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Active and Passive Optical Fiber Metrology for Detonation Velocity Measurements

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Abstract: The reaction rate of an explosive – also called detonation velocity – is the easiest parameter to measure, and also one of the most important in characterizing the process of detonation front propagation in a 1D approach. This paper presents some peculiarities that were observed during the testing of our passive/active optical methods to measure detonation velocity. Both methods were tested using bare optic fiber probes and optic fiber probes protected with a stainless steel tube. The active optical method uses a laser with a wavelength of 660 nm, and the recording system contains a window filter that blocks any radiation outside the wavelength range of 650 to 665 nm. A plastic-bonded explosive based on PETN (seismoplast) was used to test both experimental methods. For rectangular cross-section charges using the passive optical method with the two different probes, the detonation velocities obtained ranged from 7233 to 7324 m/s, with standard deviations between 1.1 and 6.0 %; for the active optical method, the experimental results for detonation velocity varied between 7261 and 7351 and were obtained with a standard deviation of 0.6 to 1.7 %.

Keywords: Detonation velocity · Optical fibers · Laser light · Detonation radiation · Seismoplast

1 Introduction

Detonation velocity (D) is one of the most important properties of an explosive and has a significant influence on its performance. Various measurement methods for detonation velocity have therefore been developed to evaluate the performance of explosives [1, 2, 3]. These describe the velocity of the detonation wave (DW), which comprises a shock front followed by a chemical reaction zone where the detonation products are formed [4, 5]. Typically, this value is obtained by measuring the average velocity of the detonation wave propagation.

According to Suceska [5], the experimental methods to measure detonation velocity can be divided into four groups: 1) Dautriche method, based on the length of the detonation propagation in two different explosives in the same time interval; 2) Electrical methods, based on the short circuit between two conductors at the moment of the DW passage, which is recorded by an oscilloscope; 3) Optical methods, based on fast streak cameras that can record the radiation emitted by the detonation process; 4) Optical fiber methods, based on the ability of the optical fibers to detect and transmit light, which is the form of radiation most frequently emitted in the detonation process. This light can be recorded by high-speed cameras, or converted into an electrical signal by a fast photodiode and recorded by an oscilloscope.

As regards electrical methods, one of the first and most widely used methods to determine the average detonation velocity is based on ionization probes, in which two wires are short-circuited when the DW crosses them. This process allows the capacitor to discharge and, consequently, an electric pulse is generated on a load resistor [1, 2, 5, 6]. Another electrical method allows the detonation velocity to be measured in a continuous process, which involves a resistive electric wire [7]. According to this method, the DW propagation causes a continuous reduction in the sensor length, and thus in its electric resistance. Under constant current excitation, continuous voltage variation then occurs in one resistor (with constant electric resistance), which is in series with the probe resistor.

Regarding optical methods, the detonation velocity of seismoplast was measured through a rotating mirror streak and framing camera. [8] For this experiment, three mirrors were needed: one orientated directly to the charge, and two others at 45 degrees to the axial position (above and below it). The detonation velocity was determined through analysis of the luminescent trace acquired by the fast streak camera, where for each given time it is possible to de-

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termine the DW position. The measurement of detonation velocity using an electronic streak camera is complex and time-consuming due to the difficulty of aligning the camera and the sample. Furthermore, the acquired data always have a reduced resolution, due to reflections in many mirrors [8].

As regards optical fiber methods with high-speed electronic streak cameras, some authors have presented a non-intrusive method for continuous measurement of detonation velocity, based on 64 PMMA optical fibers, which are connected to an electronic streak camera. Each optical fiber has a diameter of 250 μm. This high-resolution optical method has a spatial resolution of 250 μm and a time resolution of 1 ns [9,10,11,12]. These measurements are very useful to determine the performance of new materials during the development of new compositions [1,9]. In this case, small samples, in the order of 1 g, can be tested [9,10]. However, this technique requires an electronic streak camera which is very expensive [3]. For the optical fiber methods which use photodiodes to convert the optical signal into an electrical signal, one of the most recent studies [13] describes an optoelectric converter system (OPTIMEX), which works with PMMA and/or silica fibers that collect the detonation radiation and transmit it to the OPTIMEX. Here the radiation is transformed into an electrical signal and then communicated to the user through an interface served by a microprocessor board, in which process useful information for the test, such as trigger modes and distances between probes, is also provided. This technique uses PMMA optical fibers with 1 mm diameter and measures the mean detonation velocity. To render the measurement method of the mean detonation velocity portable, low-cost and versatile for use in different environments – such as in the presence of magnetic fields - some authors have discussed detonation velocity measurement with single optical fibers. In all these cases, the light results from the thermal radiation of the DW [2,5,13,14,15], and/or from the shock-induced luminescence in PMMA, as described in [16].

This paper presents a newly developed and cost-effective technique based on optical fibers connected to an optoelectronic converter and to a digital recording system to measure detonation velocity. This technique was developed and characterized in two metrological configurations: (1) the optical passive method (OPM) that measures and records the rising emitting light from thermal radiation of the DW and from the shock-induced luminescence in PMMA (2) the optical active method (OAM) that measures and records the extinguishing of laser light.

To characterize the different methods and the different probes, individual and dual tests were performed. Both methods allow the operator to use two different types of probes (bare or protected). Dual tests were carried out in a single charge to compare the different probes using the same method, and to compare the different methods using the same probe.

2 Experimental Section

2.1 Explosive

The explosive used to perform these investigations was seismoplast – a plastic, water-resistant, cap-sensitive explosive based on PETN (85–86 %) and an inert binder – with a density of 1.55 g/cm^3. This value was measured for the same explosive at Fraunhofer ICT in an unpublished work (Table 1). The seismoplast was produced by Orica in Germany for seismic exploration (currently out of production) [8,17,18,19]. Few studies are reporting the detonation velocity values for this explosive, and they vary according to the authors (Table 1).

2.2 Optical System and Probe

The basic optical system was composed of 8 optical probes, which were multi-mode PMMA optical fibers with 250 μm diameter (Raytela, PGR-FB250, produced by Toray) and variable length, terminating in SMA905 connectors; or 8 optical probes based on the same optical fiber and protected with a stainless steel tube with 0.3 mm inner diameter and 0.5 mm external diameter, to fix the position and avoid undesirable bending of the fibers inside the explosive; 8 multimode silica fiber optic cable assemblies SMA to SMA, with 250 μm diameter and 20 m length; an acquisition system, developed at LEDAP, which use 8 optical to electrical converters HFBR-2406Z (sensibility between 640–820 nm, rise time of 6.3 ns, which corresponds to a maximum frequency of acquisition of 125 MHz) from Avago Technologies; and a digital transient recorder TransCom-CompactX-XL, with an

Table 1. Densities and detonation velocities of seismoplast according to bibliographic research and respective experimental method.

Reference	D (m/s)	ρ (g/cm^3)	Method
[8]	7500	NR	rotating mirror streak and framing camera
[17]	7100	1.52	X-ray absorption
[17]	7277	1.52	composite carbon resistors
[18]	7300	1.54	NR
unpublished	7380	1.55	ionization pins

NR – Not reported

acquisition time of 4.2 ns, a sample rate of 240 MHz and a block size of 16 kS. According to the method used, the following were also added to the basic set up: laser lights with 660 nm wavelength, a power system and laser controls that were made at Fraunhofer ICT. Optical filters with a bandwidth between 650 and 665 nm were used to eliminate any radiation outside this window. These optical filters were inserted into cube boxes, which allowed them to have collimators in both faces.

The presented optical systems were operated according to two different methods: the optical passive (OPM) and the optical active (OAM) methods.

2.2.1 Optical Passive Method (OPM)

The OPM is based on 8 optical probes with 1.5 m length, which receive and transmit the light generated by the DW to the optical to electrical converters. In this method, two types of probes can be used: bare optical probes (BOPs – Figure 1 a), in which the optical fibers are in direct contact with the explosive, or protected optical probes (POPs), in which the optical fibers are protected with stainless steel tubes.

As will be described in section 2.3.1., the optical probes used for the OPM were placed across the charge and not on its surface (see Figure 1), as it is normally done. This was because of their ability to acquire light. As will be shown in 3.1.1, when the BOP is inside the explosive charge it acquires light before the BOP is shocked by the DW. When the top of the BOP is placed on the explosive surface, the light that crosses the fresh explosive [20,21] saturates the sensor before the arrival of the DW, giving a high inaccuracy in the measuring times. Another reason to place the optical probes across the charge was to keep the configuration of OPM and OAM very similar, in order to easily compare the methods.

2.2.2 Optical Active Method (OAM)

The active method (OAM) measures the detonation velocity with optical probes (BOPs and POPs with 3 m length) that receive radiation from a laser. This laser radiation is saturating the sensors and, as the sensor output presents the derivative of the input, the output is presenting zero voltage. When the detonation front shocks the optical probe, it loses its transmission capabilities and, as a result, the output of the sensor drops rapidly. After that, without radiation in the sensor input, it presents again a zero voltage, since it returns to its initial "rest" position. The active method (OAM) requires the cube boxes in order to separate the laser from the detonation radiation. Figure 2 shows the OAM applied to the rectangular cross-section explosive charge configuration.

2.3 Experimental Set-Ups

Two different types of experimental set-ups were developed: the rectangular cross-section explosive charge and the circular cross-section explosive charge configurations. To shorten the names, in the following sections these configurations will be referred to as rectangular explosive charge (REC – Figure 1) and circular explosive charge (CEC – Figure 3).

2.3.1 Rectangular Cross-Section Explosive Charge Configuration (REC)

The REC set-up, presented in Figure 1, had a length of 150 mm and a rectangular cross-section of 8×8 mm, which can accommodate up to 8 optical probes.

The lateral confinement of the explosive charge was achieved with two PP plates, with a thickness of 4 mm each, and separated by 8 mm. The PP plates were glued to

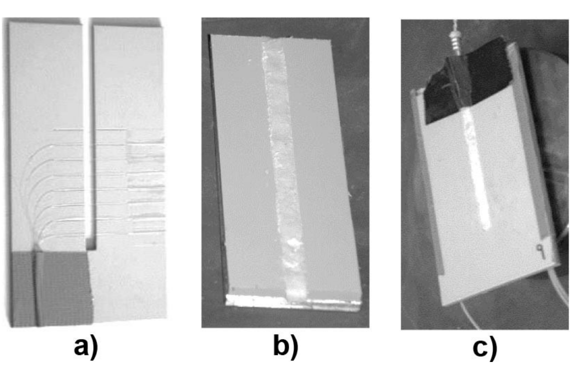

Figure 1. Experimental set-up: a) "U" plate for OPM-BOP; b) first layer of a REC; c) OAM final set-up applied to the REC.

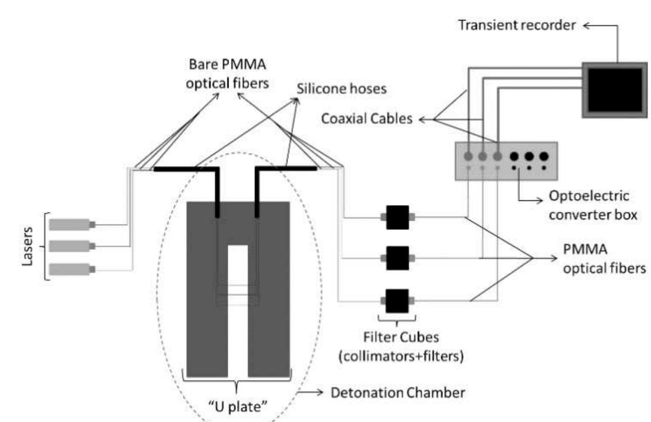

Figure 2. Schematic setup configuration for the OAM applied to the explosive charge.

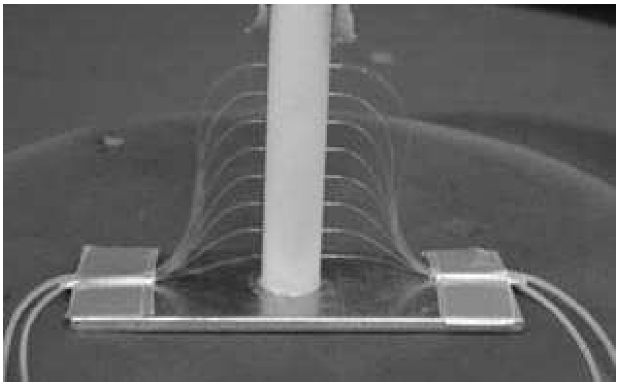

Figure 3. Experimental setup for circular cross-section explosive charge configuration with the OAM.

a metal plate and the channel between them filled with explosive (Figure 1b). The filling process was carried out manually using a tool developed for this propose. A "U" PP plate (Figure 1a), with the same thickness and an open face separation of 8 mm was glued to the PP plates (Figure 1b) and the open face separation was also filled manually with explosive (Figure 1c). Figure 1 a) shows seven PMMA BOPs with a diameter of 250 µm, inserted on slits of 0.5×0.5 mm (width and depth), passing through the open face of the "U" plate, separated by 10 mm. The optical probes fixed on the PP plate surface stay inside the explosive charge, in midplane, after the channels are filled with explosives. The final explosive charge has a cross-section of 8x8 mm and a length of 150 mm, as shown in Figure 1c). This set-up can work with both methods (OPM and OAM).

Dual tests were carried out to study one method using different probes (OPM with BOPs and POPs), and to study the different methods with the same type of probe (OPM and OAM with POPs), always simultaneously.

2.3.2 Circular Cross-Section Explosive Charge Configuration (CEC)

The CEC experimental setup, presented in Figure 3, comprises a PP tube (150 mm length, 15 mm inner diameter, 2.5 mm wall thickness) with 8 POPs separated by 10 mm. This set-up of the PP tube with the probes is prepared in the lab and then filled with explosive before the test, with tools specially developed for this propose.

The OAM was applied in a CEC set-up because this set-up is very useful to determine the detonation characteristics of explosives. This set-up will be used in the future for further measurements (such as CJ pressure and detonation front curvature).

3 Results and Discussion

This section presents the typical electrical signals obtained by the application of the OPM and OAM to measure the detonation velocity, in square or circular cross-section explosive charges.

For all electrical signals, the time when the detonation front shocks the optic probe is obtained by calculating the derivative of the electric signal and recording the time that corresponds to its maximum or minimum peak (according to the method used).

For each test, two different methods were used to calculate the mean detonation velocity (D):

1. The least-square method applied to the cumulative times and positions of the detonation front, as it propagates inside the explosive charge. In order to evaluate the precision of the different methods, the standard error of the regression line was calculated based on equation 1.

$$S = \sqrt{\frac{\sum (x - x')^2}{n - 2}} \tag{1}$$

x is the measured distance value, x' is the distance predicted value based on the linear adjustment made to the measured distances and n is the number of datasets.

2. The mean value of D_i between two consecutive probes, where D_i is calculated for each space and time interval, according to equation 2.

$$D_i = \frac{\Delta x_i}{\Delta t_i} \tag{2}$$

The mean detonation velocity (D_{mean}) presented in equation 3, as well as the standard deviation (equation 4), were calculated for all the tests.

$$D_{mean} = \frac{1}{n}\sum_{i=1}^{n} D_i \tag{3}$$

$$D_{std\ dv} = \sqrt{\frac{\sum (D_i - D_{mean})^2}{(n-1)}} \tag{4}$$

3.1 Individual Tests

3.1.1 Acquired Signals

Using the OPM, it is possible to acquire two different types of signals, quite similar to each other, according to the type of probe used (BOPs or POPs).

Figure 4 shows the electrical signals obtained in the REC configuration using BOPs, without any transformation from

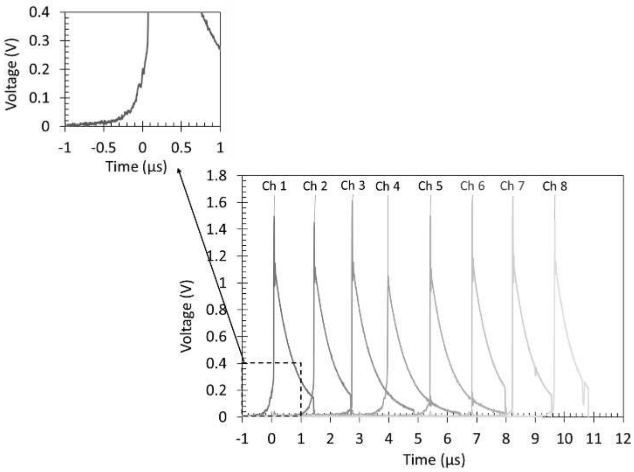

Figure 4. Electrical signals for the REC configuration, working with the OPM using BOPs and the zoom image of the initial rise of Ch1.

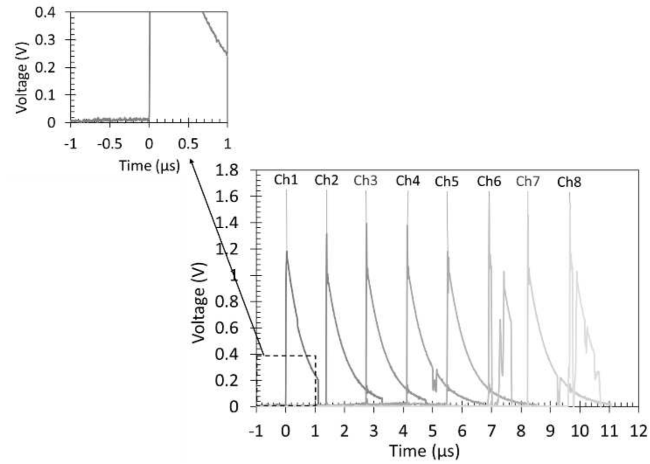

Figure 5. Electrical signals for the REC configuration, working with the OPM using POPs and the zoom image of the initial rise of Ch1.

filters and/or collimators: these signals presented a small increase in voltage (see zoom of Ch 1 in Figure 4) followed by a very fast increase, and ended with a slow decrease in voltage and then an abrupt drop. According to our understanding, the first voltage increase is due to the radiation collected by an optical probe just before it is shocked by the detonation front. The rapid increase in the voltage corresponds to the entrance of detonation radiation when the fiber is shocked, and/or to the luminescence generated in the PMMA at the moment when the fiber is shocked by the detonation front. The slow decrease in the voltage is a function of the saturation of the sensor and RC circuits constant in the output of the optoelectronic converter, and the abrupt drop corresponds to the moment when the bare optical fiber can no longer acquire radiation.

To ensure that the optic fiber probes were protected from any disturbance while placing the explosive inside the container, the optical probes were placed in stainless steel tubes (POPs). Since the inner diameter of the stainless steel tubes was 50 µm larger than the fibers' diameter, there was air between the tubes and the fibers. Figure 5 shows the electrical signals obtained by the REC configuration working with the OPM using protected optic probes (POPs).

Comparing the obtained signals in Figures 4 and 5, it can be observed that the signals in Figure 4 have a small "rising tail" (see zoom image in Figure 4), before the signals rise abruptly, while the signals in Figure 5 rise immediately (see zoom image in Figure 5) showing a very fast transition. This shows that the BOPs can collect some light slightly before the detonation front shocks the optical fiber. This phenomenon does not occur in the signals shown in Figure 5, because the fibers are protected by stainless steel tubes, so they cannot receive external radiation before being shocked. It should also be noted that the intensity of the peaks is slightly higher when the open fibers are not protected by stainless steel tubes. This shows that the fiber, when surrounded by explosives, receives DW radiation. When the fibers are protected by stainless steel tubes, the radiation acquired by the optoelectric converter is a combination of light emission by the ionization of air trapped between the optical fibers and the tubes, and the luminescense generated in the PMMA optic probe by the shock.

To be independent of radiation from the DW or from other radiation sources, and to have the possibility to use a single optical metrology method to characterize shock behavior in inert materials that are opaque, the optical active method (OAM) was developed.

Figure 6 shows the electrical signals obtained by the OAM with BOPs.

In the OAM, the optical fiber probes receive the light from a laser source. The output of these optical fiber probes is connected to the filter cubes (filters + collimators), which

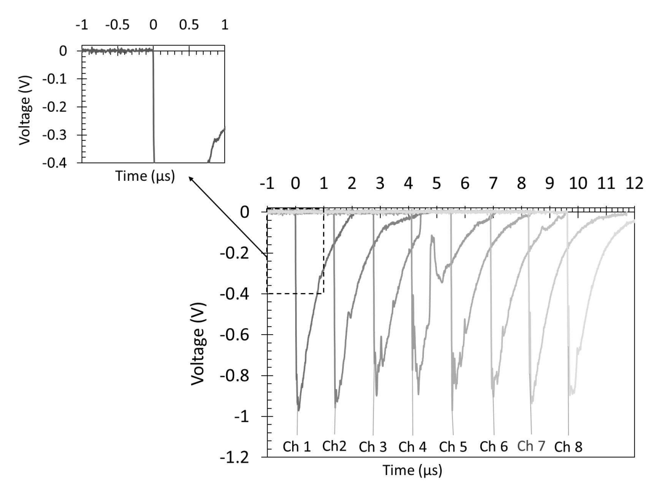

Figure 6. Electrical signals obtained by the OAM with BOPs and the zoom image of the initial drop in Ch1.

only allow laser light in a bandwidth of 650–665 nm to pass through. By this process, any interference of interfering radiation, which can come from broadband radiation source, is eliminated. After passing through the filter cubes, the optical signal is conducted to the optoelectronic converter system and transient recorder (Figure 2).

With this configuration, the electrical signals change their shape, as can be seen in Figure 6. This methodology does not work with light generated by the detonation wave but, instead, it works with the extinguishing of the laser light, due to the transmission losses of the optical fiber probe. While acquiring DW or air ionization radiation leads to increasing signals, the extinguishing of the laser light gives inverted signals, that drop abruptly immediately after the probe is shocked.

Taking a closer look at Figure 6, it is possible to see that this new type of signal starts with a zero voltage (see zoom image in Figure 6), followed by an abrupt drop, some peaks and then a slow increase, with some disturbances, until 0 V again. The zero voltage corresponds to the sensor saturation by the laser radiation, since the sensor output corresponds to the derivative of the input signal (see zoom image in Figure 6). When the fiber is shocked, it loses its transmission capabilities, which means that the sensor goes from a state of light saturation to a state of no light, leading to an abrupt drop in voltage; the peaks that are next to the abrupt drop, that disturb the relaxation of the sensor to its „rest“ position, are due to detonation radiation that is between 650–665 nm, which can pass the filters and re-excite the sensors, although never back to the saturation point. The slow rise of the signal back to its initial position is characteristic of the sensors and their RC circuits.

The electrical signals obtained by the OAM using POPs are presented in Figure 7. The type of explosive charge configuration (REC or CEC) does not interfere with the shape of the acquired electrical signals. The signals shown in Figure 7 are therefore the same for CEC and REC configurations.

Comparing Figures 6 and 7 with Figures 4 and 5, it is possible to see that the signals in the OAM do not vary as much as the OPM signals, according to the different type of probe. This is because the OAM is not dependent on external radiation and the laser light is sufficient to saturate the sensors to a point that the light, which the fibers can acquire while they are not broken, is no longer detectable. The intensity of the signals depends only on the laser power (less power means less sensor saturation) and on the damage that the optical fibers can suffer while stored in their roll and while being mounted on the measuring setups.

3.1.2 Determination of the Detonation Velocity (D) by the Least Square Method

For all calculations, the measured time interval corresponds to the cumulative distances between the centers of each optical probe.

Figure 8 shows the (x, t) diagrams for the detonation front propagation for each studied configuration: REC working with the OPM with BOPs and POPs, REC working with the OAM with BOPs and POPs, and CEC working with the OAM with POPs.

Table 2 shows the slope of the linear trend lines, obtained by the least square method (Figure 8), that give us the mean detonation velocity of the detonation front propagation in a 1D approach, as well as the respective standard error of the regression lines.

As can be seen in Figure 8, all the configurations are accurate, because all the calculated detonation values are in the range of the bibliographic results presented in Table 1 (from 7100 to 7500 m/s), and precise, because the trend lines for each test are almost coincident and there are no points that fall outside the trend lines. This is confirmed by

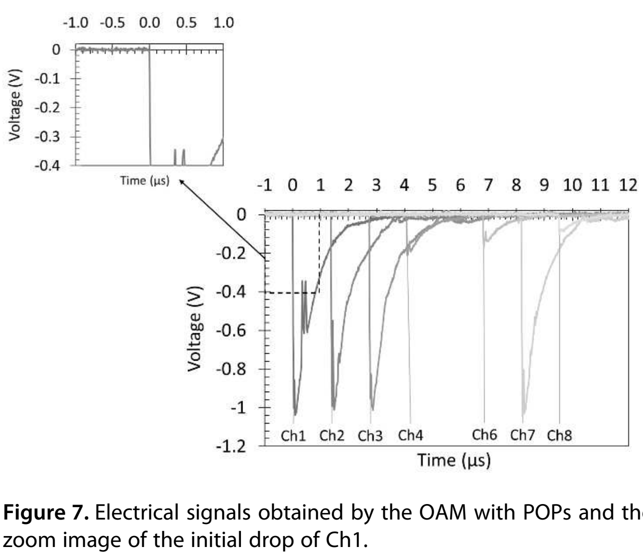

Figure 7. Electrical signals obtained by the OAM with POPs and the zoom image of the initial drop of Ch1.

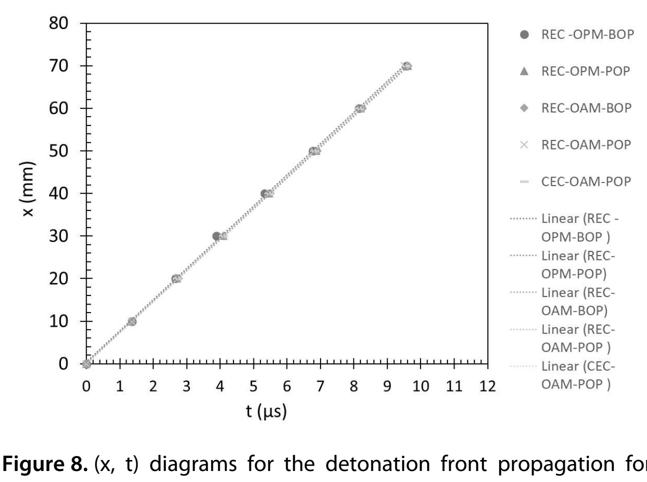

Figure 8. (x, t) diagrams for the detonation front propagation for each configuration.

Table 2. Mean detonation velocities (D), the slopes of the trend lines and the respective standard errors of the regression lines (S).

Test	X(t) slope (mm/μs)	S (mm)	D (m/s)
REC-OPM-BOP	7.324	0.613	7324
REC-OPM-POP	7.281	0.172	7281
REC-OAM-BOP	7.265	0.119	7265
REC-OAM-POP	7.351	0.075	7351
CEC-OAM-POP	7.339	0.009	7339

Table 2. The accuracy is shown by the close proximity of the calculated D values to the bibliographic ones, and the precision is shown by the S values, which represent the average distance between the measured distances and the predicted distance values based on the linear adjustment made to the measured distances. As the slits 0.5 x 0.5 ± 0.05 mm were made with a CNC machine with a dimensional tolerance of 0.05 mm, the systematic error in the distances is 0.50 mm for BOPs and 0.10 mm for POPs.

3.1.3 Measurement of the Mean Detonation Velocity (D_{mean})

Since this methodology is not cumulative, the calculation of the detonation velocity is based on time intervals and distances between two consecutive probes.

Table 3 shows the results obtained using the OPM-BOP: times ($\Delta t_{max\ peak}$), distances (Δx), results for the detonation velocity (D_i) determined according equation 2, and the mean value for the detonation velocity (D_{mean}) and standard deviation ($D_{std\ dv}$), calculated by equations 3 and 4, respectively. The results for OPM-POP, OAM-BOP, OAM-POP (all REC) and CEC-OAM-POP (D_{mean} and $D_{std\ dv}$), shown in Table 3, were calculated with the same procedure as was used for the OPM-BOP.

Comparing the values for detonation velocity obtained by the same optical method, but calculated in different ways (comparison between Tables 2 and 3) it can be seen that the mean detonation velocities do not vary more than 12 m/s between different calculations. This shows that the results are precise: we can obtain the same results from different calculations.

Table 3 also shows that the OPM is precise when using POPs because the standard deviation value is 2.4 % of the mean detonation velocity value. In the case of the OPM with BOPs, the precision is lowest, because the standard deviation value is already above 5 %. These are expected values because the POPs give more precision to the results than the BOPs.

The results obtained using the OAM working with BOPs and POPs, applied to both set-ups (REC and CEC) are also presented in Table 3. The parameters D_{mean} and $D_{std\ dv}$ were calculated as described for OPM-BOP and are shown in Table 3.

Once again, comparing the results in Table 2 with those in Table 3 for the same kind of test, it is possible to see that the detonation velocities vary as in the previous case (OPM). Here, the biggest variation is 13 m/s (for the REC-OAM-BOP), which is still very low since it is inside the range of the standard deviation. This proves that the OAM is also a precise method. The higher obtained standard deviation is 1.7 % of the average value of the detonation velocity (REC-OAM-BOPs).

Comparing the presented measurement methods (OPM and OAM in Table 3), it can be concluded that the OAM is more precise since the standard deviations had lower values in the OAM than in the OPM.

A general overview shows that the best configuration to measure the detonation velocity is OAM-POPs because it has high precision (the D values, obtained by the two different calculations vary in a range of 11 m/s) and the lowest standard deviation errors which are between 1.1 and 1 % of the mean values. It is also accurate since the obtained experimental values are inside the range of the bibliographic ones.

Table 3. Detonation velocity measured with the OPM using BOPs and POPs.

Test	Δx (mm)	$\Delta t_{max\ peak}$ (μs)	D_i (m/s)	D_{mean} (m/s)	$D_{std\ dv}$ (m/s)
REC-OPM-BOP	10.00 ± 0.500	1.371	7295	7336	441 (6.0 %)
		1.296	7717		
		1.217	8220		
		1.450	6897		
		1.429	6997		
		1.383	7229		
		1.429	6997		
REC-OPM-POP				7287	178 (2.4 %)
REC-OAM-BOP				7278	128 (1.7 %)
REC-OAM-POP				7367	79 (1.1 %)
CEC-OAM-POP				7350	75 (1.0 %)

3.2 Dual Tests

To show how versatile these methodologies can be, and to make a comparison between the recorded electric signals of the two kinds of probes used (BOPs and POPs), one experiment was carried out with both kinds of probes, and another with both optical methods (dual tests). These dual tests were performed in rectangular explosive charge configuration.

In this section, each dual test will be analyzed individually and with both mathematical treatments.

3.2.1 Probes Comparison: OPM Using BOPs and POPs Simultaneously

Figure 9 shows the results obtained in a test where the detonation velocity was measured with the OPM, using BOPs and POPs simultaneously.

Analyzing Figure 9, it is possible to observe that the odd channels (with BOPs) present a higher peak voltage than the even channels (with POPs). This shows that the BOPs receive more radiation from several sources than the POPs. Besides this, all the signals are very similar.

3.2.1.1 Least Square Method Calculation (D)

Table 4 shows the results obtained from the (x, t) diagrams and respective trend lines for the detonation front propagation, in a REC working with OPM and using both type of probes simultaneously (BOPs and POPs).

This table contains the slope of the trend lines obtained for each set of points, the S values for each calculation and the mean detonation velocities calculated by the least square method, according to the probes used.

The OPM precision is shown by Table 4 through the obtained D values, which are very close to each other, only differing by 27 m/s; and also by the S values. However, it can be noted that BOPs are slightly less precise than POPs since the S value for the BOPs is higher than for the POPs. These acquired values are also accurate because they are in the range of the bibliographic values presented on Table 1 for seismoplast.

Through a comparison between individual (Table 2) and dual (Table 4) test results, it is possible to affirm that the BOPs are the least precise probes since they have the highest S values. For the dual test, the precision of BOPs is higher than for the individual test (lower S), which is explained by the larger distance between probes (10.00 mm for the individual test, double this distance for the dual test).

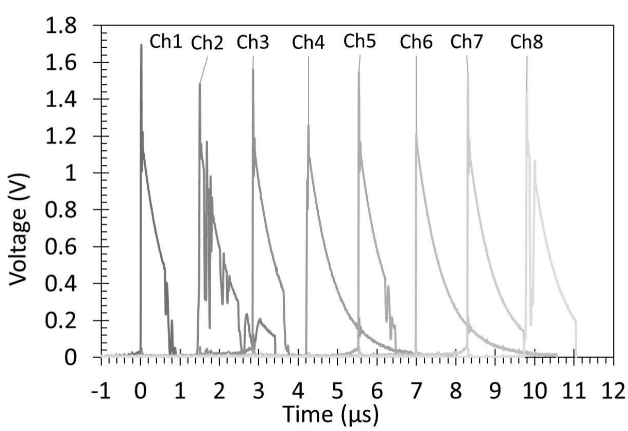

Figure 9. Signals obtained by a dual test OPM-BOP/POP. The BOPs were in channels 1, 3, 5 and 7 and the POPs were in channels 2, 4, 6 and 8.

Table 4. Mean detonation velocities (D), slopes from the equations of the trend lines and the respective standard errors of the regression lines (S). Tests performed in REC-OPM.

Test	X(t) solpe (mm/µs)	S (mm)	D (m/s)
BOPs	7.260	0.328	7260
POPs	7.233	0.196	7233

3.2.1.2 Mean Detonation Velocity Calculation (D_{mean})

Table 5 shows the results obtained for the calculation of the mean detonation velocity, with the experimental set-up using the OPM with BOPs and POPs simultaneously. In this table, the results are separated by probe type (BOPs or POPs), the space between the same kind of probe is $\Delta x = 20.00 \pm 0.050$ mm and the calculations were carried out as shown in Table 3 for OPM-BOP.

Through the analysis of the mean D in Table 5, which is acquired between two consecutive probes (now 20 mm due to the intercalation of probes), it can be demonstrated that the precision of the probes is similar since the acquired D_{mean} results varied only 7 m/s. However, POPs are more precise than BOPs, since they reduced the relative standard deviation error from 2.3 % to 1.1 %.

Comparing these results (Table 5) with the results obtained using the least square method (Table 4), the conclusions are the same: the accuracy of the probes is similar because all of them are able to produce results that match with the results already published for seismoplast (see Table 1); the precision of POPs is higher than BOPs as is proved by the S values in Table 4 and by the standard deviation errors in Table 5.

Comparing the individual (Table 3) and dual (Table 5) tests, it is clear that BOPs are less precise than POPs, since BOPs always had higher standard deviation errors than POPs, independently of the kind of test. Although, as expected, this error is lower if the probe separation is higher: it is possible to reduce the errors by half if we double the distance between the probes. With respect to accuracy, both probes can be considered accurate, since the obtained D values were always inside the range of the bibliographic values.

Table 5. Mean detonation velocity (D_{mean}) and the standard deviation ($D_{std\ dv}$) results for the OPM using BOPs and POPs simultaneously.

Test	D_{mean} (m/s)	$D_{std\ dv}$ (m/s)
REC-OPM-BOP	7244	166 (2.3 %)
REC-OPM-POP	7237	83 (1.1 %)

3.2.2. Comparison of the Methods: Simultaneous Application of the OPM and OAM Using POPs

Since it was proved before that POPs are the most precise probes, a measurement of the detonation velocity in REC, using the OPM and OAM simultaneously, was carried out with these probes. The signals obtained are shown in Figure 10.

As shown before, the signals obtained with the OPM are totally different from those obtained with the OAM: the OPM signals are rising, and the OAM signals falling. The OPM signals were already discussed above and so do not need further explanation. The OAM signals vary mostly in intensity, as shown also in Figure 7. These signal intensities are only dependent on the laser behavior (lasers lose intensity with time), and on the level of damage to the optical probe at the end of the set-up preparation. Since the optical probes are made of PMMA and are highly bendable, a little more forced bending or a little scratch are enough to cause a loss in the fiber transmission, then reducing the voltage on the falling signals.

3.2.2.1 Least Square Method Calculation (D)

Both optical methods (passive and active) using POPs were assembled to make a dual test. The obtained results were analyzed individually by method (OPM and OAM).

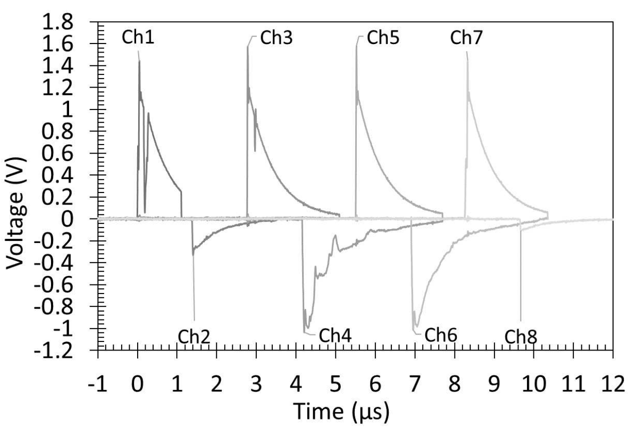

Figure 10. Signals obtained in a test with simultaneous application of OPM and OAM. The OPM-POPs are the positive signals and the OAM-POPs are the negative signals.

Table 6 presents the slope obtained from the trend lines of the acquired points, their respective S values and the obtained detonation velocity (D).

According to Table 6 the precision and the accuracy of the results do not decrease when two different optical methods, with protected optic probes, are used simultaneously in one test.

When using POPs, both methods become more precise, since the D values calculated by the least square method (Table 6) differ by only 9 m/s and the S values are similar, which shows that the precision depends more on the probe than the method.

Comparing this dual test (Table 6) with the equivalent individual tests (Table 2) with the same REC configuration, it is clear that both methods with POPs are more precise than with BOPs, because the S values vary in a small, low range (from 0.102 to 0.075 mm). All the D values obtained by the least square method are very similar (between 7252 and 7281 m/s), with the exception of the individual test REC-OAM-POPs (Table 2), where D had a slightly higher value (7351 m/s).

The accuracy of both methods in a dual test is also good because both results are inside the range of the already published results about seismoplast.

3.2.2.2 Mean Detonation Velocity Calculation (D_{mean})

As before, the mean detonation velocity calculation was also applied to the dual test using the OPM and OAM simultaneously. Table 7 shows the results (D_{mean} and $D_{std\ dv}$) of this calculation for each method, carried out as shown in Table 3. Considering the results of the mean D value presented in Table 7, it is possible to confirm the conclusions reached using the least square method calculations. Both methods are satisfactorily precise since the D_{mean} values differ by only 10 m/s.

Both methods are quite precise when using POPs since their relative errors vary between 1.1 and 0.6 %. From these results, it is possible to affirm that the OAM is more precise than the OPM, due to its very low standard deviation error (0.6 %), which is almost half of the OPM error.

Comparing this dual test (Table 7) with the equivalent individual tests (Table 3), it can be seen that the precision of the tests is mostly dependent on the distance between probes. In the dual test, the standard deviation errors are lower by approximately half when compared to the single tests, because the distance between the probes in the dual

Table 6. Mean detonation velocities (D), the slopes from the trend lines equations and their respective S values. Test performed with POPs for both OAM and OPM.

Test	X(t) slope (mm/µs)	S(mm)	D (m/s)
OPM	7.252	0.192	7252
OAM	7.261	0.102	7261

Table 7. D_{mean} and $D_{std\ dv}$ results obtained from the dual test working simultaneously with the OPM and OAM, and using the same type of probes (POPs).

Test	D_{mean} (m/s)	$D_{std\ dv}$ (m/s)
REC-OPM	7248	82 (1.1 %)
REC-OAM	7258	44 (0.6 %)

test (20.00 mm) is double the distance in the individual tests (10.00 mm). Concerning the accuracy, it is possible to affirm that all the obtained results are accurate since they all fall into the range of the literature results (Table 1).

4 Conclusions

The aim of this paper was to present precise optoelectronic metrology to measure the detonation velocity based on optical fiber probes with 250 μm diameter. This metrology can be very versatile, due to the different working methods and probes. The two different measurement methods and probes, tested in square charges of 8×8 mm, achieved good results in terms of precision and accuracy.

The OPM-BOP showed the worst S factor and standard deviation, due to the input of light before the DW shocks the probe and the possibility of bending of the probe. The OPM-POP showed positive and the OAM-BOP negative electrical signals, which indicated a very fast and precise transition due to the collision process of the DW with the probe. The electrical signals displayed comparable amplitude and both methods had a similar S factor and standard deviation.

Although the electric signals of the OAM-POP presented a precise transition, the electric signal amplitudes were not homogenous. However, the method that presented the lower standard deviation and/or S factor was the OAM-POP. The protection of the probes with stainless steel tubes also enabled an optical method capable of withstanding rough handling.

Dual tests showed that POPs had higher precision in position when compared to BOPs because their relative standard deviation errors and S values were low. The same pattern was observed in the individual tests. Dual tests also confirmed that the OAM is more precise than the OPM when used simultaneously and with the same kind of probes.

Symbols and Abbreviations

D	Detonation velocity
DW	Detonation wave
PBX	Plastic-bonded explosive
OPM	Optical passive method
OAM	Optical active method
PETN	Pentaerythritol tetranitrate or penthrite
NR	Not reported
PMMA	Poly(methyl methacrylate)
SMA	SubMiniature version A
ICT	Fraunhofer Institute for Chemical Technology
BOP	Bare optical probe
POP	Protected optical probe
REC	Rectangular cross-section explosive charge
CEC	Circular cross-section explosive charge
PP	Polypropylene
CJ	Chapman Jouguet
D_i	Local detonation velocity
D_{mean}	Mean detonation velocity
$D_{std\ dv}$	Detonation velocity standard deviation
RC	Resistance-capacity
S	Standard error of the regression line

References

[1] A. D. Tete, A. Deshmukh, R. Yerpude, Velocity of detonation (VOD) measurement techniques practical approach, *Int. J. Eng. Technol.,* **2013**, *2,* 267–265.

[2] M. Suceska, Chapter 4. Detonation, in *Test Methods for Explosives*, Springer-Veria New York **1995**, p. 91–119.

[3] P. Wei, H. L. T. Liu, D. Xia, Detonation Velocity Measurement with Chirped Fiber Bragg Grating, *Sensors* **2017**, *17*, 1–11.

[4] M. S. Shattuck, *Determination of detonation velocity of explosive compounds using optical techniques*, Master thesis, **2015**, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

[5] M. Sućeska, Experimental determination of detonation velocity, *Fragblast,* **1997**, *1*, 261–284.

[6] G. O. Nevstad, *Introduction of ionization pin probes to measure detonation velocity*, FFI-rapport 2015/00178, Norwegian Defence Research Establishment, Kjeller, Norway, **2015**.

[7] R. Mendes, J. Campos, J. Gois, C. Moutinho, Shock initiation and detonation stability of industrial explosives, *24th Int. Annual Conference of ICT*, Karlsruhe, Germany, June 29–July 2, **1993**, p. 29/1–13.

[8] M. Held, Initiation Tests, *Propellants Explos. Pyrotech.* **2002**, *27*, 39–43.

[9] I. Plaksin, J. Campos, J. Ribeiro, R. Mendes, J. Gois, A. Portugal, P. Simoes, L. Pedroso, Detonation meso-scale tests for energetic materials, *Shock Compression Condens. Matter-2001,* Atlanta, Georgia, USA, June 24–29 **2001**, p. 922–925.

[10] I. Plaksin, J. Campos, P. Simoes, A. Portugal, J. Ribeiro, R. Mendes, J. Gois, Detonation study of energetic micro-samples, *Proceedings of the 12th International Detonation Symposium*, S. Diego, California, USA, August 11–16, **2002**, p. 42–50.

[11] R. Mendes, I. Plaksin, J. Campos, J. Ribeiro, Double slapper initiation of the PBX, *AIP Conf. Proc.* **1999**, *505*, 915–918.

[12] R. Mendes, J. Ribeiro, I. Plaksin, J. Campos, Non ideal detonation of emulsion explosives mixed with metal particles, *AIP Conf. Proc.* **2012**, *1426*, 267–270.

[13] J. Pachmáň, M. Künzel, K. Kubát, J. Šelešovský, R. Maršálek, M. Pospíšil, M. Kubíček, A. Prokeš, OPTIMEX: Measurement of Detonation Velocity with a Passive Optical Fibre System, *Cent. Eur. J. Energ. Mater.* **2017**, 14, 233–250.

[14] W. Xiaoyan, Z. Hui, W. Jian, W. Gao, Design of the Fiber Detonation Velocity Measuring System Based on the FPGA, *ICEOE 2011*, Dalian, Liaoning, China, July 29–31, **2011**, p. V4/29–32.

[15] J. Quaresma, J. Campos, J. Pimenta, A. Ribeiro, R. Mendes, J. Gois, L. Deimling, T. Keicher, Hot spots sensitization and optical detonation measurements of emulsion explosives, *47th Int. Annual Conference of ICT*, Karlsruhe, Germany, June 28- July 1, **2016**, p. 34/1–16.

[16] W. G. Proud, N. K. Bourne, J. E. Field, Shock-induced luminescence in polymethylmethacrylate, *AIP Conf. Proc.* **1998**, *429*, p. 801–804.

[17] K. Hollenberg, Time Resolved Pressure Measurement of the Initiation in Gap Test Experiments, *Propellants Explos. Pyrotech.* **1986**, *11*, 155–161.
[18] J. Köhler, R. Meyer, A. Homburg, Seismoplast, in: *Explosivstoffe*, 10 ed., Wiley-VCH, Weinheim **2008**, p. 263.
[19] S. Thiboutot, P. Brousseau, G. Ampleman, Deposition of PETN Following the Detonation of Seismoplast Plastic Explosive, *Propellants Explos. Pyrotech.* **2015**, *40*, 239–332.
[20] I. Plaksin, J. Direito, J. Campos, J. Ribeiro, R. Mendes, C. Cofey, J. Kennedy, Meso-scale probing of CRZ structure in PBX: DW oscillations from ignition to failure, *AIP Conf. Proc.* **2006**, 845, 1002–1005.
[21] I. Plaksin, C. S. Coffey, J. Campos, R. Mendes, J. Ribeiro, J. Gois, Shear induced reaction localization and mechanisms of energy dissipation in PBX subjected to strong shock, *AIP Conf. Proc.* **2007**, *955*, 1427–1432.

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