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Next Generation Multidisciplinary Geophysical Monitoring Station

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Abstract

Increasingly, scientific advancement is enabled via the joint analysis and interpretation of multidisciplinary datasets which combine different data types from various co-located, independent geophysical sensing elements. Historically, sensors from different disciplines and their supporting subsystems have evolved independently. This often led to duplication of infrastructure and integration challenges associated with separate acquisition systems, with different characteristics and capabilities, attempting to share sensitive, bandwidth-constrained communications links between remote stations and data centers. These factors can significantly increase monitoring station complexity and the associated cost to deploy, operate and maintain them. Recent initiatives, such as the European Plate Observing System (EPOS), the amalgamation of the SAGE and GAGE programs in the United States and the SZ4D implementation plan, aim to combine multidisciplinary geophysical applications into cohesive, streamlined deployments.

Modern seismic data loggers, such as the Nanometrics Centaur Gen5, support integration of a wide range of sensing elements using various interfaces, while maintaining ultra-low power consumption, precise timing, local data storage and reliable real-time data transmission via a full-featured protocol, which can be optimized for different telemetry path constraints. Robust automatic outage recovery ensures maximum data availability at the data center, for all data types, as part of a single, coordinated acquisition system.

A case study is presented for a multidisciplinary monitoring station that leverages these capabilities to enable reliable and efficient data collection. The station design and end-to-end data pipeline, from remote sensing to science doorstep in the data center, are discussed.

Enabling Data Logger Capabilities

Multidisciplinary science requires, by definition, the collection of scientific data from a diverse, often evolving set of monitoring instruments. Data logger adaptability, flexibility, capacity and performance are critical to ensure changing monitoring requirements can continue to be met.

The ***Centaur Gen5 8-Channel model*** has been designed to meet the challenges of multidisciplinary remote sensing networks. The Gen5 series incorporates both hardware updates and a major operating system update with the release of ***Strata OS***. This release incorporates a new user interface to streamline support for multidisciplinary use cases, enhance network security and significantly improve Centaur's processing performance, enabling increases to existing capacity limits and the addition of new functionality, now and into the future.

Expanded and Enhanced Sensor Interfaces

8 High Resolution Channels

- Two high resolution channels have been added to the Sensor B port on the standard 6-channel unit, which is **Sensor B+** on the 8-channel unit.
- In addition to two new channels, the digitization capabilities for all high resolution inputs have been enhanced, with support added for 32 bit resolution and a doubling of the maximum sample rate, to 10 ksps and restrictions on configuration at high rates removed.

9 Analog Inputs

- Gen5 features improved flexibility in the management of the Sensor SOH and External SOH inputs, which now support miscellaneous single channel analog sensors as a primary use case, in addition to traditional sensor SOH, tamper switches, etc.
- The External SOH inputs have been updated to support ±10V input range (from ±5V), to align with the Sensor SOH inputs on the sensor connectors and provide uniform digitization across all analog inputs.

2 Dedicated Serial Ports

- A new Auxiliary connector has been added to provide two dedicated serial ports for direct integration of "Serial Sensors", such as weather stations, without impacting Nanometrics Smart Sensor integration on the Sensor ports. Sensor power is also available on this connector.
- New, custom "Serial Sensors" may now be integrated directly without requiring a firmware update. Optionally, the second serial port on the Auxiliary connector may be repurposed to function as 2 GPIO lines[1], to support direct integration with industrial control systems.

Digital "Ethernet Sensors"

- Gen5 maintains support for integration of Ethernet-enabled devices which produce TCP/IP data streams, such as GNSS receivers. Centaur acts as a client and connects to the TCP server to initiate streaming and acquire data. Packets are stored locally and fully integrated into the NP data pipeline. Note that this data type is not supported by the SeedLink streaming protocol.

Core Data Logger Features

There are key data logger features that are fundamental to all remote sensing applications, and remain critical for multidisciplinary applications.

Low Power Consumption

- Remote stations typically utilize autonomous power systems which must be designed to satisfy the system requirements year round. Minimizing station power consumption significantly reduces the complexity, cost and risk associated with operating remote sensing stations. The Gen5 8-Channel model maintains Centaurs position with low per channel power consumption for streaming data loggers, with station power budget impact of 1.7W[2] for 8 channel streaming operation.

Accurate Timing

- Correct station timing is required for accurate seismic event detection and processing using data from a network of independent stations. For multidisciplinary applications, in which independent data sets are jointly analyzed, the accurate timing applied by Centaur to all data acquired from all sensor inputs ensures consistent timing throughout, allowing accurate temporal correlation analysis.

Environmental Robustness, Reliable Operation and Ease of Use

- Remote sensing stations in isolated regions are often subject to harsh environmental conditions, and present difficult and expensive logistical challenges for installation and maintenance operations, which also have inherent Health & Safety risks. It is critical that systems continue to operate reliably when subject to extreme conditions and are easy to operate, to ensure no undue or extended maintenance activity is triggered by equipment failures or execution inefficiencies. Centaur Gen5 continues to lead in these areas with a rugged IP68 enclosure and newly extended operating temperature range (-45°C to +70°C). Centaur has a long history of reliable operation and Gen5 offers a new, more responsive UI with streamlined support for multidisciplinary applications as well as comprehensive management of metadata and system response.

Network Security

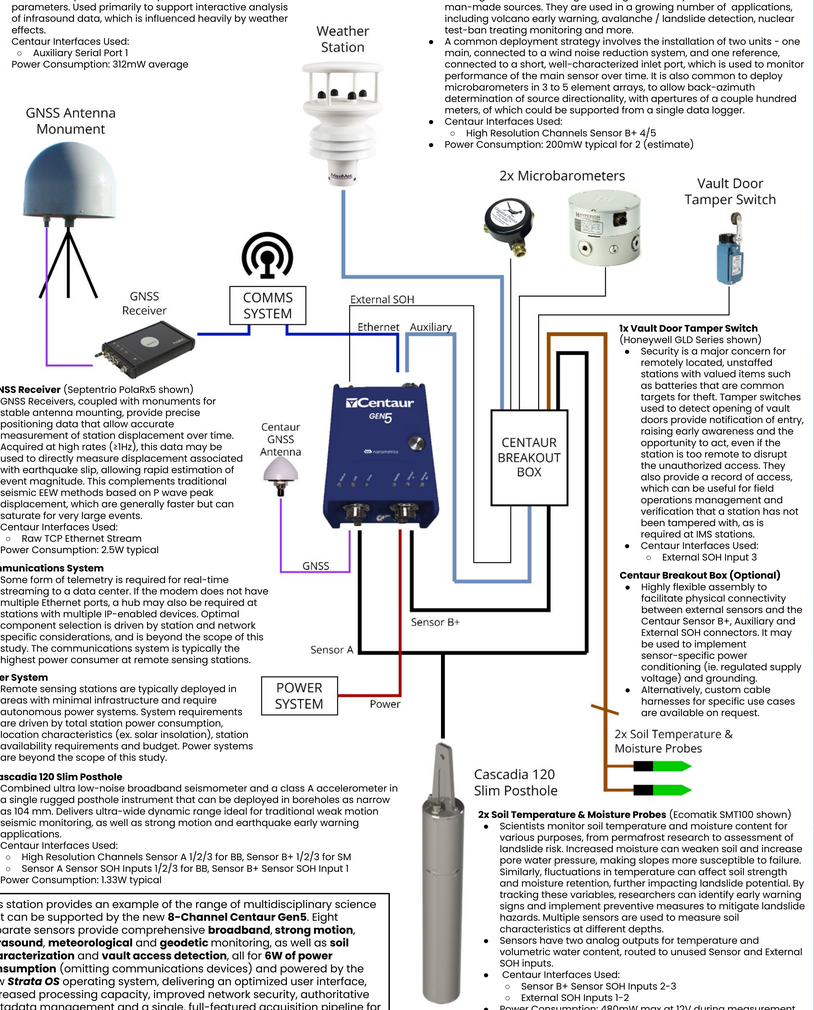
- Modern data loggers, especially those operating on shared telecommunications networks, must have the modern protections necessary to ensure ongoing compliance and be resilient to modern cyber security threats that present significant risks to operation. ***Strata OS*** delivers robust cyber security measures, including "memory-safe" firmware, HTTPS for secure communications and other updates to protect against common approaches for intrusion and maximize communication privacy.

Footnotes
1. To be available sometime following initial Gen5 launch.
2. Preliminary results, configuration dependent

Next Gen Multidisciplinary Monitoring

1x Weather Station (Gill GMX500 shown, other models from Vaisala, RM Young and others are also supported)
- Provides measurements of wind speed, wind direction, ambient temperature, humidity, rain and other weather parameters. Used primarily to support interactive analysis of infrasound data, which is influenced heavily by weather effects.
- Centaur Interfaces Used:
  - Auxiliary Serial Port 1
- Power Consumption: 312mW average

2x Microbarometers (Chaparral M64 and Hyperion IFS-5000 shown)
- Microbarometers are highly sensitive pressure sensors that can detect low-frequency sound waves, known as infrasound. These waves are below the range of human hearing and are generated by various natural and man-made sources. They are used in a growing number of applications, including volcano early warning, avalanche / landslide detection, nuclear test-ban treating monitoring and more.
- A common deployment strategy involves the installation of two units - one main, connected to a wind noise reduction system, and one reference, connected to a short, well-characterized inlet port, which is used to monitor performance of the main sensor over time. It is also common to deploy microbarometers in 3 to 5 element arrays, to allow back-azimuth determination of source directionality, with apertures of a couple hundred meters, of which could be supported from a single data logger.
- Centaur Interfaces Used:
  - High Resolution Channels Sensor B+ 4/5
- Power Consumption: 200mW typical for 2 (estimate)



1x GNSS Receiver (Septentrio PolaRx5 shown)
- GNSS Receivers, coupled with monuments for stable antenna mounting, provide precise positioning data that allow accurate measurement of station displacement over time. Acquired at high rates (>1Hz), this data may be used to directly measure displacement associated with earthquake slip, allowing rapid estimation of event magnitude. This complements traditional seismic EEW methods based on P wave peak displacement, which are generally faster but can saturate for very large events.
- Centaur Interfaces Used:
  - Raw TCP Ethernet Stream
- Power Consumption: 2.5W typical

Communications System
- Some form of telemetry is required for real-time streaming to a data center. If the modem does not have multiple Ethernet ports, a hub may also be required at stations with multiple IP-enabled devices. Optimal component selection is driven by station and network specific considerations, and is beyond the scope of this study. The communications system is typically the highest power consumer at remote sensing stations.

Power System
- Remote sensing stations are typically deployed in areas with minimal infrastructure and require autonomous power systems. System requirements are driven by total station power consumption, location characteristics (ex. solar insolation), station availability requirements and budget. Power systems are beyond the scope of this study.

1x Cascadia 120 Slim Posthole
- Combined ultra low-noise broadband seismometer and a class A accelerometer in a single rugged posthole instrument that can be deployed in boreholes as narrow as 10x14 mm. Delivers ultra-wide dynamic range ideal for traditional weak motion seismic monitoring, as well as strong motion and earthquake early warning applications.
- Centaur Interfaces Used:
  - High Resolution Channels Sensor A 1/2/3 for BB, Sensor B+ 1/2/3 for SM
  - Sensor A Sensor SOH Inputs 1/2/3 for BB, Sensor B+ Sensor SOH Input 1
- Power Consumption: 1.33W typical

This station provides an example of the range of multidisciplinary science that can be supported by the new **8-Channel Centaur Gen5**. Eight separate sensors provide comprehensive **broadband**, **strong motion**, **infrasound**, **meteorological** and **geodetic** monitoring, as well as **soil characterization** and **vault access detection**, all for **6W of power consumption** (omitting communications devices) and powered by the new ***Strata OS*** operating system, delivering an optimized user interface, increased processing capacity, improved network security, authoritative metadata management and a single, full-featured acquisition pipeline for all data types.

1x Vault Door Tamper Switch (Honeywell GLD Series shown)
- Security is a major concern for remotely located, unstaffed stations with valued items such as batteries that are common targets for theft. Tamper switches used to detect opening of vault doors provide notification of entry, raising early awareness and the opportunity to act, even if the station is too remote to disrupt the unauthorized access. They also provide a record of access, which can be useful for field operations management and verification that a station has not been tampered with, as is required at IMS stations.
- Centaur Interfaces Used:
  - External SOH Input 3

Centaur Breakout Box (Optional)
- Highly flexible assembly to facilitate physical connectivity between external sensors and the Centaur Sensor B+, Auxiliary and External SOH connectors. It may be used to implement sensor-specific power conditioning (ie. regulated supply voltage) and grounding.
- Alternatively, custom cable harnesses for specific use cases are available on request.

2x Soil Temperature & Moisture Probes (Ecomatik SMT100 shown)
- Scientists monitor soil temperature and moisture content for various purposes, from permafrost research to assessment of landslide risk. Increased moisture can weaken soil and increase pore water pressure, making slopes more susceptible to failure. Similarly, fluctuations in temperature can affect soil strength and moisture retention, further impacting landslide potential. By tracking these variables, researchers can identify early warning signs and implement preventive measures to mitigate landslide hazards. Multiple sensors are used to measure soil characteristics at different depths.
- Sensors have two analog outputs for temperature and volumetric water content, routed to unused Sensor and External SOH inputs.
- Centaur Interfaces Used:
  - Sensor B+ Sensor SOH Inputs 2-3
  - External SOH Inputs 1-2
- Power Consumption: 480mW max at 12V during measurement
  - Typically have very high sampling internals (once per hour or longer), yielding negligible power consumption

Unified Data Pipeline

For real time remote sensing networks, the primary mission of a data logger is the acquisition of remotely generated raw data, so it can be used promptly to serve the mandate of the network. Acquisition includes early data path steps such as digitization, timestamping and local recording, as well as the real time streaming to central data centers and associated capabilities such as automated recovery of data missed due to communications outages.

All data captured via any of the available sensor interfaces on Centaur is packetized, tagged and recorded locally, normalizing the handling of these separate and distinct data types. Each channel stream, including waveform and state-of-health, is associated with a standard SEED channel name, which is used to identify the channel stream throughout the data pipeline.

Centaur provides multiple options for real time data transfer, including industry standard protocols SeedLink, CD1.1 (authenticating models) and QSCD20. In general, the recommended solution for most applications is the NP protocol, streaming to an Apollo Server acquisition system at one or more data centers, due to its superior robustness, efficiency and flexibility. Apollo Server manages data acquisition from the remote network, ensuring maximum data availability, and provides low latency forwarding to downstream consumers via SeedLink. Apollo Server also provides centralized network management capabilities, including batch instrument configuration and bulk firmware distribution, to streamline maintenance of a fleet of Nanometrics data loggers. NP is a full featured protocol with several advantages:

Lightweight IP Protocol: Uses lightweight UDP/IP packets, ideal for links that are bandwidth-constrained, have intermittent outages or are TDMA-based. Also supports use of Websocket streaming, which may be preferred for streaming over the Internet to avoid firewall issues.
Automatic Outage Recovery: Apollo Server will automatically detect communications outages and will leverage the NP protocol retransmission capability to retrieve the missed data. It will continue to work to retrieve the missed data until it is either fully recovered or known to no longer be available at the source.
Real-time Prioritization: NP prioritizes real-time data ahead of recovering outages. After an outage, live data will start streaming immediately, while recovering the outage will proceed as bandwidth / throttling allows.
Multicast Streaming: NP supports multicast streaming, which allows multiple destinations to receive the same data stream, enabling use of redundant acquisition servers without requiring additional bandwidth.
Bandwidth Throttling: Configurable NP streamer feature to limit bandwidth utilization to a preset maximum, to ensure telemetry system bottlenecks do not result in dropped packets during periods of high traffic, such as the recovery of large outages.
Variable Packet Length: NP supports variable length packets, allowing use of smaller packet sizes to minimize packet latency, as preferred for EEW networks, or larger packets to minimize bandwidth overhead.
Short-term Complete: Configurable data distribution feature to temporarily buffer a real-time stream after an outage to allow time for gap recovery, to maximize data completeness while ensuring downstream clients do not receive data out-of-order, if required.
Acquisition Performance Tracking: Apollo Server provides comprehensive acquisition performance monitoring, with tracking of packet latency, bandwidth utilization, data completeness and other key metrics.
Redundant Streaming Path Support: Apollo Server gracefully supports recept of the duplicate packets. This allows implementation of sophisticated streaming topologies for mission-critical networks, such as the TRUAA EEW system, that support both redundancy, to increase system robustness, and synchronization, to simplify maintenance and maximize overall data availability.
Multidisciplinary Data Support: NP supports transport (via tunneling) of arbitrary TCP payloads, including GNSS BINEX or RTCM3 data streams. Apollo Server supports receipt and forwarding of these payloads as a generic TCP stream in the original format, and can also generate a permanent archive in that format.

NP Communications Outage Retransmission Protocol

Sample Nanometrics Data Center Architecture with Redundant Processing Toolchains

Next Gen Benefits

Next Generation Multidisciplinary remote sensing stations based on the **8-Channel Centaur Gen5**, powered by ***Strata OS***, yield several benefits:

- Using a single data logger, with several sensor interfaces available, to acquire all data types reduces the number of instruments required and **simplifies the station design and associated footprint**.
- Using a single low power data logger platform reduces overall station power consumption, **simplifying power system requirements and reducing the associated cost, complexity and operational risk**. The example station delivers high end broadband, strong motion, infrasound, meteorological and geodetic monitoring, as well as soil characterization and vault access detection, for only 6W (omitting communications devices).
- Using a single, flexible data logger platform **simplifies station maintenance procedures, inventory management and staff onboarding procedures**. There is one data logger instrument in the fleet to support and spare, with one easy-to-use system on which to train staff.
- Using a single, highly accurate timing source for all multidisciplinary data types **ensures timing consistency throughout datasets**.
- Using a single data logger platform with support for comprehensive metadata management, provides an **authoritative source for accurate metadata**, simplifying management and reducing the likelihood of subtle, hard-to-detect errors propagating into derived data products.
- Using a single data logger platform for real-time streaming, particularly with NP to Apollo Server, provides a **unified, high-performing acquisition system for all sensor types and channels**, simplifying network operation and allowing implementation of sophisticated streaming topologies, with both redundancy and synchronization to maximize system robustness and simplify data center maintenance for mission-critical networks.

The 8-Channel Centaur Gen5 is a high-performing, highly adaptable data logger platform that can acquire data from many multidisciplinary sensors concurrently via its multiple interface types, including 8 high resolution channels that support sample rates up to 10 ksps and 32 bit resolution. The new **Strata OS** delivers a UI optimized for multidisciplinary use cases, modern network security and increased processing capacity to enable new features and edge capabilities for ever-evolving monitoring requirements, **future-proofing the network** to meet the challenges of today and tomorrow.

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