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## METHODS AND DEVICES FOR IDENTIFYING PEAKS IN HISTOGRAMS

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### Abstract

A single-pass method for identifying peaks in a time of flight histogram, the single-pass method including conducting an ordered comparison of each bin with an adaptive threshold until finding a bin that exceeds the adaptive threshold; enabling peak tracking in response to finding the bin that exceeds the adaptive threshold; in response to enabling peak tracking, continuing the ordered comparison of each bin with the adaptive threshold until finding a bin that falls below the adaptive threshold; and in response to finding the bin that falls below the adaptive threshold, marking a peak location between the bin exceeding the adaptive threshold and the bin that falls below the adaptive threshold.

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a divisional of U.S. application Ser. No. 17/697,784, filed on Mar. 17, 2022, which application is hereby incorporated by reference herein in its entirety.

### TECHNICAL FIELD

[0002] The present invention relates generally to systems and methods to identify peaks in time of flight histogram data.

### BACKGROUND

[0003] Light Detection and Ranging (“LiDAR”) devices and operations, as well as other imaging approaches, may function by emitting photons into an environment and determining the length of time it takes for photons to be reflected back. Knowing the speed of the photons, the distance between a LiDAR system and an object in its field of view may be determined using Time of Flight (ToF) of the photons between emission and detection. A photon-count histogram may be generated that group photon-detection events into time ranges referred to as bins. Photon-count peaks in the histogram data can be used to identify objects at distances from a system that correspond to the time range for bins where peaks are located. However, LiDAR systems may comprise numerous pixels so peak detection can impose heavy costs on a system.

### SUMMARY

[0004] In accordance with an embodiment, a method to identify peaks in a histogram includes beginning an ordered comparison of each bin in the histogram with an adaptive threshold until finding a bin exceeding the adaptive threshold, each bin of the histogram representing a photon count corresponding to a distance from a light-ranging system; continuing the ordered comparison after finding the bin exceeding the adaptive threshold until finding a bin falling below the adaptive threshold; determining a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; finding the width exceeds a width threshold; marking a peak location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; and continuing the ordered comparison until each bin has been compared with the adaptive threshold one time.

[0005] In accordance with an embodiment, a single-pass method for identifying peaks in a time of flight histogram, the single-pass method including: conducting an ordered comparison of each bin with an adaptive threshold until finding a bin that exceeds the adaptive threshold; enabling peak tracking in response to finding the bin that exceeds the adaptive threshold; in response to enabling peak tracking, continuing the ordered comparison of each bin with the adaptive threshold until finding a bin that falls below the adaptive threshold; and in response to finding the bin that falls below the adaptive threshold, marking a peak location between the bin exceeding the adaptive threshold and the bin that falls below the adaptive threshold.

[0006] In accordance with an embodiment, a light-ranging system including: an optical source configured to emit optical pulses for light-ranging; an optical receiver configured to detect photons; a time to digital converter in communication with the optical receiver and configured to output times of flight of photons detected by the optical receiver; and a processor in communication with the time to digital converter to receive times of flight of photons detected by the optical receiver and store them in a time of flight histogram; a memory storing an instruction set that, when executed, causes the processor to begin an ordered comparison of each bin in the time of flight histogram with an adaptive threshold until a bin exceeding the adaptive threshold is found, each bin of the times of flight histogram representing a photon count corresponding to a distance from the

light-ranging system; continue the ordered comparison after finding the bin exceeding the adaptive threshold until a bin falling below the adaptive threshold is found; determine a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; find the width exceeds a width threshold; mark a peak location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; and continue the ordered comparison until each bin has been compared with the adaptive threshold one time.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0007] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0008] FIG. 1 illustrates a light-ranging system;

[0009] FIG. 2A shows an enlarged view of an optical source;

[0010] FIG. 2B shows an enlarged view of the optical receiver;

[0011] FIG. 3 depicts an embodiment of a light-sensitive pixel **104-1** of the plurality of light-sensitive pixels **104-1** to **104KK**;

[0012] FIG. 4 illustrates a photon-count histogram generation for a pixel of a light ranging system in accordance with an embodiment;

[0013] FIG. 5 depicts a histogram of photon count data in accordance with an embodiment

[0014] FIG. 6 depicts a single-pass method for identifying peaks in a ToF histogram in accordance with an embodiment;

[0015] FIG. 7 depicts a method for determining an adaptive threshold in accordance with an embodiment;

[0016] FIG. 8 depicts a window of bins of a histogram for calculating an adaptive threshold in accordance with an embodiment;

[0017] FIG. 9 depicts a window of a histogram in accordance with an embodiment;

[0018] FIG. 10 depicts routines for finding peaks in a histogram in accordance with an embodiment;

[0019] FIG. 11 depicts a peak fitting method in accordance with an embodiment;

[0020] FIG. 12 depicts a light-ranging system in accordance with an embodiment;

[0021] FIG. 13 depicts a method to identify peaks in a histogram in accordance with an embodiment; and

[0022] FIG. 14 depicts a single-pass method for identifying peaks in a time of flight histogram in accordance with an embodiment.

### DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0023] In the ensuing description, one or more specific details are illustrated, aimed at providing an in-depth understanding of examples of embodiments of this description. The embodiments may be obtained without one or more of the specific details, or with other methods, components, materials, etc. In other cases, known structures, materials, or operations are not illustrated or described in detail so that certain aspects of embodiments will not be obscured. Reference to “an embodiment” or “one embodiment” in the framework of the present description is intended to indicate that a particular configuration, structure, or characteristic described in relation to the embodiment is comprised in at least one embodiment. Hence, phrases such as “in an embodiment” or “in one embodiment” that may be present in one or more points of the present description do not necessarily refer to one and the same embodiment. Moreover, particular conformations, structures, or characteristics may be combined in any adequate way in one or more embodiments. Unless otherwise noting elements referred to with the same numeric identifier in the figures may represent

the same component.

[0024] LiDAR systems detect objects in their field of view by projecting optical pulses into the field of view. Reflections from objects in the field of view are sensed, and locations of objects in the field of view determined based on times between emission and detection. To accomplish this, photon counts are generated for time periods referred to as bins. Collectively, the bins form a photo-count histogram. Peaks in the photo count histogram can be corresponded to objects in the field of view of a LiDAR system. Similar photon-count histograms may be utilized for other types of 3D sensing and single photon avalanche diode (“SPAD”) array imaging).

[0025] As will be appreciated such systems and methods have a wide array of applications including, but not limited to, multi-zone auto-focus assistance, post process depth of field, computations imaging, Augmented Reality, Virtual Reality, autonomous robotics, gesture recognition, facial recognition, in-cabin monitoring, and many more.

[0026] Many application may be constrained by power and size limitation (such as mobile applications) while object-detection performance benefits from full histogram information. Known approaches for peak detection require sweeping histogram data multiple times to perform multiple processing routines on the data. Some example routines include cross-talk compensation, pulse segmentation, and pulse fitting. Further, as demands for increased resolution and definition increase, so to do the processing resources needed to evaluate the photon count histograms. In other words, the more pixels an imaging system utilizes, the greater processing burden needed to identify peaks in the photon-count histograms. For example, a single histogram may comprise 144, or more, bins. And, multiple data sweeps (cross-talk, pulse segmentation, and pulse fitting) are performed for each pixel. This can quickly add up to burden the resources of a LiDAR system.

[0027] Known solutions to accommodate the data demands required for full histogram processing all have downsides. Off-chip computation can increase I/O complexity, require large memory resources, and slow down computation for the required data transfers. On chip computation solutions are highly complex, also require large memories, and require multiple loops for histogram elements. Further, multiple discrete algorithms are needed for corner cases and applications.

[0028] Methods and systems that can find peaks with one iteration can cut down the processing burden for LiDAR and improve a LiDAR system.

[0029] FIG. 1 illustrates a light-ranging system.

[0030] An object **101** is disposed in a three dimensional environment positioned in front of the light-ranging system **100**. The light-ranging system **100** may be used to determine the proximity of the object **101** to the light-ranging system **100**. The object **101** is provided for explanatory purposes. The three-dimensional environment may include additional objects of various shapes or sizes disposed at varying distances from the light-ranging system **100**, and the light-ranging system **100** may determine the proximity of the various objects in the three-dimensional environment for imaging the three-dimensional environment. The object **101** may comprise multiple surfaces at various distances from the light-ranging system **100**, and the light-ranging system **100** may determine the depth of the different surfaces of the object **101**. The light-ranging system **100** may simultaneously determine the proximity of additional objects in the three dimensional environment to generate a three-dimensional image of the three-dimensional environment. The three-dimensional image may comprise a depth map of the three dimensional environment.

[0031] The light-ranging system **100** may comprise an optical source **102**, which may be referred to as an optical transmitter, and an optical receiver **104**.

[0032] FIG. 2A shows an enlarged view of an optical source **102**;

[0033] As depicted in FIG. 2A, the optical source **102** may comprise a plurality of pixels **102-1** to **102-NN** arranged as an array. Although the example of FIG. 2A illustrates the optical source and plurality of pixels **102-1** to **102-NN** as being arranged in a square  $N \times N$  array, other array shapes (e.g. ellipsoidal arrays or circular-shaped arrays) may be possible in other embodiments. Each of the plurality of pixels **102-1** to **102-NN** may comprise one or more infrared sources, modulated

light emitting diodes (LEDs), semiconductor lasers or combinations thereof, although other types of optical sources may be possible. It should also be appreciated, that in various embodiments, the optical source may comprise a single point source rather than an array of pixels. In various embodiments, the optical source may comprise semiconductor lasers, vertical-cavity surface-emitting lasers (VCSELs), quantum well lasers, quantum cascade lasers, interband cascade lasers, or the like.

[0034] The plurality of pixels **102-1** to **102-NN** may be configured to operate at the same wavelength. In other embodiments, however, the plurality of pixels **102-1** to **102-NN** may operate at different wavelengths. For example, the group **108** of pixels and the group **110** of the plurality of pixels **102-1** to **102-NN** may operate at different wavelengths. The plurality of pixels **102-1** to **102-NN** may exhibit continuous wave (CW) operation, quasi-continuous wave (QCW) operation, or pulsed operation.

[0035] Referring back to FIG. 1, in various embodiments, the light-ranging system **100** may comprise an optical source driver **112**. The operation of the optical source **102** may be controlled by the optical source driver **112**. In various embodiments, the optical source driver may generate a drive current **114** that is capable of activating the optical source **102**.

[0036] In various embodiments, the plurality of pixels **102-1** to **102-NN** may be an addressable array. The plurality of pixels **102-1** to **102-NN** may be individually addressable where an optical emitter **102-i** (shown in FIG. 2A) of the plurality of pixels **102-1** to **102-NN** is addressable independently of another emitter **102-j** of the plurality of pixels **102-1** to **102-NN**. The drive current **114** provided by the optical source driver **112** to the optical source **102** may cause an optical emitter **102-i** to be activated (and thereby emit a photon or photon pulse), while another emitter **102-j** is not activated (and thereby does not emit a photon). In various embodiments, the plurality of pixels **102-1** to **102-NN** may be addressable as a group or cluster, where one group **108** of the plurality of pixels **102-1** to **102-NN** is addressable independently of another group **110** of the plurality of pixels **102-1** to **102-NN**. In various embodiments, the drive current **114** provided by the optical source driver **112** to the optical source **102** may cause the group **108** of the plurality of pixels **102-1** to **102-NN** to be activated (and thereby emit a photon or photon pulse), while another group **110** of the plurality of pixels **102-1** to **102-NN** is not activated (and thereby does not emit a photon). Using an array of pixels **102-1** to **102-NN** that are individually addressable allows dynamically reconfiguration of an illumination pattern of the optical source **102** and/or an intensity level of each of the plurality of pixels **102-1** to **102-NN** of the plurality of pixels **102-1** to **102-NN** to adapt to various applications or environments. It should also be appreciated that all pixels may be simultaneously illuminated for projections.

[0037] Radiation (light) emanating from the optical source **102**, collectively shown in FIG. 1 as incident radiation **116** using solid arrows, may be incident upon the object **101**. The incident radiation **116** is reflected off the object **101** to produce reflected radiation **118**. It is noted that although incident radiation **116** and reflected radiation **118** are represented in FIG. 1 by few arrows, all radiation incident on and reflected from the object **101** may be combined in one beam or cone of radiation. While some part of the incident radiation **116** may be scattered depending upon the surface features of the object **101**, a significant part of the incident radiation **116** may be reflected, thereby producing the reflected radiation **118**.

[0038] The optical receiver **104** may receive the reflected radiation **118** and generates an output signal **120** in response to the reflected radiation **118** striking the optical receiver **104**. The output signal **120** may be a digital signal or an analog signal, depending on the circuitry of the optical receiver **104**.

[0039] FIG. 2B shows an enlarged view of the optical receiver.

[0040] As depicted in FIG. 2B, the optical receiver **104** may comprise a plurality of light-sensitive pixels **104-1** to **104-KK**. Although the example of FIG. 2B illustrates the light-sensitive pixels **104-1** to **104-KK** as being arranged in a square  $K \times K$  array, other array shapes (e.g. ellipsoidal arrays or

circular-shaped arrays) may be possible in other embodiments. The intrinsic spatial resolution of the light-ranging system **100** may be determined by the resolution of the optical receiver **104**. For example, since the light-sensitive pixels **104-1** to **104-KK** in the embodiment of FIG. 2B are arranged as a  $K \times K$  array, the intrinsic spatial resolution of the light-ranging system **100** may be a  $K \times K$  image. It is noted that the output signal **120** may be expressed as a  $K \times K$  matrix of measurements, or a  $1 \times K$  vector of measurements, with each entry of the matrix corresponding to the signal received from a respective pixel of the plurality of light-sensitive pixels **104-1** to **104-KK**.

[0041] FIG. 3 depicts an embodiment of a light-sensitive pixel **104-1** of the plurality of light-sensitive pixels **104-1** to **104-KK**.

[0042] In various embodiments, a light-sensitive pixel **104-1** may comprise a plurality of individual light-detecting sensors **104-1A** to **104-1D**. This may allow light-sensitive pixels to detect more reflected radiation and improve the signal to noise ratio of the output signal **120**. The individual light-detecting sensors **104-1A** to **104-1D** may be combined by an OR tree so light-sensitive pixel **104-1** captures measurements from the plurality of individual light-detecting sensors **104-1A** to **104-1D**. The individual light-detecting sensors **104-1A** to **104-1D** may comprise single-photon avalanche diodes (SPADs) photo diodes (PDs), avalanche photo diodes (APDs), or combinations thereof. In embodiments comprising SPADs, the availability of more than one light-detecting sensor may allow photon detection while one or more of the individual SPADs are recharging. In various embodiments, some or all of the plurality of light-sensitive pixels **104-1** to **104-KK** may comprise a plurality of individual light-detecting sensors. While detecting photons, the individual light-detecting sensors of a radiation-sensing pixel may be firing at random but correlated to the arrival of photons onto the radiation pixel.

[0043] Although, light-sensitive pixel **104-1** is depicted with four individual light-detecting sensors **104-1A** to **104-1D** arranged in a  $2 \times 2$  array, it will be appreciated that light-sensitive pixel **104-1** may comprise any number of individual light-detecting sensors. In various embodiments, the light-sensitive pixel **104-1** may comprise a single light detecting sensor, a  $4 \times 4$  array of individual light-detecting sensors, an  $8 \times 8$  array of individual light-detecting sensors, a  $16 \times 16$  array of individual light-detecting sensors or any other number of individual light-detecting sensors. In various embodiments, each pixel may comprise single light-sensitive sensor.

[0044] As shown in FIG. 1, the light-ranging system **100** may further comprise a processor **126** configured to receive the output signal **120** and determine the proximity of the object **101** to the light-ranging system **100** based on the output signal **120**. The processor **126** can additionally reconstruct three-dimensional images of the object **101** based on the output signal **120** as well as 2D intensity images related to reflective properties of surfaces in the scene.

[0045] The optical source driver **112** may be programmed to drive the plurality of pixels **102-1** to **102-NN** to generate incident radiation pulses. The optical source driver **112** may receive a control signal **134** from the processor **126** that initiates the optical source driver **112**. The control signal **134** may determine which of the plurality of pixels **102-1** to **102-NN** are active and which are inactive. In embodiments where the optical source **102** comprises a single point source the drive current **114** may activate the optical source **102**.

[0046] The radiation from the optical source **102** may illuminate the object **101** in a predetermined timing sequence or at predetermined timing intervals. The object **101** may reflect the incident radiation **116** and the arrival times of the pulses of reflected radiation **118** at the optical receiver **104** are proportional to twice the distance between the object **101** and the light-ranging system **100**, based on the speed of light in the measurement medium or environment.

[0047] The optical source **102** may comprise semiconductor lasers (e.g. VCSELs), while the optical receiver **104** may comprise high speed photodetectors (e.g. SPADs). The optical receiver **104** may be configured to record at least one of arrival times, pulse shapes, or intensities of the pulses of reflected radiation **118**. Reflected radiation **118** may arrive at different times at the optical receiver

**104**, depending on the respective distances between the different parts of the object **101** or other objects in the three-dimensional environment and the light-ranging system **100**. The reflected radiation **118** may be detected synchronously with a timing signal **130** that is configured to cause the optical source driver **112** to generate incident radiation **116**. The processor **126** may analyze the time-of-flight (ToF) between emission of incident radiation **116** travelling towards the object **101** and arrival of reflected radiation **118** received at the optical receiver **104** to determine the proximity of the object **101** of objects in the three-dimensional environment. A plurality of proximity measurements may be used to generate a comprehensive set of data to accurately determine both lateral spatial distances (e.g. in the x-y plane shown in FIG. 1) and depth (e.g. along the z-axis shown in FIG. 1) of the object or objects in the three-dimensional environment.

[0048] In various embodiments, photons counted at a light-sensitive pixel may be categorized based on ToF analysis to generate a histogram of estimated distances of the object or surface that reflected the radiation to the light-sensitive pixel. Conceptually, the ToF of a photon sensed at a light-sensitive pixel may be calculated and assigned to a bin that represents a distance. As additional photons are sensed during a measurement, they may be assigned to a bin. The various bins may accumulate a photon count and the distribution of photons in the various bins may be used to estimate the distance from the light-ranging system **100** of the reflective surface measured at the light-sensitive pixel. The photon-counting process may be a Poisson process.

[0049] In various embodiments, the light-ranging system **100** may comprise one or more time to digital converters. TDC **136** in communication with the optical source **102**, the optical receiver **104**, and the processor. The one or more TDCs **136** may measure the interval between the emission of incident radiation **116** from the optical source **102** and the arrival of reflected radiation **118** at the optical receiver **104** and provide it to the processor **126**. In various embodiments, the processor **126** may comprise the TDC and the interval between emission and arrival may be calculated using a timing signal **130** to trigger the emission and the time of arrival.

[0050] FIG. 4 illustrates a photon-count histogram generation for a pixel of a light ranging system in accordance with an embodiment.

[0051] The light ranging system **400** may comprise an optical source **402** (such as a VCSEL source or other optical source) and an optical receiver **404**, which may comprise an array of light sensitive pixels. The light ranging system **400** may further comprise one or more TDCs **406**. The number of TDCs may vary from embodiment to embodiment and may depend on the number of light-sensitive pixels of the optical receiver **404**. In various embodiments, the light ranging system **400** may comprise one TDC for each pixel. In various embodiments, the light ranging system **400** may comprise one TDC for each row, or column, of an array of light-sensitive pixels. As will be appreciated, there are multiple ways to configure a TDC in relation to photon detection pixels to accumulate histogram data.

[0052] An optical pulse generated by the optical source may produce photons that are reflected from the object **408**. As these photons are reflected back and hit the array of light sensitive pixels **404**, they may trigger detection events that are transmitted to the TDCs **406**. The TDCs will convert the arrival times of the photons into digital signals that are transmitted to a processor. Depending on when they arrive, the processor (such as processor **126**) may then assign them to a bin of a histogram **410**. The histogram **410** may be accumulated over multiple samples where each sample comprises an optical pulse and the photon count builds on the count from the previous samples. The horizontal axis of the histogram **410** may represent the ToF of the photons. The vertical axis of the histogram **410** may represent the magnitude of the photon count accumulated over one or more samples.

[0053] FIG. 5 depicts a histogram of photon count data in accordance with an embodiment.

[0054] The histogram may be divided into bins. Each bin may correspond to a range of ToF. Photons arriving at a light-sensitive pixel during a given time range may be counted in the corresponding bin. For example, a histogram may cover a time period of 144 nS and it may be

divided into 144 bins. Each of the 144 bins may store a count of the photons detected during a  $nS$  span. Photons detected between emission and 1  $nS$  may be counted in the first bin. Photons detected between  $nS$  and 2  $nS$  may be grouped in a second bin and so on. As mentioned, this count may be accumulated over multiple samples. Photons detected during the time period corresponding to first bin during a second sample may be added to the photon count for the first bin from the first sample. Due to the relationship between distance and time given the constant speed of light, the bins may also be corresponded to distances from the light ranging system. The shorter the time lapse between emission of a light pulse and detection by an optical receiver light sensitive pixels **404** the shorter the distance between the light ranging system and object.

[0055] A histogram **502**, may comprise a first bin **504**, a second bin **506**, continuing on to an Nth bin **508**. The first bin **504** may accumulate as photons are detected during a first time range with respect to a pulse emission. The second bin **506** may accumulate as photons are detected during a second time range with respect to a pulse emission. An Nth bin **508** may accumulate as photons are detected during an Nth time range with respect to a pulse emission. Each bin may have a magnitude that corresponds to the photon count at that bin (the number of detection events sensed during the time range for that bin over one or more samples). This is represented by the vertical axis in FIG. 5. As will be appreciated, the number of bins, and the width (duration of the range) of the bins, and the time period ranged may all vary from embodiment to embodiment.

[0056] Identifying photon count peaks in a histogram can be used to identify the distance of objects from a light ranging system. Multiple objects may produce multiple peaks. Peak detection is thus an important factor for light ranging. Known approaches for peak detection require multiple processing sweeps through a histogram to distinguish peaks from noise or optical effects, identify potential peaks, and fit the peaks.

[0057] FIG. 6 depicts a single-pass method for identifying peaks in a ToF histogram in accordance with embodiments.

[0058] In various embodiments, a single-pass method for identifying peaks comprises an ordered comparison of each bin in a histogram. The ordered comparison may begin at a first bin and continue to the last bin until each bin has been compared with a photon-count threshold. The order of the ordered comparison may be chronological with the first bin in the ordered comparison comprising the photon count for the photons with the shortest ToF in the histogram and the last bin in the ordered comparison comprising the photon count for the photons with the longest ToF in the histogram. In other words, the bin that stores data about the distance closest to a light ranging system (the closest bin) may be the first bin in an ordered comparison and the furthest bin may be the last bin in the ordered comparison. As will be explained more fully in the following paragraphs, results from the comparisons may trigger different operations for the future comparisons with operations being performed on a rolling basis in a single sweep through the histogram.

[0059] A step **602**, for each comparison of the single pass method comprises comparing the photon count of the bin with a threshold. As will be appreciated, a threshold may be determined in different ways in different embodiments. The threshold may be calculated to distinguish signal from noise.

[0060] Depending on the outcome of the comparison, the method will proceed to a next step. If the photon count exceeds the threshold, the method **600** may progress to step **604**. If the photon count is less than the threshold, the method may advance to a step **606**.

[0061] At the step **604**, it may be determined whether peak tracking has been enabled. If peak tracking has been not been enabled, peak tracking is enabled at step **608**. This may be accomplished by setting a flag indicator to a given value. Then, at step **610**, the method advances to the next bin in the ordered comparison at starts again at step **602**. Or, if no more bins are left for comparison the method is finished.

[0062] If at step **604**, it is determined that peak tracking has been previously enabled, a peak-tracking count may be incremented at step **612**. Incrementing a count may be done to track a width



of a pulse that exceeds a photon-count threshold. This width may be used for peak fitting. After incrementing, the method may advance to step **610** and advance to the next bin or finish. In various embodiments, incrementing may be not be necessary if indexing is used to identify peak width. [0063] At step **606**, it may also be determined whether peak tracking has been enabled. If not, the comparison for that bin may be finished and the method may advance to the next bin and return to step **602** (or finish depending on whether there are any bins left for comparison). If peak tracking has been enabled at step **606**, this may trigger the method to advance to peak fitting at a step **612**. At step **612**, one or more peak locations may, or may not, be marked depending on whether preconditions for determining a peak occurred (such as a minimum peak width). After it has been determined whether or not to mark a peak (and where), peaking tracking may be reset at **614** and the method may advance to step **610** to proceed to a next bin (or finish). Resetting peak tracking may allow additional peaks to be detected within a single histogram.

[0064] By way of a example, an ordered comparison may be begin with a first bin at the threshold comparison at step **602**. If the first bin is less than the threshold, the method will proceed to step **606**. Because peak tracking has not been enabled, the method will proceed to step **610**. The second bin will start a step **602** and the method will progress through the bins of the histogram from step **602** to step **606** and on to step **610** until a bin exceeds the threshold comparison.

[0065] At this point, the method will proceed to step **604** and then step **608** where peak tracking is enabled. The method will progress to step **610** and, then, to step **602** for the next bin (or finish). As long as subsequent bins exceed the threshold, the method will progress from step **602** to step **604** to step **612** and onto to step **610**. This will continue until a bin that has a photon count less than the threshold is found at step **602**. This will direct the method to step **606** and on to peak fitting at step **612** because the peak tracking was previously enabled. Peak fitting will be performed (if preconditions are met) and peak fitting reset at step **614** before proceeding to step **610**.

[0066] As will be appreciated, this approach provides a nested methodology where different routines are triggered depending on results from previous comparisons. For example, these nested routines may include a base routine (the threshold comparison), a first nested routine (peak tracking) that is only reached during the base routine after a condition (or conditions) are met, and a second nested routine (peak fitting) that is only reached during the first routine when additional conditions are met. This allows a peak to be identified during a single sweep that triggers the additional routines when needed based on the histogram. As will be appreciated implementation for these steps may vary in different embodiments.

[0067] In various embodiments, the threshold for the threshold comparison may comprise an adaptive threshold. The adaptive threshold may be re-calculated for each bin as the ordered comparison progresses through the histogram.

[0068] FIG. 7 depicts a method for determining an adaptive threshold in accordance with an embodiment.

[0069] In various embodiments, a method **700** for determining an adaptive threshold may comprise at a step **702** assembling a window for comparison. In various embodiments, this may comprise selecting a set of bins for comparison. At a step **704**, the method may comprise sorting the window. In various embodiments, this may comprise ordering the bins in terms of their magnitude (the magnitude of their photon count). And, at a step **706**, the method may comprise selecting determining an adaptive threshold from the window. In various embodiments this may comprise selecting a  $k$ th sample. The  $k$ th may be multiplied by a confidence factor, which may yield the adaptive threshold,  $t_{sub,i}$ , for an  $i$ th bin of a histogram. At a step **708**, the adaptive threshold for the  $i$ th bin,  $t_{sub,i}$ , may be compared with the photon count for the  $i$ th bin,  $h_{sub,i}$ , for example at step **602**. An adaptive threshold for each bin may be determined as the histogram sweep occurs.

[0070] In various embodiments, bins for a window (comparison bins) for an  $i$ th bin may be selected for calculating an adaptive threshold based on their proximity to the  $i$ th bin. For the purposes of reference, when bins are indexed chronologically depending on the ToF of the photons grouped in

the bins, the two closest bins to an ith bin will comprise the two bins adjacent to the ith. By way of further example, for a histogram comprising 144 bins indexed chronologically from 1 to 144 based on their ToF, the bins closest in proximity to the second bin are the first bin and the third bin. [0071] For assembling a window, a guard range may be established surrounding a bin under scrutiny. Bins within the guard range may be excluded from the set of comparison bins. This may be beneficial to prevent bins in the immediate vicinity of a bin under scrutiny from interfering with the adaptive threshold calculation. Guard bins may also be included in a window, as well as the ith bin, even if they are not used for determining an adaptive threshold.

[0072] FIG. 8 depicts a window of bins of a histogram for calculating an adaptive threshold in accordance with an embodiment.

[0073] The set of bins for calculating an adaptive threshold may be taken from a histogram. The window **800** may comprise guard bins flanking an ith bin **801**. The ith bin **801** may be at the center of the window. The ith bin may store the photon count that may be compared with an adaptive threshold calculated from the window **800**. A first set of guard bins **802A** may comprise bins counting photons having ToF less than the bin under scrutiny.

[0074] A second set of guard bins **802B** may comprise bins counting photons having ToF greater than the bin under scrutiny. As will be appreciated, increasing the number of guard bins decreases the likelihood that part of a peak will be grouped into the comparison set used for calculating the adaptive threshold. However, increasing the guard bins can make the comparison more remote from the bin under scrutiny, which may impact the accuracy of the adaptive threshold. The number of guard bins may vary depending on a system and balance these considerations.

[0075] The set of comparison bins used for calculating the adaptive threshold may be formed of two sets of comparison bins comprising N bins each. The number N may be different in various embodiments. A first set of comparison bins **804A** may comprise bins counting photons having ToF less than the bin under scrutiny. A second set of comparison bins **804B** may comprise bins counting photons having ToF greater than the bin under scrutiny. The set of bins used for calculating the adaptive threshold may thus comprise the 2N closest bins to ith bin **802** excluding the guard bins. The window **801** may comprise the first set of comparison bins **804A**, the second set of comparison bins **804B**, the first set of guard bins **802A**, the second set of guard bins **802B**, and the ith bin **801**.

[0076] Once the window is determined, the window may be sorted. In various embodiments, this may occur at step **704**. In various embodiments, this may comprise sorting comparison bins depending on their magnitude (the size of their respective photon counts). For example, set of bins with photon counts [2, 3, 1, 4, 2, 0, 2, 23, 21, 3, 2, 3, 1, 2, 0, 1] may be sorted according to magnitude by magnitude into a set of bins with photon counts [0, 0, 1, 1, 1, 2, 2, 2, 2, 2, 3, 3, 3, 4, 21, 23]. Note that FIG. 8 identifies the magnitude of a bins photon count with a number inside the bin.

[0077] To determine an adaptive threshold value from the sorted set, which may occur at step **706**, a “kth” bin may be selected from the sorted set of comparison bins as a comparison basis for the adaptive threshold. For example, if “k” is set to 12, the 12th largest member of the sorted set may be selected as the comparison basis. Carrying on with this example, the 12th member of the sorted set is 3. The value of “k” may vary in different embodiments. The comparative basis may be multiplied by a confidence factor, which may yield the adaptive threshold. For example, if the comparative basis is 3, and a confidence factor is 2, the adaptive threshold may be 6. Equation 1, below, represents this relationship for calculating an adaptive threshold,  $t_{sub.i}$ , for an ith bin.

[00001]  $t_i = w_i(k)$  Equation 1

[0078] In Equation 1,  $w_{sub.i}$  may be the set of comparison bins for the window, and a is the confidence factor.

[0079] The confidence factor may be a measure of the variance of the histogram and may be selected to reduce the likelihood of false peak detection. With more variance in histogram, it may

be more advantageous to increase the confidence factor. The confidence factor may, itself, be the product of a confidence value and a measure of histogram differential as described by Equation 2.

[00002] 
$$c = s * c \quad \text{Equation 2}$$

[0080] In Equation 2, c is a confidence value, and the s is histogram-differential measure. The confidence value c comprises a tuning parameter. The confidence value may comprise a system specific parameter, which may be set at calibration for unique system configuration. In various embodiments re-calibration may be performed during the lifetime of a device and the confidence may be updated. The histogram differential may be retrieved from a lookup table depending on the difference between the maximum and minimum values of the histogram. Max and min values may be monitored during histogram accumulation using hardware. For example, when the difference between the maximum and minimum values is greater than 5000 photons, the histogram-differential measure s may be set to 2.0. When the difference between the maximum and minimum values is less than 5000 photons but greater than 1000, the histogram-differential measure s may be set to 1.5. When the difference between the maximum and minimum values is less than 1000 photons, the histogram-differential measure s may be set to 1.0. As will be appreciated, the foregoing example is to provide for illustration different values and different rules or ranges for a lookup table may be used in various embodiments. Predefined values and decision-making rules may be system specific. They may relate to laser power and integration time, photon detection efficiency, and alignment with expected signal-to-noise ratio of the system

[0081] In various embodiments the histogram-differential measure s may be calculated. Equation 3 provides a formula for calculating the histogram-differential measure s.

[00003] 
$$s = 1 + \frac{\max(h) - \min(h)}{\max(h)} \quad \text{Equation 3}$$

[0082] In Equation 2, max (h) may refer the maximum photon count in the histogram and min (h) may refer to the minimum photon count in the histogram.

[0083] After a comparison basis has been determined, an adaptive threshold may be determined using the comparison basis and the kth value. This may be used to compare with the photon count at the ith bin, for example, at step 602. And, a new adaptive threshold may be determined for use with the next bin.

[0084] In various embodiments, the progression through a histogram may be referred to as a moving window. As the adaptive threshold for each bin is calculated, the new comparison bins may be used so the window may progress through the histogram. The window for an adaptive threshold may move through the histogram as the ordered comparison advances through the histogram.

[0085] FIG. 9 depicts a window of a histogram in accordance with an embodiment.

[0086] FIG. 9 depicts a histogram 900 of full length. As apparent from FIG. 9, a window 800 centered at an ith bin 801 only spans a portion of the histogram. For example, where a width of the window may be referred to as the number bins included in the respective window, a moving window may comprise a width equal to the sum of the widths of the first set of guard bins 802A, the second set of guard bins 802B, first set of comparison bins 804A, the second set of comparison bins 804B, and ith bin 801. This is described by Equation 4 where G is the number of guard bins.

[00004] 
$$\text{windowwidth} = 2N + 2G + 1 \quad \text{Equation 4}$$

[0087] The window 800 may thus be smaller than overall size of the histogram 900. As will be appreciated, bin selection for a window may need to be adjusted when near the beginning or end of the histogram. For example, when bin under scrutiny is less than G+N bins from the last bin in the ordered comparison the end bins for the window may be selected from the beginning of the histogram. Similarly, when less than G+N bins from the first bin, the bins for the beginning of the window may be selected from the end of the histogram.

[0088] In various embodiments, the adaptive threshold may be calculated according to an Ordered-Statistic-Constant False Alarm Rate algorithm (OS-CFAR). In various embodiments, Cell Averaging CFAR may be utilized, or other approaches. In various embodiments, CFAR may be

adapted for ToF applications using differential histogram measures for self-contained per-pixel weighting.

[0089] FIG. **10** depicts routines for finding peaks in a histogram in accordance with an embodiment.

[0090] After a threshold comparison has been made for a bin (for example at step **708**), the results of the threshold comparison may determine what follows. This may entail triggering peak tracking, moving to a next bin, or finishing the method. Peak tracking may be performed to identify the beginning and end of a peak that corresponds to an optical pulse. An optical pulse emitted by a light ranging system may have a known duration (width). It may be expected that a histogram pulse has a peak width that corresponds to a width of an optical pulse. Peak tracking may identify the rising edge and falling edge pair of a peak. The rising edge may be a first bin exceeding a threshold, and a falling edge may be a last bin exceeding a threshold.

[0091] For an ordered comparison, a method for peak fitting may entail searching for a first bin exceeding a threshold (a rising edge). Before a rising edge is found (before peak tracking has been enabled), the method may progress to a next bin in response to determining a current bin falls below a threshold. For example, if the comparison at step **708** is false (the photo count for an  $i$ th bin,  $h_{sub.i}$ , is less than adaptive threshold  $t_{sub.i}$ ), the method may advance to step **1002** where it is determined whether a rising edge has been found. This may correspond to step **606**, where it is determined whether peak tracking has been enabled and a search for a falling edge is ongoing. If it peak tracking has not been enabled, then the method progresses to step **1003** and advances to the next bin or finishes.

[0092] If the comparison at step **708** is true, the method may advance to step **1004** of a peak tracking method **1000**. Here it may be checked whether peak search is looking for a rising edge (start) or a falling edge (stop). If the search state is looking for a start, a peak start may be stored in **1008**. In various embodiments a flag or other indicator may be toggled to indicate the current peak search state to search to find a rising or falling edge. For example, a flag may be toggled at step **1006** to indicate search for a stop, which may be described as putting the system in a stop-search state. And, the flag may be toggled back to an original state at step **1014** to begin another start search, which may be reached after a stop has been found. This may be referred to as a start-search state. Also, at **1006**, a width count may be initialized for the histogram pulse. The method **1000** may advance to **1003** to advance to the next bin (at step **702**) or finish (if all bins have been searched). The location of a falling edge (stop position) may be initialized at the position of the current bin. This location may be updated if more bins exceeding the threshold are found before the peak search has been completed (before a falling edge has been found).

[0093] Subsequent bins exceeding the threshold while peak searching is enabled may advance to step **1004**. Having already toggled to a stop-search state, the method may advance to step **1010** where the current bin position may be stored as the stop position. The width count may be incremented at **1012**. As long as subsequent bins exceed the threshold while searching for a stop, the width count may be incremented and the stop position updated so the new current replaces the previous bin marked during the last cycle. This will continue until a bin falls below the threshold, which may bypass step **1004** (because the comparison at step **708** is false) and direct the method to step **1005**. If performing a start-start search (as indicated by a flag or other indicator) the method will advance to step **1004** and advance to the next bin or finish. If performing a stop search the method may advance to step **1014** where the flag or other indicator may be toggled and to the peak fitting routine because the peak search indication is enabled. The location of the last bin exceeding the threshold may have been marked as the position of falling edge (stop position) immediately before the falling edge (stop position) was found and a count for each consecutive bin exceeding the threshold may have been collected while consecutive bins exceeding the threshold were compared with the threshold. It should be appreciated, the state may be switched from start-search to stop search (or vice versa) in a different sequence in different embodiments. For example, step

**1014** may be performed after peak fitting or step **1006** may be performed after incrementing a width counter.

[0094] As will be appreciated, a single-pass method to identify peaks consistent with embodiments allows identification of multiple targets in a field of view. Cross-talk and other parasitic reflections may be detected as a target output. Differentiation in post-processing using the peaks identified by a single-pass method may be utilized to filter parasitic reflections.

[0095] A single-pass method for identifying peaks in a ToF histogram may comprise a combination of methods such a method **700** for determining an adaptive threshold, a peak tracking method **1000**, and a peak fitting method **1100**.

[0096] FIG. **11** depicts a peak fitting method in accordance with an embodiment.

[0097] In various embodiments a peak fitting method **1100** may determine if a histogram pulse detected during peak tracking exceeds a minimum width threshold at a step **1102**. This may be advantageous to filter out small transient artifacts in the histogram data, which may falsely trigger peak identification. The minimum width threshold may comprise a number of bins. Determining a width of a histogram pulse may comprise identifying a number of bins between the bin exceeding the adaptive threshold (rising edge) and the bin falling below the adaptive threshold (falling edge). This may be accomplished using a width count accumulated during peak tracking. The width of a histogram pulse may also be determined from the difference between the index of a rising edge and the index of a falling edge of the pulse, both of which may have been marked during peak tracking. The minimum width threshold, which may be referred to as a minimum peak width, can be determined from the width of an optical pulse emitted into a system. For example, the it may be a full-width half-maximum width (FWHM) of an optical pulse emitted for light ranging. It should be appreciated that the minimum peak width may vary from embodiment to embodiment. It may be wider or narrower than the FWHM. A narrower minimum peak width may be advantageous in some embodiments to detect more close targets and merged targets, while a wider width may be desirable to allow detection of weaker targets.

[0098] At step **1102**, the width of the pulse in the histogram may be compared with the minimum width threshold. If the pulse width from the histogram data is less than the minimum width threshold, the histogram pulse may be discarded and the method may progress to step **1104**. At step **1104**, peak tracking may be reset. This may allow the single-pass method for identifying peaks in a ToF histogram to begin looking for rising edges again (instead of looking for falling edges). In various embodiments, the step **1104** may comprise resetting the status of a flag or other indicator to a value that disables peak tracking. Various data may also be output also at step **1104**. These may include various confidence metrics such as confidence ratio or signal-to-noise ratio. From step **1104**, the method may progress to step **1003** and advances to the next bin of the ordered comparison or finish.

[0099] If the pulse width from the histogram is greater than the width threshold at step **1102**, the method may advance to step **1106** which comprises marking a peak location (or peak locations) between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold. This may comprise marking the peak location at a median location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold. In various embodiments, the single-pass method for identifying peaks in a ToF histogram may further comprise tracking the number of peaks marked during the single pass. This may comprise incrementing a tracker each time peak is marked.

[0100] In various embodiments, the peak fitting method may also determine whether a single pulse segment spans multiple objects in the field of view. If more than one object in a field of view are close together or at similar distances from a light-ranging system, photons reflected from them and detected by an optical receiver may produce a single large pulse in a histogram rather than multiple individual pulses. To account for this, the width of a histogram pulse, at step **1106**, may also be compared with a maximum width threshold. Again, the width of a histogram pulse may be

determined from a count during peak tracking and from indexes of the rising edge and falling edge. If the histogram pulse exceeds the maximum-width threshold multiple pulses may be fit between the rising edge and falling edge.

[0101] In various embodiments, the maximum pulse width may be set to be one bin greater than the full-width half-maximum width of the optical pulse emitted by a light ranging system. After determining that a width of a histogram pulse exceeds the minimum width at step **1102**, it may then be determined the histogram pulse is less than the maximum width. If the histogram pulse width is less than the maximum width, a single pulse may be fit between the rising and falling edges of the histogram pulse.

[0102] If the histogram pulse width is greater than the maximum width threshold, a first peak may be marked, and it may be determined whether to mark additional peaks. In various embodiments a first start position bin may be set to the rising edge (start position) determined by the peak tracking method while a first stop position bin may be set so the width of a first histogram pulse is equal to the full-width half-maximum width of the optical pulse emitted by the light-ranging system. In other words, the distance between the first start position bin and first stop position bin may be set to be equal to the full-width half-maximum width of the optical pulse emitted by the light-ranging system equation. And, a first peak may be marked between the first start position bin and the stop position bin (for example at a median position). A second start position may also be declared at this first stop position.

[0103] Any second width (width beyond the first stop position and second start position) may be compared with a minimum width threshold for subsequent peaks to determine whether to set a second peak. In various embodiments, the minimum width threshold for subsequent peaks may be equal to the minimum width threshold. For example, the remaining width (width between the second start position and the falling edge identified by the peak tracking method) may be compared to minimum width threshold to determine if a second peak should be marked. In various embodiments, the minimum width threshold for subsequent peaks may be different than the minimum width threshold for the first peak. For example, the minimum width threshold for subsequent peaks may be set equal to  $2G$ , where  $G$  is the number of guard bins.

[0104] If the minimum width threshold for subsequent peaks is exceeded by the remaining width, a second peak may be set between the stop position and associated second start position and the falling edge determined by the peak tracking method. In various embodiments, the second start position bin may be set at a bin that is located at the falling edge determined by the peak tracking algorithm minus the full-width half-maximum width of the optical pulse, or at the first stop position bin (whichever is wider). A second peak can then be fit between the second start position and the falling edge using the same approach used for the first peak. As will be appreciated, additional peaks (beyond the second peak) may also be added until the remaining width is less than the minimum width threshold for subsequent peaks.

[0105] In various embodiments, subsequent peaks may be discarded if a photon detector afterpulsing confidence score for the second peak is less than an afterpulsing confidence score threshold. Afterpulsing is due to “trapped photons” in deeper silicon layers, which cause delayed responses due to charge carrier diffusion. In other words, charge is trapped, which is slowly released after bulk photon absorption. This may cause an apparent elevated signal level at the end of a response pulse. In various embodiments, after a second peak is fit, an afterpulsing confidence score may be calculated to determine whether the shape of the tail of the histogram pulse comprises afterpulsing caused by trailing effects of the optical receiver hardware (such as a SPAD). If the afterpulsing confidence score for the second peak is too low, the second peak may be discarded.

[0106] An example confidence metric is provided as the sum of the photon count from the histogram,  $h$ , and the adaptive threshold,  $t$ , for a  $n$ th identified target as described in Equation 5.

$$[00005] \text{ Confidence}_n = \frac{\text{Math.} \sum_{i=\text{start}_n}^{\text{stop}_n} h(i)}{t(i)} \quad \text{Equation 5}$$

[0107] In various embodiments, the second peak,  $n$ , in a merged peaked cluster may be rejected if the first peak,  $n-1$ , is dramatically larger to reject elevated signal levels due to afterpulsing. A positive factor,  $p < 1$ , may be set to determine whether to reject such target, e.g.  $p=0.4$ :

[00006] Reject target  $n$  if  $\text{Confidence}_n < p \times \text{Confidence}_{n-1}$

[0108] As will be appreciated, in various embodiments, other peak fitting approaches may be utilized to mark the location of the peak or peaks.

[0109] FIG. 12 depicts a light-ranging system in accordance with an embodiment.

[0110] In various embodiments, a light-ranging system **1200** may comprise an optical source **402** configured to emit optical pulses for light-ranging. The light-ranging system **1200** may further comprise an optical receiver **404** configured to detect photons; and one or more time to digital converters **406** in communication with the optical receiver and configured to output times of flight of photons detected by the optical receiver **404**. The light-ranging system **1200** may further comprise a processor **426** in communication with the one or more time to digital converters **406** to receive the times of flight of photons detected by the optical receiver **404** and store them in a time of flight histogram. The time of flight histogram may be stored in a register **1202** or other appropriate memory. The light-ranging system may further comprise a memory **432** storing an instruction set that, when executed, causes the processor **426** to begin an ordered comparison of each bin in the time of flight histogram with an adaptive threshold until a bin exceeding the adaptive threshold is found, each bin of the histogram representing a photon count corresponding to a distance from the light-ranging system; continue the ordered comparison after finding the bin exceeding the adaptive threshold until a bin falling below the adaptive threshold is found; determine a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; find the width exceeds a width threshold; mark a peak location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; and continue the ordered comparison until each bin has been compared with the adaptive threshold one time.

[0111] The memory may comprise a non-transient computer readable memory. In various embodiments, the light-ranging system may comprise a system on a chip, or application specific integrated circuit.

[0112] In various embodiments, sorting for a window may be performed using sorting circuitry **1204**. As will be appreciated, sorting the bins of a window based on the magnitude of their photon counts may be accomplished with a fixed number of operations. In various embodiments, a simple sorting network may be utilized. An adaptive threshold may be advantageous because it allows smaller sets of bins for comparisons, which in turn may allow hardware implementation for sorting. Hardware may implement a Bose-Nelson sorting algorithm or other sorting methods.

[0113] FIG. 13 depicts a method to identify peaks in a histogram in accordance with an embodiment.

[0114] In various embodiments, the method **1300** may comprise at a step **1302**, beginning an ordered comparison of each bin in the histogram with an adaptive threshold until finding a bin exceeding the adaptive threshold, each bin of the histogram representing a photon count corresponding to a distance from a light-ranging system; at a step **1304**, continuing the ordered comparison after finding the bin exceeding the adaptive threshold until finding a bin falling below the adaptive threshold; at a step **1306**, determining a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; at a step **1308**, finding the width exceeds a width threshold; at a step **1310**, marking a peak location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; and at a step **1312**, continuing the ordered comparison until each bin has been compared with the adaptive

threshold one time.

[0115] In various embodiments, the method **1300** may further comprise, finding an other bin exceeding the adaptive threshold after marking the peak location, finding an other bin falling below the adaptive threshold, determining an other width by identifying an other number of bins between the other bin exceeding the adaptive threshold and the other bin falling below the adaptive threshold, and marking an other peak location between the other bin exceeding the adaptive threshold and the other bin falling below the adaptive threshold.

[0116] In various embodiments, the method **1300** may further comprise, calculating the adaptive threshold using Ordered Statistics-Constant False Alarm Rate.

[0117] In various embodiments, the method **1300** may further comprise, calculating the adaptive threshold for each bin.

[0118] In various embodiments, the method **1300** may further comprise, wherein calculating the adaptive threshold for each bin comprises selecting a set of bins for comparison, ordering the bins based on magnitude, and selecting a kth bin as a comparison basis.

[0119] In various embodiments, the method **1300** may further comprise, wherein the adaptive threshold is calculated for each bin by multiplying the comparison basis by a confidence factor.

[0120] In various embodiments, the method **1300** may further comprise, wherein determining the width comprises incrementing a count initialized when finding the bin exceeding the adaptive threshold and continued until finding the bin falling below the adaptive threshold.

[0121] In various embodiments, the method **1300** may further comprise, determining the width is less than a full width half maximum of a pulse width used by the light-ranging system to collect the photon count of each bin, and wherein marking the peak location comprises marking the peak location at a median location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold.

[0122] In various embodiments, the method **1300** may further comprise, determining the width is greater than a full width half maximum of a pulse width used by the light-ranging system to collect the photon count of each bin, assigning a stop position bin, a width between the stop position bin and the bin exceeding the adaptive threshold being approximately equal to the full width half maximum of the pulse width, and wherein marking the peak location comprises marking the peak location a median position between the bin exceeding the adaptive threshold and the stop position bin.

[0123] In various embodiments, the method **1300** may further comprise, determining a width between the stop-position bin and the bin falling below the adaptive threshold is greater than a minimum width threshold for subsequent peaks, marking a second peak location between the peak location and the bin falling below the adaptive threshold.

[0124] FIG. **14** depicts a single-pass method for identifying peaks in a time of flight histogram in accordance with an embodiment.

[0125] In various embodiments, the method **1400** may comprise, at a step **1402**, conducting an ordered comparison of each bin with an adaptive threshold until finding a bin that exceeds the adaptive threshold; at a step **1404**, enabling peak tracking in response to finding the bin that exceeds the adaptive threshold; at a step **1406**, in response to enabling peak tracking, continuing the ordered comparison of each bin with the adaptive threshold until finding a bin that falls below the adaptive threshold; and [0126] at a step **1408**, in response to finding the bin that falls below the adaptive threshold, marking a peak location between the bin exceeding the adaptive threshold and the bin that falls below the adaptive threshold.

[0127] In various embodiments, the method **1400** may further comprise, in response to finding the bin that falls below the adaptive threshold, disabling peak tracking.

[0128] In various embodiments, the method **1400** may further comprise, in response to disabling peak tracking, continuing the ordered comparison of each bin with the adaptive threshold until finding another bin exceeding the adaptive threshold.



[0129] In various embodiments, the method **1400** may further comprise, wherein enabling peak tracking comprises setting a flag to a peak-tracking value.

[0130] In various embodiments, the method **1400** may further comprise, wherein disabling peak tracking comprises restoring the flag to an original value.

[0131] Example 1. A method to identify peaks in a histogram: the method including beginning an ordered comparison of each bin in the histogram with an adaptive threshold until finding a bin exceeding the adaptive threshold, each bin of the histogram representing a photon count corresponding to a distance from a light-ranging system; continuing the ordered comparison after finding the bin exceeding the adaptive threshold until finding a bin falling below the adaptive threshold; determining a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; finding the width exceeds a width threshold; marking a peak location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; and continuing the ordered comparison until each bin has been compared with the adaptive threshold one time.

[0132] Example 2. The method of Example 1, further including finding an other bin exceeding the adaptive threshold after marking the peak location, finding an other bin falling below the adaptive threshold, determining an other width by identifying an other number of bins between the other bin exceeding the adaptive threshold and the other bin falling below the adaptive threshold, and marking an other peak location between the other bin exceeding the adaptive threshold and the other bin falling below the adaptive threshold.

[0133] Example 3. The method of Example 1 or Example 2, further including calculating the adaptive threshold using Ordered Statistics-Constant False Alarm Rate.

[0134] Example 4. The method of Example 1 through Example 3, further including calculating the adaptive threshold for each bin.

[0135] Example 5. The method of Example 1 through Example 4, wherein calculating the adaptive threshold for each bin includes selecting a set of bins for comparison, ordering the bins based on magnitude, and selecting a kth bin as a comparison basis.

[0136] Example 6. The method of Example 1 through Example 5, wherein the adaptive threshold is calculated for each bin by multiplying the comparison basis by a confidence factor.

[0137] Example 7. The method of Example 1 through Example 6, wherein determining the width includes incrementing a count initialized when finding the bin exceeding the adaptive threshold and continued until finding the bin falling below the adaptive threshold.

[0138] Example 8. The method of Example 1 through Example 7, further including determining the width is less than a full width half maximum of a pulse width used by the light-ranging system to collect the photon count of each bin, and wherein marking the peak location includes marking the peak location at a median location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold.

[0139] Example 9. The method of Example 1 through Example 8, further including determining the width is greater than a full width half maximum of a pulse width used by the light-ranging system to collect the photon count of each bin, assigning a stop position bin, a width between the stop position bin and the bin exceeding the adaptive threshold being approximately equal to the full width half maximum of the pulse width, and wherein marking the peak location includes marking the peak location a median position between the bin exceeding the adaptive threshold and the stop position bin.

[0140] Example 10. The method of Example 1 through Example 9, further including determining a width between the stop-position bin and the bin falling below the adaptive threshold is greater than a minimum width threshold for subsequent peaks, marking a second peak location between the peak location and the bin falling below the adaptive threshold.

[0141] Example 11. A single-pass method for identifying peaks in a time of flight histogram, the single-pass method including: conducting an ordered comparison of each bin with an adaptive

threshold until finding a bin that exceeds the adaptive threshold; enabling peak tracking in response to finding the bin that exceeds the adaptive threshold; in response to enabling peak tracking, continuing the ordered comparison of each bin with the adaptive threshold until finding a bin that falls below the adaptive threshold; and in response to finding the bin that falls below the adaptive threshold, marking a peak location between the bin exceeding the adaptive threshold and the bin that falls below the adaptive threshold.

[0142] Example 12. The single-pass method of Example 11, further including, in response to finding the bin that falls below the adaptive threshold, disabling peak tracking.

[0143] Example 13. The single-pass method of Example 11 or Example 12, further including, in response to disabling peak tracking, continuing the ordered comparison of each bin with the adaptive threshold until finding another bin exceeding the adaptive threshold.

[0144] Example 14. The single-pass method of Example 11 through Example 13, wherein enabling peak tracking includes setting a flag to a peak-tracking value.

[0145] Example 15. The single-pass method of Example 11 through Example 14, wherein disabling peak tracking includes restoring the flag to an original value.

[0146] Example 16. A light-ranging system including: an optical source configured to emit optical pulses for light-ranging; an optical receiver configured to detect photons; a time to digital converter in communication with the optical receiver and configured to output times of flight of photons detected by the optical receiver; and a processor in communication with the time to digital converter to receive times of flight of photons detected by the optical receiver and store them in a time of flight histogram; a memory storing an instruction set that, when executed, causes the processor to begin an ordered comparison of each bin in the time of flight histogram with an adaptive threshold until a bin exceeding the adaptive threshold is found, each bin of the times of flight histogram representing a photon count corresponding to a distance from the light-ranging system; continue the ordered comparison after finding the bin exceeding the adaptive threshold until a bin falling below the adaptive threshold is found; determine a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; find the width exceeds a width threshold; mark a peak location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold; and continue the ordered comparison until each bin has been compared with the adaptive threshold one time.

[0147] Example 17. The light-ranging system of Example 16, the width is determined by incrementing a count initialized when finding the bin exceeding the adaptive threshold and continued until finding the bin falling below the adaptive threshold.

[0148] Example 18. The light-ranging system of Example 16 or Example 17, wherein the peak location is marked at a median location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold.

[0149] Example 19. The light-ranging system of Example 16 through Example 18, wherein the adaptive threshold is calculated using Ordered Statistics-Constant False Alarm Rate.

[0150] Example 20. The light-ranging system of Example 16 through Example 17, wherein the adaptive threshold is calculated for each bin.

[0151] While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments, as well as other embodiments of the invention, will be apparent to persons skilled in the art upon reference to the description. It is therefore intended that the appended claims encompass any such modifications or embodiments.

## Claims

1. A light-ranging system comprising: an optical source configured to emit optical pulses for light-ranging; an optical receiver configured to detect photons; a time to digital converter in

communication with the optical receiver and configured to output times of flight of photons detected by the optical receiver; and a processor in communication with the time-to-digital converter to receive times of flight of photons detected by the optical receiver and store them in a time-of-flight histogram; a memory storing an instruction set that, when executed, causes the processor to: begin an ordered comparison of each bin in the time of flight histogram with an adaptive threshold until a bin exceeding the adaptive threshold is found, each bin of the times of flight histogram representing a photon count corresponding to a distance from the light-ranging system, continue the ordered comparison after finding the bin exceeding the adaptive threshold until a bin falling below the adaptive threshold is found, determine a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold, find the width exceeds a width threshold, mark a peak location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold, and continue the ordered comparison until each bin has been compared with the adaptive threshold one time.

**2.** The light-ranging system of claim 1, wherein the width is determined by incrementing a count initialized when finding the bin exceeding the adaptive threshold and continued until finding the bin falling below the adaptive threshold.

**3.** The light-ranging system of claim 1, wherein the peak location is marked at a median location between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold.

**4.** The light-ranging system of claim 1, wherein the adaptive threshold is calculated using Ordered Statistics-Constant False Alarm Rate.

**5.** The light-ranging system of claim 1, wherein the adaptive threshold is calculated for each bin.

**6.** The light-ranging system of claim 5, wherein calculating the adaptive threshold for each bin comprises selecting a set of bins for comparison, ordering the bins based on magnitude, and selecting a  $k$ th bin as a comparison basis.

**7.** The light-ranging system of claim 6, wherein the adaptive threshold is calculated by multiplying the comparison basis by a confidence factor.

**8.** A light-ranging system, comprising: an optical source configured to emit optical pulses for light-ranging; an optical receiver configured to detect photons; a time to digital converter in communication with the optical receiver and configured to output times of flight of photons detected by the optical receiver; and a processor in communication with the time to digital converter to receive times of flight of photons detected by the optical receiver and store them in a time of flight histogram; a memory storing an instruction set that, when executed, causes the processor to: conduct an ordered comparison of each bin with an adaptive threshold until finding a bin that exceeds the adaptive threshold, enable peak tracking in response to finding the bin that exceeds the adaptive threshold, in response to enabling peak tracking, continue the ordered comparison of each bin with the adaptive threshold until finding a bin that falls below the adaptive threshold; in response to finding the bin that falls below the adaptive threshold, mark a peak location between the bin exceeding the adaptive threshold and the bin that falls below the adaptive threshold; and determine a distance to an object in a field of view of a light-ranging system based on the marked peak location.

**9.** The light-ranging system of claim 8, wherein the instruction set, when executed, causes the processor to, in response to finding the bin that falls below the adaptive threshold, disable peak tracking.

**10.** The light-ranging system of claim 9, wherein the instruction set, when executed, causes the processor to, in response to disabling peak tracking, continue the ordered comparison of each bin with the adaptive threshold until finding another bin exceeding the adaptive threshold.

**11.** The light-ranging system of claim 8, wherein enabling peak tracking comprises setting a flag to a peak-tracking value.

**12.** The light-ranging system of claim 11, wherein disabling peak tracking comprises restoring the flag to an original value.

- 13.** The light-ranging system of claim 8, wherein the instruction set, when executed, further causes the processor to determine a width by identifying a number of bins between the bin exceeding the adaptive threshold and the bin falling below the adaptive threshold.
- 14.** The light-ranging system of claim 13, wherein the instruction set, when executed, further causes the processor to compare the width with a minimum width threshold before marking the peak location.
- 15.** A light-ranging system comprising: a non-transitory memory storage comprising instructions; and a processor coupled to the non-transitory memory storage, wherein the processor executes the instructions to: emit, by an optical source, optical pulses for light ranging, detect, by an optical receiver, photons, output, by a time to digital converter, times of flight of photons detected by the optical receiver, determine, using an ordered comparison, a first bin from a plurality of bins in the histogram that exceeds an adaptive threshold, each bin representing a photon count corresponding to a distance from the light-ranging system to an object in its field of view, determine, by continuing the ordered comparison after determining the first bin, a second bin that falls below the adaptive threshold, mark a peak location between the first bin and the second bin in response to a width identified as a quantity of bins between the first bin and the second bin exceeds a width threshold, continue the ordered comparison until each bin has been compared with the adaptive threshold once, and determine the distance to the object based on the marked peak location.
- 16.** The light-ranging system of claim 15, wherein the width is determined by incrementing a count initialized when finding the first bin and the second bin.
- 17.** The light-ranging system of claim 15, wherein the peak location is marked at a median location between the first bin and the second bin.
- 18.** The light-ranging system of claim 15, wherein the adaptive threshold is calculated using Ordered Statistics-Constant False Alarm Rate.
- 19.** The light-ranging system of claim 18, wherein the adaptive threshold is calculated for each bin.
- 20.** The light-ranging system of claim 15, wherein the optical receiver comprises single-photon avalanche diodes, and wherein the plurality of light-sensitive pixels are arranged in an array.
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