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Validation of Conceptual Progress in Time-Domain EM: Expectations & Practical Possibilities

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Abstract—The modalities to validate conceptual advancements in time-domain (TD) electromagnetics (EM) are critically examined. Upon inspecting the capabilities of the existing measurement equipment, it is concluded that expecting a physical verification of frequency-domain (FD) results is fully justified. However, comprehensive direct measurements in the case of TD frameworks do not seem warranted, with TD theories being properly verified only via numerical experiments that offer the needed controlled environment for the relevant proofs.

I. INTRODUCTION

The accelerated trend towards an ultra-fast, near-zero-latency, globally interconnected digital world, and the ever-evolving complexity of remote sensing missions fuel tremendous research efforts in the applied electromagnetic (EM) scientific community. These efforts not only yield, but also necessitate a vast amount of scientific publications that are, still, the main source of certified information for the involved players. However, confronted with an explosive amount of submissions, peer-reviewed journals are understandably compelled to raise their bar, with many editorial boards introducing (new) prerequisites for even considering works for reviewing. In the realm of the antenna and propagation journals, the IEEE Transactions in the first place, an elaborate validation of any newly proposed formalism is presently mandatory, this provision being, standardly, read as *practical validation*.

Upon noting that applied EM research has two main vectors, namely conceptual progress and device development, this study will ponder on what can be reasonably expected in terms of validation of new results. Since demanding comprehensive physical validation is self-evident for device innovation, the survey will be confined to the case of conceptual progress. The available options will be contrasted in the case of frequency-domain (FD) and time-domain (TD) EM formulations, the analysis yielding conclusions on the expectancies concerning these two classes of formalisms. Note that, in view of *causality* being the essential condition of any consistent TD framework, approaches that are problematic from this perspective, such as those involving the inverse Fourier transform (the more so in its IFFT variant), are expressly excluded from TD analyses.

The article continues by looking back at the evolutions in wireless EM transfer, this readily revealing intrinsic differences between FD and TD approaches to EM modelling. The measurement and software validation instruments will be then catalogued. The last step will be formulating our view on the feasible validation options for the two models. Since this work is circumscribed within the limits of the classical EM theory, we complement our study with an appendix on this theory's confines, from a technological and practicality perspective.

II. WIRELESS EM TRANSFER – A BRIEF REVIEW

It is beyond any doubt that the vast majority of theoretical investigations in antenna engineering (AE) are done via FD instruments, with TD tools being seldom called upon. Moreover, interestingly enough, some of these TD studies rely, actually, on FD analyses, with the TD results being inferred via a (numerical) inverse Fourier transform. At a first glance, this may point to a natural ability of the FD instruments to better capture the essence of the examined EM phenomena. However, looking back at the development of EM transfer technology may offer a different perspective on this preference.

From its very inception, radio technology was based on modulating a *relatively* narrowband signal on a carrier that is widely separated from the signal's centre frequency, a natural consequence of the heterodyne architectures becoming from the dawn of the radio the, practically, universal implementation choice. This approach is still prevalent, the only difference being that carriers are pushed deeper into the terahertz spectrum (implementations with carriers at 300 THz or higher moving from research labs towards industrial development), and there are no signs for a paradigm shift in a foreseeable future. An interesting note is in place here: base-band radio, despite being hailed in the early two-thousands for holding great promises in terms of energy efficiency, failed to take off.

This technological choice directly reflects in the employed EM models. With the signal bandwidth being consistently *relatively* narrow, FD models making use of (discrete) single-tone excitations make perfect sense. However, increasingly sophisticated modulation techniques may render this principle problematic, with the rapid changes in the signal challenging the validity of a steady-state, single-tone operation.

The alternative, TD avenue, with its mathematical intricacies, appeared as unjustified in view of its inherently *relatively* broadband character. Even the typical TD scenarios involving pulsed excitation failed to gain prominence, with the complex investigations of the group of Carl E. Baum representing a notable exception (see http://ece-research.unm.edu/summa/notes

for a collection of his celebrated "notes"). Some momentum built up after the Federal Communications Commission released in 2002 the 3.1–10.6 GHz band for unlicensed UWB applications [1], but geographic inconsistencies in band definitions prevented the development of "pulsed-communication" commercial protocols. As a result, TD EM models are confined to EMI/EMC assessment explorations (at relatively low frequencies), signal integrity assessment, and, recently, in experiments with time-varying materials [2], [3]. Nonetheless, the utility of TD models may be reexamined, especially for estimating the effect of modulation (a by-nature TD phenomenon) on carrier-based, highly-directive communication channels – back-reasoning from the observed FD operation for identifying TD causes may there be difficult, if at all possible.

To conclude with, irrespective of the choice for an FD or a TD approach, all EM models underpinning both present-day radio techniques and those expected to be developed in the (near) future are circumscribed to the realm of the *classical EM theory* (see Appendix A for a discussion on the applicable bounds). This situation presents clear conceptual benefits since it allows making use of established (mathematical) instruments for handling the field equations, and warrants the consistent use of basic, universal principles, *causality* in the first place.

III. Validation instruments

Having pointed out a practical basis for the preference for either FD or TD avenues in EM field modelling, we now return to the point made in the Introduction about the necessity of properly validating any newly-proposed formalism.

A. Measurement considerations

The ultimate validation of any theory is providing experimental proof of its correctness. The options available within the scope of AE are henceforth catalogued.

FD strategies and possibilities:

FD measurements are a domain that reached full maturity. At this point, there are excellent sources up to 200–300 GHz, and increasingly reliable and powerful sources are developed up to 1–2 THz, with photoconductive antennas [4], [5] and spintronic sources [6] presenting exceptional promises in terms of the delivered power. Furthermore, present-day Vector Network Analysers (VNAs) offer quite standardly accurate measurements (amplitude and phase) up to hundreds of GHz, with highly precise power assessment being possible well into far-infrared frequencies. The critical benefit of FD strategies is that they perform (extremely) narrowband measurements in combination with a frequency sweep over a more-or-less broad spectrum, this ensuring an intrinsic exceptionally large signal-to-noise ratio (SNR) margin.

TD strategies and possibilities:

At variance with FD measurements, TD systems face severe challenges. To begin with, ultra-short pulse generators are extremely scarce: the state-of-the-art, solid-state sources can only come down to 100 ps [7], [8], with spintronic sources offering 1 ps-long pulses [6]. The pulse energy in short pulses

is extremely low, the corresponding SNR all but excluding any direct measurement. Since retrieving signatures is crucial to any TD assessment, the only practical way of capturing them is by resorting to stroboscopic sampling, this implying, again, repetition (which, ultimately, equates to FD processing). Moreover, stroboscopic sampling is severely hampered by unwanted tail effects, jitter-induced errors, etc.

B. Numerical analysis considerations

In view of the complexity and the inherent costs of experimental validation, new concepts are currently tested in a preliminary phase via increasingly sophisticated numerical tools for ensuring maximum viability of the experimental phase. A historical perspective again offers instructive clues for properly understanding the essence of the possibilities *and* limitations of the (standard) numerical tools.

EM numerical analysis started with the finite-differences time-domain (FDTD) approach, with the celebrated paper of Yee [9] being generally taken as its inception. The critical step forward was represented by Weiland's use of the integral form of Maxwell's equation [10], this essentially setting the standard for FDTD EM analyses. It is observed that FDTD, as a method, predates EM studies, and it was primarily used in structural mechanics. Now, those examinations are by-nature TD: (i) structures fundamentally fail under shock (at a well-defined instant), and (ii) more often than not, maintaining the effect of a source until a steady-state, time-harmonic (TH) regime is reached largely exceeds the failing of any mechanical structure. That meant that at the moment when FDTD was ported to EM analysis, all basic engines (mesh generators and data-base management included) catered to the needs of structural mechanics configurations. However, EM propagation has two distinctive features that never occur in structural mechanics: (i) interfaces between (more-or-less homogeneous) domains – an interface in a material equates to a crack, hence the device is already compromised, and (ii) radiation into the embedding. Dealing with interfaces (and with zero-thickness layers) was elegantly achieved via Weiland's formalism. As for radiation into the embedding, FDTD incorporated it firstly via the absorbing boundary conditions (ABC) introduced in [11] and complemented in [12], and, later, via perfectly-matched layers (PML) introduced in [13], [14] with its coordinate stretching alternative [15], [16]. FD implementations of the finite-differences method appeared comparatively later and primarily at very low frequencies, driven by the optimisation of electrical machines (in the seventies) or the design of magnetic heads and magnetic supports (in the eighties).

Finite-differences methods are constrained by the need of using structured grids, and this conflicts with modelling slanting and, above all, curved boundaries. The answer was provided by the finite-element method (FEM) that allowed for using conformal meshes. EM FEM formulations flourished in the eighties and nineties. Initially, they were developed for either the static regime or for (low-frequency) FD, but present-day implementations are dedicated, primarily, to high-frequency studies. Note that FEM reused a lot of the results

initially developed for FDTD, especially for modelling the radiation into the embedding.

The decisive shift in AE towards EM FD frameworks occurred when the method-of-moments (MoM) moved into the mainstream position – these methods are presently the preferred tool for problem-tailored formulations that, incidentally, are the main engine behind the conceptual progress in AE. It is worth mentioning that developing TD MoM was notoriously unsuccessful, although a paradigm shift may be offered by the Cagniard-de Hoop (**C-dH**) MoM introduced in [17].

Numerical techniques have gained an almost sovereign position in AE, with the numerical validation via one of a handful "golden-standard" packages being an almost precondition for acceptance of newly proposed EM formalisms. These packages feature both TD approaches (CST Studio Suite[1] or Comsol[2]) and FD approaches (HFSS[3], Comsol, Altair Feko[4]), with coupled EM-mechanical problems being mainly tackled in TD. Interestingly enough, TD runs are predominantly used in AE for extracting FD information via FFT manipulation!

IV. VALIDATION OF NEW CONCEPTUAL FORMULATIONS

Any new (analytical) method is expected to be validated by some mechanism that is amenable to be reproduced by third-parties. In view of their foundational character, analytical methods can only be validated within a genuinely controlled environment, otherwise the attestation may be affected by method-induced discrepancies that render it at least debatable, if not irrelevant (and there are examples of experimental replication of exotic phenomena that were subsequently proven to be simply operational errors). With this in mind, it is our opinion that requesting a *certain type* of validation within a context where ensuring the needed controlled conditions is hard, or even of principle impossible, is unwarranted. However, the impossibility of providing validation via *certain* strategies does not diminish the value of those theoretical results, as long as *some* independent validation can be provided.

A. FD formulations

As stated in the Introduction, physical validation is commonly required for endorsing any new theoretical development. In the case of FD models, as shown in Section III-A, measurements are common-practice up to $60, \ldots, 100\,\text{GHz}$, and possibly up to sub-THz ranges (truly, with increasingly sophisticated equipment). Nonetheless, producing the devices for testing incurs serious technological challenges, that quickly increase above the mm-wave range. Despite of this, apart from extremely fine effects, expecting a physical validation of newly-proposed, AE FD *concepts* is warranted. Validation via numerical simulations is also possible, but pre-eminence may be given to physical validation, especially since building concept demonstrators readily offers low-TRL precursors to industrial products.

B. TD formulations

The situation is diametrically opposite in this case. The arguments provided in Section III-A indicate that, except for long pulses (that are not relevant for present-day, mainstream EM devices and technological developments), TD physical validation is, practically, impossible. The only sensible way of validating TD models is then via numerical simulations that offer the properly controlled environment and device-independent SNR, under the provision of clearly demonstrating that the created numerical environment is relevant, and sufficiently accurate for certifying the investigated phenomena. The effectiveness of this avenue was examined in [18], and was recently demonstrated by us in [19].

Upon identifying numerical studies as the instrument of choice for validating *TD conceptual works*, we highlight a number of points that should be observed when constructing the validation numerical test-bed:

- Classical TD EM theory *demands* ensuring the causality of phenomena. It is then self-evident that a precondition for conforming to this requirement is the *exclusive* use of strictly causal excitation, and there are sufficient examples of adequate *causal* pulse shapes [20], [21].
- In view of the inhomogeneity of the examined configurations, TD experiments are often done via FDTD (or FEM) tools. In such cases, it is of paramount importance to prevent *any* spurious reflections from the boundaries in the studied region. However, neither ABCs, nor PMLs ensure a truly reflectionless termination of the domain of computation (*at least* due to discretisation and truncation errors). We strongly advocate resorting to time gating the marching-on-in-time process [19], [21] as (the only) safe approach to preclude *any* spurious boundary reflections.
- FDTD solutions can be, potentially, affected by supraluminal artifacts caused by grid dispersion, as demonstrated in [22]–[25]. It is then crucial to carefully check the correlation between mesh sizes and time steps for eliminating possible grid dispersion effects – and a note on this should be mandatory in any numerical experiment.

V. CONCLUSIONS

In view of the legitimate requirement to demonstrate in scientific publications any conceptual advancement via experiments that are amenable to independent verification, our study evidenced a clear distinction between the validation options applying to FD and TD models. The capabilities of existing measurement equipment justify expecting a physical validation of FD results. However, TD frameworks are solely properly assessed via numerical experiments that are the only one offering the needed controlled environment, with measurements yielding but a confined, often inconclusive validation.

Our work also made a case for placing the AE conceptual development within the confines of the classical EM theory, a choice substantiated by the scope of practical applications and the present (mainstream) technology. In this respect, the upper frequency limit (or corresponding time rate) for applying the Drude model give practical limits of this theory's pertinence.

A. Classical EM theory: physical bounds and suitability to engineering problems

The points made in this contribution are formulated within the framework of the *classical EM theory*, having at its core the *wave-like* propagation of *fields* that interact with matter having well-defined (possibly, dispersion-affected) *bulk* properties [26]. It is not our intention to question the foundations of the EM interaction. However, it is abundantly clear that the framework of the classical EM theory, *within the limits of its applicability*, is broad enough for allowing the analysis and behavioural prediction of the overwhelming majority of the applications that are now, and will be in a foreseeable future, encountered in energy, telecommunications and (consumer) appliances – pretty much everything within the scope of electrical engineering. For ensuring the practical value of this contribution's conclusions, it is imperative to clearly outline the dividing lines of the theory's applicability:

- Operating with fields with an unambiguous spatial and temporal definition requires the observed phenomena to be sufficiently far from the level at which quantum effects become noticeable, let alone dominant. As a result, the defining time-constants τ_c (or, conversely, fundamental frequencies f_c) of the temporal evolutions must largely exceed the time-scales associated with phenomena manifesting themselves at atomic level.

- Interaction with matter requires unambiguously defined material parameters that comply to the assumptions made within the framework of the classical EM theory. Specifically, one must be able to operate with the habitual permittivity ε, permeability μ, and conductivity σ. These parameters may have spatial variation or display dispersion and anisotropy, but these features must make sense for the problem at hand[5]. Moreover, provision must be made for the existence of a background embedding with uniform ε_e and μ_e, and with $\sigma_e = 0$.

Observing the above conditions entails bounds for the safe application of the classical EM theory. We regard the interaction with matter as determinant for placing *absolute* limits on the dominant τ_c (or, conversely, f_c):

- A first limit is inferred from [27, Section 81] that gives a lower bound of about 10 nm for quantum fluctuations

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[5]For example, the validity of the definition of any EM material parameter is conditioned in the case of composites consisting of "cells" (be it natural, *e.g.* molecules, or engineered) by two elements: (i) The correlation between the size of the "cells" *and* the lattice steps, on the one hand, and the spatial support $c_0\tau_c$ of the temporal evolutions of the examined EM phenomena, on the other hand. (ii) The averaging over a sufficiently large population of "cells" such that to guarantee the "washing out" of the effect of the interaction between the "cells" and the background fields. From this perspective, assigning material parameters *is explicitly excluded* in the case of engineered materials consisting of "cells" whose physical dimensions may be "small" when compared with $c_0\tau_c$, but clearly fail to contain a sufficient population for allowing the needed (statistical) averaging, let alone identifying important EM features, such as material interfaces. In our opinion, such materials can only be accounted for by tracking the localised interactions as, incidentally, is also the standard approach in solid-state physics with excitations having wavelengths that are commensurate with inter-atomic spacing.

being deemed "washed out", this yielding $\tau_{c;min} = 10\,\text{nm}/c_0 \approx 0.033\,\text{fs}$ (or $f_{c;max} = 3 \cdot 10^4$ THz). Based on this, one can infer frequency/time-rate limits for the definition of the parameters of (standard) dielectrics.

- Upon observing that radiating/receiving devices contain conducting elements, the need to ensure an interpretation of the conductivity that can be seamlessly embedded in the classical EM framework induces tighter bounds. A first limit is obtained by requiring the pertinence of the Drude model (inherently constructed based on classical EM theory principles). Presently, the limits of the model's validity were unequivocally established via physical experiments. For example, these limits were examined in [28], [29] for good conductors (specifically, Au), in [30] for semiconductors, and in [31] for a wider class of materials. Their conclusions are summarised in Fig. 1 that replicates [29, Fig. 1], while making use of the habitual engineering measure units. Fig. 1 shows that the Drude model definitely fails at $f_{2\,eV} = 2\,\text{eV}/h = 483$ THz (the plasma edge). In fact, the model's validity is already questionable in the visible spectrum. Even lower limits can be inferred from the three conduction regimes in [32, pp. 101–104]. For example, by requesting that $2\pi f\tau \ll 1$, with f being the excitation's frequency and τ the conductor's average relaxation time, the conduction is placed within the so-called Hagen-Rubens region where the conductivity practically mantains its DC value. Based on [33, Table 1.3], this strategy yields an upper operational bound at approximately 2.5 THz for Au or Cu.

Evidently, we acknowledge that the Drude model offers but an entry-level modelling of electron conduction that is only properly described by resorting to quantum electro-dynamics arguments. Nonetheless, confining the classical EM analysis to the frequency range validating the Drude model is, in our opinion, fully justified, primarily because the present-day mainstream technology *is* confined within these limits, and, expectedly, *will remain* so in the near-future (notwithstanding niche, exotic applications requiring more sophisticated conduction models). Moreover, the physically clear, tangible Drude conduction model continues yielding remarkable theoretical advancement, as demonstrated by the recently developed, *experimentally proven*, thermal emission models [34], [35].

All the above mentioned frequency limits for the applicability of the classical EM theory, the lowest ones included, offer a sufficient margin for practical applications since, to the best of our knowledge, few antennas (at least in the sense that is currently given to these devices) operating above 2.5 THz have been described in the literature. These arguments confirm the soundness of the statement at the start of this section.

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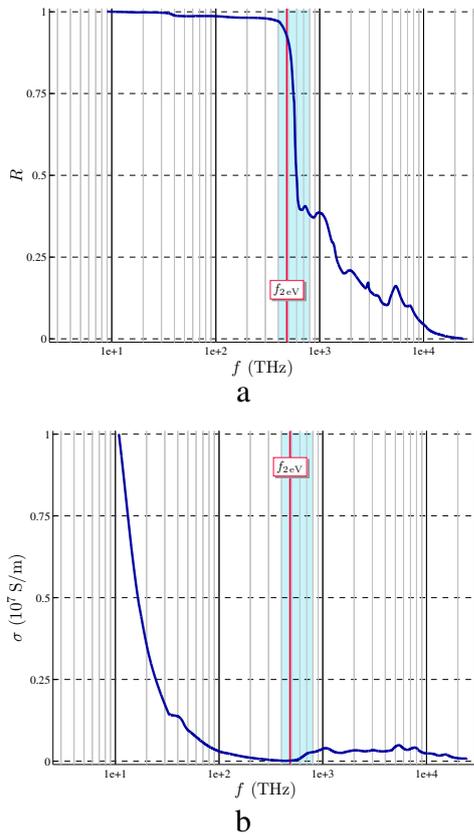
a

b

Fig. 1. Gold reflectivity R and conductivity σ as a function of frequency based on [29, Fig. 1]. $f_{2\,\mathrm{eV}} = 2\,\mathrm{eV}/h = 483\,\mathrm{THz}$, with h being Plank's constant. The directly measured DC conductivity is $4.9 \cdot 10^7\,\mathrm{S/m}$.

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