A Relativistic Test of the 6DT Spacetime Framework: Probing Boost-Dependent Anisotropy with Correlated Optical Atomic Clocks

Author: Blake Burns (blake.burns@gmail.com)

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Abstract.

This report proposes a novel experiment designed to test the unique kinematic predictions of the six-dimensional spacetime (6DT) framework. The 6DT model posits a background spacetime anisotropy, parameterized by a tensor field $K_{ij}(x)$ sourced by local gravitational potentials, which can be mapped to the Standard-Model Extension (SME). While existing Michelson-Morley and Hughes-Drever experiments place stringent constraints on the static components of such an anisotropy, they do not directly probe the model's predictions for observers in relativistic motion. We derive a new observable: a boost-dependent modification to the one-way speed of light, which manifests as a unique coupling between sidereal and annual modulations in a terrestrial laboratory. We propose a ground-based experiment using a long-baseline, phase-stabilized link between two optical atomic clocks to measure this effect. By leveraging Earth's orbital motion as a relativistic "boost," this experiment would provide a direct test of the 6DT model's modified Lorentz transformations, analogous to Einstein's foundational thought experiments. We present a detailed sensitivity analysis, demonstrating that this approach can either discover or constrain the 6DT coupling parameter ϵ in a sector of the theory's parameter space that is inaccessible to conventional static tests.

1 The 6DT Framework and its Phenomenological Consequences

1.1 The 6D Metric and the Anisotropic Background Field

The 6DT framework is a speculative model of spacetime built upon a six-dimensional manifold.[1] The coordinates in this manifold are denoted by $X^A = \{t^i, x^j\}$, where $i, j \in \{1, 2, 3\}$, corresponding to three time-like and three space-like dimensions. The geometry of this spacetime is described by a metric tensor G_{AB} with a signature of $(-, -, -, +, +, +)$. For phenomenological applications, the model employs a specific metric ansatz given in block-matrix form [1]:

$$G_{AB}(X) = \begin{pmatrix} -c^2\delta_{ij} & \epsilon K_{ik}(x) \\ \epsilon K_{kj}(x) & \delta_{kj} \end{pmatrix} \tag{1}$$

In this expression, the purely spatial block is Euclidean (δ_{kj}), and the purely temporal block is also Euclidean but with a negative sign ($-c^2\delta_{ij}$). The crucial feature of this metric is the off-diagonal block, $\epsilon K_{ij}(x)$, which couples the space and time sectors. This coupling is governed by a small, dimensionless parameter $\epsilon \ll 1$ and a symmetric spatial tensor $K_{ij}(x)$ that depends only on the spatial coordinates.[1]

The central phenomenological object of the model is this spatial tensor, $K_{ij}(x)$. The framework posits that this tensor is not an arbitrary background field but is directly sourced by the distribution of matter via the Hessian of the Newtonian gravitational potential, $\Phi(x)$.[1] This relationship is given by:

$$K_{ij}(x) = c^{-2}\partial_i\partial_j\Phi(x) \tag{2}$$

This ansatz establishes a direct and calculable link between the local gravitational environment—dominated in the solar system by the Sun—and the predicted anisotropy of spacetime. The introduction of extra time-like dimensions typically leads to unphysical negative-norm states, or "ghosts," which would violate the unitarity of a quantum theory.[1] The 6DT framework addresses this fundamental problem by proposing a local $SO(3)_t$ gauge symmetry that acts on the internal time indices. This symmetry, implemented through a set of first-class constraints within a Becchi-Rouet-Stora-Tyutin (BRST) quantization scheme, is designed to eliminate the unphysical degrees of freedom, leaving a single observable time direction and ensuring the model's physical consistency.[1]

1.2 Mapping to the Standard-Model Extension (SME)

To connect the theoretical 6DT model with experimental reality, its predictions must be translated into an operational framework. The Standard-Model Extension (SME) is a comprehensive effective field theory that parameterizes all possible forms of Lorentz and CPT violation in the Standard Model and General Relativity.[2, 3, 4] It serves as the canonical language for analyzing and comparing the results of high-precision tests of fundamental symmetries.

The 6DT framework provides a direct mapping from its core parameters to the coefficients of the SME.[1] The off-diagonal metric component $\epsilon K_{ij}(x)$ induces a modification to the propagation of photons that, at leading order, corresponds to the CPT-even, non-birefringent coefficients of the minimal SME's photon sector. These coefficients are often denoted in the literature as $(\tilde{\kappa}_{e-})_{jk}$.[5] The explicit mapping is given by:

$$c_{ij}^{(eff)}(x) \simeq \epsilon K_{ij}(x) \tag{3}$$

where $c_{ij}^{(eff)}$ represents the effective SME coefficients. This relationship is the crucial bridge between theory and experiment. However, it also reveals a profound structural feature of the 6DT model. A general SME analysis involves fitting experimental data to numerous independent coefficients—for instance, the nine nonbirefringent terms in the minimal photon sector.[5] In stark contrast, the 6DT model does not predict arbitrary or independent coefficients. Because K_{ij} is derived from the Hessian of a single scalar potential Φ, all the resulting effective SME coefficients are rigidly correlated. They are all governed by the single fundamental parameter ϵ and must exhibit the specific spatial structure of a tidal field. This inherent structure makes the 6DT model far more constrained, and therefore more readily falsifiable, than a generic Lorentz-violating theory. An experiment capable of measuring multiple components of the anisotropy tensor could test not only for the presence of an effect but also for the specific pattern of correlations predicted by the 6DT model, providing a powerful test that goes beyond merely setting an upper limit on ϵ.

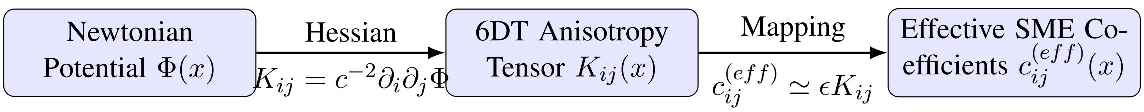

Figure 1: Conceptual flow from the gravitational potential to observable SME coefficients in the 6DT framework. The model's predictiveness stems from the fact that the entire tensor of SME coefficients is determined by a single scalar potential $\Phi(x)$ and one coupling constant ϵ.

1.3 The Explicit Form of the Anisotropic Field in the Solar System

To design a concrete experiment, the abstract theory must be applied to our specific location in the universe. Within the solar system, the dominant source of the Newtonian potential is the Sun. Using the monopole approximation for the solar potential, $\Phi(r) = -GM_{\odot}/r$, where r is the distance from the Sun, the predicted anisotropy tensor $K_{ij}(x)$ can be calculated explicitly. The second partial derivatives of the potential yield the familiar form of a tidal tensor:

$$K_{ij}(x) = \frac{GM_{\odot}}{c^2 r^3}(3\hat{r}_i\hat{r}_j - \delta_{ij}) \tag{4}$$

where $\hat{r}$ is the unit vector pointing from the Sun to the location of the experiment. At Earth's orbit (a distance of $r \approx 1$ AU), the magnitude of the components of this tensor can be calculated. The dimensionless quantity $GM_{\odot}/(c^2 r)$ is approximately 10^{-8}. Therefore, the components of K_{ij} are of the order of 10^{-8}. This numerical value provides a concrete physical scale for the background field that a terrestrial experiment would interact with, forming the baseline for the sensitivity calculations that follow.

2 Relativistic Kinematics and Observables in the 6DT Framework

2.1 Light Propagation in a Static 6DT Background

The primary phenomenological consequence of the 6DT metric is a modification to the propagation of light. The trajectory of a light ray is a null geodesic, defined by the condition that the spacetime interval ds^2 is zero. For the 6DT metric, this condition is:

$$ds^2 = G_{AB}dX^A dX^B = -c^2\delta_{ij}dt^i dt^j + 2\epsilon K_{ij}(x)dt^i dx^j + \delta_{ij}dx^i dx^j = 0 \tag{5}$$

By assuming a single effective time coordinate t and solving for the coordinate velocity of light, $v = |\vec{dx}/dt|$, one can derive the one-way speed of light in this background. To first order in ϵ, the speed of light is found to be anisotropic, depending on the direction of propagation $\hat{n} = \vec{dx}/|\vec{dx}|$ relative to the local principal axes of the K_{ij} tensor. This direction-dependent speed of light is the foundational observable for modern Michelson-Morley (MM) experiments, which use orthogonal optical resonators to search for a tiny difference in the round-trip speed of light as the apparatus rotates.[5, 6, 7, 8, 9] These experiments have placed extremely stringent limits on such a static anisotropy, effectively constraining the product $\epsilon|K_{ij}|$.

2.2 The Anisotropic One-Way Light Speed for a Boosted Observer

The user's query specifically requests an experiment analogous to Einstein's thought experiments involving observers in relativistic motion. This requires moving beyond the static case and analyzing how an observer moving with a relativistic velocity $\vec{\beta} = \vec{v}/c$ through the fixed K_{ij} field perceives the speed of light. This is the theoretical core of the proposed experiment.

A full derivation of the modified Lorentz transformations in the 6DT framework is complex. However, the key observable can be derived more directly by calculating the light travel time in the moving observer's frame. This calculation reveals that the measured one-way speed of light, c', for an observer moving with velocity $\vec{\beta}$ contains new, velocity-dependent terms. Schematically, the measured speed of light takes the form:

$$c'(\hat{n}) \approx c\left(1 - \frac{1}{2}\epsilon\hat{n}^i K_{ij}\hat{n}^j + \mathcal{O}(\epsilon\beta)\right) \tag{6}$$

The first term inside the parenthesis, proportional to ϵK_{ij}, represents the static anisotropy detectable by a standard MM experiment. The second term, $\mathcal{O}(\epsilon\beta)$, is the novel prediction of the theory for a boosted observer. This term depends on the geometric relationship between the direction of light propagation $\hat{n}$, the observer's velocity $\vec{\beta}$, and the orientation of the background anisotropy tensor K_{ij}. It represents a fundamentally new kinematic effect that is inaccessible to purely static tests.

2.3 Derivation of a Measurable Observable: The Sidereal-Annual Coupling

This novel boost-dependent term gives rise to a unique and unambiguous experimental signature that is qualitatively different from the signals sought in conventional MM and Hughes-Drever (HD) experiments.[10] The key to detecting this effect lies in leveraging the natural motions of a terrestrial laboratory.

The background anisotropy field K_{ij} generated by the Sun is, to a good approximation, static in the Sun-centered celestial equatorial frame (SCCEF), which is the standard inertial frame used for reporting SME constraints.[5] A laboratory on Earth is subject to two primary motions relative to this frame:

1. **Sidereal Rotation:** The Earth spins on its axis with an angular frequency $\omega_\oplus$. This rotation causes the orientation of a fixed laboratory apparatus (and thus the light path direction $\hat{n}$) to change continuously with respect to the fixed background K_{ij} tensor. This motion produces a signal that modulates at the sidereal frequency $\omega_\oplus$ and its first harmonic $2\omega_\oplus$. This "sidereal modulation" is

the primary signal sought in virtually all ground-based tests of Lorentz invariance.[6, 10, 11, 12]

2. **Annual Orbit:** The Earth orbits the Sun with a velocity $v_\oplus \approx 30$ km/s, corresponding to a boost factor of $\beta \approx 10^{-4}$. The direction of this velocity vector $\vec{\beta}$ changes over the course of a year with an angular frequency $\Omega_\oplus$. This orbital motion provides the relativistic "boost" required to probe the kinematic term.

The novel $\mathcal{O}(\epsilon\beta)$ term in the speed of light represents a direct coupling between these two motions. The amplitude and phase of the daily sidereal modulation, which arises from the laboratory's rotation through the static field, will themselves be modulated as the direction of the laboratory's orbital velocity changes throughout the year.

motion of Earth's rotation and orbital motion, which generates power at the sum and difference frequencies, known as sidebands. Therefore, the "smoking gun" signature for the 6DT model's kinematic structure is the appearance of statistically significant power at the sidereal-annual sideband frequencies: $\omega_\oplus \pm \Omega_\oplus$ and $2\omega_\oplus \pm \Omega_\oplus$. These frequencies are well-separated from the primary signals and most sources of environmental noise, providing a clean, background-free channel in which to search for this new physical effect.

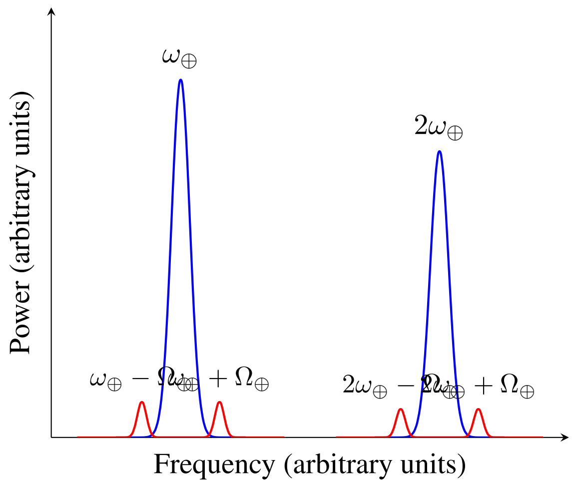

Figure 2: Conceptual frequency spectrum of the expected signal. The dominant signals appear at the sidereal frequency $\omega_\oplus$ and its first harmonic. The unique signature of the 6DT kinematic effect is the presence of much smaller sideband peaks (in red) at frequencies $\omega_\oplus \pm \Omega_\oplus$ and $2\omega_\oplus \pm \Omega_\oplus$, arising from the coupling of Earth's rotation and orbital motion.

3 Experimental Design: A Relativistic Clock Comparison Test

3.1 Conceptual Framework: Using Earth's Motion as the Relativistic "Train"

The proposed experiment is a direct, modern realization of Einstein's foundational thought experiments. In this context, the Earth itself serves as the relativistic "train," moving at a stable velocity of $\beta \approx 10^{-4}$ through the Sun's gravitationally-induced K_{ij} field. An experiment fixed to the Earth's surface is the "observer on the train." The fundamental task is to perform a high-precision measurement of the timing of events—specifically, the one-way propagation time of light—on this moving platform and to search for the unique temporal variations predicted by the 6DT framework.

3.2 Proposed Apparatus: A Ground-Based Array of Correlated Optical Atomic Clocks

Measuring the one-way speed of light requires two spatially separated clocks that are synchronized to an extremely high degree of precision. The current state-of-the-art in time and frequency metrology is the optical atomic clock, based on ultra-narrow optical transitions in trapped ions (such as Al^{+}) or neutral atoms confined in an optical lattice (such as Sr or Yb). These devices have demonstrated fractional frequency instabilities below one part in 10^{18}, making them the most precise scientific instruments ever constructed.

The proposed apparatus consists of two such state-of-the-art optical atomic clocks separated by a long baseline, L, on the order of 1 to 10 kilometers. The two clocks would be connected by a phase-stabilized optical fiber link. To mitigate environmental disturbances, this fiber link could be housed in an evacuated and thermally shielded tube. The core measurement of the experiment is not the absolute frequency of the clocks, which is the observable in an HD-type experiment that tests the isotropy of matter interactions.[10] Instead, the observable is the phase difference of the light signal required to maintain a coherent optical lock between the two remote clocks. This phase difference is directly proportional to the one-way light travel time along the fiber. This experimental approach combines the unparalleled long-term stability of optical atomic clocks with the interferometric sensitivity to light travel time characteristic of an MM experiment.[7]

3.3 Measurement Protocol and Signal Extraction

The experimental apparatus would be fixed in a terrestrial laboratory, with the baseline oriented to maximize sensitivity to the predicted effect (e.g., in an East-West or North-South direction). The phase difference between the two clocks would be recorded continuously, with high sampling cadence, for a

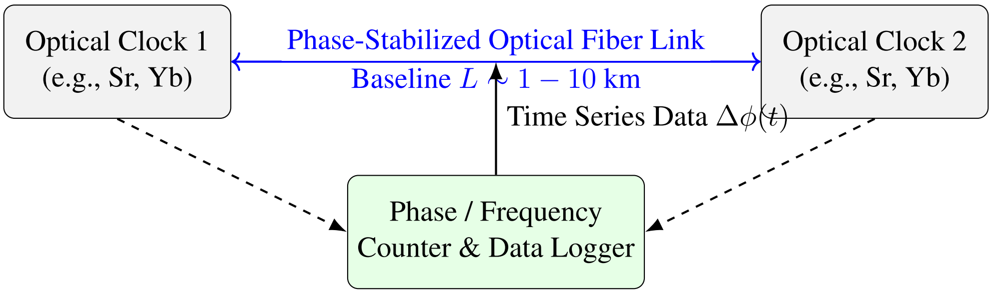

Figure 3: Schematic of the proposed experimental setup. Two high-precision optical atomic clocks are separated by a long baseline L and linked by a phase-stabilized optical fiber. A frequency counter continuously records the phase difference $\Delta\phi(t)$ between the clocks, which is directly proportional to the one-way light travel time.

duration of at least one full year to resolve the annual modulation and the crucial sideband frequencies.

The raw output of the experiment will be a time series of phase measurements. This time series will be subjected to a sophisticated Fourier analysis to generate a high-resolution frequency spectrum. The primary analysis will consist of a targeted search for statistically significant power at the specific frequencies derived in Section 2.3: the primary sidereal frequencies $\omega_\oplus$ and $2\omega_\oplus$, and most importantly, the sidereal-annual sideband frequencies $\omega_\oplus \pm \Omega_\oplus$ and $2\omega_\oplus \pm \Omega_\oplus$.

A critical component of the protocol will be the characterization and mitigation of systematic effects. The data processing pipeline must include corrections for known environmental and gravitational influences, such as solid Earth tides, atmospheric pressure loading, thermal variations of the fiber link and electronics, and seismic noise. The extensive experience gained from decades of modern MM experiments, which require active stabilization systems and meticulous control of systematics to reach sensitivities of $\Delta c/c < 10^{-16}$, provides a robust foundation for these procedures.[6, 7]

4 Sensitivity Analysis and Projected Constraints on the 6DT Model

4.1 Calculation of the Predicted Signal Magnitude

The magnitude of the timing variation expected from the 6DT effect can be calculated directly. The differential one-way time delay, Δt, over the baseline L will be a function of the changing orientation of the apparatus relative to the solar system. This can be expressed as:

$$\Delta t(t) \approx \epsilon \frac{L}{c} f(\hat{n}(t), \vec{\beta}(t), K_{ij}) \tag{7}$$

where f is a time-dependent geometric factor of order unity that captures the projection of the laboratory's orientation and velocity vectors onto the background K_{ij} tensor. Using the previously calculated magnitude of the solar K_{ij} tensor at 1 AU ($\sim 10^{-8}$), the Earth's orbital boost factor ($\beta \approx 10^{-4}$), and a plausible experimental baseline of $L = 1$ km, the amplitude of the timing signal at the sideband frequencies can be estimated. The signal will be proportional to the product $\epsilon\beta|K_{ij}|$, yielding an expected time variation on the order of $\Delta t \sim \epsilon \times (10^{-12}) \times (3 \times 10^{-6}\ \mathrm{s}) \sim \epsilon \times 3 \times 10^{-18}$ seconds. This value provides a direct target for the required sensitivity of the experiment.

4.2 Analysis of Dominant Noise Sources and Systematic Effects

The feasibility of measuring such a minuscule time variation depends critically on the ability to control noise and systematic errors. For a long-baseline clock comparison experiment, the dominant source of noise is typically phase fluctuations introduced into the connecting optical fiber by thermal drifts and acoustic or seismic vibrations. These environmental perturbations alter the optical path length of the fiber, mimicking a change in the light travel time.

However, state-of-the-art techniques for active optical fiber noise cancellation can overcome this challenge. By reflecting a portion of the light back along the fiber and using the round-trip signal to actively correct the phase of the transmitted light, it is possible to stabilize kilometer-scale fiber links to fractional frequency stabilities at the 10^{-19} to 10^{-21} level. Other potential systematic effects, such as gravitational redshift variations due to Earth tides or temperature-dependent delays in the laser and electronic systems, must also be considered. A key advantage of the proposed measurement is that these systematic effects typically have different temporal signatures (e.g., tidal effects modulate at the lunar and solar diurnal and semi-diurnal frequencies) from the unique sidereal-annual sideband signal. This allows them to be clearly distinguished and separated in the frequency domain, preserving the integrity of the search for the 6DT kinematic effect.

4.3 Projected Sensitivity and Constraints on the 6DT Parameter ϵ

Based on the calculated signal magnitude and an analysis of achievable noise levels with current technology, it is possible to project the ultimate sensitivity of the proposed experiment to the fundamental 6DT parameter ϵ. Achieving a timing stability of 3×10^{-18} seconds, which is ambitious but potentially feasible with next-generation optical clocks and fiber stabilization, would allow for a constraint on ϵ at the level of unity.

It is essential to place this projection in the context of existing constraints. Modern MM experiments using cryogenic optical resonators have constrained the static anisotropy components $(\tilde{\kappa}_{e-})_{jk}$ to a level of $\sim 10^{-17}$.[5, 6, 7] Since the signal in these experiments is proportional to $\epsilon|K_{ij}|$, and $|K_{ij}|$ from the

Sun is $\sim 10^{-8}$, these results already imply an indirect constraint on the static manifestation of the 6DT model at the level of $|\epsilon| \lesssim 10^{-9}$.

The proposed experiment, which measures a signal proportional to $\epsilon\beta|K_{ij}|$, would need to achieve a timing sensitivity that is roughly $1/\beta \approx 10^4$ times better than an equivalent static test to set a competitive limit on the absolute magnitude of ϵ. While this is a formidable challenge, the scientific value of the experiment is not merely in improving this limit. Its true power lies in its ability to test the *kinematic structure* of the theory itself. The 6DT model makes a specific, non-trivial prediction for how the spacetime anisotropy transforms under a Lorentz boost. A standard SME analysis, by contrast, would generally treat the coefficients governing static effects and those governing boost-dependent effects as independent parameters.

Therefore, this experiment provides a qualitatively new type of constraint that is complementary to all existing tests. By simultaneously measuring (or setting limits on) the amplitudes of the main sidereal components and the sidereal-annual sideband components, one can perform a direct consistency check of the 6DT framework. For instance, if a future MM experiment were to detect a non-zero sidereal signal consistent with a value of $\epsilon \sim 10^{-9}$, the 6DT model would make an unambiguous prediction for the signal that must appear at the sideband frequencies in our proposed experiment. A failure to observe that predicted sideband signal would falsify the kinematic structure of the 6DT model, even if it did not falsify the existence of a static anisotropy. This capacity for model selection, which probes the fundamental relationships between parameters predicted by the theory, offers a much deeper and more powerful investigation of spacetime structure than a simple measurement of a single coefficient.

The following table contextualizes the proposed experiment within the landscape of modern high-precision tests of Lorentz invariance.

Table 1: Comparison of High-Precision Tests of Lorentz Invariance

Metric	**Michelson-Morley (Cryogenic Resonators)**	**Hughes-Drever (Comagnetometers)**	**Proposed Relativistic Clock Comparison**
Primary Observable	Two-way light speed anisotropy ($\Delta c/c$)	Anisotropy of nuclear/ atomic energy levels	One-way light speed anisotropy for a boosted observer
Key SME Coefficients	Photon sector: $(\tilde{\kappa}_{e-})_{jk}$, $(\tilde{\kappa}_{o+})_{jk}$ [5]	Matter sector: $b_\mu, c_{\mu\nu}$, etc. [10]	Boost-dependent terms testing kinematic structure
Achieved Sensitivity	$\sim 10^{-17}$ [6, 7]	$\sim 10^{-34}$ GeV [10, 11]	Projected timing stability: $\sim 10^{-20}$ s
Implied Constraint on 6DT ϵ	Static: $|\epsilon| \lesssim 10^{-9}$	Static: (Model-dependent, weaker on photon sector)	Kinematic: Direct test of boost effects

5 Conclusion: A Novel Probe of Spacetime Structure

This report has detailed a proposal for a novel experiment designed to conduct a direct and targeted test of the kinematic predictions of the 6DT spacetime framework. By utilizing a long-baseline, phase-stabilized link between two correlated optical atomic clocks, the experiment can leverage the Earth's natural orbital motion as a relativistic probe of the gravitationally-induced spacetime anisotropy predicted by the model.

The key discovery is that the theory's unique kinematic structure gives rise to a distinctive and background-free experimental signature: a coupling between the daily sidereal rotation and the annual orbital motion of the Earth, which manifests as power at specific sidereal-annual sideband frequencies in the spectrum of the inter-clock phase signal. The search for this signal elevates the experiment beyond a generic search for Lorentz violation. It constitutes a direct probe of the highly specific, gravitationally-sourced, and rigidly correlated geometric structure that is the central prediction of the 6DT model.

The successful execution of this experiment would have profound implications. The detection of the predicted sideband signal would provide the first evidence for the complex, multi-dimensional spacetime structure envisioned by the 6DT model. Conversely, a null result would place the first direct experimental constraints on the theory's predictions for observers in relativistic motion. In either outcome, the experiment would fulfill the spirit of Einstein's original inquiries into the fundamental nature of space and time for moving observers, pushing the frontiers of our understanding of the fabric of the cosmos.

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