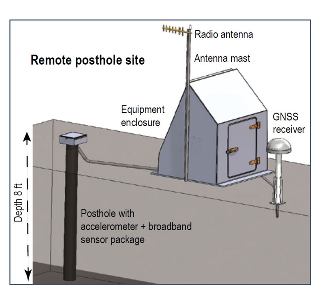
EEW Instrumentation

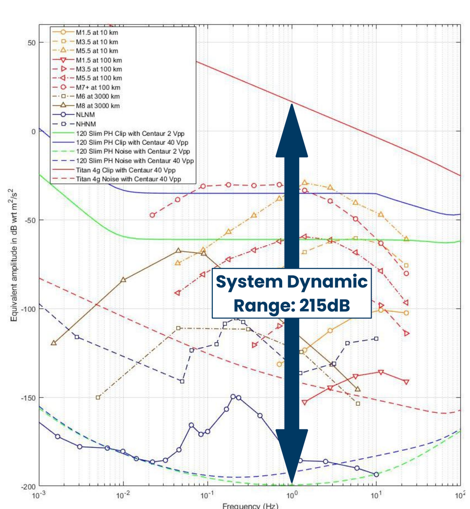
The Nanometrics Titan family of class A accelerographs and accelerometers provide **high quality Strong Motion monitoring**. Several options are available to accommodate a wide range of deployment strategies.

Metric	Class A Accelerometer	Titan
Clip Level	≥±3.5g	±4 g, ±2 g, ±1 g, ±0.5 g, or ±0.25 g
Dynamic Range	145 dB 0.02-2Hz 130 dB 2-50Hz	166 dB @ 1 Hz over 1 Hz bandwidth 155 dB, 3 to 30 Hz
Bandwidth	Required: 0.002-50Hz Desired: 0-100Hz	DC to 430 Hz
Sensitivity Accuracy	1%	±0.5%

TitanSMA **TitanEA** **Titan** **Titan Posthole**

The ultra low noise floor has allowed users to successfully execute H/V studies to **characterize site amplification effects** for operational EEW stations, in system, eliminating the need to conduct a separate broadband study.





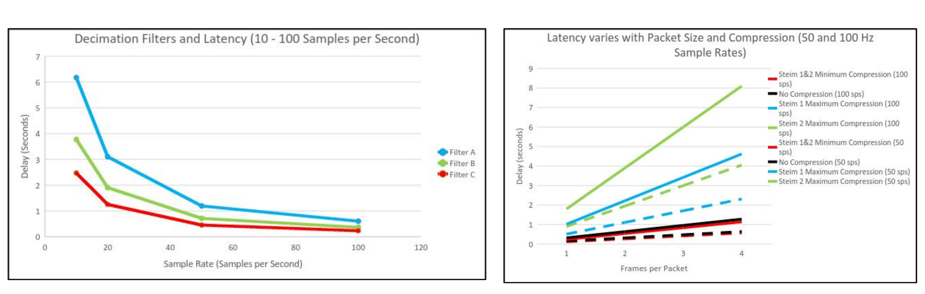
Cascadia 120 Slim PH: Strong motion and broadband monitoring in a single, integrated package, ideal for posthole deployments: simplified installation, built-in alignment, cost-effective

Real-time Data Acquisition

EEW relies on the prompt, efficient and reliable arrival of seismic data. Low latency, efficient operation and data completeness are fundamental requirements of these mission-critical systems. Every stage of acquisition has trade-offs to consider and deliberate planning is critical to ensure optimal performance.

Digitization and Packetization Considerations

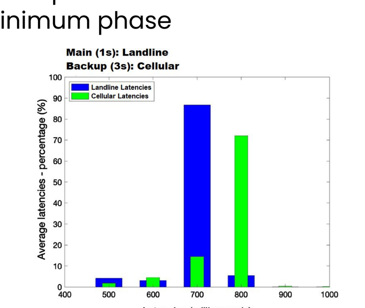
- Acausal anti-aliasing filters minimize phase distortion but introduce delay
- Data compression and low sample rates decrease bandwidth but lower packet rate
- Large packets hold data more efficiently, but are sent less frequently, increasing packet latency



Nanometrics digitizers have several parameters with which data packetization may be tuned to achieve an optimal balance between latency and bandwidth requirements.

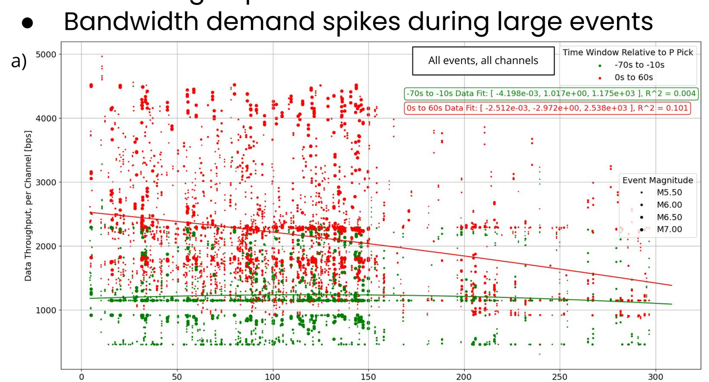
- **Frames per Packet:** # of Steim data frames per packet
- **Sample Rate:** # of samples per second for each channel
- **Sample Encoding (Compression):** Steim or Uncompressed
- **Output Type (Anti-aliasing Filter):** Linear or Minimum phase

Centaur data loggers configured to use **3 frames per packet** and **200 sps** were found to provide optimum performance for a national EEW system, achieving ***average sample latency*** of **600 to 800 ms**, as measured across 98 stations over a 30 day evaluation period.

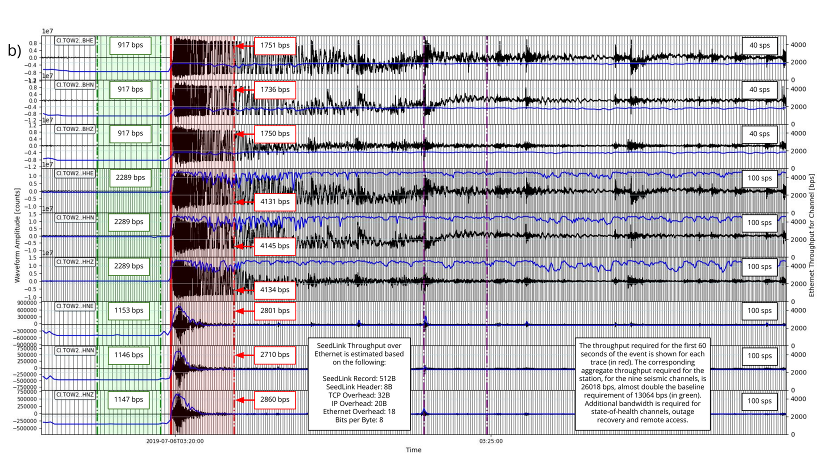


Telemetry Considerations

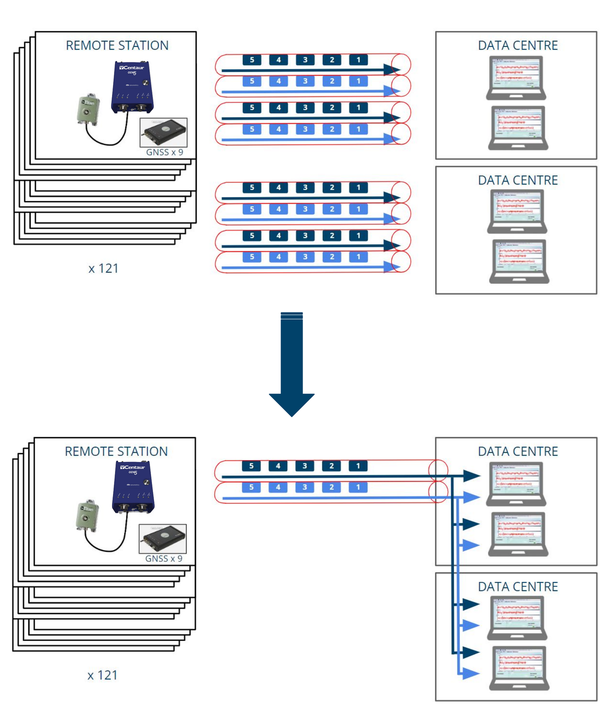
- Balance latency, robustness and bandwidth cost
- Networking capabilities
- Bandwidth demand spikes during large events



a) Average throughput demand before (green) and after (red) P phase arrival for 3423 channels across 23 >M5 events in Southern California between 2013-01-01 to 2023-01-01. Throughput demand increases significantly following the P arrival, particularly for stations closer to the event. The horizontal throughput concentrations correspond to common sample rate and compression combinations.



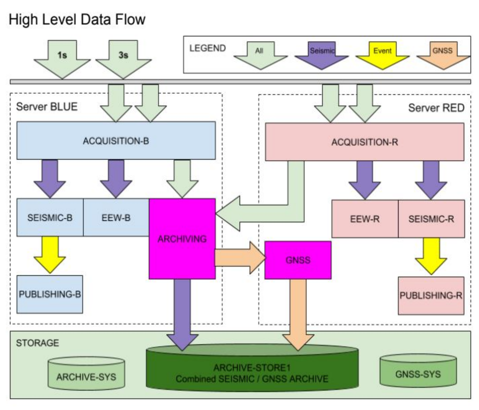
b) Data from station TOW2 for the 2019 Ridgecrest M7.1 event. This station was close to the event, with an epicentral distance of 16 km, and experienced heavy shaking which caused the broadband channels to clip. The throughput (blue trace) increases during the heavy shaking associated with the P wave arrival. Peak demand is high on High Broadband (HH) and strong motion channels (HN), but drops off quickly for strong motion. The demand for Broadband channels (BH) increases but remained relatively low due to the lower sample rate.



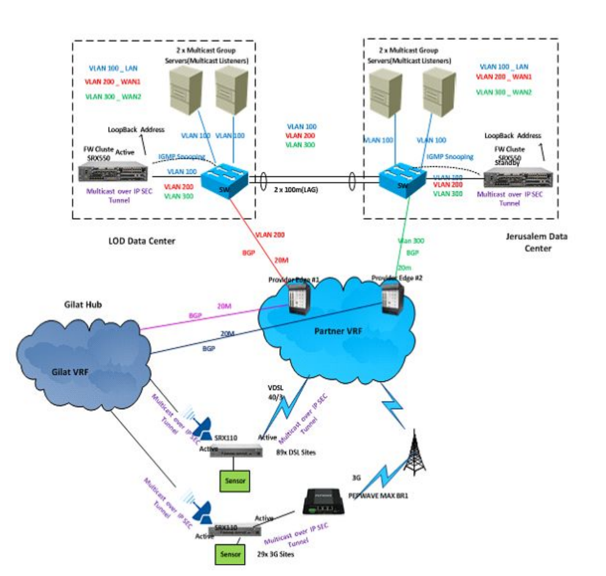
Mission-critical systems implement multiple layers of redundancy (8 in the example) to achieve maximum system robustness. NP multicast streaming allows operators to implement redundancy efficiently and cost-effectively.

Acquisition System & Data Center Considerations

- Communication protocol selection
- Network architecture and streaming topology
- Processing toolchain redundancy & synchronization
- Geographic data center redundancy
- Network security
- Multidisciplinary acquisition



Sample Data Center Architecture with Redundant Processing Toolchains



Sample Network Architecture with Multiple Data Centers

Nanometrics data loggers support the **NP protocol**, built for mission-critical EEW acquisition:

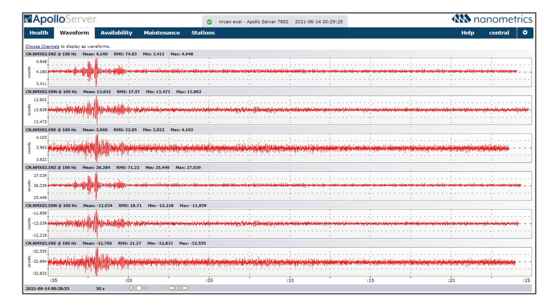
→ Lightweight UDP/IP, prioritization of real-time data, throttling, multicast, automatic outage recovery, variable length packets and more
→ Real-time acquisition of co-located geodetic data streams

Continuous Monitoring and Verification

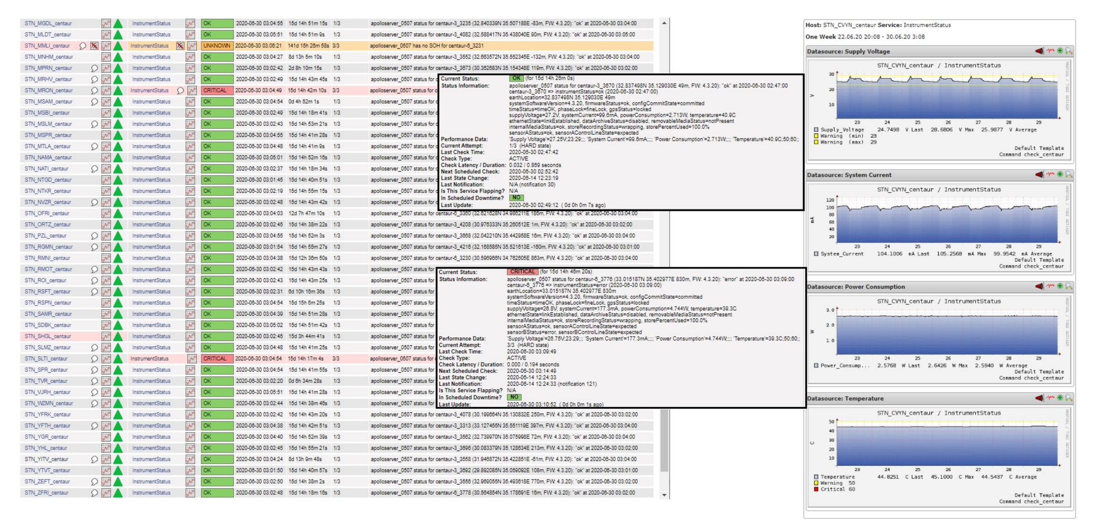
For early warning systems it is critical that end-to-end system performance is closely monitored to ensure any disruption is detected quickly to allow immediate corrective action and minimize downtime.

This includes real-time data acquisition performance, for which there are three key metrics:

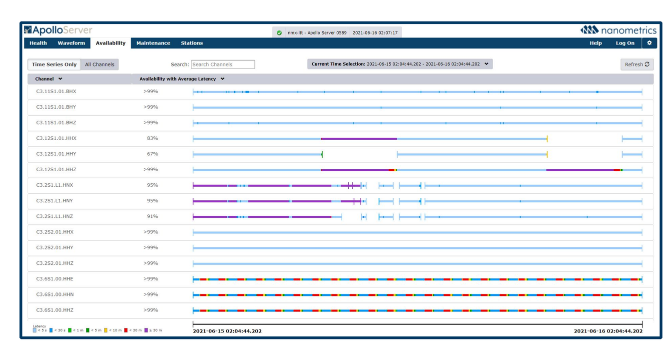
- **Latency**: measure of how promptly the data is arriving
- **Completeness**: measure of how much of the expected data is arriving
- **Data Rate**: measure how much bandwidth is being used to acquire the data



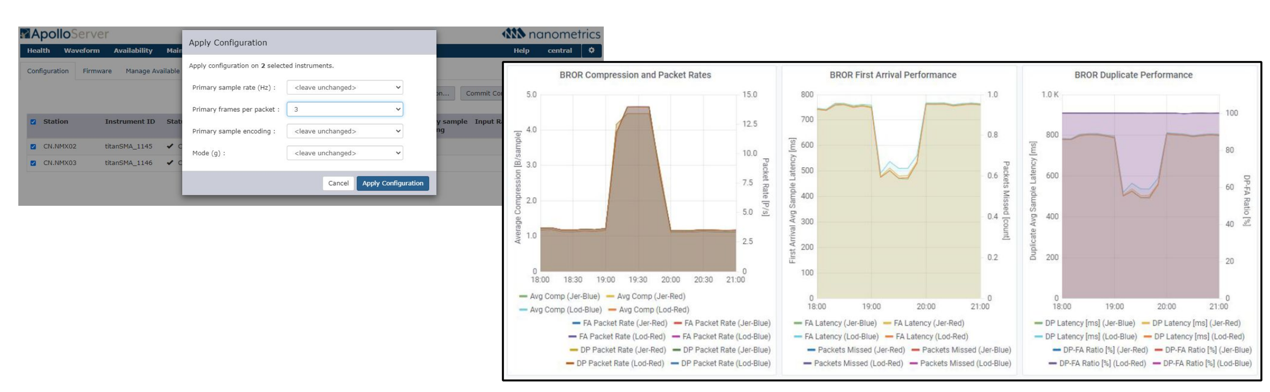
Nanometrics Apollo Server is the **Enterprise Data Center software** used to acquire data streamed using the NP protocol. Apollo Server provides comprehensive network monitoring capabilities. Detailed real-time acquisition performance metrics are captured on a per packet basis. This data can be inspected using built-in dashboards and is also available programmatically via robust APIs for real-time tracking and alerting using external network monitoring systems, such as Nagios or Zabbix.



Nanometrics data loggers support Simple Network Management Protocol, ***SNMP****, providing an industry-standard interface to integrate with common network monitoring tools, such as Nagios or SolarWinds.*



Apollo Server has centralized fleet management tools, including bulk firmware distribution and a batch configuration utility that allows the efficient, non-disruptive execution of a network bandwidth stress test. The test involves temporarily configuring network data loggers to stream uncompressed data for a period of time to simulate the effect of a large earthquake. This capability allows operators to verify telemetry network performance under stress conditions without disrupting the normal operation of the network.



EEW Experience

As a leading supplier of seismic monitoring instruments and systems for over 40 years, Nanometrics solutions have been used in many EEW systems globally. Four recent reference projects demonstrate the range of support Nanometrics can provide to organizations tasked with the challenge of implementing a robust EEW network.

PHIVOLCS
- Feasibility Study

PNSN
- Instrumentation

Canada
- Instrumentation
- Acquisition Software
- Installation Services

TRUAA

Full Turnkey
- Design
- Equipment Supply
- Construction
- Installation
- Communications
- Maintenance

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