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Best Practices for Data Acquisition System Design: Practical Wisdom for Engineers and Practitioners

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ABSTRACT: As global infrastructure ages and demands on new and existing structures increase, effective monitoring programs are essential for managing risk and public safety. This paper provides a practical guide for practitioners to design and implement structural health monitoring (SHM) systems, leveraging the combined expertise of the authors, who have extensive experience with leading equipment manufacturers.
Building on the 10 Steps of Data Acquisition System Design, the paper outlines best practices for developing robust monitoring systems tailored to bridges, dams, and other critical infrastructure. These steps include defining objectives, selecting appropriate sensors, communications design, data acquisition (DAQ) system design, power system considerations, civil works and mounting structures, installation, and managing data effectively.
A significant focus is placed on sensor and DAQ selection, exploring their critical roles in SHM system performance. The paper covers practical techniques for selecting, installing, maintaining, calibrating, and verifying sensors across traditional analog, frequency, and digital technologies. Examples from large channel count wired systems and distributed wireless monitoring systems are shared to illustrate diverse applications.
This paper aims to deliver actionable insights and practical wisdom, equipping attendees with the tools to overcome real-world challenges and achieve reliable, scalable, and long-lasting SHM implementations.

KEY WORDS: Structural Health Monitoring (SHM); Data Acquisition System Design; Sensor Selection; Critical Infrastructure Monitoring; Risk Management; Monitoring System Implementation; Wireless and Wired Monitoring

1 INTRODUCTION

Improvements and technological developments in sensors, data acquisition systems, and software in recent years have enabled engineers to implement advanced monitoring solutions on critical Structural Health Monitoring (SHM) projects worldwide. These systems often comprise hundreds or even thousands of sensors, delivering real-time performance data through synchronized acquisition platforms and intuitive visualization tools.
These developments, coupled with a rising demand for timely and reliable data, often exceed the capability of that which can be manually collected or interpreted, and thus necessitates the need for robust automation for real-time monitoring to detect potential hazards in advance.
Today, automated monitoring systems are far more cost-effective, reliable, and user-friendly than ever before, making them feasible not only for large projects with many sensors, for a more comprehensive assessment of structural behavior, but also for smaller-scale projects which, until recently, were rarely considered for, or enjoyed the benefits of automation.
There are also those projects, which started out as being manually read, but later moved to automated systems because of one or all the following: being unable to find enough qualified staff to read all the instruments, being unable to safely access the instruments to read them manually and being unable to obtain reliable data through manual readings.
While automated monitoring systems help reduce the burden on project owners by enabling reliable and timely data collection without interfering with ongoing construction activities. They also facilitate the early identification of potential issues, allowing for prompt implementation of corrective measures. Moreover, the development of wireless network technologies has made it easier to expand or reconfigure monitoring systems quickly, with minimal disruption to both the existing setup and the construction process. To support this progression from concept to implementation, Figure 1 illustrates a logical sequence of design steps that guide the development of a robust SHM system.

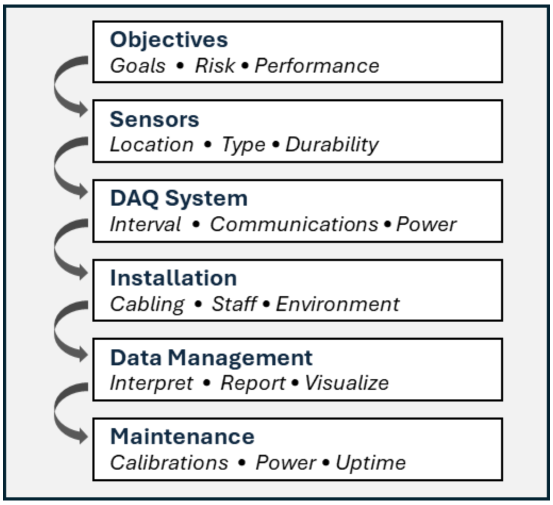

Figure 1: An overview of the SHM design process.

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2 MONITORING OBJECTIVES

The success of any SHM project, whether automated or manual, hinges on meticulous planning, precise execution, and the development of an action plan (or plans) to address the findings based on the collected data. Peck's Observational Method laid the foundational philosophy for most monitoring programs, which Dunnicliff further enhanced with a detailed, systematic approach.

Essentially, Peck emphasized the importance of defining the geotechnical questions that need to be answered and then selecting the appropriate instruments and their placement to help answer those questions; stating, without a question, there is no need for instrumentation. Dunnicliff expanded on this by underscoring the necessity of defining the purpose of the instrumentation, asserting that it should only be used if there is a valid, defensible reason.

2.1 Define the Appropriate DAS

Before the Data Acquisition System (DAS) is designed, consideration should be given to the present (and future) scope of the monitoring system, with a bias on starting simple, using systems that are easily scalable as the project needs grow, and only implemented when required, after the initial system is functioning and is well understood.

Other considerations should determine the choice between site vs cloud hosted platforms, subscription vs capital expenditures (CAPEX), the ultimate sensor, DAS, and software suppliers, the maintenance requirements and who will be ultimately responsible for operation of the DAS the over the life of the project, When these decisions have been made, we can then start to look at sensor selection and DAS design in earnest.

2.2 Stakeholders and their Interests

Structural Health Monitoring (SHM) projects often involve a wide range of stakeholders, each with distinct objectives, responsibilities, and perspectives on data utility. Key stakeholders typically include project owners, engineers, contractors, regulators, insurers, asset operators, and in some cases, the general public. Project owners and developers are primarily motivated by risk reduction, cost control, and regulatory compliance, often seeking early warnings to avoid catastrophic failure and unplanned downtime. Engineers use monitoring data to validate design assumptions, assess structural behavior under real-world conditions, and guide adaptive decision-making during construction or operation. Contractors may rely on SHM data to sequence work safely, protect temporary works, or defend against claims. Regulators and permitting authorities seek assurance that infrastructure meets safety and environmental standards, with SHM providing a traceable, defensible record of performance. Insurers may view monitoring as a tool to reduce liability and claims exposure by demonstrating proactive asset management. Operators and maintenance teams use SHM systems to prioritize interventions, plan maintenance efficiently, and extend the life of the structure. Finally, for high-visibility projects, community stakeholders and the public may demand transparency and accountability—especially when safety is a concern—making clear, visual communication of monitoring data essential. Understanding these varied motivations is crucial in designing a system that delivers the right data to the right people at the right time.

3 SENSORS

Sensors general definition, sensors are devices that detect and respond to physical input from the environment in which they are installed. Inputs may include parameters such as temperature, strain, pressure, deformation and inclination, or other environmental or structural conditions. Sensors then convert their input into signals that can be read by an observer, with a portable readout instrument, or with an electronic system, such as a computer or DAS.

The choice of any sensor is determined, for the most part, by the application and the environment in which they are to be deployed. As they must function satisfactorily, often under very harsh conditions, throughout the life of the project, they should be as simple in concept as is consistent with their function (with respect to accuracy, repeatability and response time).

Additionally, they should be robust and reliable, to be durable under the environmental and operating conditions in which they will be deployed and, ideally, have a satisfactory (well proven) performance history. Moreover, the sensors should provide optimum cost benefit ratios to deliver acceptable performance throughout the life of the project considering the sum of purchase, installation, maintenance and monitoring.

For critical applications, and/or at primary monitoring locations, consideration should be given to adopting back-up instruments, maybe of a different technology to corroborate the measurements provided and/or to substitute in the event of primary sensor failure or damage.

3.1 Sensor Selection

In keeping with the intent of this paper, with respect to best practices and practical wisdom, it is appropriate, at this point, to remind ourselves of the systematic approach to designing monitoring systems as defined by John Dunnicliff in his renowned book, "Geotechnical Instrumentation for Monitoring Field Performance" published in 1988. In this context he identified 25 important steps to be considered and, wherein, the selection of the sensors comes in at step number 8, after steps addressing; the project conditions, mechanisms which control behavior, the purpose of the instrumentation and the parameters to be measured, the predicted magnitudes of change, the remedial action to be made and the responsibility of the various stakeholders. Readers are encouraged to read more on this subject in Chapter 26 of the aforementioned reference.

When selecting a sensor, several factors need to be considered to ensure it meets the requirements of your application. Following are some key factors:

Type of Measurement - The primary consideration is to choose a sensor which can detect the measurand, i.e. the specific physical quantity, object or property to be measured (e.g., temperature, pressure, strain, load etc.).

Environmental Conditions – Consider factors such as temperature, humidity, chemicals and electromagnetic interference which can affect the sensor performance. Keep in mind too, not only any limitations of the sensor in adverse environments, but also and associated cabling or conduits.

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Durability and Lifespan - For harsh or long-term applications, sensor ruggedness and reliability are critical, check with the manufacturer for compatibility and compliance.
Measurement Range - Ensure the sensor's measuring range aligns with the physical range of the application to obtain precise readings. While choosing a sensor with a range greater than that which is likely to be measured may be considered safe, be mindful of any corresponding loss in accuracy and resolution.
Accuracy and Precision - Ensure the sensor provides the necessary accuracy (how close a measurement is to the true or actual value) and precision (how close repeated measurements are to each other) for your application
Resolution/Sensitivity – Understand what the smallest change in measurand is that the sensor can deliver and check to determine that the DAS to which the sensor will be connected can discriminate such changes (see also Measurement Range above)
Response Time – As some applications (esp. real-time systems, and where dynamic measurements are required) often need sensors with fast response times, ensure that the selected sensor can satisfy same or, with the appropriate DAS, be readily converted from one taking static measurements to dynamic measurements.
Excitation and Power Consumption – Is especially relevant in battery-powered or remote systems, therefore it is necessary to ensure the DAS can deliver the required excitation and, at the same time, not introduce any errors into the measurements.
Output Type and Signal Conditioning – Understand whether the sensor outputs analog or digital signals, or communicates via protocols like I2C, SPI, etc. and if the associated DAS requires protection circuits and signal conditioners to minimize electrical noise and errors. (Digital sensors are often preferred over analog sensors as they can reduce errors during data conversion)
Size and Mounting Constraints – It is important to understand the physical dimensions and weight of the sensor, and how and where it will be installed. Make sure adequate space is available for installation and that any fixtures required for mounting will not affect sensor operation or performance. Ensure that the physical size or weight of the sensor does not negatively impact the environment being measured.
Calibration and Maintenance – Understand any calibration and maintenance requirements required for the sensor to continue to deliver according to its stated accuracy or, where sensor access and recalibration is not possible, opt for sensors with proven long-term stability (See also Section 3.3)
Price and Availability – Does the price of the sensor meet the budget and is it readily available for deployment according to the project schedule and/or in the event replacements are needed. Consideration might also be given to the budget for more costly (reliable) sensors for long-term applications where replacement is not possible.
Careful consideration of these factors will help you choose a sensor that is efficient, reliable, and cost-effective for your specific needs.

3.2 Sensor Installation

Sensor performance is often only as good as the way in which it was installed. Therefore, it is critical that the correct installation procedures are followed and documented. Of course, installation methods will vary according to sensor type but adhering to the following guidelines will help deliver reliable performance and accurate data.

Plan Installation Procedures (Dunnicliff)

- Prepare written step-by-step procedures well in advance of scheduled installation dates
  - Including a detailed listing of required materials and tools
- Prepare installation record sheets
- Plan staff training
- Coordinate installation plans with the construction contractor
- Plan access needs and any protection of the installed instruments from damage/vandalism
- Prepare installation schedule consistent with the construction schedule.

Pre-Installation Tests (Dunnicliff)

- Check the Documentation
  - Check, by comparing with procurement document,
  - That model, dimensions, and materials are correct
  - That quantities received correspond to quantities ordered

- Check the Instruments
  - Check the cable length(s)
  - Check tag numbers on instrument & cable
  - Verify that all components fit together in the correct configuration
  - Check all components for signs of damage in transit

- Check Data Provided by the Manufacturer
  - Examine factory calibration curve & tabulated data, to verify completeness
  - Examine manufacturer’s final quality assurance inspection checklist, to verify completeness

- Function Checks
  - Connect to readout & induce change in parameter to be measured
  - Make and remake connectors several times, to verify correct functioning

- Calibration Checks (Note: This is an approximate check only)
  - Check 2 or 3 points if possible
  - Allow sensors to come to thermal equilibrium
  - Check Zero reading
  - Calibrate any Readout Instruments (used during installation and troubleshooting) regularly

3.3 Sensor Calibration & Maintenance

Where accuracy, reliability and consistency are required it is particularly important that sensors are calibrated correctly and in accordance with internationally recognized standards.
Accuracy – Certain sensors may drift over time and, if not regularly calibrated, can report biased data. Calibration

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guarantees that the sensor output is traceable to a known standard or reference which is critical when taking trustworthy measurements for confident decision making. (Where sensors are inaccessible after installation consider using types with proven long-term stability).

Consistency – Where different sensors are used in any one project, calibration allows data from each device to be compared over time. For example, two temperature sensors, from the same batch, may read slightly differently unless calibrated.

Safety and Compliance – It goes without saying that incorrect readings can lead to safety hazards including loss of reputation, asset and or life. Therefore, it is common practice for regulatory standards to require periodic calibration to maintain certification and indemnity.

System Performance – In digital twins, where historical data is integrated with, and relies upon, updates from sensors in DAS to represent near real time status, it is of paramount importance that sensors are properly calibrated as small inaccuracies can propagate and degrade the system's overall performance or decision-making.

Cost Savings - Accurately calibrated sensors help prevent inaccurate data from causing false conclusions, resource waste, and or project failures and delays.

Similarly, sensor maintenance is equally important as it contributes to ensuring accuracy, reliability, and longevity, all of which are critical for making informed decisions, maintaining asset quality, complying with safety standards, and avoiding costly downtime or repairs.

4 DESIGN - DATA ACQUISISTION SYSTEM

A DAS—also referred to as a DAQ, ADAS, or ADAQ—is the electronic backbone of any SHM program. It serves to collect, condition, log, and transmit sensor data from the field to the end user or database. Effective DAS design must align with the sensor types and quantities, sensor placement, measurement timing requirements, communication protocols, and site-specific environmental constraints. Additionally, DAS architecture should anticipate future scalability, integration with other systems, maintenance access, and power availability.

4.1 System Architecture & Scalability

DAS architectures for SHM systems typically fall into two categories: **centralized (wired)** and **distributed (wireless)**. In practice, hybrid approaches are often adopted to best suit varying site conditions, sensor layouts, and project phases.

Centralized (Wired) System – Often built using a customizable datalogger or modular components, a centralized system offers the flexibility and expandability to read a wide variety of sensors and can often be expanded to be a high channel count or high speed system.

Advantages include:

- Easier serviceability and diagnostics via a single access point
- Superior time synchronization across measurements
- Suited for real-time or safety-critical applications
- Flexibility in supporting advanced measurements and redundancies
- Robust power backup options

Additional considerations or challenges may include:

- Longer sensor cable runs may increase cost
- Higher initial setup time and effort

Distributed (Wireless) DAS – These involve smaller, self-contained DAS nodes placed closer to sensor clusters and typically use radio, LoRa, or cellular protocols for data transmission.

Advantages include:

- Reduced cabling complexity
- Modular installation
- Natural electrical isolation (air gap) for surge protection

Additional considerations or challenges may include:

- Requires management of wireless networks and data synchronization
- Battery-powered nodes may limit lifespan or require frequent servicing
- Multiple access points for maintenance

Scalability – A good DAS design should accommodate changes in monitoring scope over time. Scalability should include:

- Additional sensor capacity (via modularity or spare channels)
- Upgradeable communications infrastructure
- Data routing to multiple stakeholders or databases
- Power system upgrades (e.g., larger solar arrays, battery banks)
- Lifecycle support—ensure vendors provide long-term maintenance and part availability over the next 1, 5, or 10 years.

4.2 System Timing

Time management is central to a reliable monitoring program, understanding the different timing intervals is needed to ensure that the system operates as intended. Pro-Tip: just because you can collect data fast doesn't necessarily mean that you should. Timing considerations may include:

- Sampling Rate: Frequency of raw sensor measurements
- Recording Interval: Frequency of data logging, which may include statistical reduction (min/max/avg)
- Transmission Interval: Frequency of data being sent to the database/user
- Measurement Synchronization: How critical it is for measurements from different sensors or systems to be time-aligned. This becomes increasingly important—and potentially more complex—when multiple data acquisition devices are deployed across a site, especially when correlating events across a site.

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4.3 Data Collection

The frequency of data collection and transmission should align with the decisions that rely on that data. Data must be transmitted—and reviewed—at intervals no longer than the maximum time allowed to respond to undesirable system behavior. For instance, a safety monitoring system may require data transmission every second to enable timely alarms that protect personnel. In contrast, a system used for regulatory reporting might only need to collect data monthly or quarterly, often in conjunction with manual site inspections.

4.4 Communications

Communications are typically considered in two layers: onsite communication between sensors, loggers, and gateways; and offsite communication from a device to the cloud, server, or database. Each layer offers various communication methods, but these can generally be categorized into two types—wired and wireless—each with its own set of considerations.

Wired-Onsite: Ideal for permanent installations, wired onsite systems offer high reliability and noise immunity but require protected cable routing and can be more costly initially but may have a lower total cost of ownership (lower maintenance). Onsite wired systems may use a combination of copper or fiberoptic cables to address communication distance or electrical noise interference challenges. A wired onsite system is generally built for the specific and exclusive needs of the monitoring system.

Wireless-Onsite: Enable fast, modular deployment in difficult locations but require careful planning for power, interference, and network management. Generally built using radios that offer a point-to-point or mesh network communication. Wireless performance and protocols used are based on the selected wireless technology.

Wired-Offsite: Wired offsite connections deliver secure, consistent performance but is reliant on existing network infrastructure or it may need to be added. Typically, this taps into an existing ethernet network that is already existing or needs slight improvements to accommodate the needs and connection points of the monitoring system.

Wireless-Offsite: Wireless offsite communication provides flexible, trench-free connectivity for remote sites, but it depends on external networks and typically requires a subscription. Most often, this involves using a cellular or satellite network managed by a third-party provider, accessed through a compatible modem and associated service plan.

Pro Tip: When considering a communication option, consider seasonal conditions, for example, a radio network installed in the winter/spring may work great but the added vegetation in the summer could significantly impact onsite radio performance or give consideration to winter conditions where deep snow may cover communication antennas.

4.5 System Power: Power Budgeting & Backup

The power system is the backbone of any remote data acquisition system and is often a primary point of failure if not properly designed. Power configurations can range from simple, single-use batteries that require periodic replacement to advanced systems incorporating solar panels, charge controllers, and rechargeable batteries—ideal for long-term or high-demand deployments. Self-contained DAS units often favor compact, non-rechargeable batteries for their simplicity and reliability, while modular or scalable systems typically use rechargeable batteries paired with external charging sources such as solar or AC power. Because total power consumption depends on design decisions—like sensor type and duty cycle, logging hardware, communication method (e.g., radio, cellular, satellite), and data collection frequency—the power system should be specified last. When designing it, account for worst-case scenarios such as reduced battery performance in cold temperatures, limited sunlight during winter months, and extended outages caused by events like snow-covered solar panels.

4.6 Installation Considerations

A successful installation requires careful planning and thorough verification of sensor operation, wiring, communication links, and power systems—both in the office and in the field. Equipment should be securely mounted in enclosures designed to withstand environmental challenges. When selecting cabinets or enclosures, consider factors such as humidity, temperature extremes, corrosive environments (e.g., seawater or acidic mine conditions), lightning protection, and the need for secure mounting. A site visit before installation is essential to assess available utilities, site conditions, cable routing, and required structures for a quality setup. As with any project, qualified personnel are crucial to ensure proper handling, installation, and operation verification. Comprehensive documentation is key to a quality installation, outlining system operations, wiring, equipment labeling, and data access. Since deployed equipment often transitions through multiple field staff over time, well-documented and carefully executed installation practices help ensure the system's longevity, beyond the tenure of any individual staff member.

5 MAKING SENSE OF THE DATA

The objectives of a monitoring system must be clearly defined at the start of any project. The data produced should directly address the specific questions that need to be answered. The value of any monitoring system's data depends on its interpretability, reliability, and ability to be transformed into actionable insights for key stakeholders.

5.1 Data Interpretation

Interpreting sensor data depends on the type of measurement and the reference baseline used for comparison. Measurements with clear reference points—such as water level (relative to elevation) or tilt (relative to gravity)—are easier to understand, and thresholds can easily be established based on design specifications or comparing to other sensors. However, measurements like strain may be more relative and require establishing a baseline at installation or during an initial project event. Regardless of the sensor type, engineers must interpret data within the context of the monitored structure, considering sensor placement, behavioral characteristics, environmental conditions, and long-term performance trends.

Questionable Data & Anomalies

All monitoring systems will generate data that raises questions at some point. Questionable data may stem from external

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factors, such as environmental changes or nearby construction activities, or issues within the measurement system itself, such as sensor interference from electromagnetic noise, damaged cables, or inadequate power supply. Additionally, stakeholders might question data when it contradicts project schedules or crew activities, often to avoid disruptions.

When data is questioned, a useful first step is to ask: "Is what I'm seeing possible, or am I dealing with a faulty measurement?" In cases where the data could impact safety or project costs, the system should incorporate redundant measurements using different technologies to quickly verify whether the reported data reflects actual site conditions. While anomalies may initially appear alarming, they can often become part of the normal dataset as understanding of the system's behavior improves over time. Caution is needed when dismissing outliers as anomalies, as this could result in missing genuine early warnings. If a sensor consistently generates unreliable data, further investigation is necessary to address the root cause.

5.2 Reporting & Visualization

Data that cannot be easily understood or communicated effectively will not be used. The key question in determining how to report or visualize data is: who will use this data, and what format will best help them understand it? Technical users, such as engineers and scientists, may prefer raw data, like simple tables, for further analysis. In contrast, data intended for the general public should be presented visually, with clear indicators of what the data represents, where it's installed on the structure, and what thresholds exist and what to do if those thresholds are met. Many SHM projects involve multiple audiences, so data presentation should evolve to meet the needs of different stakeholders throughout the project's lifecycle.

6 CONCLUSION

Over the past ten years or so, modern DAS has played a key role in supporting site decisions that enhance the health and safety critical projects, and those working on them, all the while delivering significant time and cost savings during construction and operation and providing input for safer and more cost-effective designs.

Advances in sensor technology, data acquisition systems, and cloud computing have resulted in many monitoring programs involving a greater number of instruments than previously used, all of which collect data at much higher frequencies and generate vast volumes of information.

Thus, it is purported that a well-designed data acquisition system (DAS) will offer several key benefits, especially on projects which involve a large number and variety of sensor types:

Data Integration Across Sensor Types - Seamlessly collects and unifies data from diverse sensors (e.g., geotechnical, structural, environmental), enabling holistic analysis and reduces the need for manual aggregation or format conversions.

Real-Time Monitoring and Alerts - Enables high-frequency data collection and real-time transmission, which facilitates immediate alerts when thresholds are breached, thereby improving safety and responsiveness.

Improved Data Quality and Reliability - Minimizes data loss, signal noise, and errors through appropriate filtering, calibration, and validation, thus ensuring accurate and consistent data across all sensor types.

Scalability and Flexibility - Supports the addition of new sensors and or sensor types or locations without re-engineering the entire system and adapts to evolving project needs, whether during construction or long-term monitoring.

Centralized Data Management - Consolidates data into a single, accessible platform, reducing fragmentation and enhancing collaboration among engineers, analysts, and decision-makers.

Efficient Data Processing and Visualization - Supports automated analysis, dashboards, and trend detection, reducing time spent on manual review and enabling timely insights to inform decision-making.

Reduced Operational Costs - Lowers labor costs associated with manual readings and data handling, while minimizing downtime and damage through proactive maintenance.

Enhanced Regulatory Compliance and Reporting - Provides traceable, well-documented data logs to meet legal, environmental, or safety standards, and simplifies reporting for stakeholders and authorities.

In closing, the authors wish to remind readers that it still remains appropriate, that no matter how well an instrumentation DAS and monitoring program is designed, it will ever replace the need for site surveys and visual inspections. While monitoring can check specific points continuously, and alert if alarm conditions are exceeded (in a timely manner), site surveys and visual inspections (although less frequent) allow for "macroscopic" observations to be made, that a network of instruments could quite easily miss; be warned.

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