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PHASE-BASED INTERFEROMETRIC METHOD FOR PRECISE DISPLACEMENT ESTIMATION: THEORY AND COMPUTATIONAL POTENTIAL

Abstract. This paper presents the theoretical foundation and computational modeling of a novel phase-based interferometric method for precise displacement estimation in environmental monitoring applications. The method leverages the phase difference between two coherent radio signals transmitted over a wireless forward link, enabling sub-millimeter resolution without relying on reflected signals or embedded sensors. Unlike radar interferometry and distributed fiber optic systems, the proposed technique operates entirely in a forward-link architecture, making it more scalable, energy-efficient, and suitable for low-infrastructure deployments. Special attention is given to the computational procedures required for real-time signal interpretation, including instantaneous phase extraction using the Hilbert transform, phase unwrapping algorithms, and noise mitigation via digital filters. Simulation results confirm that the method is theoretically robust and computationally tractable, offering a practical path toward implementation using lightweight embedded platforms such as software-defined radios (SDRs) with GPS-disciplined oscillators. The results also demonstrate how design parameters such as carrier frequency and dual-tone spacing – affect the sensitivity and resolution of displacement estimates. This study lies at the intersection of applied computer science, signal processing, and geospatial engineering. It provides both a mathematical and algorithmic foundation for future systems aimed at distributed, real-time sensing in civil infrastructure and geohazard management.

Keywords: Wireless monitoring, signal processing, intelligent systems, phase-based interferometry, displacement monitoring, Hilbert transform.

1. Introduction

Accurate detection of small-scale ground or structural displacements is critical in applications such as landslide forecasting, infrastructure safety, and environmental monitoring. Traditional approaches rely on mechanical inclinometers, differential GPS, or optical surveying, which often suffer from limited spatial resolution, high costs, or low temporal granularity. These limitations motivate the development of lightweight, scalable, and computationally efficient alternatives.

Recent advancements in Distributed Fiber Optic Sensing (DFOS) have significantly expanded the applicability of fiber-based technologies in structural and geotechnical monitoring. The study [1] explored the potential application of fiber optic sensors in monitoring key-point displacements by leveraging their sensitivity to optical parameters and spectral changes. The results demonstrated that fiber optic sensors could accurately measure circumferential strain within the elastic range and reliably reflect key-point displacement trends through the linear relationship model. The survey [2] is a comprehensive collection of recently published research articles on Structural Health Monitoring (SHM) campaigns performed by means of Distributed Optical Fiber Sensors (DOFS). Authors show the large scale of using DOFS which are cutting-edge strain, temperature and vibration monitoring tools with a large potential pool, namely their minimal intrusiveness, accuracy, ease of deployment and more. Its most state-of-the-art feature, though, is the ability to perform measurements with very small spatial resolutions (as small as 0.63 mm). The review [3] highlights the latest progress in distributed optical fiber sensors with an emphasis on energy applications such as energy infrastructure monitoring, power generation system monitoring, oil and gas pipeline monitoring, and geothermal process monitoring. This review aims to clarify challenges and limitations of distributed optical fiber sensors with the goal of providing a pathway to push the limits in distributed optical fiber sensing for practical applications. Studies [4], [5] explore the possibilities of distributed fiber-optic sensors (DFOS) in the field of geotechnics for detecting soil deformation. The authors compare the results of the new inclinometer with a traditional inclinometer. The works show that the measurement results are consistent with the results of a traditional inclinometer, which indicates its reliability and practicality. The review [6] explores various sensor technologies in structural health monitoring (SHM), such as piezoelectric, fibre optic, force, MEMS devices, GPS, LVDT, electromechanical impedance techniques, Doppler effect, and piezoceramic sensors, focusing on advancements from 2019 to 2024. This study also shows increasing of articles from 15 in 2019 to 359 in 2023. Velocity sensors also play a crucial role in SHM by capturing the movement of structures and providing valuable data for predicting potential damage [7]-[9]. These sensors utilise two main sensing methods: electromechanical impedance techniques and the Doppler effect, each offering unique capabilities in measuring structural velocity. The paper [10] summarizes the use of GPS technology for structural health monitoring.

While InSAR and ground-based interferometric radar (GB-InSAR) have demonstrated sub-centimeter resolution through analysis of reflected signals [11]-[12], these systems rely on coherent backscattering from natural or artificial surfaces, which can be influenced by vegetation, weather, and line-of-sight constraints. In contrast, the method proposed in this study is fundamentally different: it does not rely on reflected signals. Instead, it utilizes the direct transmission of two closely spaced coherent signals from a fixed transmitter to a fixed receiver. The receiver performs phase-difference analysis to estimate relative displacement between the two endpoints. This enables continuous, low-power, and infrastructure-independent monitoring, even in environments where radar reflection is unreliable or unfeasible.

This paper focuses on laying the theoretical and computational groundwork for such a system. Rather than describing a specific hardware implementation, we develop the analytical model, examine its sensitivity, and explore algorithms necessary to convert raw phase data into actionable displacement information. In doing so, we establish a framework that merges physical modeling with digital signal processing – an essential step toward future embedded and intelligent monitoring systems.

2. Theory of phase-based sensing

Let a narrowband radio signal of wavelength λ be transmitted from a source to a receiver. If the distance $L(t)$) between them changes due to motion of the transmitter (e.g., ground sliding), the phase of the received signal will change accordingly:

$$\phi(t) = \frac{2\pi}{\lambda} \cdot L(t) \quad (1)$$

Taking the difference over time yields the displacement-sensitive expression:

$$\Delta L = \frac{\lambda}{2\pi} \cdot \Delta\phi \quad (2)$$

This relationship allows us to infer displacement from phase measurements alone, assuming the system maintains phase coherence. By transmitting two closely spaced frequencies f_1 and f_2, we obtain two phase trajectories $\phi_1(t)$, $\phi_2(t)$, and analyze their difference:

$$\Delta\phi(t) = \phi_2(t) - \phi_1(t) = \frac{2\pi \cdot \Delta f}{c} \cdot L(t) \quad (3)$$

where $\Delta f = f_2 - f_1$ is small and known, and c is the speed of light. This technique suppresses common-mode noise and enhances resolution through interferometric gain.

The effectiveness of phase-based displacement sensing strongly depends on three key parameters:

1. Carrier wavelength λ
2. Phase resolution $\delta\phi$ of the measurement system
3. Frequency stability of the system's oscillators

The minimum detectable displacement δL is determined from the phase-displacement relationship:

$$\delta L = \frac{\lambda}{2\pi} \cdot \delta\phi \quad (4)$$

While the physical basis of the method is straightforward, practical implementation requires robust signal processing techniques to extract displacement information from real-world phase measurements. Three key computational procedures are critical to the system's reliability:

1. Instantaneous Phase Extraction:

To retrieve the phase of the received signal in real time, the analytic representation of the signal is obtained using the Hilbert transform. Given a received time-domain signal $x(t)$, the complex analytic signal $z(t)$ is constructed as:

$$z(t) = x(t) + j \cdot \mathcal{H}\{x(t)\} \quad (5)$$

where $\mathcal{H}\{\cdot\}$ denotes the Hilbert transform. The instantaneous phase $\phi(t)$ is then computed as:

$$\phi(t) = arg(z(t)) \quad (6)$$

This approach allows for real-time demodulation of the carrier signal and precise tracking of phase evolution.

2. Phase Unwrapping:

Since phase is inherently modulo-2π, it is necessary to perform phase unwrapping to obtain a continuous phase trajectory over time. Numerical algorithms are applied to detect discontinuities greater than π and correct them by adding or subtracting 2π accordingly.

3. Error Mitigation Under Noise:

In practical environments, phase measurements are affected by thermal noise, multipath interference, and oscillator jitter. To mitigate these effects:

- Averaging and smoothing filters (e.g., moving average, Kalman filters) are applied to suppress high-frequency noise;
- Differential phase analysis between dual-frequency signals is used to cancel common-mode phase drift;
- Thresholding and signal quality estimation are used to discard outlier measurements.

These computational techniques are lightweight and well-suited for real-time implementation on embedded systems, such as microcontrollers or FPGA-equipped SDR platforms.

3. Results

Let us consider a signal frequency f=433 MHz, which corresponds to:

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^8\, m/s}{433 \cdot 10^6 Hz} \approx 0.692 \text{ m}$$

If the receiver can resolve a phase difference of 1° (i.e., $\delta\phi$=π/180), then:

$$\delta L \approx \frac{0.692}{2\pi} \cdot \frac{\pi}{180} \approx 0.61 \text{ mm}$$

With more advanced DSP (e.g., Hilbert transform + filtering), systems can achieve sub-degree phase resolution, making it possible to detect displacements on the order of 0.1 mm or better.

If we use two coherent signals with a small frequency separation Δf, the phase difference between them increases linearly with distance:

$$\Delta\phi(t) = \frac{2\pi \cdot \Delta f}{c} \cdot L(t) \quad (7)$$

Taking derivative over time:

$$\frac{dL}{dt} = \frac{c}{2\pi \cdot \Delta f} \cdot \frac{d(\Delta\phi)}{dt} \quad (8)$$

This magnifies displacement changes into faster phase dynamics – effectively amplifying sensitivity.

To validate the theoretical framework proposed in this study, we present a series of simulated results that illustrate the key functional relationships between phase variation and physical displacement. These results demonstrate the high sensitivity and analytical predictability of the phase-based sensing method under realistic conditions. The Figure 1 illustrates the linear relationship between phase difference (in degrees) and the corresponding displacement (in millimeters). The result confirms the core equation $\Delta L = \frac{\lambda}{2\pi} \cdot \Delta\phi$, where small phase shifts directly correlate with measurable displacement. The wavelength corresponds to 433 MHz ($\lambda \approx 0.692$ m), and results are shown for phase shifts ranging from 0° to 180°.

Figure 2 illustrates the evolution of instantaneous phase over time under a condition of uniform ground motion (constant velocity of 0.5 mm/s). As expected, the phase increases linearly, confirming that the proposed method can track displacement in real time through continuous phase accumulation.

To analyze how operating frequency influences system performance, Figure 3 presents the dependency of displacement sensitivity (in mm per degree of phase shift) on the carrier frequency. The trend reveals that lower frequencies provide greater displacement sensitivity, supporting the selection of UHF bands for high-resolution sensing.

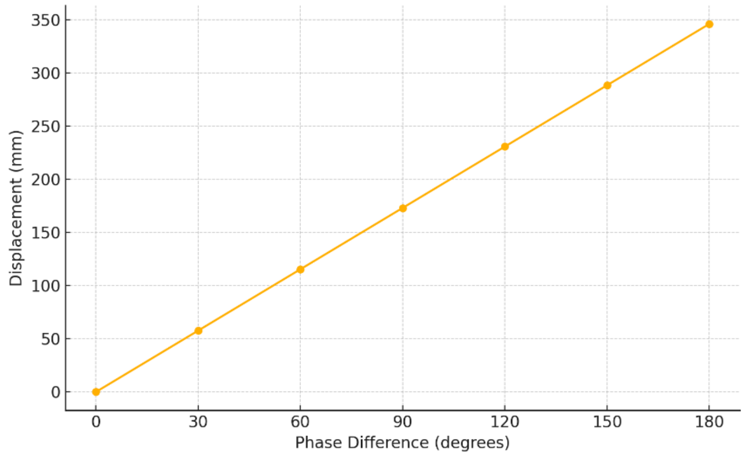

Figure 1 – Linear dependence of displacement on phase difference at 433 MHz.

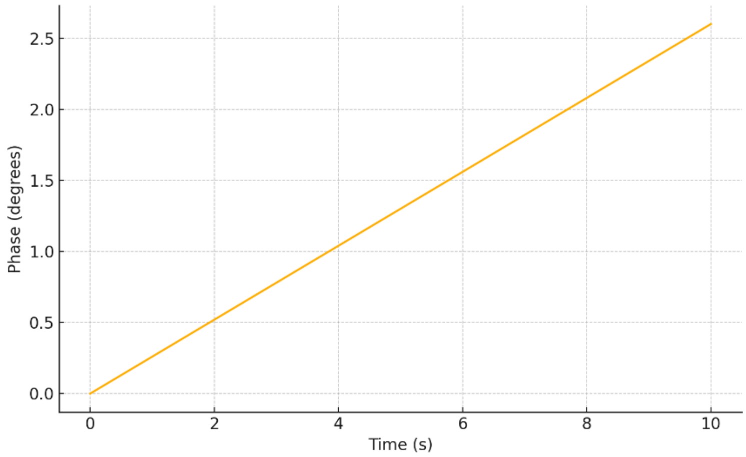

Figure 2 – Temporal evolution of phase in response to uniform displacement.

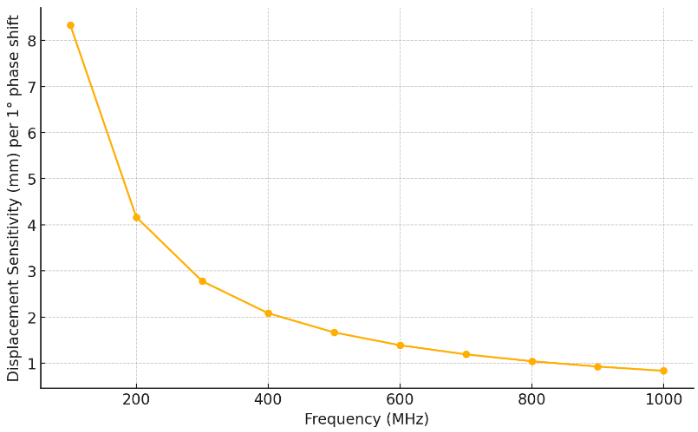

Figure 3 – Influence of carrier frequency on displacement sensitivity.

Finally, Figure 4 simulates the dual-frequency approach, where the phase difference between two closely spaced coherent signals (433 MHz and 434 MHz) is monitored over time during uniform displacement. The linearly increasing phase separation illustrates the enhanced resolution afforded by interferometric phase amplification, making this technique particularly robust in low-SNR or noisy environments.

Together, these simulation results demonstrate the feasibility, responsiveness, and computational tractability of the proposed phase-based method for precision displacement estimation in wireless settings. In the following discussion, we explore how these results compare to other displacement sensing technologies and outline the potential for embedded implementations using low-power SDR platforms.

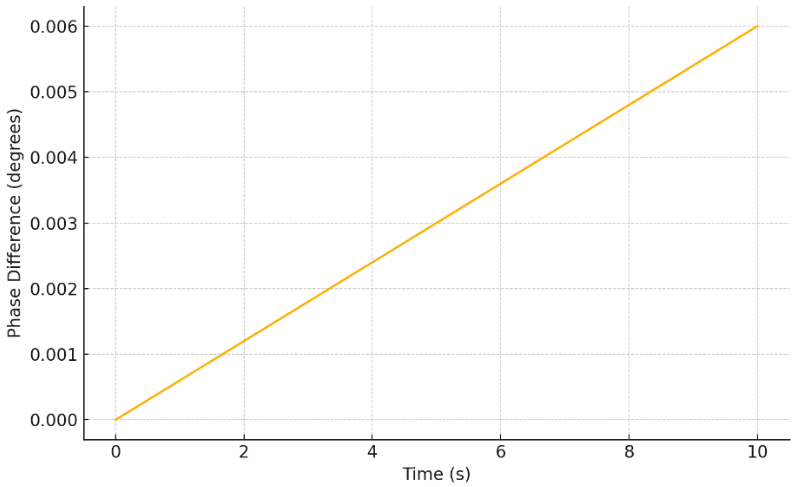

Figure 4 – Accumulation of dual-frequency phase difference during uniform motion.

4. Discussion

The results presented in the previous section confirm that phase-based interferometric sensing offers a theoretically grounded and computationally tractable method for precise displacement monitoring. In this section, we compare this approach with other commonly used geotechnical and structural monitoring techniques, while outlining its practical implications and unique advantages.

Comparison with Existing Technologies.

Distributed Fiber Optic Sensing (DFOS) technologies are widely regarded for their high spatial resolution and immunity to electromagnetic interference [1]-[5], [13]. However, their dependence on continuous optical fiber infrastructure imposes high installation costs and maintenance complexity, especially in remote or inaccessible terrains. Differential GPS (DGPS), on the other hand, provides centimeter-level accuracy [6], [14], [15], but suffers from performance degradation in environments with obstructed satellite visibility and typically requires expensive base station infrastructure. Mechanical inclinometers, while cost-effective and easy to deploy [16], lack real-time capabilities and are limited in resolution, especially for detecting slow or micro-scale deformations.

Novelty of the Proposed Method.

Unlike radar interferometry and DFOS, which rely on backscattered or embedded signals, the proposed method does not require any reflected wave or physical contact with the monitored medium. Instead, it utilizes a wireless forward-link between a transmitter and receiver, with displacement inferred solely from changes in phase difference. This makes the system inherently non-intrusive, infrastructure-light, and more deployable in challenging environments such as mountainous slopes, rural infrastructure, or temporary installations.

Computational and Energy Efficiency.

The method benefits from its low computational overhead: phase difference extraction can be performed in real time using signal demodulation and Hilbert transform techniques. Moreover, because the system can operate in a duty-cycled mode (e.g., one-minute transmission every five minutes), it is compatible with energy-autonomous deployments powered by compact solar panels or batteries. The use of GPS-disciplined oscillators (GPSDO) ensures that phase coherence is maintained across sessions, even in low-power states.

***Limitations and Future Directions*.**

Despite its promise, the method does face certain limitations. The range is constrained by the power of the transmitter and antenna design, typically below 2 km in line-of-sight conditions without amplification. Environmental noise and multipath effects may require careful site-specific calibration and filtering. Future work should focus on multi-node configurations, real-time signal quality assessment, and adaptive algorithms to compensate for noise-induced phase anomalies.

Overall, the phase-based displacement sensing method proposed here provides a compelling alternative to existing technologies, particularly for use in distributed, low-cost, and real-time monitoring systems. It complements – not replaces – other methods, and is especially suited for lightweight deployments where traditional infrastructure is unavailable or impractical.

5. Conclusions

This study has presented a theoretical and computational framework for a novel phase-based interferometric method for displacement sensing. Unlike conventional techniques such as radar interferometry, differential GPS, or distributed fiber optic sensing, the proposed approach does not rely on reflected signals or physical embedding of sensors. Instead, it leverages the phase difference between two coherent radio signals transmitted through a wireless forward link, with displacement estimated based on analytical relationships between phase and path length.

Through a series of simulations, we have demonstrated the method's sensitivity, resolution, and scalability. The results confirm that sub-millimeter displacement can be detected using modest hardware configurations operating in the UHF band. Additionally, computational procedures such as instantaneous phase extraction and phase difference analysis can be executed in real time, making the system suitable for embedded and low-power applications.

The proposed method complements existing displacement monitoring technologies by offering a cost-effective, lightweight, and scalable solution for geohazard detection, structural health monitoring, and remote sensing scenarios. Its low energy footprint and wireless nature make it particularly attractive for deployment in difficult-to-access locations where conventional technologies are impractical.

Future work will focus on prototyping, real-world validation, and the development of a software-defined radio (SDR) implementation for field experiments. Moreover, expanding the system into a multi-node sensing network may open new possibilities for spatially distributed interferometric sensing in environmental and civil monitoring contexts.

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Conflicts of Interest

The author declares no conflict of interest.

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