WHITE PAPER

TraceQ™: A New Way to Measure Motion

Introducing direct surface-relative motion measurement for mobile machines

Executive Summary

TraceQ™ is a new sensor primitive for mobile machines: a direct measurement of motion relative to the surface beneath the machine. Vehicles and other mobile systems commonly estimate motion from wheel rotation, inertial measurements, satellite positioning, perception sensors, localization systems, and software models. TraceQ™ adds a separate physical observation of how the machine actually moves over the ground, with potential value for localization, diverse redundancy, diagnostics, control, and independent operational evidence.

The technology is directly derived from NASA's Navigation Doppler Lidar, developed to support precision spacecraft landing. TraceQ™ applies the underlying Doppler-lidar measurement principle to terrestrial machines and is being developed toward a compact, silicon-based implementation suitable for commercial integration. This paper introduces the concept—not final operating specifications—and considers its relevance across mobile Physical AI, including autonomous and conventional vehicles, bipeds, quadrupeds, mobile robots, and industrial machines.

One initial application is BoundaryScore™, an independent operational-verification framework that can compare TraceQ™ measurements with selected machine-reported operational data. TraceQ™ is not BoundaryScore™ and is not limited to verification. It is the underlying measurement capability, potentially useful wherever a machine or its stakeholders need a direct and independent account of physical motion.

WHITE PAPER

1. The Motion-Measurement Gap

Every mobile machine depends on knowing how it is moving. Stability control, localization, navigation, path following, and automated operation all require an account of velocity and direction. In current systems, that account is commonly assembled from several sources. Wheel-speed sensors infer vehicle speed from rotation. Inertial measurement units observe acceleration and angular motion. GNSS provides position and velocity where signals are available. Cameras, radar, lidar, and localization systems contribute observations of the surrounding environment or changes in position over time.

Sensor fusion combines these inputs because each has useful strengths and known limitations. Wheel rotation can differ from actual travel when tires slip. Inertial estimates accumulate error over time. GNSS availability and accuracy vary with the operating environment. Perception and localization systems depend on their sensing conditions, reference features, and processing assumptions. Combining sources can produce a robust estimate, but it does not turn that estimate into a direct observation of surface-relative motion.

This distinction matters beyond navigation. A machine's internal systems may report that it is moving at a particular speed or following an intended trajectory, yet an independent observer may need to determine whether the physical behavior corresponds to that report. The issue is not that existing systems are inadequate; they are designed for control and operation. The missing element is a separate measurement channel that can serve the machine, its developer, or an external evaluator without depending entirely on the same internal data and assumptions.

2. TraceQ™ as a New Sensor Primitive

TraceQ™ addresses that gap by directly measuring a machine's velocity relative to the surface beneath it. "Sensor primitive" is used here deliberately. The concept is not another complete navigation stack, safety system, or autonomy platform. It is a fundamental physical measurement that can become an input to many different systems, just as inertial, position, and wheel-speed measurements are used in more than one application.

A useful conceptual comparison is an optical computer mouse. A mouse observes movement relative to the surface below it rather than relying on the computer to infer that motion from an intended command. TraceQ™ applies a different and substantially more advanced measurement architecture: Doppler lidar designed to measure surface-relative motion at real-world machine speeds and operating distances. The analogy describes the relationship being measured, not the device's engineering implementation or performance envelope.

The resulting signal is an observation of ego motion: the movement of the machine itself. Because it is tied to physical motion over the surface, it can provide information that is distinct from wheel rotation, commanded motion, or a state estimate generated inside the autonomy system. That independence is central to the concept. TraceQ™ is intended to add a measurement, not to reproduce an existing one under a different name.

TraceQ™ is directly derived from NASA's Navigation Doppler Lidar, developed to provide precise velocity and range information for spacecraft landing. Psionic—the company that licensed and further developed NASA's NDL technology—successfully flight-tested its system aboard a NASA F/A-18 in 2025 under challenging high-speed conditions. The broader technology lineage has also undergone extensive testing in NASA and U.S. defense contexts. Paverly participated in bringing that lineage into the development of TraceQ™ for terrestrial and commercial use. This heritage supports the measurement principle; it does not validate specifications for a future commercial device.[1–3]

3. How TraceQ™ Works and Integrates

In practical terms, a TraceQ™ device can be installed wherever a vehicle, robot, or other mobile machine provides suitable line of sight to the operating surface. Depending on the machine and application, potential locations include a bumper, underbody, grille, windshield area, or side-view mirror. The device observes relative motion between the machine and the surface and produces measurement data that can be time-aligned with other operational information. Final placement, orientation, interfaces, and integration requirements will depend on the implementation and application.

TraceQ™ is being developed as a small, low-power device. Each laser operates at only a few milliwatts, and the underlying measurement approach can obtain returns from common operating surfaces. Exact size, power, environmental limits, sampling characteristics, and other specifications will depend on the implementation and must be documented through application-specific engineering and validation.

TraceQ™ does not inspect the roadway, classify surrounding objects, determine why a machine made a decision, or replace the perception, planning, and control functions required for autonomous operation. It also does not, by itself, establish that a machine is safe. Its role is narrower and more concrete: to measure motion relative to the operating surface and make that observation available for appropriate analysis.

4. Where Direct Motion Measurement Adds Value

Operational input, localization and redundancy

Within a machine, TraceQ™ may provide an additional input for localization, vehicle dynamics, navigation, control, and diagnostics. Direct surface-relative velocity can complement wheel-speed, inertial, GNSS, and perception-based localization by contributing a physically distinct observation of motion. This may be particularly useful when wheel or track movement differs from travel over the ground, positioning is intermittent, or accumulated estimation error creates uncertainty. The value and performance of any such use must be established through application-specific integration and testing.

TraceQ™ can also provide diverse redundancy. Unlike another calculation derived from substantially the same inputs, it observes motion through a separate physical principle. Used appropriately, that independence could support discrepancy detection, diagnostics, resilience, and confidence in the machine's account of its own movement.

For conditional automation and broader hands-free driving, TraceQ™ may represent a missing enabling measurement that complements perception, localization, planning, and control. It is not sufficient by itself to enable Level 3 operation or establish safety. Its potential role is as a foundational ingredient in an architecture requiring reliable localization, redundancy, and awareness of actual physical motion.

Development, assurance and independent evidence

For safety, assurance, and regulatory audiences, the same independence can improve traceability. Machine-produced information remains important, but selected claims may be more readily examined when compared with separately measured physical behavior. The comparison does not replace a safety case, simulation, closed-course testing, telemetry, standards, or established assurance processes; it complements them with evidence about what the machine did in the physical world.

The distinction between measurement and judgment is important. TraceQ™ supplies a motion signal. The meaning assigned to that signal depends on the application, the operating context, the quality of the integration, and the analytical method applied. A direct measurement can strengthen the evidence base while leaving questions of performance, compliance, and safety to the appropriate technical and institutional processes.

The missing element is a separate measurement channel that can serve the machine, its developer, or an external evaluator without depending entirely on the same internal data and assumptions.

Across mobile Physical AI

Direct motion measurement extends across mobile Physical AI—not only autonomous vehicles, ADAS-equipped vehicles, or conventional robots. Passenger vehicles, trucks, bipeds, quadrupeds, mobile robots, construction and mining equipment, agricultural machines, and industrial systems all need to relate commanded or estimated movement to actual displacement. The common requirement is physical motion, not a particular autonomy level or machine form.

Construction, mining, agricultural, and industrial machines may experience wheel or track movement that differs from ground travel, intermittent GNSS, repetitive environments, dust, or changing surfaces. TraceQ™ is not a universal solution to those conditions; it provides another observable quantity for evaluation alongside existing sensors and models.

5. Enabling BoundaryScore™

BoundaryScore™ is an initial application of TraceQ™'s independent measurement capability. A TraceQ™-equipped machine can produce a record of real-world motion that is reconciled with selected machine-reported operational data. BoundaryScore™ can then evaluate the comparison against defined operating conditions and benchmarks and produce traceable evidence intended to support a comparable rating.

This approach does not require access to every element of a proprietary perception, planning, or control stack. Nor does it attempt to reduce the full safety of an autonomous system to a single motion measurement. It focuses on a narrower question: whether independently observed physical motion corresponds to selected operational information reported by the machine, and how that correspondence performs under a defined methodology.

TraceQ™ and BoundaryScore™ therefore have different roles. TraceQ™ is the sensor primitive that observes motion. BoundaryScore™ is the framework that uses independent measurement, machine-reported data, defined benchmarks, and governance to create an operational-verification result. TraceQ™ can support applications beyond BoundaryScore™, while BoundaryScore™ depends on an independent measurement foundation to preserve the distinction between self-reporting and external observation.

6. Development and Standards Pathway

Translating the principle into a deployable product requires work beyond the underlying measurement concept. Device architecture, packaging, integration, calibration, environmental performance, manufacturability, data interfaces, and validation must be established for intended applications. TraceQ™ is intended to be manufactured in versions appropriate to applicable industry standards and use cases, with ISO 26262 an initial development target for automotive applications. This describes the planned standards pathway, not current certification. Those activities will determine the operating specifications and use cases supported by particular TraceQ™ implementations.

The immediate purpose of this paper is to establish conceptual clarity: what TraceQ™ measures, how it differs from existing sources, and where an independent physical observation may add value. Technical specifications, validation results, and application-specific documentation can follow as the technology advances.

Notes

1. NASA Flight Opportunities, “Moon Mission for Flight-Tested Navigation Doppler Lidar.”
2. NASA, “The Sky’s Not the Limit: Testing Precision Landing Tech for Future Space Missions” (March 26, 2025).
3. NASA Technical Reports Server, “Navigation Doppler Lidar Performance Assessment and Trajectory Reconstruction of the Intuitive Machines IM-1 Lunar Landing” (2025).