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## **REFLECTION-DECOUPLED ANALYSIS IN THE TDR SIGNAL DIGITAL PROCESSING PIPELINE**

Time-domain reflectometry (TDR) is a widely adopted method for non-destructive characterisation of inhomogeneous materials, including soils, biological tissues, and composite structures. Its principle relies on launching a broadband electromagnetic pulse into a transmission-line probe immersed in the material under test and recording the reflected waveform. A single Fourier transform then converts this temporal record into the frequency-dependent complex dielectric permittivity (CDP) spectrum, covering a range from tens of megahertz to several gigahertz [1]. A critical challenge in this workflow is the sensitivity of the recovered spectrum to source instability, connector imperfections, and cable length variations – artefacts that corrupt the measured reflection coefficient and, consequently, the retrieved material parameters.

The classical approach to compensating for these systematic errors is the Dual Reflection Analysis (DRA) method [2]. DRA exploits the ratio of two successive reflections – the first from the air-material interface and the second from the probe termination – to cancel the source transfer function.

Reflection-Decoupled Analysis (RDA) addresses these limitations through the introduction of a dedicated Mismatched Section (MS) – a precisely characterised, geometrically stable segment of transmission line (typically air-filled or PTFE-filled) inserted between the feed cable and the measurement probe [3]. The dielectric properties of the MS are known a priori and do not change with environmental conditions, making the first reflection from the MS entrance a fully deterministic reference signal that encodes the instantaneous state of the source, the connector, and the entire feed cable. In every acquisition cycle, RDA processes two physically separated waveforms: the reference reflection  $R_1(\omega)$  from the MS entrance and the measurement reflection  $R_2(\omega)$  from the probe–material interface. Because  $R_1(\omega)$  contains the complete source signature, the material-dependent reflection coefficient can be deconvolved as:

$$\rho(\omega) = R_2(\omega) / [R_1(\omega) \cdot H_{MS}(\omega)],$$

where  $H_{MS}(\omega)$  is the analytically computed transfer function of the MS. This division effectively removes the source function from every measurement without the need for explicit calibration procedures such as the Short-Open-Load (SOL) protocol that is standard in vector network analysis.

The practical consequence is that RDA operates as a continuous, in-situ self-calibrating system [3].

Within a full TDR digital signal processing pipeline, RDA is positioned upstream of the inverse problem solver. The recommended pipeline architecture consists of the following sequential stages: (1) signal acquisition – synchronous averaging of  $N$  waveforms to suppress AWGN; (2) adaptive denoising – Savitzky-Golay or wavelet thresholding to preserve edge sharpness; (3) baseline correction – polynomial trend subtraction to remove DC drift; (4) windowing – Tukey window application before FFT to reduce spectral leakage; (5) RDA deconvolution – extraction of the clean reflection spectrum  $\rho(\omega)$ ; (6) inversion – retrieval of CDP parameters via a hybrid optimisation algorithm.

The inclusion of RDA as stage 5 decouples the quality of the spectral estimate from cable-assembly variability. Laboratory tests reported in [3] demonstrate that RDA maintains CDP retrieval accuracy (relative error below 2 %) over cable length variations of up to 3 m and temperature shifts of  $\pm 20$  °C, conditions under which classical DRA degrades to errors exceeding 8 %. This robustness is of particular importance for embedded monitoring systems operating in field environments where controlled calibration is impractical.

The principal advantages of RDA are: single-shot self-calibration inherent to every measurement cycle; independence from probe length, enabling short probes in high-loss media; compatibility with low-cost TDR hardware, since the MS can be fabricated from standard semi-rigid coaxial cable. The main limitation is the increased complexity of the probe assembly and the requirement for accurate characterisation of  $H_{MS}(\omega)$ , which must account for the geometry and temperature dependence of the MS permittivity.

#### **References:**

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