

# GPS2Quantum™

*Bridging Classical GPS and the Quantum Navigation Era*

Technical Whitepaper · February 2026 · [gps2quantum.com](https://gps2quantum.com)

## Abstract

GPS2Quantum is an iOS application that performs a real-time coordinate transformation from classical GPS/WGS84 geodetic coordinates into spherical quantum-frame state representations — the format in which next-generation quantum inertial navigation hardware will natively express position. The app operates as a simulation layer, using existing GPS infrastructure to generate structured quantum state output (radius  $r$ , polar angle  $\theta$ , azimuthal angle  $\phi$ ) annotated with sensor-class-specific uncertainty parameters modeled on cold-atom interferometry physics.

This whitepaper situates GPS2Quantum within the rapidly advancing field of quantum navigation, analyzes the hardware roadmap required for native quantum positioning, benchmarks the app against the current state-of-the-art in deployed quantum navigation systems (specifically Q-CTRL's Ironstone Opal), and articulates the app's unique role as a conceptual bridge, simulation testbed, AI context tool, and data-format pioneer for the quantum navigation era.

## 1. The Quantum Navigation Landscape

### 1.1 Why GPS Has a Successor Problem

The Global Positioning System underpins virtually every navigation system in commercial aviation, maritime shipping, autonomous vehicles, precision agriculture, and defense operations. Yet GPS is increasingly vulnerable. More than 1,000 commercial flights per day are disrupted by jamming or spoofing incidents. In conflict zones, GPS denial has become a standard tool of warfare. The economic cost of a single major GPS outage is estimated at over \$1 billion per day.

The solution that has emerged from decades of physics research is quantum navigation: positioning systems that derive location from the fundamental laws of quantum mechanics rather than from satellite signals. Because quantum sensors measure inertial forces and geophysical field variations directly — not radio signals — they cannot be jammed, spoofed, or denied.

*Quantum navigation is not a incremental improvement to GPS. It is an architectural replacement built on entirely different physics — one that happens to produce outputs in formats classical GPS users have never encountered.*

## 1.2 Two Branches of Quantum Navigation

Two distinct technology branches are converging toward GPS-independent positioning:

Cold-Atom Inertial Navigation	Quantum-Assured Map Matching
Measures inertial forces (acceleration, rotation) using laser-cooled atoms near absolute zero	Reads Earth's magnetic/gravitational field variations and matches against geophysical maps
Outputs position as spherical quantum state ( $r, \theta, \varphi$ ) via dead reckoning	Outputs GPS-equivalent X/Y coordinates; altitude from classical baro input
GPS-independent from first principles; no external reference required	Requires pre-existing geophysical maps; passive, unjammable
Current form factor: laboratory scale (0.5–1 m <sup>3</sup> ); miniaturization roadmap to ~2035–2045	Current form factor: 12U rack, <100W; Q-CTRL Ironstone Opal deployed in 2025

GPS2Quantum's simulation frame — `cold_atom_simulated` — models the output of the first branch. Its coordinate schema ( $r, \theta, \varphi$ ) is the native language of cold-atom inertial sensors, not yet available in hardware small enough to fit in a consumer device, but well-defined and increasingly standardized in the research literature.

## 2. The GPS2Quantum™ Coordinate Transform

### 2.1 Three-Step Transformation Pipeline

The app performs a mathematically rigorous three-stage transformation on every GPS fix it receives:

- Stage 1 — WGS84 Geodetic to ECEF Cartesian: Latitude, longitude, and altitude from the GPS receiver are converted to Earth-Centered, Earth-Fixed (ECEF) Cartesian coordinates ( $X, Y, Z$ ), placing the position in a 3D coordinate system anchored at Earth's center of mass.
- Stage 2 — ECEF to Spherical Quantum State: The ECEF coordinates are transformed into spherical coordinates — radius  $r$  (distance from Earth's center), polar angle  $\theta$  (colatitude from the North Pole in radians), and azimuthal angle  $\varphi$  (longitude in radians). This is the natural output format of cold-atom interferometers operating in free-fall gravity measurement mode.

- Stage 3 — Sensor Simulation Layer: The spherical state is annotated with sensor-class-specific parameters: drift rate, operational condition, and elapsed drift time  $\delta t$ . This models the accumulated positional uncertainty a real quantum sensor of the selected class would exhibit at that location after operating for the specified duration.

## 2.2 Sensor Classes and Physical Grounding

GPS2Quantum supports multiple sensor classes that correspond to real-world quantum sensor performance tiers:

<b>Consumer Grade (MEMS)</b>	Drift rate: ~0.1 m/s. Analogous to MEMS IMUs found in smartphones today. Used as the baseline for comparison.
<b>Navigation Grade</b>	Drift rate: ~0.01 m/s. Corresponds to ring-laser gyroscopes and high-end classical IMUs used in aviation.
<b>Strategic Grade (Quantum)</b>	Drift rate: ~0.005 m/s. Models cold-atom interferometer performance targets for submarine and strategic navigation.
<b>Cold Atom Simulated</b>	The primary frame. Represents idealized quantum inertial sensor output in the cold_atom_simulated coordinate frame.

## 2.3 Sample Output: Apple Park, Cupertino

The following output was generated by GPS2Quantum at Apple Park (One Infinite Loop campus area), demonstrating the transformation for a real-world landmark location:

<b>Reference ECEF</b>	X: -2,691,389.84 m   Y: -4,305,623.67 m   Z: 3,847,018.43 m
<b>Sensor Class</b>	Navigation Grade
<b>Operational Condition</b>	Static/Lab
<b>Drift Rate</b>	0.01 m/s
<b>Radius (r)</b>	6,370,363.04 m
<b>Polar Angle (<math>\theta</math>)</b>	0.9224 rad
<b>Azimuthal Angle (<math>\varphi</math>)</b>	-2.1295 rad
<b>Positional Drift (1D)</b>	0.000 m (at $\delta t = 0$ )
<b>Frame</b>	cold_atom_simulated
<b>Method</b>	GPS2Quantum™ Transform

## 3. Hardware Roadmap: From Lab to iPhone

### 3.1 What Hardware Each Attribute Requires

To natively measure the three quantum state attributes without GPS — i.e., from first-principles quantum sensing — each requires distinct hardware that does not yet exist at mobile scale:

#### Radius ( $r$ ) — Quantum Gravimeter

Measures gravitational acceleration to ppb precision via cold-atom free-fall interferometry, from which absolute distance from Earth’s center can be derived. Current laboratory gravimeters (e.g., Muquans AQG, iXblue) occupy 0.5–1 m<sup>3</sup> and consume 20–50W for laser cooling alone. The most compact fieldable sensor heads are approximately shoebox-sized but require external laser and electronics racks. Gravity measurement is the most mature cold-atom application and the most likely to miniaturize first.

#### Polar Angle ( $\theta$ ) — Multi-Axis Quantum Accelerometer

Measures the gravity vector’s elevation component — effectively the latitude proxy — using a 3-axis cold-atom accelerometer with a grating magneto-optical trap (GMOT). A single diffraction grating chip generates all cooling beams from one incident laser. Current prototype sensor heads are approximately coffee-mug sized (~500 cm<sup>3</sup>), but this excludes the laser system, vacuum chamber, and electronics. Sandia National Laboratories has demonstrated silicon photonic microchip components performing atom interferometry, collapsing the laser system to chip scale.

#### Azimuthal Angle ( $\phi$ ) — Quantum Sagnac Gyroscope

The most challenging attribute. Measures Earth’s rotation rate via the quantum Sagnac effect — the phase shift between counter-propagating atom matter waves. Sensitivity scales with the enclosed area of the atom loop, creating a hard physics tension: miniaturization directly degrades performance. State-of-the-art atom gyroscopes require table-scale setups (1–2 m baseline). NV-center or nuclear spin gyroscopes may offer an alternative miniaturization path. This attribute defines the long end of the iPhone integration timeline.

### 3.2 The Shared Infrastructure Challenge

All three attributes share a common hardware stack whose miniaturization is the primary bottleneck:

Component	Current Size	Target Size	Est. Timeline
Atom chip (BEC/cold atom source)	~10 cm <sup>2</sup>	~1 cm <sup>2</sup> chip-scale	2027–2029
UHV micro-vacuum chamber	~500 cm <sup>3</sup>	MEMS-scale, ~1 cm <sup>3</sup>	2028–2032
PIC laser system (Raman + cooling)	Discrete fiber bench	Single PIC die, ~1 cm <sup>2</sup>	Demonstrated 2024 (Sandia)

Component	Current Size	Target Size	Est. Timeline
Magnetic trap / field coils	Discrete wound coils	Microfabricated thin-film	2026–2028
Detection / readout ASIC	FPGA board	Integrated ASIC	2027–2030
Power (laser cooling)	20–50 W	<1 W target	2030–2035+

*The single largest unsolved obstacle is power. Laser cooling atoms to microkelvin temperatures currently demands 20–50W of precisely stabilized laser power. Until integrated photonics and MEMS vacuum technology drive this below ~0.5W, no quantum inertial sensor will fit in a mobile phone regardless of physical sensor size.*

### 3.3 Projected Timeline to iPhone-Scale Integration

Attribute	Governing Physics	Estimated iPhone-Scale Integration
Radius (r)	Quantum gravimetry (scalar, most mature axis)	~2032–2035: gravimeter chips closest to fieldable; gravity is the most advanced cold-atom application
Polar Angle ( $\theta$ )	Multi-axis quantum accelerometry	~2033–2037: requires 3D GMOT chip; MiniXQuanta-type programs targeting this within the decade
Azimuthal Angle ( $\varphi$ )	Quantum Sagnac gyroscope	~2038–2045: area-sensitivity scaling is a hard physics barrier; NV-center gyroscopes may offer alternative path

## 4. Current State of the Art: Q-CTRL Ironstone Opal

### 4.1 A Different Quantum Navigation Architecture

Q-CTRL's Ironstone Opal, named TIME Best Inventions of 2025 and field-validated in air, land, and maritime trials through 2025, represents the first commercially deployed quantum navigation system achieving true quantum advantage. It is critically important, however, to understand that Ironstone Opal operates on an entirely different architectural principle than cold-atom inertial navigation — one that sidesteps almost every hard physics problem in the roadmap above.

Rather than measuring inertial forces to compute position by dead reckoning, Ironstone Opal uses quantum magnetometers to read Earth's magnetic field with extreme sensitivity, then uses AI-driven software to match those readings against pre-existing geophysical maps — determining position the way a hiker navigates by matching landmarks to a topographic map.

*Ironstone Opal has achieved up to 111x greater positioning accuracy than conventional GPS backup systems in airborne field trials, with positioning accuracy down to 4 meters. A minimal hardware configuration has a total volume of 4.2 liters — today.*

## 4.2 Current Deployment Specifications

<b>Form Factor</b>	Single 12U rack (field configuration); minimal sensor package: 4.2 liters
<b>Power Consumption</b>	<100W total system
<b>Navigation Accuracy</b>	Up to 111x better than high-end INS in airborne trials; 4m positioning accuracy
<b>Operational Duration</b>	Validated continuously for 144+ hours on Royal Australian Navy vessel MV Sycamore
<b>Platforms Validated</b>	Fixed-wing aircraft (Cessna 208B), ground vehicles, UAVs, maritime vessel
<b>Key Attribute</b>	Unjammable, unspoofable, passive (emits no detectable signals)
<b>Partners</b>	Lockheed Martin (DOD/DIU contract), Northrop Grumman, Airbus; DARPA RoQS program (A\$38M)
<b>Commercial Status</b>	Available for presale; evaluation kit previewed at Singapore Airshow, February 2026

## 4.3 How Ironstone Opal Maps to GPS2Quantum's Quantum State

Ironstone Opal directly and immediately solves two of the three GPS2Quantum quantum state attributes:

Attribute	Ironstone Opal Status	Notes
Radius (r)	Not natively provided by MagNav	Supplied by classical barometric altimeter or INS; gravimetric nav work in earlier development stage
Polar Angle ( $\theta$ )	Solved — field-validated	Magnetic map matching delivers latitude to 4m accuracy today
Azimuthal Angle ( $\varphi$ )	Solved — field-validated	Magnetic map matching delivers longitude to 4m accuracy today

Ironstone Opal has effectively collapsed the 2033–2037 cold-atom inertial timeline for  $\theta$  and  $\varphi$  to right now — but via map matching rather than inertial sensing, at rack scale and 100W rather than chip scale and 0.5W. The miniaturization path for MagNav to smartphone scale is meaningfully shorter than for cold-atom IMUs, as quantum magnetometers do not require UHV

vacuum chambers or laser cooling to microkelvin temperatures. Chip-scale atomic magnetometers (CSAMs) already exist at centimeter scale. A plausible trajectory puts MagNav-based  $\theta/\varphi$  positioning in a smartphone-scale device by 2028–2030.

## 5. GPS2Quantum’s Role in the Quantum Navigation Ecosystem

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### 5.1 Four Distinct Functions

GPS2Quantum serves four layered and complementary purposes, all of which become more valuable as quantum navigation hardware matures:

#### Function 1: Conceptual Bridge and Translation Layer

Quantum navigation hardware outputs position in spherical or inertial frames that classical GPS users have never encountered. GPS2Quantum takes any GPS coordinate — a location anyone can generate from an iPhone — and shows what that same location looks like expressed as a quantum state in the `cold_atom_simulated` frame. It makes an abstract, future technology immediately tangible and comprehensible today, without requiring access to hardware that does not yet exist at consumer scale.

#### Function 2: Quantum Sensor Performance Simulator

The simulation parameters section — sensor class, operational condition, drift rate, drift time  $\delta t$  — models accumulated uncertainty from different quantum sensor grades over user-specified durations. A one-year simulation on a Strategic Grade sensor at Challenger Deep (altitude  $-10,516\text{m}$ ) yielded a 273km uncertainty radius — precisely the kind of analysis a navigation systems engineer evaluates when assessing whether a quantum IMU can survive a long-duration autonomous submarine mission without a GPS fix. GPS2Quantum is a quantum sensor performance estimator accessible on any iPhone.

#### Function 3: AI Context Injection Tool

This function is explicitly architected into the app. The metadata field in every GPS2Quantum output reads: “Share or copy/paste this GPS2Quantum™ Simulation result into any AI chat context window for an initial analysis.” The app generates structured, information-dense quantum state output that primes an AI conversation with coordinates, sensor parameters, uncertainty data, and frame metadata — enabling sophisticated analysis of quantum navigation scenarios at any location worldwide without requiring domain expertise from the user.

#### Function 4: Data Format Pioneer

GPS2Quantum is pre-standardizing a data schema — the `r/ $\theta/\varphi$  cold_atom_simulated` frame representation with associated uncertainty and sensor metadata — before the hardware that will

natively generate it exists at consumer scale. As Ironstone Opal and successive quantum navigation products enter the market, the coordinate formats they output will need to be legible to developers, integrators, and users. GPS2Quantum has been generating and publishing that format since before commercial deployment existed, creating a head start in format familiarity.

## 5.2 Use Cases Across the Quantum Navigation Maturity Curve

Timeframe	State of Quantum Navigation	GPS2Quantum Role
Now (2026)	Ironstone Opal deployed at rack scale; cold-atom IMUs lab-bound	Education, simulation, AI context injection, format familiarization
Near-term (2028–2030)	MagNav at compact/portable scale; first defense-grade cold-atom IMUs	Reference implementation for output format; sensor comparison tool
Mid-term (2032–2037)	Chip-scale quantum gravimeters; early mobile quantum accelerometers	Calibration reference; hybrid classical/quantum output translation
Long-term (2038+)	Full 3-axis quantum IMU approaching mobile scale	Legacy bridge for classical GPS data; quantum coordinate standard

## 6. Technical Appendix: Coordinate Transformation Reference

### 6.1 WGS84 to ECEF

Given geodetic coordinates ( $\varphi$  latitude,  $\lambda$  longitude,  $h$  altitude) and WGS84 parameters (semi-major axis  $a = 6,378,137.0$  m, eccentricity  $e^2 = 0.00669437999014$ ):

$N(\varphi)$	$a / \sqrt{1 - e^2 \cdot \sin^2\varphi}$ [prime vertical radius of curvature]
$X$	$(N(\varphi) + h) \cdot \cos\varphi \cdot \cos\lambda$
$Y$	$(N(\varphi) + h) \cdot \cos\varphi \cdot \sin\lambda$
$Z$	$(N(\varphi)(1 - e^2) + h) \cdot \sin\varphi$

### 6.2 ECEF to Spherical Quantum State

$r$ (Radius)	$\sqrt{X^2 + Y^2 + Z^2}$
$\theta$ (Polar)	$\arccos(Z / r)$ [colatitude from North Pole, in radians]

$\varphi$ (Azimuthal)	$\arctan2(Y, X)$ [longitude in radians, range $-\pi$ to $+\pi$ ]
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### 6.3 Uncertainty Propagation Model

Positional Drift (1D)	$d_1 = \text{drift\_rate} \times \delta t$ [meters along primary axis]
Uncertainty Radius (3D)	$d_3 = d_1 \times \sqrt{3}$ [isotropic 3D uncertainty sphere radius]
Frame	cold_atom_simulated: spherical coordinates anchored to Earth's center of mass, consistent with cold-atom interferometer output conventions in the current navigation research literature

## 7. Conclusion

Quantum navigation is no longer a theoretical future — it is an engineering present. Q-CTRL's Ironstone Opal has achieved field-validated, commercially deployable quantum-assured positioning at rack scale in 2025. Cold-atom inertial sensors will progressively miniaturize toward mobile scale over the 2030–2045 timeframe, with gravitational (radius) measurements leading and rotational (azimuthal) measurements trailing.

GPS2Quantum occupies a unique and durable position across this entire arc: it is simultaneously the only consumer-accessible tool for generating quantum-frame coordinate data from classical GPS inputs, a physics-grounded simulator for evaluating quantum sensor performance across all classes and environments, a structured data injector for AI-assisted quantum navigation analysis, and an early implementor of the coordinate schema that next-generation quantum navigation hardware will natively emit.

The app runs on hardware that fits in a pocket. The sensors it simulates will eventually do the same. GPS2Quantum is the bridge between those two moments in time.

*GPS2Quantum is available on the iOS App Store. Technical inquiries, partnership discussions, and API integration requests: [gps2quantum.com](https://gps2quantum.com)*

## References & Further Reading

- Gersemann et al. "Developments for quantum inertial navigation systems employing Bose–Einstein condensates." Applied Physics Reviews 12, 031306 (2025). doi:10.1063/5.0250666
- Muradoglu et al. "Quantum-assured magnetic navigation achieves positioning accuracy better than a strategic-grade INS in airborne and ground-based field trials." arXiv:2504.08167 (2025).

- Salducci et al. “Quantum sensing of acceleration and rotation by interfering magnetically launched atoms.” *Science Advances* 10, eadq4498 (2024). doi:10.1126/sciadv.adq4498
- Geiger et al. “High-accuracy inertial measurements with cold-atom sensors.” *AVS Quantum Science* 2, 024702 (2020). arXiv:2003.12516
- Sandia National Laboratories. “Atom Interferometry.” Quantum Sensing Program. [sandia.gov/quantum/atom-interferometry/](https://sandia.gov/quantum/atom-interferometry/)
- Q-CTRL. “Ironstone Opal: GPS-Free Quantum Navigation.” [q-ctrl.com/ironstone-opal](https://q-ctrl.com/ironstone-opal)
- Burkey. “How Quantum Sensing Will Help.” LLNL-TR-2004820. Lawrence Livermore National Laboratory (2025).
- TIME Magazine. “Best Inventions of 2025: Q-CTRL Ironstone Opal.” October 9, 2025.
- MiniXQuanta Project. ANR-20-CE47-0008. Agence Nationale de la Recherche, France.
- Compact Cold-Atom Interferometer with Grating MOT and PIC-Compatible Laser System. *Nature Communications* 13, 5131 (2022). doi:10.1038/s41467-022-31410-4