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Criteria for Automated Estimation of Time of Flight in TDR Analysis

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***Abstract*—In this paper, 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 (MD), zero derivative, and tangent crossing (TC)] 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 biwire 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 biwire used as a sensing element for water-level measurement. The results show that, among the tested criteria, TC appears to provide a very good performance in terms of systematic errors and superior performance in terms of repeatability. The popular MD criterion appears to be more prone to random errors due to noise and TDR artifacts. The results of this paper are relevant to many practical applications of TDR, ranging from fault location in cables to media interface sensing.**

***Index Terms*—Calibration, digital filters, estimation error, fault location, length measurement, level measurements, nonlinearities, time measurement, time-domain reflectometry (TDR).**

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 the liquid level in intravenous medical infusions [4], crack/strain sensing in reinforced concrete structures [5], and dielectric characterization of liquids [6], [7].

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. The traditional waveform analysis has used the fitting of tangent lines to the waveform reflection to determine the travel time [10]–[12]; this travel time is related to the signal phase velocity.

Successively, Robinson *et al.* [13] argued that it is more appropriate to calculate the ToF from the apices of the derivative of the waveform. In their work, the medium under test is strictly divided into homogeneous segments and experimental conditions are rigorously controlled, and therefore the $S_{11}(f)$ scattering parameter can be evaluated using the recursive schemes proposed by Feng *et al.* [13, eq. (6)], 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 are stressed.

In [14], on the other hand, an algorithm for wire integrity analysis in helicopters, tiltrotors, and aircrafts 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 that 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 that 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].

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Starting from these considerations and from the results reported in [17], the goal of this paper 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 water-level measurements [15] or TDR-based localization of leaks in underground water pipes [16]. In fact, one of the goals of this paper is to pave the way for the implementation of fully automated algorithms that could improve the accuracy and efficiency in TDR waveform analysis.

For this purpose, in this paper, three different criteria for ToF estimation using the derivative of reflectograms are compared:

1) maximum derivative (MD);
2) zero derivative (ZD);
3) tangent 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 biwire 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 (EM) test signal (often a steplike 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 toward 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 this paper, 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, and the 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 the following:

1) length measurement accuracy (for cables with known propagation velocity);
2) velocity measurement accuracy (for cables with known length);
3) 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. The estimated lengths are fitted to a straight line in the least squares sense, giving the following error model:

$$l(l_0) = (1 + \mathrm{er}_G) \cdot l_0 + e_O + e_{\mathrm{nl}}(l_0) \tag{1}$$

where l_0 is the real length and l its estimated value. The meaning of the parameters in (1) is given as follows.

1) er_G*:* Relative gain error (mismatch between the slope of the fitted straight line and unity).
2) e_O*:* Offset error (y-intercept of the fitted straight line).
3) $e_{nl}(l_0)$*:* 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 the estimated and the true cable length, and gain error is related to a multiplicative factor that proportionally alters all measured lengths.

B. Processing for Denoising and 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 that 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 has been used for denoising, with an

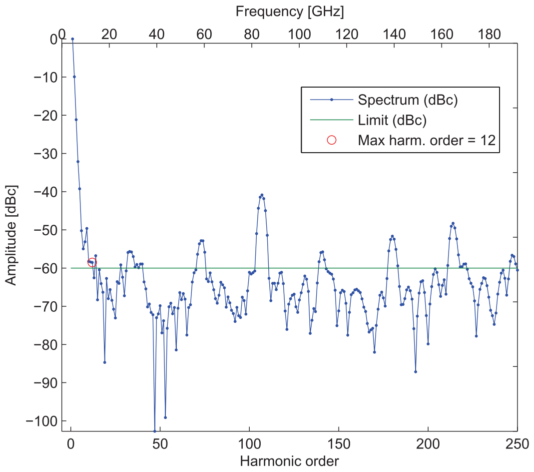


Fig. 1. Nicolson FFT spectrum, noise floor limit, and maximum harmonic order.

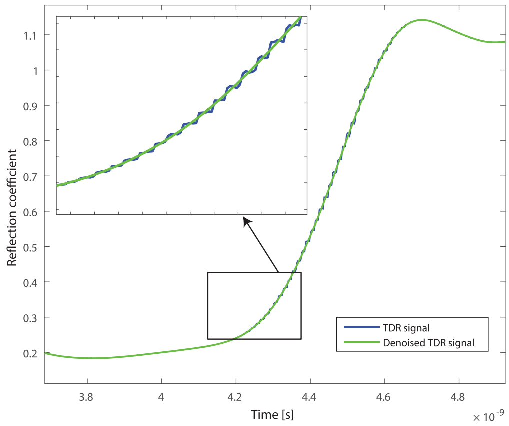


Fig. 2. Noisy (blue or dark gray) and denoised (green or light gray) signal.

approach already adopted in [16]. Such a 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;
5) inverse FFT (Fig. 2).

Such a 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 difference derivative approximation. Moreover, this technique excellently performs 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, the 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	$0.83 \cdot c$
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.

In the following sections, brief descriptions of the experimental setup and 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 $\leq$300 ps. In order to work in low-noise conditions, signal averaging was also applied (128 averages per reflectogram). Such a 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 EM propagation velocity is $0.83 \cdot c$, with c being 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 biwire cables

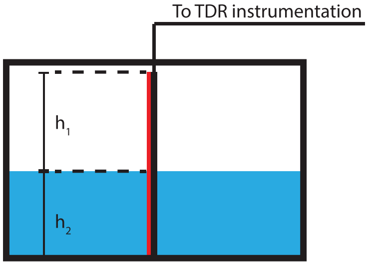


Fig. 3. Sketch of the experimental setup for water-level measurement.

(also terminated in OC), with unknown electrical specifications. For this class of experiments, test signals with a rise time of ≃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 random 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 biwire was inserted into a graduated transparent cylindrical container. A 1-m-long RG-58 coaxial cable was used to connect the beginning of the biwire 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 biwire under test. In this configuration, water was progressively added into the container, with a consequent increase in the water level. As reported in [15], in such a configuration, the biwire 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 biwire under test, which may be accurately located using the presented automatic processing algorithm, and will be thoroughly discussed 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 Section I, are detected according to different criteria (Fig. 4): 1) MD; 2) ZD; and 3) 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.

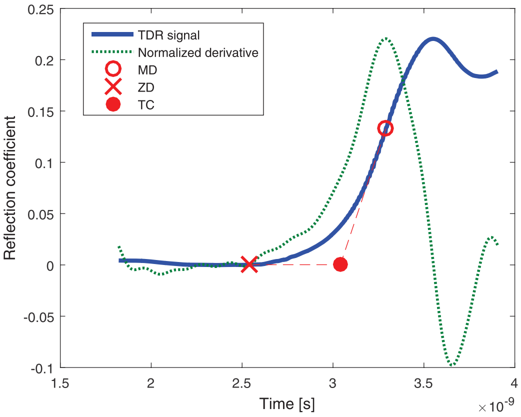


Fig. 4. Rising edge of the reflectogram acquired on a 15-cm-long coaxial cable, its derivative, and POIs.

The three criteria have different features listed as follows.

1) 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.
2) 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.
3) By their definitions, it follows that $t_{\mathrm{ZC}} \leq t_{\mathrm{TC}} \leq t_{\mathrm{MD}}$.
4) Since the MD point is the rightmost, and can never fall before the knee of the steplike pulse, it will overestimate more often than underestimate the ToF; the contrary happens for the ZD point.
5) By simple geometric considerations, the TC point is more stable near the knee of the pulse, and in the case of overestimation by MD and underestimation by ZC, it represents a convenient tradeoff.

IV. EXPERIMENTAL RESULTS

A. Measurements on Cables With Known Propagation Velocity

As mentioned in section III-A, preliminary tests were performed on coaxial cables with known propagation velocity. Measurements were performed on three sets of cables:

1) 0.1–0.5 m;
2) 1–5 m;
3) 10–30 m.

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

TABLE II

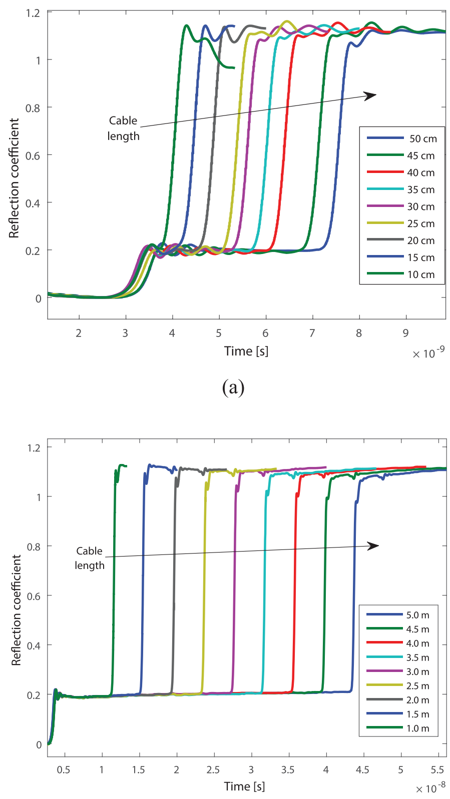
GAIN, OFFSET, AND NONLINEARITY ERRORS IN THE ESTIMATION OF CABLE LENGTH WITH THE THREE CONSIDERED CRITERIA

		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 · 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



(a)

(b)

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

Every reflectogram shows reflections of different nature: the first is weaker, determined by the mismatch between the interconnection cable and the cable under test (50–75 Ω), and 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 with 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 MD and TC, the latter performing significantly better for short cables. From the results in Table III, on the other hand, the best performing criterion for propagation velocity estimation is TC. 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 six 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 the resulting noisy reflectograms is reported in Fig. 6. The bias and standard deviation of the estimated cable lengths have been evaluated as a function of filtering depth (harmonic order). Some explanatory results are shown in Figs. 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

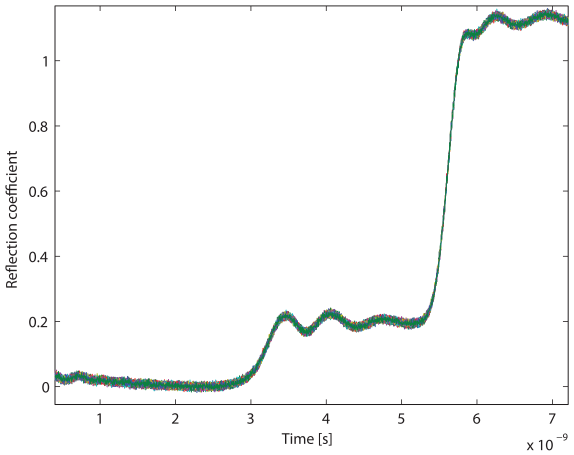
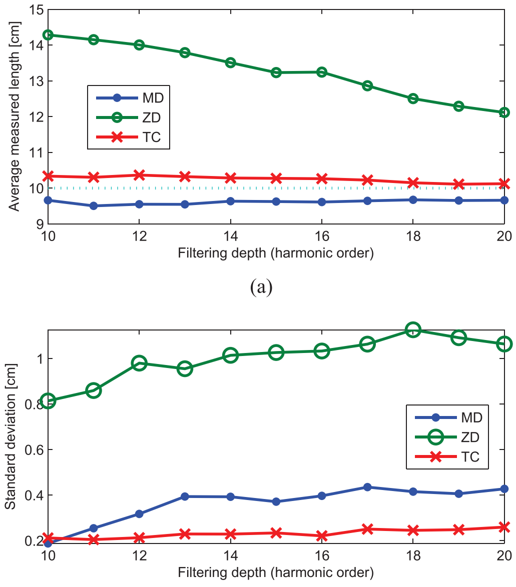


Fig. 6. Set of 100 noisy reflectograms ($l = 30$ cm).



(a)

(b)

Fig. 7. Repeatability analysis for a 10-cm-long cable in terms of average measured length (a) and standard deviation (b).

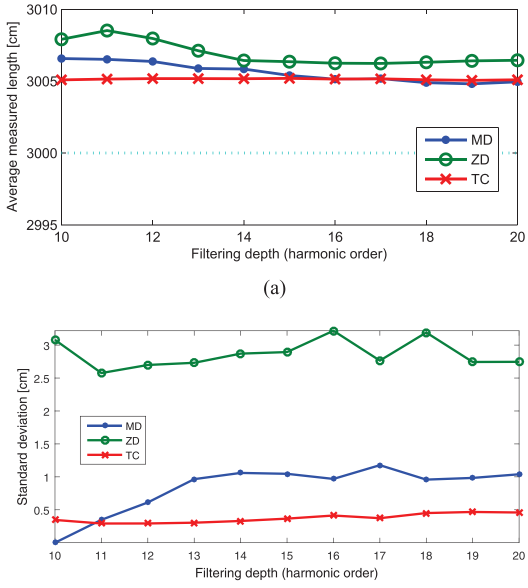
cable lengths and the real cable length, reported as a horizontal dashed line.

Figs. 7 and 8 show that the TC algorithm outperforms the other two in terms of repeatability (standard deviation of the estimates) and also has very good bias properties. TC, 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 the results similar to those reported in this section.

C. Measurements on Cables With Unknown Electrical Parameters

Additional measurements have been performed on biwires with an AWG-18 inner conductor (cross section in Fig. 9), with unknown electrical specifications, in the range 5–30 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].



(a)

(b)

Fig. 8. Repeatability analysis for a 30-m-long cable in terms of average measured length (a) and standard deviation (b).

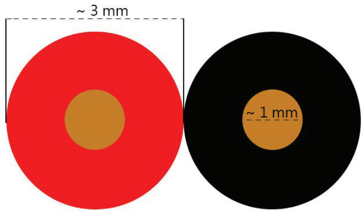


Fig. 9. Cross section and dimensions of the tested biwire.

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
$\max \lvert e_{nl} \rvert$	48.94 cm	15.73 cm	12.66 cm
v/c	0.6379	0.6591	0.6558

The results are summarized in Table IV, and er_G was not computed since the true value for propagation velocity was not available. Also in this case, the TC 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: 1) the lowest value for propagation velocity is estimated with MD and 2) the highest one comes from the ZD, TC standing in the middle.

V. TEST APPLICATION: WATER-LEVEL MEASUREMENT

In order to test the three presented criteria in a different application scenario, they were comparatively used for

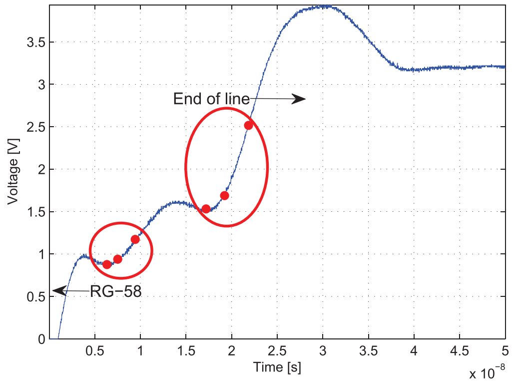


Fig. 10. TDR signal on a completely dry probe.

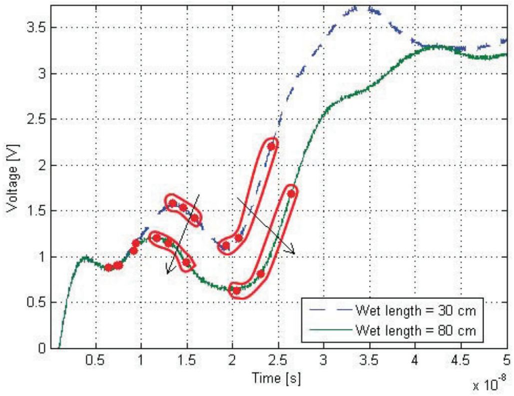


Fig. 11. TDR signal on a wet probe.

TDR-based water-level measurement [4], [22], with the experimental setup described in Section III-B. The coaxial interconnection between the biwire 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 biwire under test according to the three criteria (ZD, TC, and MD, respectively). When a certain fraction of the biwire length is submerged in 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 Fig. 11, the variation in the position of the detected features with regard to the increase in the wet length is also pointed out. Going from the leftmost feature set toward the last on the right, the algorithm has been used to detect the following:

1) the interface between the coaxial cable and the biwire;
2) the air–water interface on the biwire;
3) the end of the biwire.

A. Basic Theoretical Computations

In the proposed experimental setup, the test signal has to travel twice the length of the biwire, 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:

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

where h_1 and h_2 are the biwire lengths surrounded by the first and second media, respectively (see Fig. 3), the factor 2 is due to the round trip, $c/(\epsilon_{\text{eff1}/2})^{1/2}$ is the propagation velocity in each medium, and c is the propagation velocity in void. Therefore, the total propagation time in the biwire is simply given by

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

with l the total length of the biwire ($l = h_1 + h_2$).

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. Experimental Design

For this specific application, the set of experiments has been designed as follows.

1) TDR measurements have been performed in order to construct calibration curves, with confidence intervals quantifying the repeatability.
2) TDR measurements were performed by raising the water level at intervals of about 5 cm and acquiring 100 reflectograms per level.
3) 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.
4) 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%.
5) The quantity affecting the measurement repeatability is essentially the instrumentation noise. Other influence quantities have been kept practically constant during the experiments.
6) 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).
7) Calibration curves, e.g., for other values of temperature should be obtained with separate calibration experiments.

The authors 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.

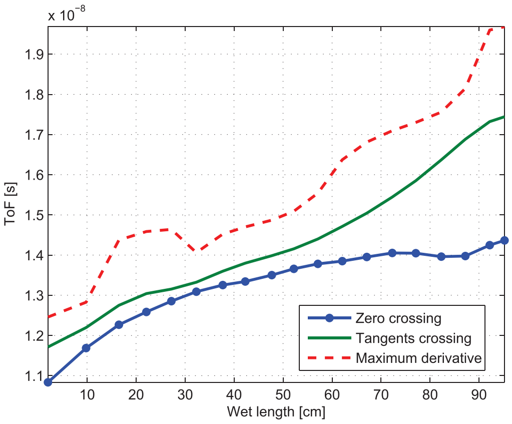


Fig. 12. ToF versus wet biwire length: compared calibration curves.

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

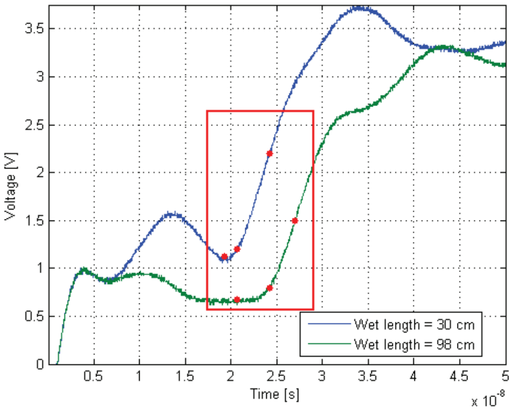


Fig. 13. Reflectogram flattening in the presence of high wet lengths.

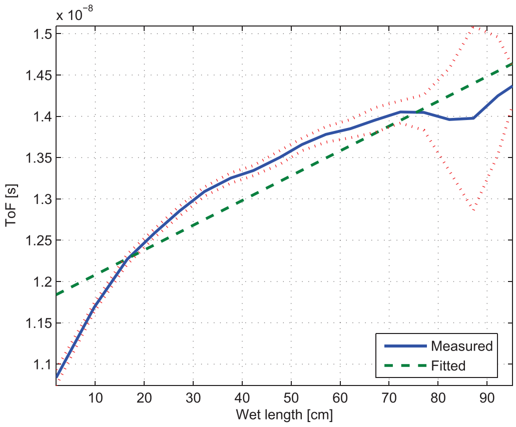


Fig. 14. Water-level measurement calibration curves: ZD.

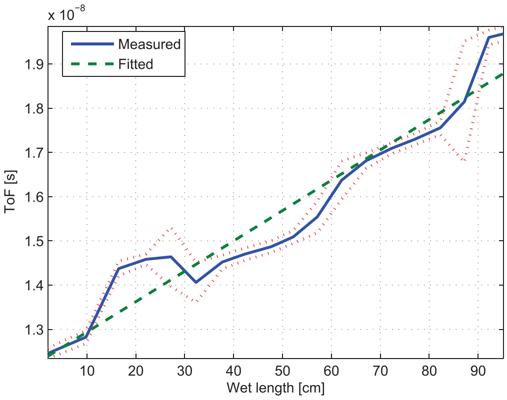


Fig. 15. Water-level measurement calibration curves: MD.

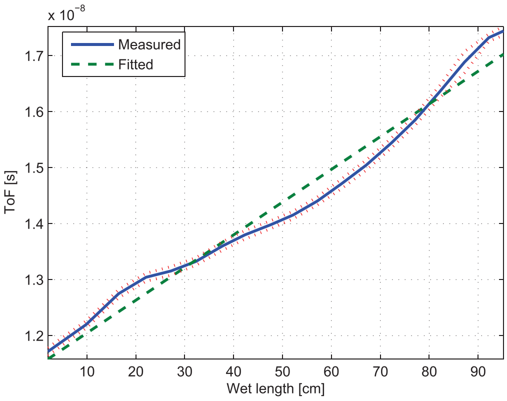


Fig. 16. Water-level measurement calibration curves: TC.

The results in Table V reproduce and confirm those of Section IV-C regarding the reliability and robustness of the TC criterion.

The best performing criterion appears to be TC because of better linearity all over the considered wet length range. The 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 with high wet lengths (as shown in Fig. 13), which makes ZD unreliable. From a qualitative point of view, the excellent performance of the TC criterion is a direct consequence of using information coming from 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 (Figs. 14–16) and summarized in Table V. From this point of view, the TC criterion outperforms the other two achieving a repeatability error that is an order of magnitude lower.

VI. CONCLUSION

In this paper, 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 the presence of noise.

The measurements performed on biwires 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 MD of the signal is the information of a comparatively poor value if used alone; on the contrary, it leads to the best and most robust results if merged with the ZD information, i.e., into the TC 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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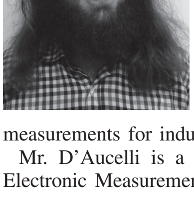

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