ZT-WP-003 | ZERO-TRANSIT RESEARCH WORKING PAPER

A Universal Sensor Interface for Heterogeneous Precision Instrument Networks

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Research status: Foundational concept / methods architecture. This working paper defines testable research structure and does not report a validated long-range detection effect, operational observatory, government partnership, or deployed capability.

ABSTRACT

The Zero-Transit observatory concept depends on combining instruments that were not originally designed to function as a single detector. This paper proposes a Universal Sensor Interface (USI) as an ingestion and provenance contract rather than a hardware monoculture. The USI defines minimum requirements for timestamping, calibration state, uncertainty, source identity, health metadata, raw-packet retention, and transformation lineage. It is intended to allow electromagnetic, optical, timing, particle, radiation, and environmental instruments to remain independently interpretable while participating in cross-domain correlation. The paper distinguishes transport synchronization from scientific simultaneity, specifies data-product tiers, describes schema and provenance requirements, and outlines validation tests for adding a new instrument family. The design is intentionally compatible with commercial, partner, government, and future custom instruments while avoiding the assumption that any one measurement modality is privileged.

Keywords: *sensor interface, multisensor fusion, precision timing, metadata, provenance, interoperability, instrumentation*

1. Design Objective

The USI exists to solve an integration problem: how can measurements from dissimilar instruments be compared without erasing the information needed to interpret each instrument on its own terms? The answer is not to force every sensor into a single normalized waveform. Instead, Zero-Transit defines a common envelope around heterogeneous payloads while preserving native data and instrument-specific semantics.

The envelope includes stable source identity, time metadata, calibration state, units, uncertainty, health, location, transformation history, and links to the native payload. This is an interface contract, not a claim that the measurements represent the same physical variable.

2. Lessons from Multisensor Fusion

Multisensor data fusion literature emphasizes that combining sensors requires explicit attention to alignment, uncertainty, registration, and the level at which information is fused (Hall and Llinas 1997). Zero-Transit adopts a conservative version of that principle. Raw sensor packets remain distinct; higher-level correlations are derived products with their own provenance.

This separation matters because premature normalization can turn calibration assumptions into apparent cross-channel similarity. The USI therefore makes normalization reversible and stores conversion parameters with the derived product.

3. Time as Scientific Metadata

Precision timing is central because candidate correlations may be defined by relative arrival time or phase. A timestamp without uncertainty is insufficient. The USI should record the clock source, synchronization protocol, estimated offset, jitter, leap-second handling, holdover state, and any post-acquisition correction.

White Rabbit demonstrates a practical architecture for sub-nanosecond timing distribution over Ethernet in precision measurement systems (Moreira et al. 2009). Zero-Transit can use such systems where justified, but the interface must also support less precise sensors by carrying honest uncertainty. Scientific simultaneity is an inference from measured time and uncertainty, not a property assumed because packets arrived close together.

4. Three Data Products

The USI defines three product tiers. Raw products preserve the instrument-native payload and acquisition metadata. Corrected products apply declared calibration or synchronization adjustments while retaining links to the raw source. Exploratory products apply analytical transforms, filters, features, or models for research use.

No tier deletes the lower tier. An exploratory anomaly score can therefore be traced to the corrected values and then to the original packet. This design prevents an analyst from confusing a derived feature with the physical observation.

5. Provenance Contract

FAIR principles emphasize interoperable and reusable research objects (Wilkinson et al. 2016), while PROV-O provides a model for describing derivation and responsibility (Lebo, Sahoo, and McGuinness 2013). The USI can encode these ideas in a compact machine-readable envelope: entity identifiers for packets and datasets, activities for calibration or transforms, and agents for instruments, services, or human reviewers.

Checksums should be used to bind stored metadata to source payloads. Version identifiers should apply to schemas, firmware, calibration files, analysis code, and model artifacts. The result is an evidentiary chain that can be re-evaluated when an instrument or algorithm changes.

6. Instrument Admission Tests

Adding an instrument family to the network should require more than a functioning API. Admission tests should confirm stable identity, bounded timing behavior, interpretable units, calibration records, known failure modes, raw-data export, health telemetry, and the ability to reproduce a synthetic or known input.

An instrument that cannot meet every high-precision requirement may still be useful as context. The USI therefore supports quality classes rather than forcing a binary accepted/rejected decision. A weather station can provide environmental context without being treated as a precision event detector.

7. Security and Partitioning

The same interface may be used across public, partner, and controlled environments, but payload movement must respect domain boundaries. Metadata can often be shared more broadly than raw data. The system should separate scientific provenance from authorization state so that a dataset can remain scientifically identifiable even when access is restricted.

Release transformations should be explicit products, not silent copies. If a controlled dataset is downsampled, redacted, or summarized for public use, the public artifact should carry provenance indicating that it is derived and should not be mistaken for the source.

8. Conclusion

The USI turns heterogeneity from a liability into a testable feature of the research program. The architecture does not require all sensors to agree; it requires the system to know exactly what each sensor measured, when it measured it, how uncertain the measurement was, and how later analysis changed the representation. That is the minimum foundation for credible cross-domain correlation.

References

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