Link sito dell'editore: https://ieeexplore.ieee.org/document/7328727

Link codice DOI: https://doi.org/10.1109/TIM.2015.2495721

Citazione bibliografica dell'articolo:

N. Giaquinto, G. M. D'Aucelli, E. De Benedetto, G. Cannazza, A. Cataldo, E. Piuzzi, A. Masciullo, "Criteria for Automated Estimation of Time of Flight in TDR Analysis," pubblicato in IEEE Transactions on Instrumentation and Measurement, 2016, vol. 65, no. 5, pp. 1215-1224

Criteria for Automated Estimation of Time of Flight in TDR Analysis

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***Abstract*—In this work, a performance analysis, in terms of accuracy, linearity and repeatability, of three criteria to estimate the time of flight in time domain reflectometry (TDR) signals is carried out. In a first set of experiments, the three criteria (referred to as 'maximum derivative', 'zero derivative', and 'tangents crossing') are applied to TDR signals propagating along a set of coaxial cables, with different known lengths and known electrical parameters. In a second set of experiments, the same criteria are applied to bi-wire cables in air, with different known lengths and unknown electrical parameters. Finally, in the last set of experiments, the criteria are applied in a more complex situation, i.e. on a bi-wire used as a sensing element for water level measurement. Results show that, among the tested criteria, 'tangents crossing' appears to provide a very good performance in terms of systematic errors and superior performance in terms of repeatability. The popular 'maximum derivative' criterion appears to be more prone to random errors due to noise and TDR artifacts. The paper results are relevant to many practical applications of TDR, ranging from fault location in cables to media interface sensing.**

***Index Terms*—time domain reflectometry, time measurement, length measurement, level measurements, fault location, calibration, nonlinearities, estimation error, digital filters.**

I. Introduction

TIME of Flight (ToF) is a well-known concept, and it is used in a variety of fields; in time domain reflectometry (TDR), the ToF indicates the time it takes for a test signal to travel a certain distance through a medium. The evaluation of the ToF in TDR measurements is essential for a number of applications. One of the first TDR-based applications, which is the localization of faults in electrical cables, strongly relies on measurements of the ToF; in fact, the ToF of the TDR test signal up to the defect or fault is used to infer the position of the fault [1], [2]. Furthermore, measurements of the ToF of TDR signals are at the basis of applications in several fields, such as leak detection in underground water pipes [3]; real-time monitoring of the flow and of the liquid level in intravenous (IV) medical infusions [4]; crack/strain sensing in reinforced concrete structures [5]; dielectric characterization of liquids [6], [7]; etc.

However, in spite of the widespread use of TDR, the accurate measurement of the ToF is still an open issue [8], [9]. As a matter of fact, the estimation of the ToF has always been considered one of the major sources of uncertainty in TDR measurements. Traditional waveform analysis has used the fitting of tangent lines to the waveform reflection to determine travel time [10]–[12]; this travel time is related to to the signal phase velocity.

Successively, Robinson et al. argued that it is more appropriate to calculate the ToF from the apices of the derivative of the waveform [13]. In their work the medium under test is strictly divided into homogeneous segments and experimental conditions are rigorously controlled, therefore the $S_{11}(f)$ scattering parameter can be evaluated by using the recursive schemes proposed by Feng et. al. (Eq. 6 in [13]), together with Cole-Cole equations, for each individual segment. These conditions are verified, e.g., when measuring the dielectric constant of a perfectly homogeneous medium by a purposely designed TDR probe. In [13], in fact, 'the importance of high-quality probe construction and the importance of minimizing long cables' is stressed.

In [14], on the other hand, an algorithm for wire integrity analysis in helicopters, tiltrotors, aircrafts, etc. is considered. In this case the probe consists of a wire running through an arbitrarily inhomogeneous medium. Moreover, faults can be wire-to-wire and wire-to-shield, generating waveforms which usually need to be interpreted by experienced personnel; finally, faults can be irregular. For such cases, 'simple derivative algorithms will not suffice in detecting the correct fault' [14]; the proposed algorithm is therefore completely different (with some features in common with stock market analysis).

The authors are, instead, interested in a class of TDR applications which stands, in some way, in between those considered in [13] and [14]. These applications require the development of cost-effective sensing and monitoring TDR systems, often involving the impossibility to strictly control every single parameter [3], [4], [15], [16].

Starting from these considerations and from the results reported in [17], the goal of the present work is to demonstrate the performance of different derivative based methods for the estimation of ToF in simple TDR signals like those encountered in [3], [4], [15], and [16].

In fact, it is worth mentioning that the presented criteria can be particularly useful in applications, such as TDR-based

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Manuscript received June XX, 2015; revised Month XX, 201X.

water level measurements [15] or TDR-based localization of leaks in underground water pipes [16]. In fact, one of the goals of the present work is to pave the way for the implementation of fully- automated algorithms which could improve accuracy and efficiency in TDR waveform analysis.
To this purpose, in this work, three different criteria for ToF estimation using the derivative of reflectograms are compared, namely:

- Maximum derivative (MD);
- Zero derivative (ZD);
- Tangents crossing (TC).

For a comparison of the algorithms, a large set of measurements was carried out on cables with different lengths (from 10 cm to 30 m) and with known electrical parameters. The accuracy of the methods is evaluated in terms of systematic (gain, offset and nonlinearity) and random errors (repeatability) in the presence of noise.
In the following, after briefly illustrating the theoretical background (Section II), a general description of the methods (Section III) is carried out. The accuracy of the three criteria in terms of gain, offset and nonlinearity errors is examined in Section IV-A, and a discussion of algorithm robustness in the presence of noise is carried out in Section IV-B. In Section IV-C, the performance of the three considered criteria is checked on bi-wire cables with known length and unknown electrical parameters. Finally, in Section V, the presented criteria are applied to water level measurements as test application, and their performance is assessed in terms of nonlinearity, sensitivity and repeatability.

II. Background

In TDR measurements, an electromagnetic test signal (often a step-like voltage signal) is propagated through the device under test (DUT), which may be any kind of transmission line. A portion of the signal is reflected back towards the generator and, through the analysis of the reflected signal, it is possible to infer the desired information on the DUT. For the purpose of the present work, the considered DUTs are electrical cables. However, the reported considerations and the obtained results can be extended to any other suitable device (TDR probes of any kind, and any couple of conductors capable of propagating TEM waves).

For example, let us consider a rising edge voltage signal (as TDR test signal) applied to one end of an ideal electrical cable, with the other end open circuited (OC). The reflectogram, which is the direct output of a TDR measurement, is the sum of two contributions (i.e. the reflected wave and the transmitted wave), and it displays the value of voltage as a function of the travel time (t).
If signal losses are negligible and the applied signal is an ideal step, the observed reflectogram will show two rising edges with a delay of $\Delta t = 2l/v$, where l is the length of the cable and v is the signal propagation velocity. In practical applications, instead, measured reflectograms show neither steep edges nor constant patterns between them; on the contrary, they often show one or more artifacts or anomalies depending on losses, multiple reflections, presence of faults along the cable. These anomalies may be quite difficult to classify and may require specific waveform analysis algorithms [18].

From a practical point of view, the accuracy of the ToF measurement can be identified with:

- length measurement accuracy (for cables with known propagation velocity);
- velocity measurement accuracy (for cables with known length);
- linearity and repeatability of the calibration curve, in a ToF-based measurement (e.g. water level measurement).

A. Gain, offset and nonlinearity model

It is common to characterize the accuracy of length measurements with its absolute error, i.e. the difference between the estimated length and its real value.
In this paper the performance of each criterion is assessed by evaluating gain, offset and nonlinearity error components. Estimated lengths are fitted to a straight line in the least squares sense, giving the following error model:

$$l(l_0) = (1 + er_G) \cdot l_0 + e_O + e_{nl}(l_0) \qquad (1)$$

Where l_0 is the real length and l its estimated value. The meaning of the parameters in (1) is:

- er_G: relative gain error (mismatch between the slope of the fitted straight line and unity);
- e_O: offset error (y-intercept of the fitted straight line);
- $e_{nl}(l_0)$: integral nonlinearity error (difference between measured lengths and fitted straight line);

From a practical point of view, offset error is associated with the goodness of the agreement between estimated and true cable length, gain error is related to a multiplicative factor which alters proportionally all measured lengths.

B. Processing for Denoising and for Derivative Calculation

Since the three criteria considered in this paper are based on the direct analysis of the first derivative of the signal, it is important to be able to accurately compute it. The simple finite difference approximation is too sensitive to noise in most practical cases and, therefore, a denoising technique is necessary.

In [19], it was demonstrated that wavelet-based denoising methods, using empirically chosen thresholds, optimally adapt the denoised signal to the signal which must be recovered. However, the wavelet denoising technique is particularly case-dependent and, although providing excellent results [20], needs to be fine-tuned for each combination of test signal and acquisition instrumentation adopted.
In this paper, in order to avoid complex and case dependent fine tuning, Nicolson's technique [21] together with high order harmonics filtering have been used for denoising, with an approach already adopted by the authors in past works [16]. Such denoising technique can be briefly outlined as follows:

1) signal detrending;
2) fast Fourier transform (FFT);
3) high order harmonics suppression (Fig. 1);
4) frequency domain derivative evaluation;

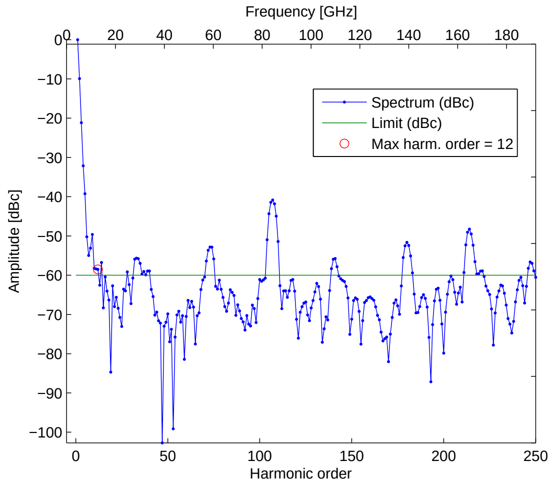


Fig. 1. Nicolson FFT spectrum, noise floor limit and maximum harmonic order.

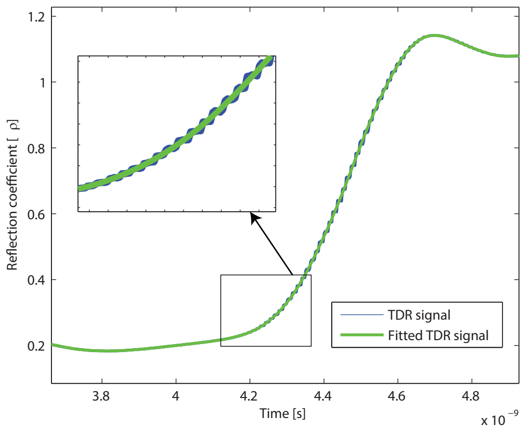


Fig. 2. Noisy (blue / dark gray) and denoised (green / light gray) signal.

5) inverse fast Fourier transform (IFFT, Fig. 2).

Such filtering routine eliminates noise without introducing undesired filter-dependent ripple, and it also enhances peaks in the derivative which, indeed, are not detectable in the finite differences derivative approximation. Moreover, this technique performs excellently against noise without introducing any delay in relevant features. Fig. 2 shows a typical denoising step and, in detail, one of the signal peaks, whose position in time is unchanged between the original noisy signal and its denoised version.

Step 3) includes rough low-pass filtering, by simple high order harmonics suppression. The specific harmonic order to be chosen is not a critical issue, since with Nicolson technique any reasonably low harmonic order (as detailed in Section IV-B works very well against noise while preserving required signal features. Therefore, results reported in Section IV-A have been achieved by filtering harmonics under a reasonably chosen noise floor (-60 dBc). However, in Section IV-B algorithms have also been tested against different harmonic orders in terms of repeatability.

TABLE I
DUT ELECTRICAL PARAMETERS

Parameter	value
Type	Coaxial
Impedance	75 Ω
Capacitance	54 pF/m
Propagation velocity	0.83 · c
Attenuation, 10 MHz	3 dB / 100 m
Attenuation, 50 MHz	5.6 dB / 100 m
Attenuation, 100 MHz	7.9 dB / 100 m
Attenuation, 230 MHz	12.3 dB / 100 m
Attenuation, 300 MHz	14.2 dB / 100 m
Attenuation, 400 MHz	16 dB / 100 m
Attenuation, 860 MHz	24.7 dB / 100 m
Attenuation, 1 GHz	26.1 dB / 100 m

III. MATERIALS AND METHODS

As aforementioned, the algorithm and the ToF estimation criteria were tested on real reflectograms (rather than on synthesized ideal reflectograms). In fact, although it would have been easier to synthesize ideal reflectograms and test, for example, the noise robustness of each criterion, it is clear that measured reflectograms exhibit unpredictable TDR-related features, e.g., limited rise time of the test signal; artifacts in the test signal; oscillations in the reflectogram due to multiple reflections; different slopes between the two rising edges; amplitude noise and sampling jitter. A synthetic reproduction of such features and effects would be largely arbitrary, and so would be the final results of the analysis.

In the following subsections, a brief description of the experimental setup and of the three considered criteria for the estimation of the ToF are given.

A. Experimental Setup for Measurements on Cables with Known Parameters

In the first experimental setup, the reflectograms have been acquired using a Campbell Scientific TDR100 reflectometer. It provides a 250 mV step signal in an output impedance of 50 Ω, with nominal time response of combined pulse generator and sampling circuit ≤ 300 ps. In order to work in low noise conditions, signal averaging was also applied (128 averages per reflectogram). Such measurement configuration guarantees reliable, clean and stable reflectograms, suitable for characterizing the systematic errors of the algorithms. These experiments have been performed on coaxial cables (terminated in OC), whose nominal e.m. propagation velocity is $0.83 \cdot c$, being c the velocity of light in void. Other electrical parameters of the DUTs are detailed in Table I.

After assessing gain, offset and nonlinearity errors, measurement repeatability has also been assessed by adding white noise to acquired waveforms and applying different filtering depths (Section IV-B).

Successively, to verify the robustness of the developed methodology, additional tests were performed on bi-wire cables (also terminated in OC), with unknown electrical specifications. For this class of experiments, test signals with rise time of $\simeq 4$ ns were generated using an arbitrary waveform generator (80 MHz Agilent 33250A) and reflectograms were acquired using a LeCroy LT262 350 MHz oscilloscope in RIS (random

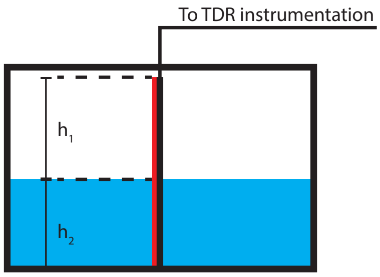


Fig. 3. Sketch of the experimental setup for water level measurement.

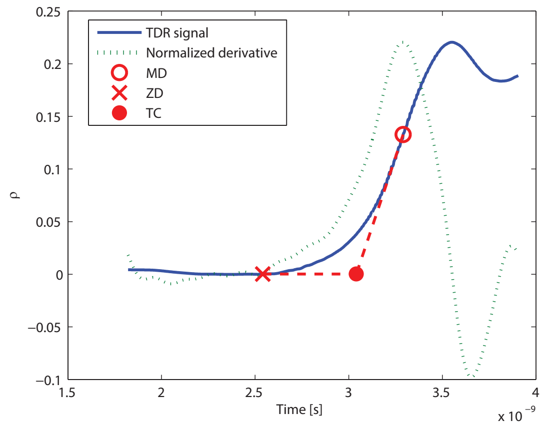


Fig. 4. Rising edge of reflectogram acquired on a 15 cm long Coaxial Cable, its derivative and POIs.

interleaved sampling) mode. The authors have used instrumentation with poorer performance in order to demonstrate the performance of the developed algorithms in a more cost-effective environment.

B. Experimental Setup for Water Level Measurement Application

The algorithms presented in [17] (and here reviewed and enhanced) were tested on a typical ToF related practical application, namely TDR-based water level monitoring [15]. The schematic of the setup is shown in Fig. 3. A bi-wire was inserted in a graduated, transparent, cylindrical container. A 1 m-long RG-58 coaxial cable was used to connect the beginning of the bi-wire to an arbitrary waveform generator (80 MHz Agilent 33250A). This waveform generator was used to apply a 100 kHz square-wave test signal to the bi-wire under test. In this configuration, water was progressively added into the container, with a consequent increase of the water level. As reported in [15], in such a configuration, the bi-wire acts as a sensing element (or probe) for TDR-based measurements of the level of water inside the container. Since the container was graduated, after each water-addition step, the resulting true water level could be measured by eye.

On a side note, it is worth mentioning that the choice of the interconnection scheme described above was purposely made to introduce an impedance mismatch between the signal source and the bi-wire under test, which may be accurately located using the presented automatic processing algorithm, and will be thoroughly discussed later in Section V.

C. Time of Flight Estimation Criteria

The value of the ToF is estimated as the time interval between two critical points detected on the reflectogram, which conventionally identify rising and/or falling edges on the signal. These points of interest (POIs), as anticipated in the introduction, are detected according to different criteria (Fig. 4):

- Maximum derivative (MD);
- Zero derivative (ZD);
- Tangents crossing (TC).

The first criterion identifies the signal edges with the absolute maximum of the derivative in the rising region, meaning the maximum for rising edges and the minimum for falling edges. The second criterion identifies the edges with the last zero crossing of the derivative before the MD point. In other words, it is used to identify the leading edge of the test signal. Finally, the third criterion, as simple and widespread as the first, models the rising edge as a smoothed ramp, and identifies the crossing of the tangents to the reflectogram for the MD and ZD points.

The three criteria have different features listed below:

- The MD criterion evaluates the ToF on the basis of maximum-energy points of the pulses, and it is essentially linked to the group velocity;
- The ZD and TC criteria evaluate the ToF on the basis of the leading edges of the pulses, and they are essentially linked to the phase velocity of the faster sinusoidal component;
- By their definitions, it follows that $t_{ZC} \leq t_{TC} \leq t_{MD}$;
- Since the MD point is the rightmost, and can never fall before the 'knee' of the step-like pulse, it will overestimate more often than underestimate the ToF; the contrary happens for the ZD point;
- By simple geometric considerations, the TC point is more stably near the knee of the pulse, and in case of overestimation by MD and underestimation by ZC, it represents a convenient trade-off.

IV. Experimental Results

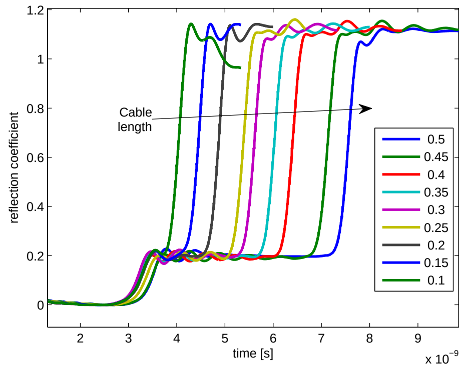
A. Measurements on Cables with Known Propagation Velocity

As mentioned in the previous Section, preliminary tests were performed on coaxial cables with known propagation velocity. Measurements were performed on three sets of cables:

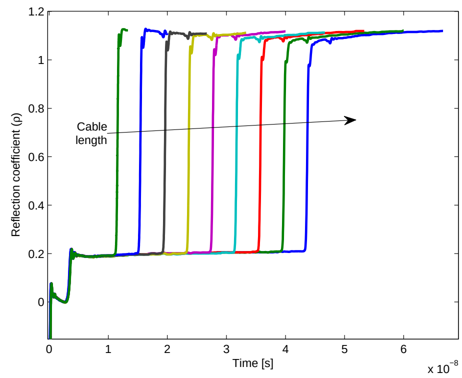
- 0.1 m - 0.5 m;
- 1 m - 5 m;
- 10 m - 30 m;

Each set encompassed nine cables of linearly spaced lengths, except for the last one, which had 5 linearly spaced lengths. Measured reflectograms from two sets of cables are shown in Fig. 5.

Every reflectogram shows reflections of different nature: the



(a)



(b)

Fig. 5. Measured reflectograms for cable lengths from 10 cm to 50 cm (a) and from 1 m to 5 m (b).

first is ‘weaker’, determined by the mismatch between the interconnection cable and the cable under test (50 Ω - 75 Ω), the other is ‘stronger’, determined by the open circuit termination. Since cable lengths of largely different values, ranging from 10 cm to 30 m have been considered, different phenomena such as edges of different steepness and multiple reflections are visible.

Lengths of even higher magnitude (kilometers) are also of great interest for some applications. Losses and dispersive behaviors are dominant in these cases which are, however, beyond the scope of this paper.

The performances of the considered criteria are summarized in Table II, which shows offset, gain and nonlinearity error contributions in detail.

It must be highlighted that gain error depends on the propagation velocity, which is given by the manufacturer with no further uncertainty specification. Propagation velocity, however, can also be estimated from ToFs and true lengths and compared to its nominal value for the purpose of criteria testing. Such velocity measurements are reported in Table III, showing an excellent agreement with the manufacturer specifications.

As regards gain, offset and nonlinearity errors, the best performing criteria are clearly maximum derivative and tangent crossing, the latter performing significantly better for short cables. From the results in Table III, on the other hand, the

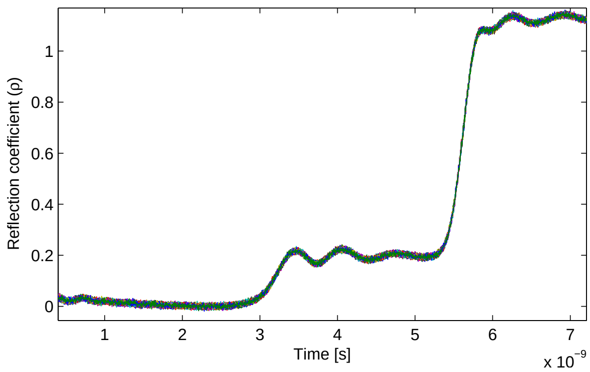


Fig. 6. Set of 100 noisy reflectograms ($l = 30$ cm).

best performing criteria for propagation velocity estimation is tangents crossing. In fact, it allows an estimation of the propagation velocity with a 0.14% error with respect to its nominal value.

B. Repeatability study

Repeatability assessment has been performed by considering 6 cable lengths among the full set of DUTs previously described. One hundred realizations of white noise have been summed to each reflectogram and, afterward, the three criteria have been applied to noisy signals. Noise standard deviation has been reasonably chosen as 0.5% of the entire reflectogram span. An example of resulting noisy reflectograms is reported in Fig. 6. The bias and standard deviation of estimated cable lengths have been evaluated as function of filtering depth (harmonic order). Some explanatory results are shown in Figures 7 and 8 for the shortest (10 cm) and the longest (30 m) cables respectively, considering harmonic orders from 10 to 20. Here the bias values are, for the sake of clarity, expressed by representing the average estimated cable lengths and the real cable length, reported as a horizontal dashed line.

Figures 7 and 8 show that the tangent crossing algorithm outperforms the other two in terms of repeatability (standard deviation of the estimates) and has also very good bias properties. Tangent crossing, therefore, can be, at this step, considered the most robust among the tested criteria.

Other noise standard deviations in a range up to 1% of the reflectogram span have also been tested, always achieving results similar to those reported in this Section.

C. Measurements on Cables with Unknown Electrical Parameters

Additional measurements have been performed on bi-wires with AWG-18 inner conductor (cross section in Fig. 9), with unknown electrical specifications, in the range of 5 m - 30 m. These cables are of particular interest because of their good sensitivity to changes in the dielectric constant of the surrounding environment, which makes them suitable in many sensing applications [3].

Results are summarized in Table IV: er_G was not computed since the true value for propagation velocity was not available.

TABLE II
GAIN, OFFSET AND NONLINEARITY ERRORS IN THE ESTIMATION OF CABLE LENGTH WITH THE THREE CONSIDERED CRITERIA

		0.10 m - 0.50 m	**1.00 - 5.00 m**	**10.00 m - 30.00 m**
e_O [cm]	*Max derivative*	-0.475	-0.559	0.081
	Zero derivative	3.433	1.675	2.027
	Tangent crossing	0.387	0.328	0.994
er_G [%]	*Max derivative*	1.125	0.395	0.143
	Zero derivative	-2.522	0.122	0.143
	Tangent crossing	0.284	0.328	0.141
$\max \lvert e_{nl} \rvert$ [cm]	*Max derivative*	0.28	0.29	0.28
	Zero derivative	2.13	2.40	2.27
	Tangent crossing	0.27	0.41	0.59

TABLE III
PROPAGATION VELOCITY ESTIMATED WITH THE THREE CONSIDERED CRITERIA (NOMINAL VELOCITY: $0.83 \cdot c$)

		0.10 m - 0.50 m	**1.00 - 5.00 m**	**10.00 m - 30.00 m**
v/c	*Max derivative*	0.8208	0.8267	0.8288
	Zero derivative	0.8515	0.8290	0.8288
	Tangent crossing	0.8276	0.8273	0.8288

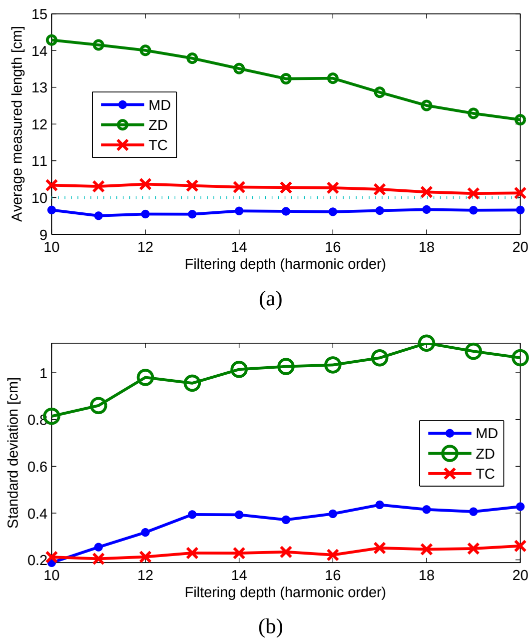


Fig. 7. Repeatability analysis for 10 cm long cable.

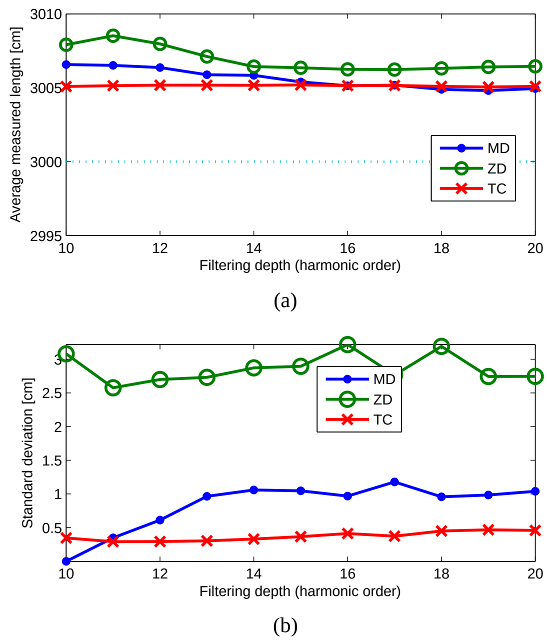


Fig. 8. Repeatability analysis for 30 m long cable.

Also in this case, tangents crossing criterion appears to have better performances in terms of offset and maximum nonlinearity error (Table IV).

Propagation velocity values were also computed from the estimated ToFs. Such values demonstrate that the three criteria behave in the same way on two different kinds of DUTs: the lowest value for propagation velocity is estimated with MD, and the highest one comes from the ZD, TC standing in the middle.

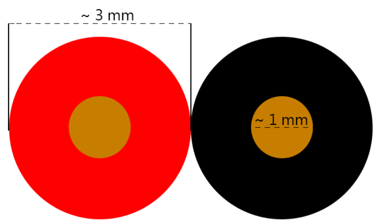


Fig. 9. Cross section and dimensions of the tested biwire.

V. TEST APPLICATION: WATER LEVEL MEASUREMENT

In order to test the three presented criteria in a different application scenario, they were comparatively used for TDR-based water level measurement [22] [4], with the experimental setup described in Section III-B. The coaxial interconnection between the bi-wire and the instrumentation introduces an impedance mismatch between the signal source and the actual probe, which may be accurately located using the presented processing algorithms, as shown in Fig. 10.

The two sets of features depicted with dots represent the beginning and the end of the bi-wire under test according

TABLE IV
GAIN, OFFSET AND MAXIMUM ERRORS IN THE ESTIMATION OF THE LENGTH OF THE BIWIRES WITH THE THREE CONSIDERED CRITERIA

	Max derivative	Zero derivative	Tangents crossing
er_G	N/A	N/A	N/A
e_O	-25.10 cm	-25.61 cm	-10.68 cm
$\max\|e_{nl}\|$	48.94 cm	15.73 cm	12.66 cm
v/c	0.6379	0.6591	0.6558

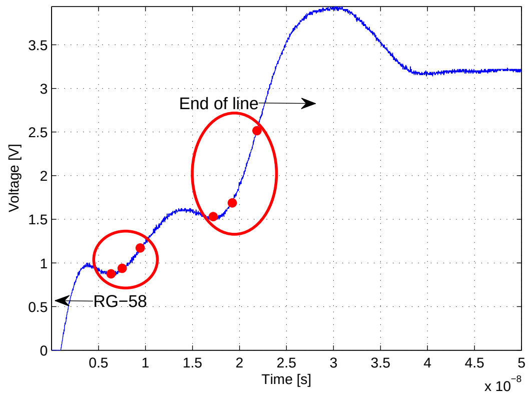


Fig. 10. TDR signal on completely dry probe.

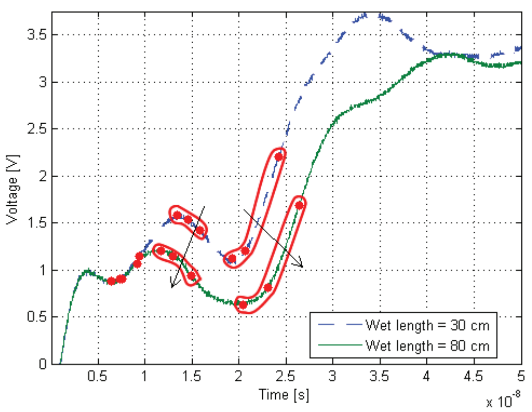


Fig. 11. TDR signal on wet probe.

to the three criteria (zero derivative, tangent crossing and maximum derivative respectively). When a certain fraction of the bi-wire length is submerged by water, a discontinuity in the effective dielectric permittivity of the medium surrounding the probe occurs. Therefore, another impedance mismatch becomes clearly visible in the reflectogram, thus enabling the algorithm to detect another set of features, as shown in Fig. 11. In the same figure, the variation in the position of the detected features with regard to the increase of the wet length is also pointed out. Going from the leftmost feature set towards the last on the right, the algorithm has been used to detect:

- The interface between the coaxial cable and the bi-wire;
- The air-water interface on the bi-wire;
- The end of the bi-wire.

A. Basic Theoretical Computations

In the proposed experimental setup, the test signal has to travel twice the length of the bi-wire, which is surrounded by two different media with their respective ϵ_{eff} values, which represent the effective dielectric constant seen by the traveling wave. With respect to this simple model, the overall propagation time in each media can be computed as follows:

$$\tau_1 = 2\frac{h_1 \cdot \sqrt{\epsilon_{eff1}}}{c};\ \tau_2 = 2\frac{h_2 \cdot \sqrt{\epsilon_{eff2}}}{c} \tag{2}$$

where h_1 and h_2 are the bi-wire lengths surrounded by the first and second medium respectively (see Fig. 3), the factor 2 is due to the round trip, $c/\sqrt{\epsilon_{eff1/2}}$ is the propagation velocity in each medium and c is the propagation velocity in void. Therefore, the total propagation time in the bi-wire is simply given by

$$\tau = \tau_1 + \tau_2 = \frac{2}{c}\left[h_2(\sqrt{\epsilon_{eff2}} - \sqrt{\epsilon_{eff1}}) + l\sqrt{\epsilon_{eff1}}\right] \tag{3}$$

with l the total length of the bi-wire ($l = h_1 + h_2$).

Equation (3) is clearly linear with respect to h_2, meaning that measuring τ should provide an excellent benchmark for the three estimation criteria.

B. Experiment design

For this specific application, the set of experiments have been designed as follows:

- TDR measurements have been performed in order to construct calibration curves, with confidence intervals quantifying the repeatability;
- TDR measurements were performed by raising the water level at intervals of about 5 cm, and acquiring 100 reflectograms per level;
- True water level values were directly read on the cylindrical container, which was graduated at 1 mm steps. The reading error can, therefore, be neglected;
- All the measurements were performed in a period of time of the order of a few minutes, with ambient temperature between 24 °C and 26 °C, and with ambient humidity between 50% and 55%;
- The quantity affecting the measurement repeatability is essentially the instrumentation noise. Other influence quantities have been kept practically constant during the experiments;
- The obtained calibration curves are valid for the ambient conditions specified above, and for the specific instrumentation used, with its metrological characteristics (especially in terms of frequency response and rise time);
- Calibration curves e.g. for other values of temperature should be obtained with separate calibration experiments.

The author did not perform a complete uncertainty characterization of the water level measurement system (considering different temperatures etc.), because the purpose of the study is only to illustrate the performance of the ToF estimation methods in a practical application different from cable length measurement.

C. *Water level measurement as ToF estimation benchmark*

In Fig. 12 measured calibration curves for each criterion presented in Section III-C are comparatively plotted.
The results in Table V reproduce and confirm those of Section IV-C regarding the reliability and robustness of tangents crossing criterion.

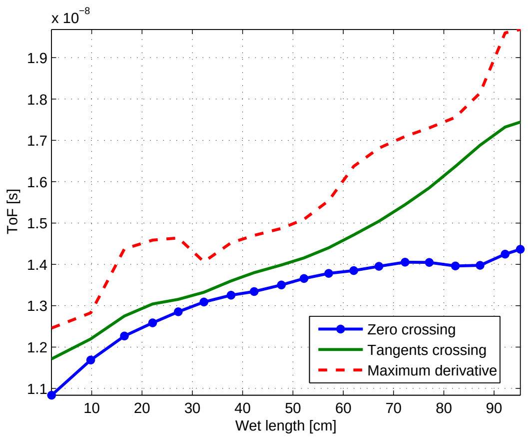


Fig. 12. ToF vs Wet bi-wire length: compared calibration curves.

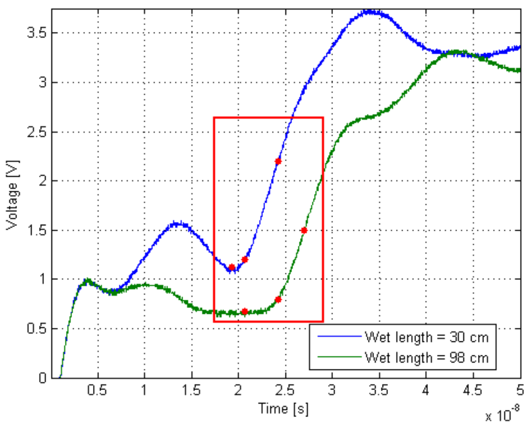


Fig. 13. Reflectogram flattening in presence of high wet lengths.

The best performing criterion appears to be TC because of better linearity all over the considered wet length range. ZC criterion shows a similar performance in terms of linearity; nevertheless, its linearity is impaired for greater wet lengths. The reason of ZD criterion performance degradation is due to the flattening of the reflectogram in correspondence of high wet lengths (as depicted in Fig. 13), which makes zero derivative unreliable. From a qualitative point of view, the excellent performance of the TC criterion is a direct consequence of

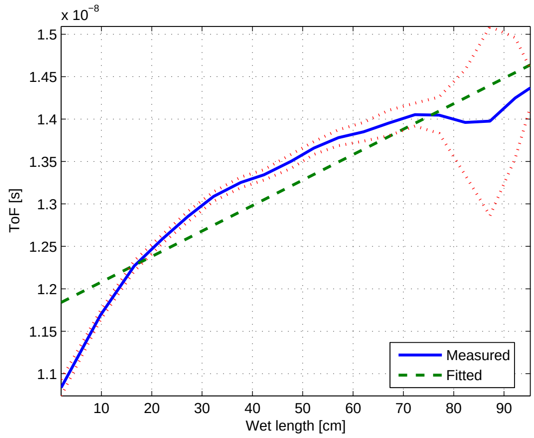


Fig. 14. Water level measurement calibration curves: zero derivative.

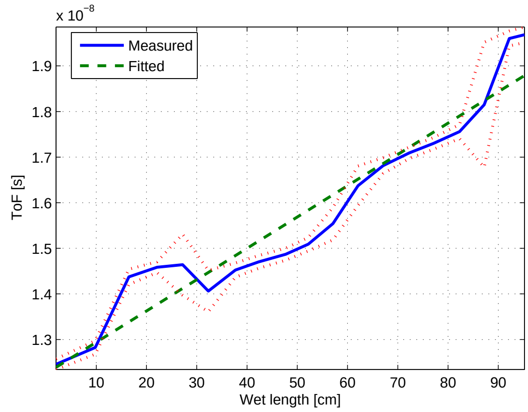


Fig. 15. Water level measurement calibration curves: maximum derivative.

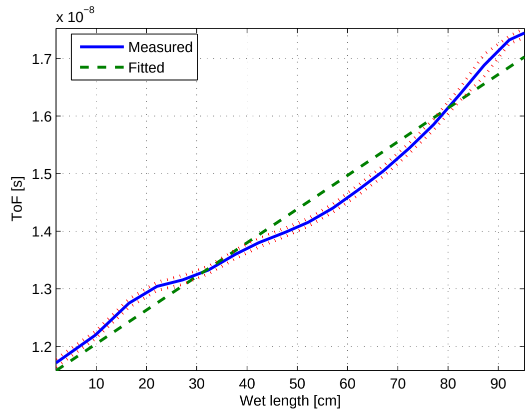


Fig. 16. Water level measurement calibration curves: tangents crossing.

TABLE V
NONLINEARITY ERRORS FOR EACH CRITERION

	Max derivative	**Zero derivative**	**Tangents crossing**
$\max\lvert e_{nl}\rvert$ [ns]	1.0176	1.0041	0.4716
Sensitivity [ns/cm]	0.0686	0.0300	0.0584
2σ [ns]	1.3703	1.1143	0.1905

using information coming from both the other two examined criteria to achieve, overall, a greater robustness.

The 100 repeated measurements have been used to compute the 95% confidence levels reported (red dotted lines) for each calibration curve (Fig. 14, 15 and 16) and summarized in Table V. From this point of view, tangents crossing criterion outperforms the other two achieving a repeatability error which is an order of magnitude lower.

VI. CONCLUSION

In this work, three different criteria for the estimation of the ToF of TDR signals are compared. The goal of the present analysis was to develop criteria that could provide more application-oriented and instrument-independent results, so as to employ and automate the proposed criteria in several practical applications of TDR measurements (such as TDR-based leak detection).
The measurements performed on coaxial cables (with known propagation velocity) show that the TC criterion has excellent performance in terms of systematic errors, and outperforms the other two criteria as regards repeatability, especially in presence of noise.

The measurements performed on bi-wires in free air (with unknown propagation velocity) confirm that TC provides the best performance, in terms of nonlinearity and offset errors. Finally, in the specific water level measurement application, the TC criterion outperforms the other two, yielding a more linear and repeatable calibration curve, while keeping a reasonably high sensitivity, followed by ZD.

The overall results indicate, therefore, that the 'maximum derivative' of the signal is information of comparatively poor value if used alone; on the contrary, it leads to the best and most robust results if merged with the 'zero derivative' information, into the 'tangents crossing' criterion. This is observable in nearly ideal situations (coaxial cables and twin cables in air), and is particularly clear in less ideal situations (sensing applications). It is therefore an excellent candidate for many TDR measurement applications.

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