Department of Electrical and Electronic Engineering

MSc in Optical Communications and Signal Processing

[Field Trail for Covert Rangefinding]

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Signed: Xiuwei Zhang

Date: 04/12/2024

Abstract

Inspired by quantum rangefinding, this project adopts a semiclassical approach, where the source is kept in classical form and the detection part simulates a quantum light source. The advantage of quantum illumination in noise reduction stems from the entanglement and correlation of energy and time. To enhance the detection capability in noisy environments, we introduce energy-time correlation into the classical light source so that it maintains the advantage of noise reduction while increasing the brightness to enhance the long-range detection capability. The experiments focus on long-range detection, and the system's resistance to solar noise is tested up to about 150 meters in both daytime and nighttime environments. The experimental results have shown that quantum rangefinding has the potential to realize accurate covert sensing and long-range detection in complex environments.

Acknowledgement

2024 is coming to the end, and it also signaled that the end of my career at Bristol is approaching. A year has flown by, but I feel like it has only just passed since I arrived on campus. I cannot help but be grateful for all the help and support I have received along the way. I would like to express my heartfelt thanks to all those who have supported and helped me throughout my research and studies.

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I am also deeply grateful to my other teachers, especially Dr. Carrie Weidner, Professor Martin Cryan, and Dr. Shuangyi Yan, for their unconditional support and encouragement throughout my studies and research. Their care and understanding allowed me to focus on my academic pursuits and successfully complete my degree.

Lastly, I extend my sincerest gratitude to my parents for their love and care, their comforting presence during moments of solitude, and their unwavering support and trust in me.

Although I may not return to Bristol often after graduation, and this might even be our last meeting. I will always cherish the memories of the incredible faculty at the University of Bristol. You listened to my questions with patience, offered guidance with generosity, and extended genuine care. Thank you all!

CONTENTS

1 Introduction

Rangefinding is a fundamental technology with a wide range of applications, including navigation, civil engineering, defense and environmental monitoring. In modern rangefinding methods, it is usually accomplished by laser ranging or LIDAR ranging, which uses a laser pulse transmitter to emit a pulsed laser beam, then receives the reflected laser beam through a receiver and determines the distance to the target by calculating the return time and speed of light [1]. This calculation provides critical spatial data that is essential for geographic mapping, geographic information system (GIS) development, and accurate measurements.

Laser systems such as LIDAR are widely used in modern rangefinding because of their high accuracy and efficiency. Among them, pulsed laser sources stand out due to their high brightness, narrow spectral line widths and distinct temporal characteristics. These features enable them to resist interference from solar background radiation and thus perform reliable long-range measurements. However, quantum light sources, despite their unique advantages such as energy-time correlation, are limited by their limited brightness, which restricts their performance under high background conditions [2].

To address this challenge, this project explores methods that utilize frequency flexibility to propagate signals at multiple wavelengths. This technique improves the robustness of detection and extends the operating range, especially in environments with changing light and weather conditions. Inspired by quantum illumination, the project employs an enhanced light source that combines the advantages of improved signal-to-noise ratio and increased brightness [2].

The system has been initially tested in a controlled indoor environment and the focus of this research is to extend its application to real world conditions. The goal of the experiment is to achieve long detection distances, and the tests will be conducted between the Queen's Building and the Wills Memorial Building at the University of Bristol. Data will be collected under various conditions such as day and night or different weather conditions to analyze the performance of the system and its ability to withstand solar background noise.

By processing the experimental data in MATLAB, the study assesses the practical feasibility and theoretical potential of the system for covert quantum rangefinding. The results of the study are expected to highlight the suitability of the system for applications that require precise remote measurements in complex environments. In addition, the automation introduced during the experiment reduces human error and simplifies the process, making the method more scalable for future use.

2 Literature Review

2.1 Quantum Rangefinding

Quantum illumination has received much attention in the field of remote sensing due to its excellent ability to enhance detection sensitivity in noisy or lossy environments [3, 4, 5]. It is applied in a covert operation called quantum rangefinding. The background noise is suppressed by utilizing energy-time correlated paired photon sources [6, 7]. This method outperforms conventional weakly coherent state pulses at the same photon level, and its superiority was verified by the study of Liu et al. [8]. Earlier studies have also shown that quantum illumination performs better under low signal-to-noise conditions compared with conventional techniques, not only achieving higher signal-to-noise ratios, but also more distant target detection at the same signal-to-noise ratio [9]. These findings highlight the potential advantages of quantum illumination in dealing with target detection in complex environments [3, 8, 10].

As the combination of quantum information and sensing technology, quantum rangefinding enables more efficient distance detection through quantum properties. In recent years, research has focused on developing theoretical limits and experimental realizations of quantum rangefinding. For example, using entangled states and time-resolved single-photon techniques, it has been shown that the rangefinding accuracy of weakly reflecting targets is greatly improved [11, 12]. In addition, the application of bimodal compressed states as photonic probes has shown significant quantum advantages in noisy backgrounds [12].

On the experiment, Maccarone et al. investigated an underwater depth imaging method based on time-dependent single photon counting, which provides technical support for the application of quantum rangefinding in complex environments [11]. The detection algorithm optimized by combining quantum hypothesis testing achieves an error probability close to the quantum limit [12].

Quantum rangefinding utilizes entangled photon pairs to generate low-brightness broadband single photons, which can improve target detection sensitivity through its strong temporal and spectral correlation even under high background noise [8, 10]. For covert applications, Hao et al. (2022) experimentally verified the entanglement-enhanced covert sensing technique, in which the utilization of entangled photon pairs significantly improves the sensing efficiency and covertness when compared with the conventional method [13]. In addition, Qian et al. (2023) proposed “Quantum Induced Coherent LiDAR (QuIC LiDAR)”, which further demonstrates the significant progress of quantum rangefinding in the field of high-precision sensing by utilizing the entanglement property to resist environmental noise and interference [14].

2.2 Long Distance Quantum Rangefinding

Long-range quantum rangefinding using photon-efficient and entanglement-based techniques is essential for accurate measurements in challenging environments. For example, quantum pulse compression techniques have greatly improved temporal resolution and established a benchmark for noise-tolerant accuracy. This is a key development to overcome the limitations of classical systems [15]. In addition, Gaussian entanglement further improves the signal-to-noise ratio and provides better system robustness for long-range measurements, especially under noisy conditions [16].

Photonically efficient 3D imaging systems have made remarkable achievements in photon efficiency, solving the problem of rangefinding ambiguity. Dai et al. (2023) demonstrated how photon efficiency techniques can improve the quality of long-range imaging without introducing ambiguity, bringing a breakthrough in practical quantum rangefinding [17]. These systems utilize entangled photon pairs to achieve high-resolution remote sensing results.

Another critical development is the integration of quantum memories, which enable long-range entanglement. In their 2021 study, Li et al. demonstrated atomic photon entanglement over 101 km of telecommunication fiber, demonstrating the potential of quantum memories to extend the operational range of quantum systems [18]. In addition, Li et al. (2021) achieved a continuous entanglement distribution over 248 km, highlighting the growing capabilities of transnational quantum communications [19].

Finally, high-rate quantum teleportation enhances the scalability and efficiency of quantum systems, providing a foundation for global quantum networks capable of supporting secure communications and advanced rangefinding applications [20].

3 Methodology

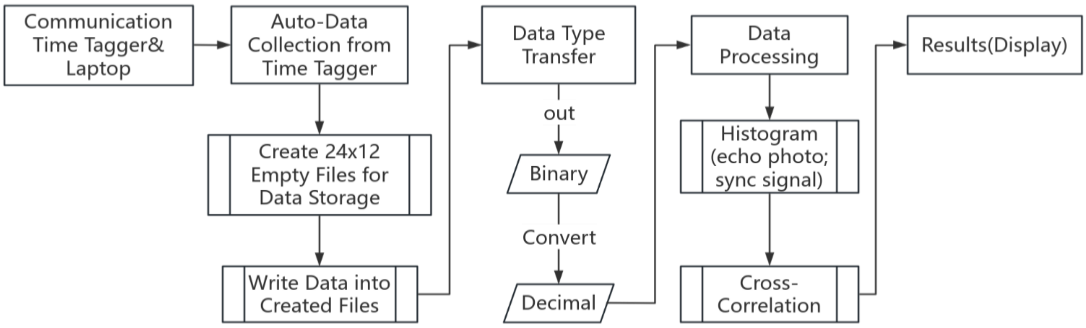

Fig.1. Experimental Flowchart

Data Collection

Through establishing a communication link between the TT (Time Tagger) and the laptop, a real-time automated data collection protocol was implemented to continuously record time tagger events.

Data Store

Pre-created 24 x 12 empty .out files (data collected every five minutes for 24 hours) were used to store the collected Time Tagger data. Convert the data (.ptu files) collected from the data collection device (Time Tagger) using the .ptu format conversion .out format code provided by the supplier to binary .out format and then write them systematically to the respective files for subsequent processing.

Data type conversion

Convert the collected data from the binary format .out file into a human-readable decimal format which can be convenient for further analysis and processing.

Data processing

The following two main types of processing are performed on the transformed data:

Histogram analysis:

Segmenting the data and generating histograms to visualize the distribution of key parameters such as echo time and sync signal.

Cross-correlation analysis:

Identify the time delay between the echo signal and the synchronization pulse and its relationship to improve the rangefinding accuracy through cross-correlation calculations.

Results Display

Visualize and analyze the processed data to validate the performance of the covert quantum rangefinding system and ensure its reliability and efficiency in challenging environments.

4 Experiment

4.1 Experiment Overview

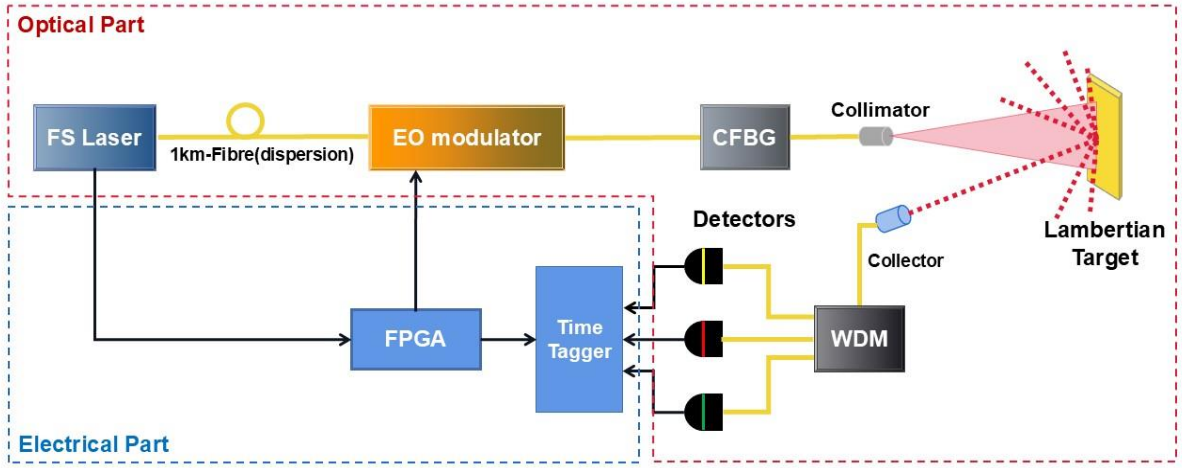

Fig.2. Schematic diagram of the experimental set-up. CFBG: chirped fibre Bragg gratings, EO modulator: electro-optical intensity modulator, FPGA: field-programmable gate array, FS laser: femtosecond laser, WDM: wavelength-division multiplexing.

Figure 2 has shown the schematic block diagram of the frequency-flexible light source system developed in the experiment. In the experiment, a femtosecond laser with high repetition frequency and wide spectral bandwidth was used as the initial light source. The broadband optical pulses generated by the laser are broadened from femtoseconds to nanoseconds after being transmitted over a long distance through a dispersive fiber. The broadened pulse is fed into an electro-optical (EO) intensity modulator, through which the optical signal is selected into three separate wavelength channels. The switching operation of the modulator is controlled by electrical signals synchronized with the laser, modulated with pseudo-randomly encoded delay signals processed by a field-programmable gate array (FPGA) to introduce different unique time delay for each wavelength channel. Note that due to the limitations of the FPGA delay module, the electrical signals are repeated at a low frequency to satisfy the time delay processing requirements.

There is a significant advantage of using three single-photon detectors (detectors) in this experiment. Compared with the traditional method of using only a single detector, the configuration of multiple detectors significantly enhances the system's immunity to interference under strong noise and background light conditions. The greater the number of channels, the more significant the noise reduction effect, Whereas the use of only one detector significantly reduces its noise reduction capability. Signal reliability is further improved by separating the return photon signal into three channels with independent detection via wavelength division multiplexer (WDM).

Another point is the use of TT (time tagger), which realizes precise time measurement and data processing. In the experiment, photons are emitted at fixed intervals, reflected by the target and then received. time tagger records the time of emission and reception of each photon and calculates the time difference between the two to obtain the time of flight of the photon, and thus accurately measure the distance to the target. The reference and return photon signals are connected to the time tagger for independent recording.

4.2 Data Collection Equipment (Time Tagger) Store Data

The high-performance Time Correlated Single Photon Counting (TCSPC) module supports two main data acquisition modes: T2 mode and T3 mode. Each mode is tailored to specific experimental setups and applications, providing the flexibility to perform photon timing measurements.

4.2.1 T2 Mode

In T2 mode, the device records the arrival time of detected photons as an absolute timestamp relative to the internal clock. Each detected photon is timestamped with a picosecond resolution, providing a continuous stream of timing data [21].

Main Features and Benefits:

1. **Absolute photon timing:**

The T2 mode captures the exact arrival time of each photon, making it ideal for applications such as photon correlation studies and non-repetitive event detection.
This allows researchers to analyze photon statistics such as g^2 measurements or time intervals between photons.

2. **No external synchronization is required:**

Unlike T3 mode, T2 mode does not require a periodic trigger signal, making it suitable for experiments with non-synchronized or non-repeating photonic events, such as quantum rangefinding or single-photon avalanche diode (SPAD) calibration.

3. High photon throughput:

The T2 mode handles only the photon arrival time and does not consider the synchronization period, so it can efficiently handle high photon detection rates.

4. **Flexible experimental applications:**

T2 mode is particularly suitable for applications such as free-space quantum communication, high-resolution time stamping, and complex quantum experiments where external period triggers cannot be used.

4.2.2 T3 Mode

T3 Mode records photon arrival times relative to an external periodic synchronization signal, such as a pulsed laser. Each event includes both the time within a pulse period (start-stop timing) and the pulse index [21].

Main Features and Advantages:

1. Synchronization with Periodic Sources:

T3 Mode is specifically designed for time-resolved experiments like fluorescence lifetime imaging microscopy (FLIM) and time-tagged time-resolved (TTTR) spectroscopy.
Photon events are recorded relative to periodic triggers, providing phase-correlated timing information.

2. Pulse-by-Pulse Information:

By tagging photons to specific synchronization pulses, T3 Mode enables detailed analysis of pulse-resolved dynamics, such as fluorescence decay curves.

3. Optimized for Repetitive Phenomena:

Ideal for experiments where photon timing depends on repetitive excitation pulses, such as those from pulsed lasers.

4.2.3 How Data Collection Equipment (Time Tagger) Store Data

Because T2 Mode records the absolute timestamps of photon arrivals with high time resolution and independence, it does not require the support of external trigger signals and can directly process non-periodic or random photon events. At the same time, T2 Mode can also work effectively in high photon flux environments, avoiding data loss or delay due to the limitation of external trigger signals. This design ensures complete and accurate time-stamped data in complex experiments and is ideal for analyzing photon time distributions and event correlations. Since it can record the exact reference period of the electrical signal as well as it can record all the data from our current processing method of calculating relative time via matlab code, we use T2 mode

For implementing an automated data collection system, it is critical to figure out the way Time Tagger stores data in T2 Mode binary 32bits. It will be analyzed in detail below.

```
T2Record = fread(fid, 1, 'ubit32'); % all 32 bits:
% +-------------------------------+ +-------------------------------+
% |x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|x| |x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|
% +-------------------------------+ +-------------------------------+
dtime = bitand(T2Record,33554431); % the last 25 bits:
% +-------------------------------+ +-------------------------------+
% | | | | | | | |x|x|x|x|x|x|x|x|x| |x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|
% +-------------------------------+ +-------------------------------+
channel = bitand(bitshift(T2Record,-25),63); % the next 6 bits:
% +-------------------------------+ +-------------------------------+
% | |x|x|x|x|x|x| | | | | | | | | | | | | | | | | | | | | | | | | | |
% +-------------------------------+ +-------------------------------+
special = bitand(bitshift(T2Record,-31),1); % the last bit:
% +-------------------------------+ +-------------------------------+
% |x| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
% +-------------------------------+ +-------------------------------+
```

The code and comments above show Time Tagger storing data in a 32-bit binary structure.


```
T2Record = fread(fid, 1, 'ubit32'); % all 32 bits:
% +-------------------------------+ +-------------------------------+
% |x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|x| |x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|
% +-------------------------------+ +-------------------------------+
dtime = bitand(T2Record,33554431); % the last 25 bits:
% +-------------------------------+ +-------------------------------+
% | | | | | | | |x|x|x|x|x|x|x|x|x| |x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|x|
% +-------------------------------+ +-------------------------------+
```


The bitand operation is a bitwise AND, used to mask out the high 7 bits and retain only the lower 25 bits of the data. The constant "33554431" is the binary number "1111111111111111111111111", corresponding to the decimal number 2^25 - 1.

dtime represents the time offset, in picoseconds (ps), with a range from 0 to 2^25 - 1. Its purpose is to reflect the time stamp of photon events in the record, and combined with subsequent overflow correction values, it can yield an absolute timestamp.


```
channel = bitand(bitshift(T2Record,-25),63); % the next 6 bits:
% +-------------------------------+ +-------------------------------+
% | |x|x|x|x|x|x| | | | | | | | | | | | | | | | | | | | | | | | | | |
% +-------------------------------+ +-------------------------------+
```


“bitshift(T2Record, -25)”: This operation shifts the record 25 bits to the right, discarding the lowest 25-bit timestamp. “bitand(..., 63)”: This performs a bitwise AND with the constant 63 (which is binary 111111, corresponding to the decimal number 2^6 - 1), retaining the lowest 6 bits of the result after the shift.

The result is the "channel", which represents the record's channel number and has a range from 0 to 63.

The channel number is used to indicate which detector captured the photon event. In the experiment, multiple detectors (or channels) can record signals simultaneously, supporting multi-channel parallel detection, which enhances experimental efficiency.

```
special = bitand(bitshift(T2Record,-31),1); % the last bit:
% +-------------------------------+ +-------------------------------+
% |x| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
% +-------------------------------+ +-------------------------------+
```

“bitshift(T2Record, -31)”: This operation shifts the record 31 bits to the right, leaving the highest bit. “bitand(..., 1)”: This performs a bitwise AND with the constant 1 (which is binary 00000001), extracting the lowest bit of the result.

Special indicates whether the record is a special event. special = 0: Regular photon record; special = 1: Special record (e.g., time overflow, synchronization events, etc.).

This field is used to distinguish normal photon events from special records and to guide subsequent processing logic.

5 Experimental Results

5.1 Automated Rangefinding System

The first experiment was for a 24-hour duration with data collection at 20-minute intervals, but since the data collection device (Time Tagger) did not have the function of automated data collection, data could only be collected manually using human hands. After going through the whole process of this data collection, the importance of an automated system was deeply realized. This process is undoubtedly expensive in terms of labor costs, and the errors generated are not guaranteed due to the fact that the physical strength and energy of a human being decreases over time. And the subsequent experiments for the duration of 24 hours every 5 minutes for data collection. Therefore, in order to reduce the labor consumption and ensure the accuracy of the experimental data, automated data collection is crucial for the whole experiment, which is also my most important work in this project.

The system is based on the original code provided by the supplier for modification and innovation, after understanding how Time Tagger stores data in binary 32bit species, based on the original code that can only output binary .out files for innovation, so that it can realize the creation of a certain number of empty .out files, the collected data in order to collect into the .out file, and convert them into readable decimal data.

5.1.1 Automated Creation of Batch Files and Data Padding

In order to achieve efficient data management, the system automatically generates a series of numbered .out files as containers for data storage before data collection begins. After each experimental measurement, the system automatically populates the collected data in binary format into the corresponding .out files. This approach not only avoids manual intervention, but also provides standardized input for subsequent data processing.

Core code:

```
outputDir = 'C:\output\';
numFiles = 10;

% Check whether the output directory exists, and if it doesn't, create it
if ~exist(outputDir, 'dir')
    mkdir(outputDir);
end

for fileIndex = 0:numFiles-1
    % Generate the filename and add the path
    filename = sprintf('%s%05d.out', outputDir, fileIndex);
    % Open file
    fid = fopen(filename, 'wb');
if (fid<0)
    fprintf('Cannot open file %s\n', filename);
    return;
end;
......
fclose(fid);
fprintf('File %s generated successfully\n', filename);
```

Analysis:

By cycling through the creation of a fixed number of empty files, the system can quickly locate and store the data after it has been collected, ensuring that the experimental data is organized. Each file is named in the standard .out format, which facilitates batch management and subsequent processing. This design effectively reduces human errors during the storage of experimental data, while improving the automation of the experiment.

5.1.2 Real-time Binary Data Conversion

In order to facilitate the subsequent analysis of the experimental data, the system calls the customized binaryto10 function immediately after the completion of data acquisition to convert the binary file into a more readable decimal file. The converted data file can directly display the measured time tags, channel numbers and other key information, laying the foundation for subsequent analysis of experimental data.

The core task of this function is: Read the raw data from the binary file expressed in 32-bit records. Parse the data for timestamps (time tag), channel numbers (channel), special tags (special) and overflow correction information (overflow correction). The parsed information is output in decimal format to the specified .out file.

This process realizes the conversion of data from raw records to structured information and is an important step in the analysis of experimental data.

Core code:

```
for i = 1:TTResult_NumberOfRecords
    RecNum = i;
    T2 = fread(fid, 1, 'ubit32'); % Reading a 32-bit T2 record
    T2Record = T2;
    dtime = bitand(T2Record, 33554431); % lower 25 bits used as the timetag.
    channel = bitand(bitshift(T2Record, -25), 63); %next 6 bits channel number
    special = bitand(bitshift(T2Record, -31), 1); % highest bit special marker
    timetag = OverflowCorrection + dtime; % Calculating timestamps

    if special == 0
        fprintf(outputFile, '%i CHN %1x %i\n', RecNum, channel + 1, timetag);
    else
        if channel == 63 % Handling of overflow situations
            if Version == 1
                OverflowCorrection = OverflowCorrection + T2WRAPAROUND_V1;
            else
                if dtime == 0
                    OverflowCorrection = OverflowCorrection + T2WRAPAROUND_V2;
                else
                    OverflowCorrection = OverflowCorrection + T2WRAPAROUND_V2
                * dtime;
                end
            end
        elseif channel == 0
            fprintf(outputFile, 'Sync: TimeTag=%d\n', timetag);
        elseif (channel >= 1) && (channel <= 15)
fprintf(outputFile, 'Marker: TimeTag=%d, Channel=%d\n', timetag, channel);
        end
    end
end
```

Inspired by the principle of Time Tagger storing data in 32-bit binary in T2 mode, this code implements the line-by-line parsing and sorting process of accepting electrical signals from a single-photon detector to record 32-bit binary data from different channels in T2 mode, and the main functions include the extraction of record timestamps and channel information, as well as the processing of special marking and overflow situations. Specifically, each 32-bit data record is divided into three parts: the lowest 25 bits denote the timestamp (dtime), the 25th to 30th bits denote the channel number (channel), and the highest bit serves as the special tag bit (special). These fields are extracted by bitwise operations and the parsed result is output to a text file in combination with the RecNum.

When dealing with timestamps, the code ensures timeline continuity through an OverflowCorrection mechanism. This mechanism dynamically adjusts the value of the timestamp using the device's two winding methods (for version 1 and version 2, respectively). When the special tag bit is 1 and the channel number is 63, it is considered that an overflow has occurred, and the code is corrected accordingly based on the specific version judgment. For version 1, the predefined winding back constant (T2WRAPAROUND_V1) is directly accumulated; for version 2, the multiplier of the winding back is further calculated based on the timestamp value (dtime). With this design, the data discontinuity problem caused by device timestamp wrapback is solved, thus ensuring the accuracy of the parsing results.

In addition, the code categorizes special events. When the special mark bit is 1, if the channel number is 0, it is recorded as a synchronization event (Sync) and outputs the timestamp value; if the channel number is between 1 and 15, it is recorded as a marker event (Marker) and outputs the timestamp and channel number. This kind of classification processing not only improves the logical clarity of device data parsing, but also provides rich event information for subsequent analysis and visualization of experimental data.

The code significantly improves the usability of device output data through efficient data parsing and fine-grained overflow correction strategies. It not only supports binary file processing for different versions of devices, but also achieves full compatibility with synchronized and tagged events. As an important tool for data processing in photon timing devices, the code has wide applicability in quantum optical measurements, time-correlated single-photon counting (TCSPC), and automated rangefinding systems.

5.1.3 Configurable Time Intervals Between Cycles

In the experimental design, we have fully considered the recovery time of the equipment and the requirements of the experimental environment by incorporating an adjustable cycle interval control function. The researcher can freely set the waiting time between each measurement according to the experimental requirements to maximize the utilization of the experimental equipment and the reliability of the data.

```
disp('Waiting for 5 seconds...');
pause(5); % pause 5 seconds
disp('5 seconds have passed.');
```

The interval time between experimental cycles can be flexibly set according to equipment performance and experimental requirements. For high-precision light quantum rangefinding experiments, this feature can make each data collection maintain at an identical interval, greatly reducing manual errors.

5.1.4 Conclusion

The automated rangefinding system developed in this study significantly optimizes the efficiency and reliability of the data acquisition process in quantum optical rangefinding experiments. By addressing the limitations of manual operations, such as labor-intensive, time-consuming, and potential human errors, the system enables more accurate and consistent data collection. Key innovations include automated batch file creation for standardized data storage, proposed real-time binary to decimal data conversion for enhanced data readability, and flexible and configurable time intervals to accommodate diverse experimental conditions.

The automated framework not only ensures the integrity and continuity of experimental data, but also improves the reproducibility and scalability of experiments. In particular, the system enables seamless data management and reduces the need for manual intervention, laying the foundation for high-precision analysis in time-correlated single-photon counting (TCSPC) and other quantum communication applications.

5.2 Data Processing

5.2.1 Cross-Correlation

Cross-correlation is a widely used technique in signal processing that measures the similarity between two signals and helps identify their time delay relationship. The basic principle is to slide one signal over another in time and compute the matching degree at each time offset. The cross-correlation value reflects how similar the two signals are at a specific delay. Mathematically, the cross-correlation function can be expressed as:

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} x(t)y(t+\tau)dt$$

For discrete signals, the formula simplifies to:

$$R_{xy}(\tau) = \sum_{n} x[n] * y[n+\tau]$$

Where x(t) and y(t) are the two signals, and τ is the time delay, representing the shift of y(t) relative to x(t). By computing the sum of the products of these signals at different time delays, we obtain a cross-correlation value sequence.

In practical applications, the key information is often extracted by locating the maximum peak in the cross-correlation sequence. For example, in radar or quantum rangefinding systems, the transmitted reference signal x(t) and the received echo signal y(t) can be cross correlated to determine the time delay between the signals, which is directly related to the target distance. By identifying the peak position of the cross-correlation, the distance to the target can be estimated.

For example, suppose there are two simple discrete signals:

$$\mathrm{x} = [1, 2, 3];\ \mathrm{y} = [0, 1, 2, 3, 0]$$

We wish to compute x and y's cross-correlation. The steps are as follows:

1. Combine x and y are aligned and the dot product of the overlapping regions is computed. For example, when $\tau = 0$:

$$R_{xy}(0) = 1 * 1 + 2 * 2 + 3 * 3 = 14$$

2. Slide x one place to compute the values associated with the next set of offsets. For example, when τ = 1:

$$R_{xy}(1) = 0 * 1 + 1 * 2 + 2 * 3 = 8$$

3. Repeat this process until the entire sliding range is computed. The final cross-correlation sequence may be:

$$R_{xy} = [3.8.14.8, 3]$$

From the graph, these values can be plotted as a curve where the peak $R_{xy}(0) = 14$ indicates that the signals are at the $\tau = 0$ is best matched.

In practical applications, e.g. in quantum rangefinding, the transmit signal can be taken as $\mathrm{x(t)}$ and the echo signal as $\mathrm{y(t)}$. By calculating their cross-correlation and finding the location of the highest peak of the correlation curve, the time delay of the echo signal can be determined τ_{peak}.

Using Eq:

$$\mathrm{Distance} = \frac{\mathrm{c} * \tau_{\mathrm{peak}}}{2}$$

In which c is the speed of light, the distance to the target can be calculated. Cross-correlation not only effectively handles signals affected by noise, but also extracts similarity strengths, but its computational complexity is high and usually requires the use of fast algorithms (e.g., FFT) or dedicated hardware acceleration to improve efficiency.

The main advantage of cross-correlation is its ability to effectively detect matching relationships between signals, even in the presence of noise. By accumulating the overall similarity, cross-correlation provides a more reliable measure of signal similarity than point-by-point comparisons. However, the computational complexity of cross-correlation can be high, especially when dealing with large datasets or real-time processing. To improve efficiency, fast algorithms such as Fast Fourier Transform (FFT) or hardware acceleration are often employed.

5.2.2 Coincidence-based Cross-Correlation Method for Distance Estimation

In order to extract distance information from the echo signals, a coincidence-based correlation method is used. First, a reference signal is constructed by interpolating a 100 kHz synchronized signal with a 500-PRCS pattern. Next, we compute the cross-correlation between the reference and return signals by summing the coincidence counts over the entire integration period and shifting them at each cycle. Finally, the round-trip time is estimated by locating the peak of the cross-correlation and the range is determined using this time value.

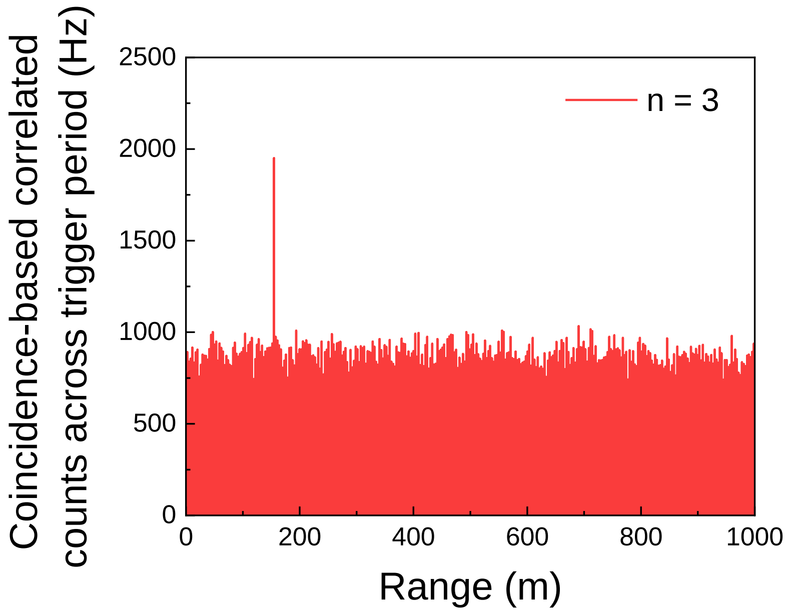

Fig.3.Processed data

The image above is the processed data. As shown, the peak position is the measured distance(154.815m) to the facade of the Wells building. As previously described, the results were processed by calculating the cross-correlation between the normalized reference electrical signal and the echo photons detected by the triple-energy channel.

6 Discussion of the Technologies

The centerpiece of this research is the covert quantum rangefinding technique, which enhances the detection capability of the system by introducing a semiclassical approach. Different from the traditional method, this system retains the light source in classical form while simulating the properties of quantum light source in the detection part. Through introducing the energy-time correlation into the classical light source, the system not only retains the advantage of quantum illumination in noise suppression, but also enhances the brightness of the light source, thus strengthening the long-distance detection capability. This design is particularly suitable for realizing covert measurements in complex environments. Experimental results show that the system exhibits excellent noise rejection performance at a range of 150 meters both during the daytime when the solar noise is significant and at night in low-light environments, which verifies its potential in long-range and covert detection.

To support this central experiment, the study also developed an automated data acquisition system that was used to reduce manual intervention and increase the efficiency of data processing. The automated system is based on the parsing of raw binary data files and utilizes MATLAB to implement the data reading and conversion functions. However, the performance of MATLAB itself is limited by the nature of the interpretive language due to its long loop running time, especially when processing large-scale data, resulting in delays in real-time processing in high-frequency acquisition experiments.

To solve this problem and realize true real-time rangefinding, rewriting the data processing algorithms in C++ can be considered in the future. Compared to MATLAB, C++ has higher execution efficiency and can significantly reduce data parsing and conversion time. In real-time rangefinding scenarios, data processing is expected to be completed within 0.1 to 1 second, which in turn allows for the timely calculation of the target distance during each data collection interval. By adopting the real-time processing algorithm implemented in C++, the system is expected to further improve its performance in highly dynamic environments, making the covert quantum rangefinding technology useful in more practical application scenarios.

7 Conclusion

The experiment successfully demonstrated the capability of a quantum-inspired energy-time correlation method in achieving significant noise suppression under challenging conditions, including strong solar background interference and high transmission losses of nearly 100 dB. Although precise distance measurement was not the primary focus of this study, the results underline the robustness and practicality of the approach for applications in complex environments.

In order to further improve the performance of the system and achieve near real-time processing, future research will be conducted by converting the data processing algorithms to C++, which is efficient enough to support fast distance calculations during data collection intervals. Realizing real-time processing requires the system to process the data within a collection interval of typically 0.1 to 1 second. This improvement will significantly advance the system towards real-world applications that are not only stable under noisy and lossy conditions, but also dynamic and time-sensitive scenarios.

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