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CA 2467898 A1 2005/11/21

(21) 2 467 898

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) A1

(22) **Date de dépôt/Filing Date:** 2004/05/21

(41) **Mise à la disp. pub./Open to Public Insp.:** 2005/11/21

(51) **Cl.Int.^{7}/Int.Cl.^{7}** G01P 13/00

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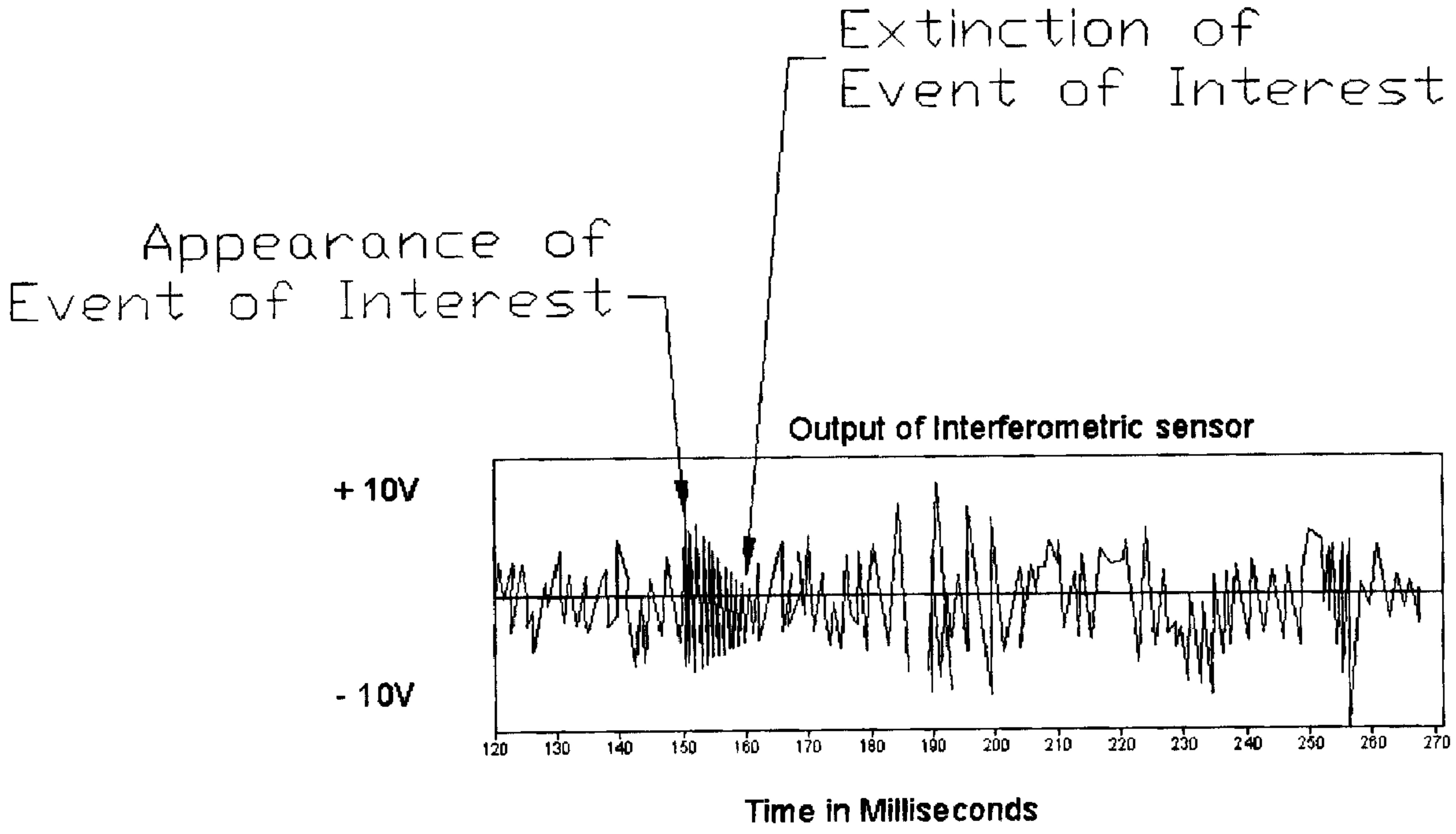
(54) **Titre :** CAPTEURS A FIBRES OPTIQUES ET METHODE
(54) **Title:** FIBER OPTIC SENSOR METHOD AND APPARATUS



(57) **Abrégé/Abstract:**
The invention relates to the simultaneous use of an interferometric sensor and a phase-OTDR sensor, both preferably on the same fiber optic cable. The interferometric sensor determines when a a sensed disturbance is of interest, and the phase OTDR sensor locates the sensed disturbance.

Fiber Optic Sensor Method and Apparatus

Abstract

The invention relates to the simultaneous use of an interferometric sensor and a phase-OTDR sensor, both preferably on the same fiber optic cable. The interferometric sensor determines when a a sensed disturbance is of interest, and the phase OTDR sensor locates the sensed disturbance.

Fiber Optic Sensor Method and Apparatus

This invention relates to a method of locating a disturbance using a fibre optic sensor. According to the invention, the fibre optic cable can be used to detect a wide variety of disturbances. For example, the sensor can be buried shallowly in the ground to detect the disturbance caused by an intruder passing over it, or it can be located in for example a pipeline, to detect a disturbance caused by a leak from the pipeline. In structures like wire-wrapped concrete pipes or bridge cables, it can be laid in the pipe or in contact with the bridge cable, to detect the disturbance caused when a reinforcing wire snaps.

A disturbance, either a pressure change or a seismic disturbance, can be detected with a high degree of sensitivity by an optical fibre using interferometric sensing. If a long length, such as the entire length, of the fibre optic sensor the sensor is known as a "distributed" sensor.

Many techniques have been used to attempt to determine the location of a disturbance in a distributed fiber optic sensor. These sensors utilize the actual fiber as the sensor and do not require gratings or other intrusions into the fiber to make it sensitive to the measurand. The distributed sensor has a significant advantage in signal to noise ratio in that the sensor is not displaced longitudinally from the disturbance, as in the case with fixed sensors. Because the distance from the nearest sensing point to the source of the disturbance is minimized, the deterioration of the signal to noise ratio resulting from signal attenuation with distance is also minimized.

A truly distributed sensor offers many advantages. However, if the sensor is interferometric in nature, a disturbance anywhere along the fiber produces a similar effect. Locating the point of the disturbance is difficult in this type of sensor but is vital for most monitoring applications.

Udd (USP 5,636,021), Tapanes (USP 6,621,947), Taylor (USP 5194847 and SPIE paper April, 2003) and others have tried to achieve the location of the disturbance using amplitude ratios of counter-propagating beams, arrival times of disturbances in loop interferometers, and using phase-sensitive optical time–domain reflectometry respectively.

In each case, the accuracy of the location, the quality of the detected signal, or both, can limit the usefulness of the sensor.

The present invention proposes a combination of technologies that can solve these problems for many applications.

Taylor et al (SPIE paper April 2003) has found that a disturbance caused by an intruder can be located using a phase-sensitive optical time domain reflectometer (Phase OTDR) in a particular arrangement. The utility of Rayleigh-backscatter in estimating the location of a disturbance is valuable, but suffers from large noise components and limited bandwidth in long sensors because of the travel time of the pulse to the far end of the sensor and back. For certain limited uses, this may be sufficient, but in the case of monitoring structures, a much higher bandwidth is more useful in identifying the nature of the disturbance, such as the failure of a pre-stressing wire. Paulson (5,798,457) recognizes that there is a need to identify the characteristics of the source to be useful in monitoring structures, and that the bandwidth needed may exceed 5 KHz. to 12 KHz. or higher.

Interferometric sensors such as described by Udd (5,636,021) can have sufficient bandwidth, but cannot accurately locate the position of a disturbance, especially if the return legs of the Sagnac loops (as used by Udd) are also subject to the disturbance. In this case, the ratiometric approach to estimate the position of the disturbance does not work well.

The present invention uses a combined sensor with a phase-OTDR and an interferometric sensor to overcome these limitations. The output of one technique needs to be correlated with the output of the other technique in order that the user might associate a disturbance position as calculated by phase-OTDR with a particular set of features detected by an interferometric sensor.

To accomplish this in an environment where both sensors constantly produce signals and noise requires an innovative approach.

A method of doing this relies on several factors. First, the identification of an event of interest can only really be discerned by the higher bandwidth interferometric sensor. If the sensor is deployed in an environment where many noises are generated, then the recognition that a particular event contains the characteristics of interest is required. When such an event is recognized, then the position of the source of the event must be discerned. This could be done by examining the temporal appearance and extinction of some characteristics of the event on both sensors. Because each event will affect both sensors for the same time, starting at the same time, and ending at the same time if the sensors are in the same position relative to the structure they are monitoring, then a temporal correlation of the appearance and extinction of the features distinguishing that event from background noise should allow the event as it appears on each separate sensor to both be identified as the event of interest.

For example, in a pre-stressed water pipeline such as discussed by Paulson (USP 6,082,193), a distributed interferometric sensor and a phase OTDR can both be constructed in an optical fiber deployed within the pipeline. Flow noise, traffic disturbances and other features will produce noise effects on both sensor paths. The failure of a pre-stressing wire would generate a burst of sound that would travel through the water and encounter the sensing fiber, disturbing it. The acoustic wave would also travel in both directions along the pipeline, becoming slowly attenuated, resulting in a slow extinction of the disturbance in both sensing paths.

By continuously monitoring the interferometric sensor, the event can be recognized as being one of interest. A buffer of information indicative of the output of the Phase OTDR is kept. When an event of interest is ascertained from the interferometric sensor, reference is made to the Phase OTDR results of the times just before and during that appearance of the anomalies of interest on the interferometric sensor. The Phase OTDR outputs are then used to determine the location along the sensor of the anomaly of interest.

The invention will be described with reference to the following drawings, in which:

Description of the Drawings

Figure 1 shows the output of an interferometric sensor recorded over a period of time indicated in milliseconds, and containing a sensed event of interest,

Figure 2 shows the output of a phase OTDR sensor, operating to do a scan which takes approximately 150 microseconds commencing at the 130 millisecond mark in Figure 1.

Figure 3 shows the output of a phase OTDR sensor, operating to do a scan which takes approximately 150 microseconds, commencing at the 140 millisecond mark in Figure 1.

Figure 4 shows the output of a phase OTDR sensor, operating to do a scan which takes approximately 150 microseconds, commencing at the 150 millisecond mark in Figure 1.

Figure 4 shows the output of a phase OTDR sensor, operating to do a scan which takes approximately 150 microseconds commencing at the 160 millisecond mark in Figure 1.

Figure 5 shows the output of a phase OTDR sensor, operating to do a scan which takes approximately 160 microseconds commencing at the 160 millisecond mark in Figure 1

Detailed Description

The intereferometric sensor of the invention operates continuously and is monitored for anomalies of interest.

The phase OTDR sensor operates at discrete, spaced intervals. In the example given here, it operates once every 10 milliseconds. It operates just lone enough for an OTDR scan of the entire length of the optical fibre. In the example, this takes 150 microseconds. These phase OTDR scans are retained for a suitable period, and are then discarded. The suitable period depends on how quickly the interfereometric sensor scans are examined for events of interst, as, when an event of interest ids found, the phase OTDR scans for the period surrounding it will be wanted.

In Figure 1, it is seen that an event of interest occurs at approximately 150 milliseconds after commencement of the interferometer scan.
It continues until approximately 160 milliseconds after commencement.

Once this is determined, the phase OTDR scans that occurred at 130 milliseconds, 140milliseconds, 150 milliseconds and 160 milliseconds are retrieved and examined.

The phase OTDR traces at 130 milliseconds (Figure 2) and 140 milliseconds (Figure 3) are considered as base conditions, before the event of interest. They are of course full of noise, but the noise does not vary much over the 10 milliseconds between them.

When the 150 millisecond phase OTDR trace is examined, a difference appears at approximately the 87 microsecond point along the trace, where the trace is dissimilar to that at the receors taken at 130 milliseconds or 140 milliseconds on the interfereometer trace. A lesser difference, in the same spot is recognized in the trace taken at 160 milliseconds. (Figure 5).

Distance along the phase-OTDR time record correlates to distance along the optical fibre. Thus, from the fact that the anomaly shows up at 87 microseconds, the location at which the disturbance occurred along the optical fibre is known precisely.

The result is that because the appearance of the anomaly on both systems at about 150 m sec (absolute time reference not required) and the duration of the anomaly extending to 170 msec, there is good reason to believe that the same event caused both anomalies, and that the anomaly occurred at a position represented by an 87 microsecond delay on the phase-OTDR

In the particular experimental set-up , 87 microseconds would represent a distance of about 87/9.73=8.94 km.
Similarly, if a noise event appears that had a shorter duration, or a different start or stop time, then it can be rejected as the cause of the anomaly of interest detected by the interferometric sensor.

Another way of visualizing the waveforms is to calculate the difference between any given trace and the average of the preceding traces. Absent damage etc. to the fiber, the average of a number of traces would tend to be consistent, but the difference between any given trace and the foregoing average would help to indicate the temporal anomalies. To reduce noise, the long term average might use an average of many seconds of data, but the short term temporally varying trace might be the average of traces over a few milliseconds.

The apparatus for this technique can be a single and/or multiple fiber optic sensor deployed in contact with the structure, or in contact with the fluid within a pipeline. The fiber(s) would have at least one optical circuit that used an interferometric sensor, such as a Sagnac effect sensor and/or a type of sensor that has consistent sensitivity over its length, such as a Michelson sensor. The advantage of constant sensitivity sensor is that because it has the same sensitivity over its length, it allows a constant threshold of interest to be used everywhere in the sensor. Combined with the interferometric sensor in either the same or a separate but nearby fiber, would be the phase-sensitive OTDR. The phase-OTDR fiber would also be exposed to the measurand along its length and would be sampled sufficiently often that the duration and other characteristics of a disturbance could be determined. Only sufficient detail from the phase-OTDR need be gathered to remove ambiguity from the association with the interferometric sensor. It is important that if the same fiber is not used for both sensing systems, that the fibers both be in the same locations relative to the structure. Otherwise, the actual disturbance seen on one fiber would not necessarily have a corollary on the other.

In water pipelines, the propagation of the disturbance in both directions from the source offers the chance to greatly improve the accuracy of the location estimate, by using the expected symmetrical propagation pattern over many Phase-OTDR traces to more accurately measure the position of the origin of the disturbance, and to eliminate from consideration the portions of the trace that result from other noises in the pipeline.

The preferred aspects of the invention are:

- The use of two distributed sensors in close proximity to each other or in the same fiber
- One of the sensors is interferometric and preferably is constructed to have consistent sensitivity over its length
- The other of the sensors uses phase-OTDR technique
- The Phase-OTDR must refresh at least 10 times per second and offer a spatial resolution of 0.2 km or less
- Continuously monitoring the outputs of one or both sensors
- When an event of interest is detected, analyzing the output of the higher bandwidth sensor to recognize or identify characteristics indicative of the type of source of disturbance

- Comparing the Phase-OTDR traces that occur about the same time as the interferometric event of interest to find a temporal correlation between the anomalies on each sensor
- Identifying characteristics of the event of interest on both sensors to identify the location of the event using the phase-OTDR trace
- Reporting the results of the analysis

Figure 1

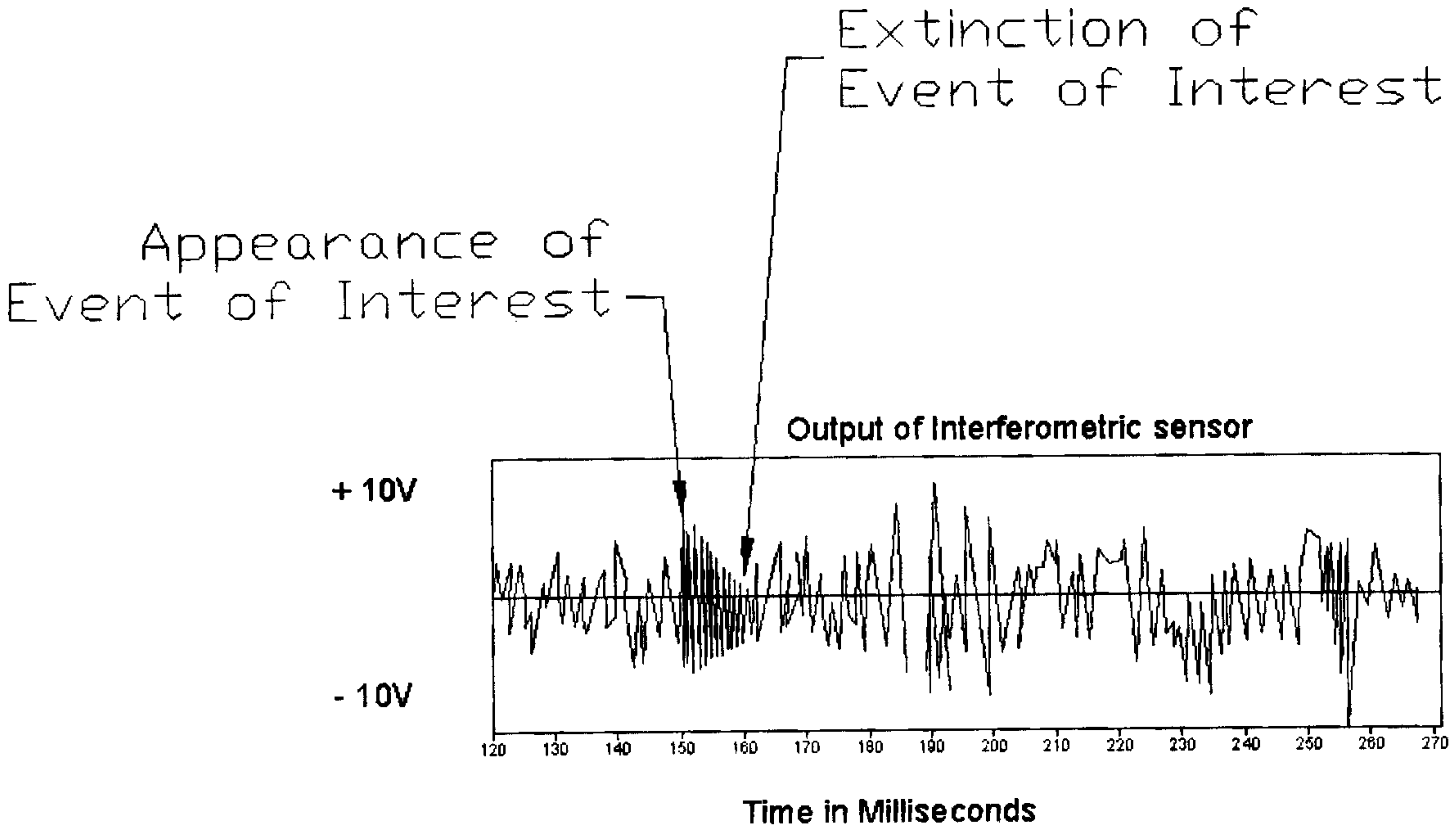

Extinction of
Event of Interest
Appearance of
Event of Interest
Output of Interferometric sensor
+ 10V
- 10V
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
Time in Milliseconds

Figure 2

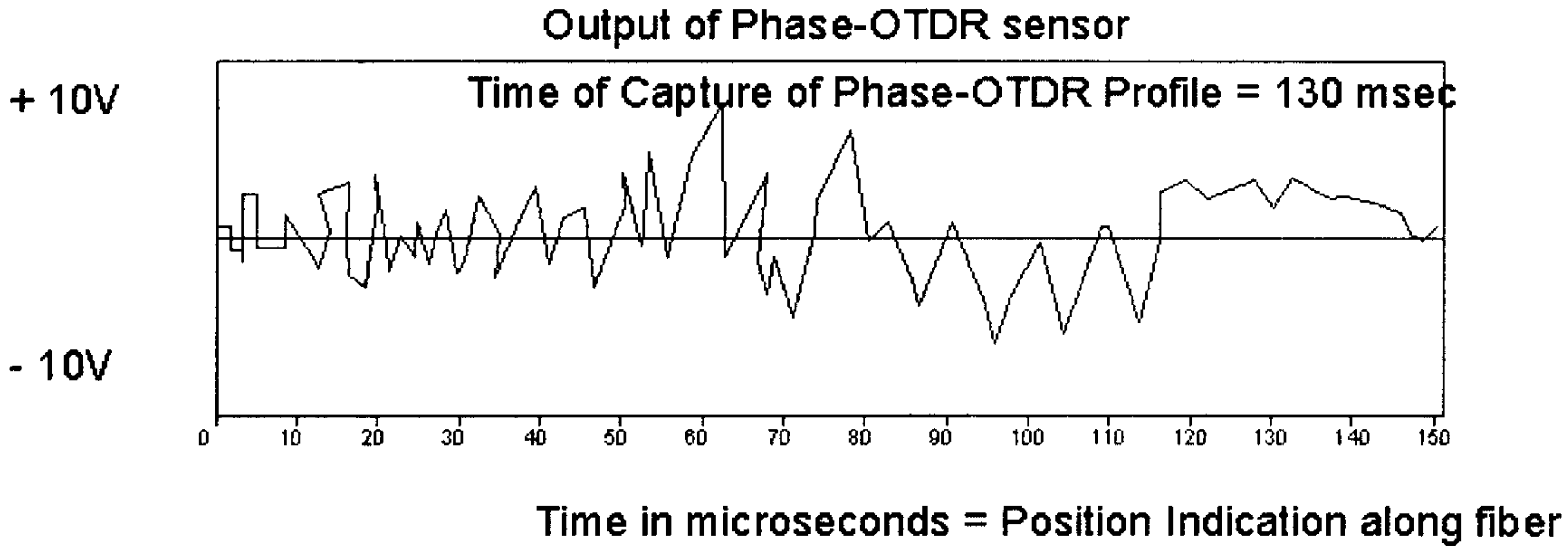

Output of Phase-OTDR sensor
Time of Capture of Phase-OTDR Profile = 130 msec
+ 10V
- 10V
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time in microseconds = Position Indication along fiber

Figure 3

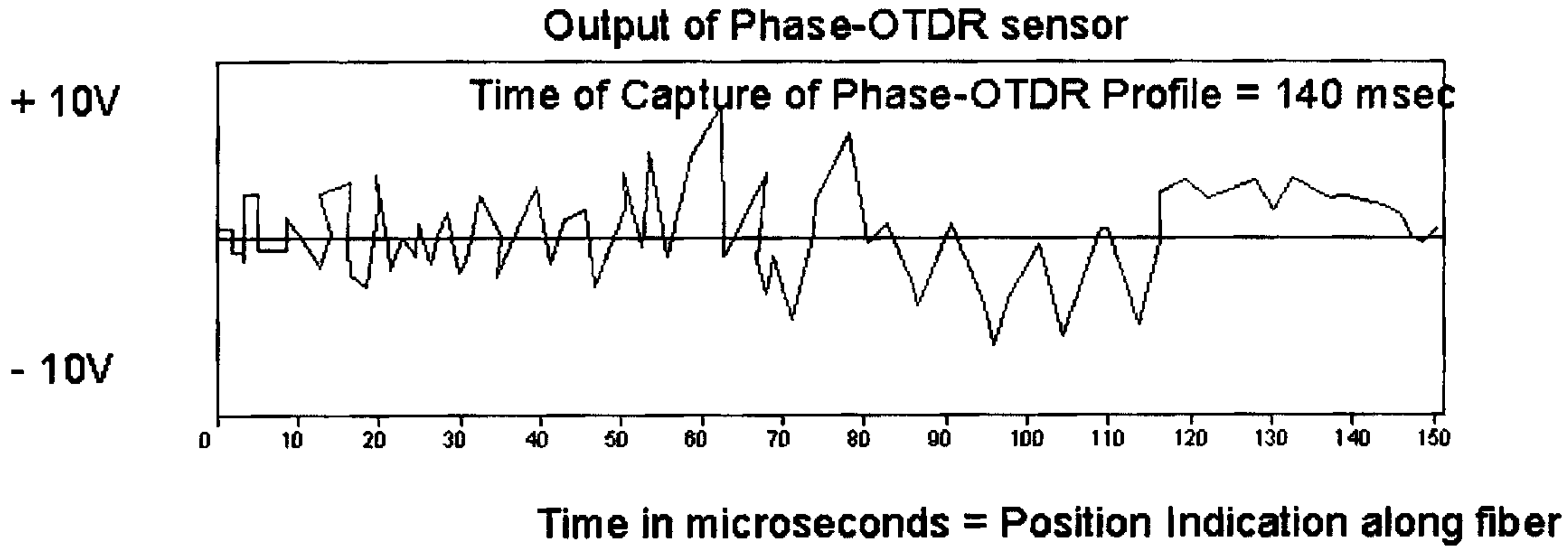
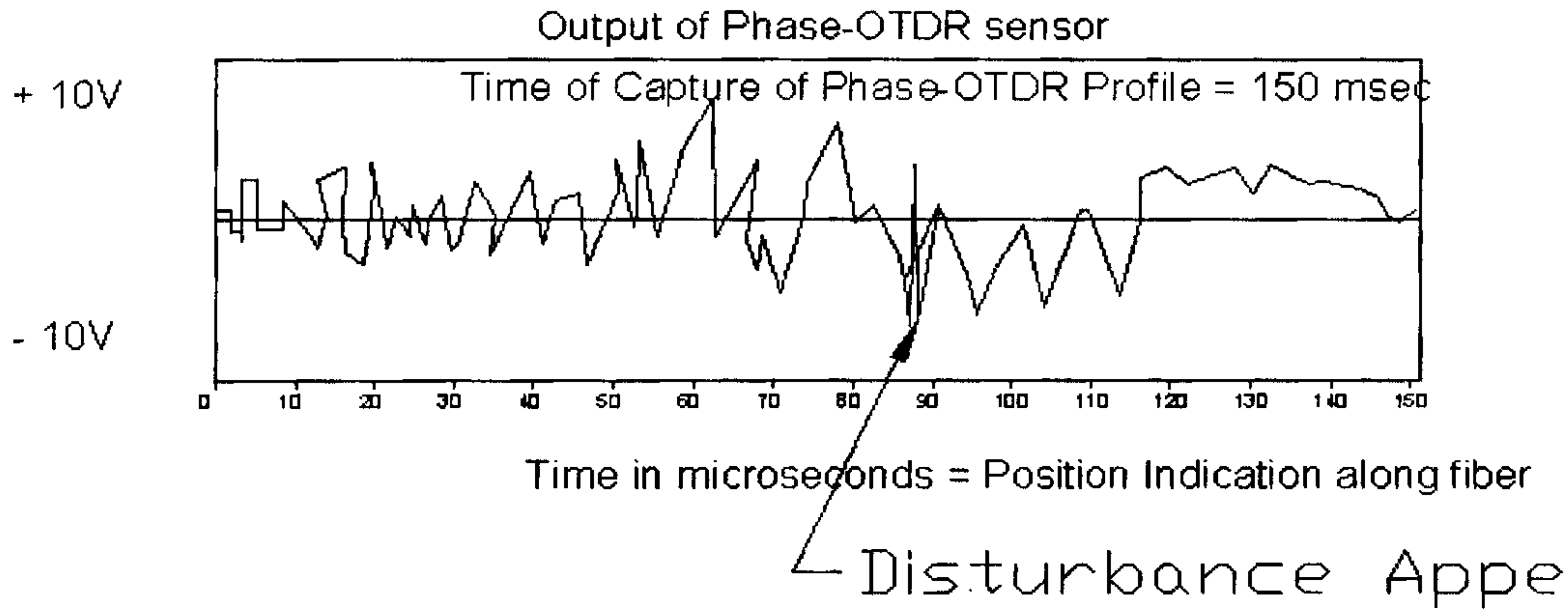
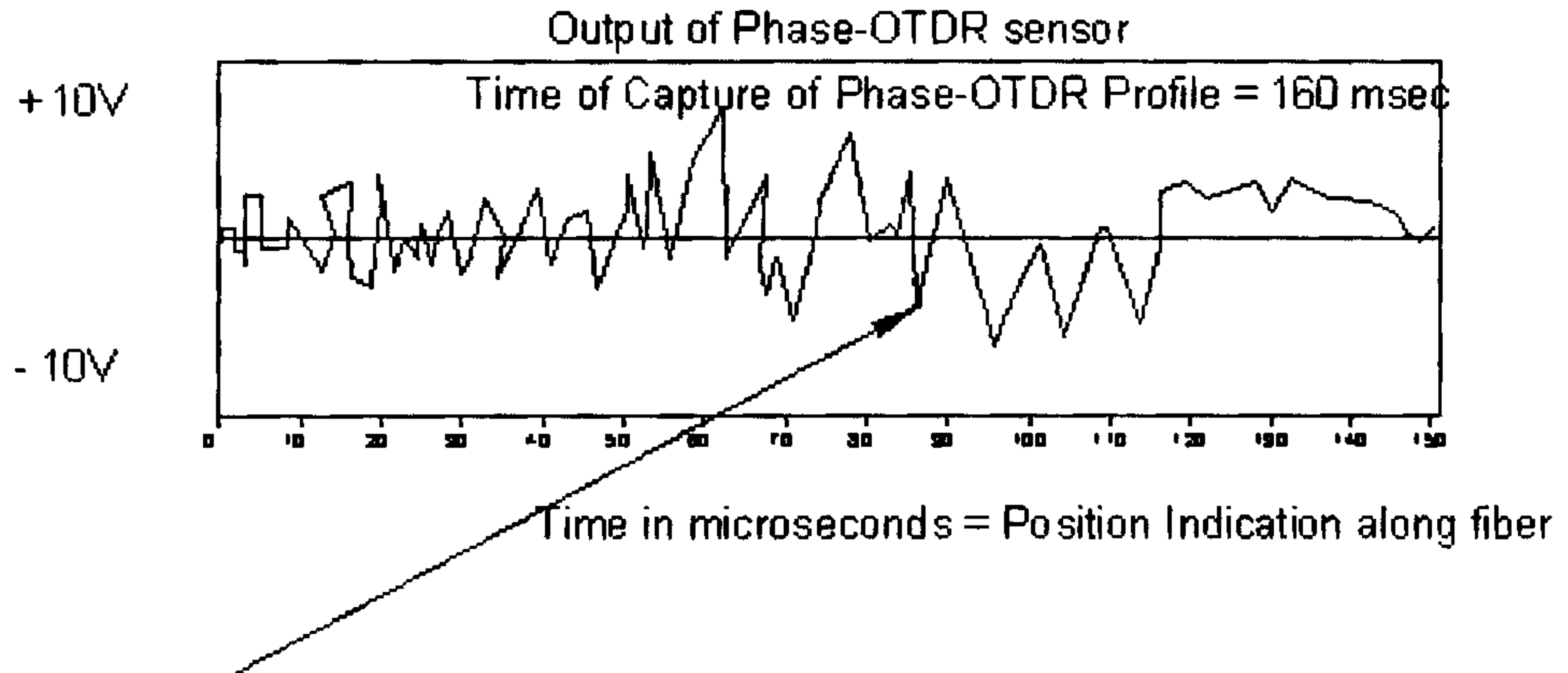

Output of Phase-OTDR sensor
Time of Capture of Phase-OTDR Profile = 140 msec
+ 10V
- 10V
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time in microseconds = Position Indication along fiber

Figure 4

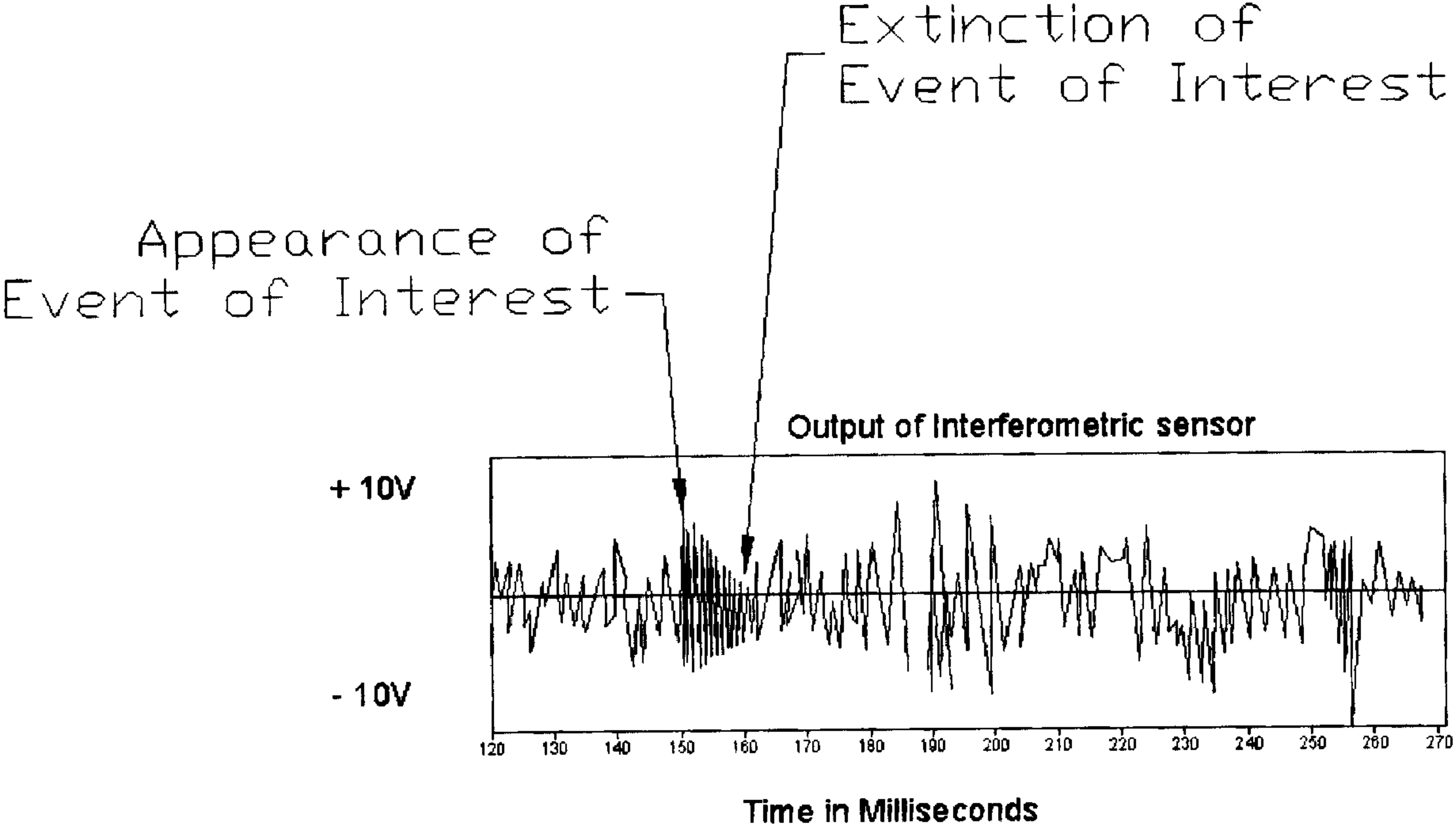


Disturbance Appears at 150 msec at Position represented by 87 microsecond delay

Figure 5



Disturbance still barely discernable at
160 msec at
Position represented
by 87 microsecond delay


Extinction of Event of Interest
Appearance of Event of Interest
Output of Interferometric sensor
+ 10V
- 10V
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
Time in Milliseconds