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Mimeault

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(54) **DISTANCE DETECTION METHOD AND SYSTEM**

(56) **References Cited**

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Akindinov et al., "Detection of Light Pulses Using an Avalanche-Photodiode Array with a Metal-Resistor-Semiconductor Structure", Instruments and Experimental Techniques, Nov. 2004, vol. 48, No. 3 205, pp. 355-363, Russia.

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(51) **Int. Cl.**
G01C 3/08 (2006.01)
G01S 7/487 (2006.01)

(57) **ABSTRACT**

There is provided a system and method for detecting a distance to an object. The method comprises providing a lighting system having at least one pulse width modulated visible-light source for illumination of a field of view; emitting an illumination signal for illuminating the field of view for a duration of time y using the visible-light source at a time t ; integrating a reflection energy for a first time period from a time $t-x$ to a time $t+x$; determining a first integration value for the first time period; integrating the reflection energy for a second time period from a time $t+y-x$ to a time $t+y+x$; determining a second integration value for the second time period; calculating a difference value

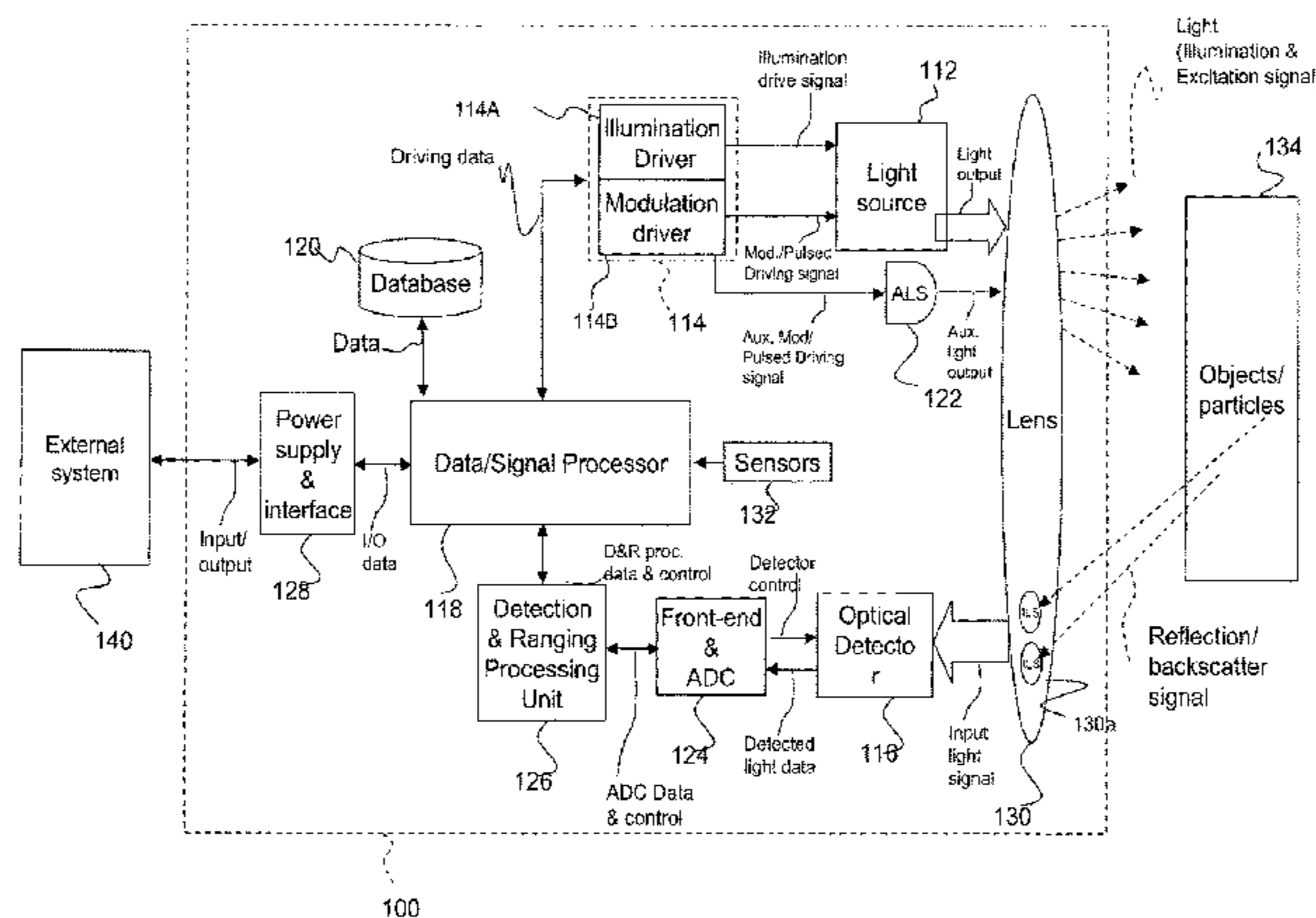
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CPC **G01S 7/487** (2013.01); **G01S 7/4861** (2013.01); **G01S 7/4865** (2013.01); **G01S 17/10** (2013.01); **G01S 7/003** (2013.01)

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CPC . G01S 7/34; G01S 7/282; G01S 7/285; G01S 7/481; G01S 7/483; G01S 7/484;

(Continued)



between the first integration value and the second integration value; determining a propagation delay value proportional to the difference value; determining the distance to the object from the propagation delay value.

3 Claims, 17 Drawing Sheets

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G01S 17/10 (2006.01)
G01S 7/00 (2006.01)
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 CPC G01S 7/487; G01S 7/493; G01S 7/497;
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 G01S 13/9303; G01S 17/32; G01S 17/36;
 G01S 17/105; G01C 3/08; G02B 5/136;
 B60K 31/0008
 USPC 180/167, 169; 250/208.1, 559.38; 327/1,
 327/4.01, 4.06, 5.01, 5.03, 5.06, 28, 72,
 327/149; 342/70, 110, 118, 135, 137
 See application file for complete search history.

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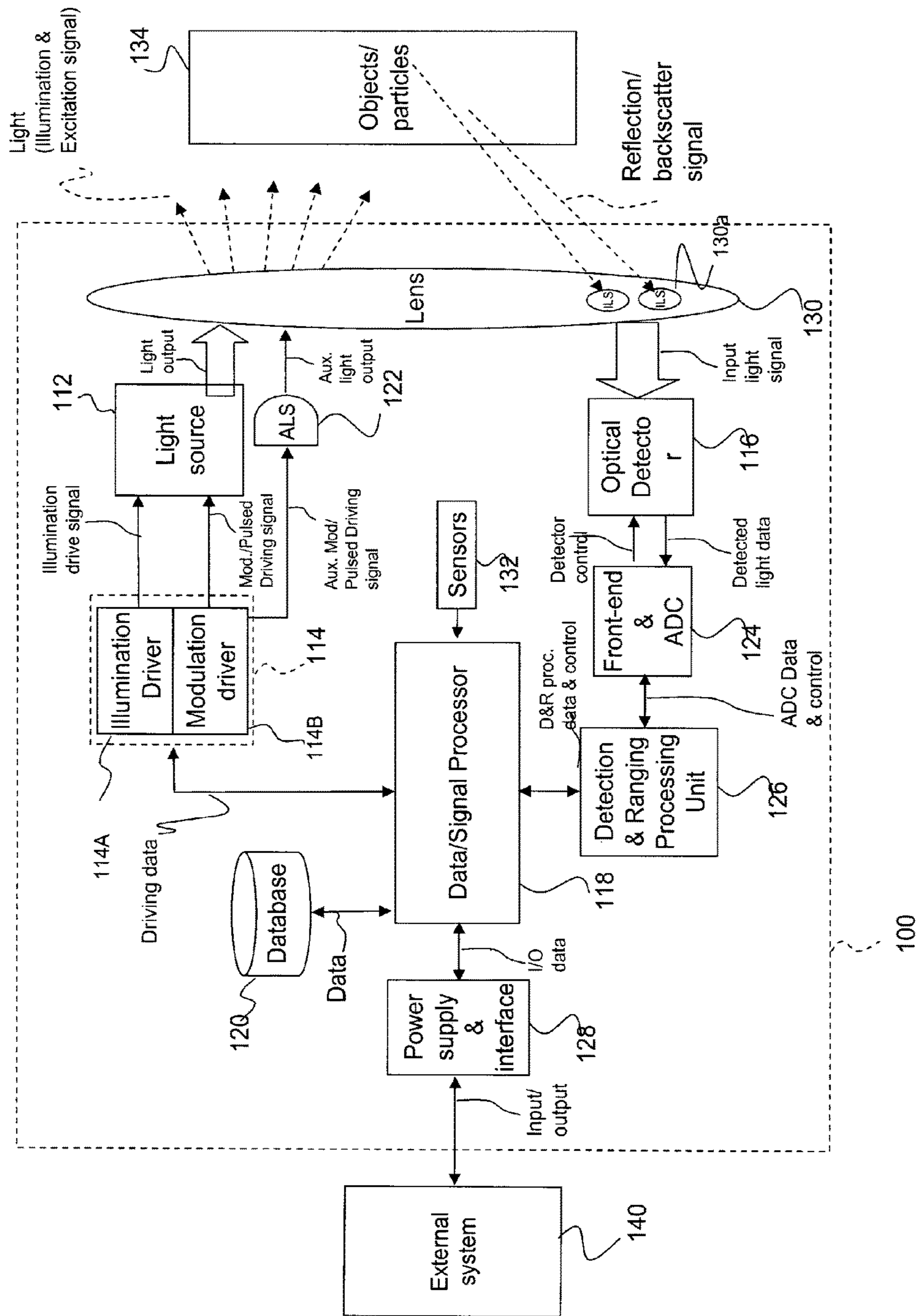


Figure 1

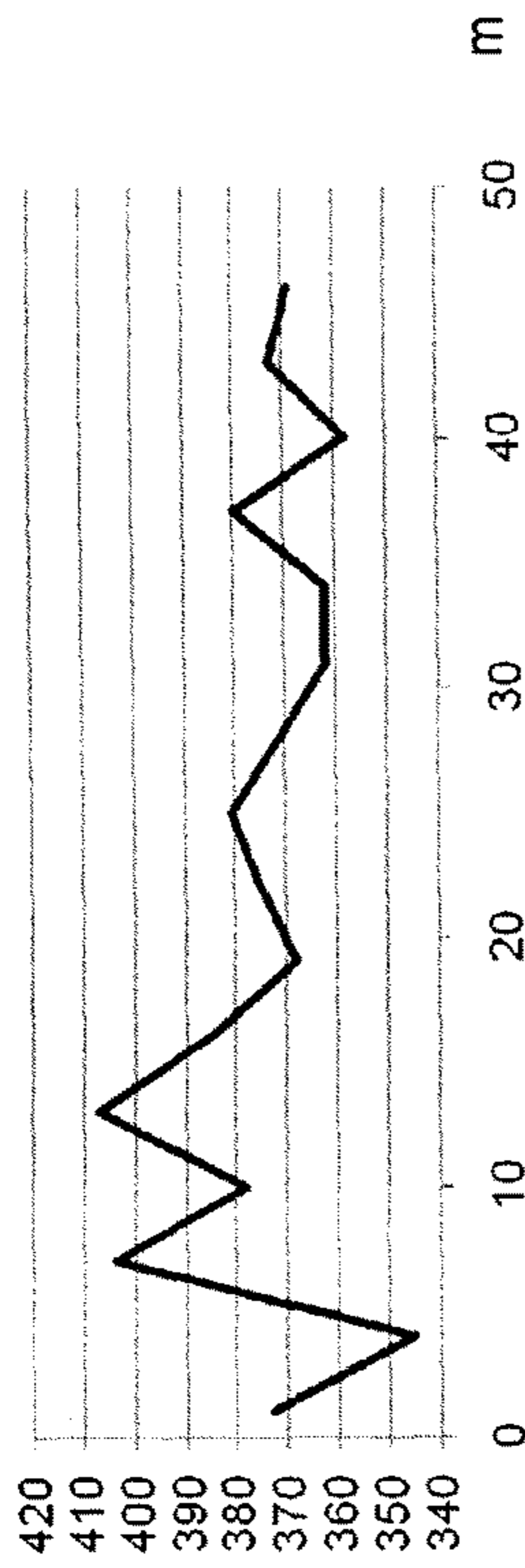


Figure 2a

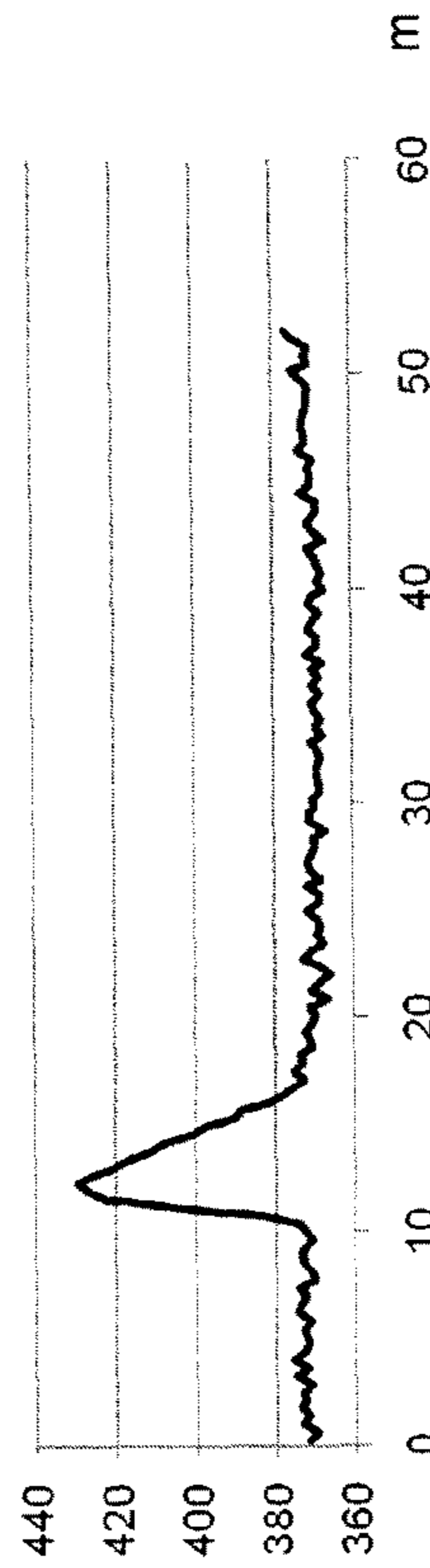


Figure 2b

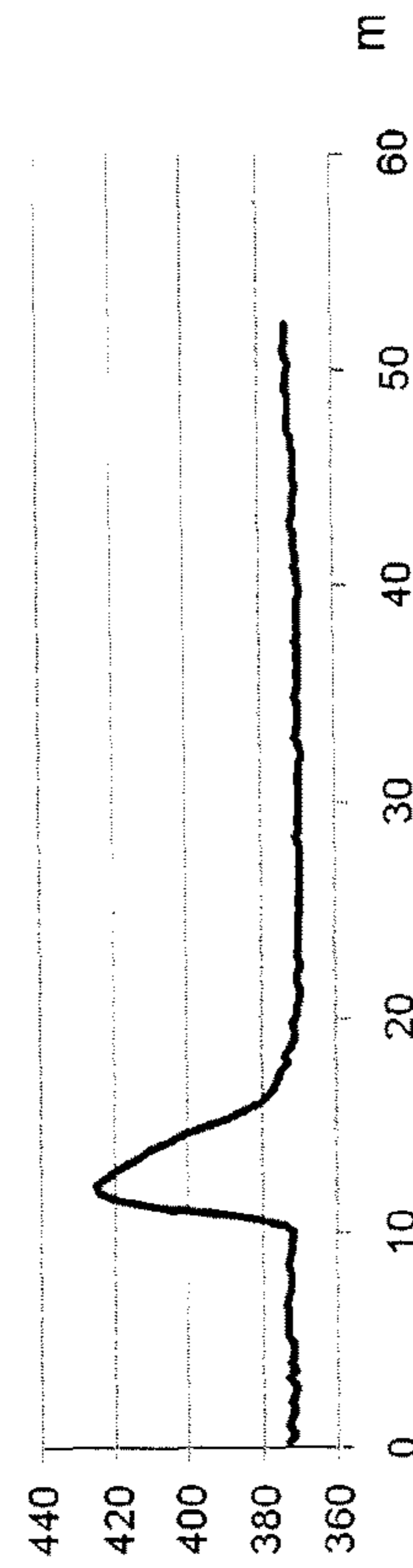


Figure 2c

Source 50KHz
 ADC 50MSPS

Range (m)	1/R2	Shift_step	Refresh Rate	Resolution (m)	Accumulation	S/N	Gain
1	100.00	128	100	0.02	4	70.71	0.71
10	1.00	64	100	0.05	8	1.00	1.00
20	0.25	32	100	0.09	16	0.35	1.41
30	0.11	16	100	0.19	31	0.22	2.00
40	0.06	16	50	0.19	63	0.18	2.83
50	0.04	8	50	0.38	125	0.16	4.00
60	0.03	8	50	0.38	125	0.11	4.00
70	0.02	4	25	0.75	500	0.16	8.00
80	0.02	4	25	0.75	500	0.13	8.00
90	0.01	2	10	1.50	2500	0.22	17.89
100	0.01	2	10	1.50	2500	0.18	17.89

Figure 3

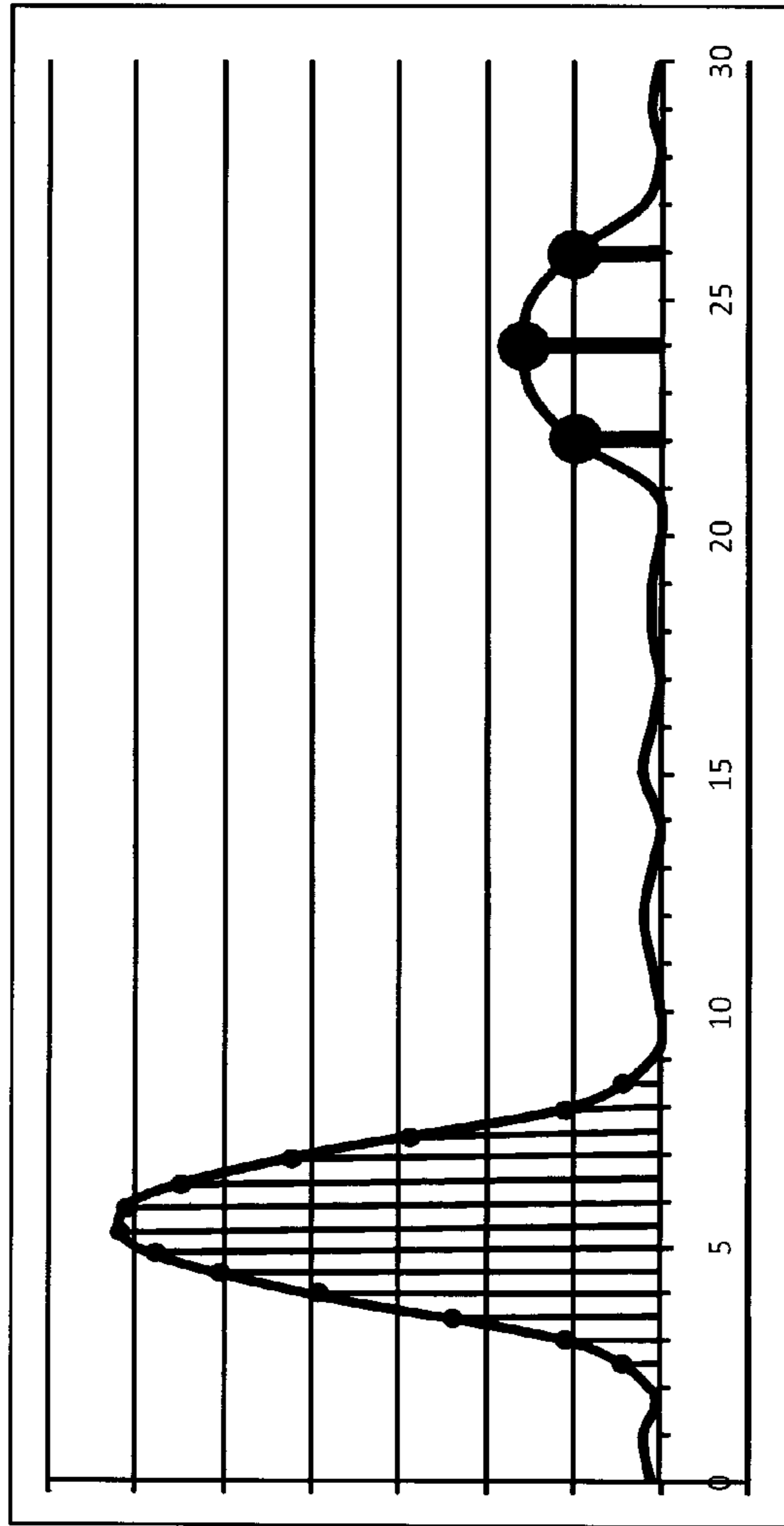


Figure 4

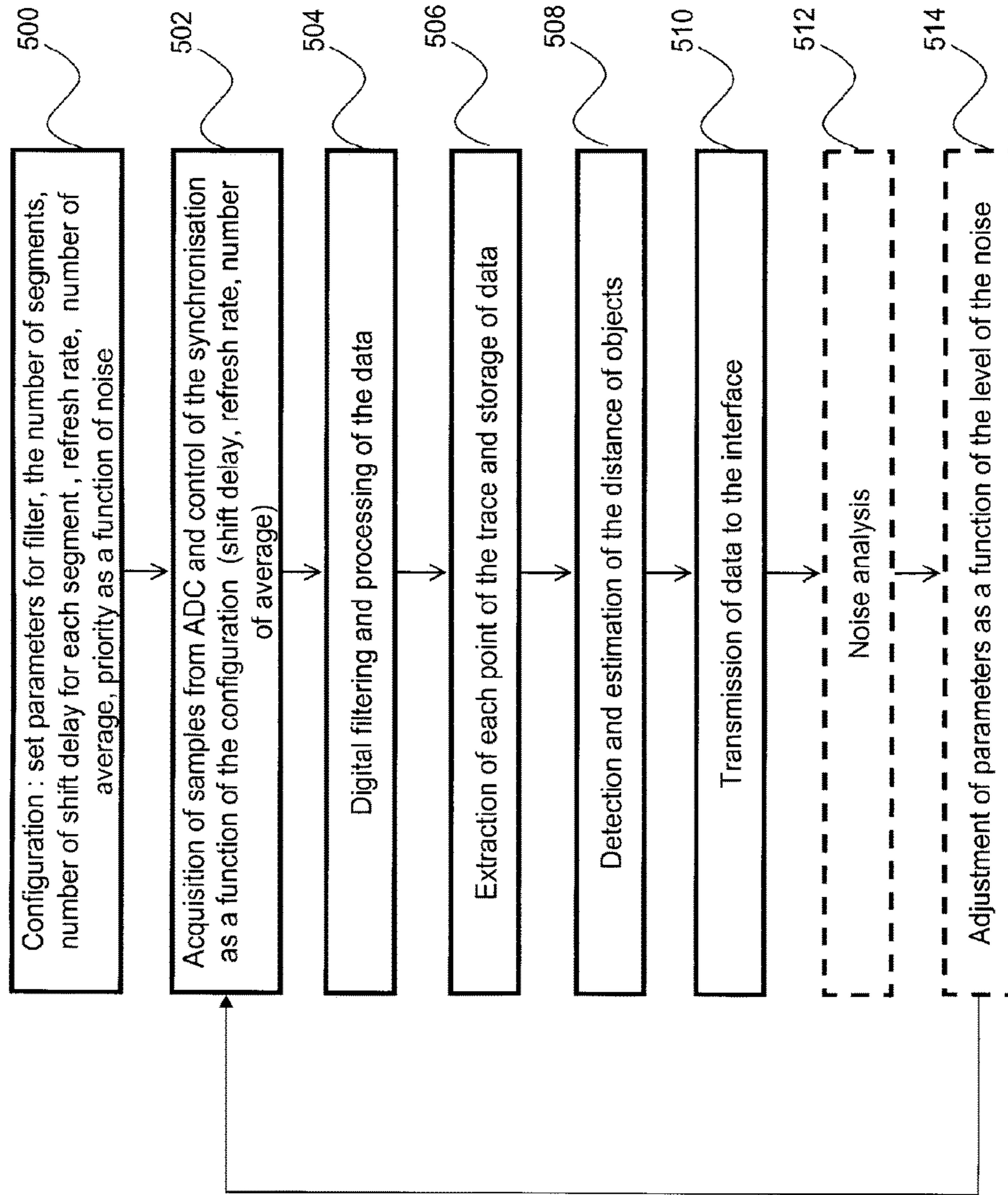


Fig. 5

P=20
D=5ns

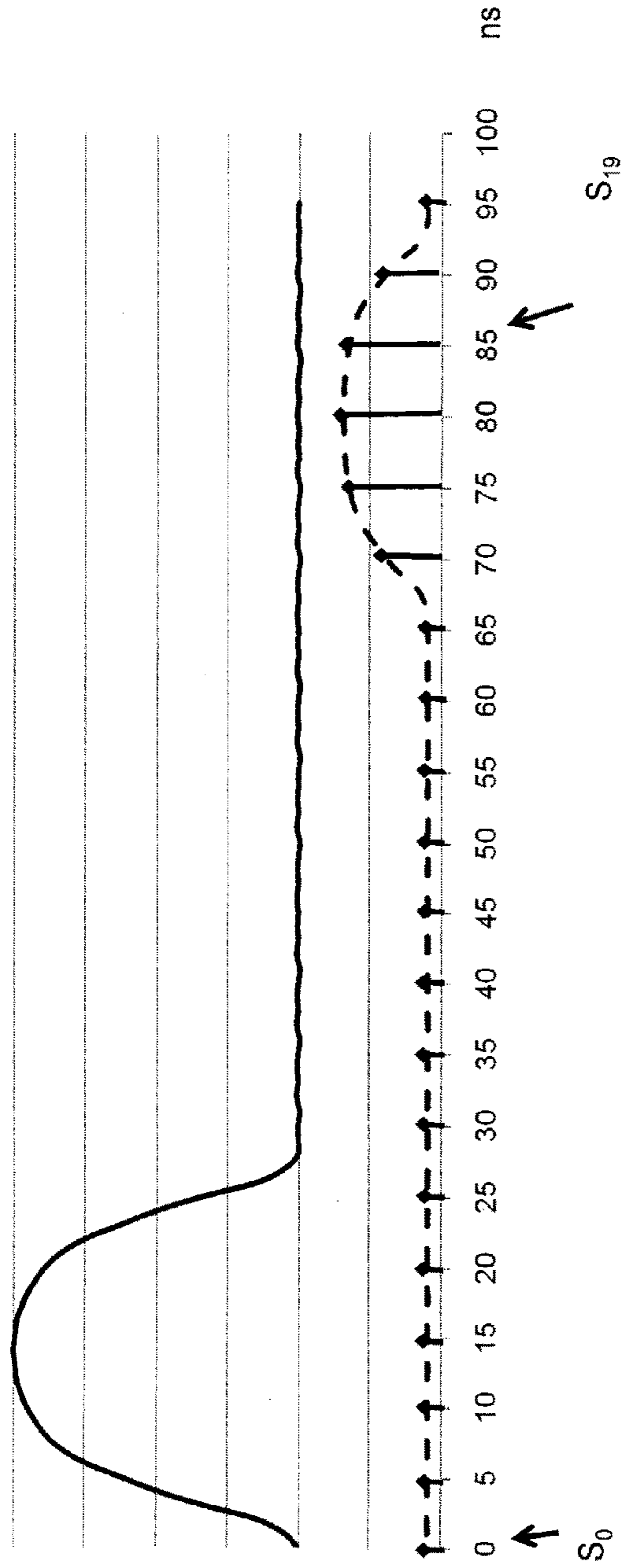


Fig. 6

Optical pulse
 Frequency: 100KHz
 Width: 20ns

Max Range (m)	Time for reflected back signal (ns)	Shift step (ns)	Number of step	Refresh Rate (Hz)	Accumulation	S/N improvement by accumulation
10	85	1	85	1	1176	34
10	85	1	85	10	118	11
10	85	5	17	1	5882	77
10	85	5	17	10	588	24
30	215	1	215	1	465	22
30	215	1	215	10	47	7
30	215	5	43	1	2326	48
30	215	5	43	10	233	15

Figure 7

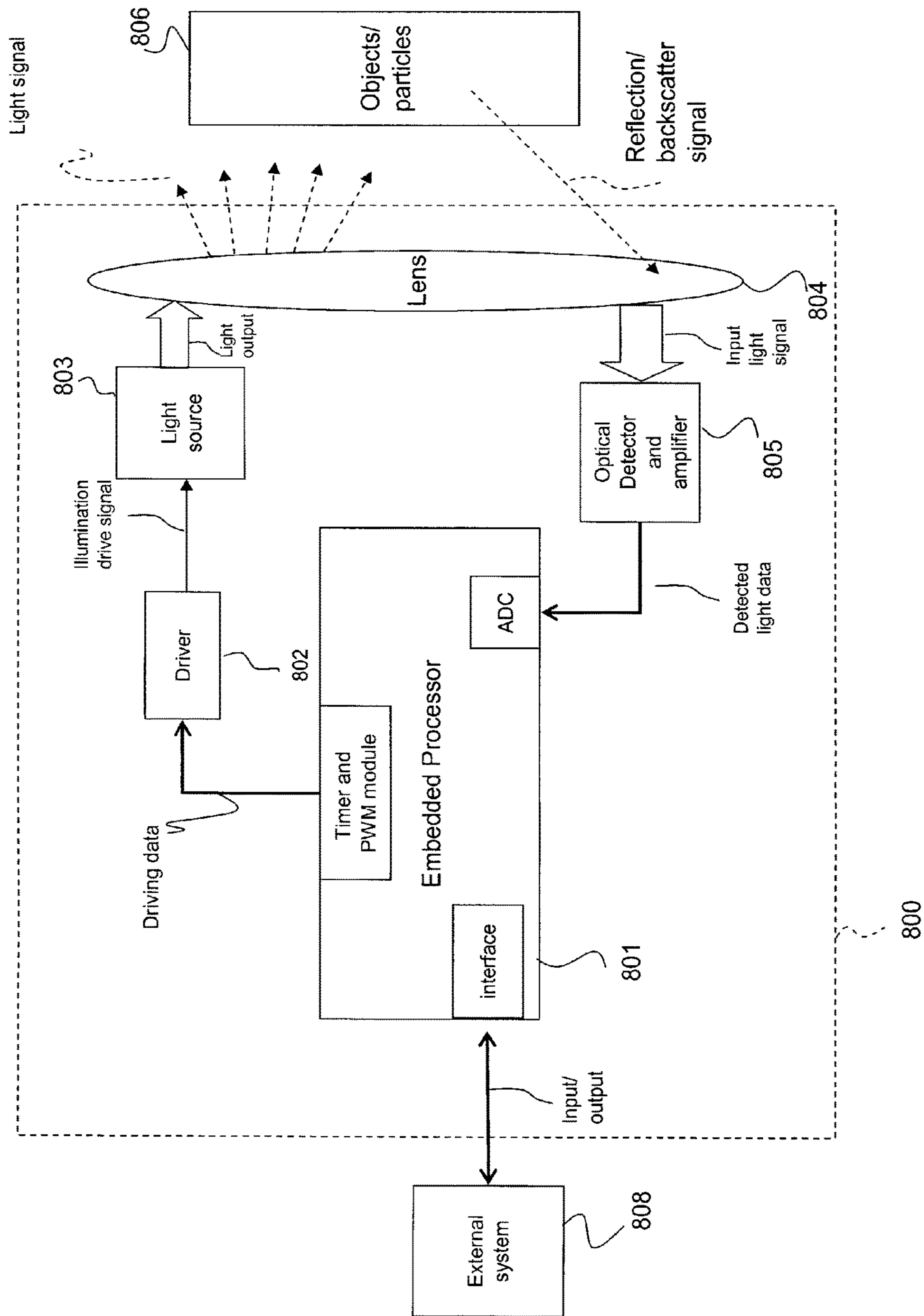


Figure 8

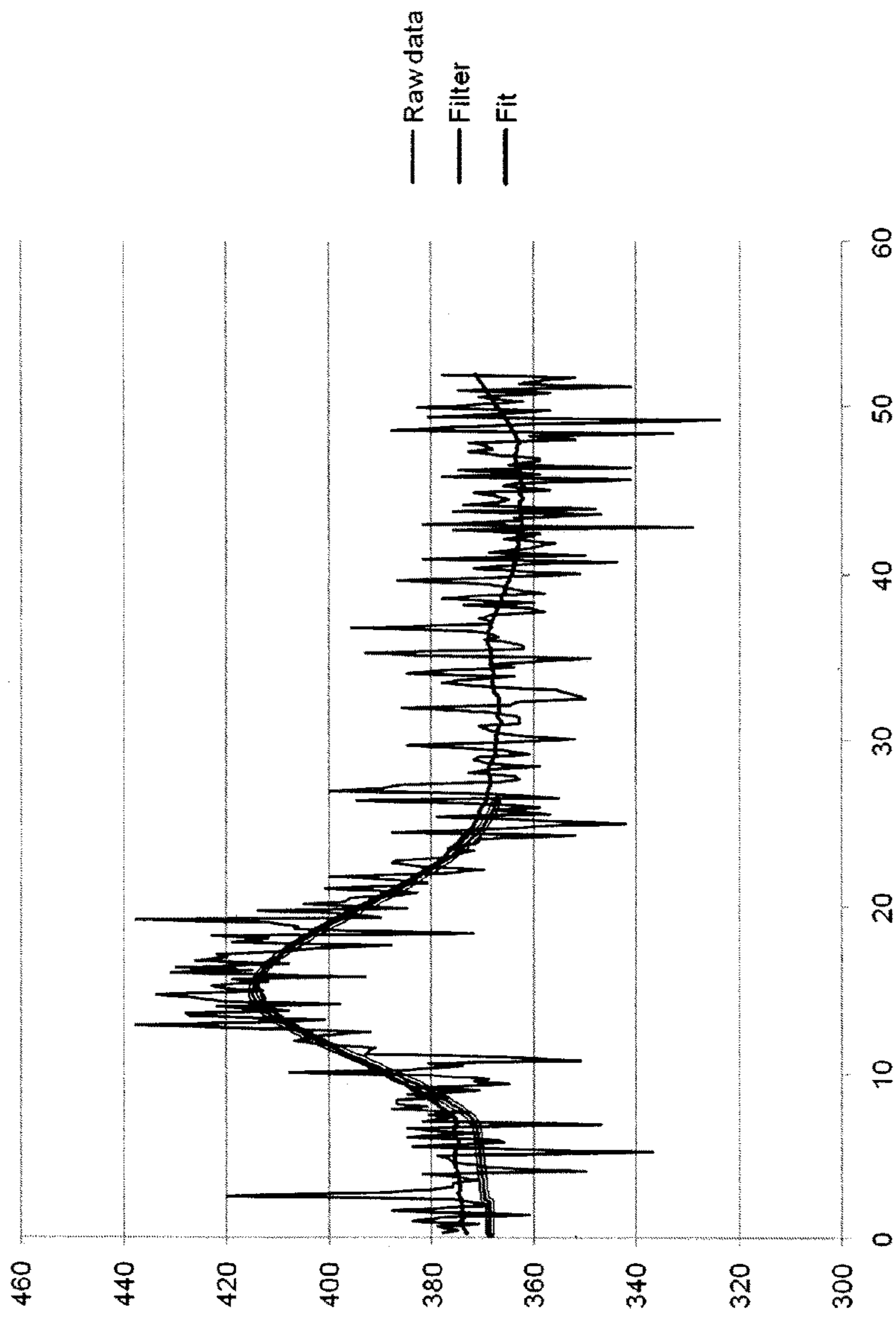


Figure 9

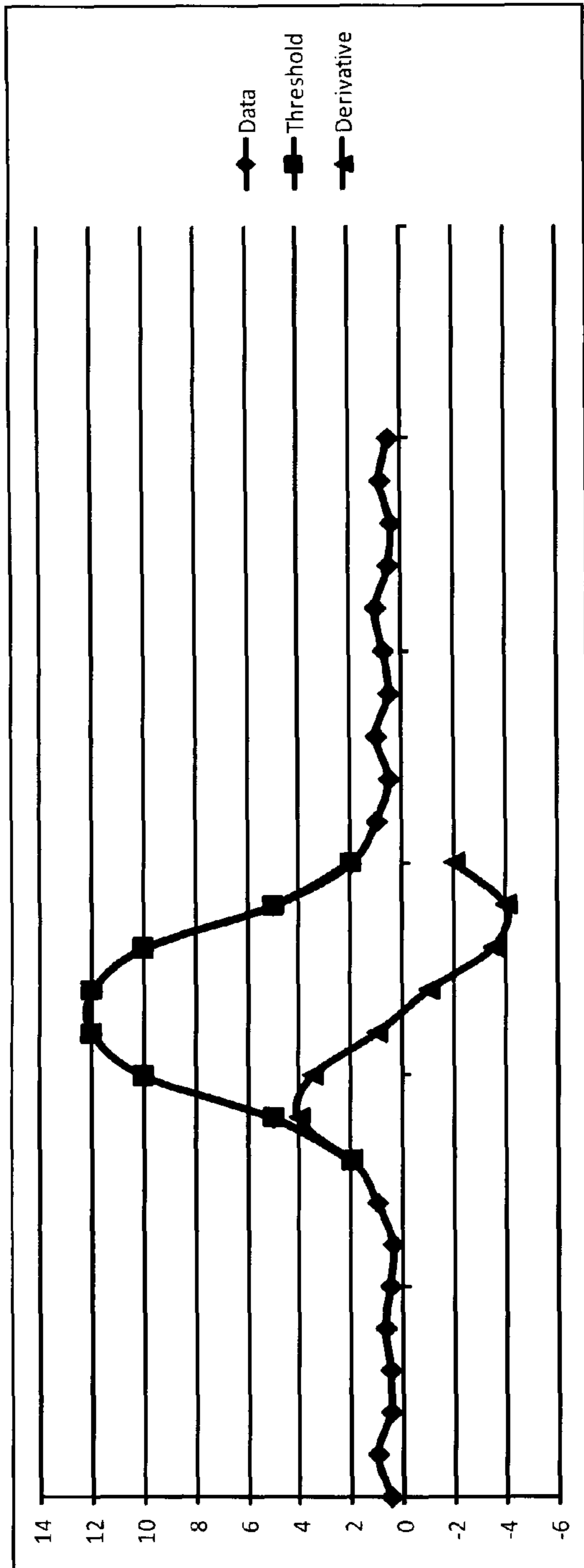


Fig. 10

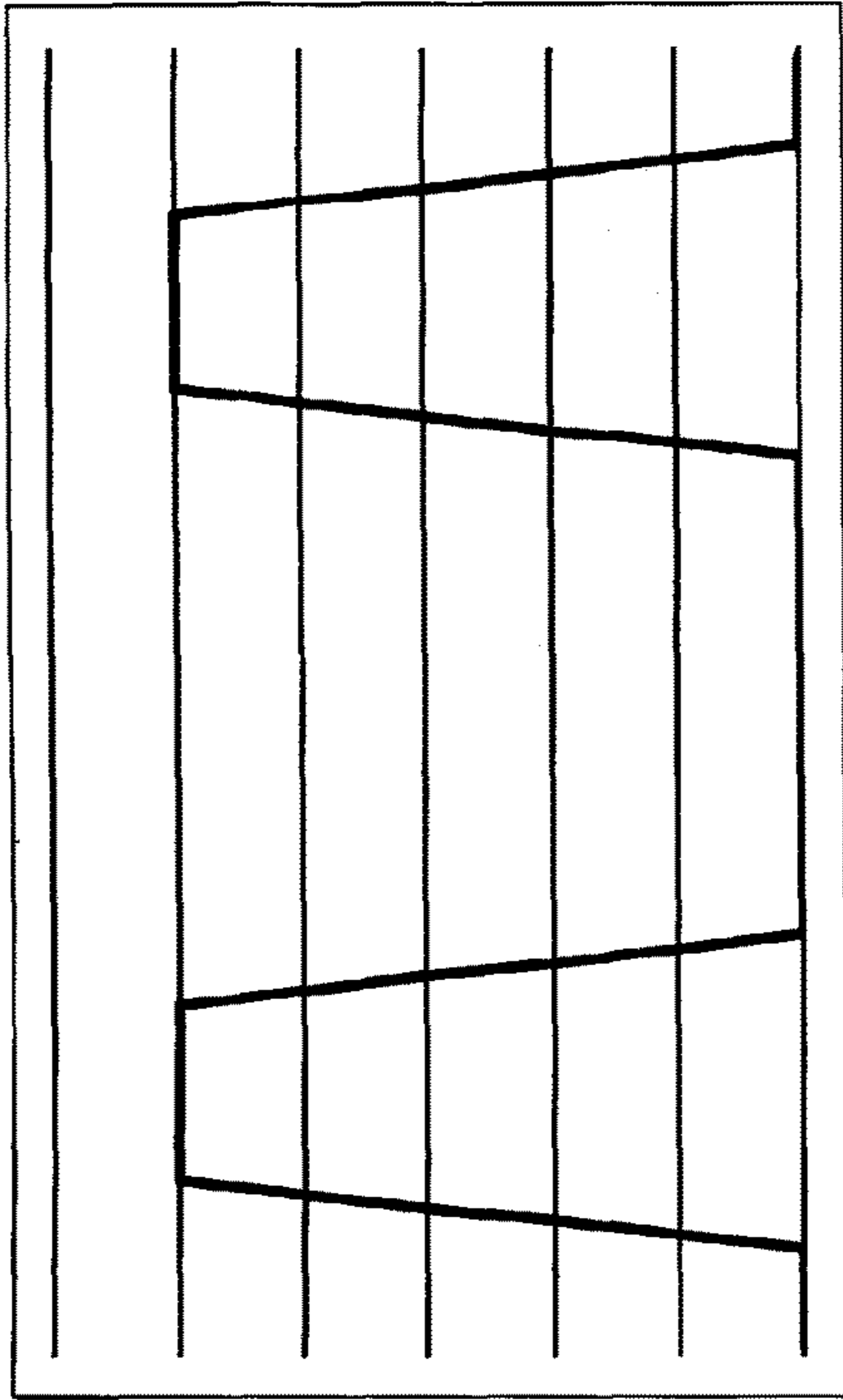


Fig. 11

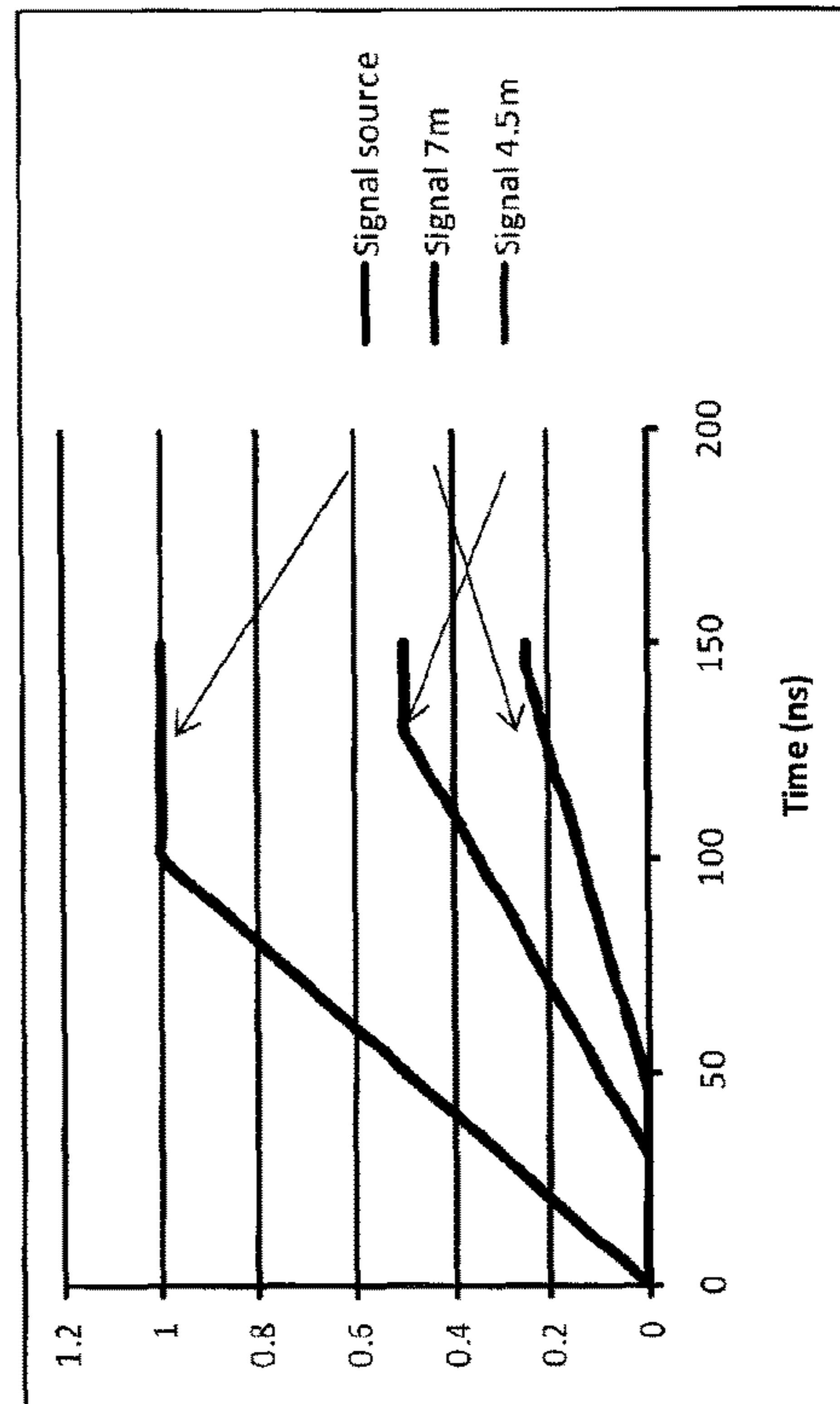


Fig. 12

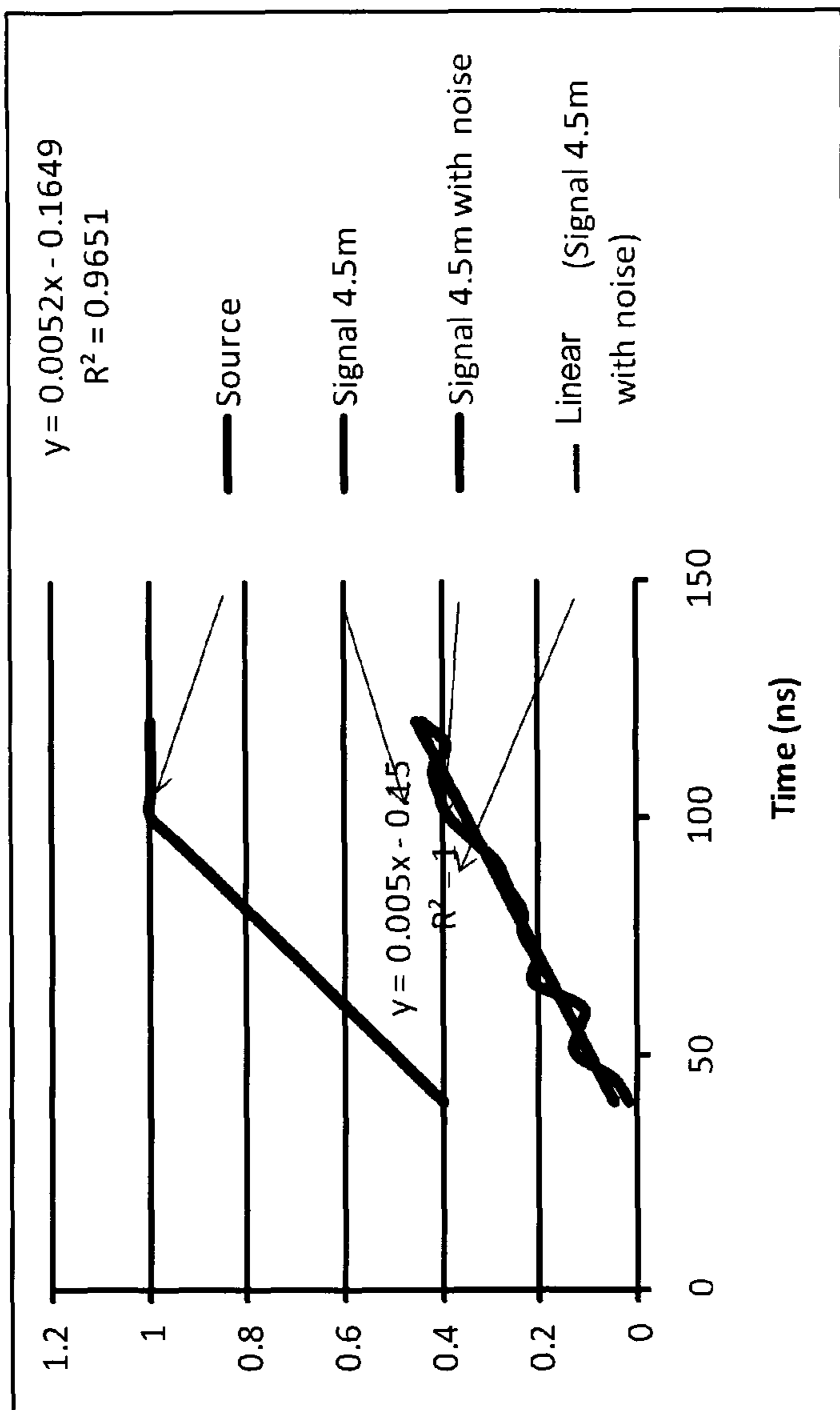


Fig. 13

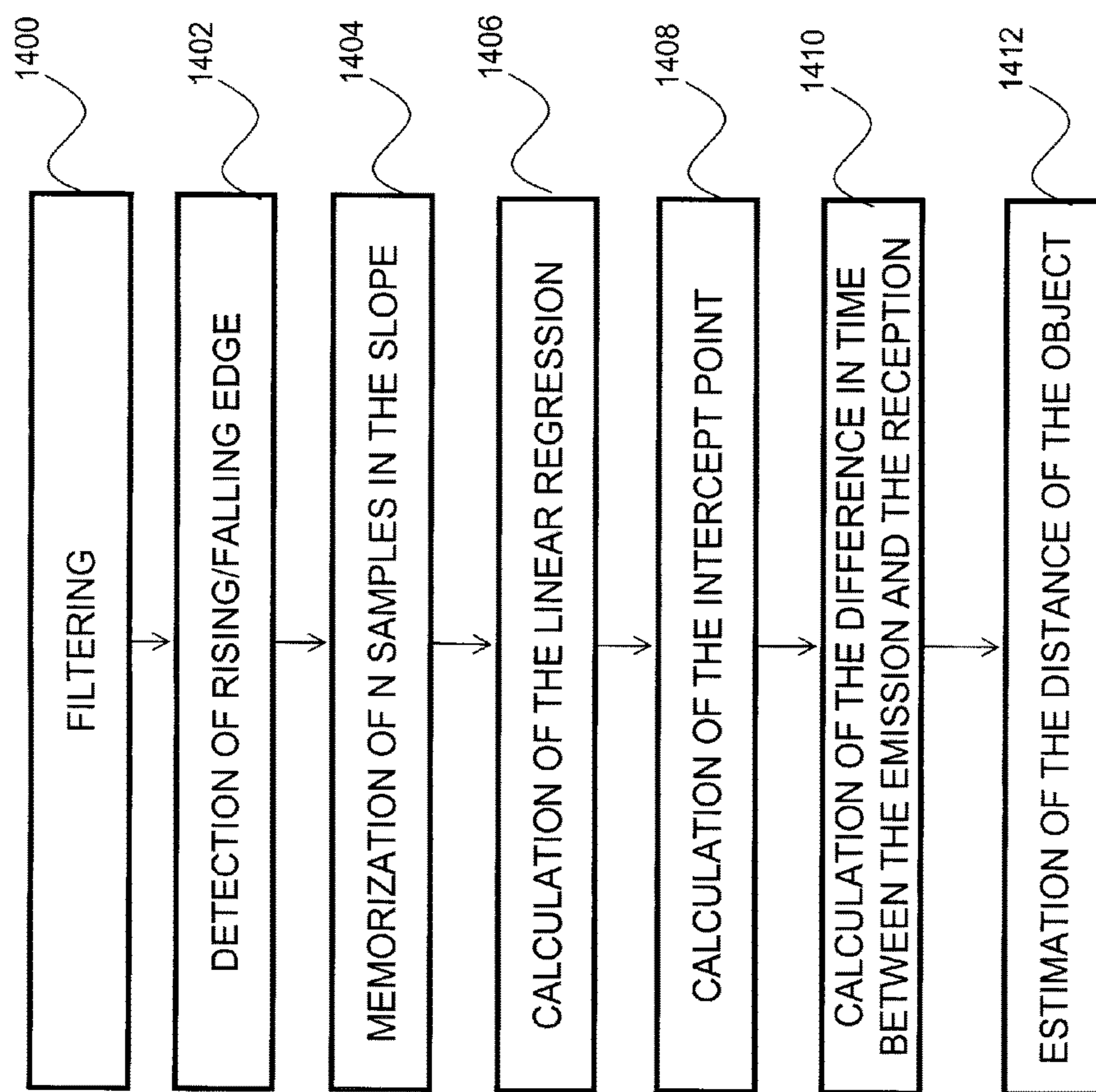


Fig. 14

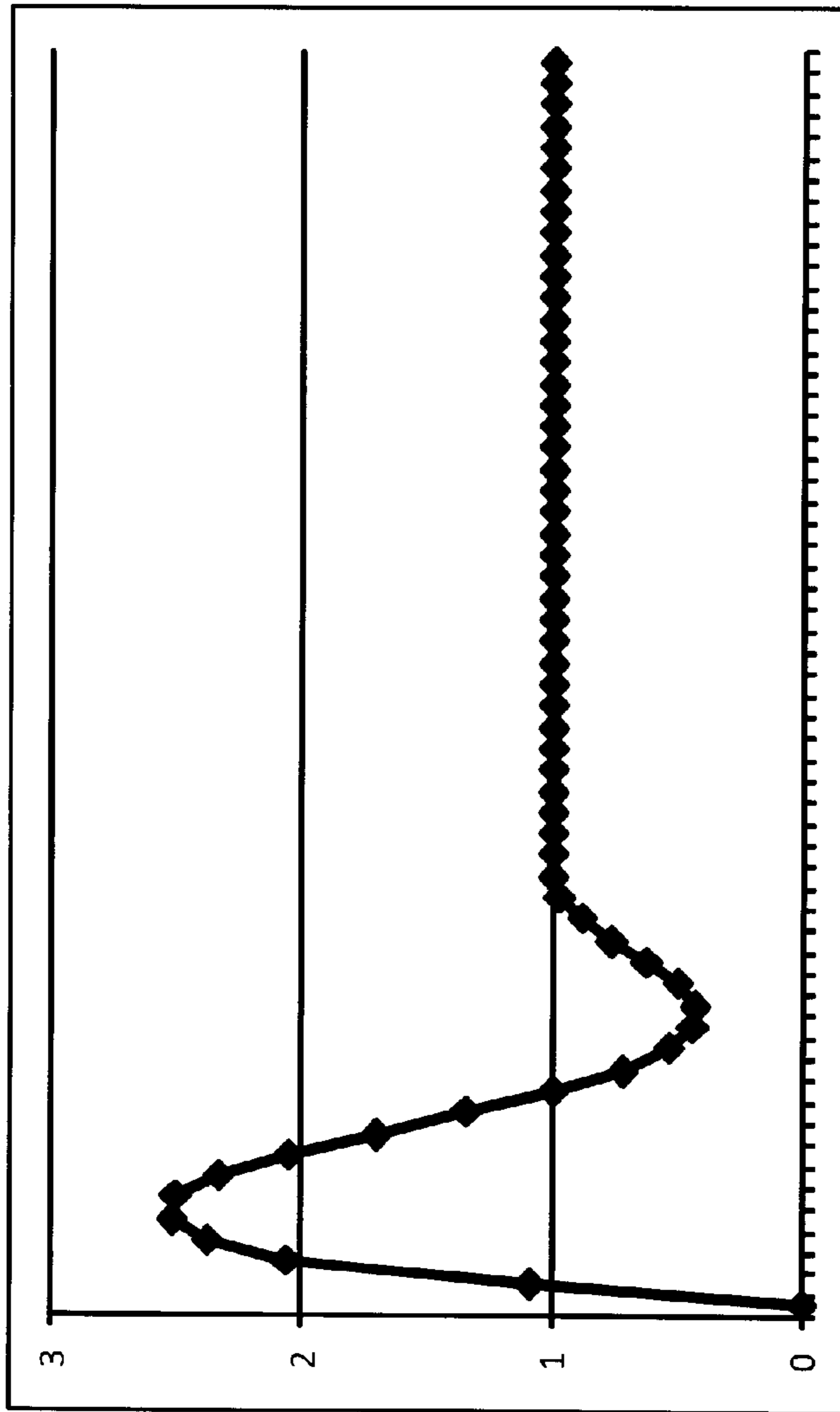


Figure 15

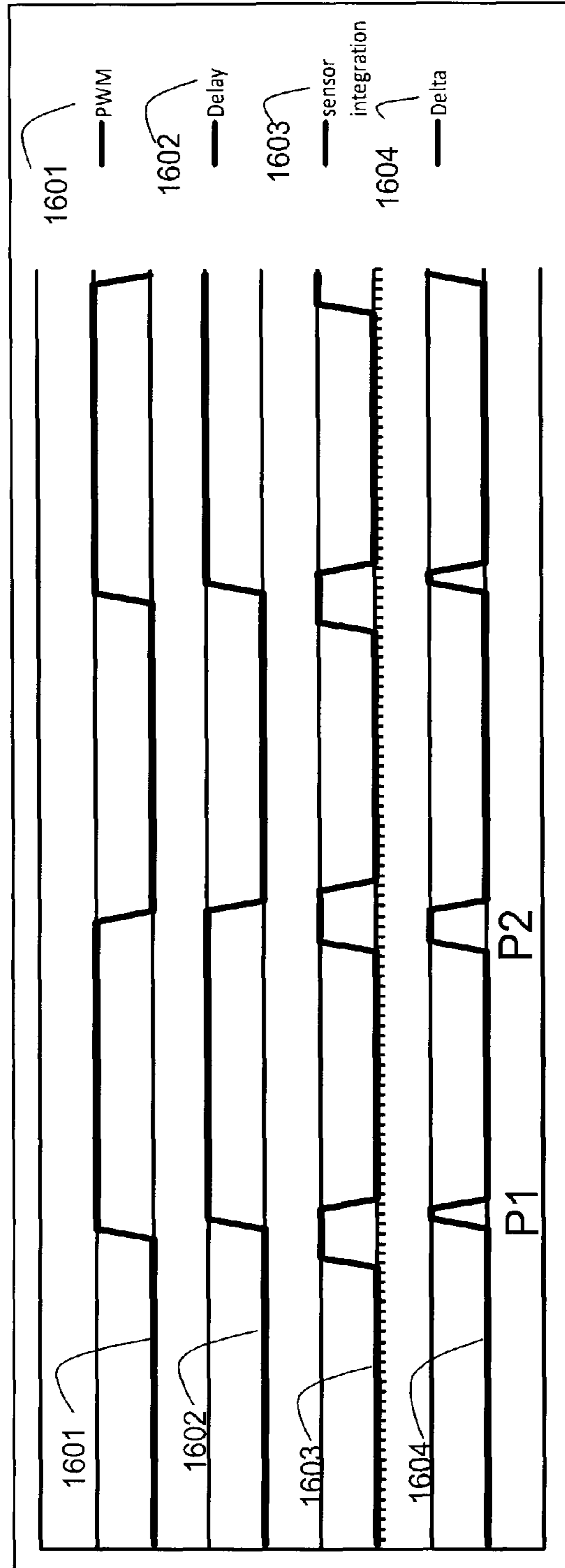


Figure 16

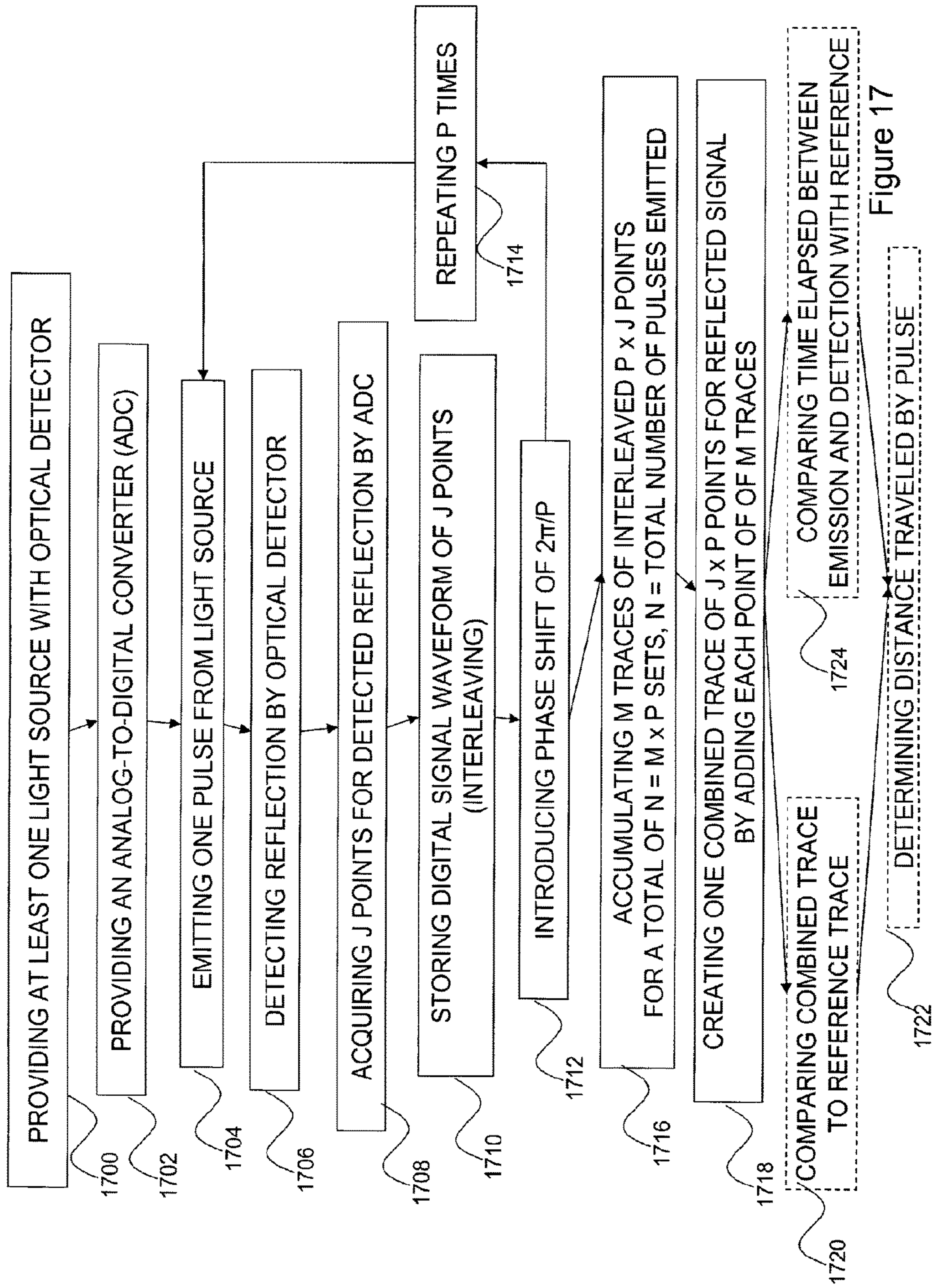


Figure 17

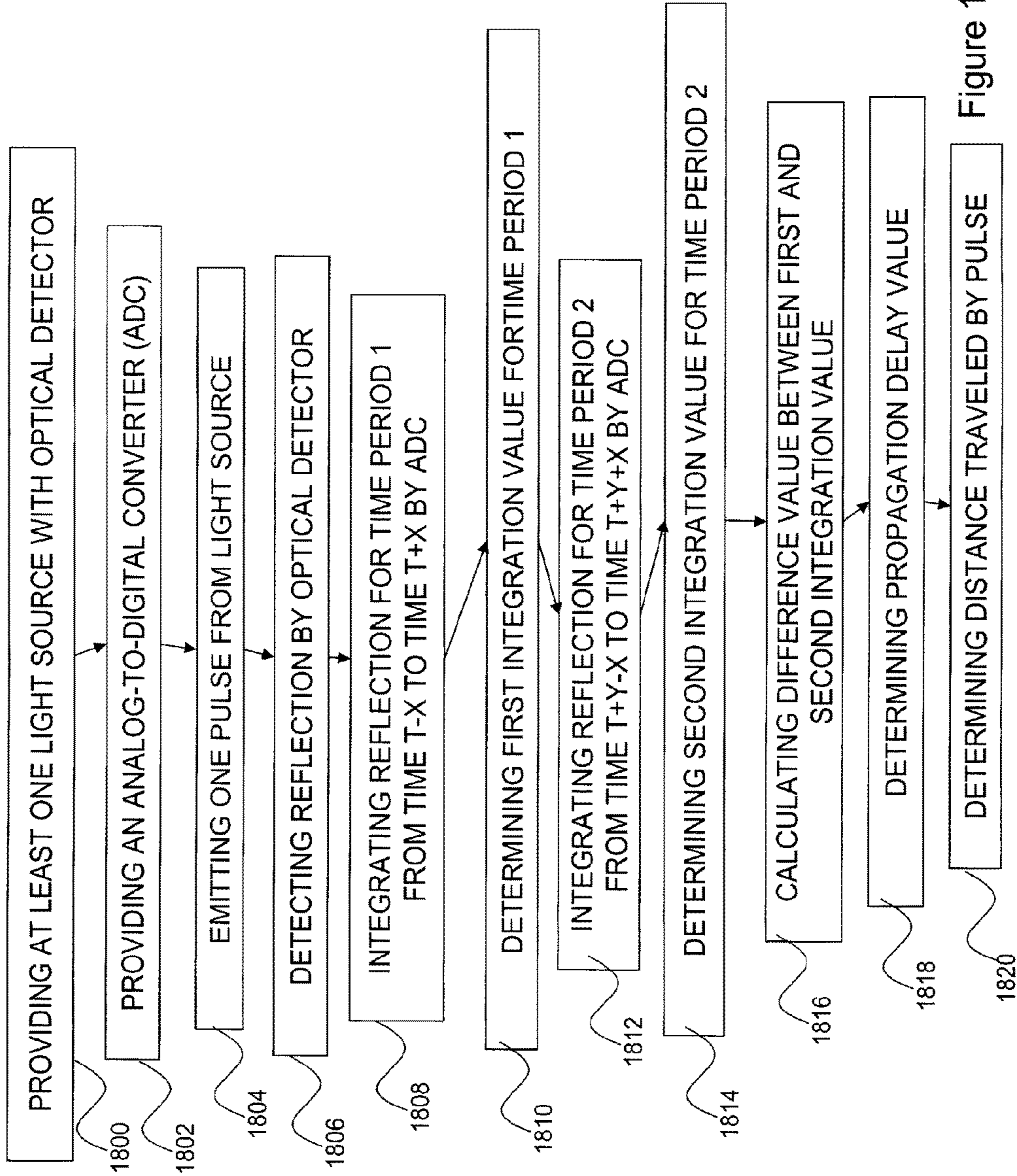


Figure 18

DISTANCE DETECTION METHOD AND SYSTEM

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a reissue application based on U.S. application Ser. No. 13/632,191 filed on Oct. 1, 2012, which previously issued as U.S. Pat. No. 8,619,241.

TECHNICAL FIELD

The invention relates to methods and systems for improving the measurement of light transit time reflected by different types of objects in detection and ranging methods and systems.

BACKGROUND OF THE ART

Several methods are used to measure the distance between an apparatus and an object. Optical range-finding systems frequently rely on the time-of-flight principle and determine the distance between the apparatus and the object by measuring the time a short pulse of light emitted from the apparatus takes to reach an object and be reflected to a photo-detection circuit. Conventional optical rangefinders use a counter initiated at the starting pulse and then stopped when the receiver circuit detects the pulse echo of a value higher than a specific threshold. This threshold can be set low to provide sensitivity but the system will generate false alarms from transient noise. It can be set high to avoid false alarms but the system will not detect objects that return weak signal reflection. In bad weather conditions, such as rain or snow, several pulse echoes can be generated. Some techniques help to detect a certain number of echoes and may be used to reject some reflections but they have their limitations.

Some optical rangefinders use other methods to be more robust against false alarms. One method is based on the use of an analog-to-digital converter (ADC) for the digitalization of the waveform of the echoed back signal. Once digitalized, the waveform can be processed by digital signal processing circuits to improve the performance of the system.

Several techniques are already known for improving the performance of an optical rangefinder using an ADC. Averaging is an efficient way to improve the signal to noise ratio (SNR). However, averaging has an impact on response time and may render the system too slow for some applications.

The resolution of distance measurement can be enhanced by using a clock pulsed delay circuit technique. Using an integer (N) division of the clock pulse signal with a delay circuit and by rearranging each echo light pulse sample data, this technique improves the resolution by a factor N. However, this technique has an impact on the number of averages if the averaging technique is also used to improve the SNR.

Digital correlation is another digital processing technique for increasing the resolution of the range measurement. By correlating the echo pulse signal with a pre-stored wave-

form, the distance to the object can be estimated by using the peak value of the result of the correlation function.

Several digital processing techniques have been elaborated to improve the performance of rangefinders but none consider that the need, in terms of resolution and signal to noise improvement, is not constant as a function of the range for most of range-finding applications.

SUMMARY

It is therefore an aim of the present invention to address at least one of the above mentioned difficulties

The present system improves the detection of the presence and the measure of the distance of objects, while optimizing the performance (resolution, repetition rate, etc) by adapting a range-dependant processing as a function of the need of different applications.

The present system can be adapted for use with a lighting system for lighting purposes as well as for the detection and ranging purposes.

The present system also improves the detection of rain, snow, fog, smoke and can provide information about current weather conditions.

According to a broad aspect of the present invention, there is provided a method for detecting a distance to an object. The method comprises providing a lighting system having at least one pulse width modulated visible-light source for illumination of a field of view; emitting an illumination signal for illuminating the field of view for a duration of time t ; using the visible-light source at a time t ; integrating a reflection energy for a first time period from a time $t-x$ to a time $t+x$; determining a first integration value for the first time period; integrating the reflection energy for a second time period from a time $t+y-x$ to a time $t+y+x$; determining a second integration value for the second time period; calculating a difference value between the first integration value and the second integration value; determining a propagation delay value proportional to the difference value; determining the distance to the object from the propagation delay value.

BRIEF DESCRIPTION OF THE DRAWINGS

Having thus generally described the nature of the invention, reference will now be made to the accompanying drawings, showing by way of illustration a preferred embodiment thereof and in which:

FIG. 1 is a block diagram of an embodiment of the lighting system;

FIG. 2 shows an example of a reflected signal with accumulation and phase shift techniques wherein FIG. 2a is a trace obtained with no accumulation and no phase shift, FIG. 2b has accumulation and phase shift improvements and FIG. 2c has a greater number of accumulations and phase shifts;

FIG. 3 is a table of example setup parameters for the segmentation;

FIG. 4 shows an example of a reflected signal with adjusted parameters as a function of the distance;

FIG. 5 is a flow chart of an embodiment of the segmentation process;

FIG. 6 shows an example of the accumulation and phase shift technique for a 10 m range finder using the one sample by optical pulse technique;

FIG. 7 is a table of example setup configuration for the accumulation and phase shift technique using the one sample by optical pulse technique;

FIG. 8 is a block diagram of a lidar module using an embedded processor;

FIG. 9 shows a noisy signal fitted and filtered;

FIG. 10 presents a Gaussian pulse with a zero-crossing point of the first derivative;

FIG. 11 shows a typical PWM pattern with slope adjustment;

FIG. 12 shows a rising edge signal from a source and reflected signals;

FIG. 13 shows a 10% to 90% rising edge of an echo back noisy signal with linear regression;

FIG. 14 is a flow chart of an embodiment of the PWM edge technique for detection and ranging; and

FIG. 15 shows a rising edge with overshoot stabilizing after one cycle of the resonance frequency;

FIG. 16 shows a timing diagram of the method using an integration signal from the reflected signal and synchronized with rising edge and falling edge of the PWM lighting source;

FIG. 17 is a flow chart of the main steps of a method for acquiring a detected light optical signal and generating an accumulated digital trace; and

FIG. 18 is a flow chart of the main steps of a method for detecting a distance to an object.

It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

DETAILED DESCRIPTION

FIG. 1 is a block diagram illustrating an embodiment of a lighting system equipped with the present system. The lighting system 100 has a visible-light source 112. The visible-light source 112 has, as a first purpose, the emission of visible light for illumination or visual communication of information, like signaling, for human vision. The primary purpose of emitting light is controlled according to specific criteria like optical power, field of view and light color, to meet requirements defined through a number of regulations. In the preferred embodiment, the visible-light source 112 has one or more solid-state lighting devices, LEDs or OLEDs for instance.

The visible-light source 112 is connected to a source controller 114, so as to be driven into producing visible light. In addition to emitting light, the system 100 performs detection of objects and particles (vehicles, passengers, pedestrians, airborne particles, gases and liquids) when these objects are part of the environment/scene illuminated by the light source 112. Accordingly, the source controller 114 drives the visible-light source 112 in a predetermined mode, such that the emitted light takes the form of a light signal, for instance by way of amplitude-modulated or pulsed light emission.

These light signals are such that they can be used to provide the lighting illumination level required by the application, through data/signal processor 118 and source controller 114, while producing a detectable signal. Accordingly, it is possible to obtain a light level equivalent to a continuous light source by modulating the light signal fast enough (e.g., frequency more than 100 Hz) to be generally imperceptible to the human eye and having an average light power equivalent to a continuous light source.

In an embodiment, the source controller 114 is designed to provide an illumination drive signal, such as a constant DC signal or a pulse-width modulated (PWM) signal, that is normally used in lighting systems to produce the required

illumination and control its intensity. The illumination drive signal is produced by the illumination driver sub-module 114A of the controller 114.

A modulated/pulsed driving signal supplies the fast modulation/pulse sequence required for remote object detection. This modulated/pulsed drive signal is produced by a modulation driver sub-module 114B of the controller 114. The amplitude of short-pulse (typ. <50 ns) can be several times the nominal value while the duty cycle is low (typ. <0.1%).

The modulator driver 114B can also be used to send data for optical communication. Both driving signals can be produced independently or in combination. Sequencing of the drive signals is controlled by the data/signal processor 118. The light source 112 can be monitored by the optical detector 116 and the resulting parameters sent to the data/signal processor 118 for optimization of data processing.

An alternative for sourcing the light signal for detection involves an auxiliary light source (ALS) 122, which can be a visible or non-visible source (e.g., UV or IR light, LEDs or laser) using the modulation driver 114B. The auxiliary light source 122 provides additional capabilities for detecting objects and particles. UV light source (particularly around 250 nm) can be used to limit the impact of the sunlight when used with a UV detector. IR light can be used to increase the performance and the range of the detection area. IR lights and other types of light can be used to detect several types of particles by selecting specific wavelengths. The auxiliary light source 122 can also be useful during the installation of the system by using it as a pointer and distance meter reference. It can also be used to determine the condition of the lens.

The visible-light source 112 is preferably made up of LEDs. More specifically, LEDs are well suited to be used in the lighting system 100 since LED intensity can be efficiently modulated/pulsed at suitable speed. Using this feature, current lighting systems already installed and featuring LEDs for standard lighting applications can be used as the light source 112 for detection applications, such as presence detection for energy savings, distance and speed measurements, fog, rain, snow or smoke detection and spectroscopic measurements for gas emission or smog detection.

The system 100 has at least one lens 130 through which light is emitted in an appropriate way for specific applications. At least one input lens section 130a of at least one lens 130 is used for receiving the light signal, for instance reflected or diffused (i.e., backscattered) by the objects/particles 134. This input lens section 130a can be at a single location or distributed (multiple zone elements) over the lens 130 and have at least one field of view. Several types of lens 130 can be used, such as Fresnel lenses for example. A sub-section of the lens 130 can be used for infrared wavelength. A sub-section of the lens 130 can be used for optical data reception.

A detector 116 is associated with the visible-light source 112 and/or auxiliary light source 122 and the lens 130. The detector module 116 is an optical detector (or detectors) provided so as to collect light emitted by the light source 112/ALS 122 and back-scattered (reflected) by the objects/particles 134. Detector module 116 can also monitor the visible-light source 112 or auxiliary light source 122. The light signal can also come from an object 134 being the direct source of this light (such as a remote control) in order to send information to the data/signal processor through the optical detector module 116. The optical detector module 116 is, for example, composed of photodiodes, avalanche

photodiodes (APD), photomultipliers (PMT), complementary metal-oxide semiconductor (CMOS) or charge-coupled device (CCD) array sensors.

Filters are typically provided with the detector module **116** to control background ambient light emitted from sources other than the lighting system **100**. Filters can also be used for spectroscopic measurements and to enhance performance of the light source **112**.

A front-end and analog-to-digital converter (ADC) **124** is connected to detector **116** and receives detected light data therefrom and controls the detector **116**. For instance, adjusting the Vbias of an APD detector can be one of the detector controls to optimize the gain of the receiver section for an Automatic Gain Control (AGC). Analog filters can be used for discriminating specific frequencies or to measure the DC level.

A detection and ranging digital processing unit **126** is connected to the front-end **124**, and controls parameters such as gain of amplifier, synchronization and sample rate of the ADC. The detection and ranging digital processing unit **126** receives data from ADC and pre-processes the data.

The data/signal processor **118** is connected to the detection and ranging processing module **126** and receives pre-processed data. The data/signal processor **118** is also connected to the source controller **114**, so as to receive driving data therefrom. The data/signal processor **118** has a processing unit (e.g., CPU) so as to interpret the pre-processed data from the detection module **126**, in comparison with the driving data of the source controller **114**, which provides information about the predetermined mode of emission of the light signals emitted by the visible-light source **112**.

Accordingly, information about the object (e.g., presence, distance, speed of displacement, composition, dimension, etc.) is calculated by the data/signal processor **118** as a function of the relationship (e.g., phase difference, relative intensity, spectral content, time of flight, etc.) between the driving data and the detected light data, is optionally pre-processed by the front-end and ADC **24** and the detection and ranging processing unit **126**. A database **120** may be provided in association with the data/signal processor **118** so as to provide historical data or tabulated data to accelerate the calculation of the object parameters.

In view of the calculation it performs, the data/signal processor **118** controls the source controller **114** and thus the light output of the visible-light source **112**. For instance, the visible-light source **112** may be required to increase or reduce its intensity, or change the parameters of its output. For example, changes in its output power can adapt the lighting level required in daytime conditions versus nighttime conditions or in bad visibility conditions such as fog, snow or rain.

The system **100** can be provided with sensors **132** connected to the data/signal processor **118**. Sensors **132** can be an inclinometer, accelerometer, temperature sensor, day/night sensors, etc. Sensors **132** can be useful during the installation of the system and during operation of the system. For example, data from an inclinometer and accelerometer can be used to compensate for the impact on the field of view of an effect of the wind or any kind of vibration. Temperature sensors are useful to provide information about weather (internal, external or remote temperature with FIR lens). Information from sensors **132** and data/signal processor **118** and light from light source **112** and auxiliary light source **122** can be used during installation, in particular for adjusting the field of view of the optical receiver. The auxiliary light source **112** can be used as a pointer and distance meter.

The system **100** has a power supply and interface **128**. The interface section is connected to a Data/signal processor and communicates to an external traffic management system (via wireless, power line, Ethernet, CAN bus, USB, etc.).

Segmentation of the Digital Processing as a Function of the Range

Several range finding applications need different performances as a function of the range. For automotive applications, such as Adaptive Cruise Control (ACC), it could be useful to detect a vehicle more than 100 meters ahead but the needs in terms of accuracy and repetition rate are not the same as for short range applications such as pre-crash mitigation. Basically, for a short range application, the reflected signal is strong but, usually, the needs for a good resolution and fast refresh rate of the data are high. For a long range application, the opposite is true, the reflected signal is weak and noisy but the need for resolution and refresh rate is less demanding.

Phase shifting control techniques can improve accuracy using a digital acquisition system with low sample rate. For instance, a relatively low cost ADC (ex.: 50 MSPS) can have an improved temporal resolution if successive acquisitions are delayed by an equivalent fraction of the acquisition time period but this technique has an impact on SNR and refresh rate when averaging is used.

To optimize the performance, one can adjust specific parameters as a function of the distance. Using the detection and ranging digital processing unit **126** and the Data/signal Processor **118**, allows to control the number of shift delay by period, the number of accumulation and the refresh rate for each data point sampled or for several segments. For shorter distances, with an echo back signal which is relatively strong, the number of shift delays and the refresh rate can be higher to improve the resolution and the response time. The number of accumulation (or other time-integration techniques) would be lower but sufficient at short distances (trade-off between signal-to-noise ratio, resolution and number of results per second).

The accumulation technique improves the signal-to-noise ratio of the detected light signal using multiple measurements. In order to produce one distance measurement, the technique uses M light pulses and for each light pulse, a signal detected by the optical detector is sampled by the ADC with an ADC time resolution of 1/F second thereby generating M lidar traces of j points (S_1 to S_j) each. Points of the M lidar traces are added point per point to generate one accumulated digital lidar trace of j points.

The phase shift technique is used to improve the time resolution of the trace acquired by the ADC and limited by its sample rate F Hz. The phase shift technique allows for the use of a low cost ADC having a low sample rate F by virtually increasing the effective sample rate. The effective sample rate is increased by a factor P by acquiring P sets corresponding to P light pulses while shifting the phase between the emitted light pulse and the ADC sampling rate. The phase shifting between each acquisition corresponds to $2\pi/P$. The P sets obtained are then combined in a single trace by interleaving the P sets such that the resulting trace is equivalent to a single measurement with a temporal resolution $(1/F \times P)$ second.

By combining the accumulation and the phase shift techniques, an accumulation of M sets is performed for each one of the P phase shifts, for a total of $N=M \times P$ acquisition sets. Using the N sets, the detection and ranging digital processing unit **126** and the Data/signal Processor **118** creates one combined trace of the reflected light pulse. Each point in the combined trace is an accumulation of $M=N/P$ sets and the

effective time resolution of the combined trace is $1/(F \times P)$ second. To store one complete trace, the length of the buffer is at least $j \times P$ elements and the number of bit of each element is a function of the resolution of the ADC (number of bits, B) and the number of accumulations M. To prevent overflow, each element of the buffer should have at least $B + \log_2 M$ bits. Example results of the accumulation and phase shift techniques are shown in FIGS. 2a, 2b and 2c. For that experimentation, a target is approximately at a distance of 12 meters and the system use an ADC at 50 MSPS. FIG. 2a shows a trace obtained with no accumulation and no phase shift. The signal is noisy with a lack of resolution and it is very difficult to identify the target. FIG. 2b shows an improvement in terms of signal to noise ratio by accumulating 64 sets with 8 shift delays. Finally, FIG. 2c shows how an accumulation of 1024 sets with 256 shift delays can improve the signal-to-noise ratio and resolution.

Accumulation and shift control can be done by a programmable logic, a Field Programmable Gate Array (FPGA) for example. Phase shifting can be controlled by delaying the clock of the ADC converter 130 by a fraction of a period or by delaying the driver of the optical source.

FIG. 3 shows one example of setup configurations for this method using different parameters as a function of the distance. For different distances (for instance, for a range from 1 m to 100 m), one can optimize the temporal resolution, the number of accumulation and the refresh rate and make tradeoffs in terms of sensibility, accuracy and speed as a function of the distance to a target.

FIG. 4 shows a reflected signal with a first echo from an object closer to the system and a second echo from another object further from the source. The amplitude of the first echo is higher and the system optimizes the temporal resolution. The amplitude of the second echo back pulse from the farther object is lower and the system optimizes the SNR by using more accumulation instead of optimizing the resolution.

The value of each parameter can be adaptive as a function of the echo back signal. After analyzing the level of the noise, the system can optimize the process by adjusting parameters as a function of the priority (resolution, refresh rate, SNR). For example, if the noise is lower than expected, the system can reduce the number of accumulation and increase the number of shift delays to improve the resolution.

FIG. 5 shows a flow chart of a typical process for this method. In this flowchart and in all other flowcharts of the present application, some steps may be optional. Some optional steps are identified by using a dashed box for the step. Configuration 500 sets several parameters before the beginning of the process. Acquisition 502 starts the process by the synchronization of the emission of the optical pulses and the acquisition of samples by the ADC. Digital filtering and processing of the data 504 make the conditioning for the extraction and storage in memory of a lidar trace 506. Detection and estimation of the distance 508 is made, typically using a reference signal and measuring the lapse of time between the emission and the reception of the signal. The transmission of the results 510 (the detection and the estimation of the distance) are transmitted to a external system. Noise analysis 512 is performed and an adjustment of the parameters as a function of the level of the noise 514 can be made to optimize the process.

Based on shift delay and accumulation techniques, it is possible to optimize the cost of optical range finder systems particularly for short range distance measurement. By using only one sample per optical pulse, the ADC has to acquire

samples at the frequency of the optical pulse emission. For a system driving optical pulses at L Hz, the ADC converts L samples per second with P shift delay of D ns of delay. FIG. 6 shows an example of that technique for a ten meter range finder. The source emits a 20 ns optical pulse at T=0 ns at several KHz (ex.: 100 KHz). In the air, the optical pulse takes approximately 65 ns to reach a target at ten meters and to reflect back to the sensor of the system. Each time a pulse is emitted, the ADC acquires only one sample. The ADC works at same frequency as the optical pulse driver (ex.: 100 KHz). For each one of the first twenty optical pulses, the system synchronizes a shift delay of 5 ns between the optical pulse driver and the ADC. After 20 pulses, the system samples the reflected back signal 95 ns after the pulse was emitted, just enough to detect the end of the reflected back signal from a target at 10 meters. For this example, if the system works at 100 KHz, after 200 us, a complete 10 meters Lidar trace is recorded. To improve the signal-to-noise ratio, one can accumulate up to 5000 times to have one complete lidar trace per second. FIG. 7 is a table showing setup configuration for this method. For a maximum range of 10 meters and 30 meters, the table shows tradeoffs between accuracy (temporal resolution), sensibility (improvement of the signal to noise ratio by accumulation) and speed (refresh rate).

Nowadays, embedded processors, microcontrollers and digital signal processor, have a lot of processing power with fixed-point or floating-point units with hundreds of Mega Floating point Operations per Second (MFLOPS) of performance. They are highly integrated with analog-to-digital converters, timers, PWM modules and, several types of interface (USB, Ethernet, CAN bus, etc). Using the last technique described, mainly because the requirement in terms of speed of the ADC is low, the major part of the range finder system can be integrated in an embedded processor. FIG. 8 shows a block diagram of a lidar module 800 using an embedded processor optimizing the cost of the range finder system. The embedded processor 801 controls the timing for the driver 802 sourcing the light source 803. A light signal is emitted in a direction determined by the optical lens 804. A reflection signal from objects/particles 834 is received on the optical lens 804 and collected by the optical detector and amplifier 805. The embedded processor 801 uses an embedded ADC to make the acquisition of the lidar trace and processes the data and sends the information to an external system 840. The system 800 can use several sources being driven sequentially using one sensor or several sensors. The frequency of acquisition is at the frequency of optical source multiplied by the number of optical sources.

Moving Average, Filters, Frequency Analysis and Peak Detection

Instead of collecting N data and then performing an average (one average at each $1/N \times [\text{frequency of the source}]$), moving average techniques permit to constantly have the last N samples to perform an average. Using a FIFO by adding a new data and subtracting the first data accumulated is an example of an implementation of that technique.

Using too much integration time for averaging can generate a problem when detecting moving objects. Averaging techniques can consider a signal from moving objects as noise and will fail to discriminate it. Frequency domain analysis can be useful for this kind of situation. Wavelet transform is very efficient for signal analysis in time/frequency domain and is sensitive to the transient signals. By separating the echo back signal in several segments and analyzing the spectral frequency, the system can detect the

frequency of the pulse of the source in a specific segment. Averaging parameters can be adjusted as a function of events detected by the spectral analysis process. For instance, the number of averages should be reduced when moving objects are detected sequentially in different segments.

Low pass filters can be used as pre-processes on each trace before averaging. Filters may be particularly efficient when more than one sample is available on an echo pulse. Information from noise analysis and from the information of the signal waveform emitted by the source can also help to discriminate a signal and to adjust the parameters. Specific processing functions can be used for each point of the trace or by segment.

Another way to optimize the detection of an object and the measurement of the distance is using a reference signal and making a fit with the lidar trace. The reference signal can be a pattern signal stored in memory or a reference reflection signal of an optical pulse detected by a reference optical detector. This reference optical detector acquires a reference zero value and this reference signal is compared to the lidar trace. Detection and distance is based on comparison between both signals. Fit can be made by convolution.

FIG. 9 shows a noisy signal fitted and filtered to diminish the effects of the noise. FIG. 9 presents the effect of signal filtering and curve fitting. The raw data curve is the noisy signal as received from the sensor. The filter curve is the raw data curve after filtering by correlation with an ideal (no noise) pulse. This removes the high-frequency noise. Finally the fit curve presents the optimal fitting of an ideal pulse on the filtered signal. Fitting can improve distance stability especially when the signal is weak and still too noisy even after filtering.

When a signal waveform has a Gaussian profile, it is possible to use a method based on a zero-crossing point of the first derivative to detect the peak of the waveform. This technique requires a previous filtering to remove the noise. When the detection of an event (echo back pulse from an object) occurs, the system will detect N consecutive points over a predetermined threshold. The value of N depends notably on the sample rate and the width of the pulse from the source. By computing the first derivative of those selected points and interpolating to find the zero-crossing point, an estimation of the peak of the signal can be found.

FIG. 10 shows an example of a Gaussian pulse with selected data over a predefined threshold and the result from the derivative calculation of those selected data. One can see the zero crossing from the derivative plot representing the peak of the pulse.

Illumination Driver as a Source for Rangefinder with Edge Detection

Switch-mode LED drivers are very useful notably for their efficiency compared to linear drivers. PWMs permit a very high dimming ratio without drifting the wavelength usually generated by linear drivers. Their performance is particularly well suited for high power LEDs. However, switch-mode LED drivers are noisier and the EMI can be an issue for some applications. One way to address this issue is to use a gate rising/falling slope adjust circuit to decrease the speed of transitions. Transitions at lower speed mean less EMI. FIG. 11 presents a typical PWM signal with slope adjustment.

For range-finding applications, the rapid transition of the signal is generally required. Usually, to get good performance, electronic circuits need to detect fast transition signals within a few nanosecond of resolution. Using a LED light source with a PWM driver with adjustment to diminish

the speed of the slope as the source for detection and ranging is, in principle, not very helpful.

One solution is to use the same LED light source for illumination and for detection and ranging with a PWM circuit controlling the intensity of illumination. The PWM LED light source has a relatively constant slope during its rising/falling edge to reduce EMI (rising/falling edge of 100 ns for example). The optical signal from the source is sampled to be able to determine the starting time of the pulse (T₀). Electrical synchronization signal can also be used to indicate the starting point. The reflected signal is sampled with enough temporal resolution to have several points during the slope of the signal when an object in the field of view returns a perceptible echo.

FIG. 12 shows an example of a rising edge from a source, an echo back signal from an object 4.5 meters away from the source (≈ 30 ns later) and another from an object at 7 meters from the source (≈ 45 ns later). Calculating the slope by linear regression or other means, an evaluation of the origin of the signal is made and the elapsed time between the signal from the source and an echo back signal can be determined. Based on that result, one can estimate the presence and the distance of the object reflecting the signal.

FIG. 13 represents a 10% to 90% rising edge of an echo back noisy signal from an object at 4.5 meters from the source. With linear regression, one can calculate the intercept point and get a good estimate of the delay between the two signals. Samples close to the end of the slope have a better SNR. One can determine different weights in the calculation as a function of the level of the noise. Both rising and falling edges can be used. During the calibration process, a threshold can be set to discriminate the presence or the absence of an object. Averaging and filtering techniques can be used to diminish the level of noise and shifting techniques can also be used to have more points in the slope. As shown in FIG. 9, even with a noisy signal, this method can give good results.

FIG. 14 shows a flow chart of the typical process for this method. The echo back signal is filtered **1400**, typically using a band-pass filter based on the frequency of the transition. Rising and falling edges are detected **1402** and samples are taken in the slope **1404** to memorize a digital waveform of the slope. The calculation of the linear regression **1406** is made and permits to calculate the intercept point **1408**. Based on that information, the calculation of the difference in time between the signal emission and the signal received **1410** allows to estimate the distance to the object **1412**.

This method can be improved by using demodulation and spectral analysis techniques. The base frequency of the PWM can be demodulated and the result of this demodulation will give an indication of a presence of an object. By selecting a frequency based on an harmonic coming from the slopes of the PWM signal, one can estimate the position of the object by spectral analysis of different segments. Knowing the approximated position, the acquisition of samples will be adjusted to target the rising and the falling edge.

By using the edge detection technique, one can use a standard LED driver for the purpose of lighting and also for the purpose of detection and ranging. The frequency of the PWM might be in the range from a few KHz up to 1 MHz. High frequency modulation can improve the SNR notably by averaging techniques. When the optical output of the source is coupled by optical path (reflection from lens or mirror or use of fiber optic), this method permits using a PWM source for a LED lighting system completely electrically isolated from the receiver.

11

Other types of rising/falling edge detection can be used with this method with the appropriate curve fitting technique. If EMI is not an issue, the electronic driver can generate a fast rising edge and/or falling edge with some overshoot at a resonance frequency. This signal adds more power at a specific frequency and increase the signal that can be detected by the receiver. FIG. 15 shows a rising edge with overshoot stabilizing after one cycle of the resonance frequency.

Recognition of Predetermined Patterns

Different shapes of objects reflect a modified waveform of the original signal. The echo back signal from a wall is different when compared to the echo back signal from an object with an irregular shape. Reflection from two objects with a short longitudinal distance between them also generates a distinct waveform. By memorizing in database a several types of waveforms, this data can be used to improve the digital processing performance. Digital correlation can be done to detect a predetermined pattern.

Tracking

Averaging techniques do not perform very well with moving objects. By tracking a moving object, one can anticipate the position of the object and adapt to the situation. Averaging with shifting proportional to the estimated position is a way to improve the SNR even in the case of moving objects. Tracking edges is another way to adjust the acquisition of the waveform with more points in the region of interest. Spectral analysis can also be used to lock and track an object.

Weather Information and Condition Monitoring

The system can be used as a road weather information system (RWIS) and thus provide information about temperature, visibility (fog, snow, rain, dust), condition of the road (icy) and pollution (smog). Pattern recognition based on low frequency signals and spikes can be implemented to do so. The recognition of bad weather condition patterns helps to discriminate noise from objects. The system can be used to adjust the intensity of light depending on weather conditions. Monitoring the condition of the lens is also possible (dirt, accumulation of snow, etc). This monitoring can be done by the measurement of the reflection on the lens from the source or from an auxiliary source.

Detection Based on Integration Time

FIG. 16 shows a timing diagram of the method using an integration signal from the reflected signal and synchronized with the rising edge and the falling edge of the PWM lighting source.

This method uses a sensor or an array of sensors (1D or 2D array—CCD, CMOS) with an integrator, or electronic shutter, and a PWM light source or a pulsed auxiliary light source. FIG. 16 shows a PWM signal (PWM curve 1601) with an adjustable duty cycle to control the intensity of light for illumination purposes. Before the rising edge of the PWM pulse, at time $t-x$, the sensor starts the integration (sensor integration curve 1603) of the reflected signal. At time $t+x$, the sensor stops the integration. The same process is performed at the falling edge of the PWM. The light pulse from the source is delayed (delay curve 1602) proportionally to the travelled distance. The delta curve 1604 shows that the integration P1 for the rising edge is smaller than the integration P2 for the falling edge because of the delay of travel of the light signal. In fact, if an object is very close to the source, the integration value from the rising edge will be approximately equal to the integration value from the falling edge. But, if an object is further, the integration value of rising edge will be less than the integration value of the

12

falling edge. The difference between the values is proportional to the distance. The relationship is:

$$\text{Distance} = c \times (\text{INT}/4) * (P2 - P1) / (P2 + P1),$$

5 where c represents the velocity of light, INT represents the integration time, P1 represents the integration value synchronized with the rising edge of the optical pulse and P2 represents the integration value synchronized on the falling edge of the optical pulse.

10 When an illumination background from other lighting sources is not negligible, measurement of the background B during an integration time INT when the optical source of the system is off can be made and subtracted from each integration value P1 and P2. The relationship with non
15 negligible background is:

$$\text{Distance} = c \times (\text{INT}/4) * ((P2 - B) - (P1 - B)) / (P2 + P1 - 2B),$$

where B is the integration value of the optical background level when the optical source of the system is off.

20 In the case where the integration time is larger than the width of the pulse of the optical source, the same technique can be used by switching the synchronisation of the signal of the optical source and the signal to the sensor integration time. The result becomes:

$$\text{Distance} = c \times (\text{INT}/4) * (P1 - P2) / (P2 + P1),$$

25 where c represents the velocity of light, INT represents the integration time, P1 represents the integration value when optical pulse is synchronized with the rising edge of integration and P2 represents the integration value when the optical pulse is synchronized with the falling edge of integration.
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When an illumination background from other lighting sources is not negligible, the relationship is:

$$\text{Distance} = c \times (\text{INT}/4) * ((P1 - B) - (P2 - B)) / (P2 + P1 - 2B).$$

35 Values from the signal integration are memorized. In the case of an array of sensors, each "pixel" is memorized. Several integrations can be performed and an averaging process can be done to improve signal to noise ratio. In the case of an array, we also can improve signal to noise ratio by using a groups of pixel and combining them to form a larger pixel (binning)

40 In summary, with reference to FIG. 17, the main steps of the method for acquiring a detected light optical signal and generating an accumulated digital trace are shown. The method comprises providing a light source with an optical detector for illumination of a field of view 1700; providing an analog-to-digital converter (ADC) 1702; emitting one pulse from the light source in the field of view 1704; detecting a reflection signal of the pulse by the optical detector 1706; acquiring j points for the detected reflection signal by the ADC 1708; storing, in a buffer, the digital signal waveform of j points 1710; introducing a phase shift of $2\pi/P$ 1712; repeating, P times 1714, the steps of emitting 1704, detecting 1706, acquiring 1708, storing 1710 and introducing 1712 to store 1710, in the buffer, an interleaved waveform of $P \times j$ points; accumulating 1716 M traces of interleaved $P \times j$ points for a total of $N = M \times P$ acquisition sets, N being a total number of pulses emitted; creating one combined trace of the reflected signal of $j \times P$ points by adding each point of the M traces 1718.

45 Additionally, the combined trace can be compared 1720 to a detected reference reflection signal of the pulse to determine 1722 a distance traveled by the pulse.

50 Alternatively, a timer can be triggered to calculate a time elapsed 1724 between the emission of the pulse and the

13

detection of the reflection signal to determine a distance traveled **1722** by the pulse based on the time elapsed.

In summary, with reference to FIG. **18**, the main steps of the method for detecting a distance to an object are shown. The method comprises providing a lighting system **1800** 5 having at least one pulse width modulated visible-light source for illumination of a field of view; emitting an illumination signal **1802** for illuminating the field of view for a duration of time y using the visible-light source at a time t ; integrating a reflection energy for a first time period 10 from a time $t-x$ to a time $t+x$ **1808**; determining a first integration value for the first time period **1810**; integrating the reflection energy for a second time period from a time $t+y-x$ to a time $t+y+x$ **1812**; determining a second integration value for the second time period **1814**; calculating a 15 difference value between the first integration value and the second integration value **1816**; determining a propagation delay value proportional to the difference value **1818**; determining the distance to the object from the propagation delay value **1820**.

While illustrated in the block diagrams as groups of discrete components communicating with each other via distinct data signal connections, it will be understood by those skilled in the art that the illustrated embodiments may be provided by a combination of hardware and software 25 components, with some components being implemented by a given function or operation of a hardware or software system, and many of the data paths illustrated being implemented by data communication within a computer application or operating system. The structure illustrated is thus provided for efficiency of teaching the described embodiment.

What is claimed is:

1. A method for detecting a distance to an object, comprising: 35

providing a lighting system having at least one pulse width modulated visible-light source for illumination of a field of view;

emitting an illumination signal for illuminating said field of view for a duration of time y using said visible-light source at a time t , said time t being a center of a transition from a non-illuminated state to an illuminated state of said field of view, for at least one pulse; 40

starting an optical sensor for integrating a reflection energy captured by said [visible-light source] optical

14

sensor, of a reflection of said illumination signal, for a first time period at a time $t-x$ of a first one of said at least one pulse;

stopping said optical sensor for said first time period at a time $t+x$ for said first one of said at least one pulse and determining a first integration value for said first time period;

starting said optical sensor for integrating said reflection energy captured by said [visible-light source] optical sensor, of said reflection of said illumination signal, for a second time period at a time $t+y-x$ for a second one of said at least one pulse, said second one being one of said first one and another one of said at least one pulse, y being greater than x ;

stopping said optical sensor for said second time period at a time $t+y+x$ for said second one of said at least one pulse and determining a second integration value for said second time period;

measuring a background integration value for non-negligible illumination background from other lighting sources during an integration time $2x$ when said visible-light source is not emitting;

subtracting from each said first integration value and said second integration value said background integration value to obtain background compensated first integration value and second integration value;

calculating a difference value between said background compensated first integration value and said background compensated second integration value;

determining a propagation delay value proportional to said difference value;

determining said distance to said object from said propagation delay value.

2. A method as claimed in claim 1, further comprising: 35 providing a threshold distance to a pre-identified object; comparing said distance to said object with said threshold distance;

determining said object to be said pre-identified object if said comparison is positive.

3. A method as claimed in claim 1, further comprising, when said x is greater than said y , said integrating being larger than a width of the pulse,

switching a synchronisation of said illumination signal with said starting said optical sensor.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : RE46,930 E
APPLICATION NO. : 14/984704
DATED : July 3, 2018
INVENTOR(S) : Mimeault

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

At Column 1, under the heading "*CROSS-REFERENCE TO RELATED APPLICATIONS*," replace Lines 15-17 (approx.), with the following:

--*NOTICE: More than one reissue application has been filed for the reissue of U.S. Patent No. 8,619,241 B2. The reissue applications are U.S. Reissue Patent Application Serial No. 16/011,820, filed on June 19, 2018, which is a divisional reissue application of U.S. Reissue Patent Application Serial No. 14/984,704 (the present application), filed on December 30, 2015, now U.S. Reissue Patent No. RE46,930 E, issued July 3, 2018, which is a reissue application of U.S. Patent Application Serial No. 13/632,191, filed on October 1, 2012, now U.S. Patent No. 8,619,241 B2, issued December 31, 2013.--*

Signed and Sealed this
Twenty-third Day of March, 2021



Drew Hirshfeld
*Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office*