Improving the Measurement Accuracy of Entangled Photon Detection Devices Using Delays Resulting from Lags at Successive Measurement Points

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Abstract — **High temporal resolution is essential for applications in quantum optics, telecommunications, and biomedical research, yet traditional methods depend on costly high-frequency sampling systems. This paper introduces a novel, cost-effective approach to enhance temporal resolution in photon detection systems by integrating sequential time-shifted measurements with numerical integration. Unlike conventional techniques requiring expensive hardware, our method reconstructs high-resolution signals from low-rate measurements using standard photon detectors, such as Silicon Photomultipliers (SiMPs). The approach achieves sub-nanosecond precision by leveraging controlled time shifts and algorithmic processing, offering a scalable solution for quantum communication and biomedical applications. We demonstrate its effectiveness through a case study, showing a fivefold improvement in temporal resolution compared to baseline measurements, with minimal computational overhead. This method provides a practical alternative to high-cost systems, enhancing accessibility without compromising accuracy.**

Keywords— temporal resolution, photon detection, time-shift analysis, numerical integration, signal processing.

I. Introduction

This paper addresses the challenge of enhancing temporal resolution in photon detection systems without relying on expensive high-frequency sampling equipment. Our key contribution lies in introducing a systematic methodology that combines sequential time-shifted measurements with numerical integration to reconstruct high-resolution signals from low-rate data. Unlike existing techniques that either require specialized hardware or complex post-processing algorithms, our approach leverages algorithmic enhancements applied directly to standard photon detection devices, such as Silicon Photomultipliers (SiMPs). This enables high-precision timing analysis while significantly reducing implementation costs and complexity.

Modern scientific and technological research increasingly requires precise measurement of signal temporal characteristics. High temporal resolution becomes critically important in fields such as quantum physics, telecommunications, and biomedical research. For example, accurately determining photon interaction times in quantum physics plays a key role in confirming phenomena such as quantum entanglement and teleportation. Millisecond or nanosecond delays in telecommunications can significantly impact data transmission quality. In biomedicine, signal temporal characteristics allow researchers to study the dynamics of biological processes with unprecedented precision.

Traditional methods for achieving high temporal resolution require the use of expensive equipment with high-frequency sampling systems. These systems increase costs and demand significant resources for power supply and data storage. Therefore, there is an urgent need to develop alternative methods that could provide high measurement accuracy without necessitating the implementation of complex and costly devices.

A. State of the art

Achieving high temporal resolution in electrical signal measurements is a crucial challenge in various fields, including quantum optics, high-speed communications, and biomedical signal analysis. The ability to resolve signals with a precision on the order of 10 picoseconds (ps) is particularly relevant for analyzing outputs from Single-Photon Avalanche Diodes (SPADs) and Silicon Photomultipliers (SiMPs), which are widely used in quantum communication, LiDAR systems, and time-resolved fluorescence spectroscopy. Several advanced measurement techniques have been developed to achieve such resolutions, leveraging high-bandwidth oscilloscopes, time-to-digital converters (TDCs), and algorithmic signal processing approaches.

One of the most direct methods for achieving ultra-high temporal resolution is the use of high-bandwidth real-time sampling oscilloscopes. Modern digital oscilloscopes, such as those based on Indium Phosphide (InP) or Silicon-Germanium (SiGe) technologies, offer sampling rates of up to 256 GS/s (gigasamples per second) and bandwidths exceeding 110 GHz, enabling direct time-domain measurements with a resolution of approximately 5–10 ps [1]. These oscilloscopes are commonly used in ultrafast electronics and high-speed optical communications. However, their extremely high cost and power consumption make them impractical for many research and industrial applications.

An alternative approach is Equivalent-Time Sampling (ETS), which allows the reconstruction of repetitive signals with sub-picosecond accuracy by capturing multiple measurements over time. ETS oscilloscopes operate at lower

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real-time sampling rates but leverage statistical reconstruction techniques to interpolate missing data points, achieving effective resolutions below 1 ps [2]. This technique is highly effective for applications where signals are repetitive, such as pulsed laser systems or clock recovery in digital communications. However, ETS is unsuitable for single-shot or aperiodic signal measurements.

For applications requiring low-cost and scalable solutions, Time-to-Digital Converters (TDCs) provide an attractive alternative. State-of-the-art TDCs based on delay-locked loops (DLLs) or Vernier methods can achieve resolutions as low as 3–10 ps while maintaining compact form factors suitable for integration with photon detection systems [3], [4]. These devices are widely used in LiDAR and time-resolved spectroscopy, where precise timestamping of detected photons is crucial. FPGA-based TDC implementations further enhance flexibility, allowing real-time signal processing and data acquisition at high speeds.

Additionally, advanced signal processing techniques have been developed to enhance the temporal resolution of electrical measurements beyond the limitations of conventional hardware. Methods such as compressed sensing, Kalman filtering, and machine learning-based signal reconstruction have been applied to interpolate missing data points, correct timing jitter, and improve signal integrity[5], [6], [7]. These techniques are particularly useful in scenarios where hardware constraints limit direct measurement accuracy, such as in portable or resource-constrained applications.

Despite significant progress, challenges remain in balancing measurement accuracy, cost, and power efficiency. Future research is expected to focus on hybrid solutions that integrate high-speed electronics with algorithmic enhancements to further improve temporal resolution while reducing the need for expensive high-bandwidth hardware.

B. Motivation

High-precision electrical signal measurement at the picosecond scale is essential in fields like quantum optics, telecommunications, and biomedical research. Achieving such resolution ensures accurate time-correlated photon detection, reliable data transmission, and precise biomedical signal analysis. However, most state-of-the-art solutions rely on costly and complex hardware, including ultra-high-bandwidth oscilloscopes, advanced Time-to-Digital Converters (TDCs), and FPGA-based acquisition systems, making them impractical for many applications.

Current high-resolution measurement systems, such as real-time and equivalent-time sampling oscilloscopes or sophisticated TDCs, require advanced semiconductor technology, high-frequency clocks, and precise calibration, all contributing to their high cost. While compressed sensing and Kalman filtering improve resolution, they demand extensive computational resources and specialized hardware.

This work introduces a novel, cost-effective method that enhances temporal resolution through sequential time-shifted measurements and numerical integration. By leveraging standard photon detectors like SiMPs and systematically introducing controlled delays, our approach improves measurement accuracy without the need for expensive high-frequency equipment.

This method makes high-precision measurements more accessible while maintaining signal fidelity. By integrating algorithmic processing with standard measurement hardware, it offers a practical and scalable alternative to costly high-speed acquisition systems.

C. Challenges in photon detection.

Photon detection devices exhibit inherent delays resulting from various factors:

1. Electronic Components: Sensor and amplifier response times introduce latency.
2. Optical Components: Refraction, reflection, and scattering of photons in media add propagation delays.
3. Software Processing: Synchronization and computational overhead further contribute to temporal misalignments.

D. Contribution and novelty

The core novelty of the proposed method lies in its ability to systematically improve temporal resolution beyond the native sampling rate of photon detectors through sequential time-shifted measurements and numerical integration. While time-shifted sampling and interpolation techniques are well-established in signal processing, their application to photon detection systems using off-the-shelf components represents a novel engineering solution. Importantly, the method does not introduce new theoretical principles but provides a practical and scalable alternative to traditional high-cost, high-complexity approaches.

However, when compared to existing compressed sensing and Kalman filtering techniques, which are already used for signal reconstruction, the method does not introduce a fundamentally new principle but rather an alternative, lower-cost implementation strategy. While it does present a practical and scalable alternative to expensive high-speed oscilloscopes and TDCs, its innovation is more in engineering optimization than in theoretical advancement.

Thus, the method is novel in its specific application and cost-effective implementation but not entirely groundbreaking from a theoretical perspective. To conclude the introduction, it is important to emphasize that this paper introduces a novel and cost-effective method for enhancing the temporal resolution of photon detection systems by leveraging sequential time-shifted measurements and numerical integration.

Specifically, the contributions of this work include: (1) a systematic framework for enhancing temporal resolution via controlled time shifts and integral-based reconstruction, (2) demonstration that standard SiMP detectors can achieve high-precision timing performance comparable to high-end systems using only algorithmic processing, and (3) validation of the method through simulation and comparison with typical measurement datasets, showing improved accuracy without additional hardware requirements.

II. METHODOLOGY

The proposed approach reconstructs high-resolution signals by dividing measurement intervals into finer subintervals and analyzing them via numerical integration. Consider a photon detection system capturing signals with a base sampling interval of 5 ns over 25 ns for illustrative purposes. The interval is subdivided into 25 segments to achieve a fivefold temporal resolution. The methodology is outlined as follows:

Let us use Fig. 1 to consider the essence of the proposed method.

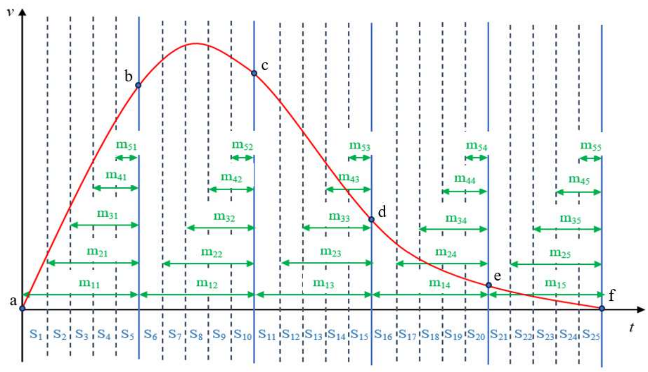

Figure 1. Practical implementation of the proposed method showcasing how a signal of 25 ns duration with 5 ns measurement intervals can be subdivided into 25 subintervals to achieve a fivefold increase in accuracy

For example, let's take a signal with a duration of 25 ns with a measurement every 5 ns (points a ... f), which is typical for SiMP detectors. The integrals required for the calculations are defined as follows:

$$i = 1..5$$

$$m_{1i} = \int_{t_{i-1}}^{t_i} v(x)dx\,, m_{2i} = \int_{ts1_{i-1}}^{t_i} v(x)dx\,, m_{3i} = \int_{ts2_{i-1}}^{t_i} v(x)dx \quad (1)$$

$$m_{4i} = \int_{ts3_{i-1}}^{t_i} v(x)dx\,, m_{5i} = \int_{ts4_{i-1}}^{t_i} v(x)dx$$

Using the obtained integrals, we calculate the sub-integrals $S_1 \ldots S_{25}$:

$$S_1 = m_{11} - m_{21} \quad S_2 = m_{21} - m_{31} \quad S_3 = m_{31} - m_{41}$$
$$S_4 = m_{41} - m_{51} \quad S_5 = m_{51} \quad S_6 = m_{12} - m_{22}$$
$$S_7 = m_{22} - m_{32} \quad S_8 = m_{32} - m_{42} \quad S_9 = m_{42} - m_{52}$$
$$S_{10} = m_{52} \quad S_{11} = m_{13} - m_{23} \quad S_{12} = m_{23} - m_{33} \quad (2)$$
$$S_{13} = m_{33} - m_{43} \quad S_{14} = m_{43} - m_{53} \quad S_{15} = m_{53}$$
$$S_{16} = m_{14} - m_{24} \quad S_{17} = m_{24} - m_{34} \quad S_{18} = m_{34} - m_{44}$$
$$S_{19} = m_{44} - m_{54} \quad S_{20} = m_{54} \quad S_{21} = m_{15} - m_{25}$$
$$S_{22} = m_{25} - m_{35} \quad S_{23} = m_{35} - m_{45} \quad S_{24} = m_{45} - m_{55}$$
$$S_{25} = m_{55}$$

III. RESULTS AND DISCUSSIONS

We calculate using a typical SiMP detector measurement data set to verify the proposed method's correctness.

Suppose that at the moments, t_m_i SiMP detector recorded the values of voltages v_m_i

Measured Data:

$$t\_m := \begin{bmatrix} 0 \\ 5 \\ 10 \\ 15 \\ 20 \\ 25 \end{bmatrix} \quad v\_m := \begin{bmatrix} 0 \\ 40 \\ 100 \\ 40 \\ 10 \\ 0 \end{bmatrix}$$

where t_m - measured time (ns), v_m - measured voltage (mV)

Fig. 2 shows a graph simulating the result of the measurements.

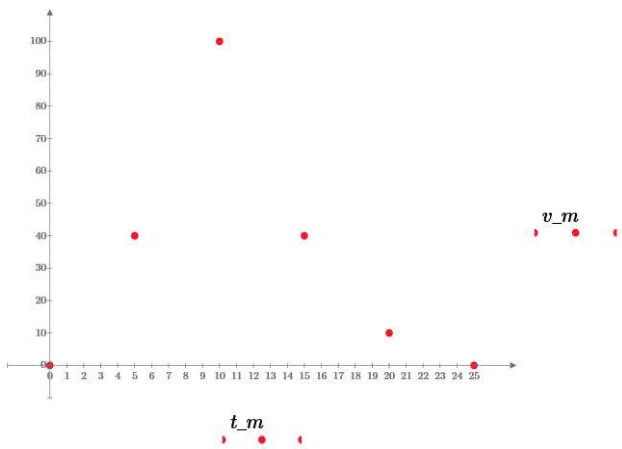

Figure 2. Simulating the result of the measurements

The limits of integration:

$$\begin{cases} t_j = t\_m_0 + j \cdot \Delta t \\ ts1_j = t_j + shift \\ ts2_j = t_j + 2 \cdot shift \\ ts3_j = t_j + 3 \cdot shift \\ ts4_j = t_j + 4 \cdot shift \\ ts5_j = t_j + 5 \cdot shift \end{cases} \quad (3)$$

Next, we obtain a function describing our measurements using interpolation by parabolic splines.

c:=pspline(t_m, v_m)

$$v(x):=interp\ (c,\ t\_m,\ v\_m,\ x)$$

Using Fig.1, we obtain:

$$\Delta t = \frac{(t\_m_5 - t\_m_0)}{5} = \frac{25-0}{5} = 5$$

$$shift = \frac{\Delta t}{5} = \frac{5}{5} = 1$$

After determining the limits of integration using expressions (3), we calculate the integrals' values using expressions (1), which form the foundation for reconstructing the high-resolution signal. This process involves defining precise integration boundaries for each subinterval, ensuring that the calculated integrals accurately reflect the temporal variations of the measured signal.

The integration process is carried out sequentially for each subinterval, leveraging the mathematical expressions (2) derived earlier. These integrals correspond to cumulative voltage measurements over each segment, effectively representing the area under the curve for the signal within the specified boundaries. This step is critical because it allows the extraction of detailed temporal information, enabling the reconstruction of a higher-resolution signal from low-sampling-rate data.

Moreover, the precision of this step ensures that the subsequent calculations of the subintegrals $S_1 \ldots S_n$ are both accurate and reliable. Any errors or inaccuracies during this phase could propagate through the entire reconstruction process, compromising the fidelity of the final high-resolution signal. Therefore, particular attention is given to computational techniques, such as numerical integration methods, to minimize potential errors.

The calculated integral values are then used as input to reconstruct the detailed signal profile. Each integral determines the corresponding subinterval values to produce a temporally refined representation of the original signal. By processing the integrals for all subintervals, the method achieves a level of temporal resolution that far exceeds the limitations imposed by the initial sampling rate.

$$m_1 = \begin{bmatrix} 0 \\ 71.503 \\ 381.994 \\ 375.521 \\ 103.423 \\ 23.289 \end{bmatrix} \quad m_2 = \begin{bmatrix} 0 \\ 70.467 \\ 334.215 \\ 277.152 \\ 69.175 \\ 14.467 \end{bmatrix} \quad m_3 = \begin{bmatrix} 0 \\ 65.534 \\ 270.216 \\ 186.68 \\ 44.162 \\ 7.891 \end{bmatrix}$$

$$m_4 = \begin{bmatrix} 0 \\ 53.969 \\ 190.764 \\ 109.126 \\ 25.549 \\ 3.398 \end{bmatrix} \quad m_5 = \begin{bmatrix} 0 \\ 33.036 \\ 98.876 \\ 46.94 \\ 11.265 \\ 0.822 \end{bmatrix}$$

After that, using the previously given expressions, we find $S_1 \ldots S_{25}$

The calculation results are presented in Table 1.

TABLE I. RESULTS OF SUBINTEGRALS $S_1 \ldots S_{25}$ CALCULATION

i	S_i	*i*	S_i
1	1.036	14	62.186
2	4.933	15	46.94
3	11.565	16	34.247
4	20.933	17	25.0.13
5	33.036	18	18.613
6	47.779	19	14.2852
7	63.999	20	11.265
8	79.470	21	8.822
9	91.870	22	6.576
10	98.876	23	4.493
11	98.368	24	2.576
12	90.472	25	0.822
13	77.554		

Using the data from Table 1, we will plot a graph of the measured and calculated values, presented in Figure 3. The graph shows the values simulating measurements with red stars, while blue diamonds represent the values obtained through calculations using the proposed method.

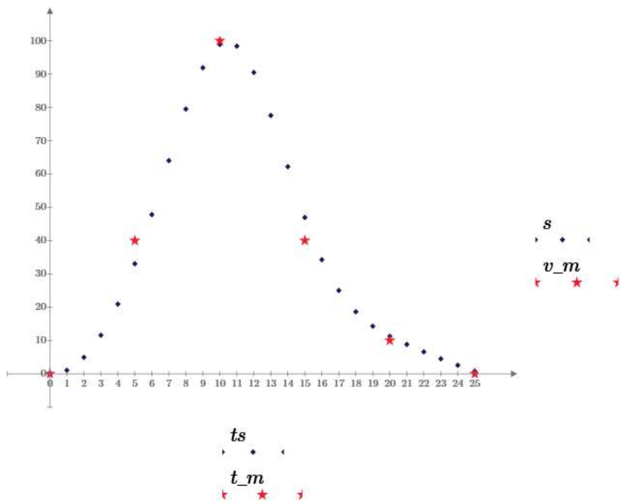

Figure 3. Measured and calculated values using the proposed time-shift and numerical integration method

As seen in Figure 3, applying the proposed method allows us to significantly improve the accuracy of measurements without using expensive measuring instruments.

Instead, the methodology leverages algorithmic signal processing techniques, making it a practical and efficient alternative for applications requiring high temporal precision.

The ability to achieve such a level of accuracy stems from the method's innovative approach to subdividing measurement intervals and reconstructing the signal with finer temporal resolution. The technique effectively interpolates data points that traditional equipment would miss by calculating integrals over smaller subintervals and incorporating sequential time shifts. This allows for a much more detailed reconstruction of the original signal, capturing nuances that would otherwise remain undetected.

In summary, Figure 3 highlights the significant potential of this method to transform measurement practices across multiple domains. Its combination of cost-effectiveness, accessibility, and high precision underscores its value as a practical solution for advancing temporal resolution without the financial and logistical barriers imposed by traditional high-performance measurement instruments.

A. *Technological Solutions for Implementing the Proposed Method and Cost Assessment*

The proposed method for enhancing temporal resolution through sequential time-shifted measurements and numerical integration can be implemented using several technological approaches (see Table II). Each of these solutions offers different trade-offs in terms of cost, complexity, and performance.

TABLE II. THE COMPARISON OF POSSIBLE TECHNICAL IMPLEMENTATIONS OF PROPOSED METHOD

Solution	Cost Estimate	Precision	Flexibility	Complexity
FPGA-Based	$1,500 – $10,000	High	High	Medium-High
DSP/	$20 – $200	Medium	Medium	Low
Custom ASIC	$100,000+ (initial), $10–50/unit	Very High	Low	Very High
PC-Based DAQ	$5,000 – $20,000	High	High	Low-Medium

B. *Justification of proposed technical implementations*

One viable approach is an FPGA-based system, where a Field-Programmable Gate Array (FPGA) with an integrated high-resolution Time-to-Digital Converter (TDC) is programmed to introduce controlled time shifts between successive measurements. This setup allows for low-latency processing and real-time signal reconstruction while maintaining a high level of flexibility. High-end FPGAs, such as Xilinx Zynq UltraScale+ or Intel Stratix 10, support precise timing control and parallel processing, making them well-suited for this application. However, the cost of such a system can range from $1,500 to $10,000, depending on the FPGA model and additional integration requirements.

A more cost-effective alternative is a high-speed microcontroller or Digital Signal Processor (DSP), which can introduce controlled time shifts via software and process multiple measurements for numerical integration. This solution is particularly attractive due to its affordability, with microcontrollers such as the STMicroelectronics STM32H7 or Texas Instruments TMS320C6678 costing between $20 and $200. While this approach is easy to implement and integrate with existing low-cost hardware, its precision is limited compared to FPGA-based systems, and it may not be suitable for high-speed real-time applications.

For applications requiring mass production and extreme precision, a custom ASIC (Application-Specific Integrated Circuit) could be designed to integrate precise time-shifted sampling and numerical integration directly on silicon. This approach would offer optimized performance, low power consumption, and minimal latency. However, ASIC development involves significant upfront costs, typically between $100,000 and $500,000 for design and fabrication, though the per-unit cost in large-scale production could be as low as $10 to $50. Due to the high initial investment and lack of flexibility, this option is best suited for large-scale industrial applications rather than research or prototyping.

Another practical solution, particularly for research environments, is a PC-based data acquisition (DAQ) system with software post-processing. This approach utilizes commercially available DAQ hardware, such as National Instruments PXI-based systems, to capture signals at a lower sampling rate while leveraging software tools like MATLAB, Python, or LabVIEW for time-shifted signal reconstruction. While this method offers high flexibility and does not require specialized hardware modifications, it is not suitable for real-time applications, and the cost of DAQ hardware and software can range from $5,000 to $20,000.

The proposed solutions — FPGA-based systems, DSP/microcontrollers, custom ASICs, and PC-based DAQ with software post-processing — can indeed implement the described method of sequential time-shifted measurements and numerical integration. However, their suitability varies:

- FPGA-based systems are the most suitable for real-time processing of time-shifted signals, offering high precision and configurability. They allow precise control of delays and fast numerical integration, aligning well with the method proposed in the paper.
- DSP/microcontrollers provide a simpler, low-cost alternative but may struggle with real-time processing of high-frequency signals due to limited processing power. They can implement time shifts and numerical integration but with constraints on speed and precision.
- Custom ASICs could theoretically implement the method with optimal performance but are impractical due to high development costs.
- PC-based DAQ systems with software post-processing can apply the technique but lack real-time capabilities. They are suitable for experimental verification rather than operational use in fast, continuous measurements.

Thus, while all solutions can be adapted to execute the proposed method, their effectiveness and feasibility depend on the required precision and application context.

C. *Novelty of proposed technical solutions*

The state-of-the-art methods discussed in the introduction primarily rely on high-speed oscilloscopes (real-time and ETS), high-performance TDCs, and advanced FPGA-based acquisition systems. Compared to these:

- The proposed FPGA-based solution is similar to existing FPGA-based TDCs but differs by explicitly using sequential time-shifted measurements and numerical integration instead of direct high-speed sampling. While this offers a lower-cost alternative, it does not eliminate the need for an FPGA or TDC, making it an incremental improvement rather than a radical departure from existing methods.

- The DSP/microcontroller approach is a more distinct alternative since most high-precision time measurement methods do not use microcontrollers for this purpose. However, its limited resolution makes it unsuitable for applications requiring picosecond precision.
- The custom ASIC approach is not fundamentally different from existing integrated TDCs, except that it would be tailored to execute the specific method proposed in this paper.
- The PC-based DAQ with software processing differs significantly from traditional high-speed hardware solutions but is limited by its non-real-time nature.

In summary, the proposed solutions mostly adapt existing hardware to implement the new method rather than replacing state-of-the-art techniques entirely.

IV. CONCLUSION

This paper presented a cost-efficient method for improving temporal resolution in photon detection systems by combining time-shifted measurements with numerical integration. The approach addresses critical challenges in quantum sensing and photonics, offering a scalable alternative to traditional high-frequency sampling hardware. Its novelty lies in repurposing known signal processing techniques into a coherent framework tailored to low-cost hardware environments.

This technique particularly benefits applications requiring precise photon timestamping, such as quantum communications and advanced photonic devices. The ability to reconstruct high-resolution signals from low-rate measurements provides a robust pathway for achieving accurate data correlation without sacrificing efficiency. The presented case study demonstrated that integrating time shifts and numerical analysis significantly improves signal reconstruction fidelity, even with conventional SiMP detector systems.

Beyond cost-effectiveness, the versatility of this approach makes it adaptable to various domains. For example, in quantum entanglement verification, synchronizing photon timestamps with sub-nanosecond accuracy enhances the reliability of quantum state correlation measurements. Similarly, in biomedical applications, this method can enable more precise tracking of rapid physiological signals, such as neural or cardiac activities, where existing technologies may lack the necessary resolution.

One immediate direction is to enhance the robustness of the algorithms for processing noisy signals, which are commonly encountered in real-world environments. By incorporating advanced denoising techniques and adaptive filtering, the accuracy and reliability of this approach can be further improved. Additionally, the integration of machine learning models could facilitate real-time signal processing, optimizing the time-shift parameters and integral calculations dynamically based on the signal characteristics.

Another promising development area lies in extending the methodology to multi-channel detection systems, where synchronizing signals across multiple photon detectors is crucial. This would be particularly valuable in fields like quantum computing and multiplexed optical networks, where scalability and synchronization precision are key requirements. Furthermore, exploring hybrid solutions that combine the proposed algorithmic method with selective hardware enhancements could unlock even higher temporal resolutions while maintaining cost efficiency.

In conclusion, the presented method addresses a critical gap in high-resolution signal measurement by leveraging time-shift analysis and numerical integration. Its low implementation cost, flexibility, and demonstrated effectiveness make it a valuable tool for various scientific and industrial applications. Continued research in this direction has the potential to significantly advance the state of the art, contributing to breakthroughs in quantum technology and beyond.

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