Method for improving the time resolution of a TOF system *

LI Shao-Li(李绍莉)[1,2,3;1)] HENG Yue-Kun(衡月昆)[1,2;2)] ZHAO Tian-Chi(赵天池)[4]
FU Zai-Wei(付在伟)[5] LIU Shu-Lin(刘术林)[2] QIAN Sen(钱森)[2]
LIU Shu-Dong(刘曙东)[2] CHEN Xiao-Hui(陈晓辉)[1,2,3] JIA Ru(贾茹)[6]
HUANG Guo-Rui(黄国瑞)[7] LEI Xiang-Cui(雷祥翠)[1,2,3]

[1] State Key Laboratory of Particle Detection and Electronics, Beijing 100049, China
[2] Institute of High Energy Physics, Chinese Academy of Science, Beijing 100049, China
[3] Graduate University of Chinese Academy of Science, Beijing 100049, China
[4] Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
[5] Department of Physics, Nanjing University, Nanjing 210093, China
[6] Department of Science and Technology, Central China Normal University, Wuhan 430079, China
[7] Department of Science and Technology, Guangxi University, Nanning 530004, China

Abstract: In order to study the possibility of improving the timing performance of the time of flight (TOF) systems, which are made of plastic scintillator counters, and read out by photomultiplier tubes (PMT) with mesh dynodes and conventional electronics, we have conducted a study using faster PMTs and ultra fast waveform digitizers to read out the plastic scintillators. Different waveform analysis methods are used to calculate the time resolution of such a system. Results are compared with the conventional discriminating method based on a threshold and pulse height. Our tests and analysis show that significant timing performance improvements can be achieved by using this new system.

Key words: scintillator counter, TOF system, waveform sampling, waveform analysis, time resolution

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1 Introduction

TOF systems in high energy physics experiments, such as the ones used in BESIII [1, 2], CDF II [3], BELLE II [4] and others consist of long plastic scintillator bars read out at two ends by fine mesh PMTs that can work in a magnetic field. The output signals are sent to the readout electronics via long analog cables. Leading edge discriminators with pulse height correction are used to determine the arrival time of particles that penetrate the scintillator bars. The time resolution of the BESIII barrel TOF system is about 78 ps [5] while the TOF time resolutions of the CDF II experiment and BELLE experiment are 100 ps and 85 ps, respectively.

An important factor that determines the particle identification (PID) capability of TOF systems is their time resolution. One of the main determining factors of the TOF intrinsic time resolution is the performance of the scintillator, including attenuation length, decay time, photon yield, rise time, transit time fluctuation, etc. Other factors such as the rise time of the PMTs, the bandwidth of the amplifiers and the readout electronics can affect the TOF time resolution. In addition, the conventional discriminating method with amplitude corrections that is used to determine the signal arrival time can also affect the TOF performance.

Due to the new progress in technology, it is now conceivable to use a new scintillator readout method that employs ultra fast PMTs, such as PMTs based on microchannel plates (MCP-PMT) read out by high bandwidth waveform digitizers directly attached to the PMT base. We have investigated this new approach in order to see how much improvement it can achieve.

2 The experimental setup

The experiment uses a cosmic ray and the setup is shown in Fig. 1. Two EJ200 plastic scintillator bars 2380 mm long and 50 mm thick each placed on top of each other are coupled with four GDB60 PMTs by sili-

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1) E-mail: shaoli.ah@gmail.com

2) E-mail: hengyk@ihep.ac.cn

cone oil at both ends of each scintillator bar. The scintillator bars are wrapped with aluminum foil and then covered with light tight cloth. The GDB60 PMT used here has an 800 ps rise time. Outputs from the four PMT GDB60 go into the Lecroy 7100 oscilloscope which has a quad input with a 10 Gs/s sampling rate, 1 GHz bandwidth and 8 bits vertical resolution to record the waveforms. With waveform files that contain all information, we can do offline analysis about the system performance.

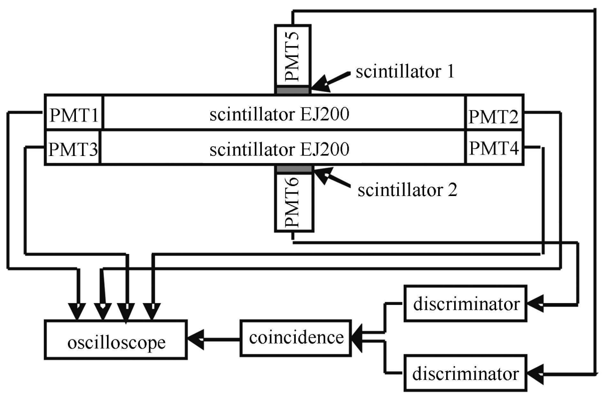

Fig. 1. The experimental setup and readout system.

The trigger is made of two fast plastic scintillator counters placed in the middle of the long scintillator bars. These two counters are Type BC420 with an area of 50 mm×50 mm read out by PMT 5 and 6 (XP2020). Signals from PMT 5 and 6 are first discriminated and then they go to the coincidence unit. The output from the coincidence unit is used as the external trigger for the oscilloscope. Since we use the time differences from the two ends to determine the time resolution of the system, signals generated from the middle of the counters would give out the worst time resolution.

3 Offline waveform analysis

3.1 Waveform reconstruction, noise and amplitude

Figure 2(a) shows a waveform of cosmic ray signal reconstructed from the waveform file recorded by the oscilloscope. The time window is 1 μs. The data points which are recorded 150 ns before any particle passes through the scintillator counter are noise. Fig. 2(b) shows the noise spectrum and the baseline offset is 0.13 mV. Ten points near the peak of every pulse are plotted and fitted with normal distribution to get the peak value. The amplitude of the signal pulse is the fitted peak value of the normal distribution minus the baseline offset.

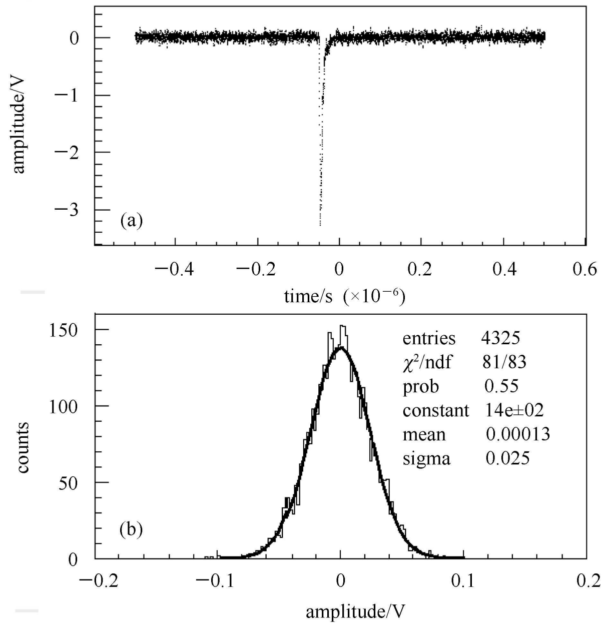

Fig. 2. (a) The waveform of a pulse; (b) The noise spectrum.

3.2 Distribution of amplitude, charge and rise time

The oscilloscope sampling rate is 10 Gs/s, which means the time interval between two neighboring points is 100 ps. The charge value of a pulse can be obtained from the numerical time integral from 40 ns before the peaking time to 60 ns after [6], this time integral contains 1000 points in all.

Charge values can be calculated by the summation of the measured voltage in the 1000 time interval:

$$Q=\frac{t\times\sum_i V_i}{R}=\frac{100\times\sum_i V_i}{50}=2\times\sum_i V_i \text{ pC}. \qquad (1)$$

Since the oscilloscope is set at 1 V/div, 8 divisions in all and the vertical resolution is 8 bits, so the precision of voltage (amplitude) measurement is $\sigma_{V_i}=\frac{1\text{ V}\times 8}{2^8}=0.03125$ V. σ_{V_i} is the precision of the amplitude of every recorded waveform data point. The pulse lasts about 10 ns. From Eq. (1), the rough charge measurement precision is

$$\sigma_{\mathrm{Q}}\approx\sqrt{\sum_{i=0}^{i<1000}(2\sigma_{V_i})^2}=\sqrt{1000\times(2\times0.03125)^2}=1.976\text{ pC}. \qquad (2)$$

So, if the charge of a pulse is 300 pC, the precision of charge measurement is 0.66% roughly.

Figure 3 shows the distribution of amplitude, charge and rise time of the recorded cosmic ray signal (The rise time is the time required for signal amplitude to change

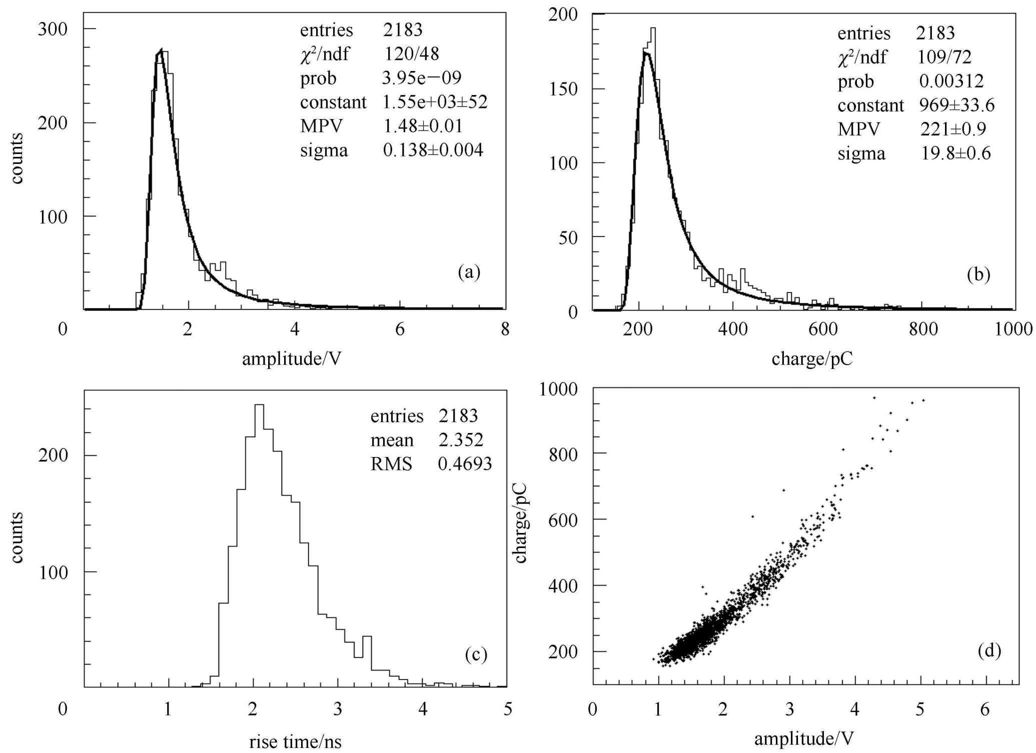

Fig. 3. (a) The amplitude distribution; (b) The charge distribution; (c) The rise time distribution; (d) Charge vs. amplitude.

from 10% to 90% of the peak height.). We fit the measured amplitude and charge distributions by landau distributions shown in Fig. 3(a), (b) and the rise time is shown in Fig. 3(c) with a mean of 2.352 ns marked as τ. Note that the EJ200 scintillator has a decay time of 2.1 ns marked as τ_1 and the rise time of PMT GDB60 is about 800 ps as τ_2. The following equation can be established:

$$\tau=\sqrt{\tau_1^2+\tau_2^2}. \tag{3}$$

The relationship between signal amplitudes and total charge values is reasonably linear as shown in Fig. 3(d).

3.3 The discriminating methods

The discriminating methods are used to determine the signal start time (the same as the discriminating time which is the time when signal amplitude reaches the threshold value) and calculate the system time resolution. Fig. 4(a), (b), (c) and (d) correspond to four different ways to calculate the start time of the cosmic ray signal. In Fig. 4(a) we try to simulate the traditional discriminating method with amplitude corrections through the first method. The other three methods (as shown in Fig. 4(b), Fig. 4(c) and Fig. 4(d)) describe how to analyse the time using data points from the waveform files.

The traditional discriminating method only measures the time of discrimination. In the first method, as the amplitude has already been known, a threshold can be set to 20% of the amplitude value. For example, when the value of amplitude is 1.48 V, the threshold is 0.296 V. Using a linear fitting with two nearby recorded points from the waveform: $(t_1,\ a_1)$ and $(t_2,\ a_2)$ as shown in Fig. 4(a), the discriminating time value can be calculated with the following equation:

$$t=t_1+\frac{(t_2-t_1)\times(\text{threshold}-a_1)}{a_2-a_1}, \tag{4}$$

where t_1 and t_2 are the time values of the two points, a_1 and a_2 are the amplitude values.

The second method (Fig. 4(b)) shows a way of using more waveform information to do the calculation. From the rising edge of the signal, an amplitude interval which starts from 20% of the signal height (amplitude of the signal) and ends at 60% of the signal height is chosen. The threshold is the same value, and then the time value can be obtained by the linear fitting of data points inside this interval. Since the fitting interval starts from 20% of the signal height, if the threshold value is set under this, we can extrapolate the linear curve to the threshold value (for exanple, 5% of the signal height). As the cosmic ray signal rises very fast (less than 3 ns) and the sampling rate of the oscilloscope is very high (10 Gs/s), we now assume that the rise edge of the signal fits the linear curve. That is why we can do the extrapolation.

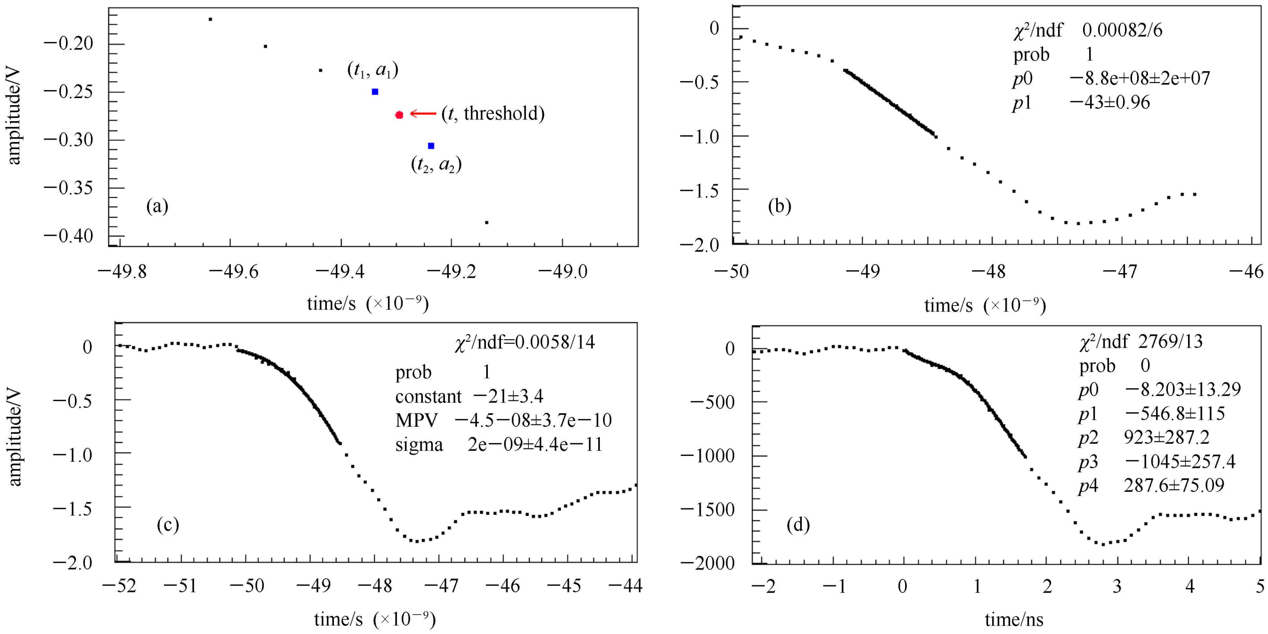

Fig. 4. Diagram of calculating the start time, we only show part of the cosmic ray signal waveform so you can have a clear view: (a) the first method: simulating the traditional discriminating method; (b) the second method: linear fitting; (c) the third method: Landau fitting; and (d) the fourth method: fourth order polynomial fitting.

Considering more points are used, the time value should be more accurate than the first method.

The third method (Fig. 4(c)) also uses data points inside an amplitude interval. The difference from the second method is that the interval is from 0% to 50% of the signal height and the model used is the Landau distribution. In Fig. 4(c), the Landau curve is drawn, which covers this interval and the time value can be obtained based on the Landau function and threshold value.

The fourth method (Fig. 4(d)) uses data points inside an amplitude interval from 0% to 50% of the signal height which is the same interval as we used in the third method. We try to use a polynomial curve fitting the data points. Here we fit the data points with a fourth order polynomial curve to obtain the discriminating time value.

The time interval chosen in Method two is 20% to 60% because the other part of the rising edge curves a lot which does not fit the linear model. Since the more points you use in the third method the more fitting errors you will get [7], we choose the time interval from 0% to 50% in Method three. This interval guarantees that enough waveform information will be used while the fitting error will not be too large. The fitting interval chosen for method four is the same as with method three so we can compare results from these two different fitting methods.

The first method which calculates the time value only uses two points while the other three methods use more data points from the waveform. We expect to see that the time resolution will be better if more waveform information is used. Fig. 4 (b), (c) and (d) indicates that the Landau curve and polynomial curve fit the waveform better than the linear curve. This means the time resolution given from Landau and polynomial fitting should be better than the other two.

Although the choice of fitting time interval can influence the result, the third and fourth methods which use the Landau and fourth order polynomial fitting give better time resolution than the other two methods. As we studied, changes in the time interval (like plus or minus 10% of the signal amplitude) will not change the best time resolution value much, but time resolution values calculated using a too small (like 5% or 10% of the signal amplitude) or big (like 40% of the signal amplitude) threshold value will vary a lot.

3.4 Time resolution of the system

There are four channels of signals from PMT GDB60 and the discriminating time values are noted as T_1, T_2, T_3 and T_4. The time resolution of the system can be calculated based on this:

$$T=\frac{(T_1+T_2)-(T_3+T_4)}{4}, \tag{5}$$

$(T_1+T_2)-(T_3+T_4)$ can reduce the hitting position variation of the cosmic ray and the uncertainty of start time of the system.

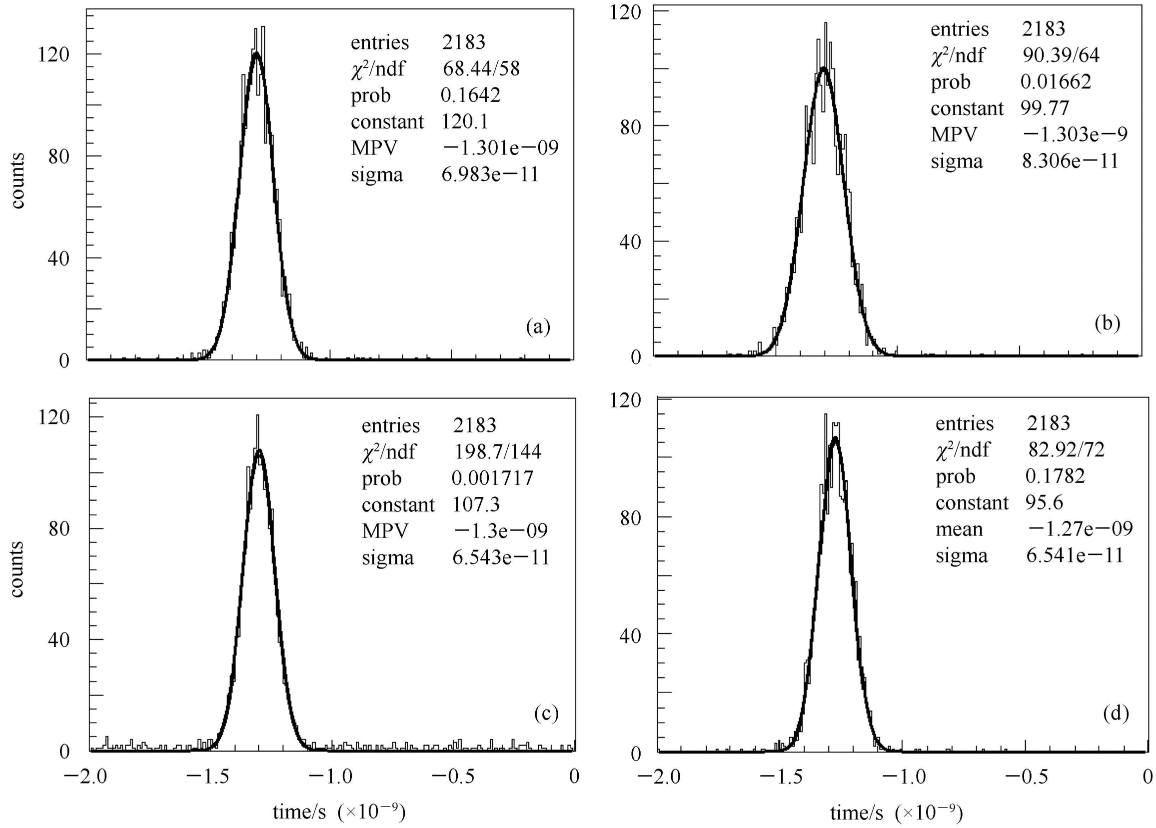

Fig. 5. Time resolutions from four different methods for a threshold of 15% amplitude. All the events are taken from the same PMT. (a) the first method; (b) the second method; (c) the third method; (d) the fourth method.

Figure 5 shows the examples of spectra of time T calculated from four different methods fitted by normal distributions and the threshold value was assumed to be 15% of the signal amplitude. The time resolution values calculated from the first, second, third and fourth methods are 69.8 ps, 83.6 ps, 65.43 and 65.41 ps separately.

The time resolution given from Fig. 5 is the time resolution of one end. Our setup uses a two end readout system, so the time resolution of one TOF counter here is the value divided by $\sqrt{2}$. Fig. 6 shows the threshold of different percentage vs. time resolution. Please note that the time resolution values here have already been divided by $\sqrt{2}$. The best time resolution of TOF read out at two ends is 46.3 ps using a Landau or polynomial fitting when the threshold is 15% of the signal amplitude.

From Fig. 6, we can see that the Landau and polynomial fitting method give the best result while polynomial fitting is simpler. The linear fitting method is the worst one for the reasonable actual threshold value. In addition, the Landau curve fits the waveform better at the starting part and worse at the crest part. The low threshold area corresponds to the starting area of the rise edge where the waveform curves a lot, that's why the linear fitting become worse.

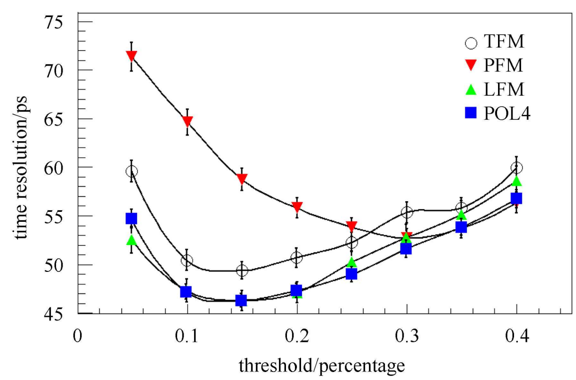

Fig. 6. Threshold vs. time resolution with error bars. TFM refers to the traditional fitting method. PFM refers to the linear fitting method. LFM refers to the Landau fitting method. POL4 refers to the fourth order polynomial fitting method.

4 Conclusions and discussions

The ultra fast PMT and waveform sampling technique used in our experiment significantly improve the time resolution of the TOF system since detailed information about the signal shapes can be obtained from the waveforms and used in the analysis.

We have shown that among the four methods studied, the waveform analysis based on Landau and fourth order polynomial curves are better than the traditional discrimination method which give the best time resolution of 46.3 ps, this is significantly better than the performance of current TOF systems. This is due to the fact that more accurate information can be obtained by fitting the rising edges of the recorded waveforms, which is much better than simply using a linear function extrapolation. Results from the first method are better than we have expected, mainly because the waveform information is still used here to calculate the amplitude and the start time. While the Landau, polynomial and linear fitting method rely on the choice of fitting time interval, the traditional fitting method only uses two recorded points.

Technologies of a fast PMT and a high sampling rate waveform digitizer are developing rapidly [8] and waveform digitizers with 10 Gs/s sampling rate or higher may become available in the near future. They can be considered to implement the techniques described in this paper in the future TOF systems. The oscilloscope used to record waveforms in our test would be replaced by integrated high rate waveform digitizers that are compact and inexpensive. The long analog cables that limit signal bandwidth in a conventional TOF system can be eliminated.

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