Classical and Extended Electrodynamics

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Lee Hively, PhD
Senior Scientist
Oak Ridge National Laboratory (retired) EED/SHP

Martin Land
Hadassah College

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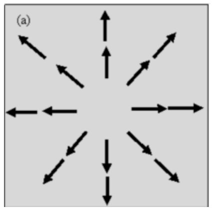
Outline

1. Why is Classical Electrodynamics (CED) incomplete?
2. What is Extended Electrodynamics (EED)?
3. EED work by others: theory, experiment, simulation
4. Our recent EED work: theory, experiment
5. Future work (examples)
6. Conclusions
7. Questions
8. Back-up slides: detailed derivations and references

1. Why is CED incomplete? (1)

Answer:

CED gauges away irrotational component of vector potential (A).[1,2]



An irrotational vector field radiates outward from a central source, or inward toward a central sink.

Specifically, the magnetic (**B**) and electric (**E**) fields are invariant for… $\mathbf{A} \rightarrow \mathbf{A} + \nabla\Lambda$; Λ =gauge function

$$\Phi \rightarrow \Phi - \frac{\partial \Lambda}{\partial t}$$; Φ=scalar potential

However, **A**(irrotational) has been measured.[3]

A(irrotational) ⇔ **J**(irrotational), which also has been measured.[4]

*****Key point: EED supported by A^{IR} and J^{IR}*****

[1]J.D. Jackson, *Classical Electrodynamics*, John Wiley publ. (1961)

[2]R. Feynman, *Feynman Lectures on Physics,* Vol. II, Ch. 15-17 (Addison Wesley, MA, 1964)

[3]M. Daibo, *et al., IEEE Trans. Magn.* 51, 1000604 (2015); *IEEE Trans. Appl. Supercond.* 26, 0500904 (2016); G. Rousseaux, *et al., Eur. Phys. J. D* 49, 249 (2008)—classical analog to Aharonov-Bohm effect in quantum physics

[4]C.G. Camara, *et al., Nature* 455, 1089 (2008); R.G. de Peralta Menendez *et al., Comput. Math. Meth. In Medicine* 2015, 801037 (2015)

1. Why is CED incomplete (2)

EED resolves another CED paradox: Haag's theorem[1]

- Under CED, two Hilbert representations are <u>in</u>equivalent
- Meaning that unitary QFT mapping is not unique
- The analyst must choose the "right" representation from an $\aleph_2$-infinitude of inequivalent representations

- EED is based on the Stueckelberg Lagrangian[2]
- <u>EED resolves inequivalent unitary QFT representations[3]</u>

[1] J. Earman and D. Fraser, "Haag's Theorem and Its Implications for the Foundations of Quantum Field Theory," *Erkenntnis* <u>64</u>, 305 (2006)
[2] E. Stueckelberg, "Forces of interaction in electrodynamics and in the field theory of nuclear forces," *Helv. Phys. Acta*. <u>11</u>, 225-299 (1938) Parts I-III
[3] E. Seidewitz, "Avoiding Haag's theorem with parameterized quantum field theory," *Foundations of Physics* <u>47</u>, 355 (2017)

2. What is EED? (1)

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t};$$

$$\mathbf{B} = \nabla \times \mathbf{A};$$

Irrotational component

Scalar field

$$C = \nabla \bullet \mathbf{A} + \frac{1}{c^2}\frac{\partial \Phi}{\partial t};$$

Solenoidal component

$$\nabla \times \mathbf{B} - \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} - \nabla C = \mu \mathbf{J};$$

Irrotational current drives scalar field

$$\nabla \bullet \mathbf{E} + \frac{\partial C}{\partial t} = \frac{\rho}{\varepsilon}.$$

Key results: EED is provably unique[1]

A and J satisfy the Helmholtz theorem[2]

ε= permittivity, μ=permeability (homogeneous, not vacuum)

[1]D.A. Woodside, *Am. J. Phys.* 77, 438-446 (2009)

[2]D.J. Griffiths, *Introduction to electrodynamics*, Prentice-Hall publ. (2007)

2. What is EED? (2)

Answer: CED is a sub-set of EED:

*Classical wave equations for **A**, **B**, **E**, Φ: **no gauge condition**

***A** and Φ are independent, physical fields without arbitrariness

*Charge conservation over classical times+

*Transverse, free-space electromagnetic (TEM) waves

*Relativistic covariance

+Different answer over (sub)Heisenberg times (see slide 9)

2. What is EED (2a)

EED includes A^{IR} and J^{IR}

Synonyms for “irrotational” are…

- Curl-free
- Longitudinal
- Gradient driven

2. What is EED? (3)

Answer: EED predicts important new physics...

*Corrected media-interface-matching conditions for ρ_A and $\mathbf{J_A}$

*Scalar-longitudinal wave (SLW): **B**=0, *C*≠0, **E** longitudinal

*Scalar wave (SW): **B**=**E**=0, *C*≠0

*Four new force terms in momentum conservation equation

$$\varepsilon\mu\frac{\partial}{\partial t}\left(\frac{\mathbf{E}\times\mathbf{B}}{\mu}-\frac{C\mathbf{E}}{\mu}\right)+\rho\mathbf{E}+\frac{\nabla\times\mathbf{B}C}{\mu}+\mathbf{J}\times\mathbf{B}=\mathbf{J}C+\frac{\nabla C^2}{2\mu}+\nabla\bullet\overleftrightarrow{\mathbf{T}}$$

*Three new terms in energy conservation equation

$$\frac{\partial}{\partial t}\left(\frac{\mathbf{B}^2}{2\mu}+\frac{C^2}{2\mu}+\frac{\varepsilon\mathbf{E}^2}{2}\right)+\nabla\bullet\left(\frac{\mathbf{E}\times\mathbf{B}}{\mu}+\frac{C\mathbf{E}}{\mu}\right)+\mathbf{J}\bullet\mathbf{E}=\frac{\rho C}{\varepsilon\mu}.$$

*Cosmology only accounts for visible matter (5%)

*New terms may explain dark matter (27%) & dark energy (68%)?

2. What is EED? (4)

Answer: Important prediction for scalar field (*C*)

Charge non-conservation on sub-Heisenberg time-scales:

$$\frac{\partial^2 C}{\partial c^2 t^2} - \nabla^2 C = \mu\left(\frac{\partial \rho}{\partial t} + \nabla \bullet \mathbf{J}\right).$$

C-dynamics at a point in space-time
The term ($\varepsilon\mu$) is $1/c^2$ in the propagation medium (not necessarily vacuum)

•Classical measurements are for $\Delta t >> h/4\pi\Delta E$, corresponding to a **time average** of the *C*-wave equation. Then, RHS is zero (charge conservation), and LHS is zero (no dissipation in *C*).

•LHS corresponds to particle-antiparticle (PAP) fluctuations
-PAP fluctuations drive *C*-fluctuations…
-and vice versa

2. What is EED? (5)

Answer: Prediction of 8 SLW validation criteria

1. No magnetic field (**B**=**0**)
2. Electric field (**E**≠**0**) parallel to direction of propagation
3. Non-zero scalar field (*C*≠0)
4. *C* generated by an irrotational current
5. $1/r^2$ attenuation in free-space propagation
6. Isotropic radiation pattern from monopole antenna
7. No skin-effect dissipation in linear, conductive media
8. SLW power comparable to classical TEM wave

Our preliminary test results are consistent with items 4-8 (slides 15-21)

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Answer for SW: Item 2 changes for SW: **E**=0

3. Previous work by others (1)

Eight peer-reviewed papers have independently verified EED

- V.A. Fock and B. Podolsky, "On Quantization of Electro-magnetic Waves and Interaction of Charges in Dirac Theory," *Phys. Zs. Sowijetunion* 1, 798 (1932)
- E. C. G. Stueckelberg, "Forces of interaction in electrodynamics and in the field theory of nuclear forces," *Helv. Phys. Acta*. 11, 225-299 (1938) Parts I-III (Swiss)
- T. Ohmura, "A new formulation on the electromagnetic field," *Prog. Theor. Phys.* 16, 684-685 (1956)--Japan
- Y. Aharonov and D. Bohm, "Further discussion of the role of electromagnetic potentials in the quantum theory" *Phys. Rev.* 130, 1625-1632 (1963)--Israel
- C-D. Munz, R Schneider, E Sonnendrücker, and U. Voss, "Maxwell's equations when charge conservation is not satisfied," *C. R. Acad. Sci. Paris I* 328, 431 (1999)—motivated by charge non-conservation in EM simulations--Germany
- K.J. van Vlaenderen and A. Waser, "Generalization of classical electrodynamics to admit a scalar field and longitudinal waves," *Hadronic J.* 24, 609-628 (2001)
- D.A. Woodside, "Three-vector and scalar field identities and uniqueness theorems in Euclidean and Minkowski spaces," *Am. J. Phys.* 77, 438-446 (2009)
- J. C. Jiménez and A. L. Maroto, "Cosmological magnetic fields from inflation in extended electromagnetism," *Phys. Rev. D* 83, 023514 (2011)--Spain

Woodside showed EED is *provably unique*

4. Our recent work (1)

Key result: 2 new wave classes (scalar-longitudinal and scalar waves)

Int. J. Signal and Imaging Systems Engineering, Vol. 5, No. 1, 2012 3

Toward a more complete electrodynamic theory

L.M. Hively*

Computational Sciences and Engineering Division,
Oak Ridge National Laboratory,
37831-6418, TN Oak Ridge, USA
E-mail: hivelylm@ornl.gov
*Corresponding author

G.C. Giakos

Department of Electrical and Computer Engineering,
The University of Akron,
Akron, 44325 OH, USA
E-mail: giakos@uakron.edu

Abstract: Maxwell's equations require a gauge condition for specific solutions. This incompleteness motivates use of a dynamical quantity, $\xi = -\nabla \cdot A - \varepsilon\mu\, \partial\varphi/\partial t$. Here, A and φ are the vector and scalar potentials, with permeability and permittivity, ε and μ, respectively. The results are:

- relativistic covariance
- classical wave solutions
- elimination of inconsistency between the media-interface matching for φ and for Gauss' law
- independent determination of A and φ
- prediction of two new waves, one being a charge-fluctuation-driven scalar wave, having energy but not momentum
- a second longitudinal-electric wave with energy and momentum
- experimental suggestions.

Keywords: electrodynamics; electromagnetics; LEW; longitudinal electric wave; scalar wave.

4. Our recent work (2)

Key result: two novel antennas for sending/receiving SLW

(12) **United States Patent**
Hively

(10) **Patent No.: US 9,306,527 B1**
(45) **Date of Patent: Apr. 5, 2016**

(54) **SYSTEMS, APPARATUSES, AND METHODS FOR GENERATING AND/OR UTILIZING SCALAR-LONGITUDINAL WAVES**

(71) Applicant: **GRADIENT DYNAMICS LLC**, McLean, VA (US)

(72) Inventor: **Lee M. Hively**, Philadelphia, TN (US)

(73) Assignee: **GRADIENT DYNAMICS LLC**, McLean, VA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/726,305**

(22) Filed: **May 29, 2015**

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H03H 2/00 (2006.01)
H01Q 1/36 (2006.01)
H04B 13/02 (2006.01)

(52) **U.S. Cl.**
CPC ***H03H 2/005*** (2013.01); ***H01Q 1/362*** (2013.01); ***H04B 13/02*** (2013.01)

(58) **Field of Classification Search**
CPC H01Q 9/16; H01Q 1/36; H01Q 9/04
USPC 343/791, 792, 895
See application file for complete search history.

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Primary Examiner — Hoang V Nguyen
(74) *Attorney, Agent, or Firm* — Pillsbury Winthrop Shaw Pittman LLP

(57) **ABSTRACT**

Scalar-longitudinal waves (SLWs) may be transmitted and/or received. A first apparatus configured to transmit and/or receive SLWs may include a linear first conductor configured to operate as a linear monopole antenna at a first operating frequency. The first apparatus may include a tubular second conductor coaxially aligned with the first conductor and an annular balun configured to cancel most or all return current on an outer surface of the second conductor during operation such that the first conductor transmits or receives SLWs. A second apparatus configured to transmit and/or receive scalar-longitudinal waves may include a bifilar coil formed in an alternating fashion of a first conductor and a second conductor such that an electrical current in the coil will propagate in opposite directions in adjacent turns of the coil thereby cancelling any magnetic field so that during operation the coil transmits or receives SLWs.

4. Our recent work (3)

Key Result: test evidence for 5 of 8 validation criteria for SLW

PHYSICS ESSAYS **32**, 1 (2019)

Classical and extended electrodynamics

Lee M. Hively[1,a)] and Andrew S. Loebl[2]
[1]*4947 Ardley Drive, Colorado Springs, Colorado 80922, USA*
[2]*9325 Briarwood Blvd., Knoxville, Tennessee 39723, USA*

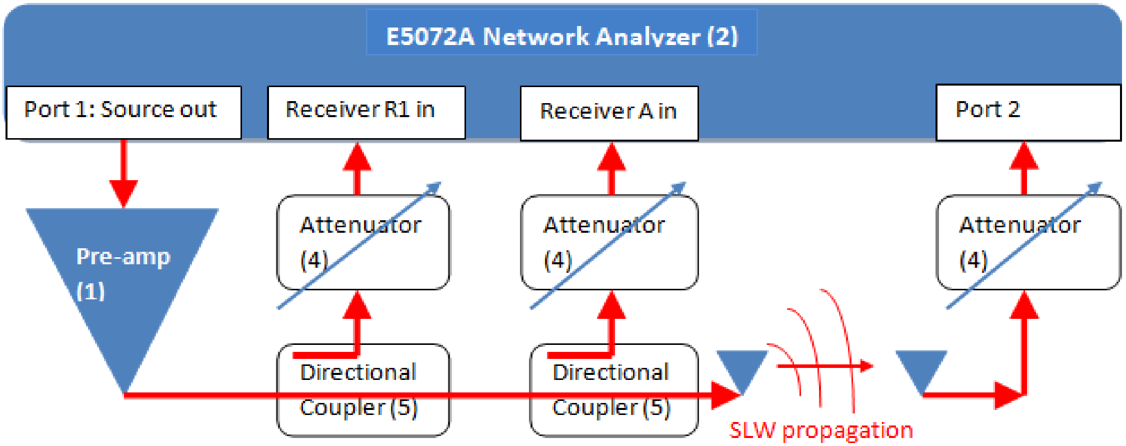
(Received 21 November 2018; accepted 8 February 2019; published online 25 February 2019)

Abstract: Classical electrodynamics is modeled by Maxwell's equations, as a system of eight scalar equations in six unknowns, thus appearing to be overdetermined. The no-magnetic-monopoles equation can be derived from the divergence of Faraday's law, thus reducing the number of independent equations to seven. Derivation of Gauss' law requires an assumption beyond Maxwell's equations, which are then overdetermined as seven equations in six unknowns. This overdetermination causes well-known inconsistencies. Namely, the interface matching condition between two different media is inconsistent for a surface charge and surface current. Also, the irrotational component of the vector potential is gauged away, contrary to experimental measurements. These inconsistencies are resolved by extended electrodynamics (EED), as a *provably unique system of 7 equations in 7 unknowns*. This paper provides new physical insights into EED, along with preliminary experimental results that support the theory.
[http://dx.doi.org/10.4006/0836-1398-32.1.112]

4. Our recent work (3a)

Key result: use of standard laboratory instruments in SLW tests

Item	Make/Model/Description	#	Connectors
1)Pre-amplifier	IFI T186-50 TWT (50W, 6-18GHz)	1	Nf-Nf
2)Network analyzer	Agilent E5071C (151dB dynamic range)	1	Nf-Nf
3)Calibration kit	Agilent N6314A Type n	1	N
4)Wave attenuator	Minicircuits FW-20+ (1W, 20dB)	3	SMAm-SMAf
5)Directional coupler	Fairfield MW MC0412-30 (50W, 30dB)	2	SMAf (all)
6)Rotary positioner	Newmark RT-3-10 rotary stage	1	n/a
7)Linear positioner	Newmark EB-1500-1 linear stage	1	n/a
8)Stage controller	Newmark NSC-G2 stage controller	1	n/a
RG-405/U cable	3' length	1	N-male to N-male
RG-405/U cable	1' length	1	N-male to SMA-male
RG-405/U cable	2' length	3	SMA-male to SMA-male
RG-405/U cable	6" length	1	SMA-male to SMA-male
RG-405/U cable	5' length	1	SMA-female to N-male
RG-405/U cable	5' length; straight SMA plug to …	8	straight SMA female jack
RG-405/U cable	2' length; straight SMA plug to …	3	straight SMA female jack



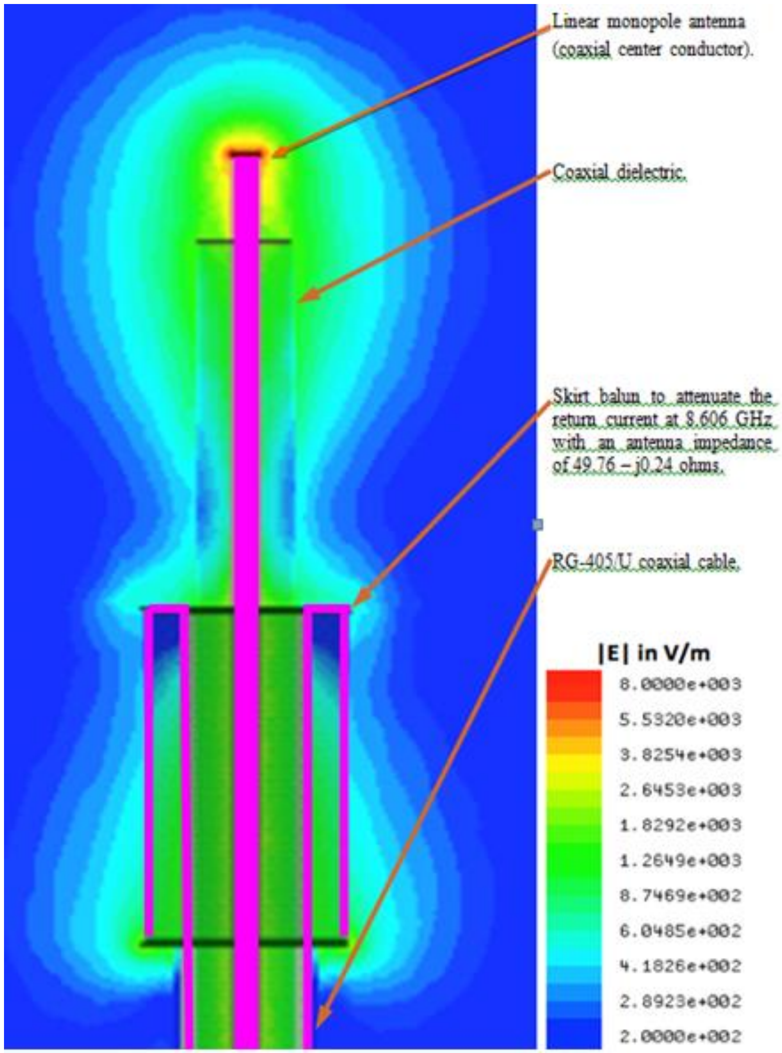
4. Dynamic Range Estimate (3b)

Key result: SLW power in typical range of TEM waves

Item	dB
Initial power output from network analyzer	0
Additional power from pre-amplifier	46.5
Insertion loss of components and cable (3 dB/m)	-10.0
Network analyzer dynamic range (10 dB margin)	141.0
Net dynamical range	177.5

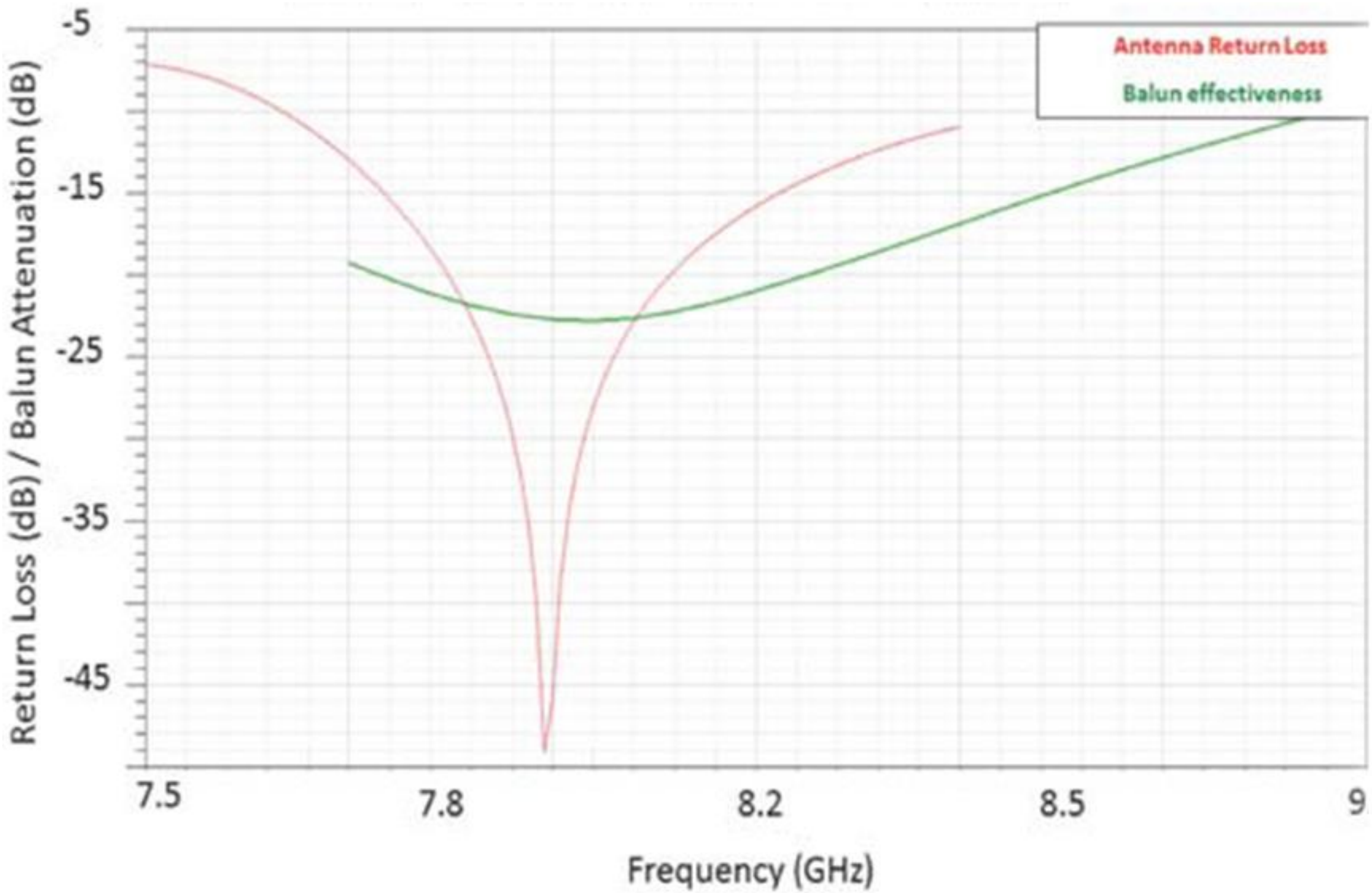
4. Our recent work (3c)

Key result: skirt balun eliminates displacement current, gives irrotational J



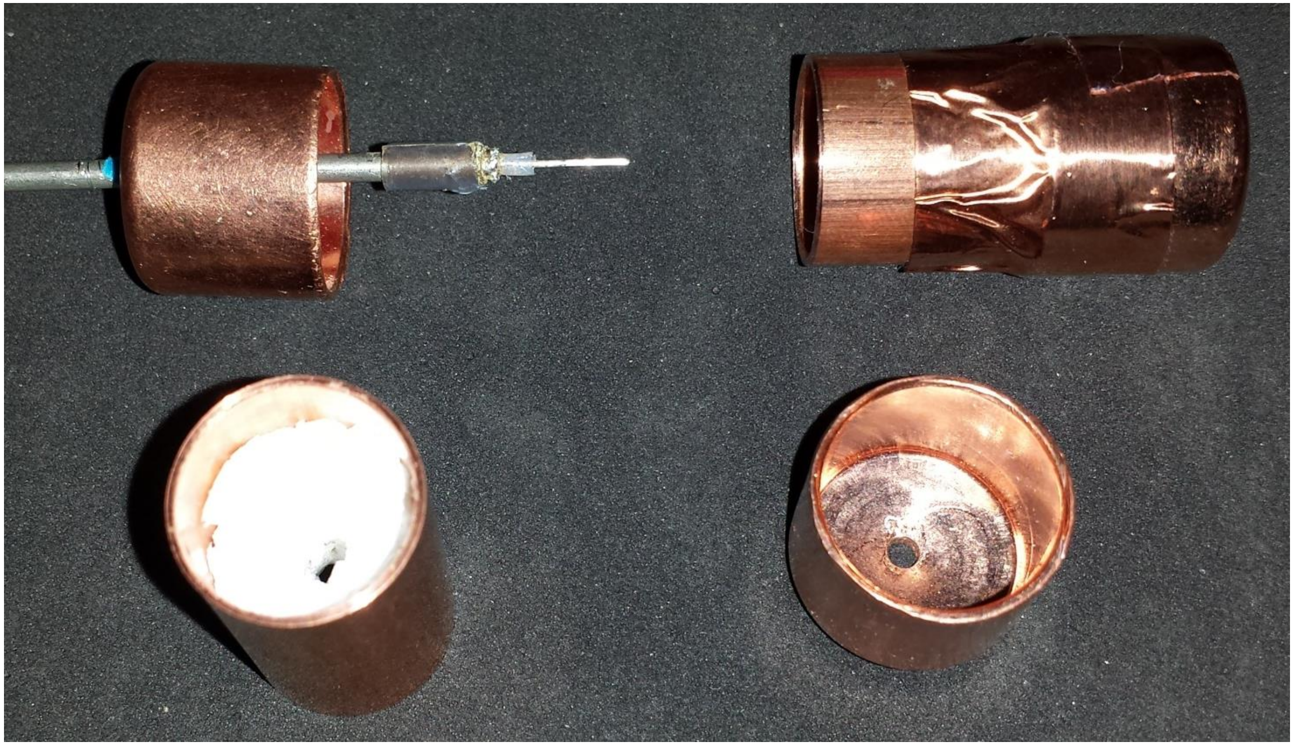
4. Our recent work (3d)

Key result: SLW antenna tuning via the skirt balun



4. Dynamic Range Estimate (3e)

Key result: SLW propagates through solid-copper Faraday enclosure

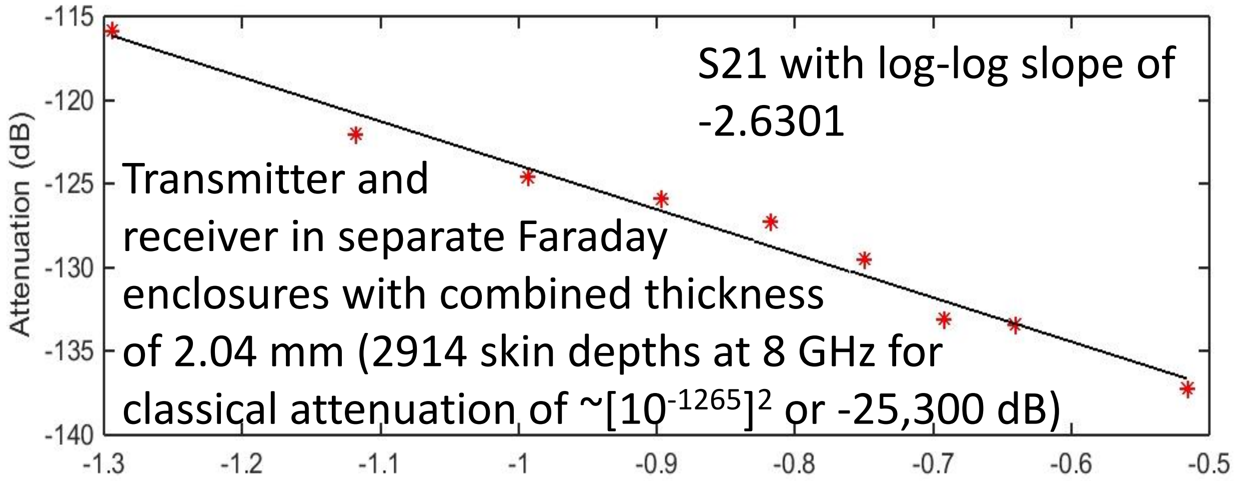


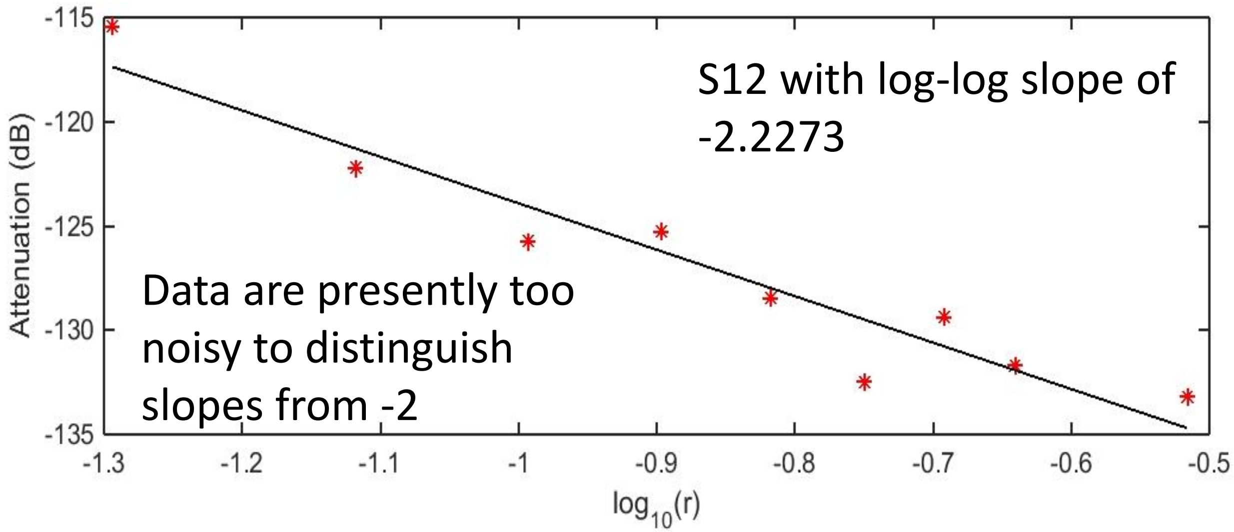
Tube dimensions: 1.02mm thick, 14.34mm ID, 15.85mm OD, 28.89mm long

Cap dimensions: 1.05mm thick, 15.80mm ID, 17.80mm OD

4. $1/r^2$ free-space propagation of SLW (3f)

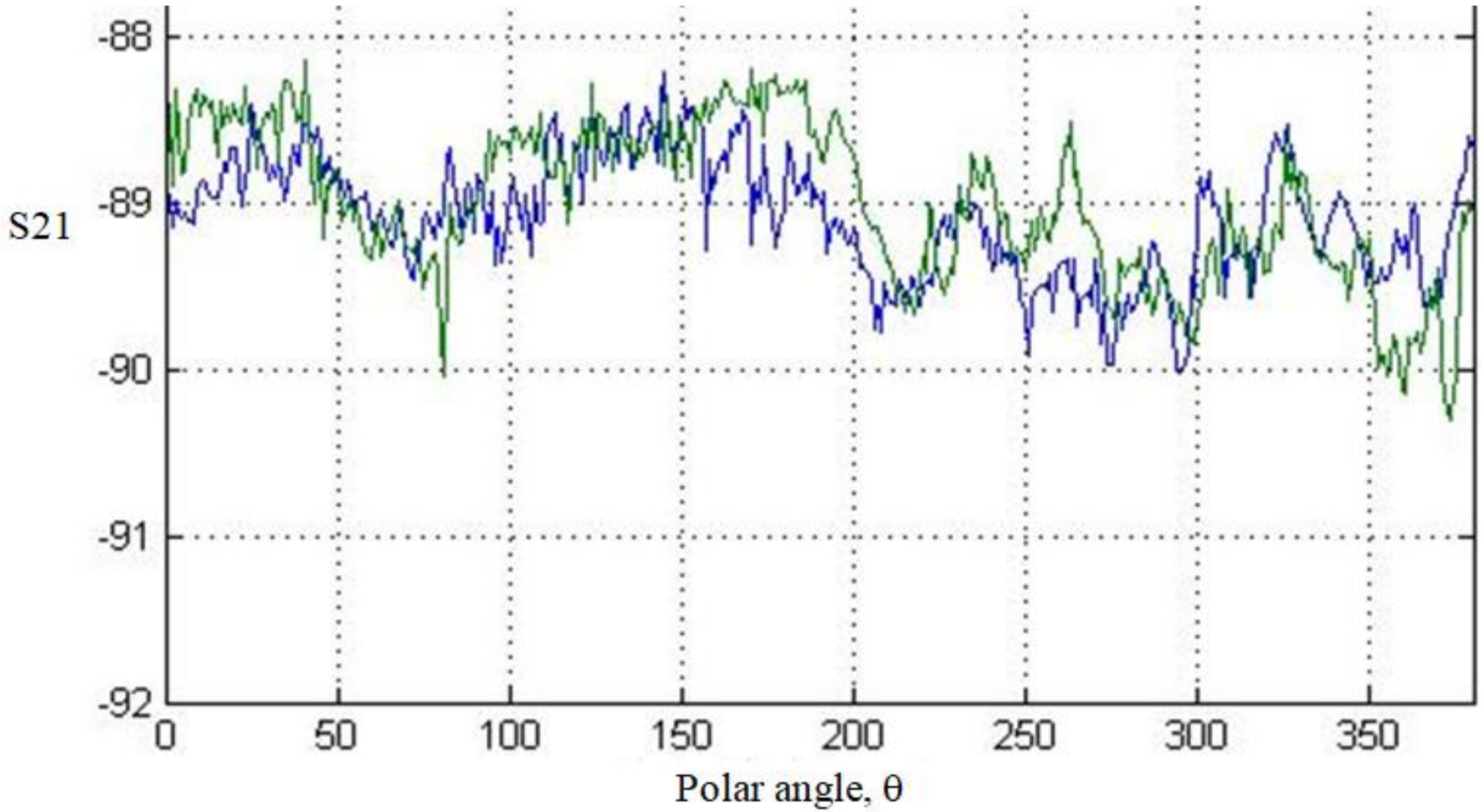
Key result: validation of no skin-depth constraint for SLW





4. Our recent work (3g)

Key result: validation of isotropic wave pattern for SLW antenna



4. Quantitative EED predictions (3h)

Item	Brief description of testable prediction	Reference
1	The interface matching condition for ρ_A is…	Eq. (12)
2	The interface matching condition for $\mathbf{J}_A$ is…	Eq. (14)
3	The SLW has a scalar field, $C = \nabla \bullet \mathbf{A} + \varepsilon\mu\partial\Phi / \partial t$.	Eq. (20)
4	The scalar field is also charge-fluctuation driven.	Eq. (25)
5	The interface matching condition for C is…	Eq. (26)
6	The SLW has drivers: $\mathbf{J}^{IR} = \nabla\kappa \Leftrightarrow \mathbf{A}^{IR} = \nabla\alpha \Leftrightarrow \mathbf{B} = 0$.	Eq. (36)*
7	The SLW has a longitudinal $\mathbf{E}$ – field.	Sec. VI
8	The SLW is unconstrained by the skin effect.	Sec. VI*
9	C is a pseudo-scalar field.	Sec. VI
10	The SLW has a power comparable to the TEM wave.	Eq. (37)*
11	The SLW free-space attenuation goes like $1/r^2$.	Eq. (38)*
12	The SLW monopole radiation is isotropic.	Eq. (38)*
13	The scalar wave arises from $\Phi = -\dot{\alpha}$ and…	Eq. (42)
14	The scalar-field energy density is $C^2 / 2\mu$.	Eq. (44)
15	The SLW power density vector is $C\mathbf{E} / \mu$.	Eq. (44)
16	Energy balance has a new source, $\rho C / \varepsilon\mu$.	Eq. (44)
17	The SLW momentum density is $-C\mathbf{E} / \mu$.	Eq. (45)
18	Momentum balance has a mixed-mode term, $\nabla \times \mathbf{B}C / \mu$.	Eq. (45)
19	Momentum balance also has source term, $\mathbf{J}C$.	Eq. (45)
20	The scalar-field pressure density is $\nabla C^2 / 2\mu$.	Eq. (45)

4. Our recent work (3i)—Summary

CED cannot explain these results

SLW predictions by EED are validated by these experiments…

- No constraint by skin effect in linearly conductive media
- Free-space attenuation is not inconsistent with $1/r^2$ ($r/\lambda \leq 16$)
- Isotropic radiation pattern from linear, monopole antenna
- Irrotational current as driver
- Power level comparable to TEM wave (standard instrumentation)

4. Our recent work (4)

Key results: Scalar field ($C \neq 0$) affects only irrotational dynamics
Dispersion relation for SLW related to Hubble constant and Ricci tensor
Scalar field related to irrotational-displacement field

PHYSICS ESSAYS **32**, 3 (2019)

Electrodynamics in curved space-time: Free-space longitudinal wave propagation

Ole Keller[1,a)] and Lee M. Hively[2,b)]
[1]*Aalborg University, Skjernvej 4, DK-9220 Aalborg Øst, Denmark*
[2]*4947 Ardley Drive, Colorado Springs, Colorado 80922, USA*

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Abstract: Jiménez and Maroto [Phys. Rev. D **83**, 023514 (2011)] predicted free-space, longitudinal electrodynamic waves in curved space-time, if the Lorenz condition is relaxed. A general-relativistic extension of Woodside's electrodynamics [Am. J. Phys. **77**, 438 (2009)] includes a dynamical, scalar field in both the potential- and electric/magnetic-field formulations without mixing the two. We formulate a longitudinal-wave theory, eliminating curvature polarization, magnetization density, and scalar field in favor of the electric/magnetic fields and the metric tensor. We obtain a wave equation for the longitudinal electric field for a spatially flat, expanding universe with a scale factor. This work is important, because: (i) the scalar- and longitudinal-fields do not cancel, as in classical quantum electrodynamics; and (ii) this new approach provides a first-principles path to an extended quantum theory that includes acceleration and gravity.
 [http://dx.doi.org/10.4006/0836-1398-32.3.282]

4. Our recent work (5)

Key results: Scale factor in Lagrangian formulation is irrelevant
SLW propagation is confined to the energy shell

Ohmura's extended electrodynamics: longitudinal aspects in general relativity

Ole Keller[1] **and Lee M Hively**[2]

[1] Institute of Physics, Aalborg University, Skjernvej 4, DK-9220 Aalborg Øst, Denmark
[2] Oak Ridge National Lab (retired), 4947 Ardley Drive, Colorado Springs, CO 80922, United States of America

E-mail: okeller@nano.aau.dk and lee.hively314@comcast.net.us

Keywords: field theory, electrodynamics, general relativity

Abstract

Jiménez and Maroto ((2011) *Phys. Rev.* D **83**, 023514) predicted that free-space, longitudinal electrodynamic waves can propagate in curved space-time, if the Lorenz condition is relaxed. The present work studies this possibility by combining and extending the original theory by Ohmura ((1956) *Prog. Theor. Phys.* **16**, 684) and Woodside's uniqueness theorem ((2009) *Am. J. Phys.* **77**, 438) to general relativity. Our formulation results in a theory that applies to both the field- (**E**, **B**) and potential- (Φ, **A**) domains. We establish a self-consistent, longitudinal wave-propagation theory for the microscopic longitudinal part of the electric field ($\mathbf{E}^L$). We first show that the product of the parameters used previously for the extension of classical electrodynamics can be expressed as a superposition of microscopic displacement modes, which are confined to the energy shell, $|\omega| = cq$. We then show that nonlinear electrodynamic mixing allows creation of longitudinal waves in the near-field region of a source. A propagator approach gives substantial physical insight into the emission process.

Journal of Physics Communications **3** (06Nov2019) paper# 115002

5. Future work (examples)

EED simulator (e.g., COMSOL multi-physics)
Compelling validation of scalar-longitudinal wave
Compelling validation of scalar wave
Measurement of speed of SLW and SW
Reverse engineer Russian coal-mine antenna
SLW as chemistry catalyst: $\mathbf{H}_{EED} = \left(\frac{\varepsilon \mathbf{E}^2}{2} + \frac{\mathbf{B}^2}{2\mu}\right) + (\rho - \varepsilon \nabla \bullet \mathbf{E})\Phi - \mathbf{J} \bullet \mathbf{A} + \frac{C^2}{2\mu} + \frac{C \nabla \bullet \mathbf{A}}{\mu}.$
New Hamiltonian terms: fast computing of NP-hard problems[1]
High-temperature superconductivity: phonon-$\mathbf{E}^{IR}$ coupling
Power extraction from SLW/SW stellar emissions
Communications/imaging via SLW/SW + TEM (bandwidth tripled)
Propellant-less propulsion

[1]D.S. Abrams and S. Lloyd, "Nonlinear Quantum Mechanics Implies Polynomial-Time Solution for NP-Complete and #P Problems," *Phys. Rev. Lett.* **81**, 3992 (1998)

6. Conclusions

1) **EED changes all of modern physics after 155 years**
2) EED is supported by $\mathbf{A}^{IR}$ and $\mathbf{J}^{IR}$ (slide 3)
3) EED is provably unique (slide 5)
4) EED eliminates incompleteness and inconsistency in CED
5) EED is gauge-free (slide 6)
6) CED is a sub-set of EED (slide 6): irrotational component
7) EED makes specific, quantifiable predictions (slide 22)
8) EED has many potential, novel applications (slide 26)

7. Questions?

Dr. Lee Hively
lee.hively314@comcast.net

Pre-Maxwell Equations

$$\nabla \cdot \mathbf{e} - \frac{1}{c_5}\frac{\partial \epsilon^0}{\partial \tau} = \frac{e}{c} j^0$$

$$\nabla \times \mathbf{e} + \frac{1}{c}\frac{\partial \mathbf{b}}{\partial t} = 0$$

$$\nabla \times \mathbf{b} - \frac{1}{c}\frac{\partial \mathbf{e}}{\partial t} - \frac{1}{c_5}\frac{\partial \boldsymbol{\epsilon}}{\partial \tau} = \frac{e}{c}\mathbf{j}$$

$$\nabla \cdot \mathbf{b} = 0$$

$\nabla \cdot$ [redacted]

$$\nabla \epsilon^0 + \frac{1}{c}\frac{\partial \boldsymbol{\epsilon}}{\partial t} + \sigma \frac{1}{c_5}\frac{\partial \mathbf{e}}{\partial \tau} = 0$$

EED and SHP

Stueckelberg-Horwitz-Piron formalism

External chronological parameter τ

Event in spacetime $x(\tau) = \big(ct(\tau), \mathbf{x}(\tau)\big)$

Five electromagnetic potentials

$$a(x,\tau) = a(t,\mathbf{x},\tau) = \left(a^0, \mathbf{a}, a^5\right)$$

Field strengths

$$\mathbf{e}(x,\tau) = -\frac{1}{c}\frac{\partial \mathbf{a}}{\partial t} - \nabla a^0 \qquad \mathbf{b}(x,\tau) = \nabla \times \mathbf{a}$$

$$\boldsymbol{\epsilon}(x,\tau) = \sigma \frac{1}{c_5}\frac{\partial \mathbf{a}}{\partial \tau} + \nabla a^5 \qquad \epsilon^0(x,\tau) = \sigma \frac{1}{c_5}\frac{\partial a^0}{\partial \tau} + \frac{1}{c}\frac{\partial a^5}{\partial t}$$

$$\frac{c_5}{c} < 1 \qquad \sigma = \pm 1$$

Gauge Condition

Gauge invariance of pre-Maxwell equations

$$a^0(x,\tau) \to a^0(x,\tau) - \frac{1}{c}\frac{\partial}{\partial t}\Lambda(x,\tau)$$

$$\mathbf{a}(x,\tau) \to \mathbf{a}(x,\tau) + \nabla\Lambda(x,\tau)$$

$$a^5(x,\tau) \to a^5(x,\tau) + \sigma\frac{1}{c_5}\frac{\partial}{\partial \tau}\Lambda(x,\tau)$$

SHP Lorenz condition

$$\frac{1}{c}\frac{\partial a^0}{\partial t} + \nabla\cdot\mathbf{a} + \frac{1}{c_5}\frac{\partial a^5}{\partial \tau} = 0$$

Correspondence with EED

Define $C = \frac{1}{c}\frac{\partial a^0(x,\tau)}{\partial t} + \nabla \cdot \mathbf{a}(x,\tau)$

Lorenz condition $\Rightarrow C = -\frac{1}{c_5}\frac{\partial a^5(x,\tau)}{\partial \tau}$

Write τ-independent 4-vector potential

$$a^0(x,\tau) = A^0(x) \qquad \mathbf{a}(x,\tau) = \mathbf{A}(x)$$

pre-Maxwell $\mathbf{e}$ and $\mathbf{b}$ fields behave like Maxwell $\mathbf{E}$ and $\mathbf{B}$ fields

$$\mathbf{e}(x,\tau) = -\frac{1}{c}\frac{\partial \mathbf{a}(x,\tau)}{\partial t} - \nabla a^0(x,\tau) = -\frac{1}{c}\frac{\partial}{\partial t}\mathbf{A}(x) - \nabla \Phi(x) = \mathbf{E}(x)$$

$$\mathbf{b}(x,\tau) = \nabla \times \mathbf{a}(x,\tau) = \nabla \times \mathbf{A}(x) = \mathbf{B}(x)$$

ϵ Fields for τ-Independent $\mathbf{E}$ and $\mathbf{B}$

$$\epsilon^0 = \sigma \frac{1}{c_5}\frac{\partial \Phi}{\partial \tau} + \frac{1}{c}\frac{\partial a^5}{\partial t} \rightarrow \frac{1}{c}\frac{\partial a^5}{\partial t}$$

$$\frac{1}{c_5}\frac{\partial \epsilon^0}{\partial \tau} = \frac{1}{c_5}\frac{\partial}{\partial \tau}\frac{1}{c}\frac{\partial a^5}{\partial t} = \frac{1}{c}\frac{\partial}{\partial t}\left(\frac{1}{c_5}\frac{\partial a^5}{\partial \tau}\right) = -\frac{1}{c}\frac{\partial C}{\partial t}$$

$$\boldsymbol{\epsilon} = \sigma \frac{1}{c_5}\frac{\partial \mathbf{a}}{\partial \tau} - \nabla a^5 \rightarrow -\nabla a^5$$

$$\frac{1}{c_5}\frac{\partial \boldsymbol{\epsilon}}{\partial \tau} = -\frac{1}{c_5}\frac{\partial}{\partial \tau}\nabla a^5 = -\nabla\left(\frac{1}{c_5}\frac{\partial a^5}{\partial \tau}\right) = \nabla C$$

pre-Maxwell for τ-Independent $\mathbf{E}$ and $\mathbf{B}$

Homogeneous equations

$$\nabla \times \mathbf{e} + \frac{1}{c}\frac{\partial \mathbf{b}}{\partial t} = 0 \quad \rightarrow \quad \nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \cdot \mathbf{b} = 0 \quad \rightarrow \quad \nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \boldsymbol{\epsilon} - \sigma \frac{1}{c_5}\frac{\partial \mathbf{b}}{\partial \tau} = 0 \quad \rightarrow \quad -\nabla \times \nabla a^5 \equiv 0$$

$$\nabla \epsilon^0 + \frac{1}{c}\frac{\partial \boldsymbol{\epsilon}}{\partial t} + \sigma \frac{1}{c_5}\frac{\partial \mathbf{e}}{\partial \tau} = 0 \quad \rightarrow \quad \nabla\left(\frac{1}{c}\frac{\partial a^5}{\partial t}\right) + \frac{1}{c}\frac{\partial}{\partial t}\left(-\nabla a^5\right) \equiv 0$$

pre-Maxwell for τ-Independent $\mathbf{E}$ and $\mathbf{B}$

Inhomogeneous equations

$$\nabla \cdot \mathbf{e} - \frac{1}{c_5}\frac{\partial \epsilon^0}{\partial \tau} = \frac{e}{c} j^0 \qquad \rightarrow \qquad \nabla \cdot \mathbf{E} + \frac{1}{c}\frac{\partial C}{\partial t} = \frac{e}{c} j^0$$

$$\nabla \times \mathbf{b} - \frac{1}{c}\frac{\partial \mathbf{e}}{\partial t} - \frac{1}{c_5}\frac{\partial \boldsymbol{\epsilon}}{\partial \tau} = \frac{e}{c}\mathbf{j} \qquad \rightarrow \qquad \nabla \times \mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} - \frac{1}{c}\nabla C = \frac{e}{c}\mathbf{j}$$

$$\nabla \cdot \boldsymbol{\epsilon} + \frac{1}{c}\frac{\partial \epsilon^0}{\partial t} = \frac{e}{c} j^5 \qquad \rightarrow \qquad -\nabla^2 a^5 + \frac{1}{c^2}\frac{\partial^2 a^5}{\partial t^2} = \frac{e}{c} j^5$$

Solve wave equation for a^5

Find

$$C = -\frac{1}{c_5}\frac{\partial a^5(x,\tau)}{\partial \tau}$$

8. Back-up slides follow

1. Maxwell's Equations

https://en.wikipedia.org/wiki/A_Dynamical_Theory_of_the_Electromagnetic_Field
(20 scalar equations in 20 unknowns, excluding Faraday's law)

Vector calculus form (SI units):
https://en.wikipedia.org/wiki/Maxwell%27s_equations

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega} \rho \,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot \mathrm{d}\boldsymbol{l} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma} \mathbf{B}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{l} = \mu_0\left(\iint_{\Sigma} \mathbf{J}\cdot \mathrm{d}\mathbf{S} + \varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma} \mathbf{E}\cdot \mathrm{d}\mathbf{S}\right)$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

1. What's wrong with CED?-- Incomplete

$\nabla \bullet \mathbf{B} = 0$ (1) (physics: no magnetic monopoles)

$\nabla \bullet \nabla \times \mathbf{A} = 0$ (2) (mathematical identity)

$\nabla \bullet (\mathbf{B} - \nabla \times \mathbf{A}) = 0$ (3) (subtract Eq. 2 from Eq. 1)

$\mathbf{B} = \nabla \times \mathbf{A}$ (4) (solution to Eq. 3)

$\nabla \times \nabla \Lambda = 0$ (5) (mathematical identity, Λ = gauge function)

$\mathbf{B} = \nabla \times (\mathbf{A} + \nabla \Lambda)$ (6) (add Eq. 5 to Eq. 4)

$\mathbf{A} \rightarrow \mathbf{A} + \nabla \Lambda$ (7) (**B** invariant under this transformation)

1. What's wrong with CED?-- Incomplete

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$\nabla \times \nabla \Lambda = 0$ (5) (mathematical identity, $\Lambda =$ gauge function)

$\mathbf{B} = \nabla \times (\mathbf{A} + \nabla \Lambda)$ (6) (add Eq. 5 to Eq. 4)

$\mathbf{A} \rightarrow \mathbf{A} + \nabla \Lambda$ (7) ($\mathbf{B}$ invariant under this transformation)

$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$ (8) (physics: Faraday's law)

$\nabla \times \left(\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t} + \nabla \Phi \right) = 0$ (9) (substitution from Eq. 6 with $\Phi = \frac{\partial \Lambda}{\partial t}$)

$\mathbf{E} = -\nabla \Phi - \frac{\partial \mathbf{A}}{\partial t}$ (10) (solution to Eq. 9)

$\Phi \rightarrow \Phi - \frac{\partial \Lambda}{\partial t}$ (11) ($\mathbf{E}$ invariant with substitution from Eq. 7)

1. What's wrong with CED?-- Incomplete

$\mathbf{A} \rightarrow \mathbf{A} + \nabla\Lambda$ (7) **Infinitude of choices for Λ**

$\Phi \rightarrow \Phi - \frac{\partial \Lambda}{\partial t}$ (11) **Gauge condition: same as changing Maxwell's Eqs.**

To explain this incompleteness,
Go back to Faraday's law:

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \quad (8) \quad \text{(Faraday's law)}$$

$$\nabla \bullet \left(\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \right) \quad (12) \quad \text{(divegence of Faraday's law)}$$

$$\nabla \bullet \nabla \times \mathbf{E} = -\frac{\partial}{\partial t} \nabla \bullet \mathbf{B} \quad (13) \quad \text{(mathematical identity: } \nabla \bullet \nabla \times \mathbf{E} = 0\text{)}$$

$$\nabla \bullet \mathbf{B} = f(\mathbf{r}) = 0 \quad (1) \quad \text{(physically meaningful solution: RHS=0)}$$

- **Eq. (1) is derivable from Eq. (8)**

1. What's wrong with CED?– Over-Determined

$\nabla \bullet \mathbf{B} = 0$ (1) (one scalar equation, derivable from Eq. 8)

$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$ (8) (one 3D vector Eq. or 3 scalar Eqs.)

$\nabla \bullet \mathbf{E} = \frac{\rho}{\varepsilon}$ (14) (one scalar equation)

$\nabla \times \mathbf{B} - \varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} = \mu\mathbf{J}$ (15) (one 3D vector Eq. or 3 scalar Eqs.)

- Total scalar equations = 8
- Total unknowns = 3 scalar components each of $\mathbf{E}$ and $\mathbf{B}$ = 6
- ρ and $\mathbf{J}$ as source terms

- **Over-determined system of 7 equations and 6 unknowns, since Eq. (1) is derivable from Eq. (8)**
- **Gauge condition (e.g., Lorenz gauge) does NOT complete MEs**

1. What's wrong with CED?– Over-Determined

- J.A. Stratton, Electromagnetic Theory, McGraw-Hill publ. (1941): divergence-curl redundancy resolved by *assuming* charge conservation (page 6).
- E.M. Sousa and U. Shumlak, *J. Comp. Phys.* 326, 56 (2016): "Maxwell's equations are over-determined with six scalar unknowns and eight equations." (page 59, two lines below Eq. 9).
- C.-D. Munz *et* al., C.R. Acad. Sci. Paris 328, 431 (1999): "Maxwell's equations are overdetermined…" (page 431, first line of abstract).

1. What's wrong with CED?--Inconsistent

$$\nabla \bullet \mathbf{E} = \frac{\rho}{\varepsilon} \qquad (14)$$

Corresponding interface matching condition is:

$$\varepsilon_2 \mathbf{E}_{2n} - \varepsilon_1 \mathbf{E}_{1n} = \varepsilon_2 \left(-\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} \right)_{2n} - \varepsilon_1 \left(-\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} \right)_{1n} = \rho_A \qquad (16)$$

Counterpart equation for scalar potential is:

$$\frac{\partial^2 \Phi}{\partial c^2 t^2} - \nabla^2 \Phi = \frac{\rho}{\varepsilon} \qquad (17)$$

Corresponding interface matching condition is:

$$-\left(\varepsilon \nabla \Phi\right)_{2n} + \left(\varepsilon \nabla \Phi\right)_{1n} = \rho_A \qquad (18)$$

Eq. (16) has additional terms $-\varepsilon_2 \left(\frac{\partial \mathbf{A}}{\partial t} \right)_{2n} + \varepsilon_1 \left(\frac{\partial \mathbf{A}}{\partial t} \right)_{1n}$ not in (18)

Inconsistency does not arise from use of potentials (gauge invariant)

1. What's wrong with CED?--Inconsistent

Classical derivation from Gauss' law (first Eqn. on slide 34):

$$\int dV\left(\varepsilon\nabla\bullet\mathbf{E}=\rho\right)\Rightarrow\int\varepsilon\mathbf{E}\bullet d\mathbf{S}=\int\rho_{\mathrm{A}}dS\Rightarrow\varepsilon_2\mathbf{E}_{n2}-\varepsilon_1\mathbf{E}_{n1}=\rho_{\mathrm{A}}$$

Derivation from MCE version of Gauss' law:

$$\varepsilon\left(\nabla\bullet\mathbf{E}+\frac{\partial C}{\partial t}\right)=\varepsilon\left(-\nabla\bullet\nabla\Phi-\nabla\bullet\frac{\partial\mathbf{A}}{\partial t}+\frac{\partial\nabla\bullet\mathbf{A}}{\partial t}+\varepsilon\mu\frac{\partial^2\Phi}{\partial t^2}\right)=\rho$$

Now apply the Divergence Theorem, as before:

$$\int dV\varepsilon\left(-\nabla\bullet\nabla\Phi+\varepsilon\mu\frac{\partial^2\Phi}{\partial t^2}=\rho\right)\Rightarrow\int-\varepsilon\nabla\Phi\bullet d\mathbf{S}=\int\rho_{\mathrm{A}}dS\Rightarrow$$

$$-\varepsilon_2\nabla\Phi_{n2}+\varepsilon_1\nabla\Phi_{n1}=\rho_{\mathrm{A}}$$

Last equation is consistent with MCE version of Gauss' law and with wave equation for Φ (2nd Eqn. on slide 51)

1. What's wrong with CED?--Inconsistent

Classical derivation from Ampere's law:

$$\int \frac{d\,\mathbf{S}}{\mu} \bullet \left(\nabla \times \mathbf{B} - \varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} = \mathbf{J} \right) \Rightarrow \int \frac{\mathbf{B}}{\mu} \bullet d\,\mathbf{l} = \int \mathbf{J}_{\mathrm{A}} \bullet d\,\mathbf{S} \Rightarrow -\left(\frac{\mathbf{B}}{\mu} \right)_{2t} + \left(\frac{\mathbf{B}}{\mu} \right)_{1t} = \mathbf{J}_{\mathrm{A}}$$

Derivation from **A**-wave equation:

$$\int dV \left[\varepsilon\mu \frac{\partial^2 \mathbf{A}}{\partial t^2} - (\nabla \bullet \nabla)\mathbf{A} = \mu \mathbf{J} \right] \Rightarrow \int \left(\frac{d\mathbf{S}}{\mu} \bullet \nabla \right) \mathbf{A} = \int d\mathbf{S} \bullet \mathbf{J}$$

$$\Rightarrow -\left[\frac{\left(n \bullet \nabla \right) \mathbf{A}}{\mu} \right]_2 + \left[\frac{\left(n \bullet \nabla \right) \mathbf{A}}{\mu} \right]_1 = \mathbf{J}_{\mathbf{A}}$$

Last equation is consistent with EED version of Ampere's law and with **A**-wave equation

1. What's wrong with CED?--Summary

1. Gauge invariance: 4-gradient in 4-potential **gauged away**
   Contrary to experiments and to Helmholtz Theorem
2. Divergence-curl redundancy: 7 equations in 6 unknowns
3. Inconsistency in interface matching condition for ρ
4. Inconsistency in interface matching condition for **J**
5. Green's function evaluation of Lorenz gauge: **non-zero**
   EED is then **gauge-free**
6. No explicit term(s) in CED for irrotational current

1. CED versus EED

Energy-potential mountain

CED: only circulating (solenoidal) current with return path

EED: solenoidal + irrotational (non-circulating) current

1. What's new in EED?

Energy-potential mountain as before

CED: circulating (solenoidal) current only

EED: solenoidal + irrotational (non-circulating) current

CED is a special case of EED with additional predictions

3. Previous work by Woodside (vital contribution)

Helmholtz Theorem: decompose 3D vector field, W:

$$\mathbf{W} = -\nabla\Lambda + \nabla\times\mathbf{V}$$

← solenoidal

↖ irrotational

Woodside[1] proved generalization in 3D+time (4D):

$$\mathbf{W} = \text{(four-irrotational term)} + \text{(four-solenoidal term)}$$

Woodside[2] proved only 2 physical solutions:

One corresponds to Lorenz gauge, $\partial_\mu A^\mu = 0$ (classical ED)

Second has zero four-curl of A^μ: $\partial^\mu A^\nu - \partial^\nu A^\mu = 0$ (new)

Woodside[3] derived the Maxwell-Woodside equations (slide 5)

This derivation assumes only Minkowski 4-space

[1] D.A. Woodside, *J. Math. Phys.* 40, 4911-4943 (1999)

[2] D.A. Woodside, *J. Math. Phys.* 41, 4622-4653 (2000)

[3] D.A. Woodside, *Am. J. Phys.* 77, 438-446 (2009)

1. Extended Electrodynamics (EED)

Begin theory with modified Stueckelberg Lagrangian (1938):

$$\mathcal{L} = \frac{\varepsilon c^2}{2}\left[\frac{1}{c^2}\left(\nabla\Phi + \frac{\partial \mathbf{A}}{\partial t}\right)^2 - \left(\nabla \times \mathbf{A}\right)^2\right] - \rho\,\Phi + \mathbf{J}\bullet\mathbf{A} - \frac{\varepsilon c^2}{2}\left(\nabla\bullet\mathbf{A} + \frac{1}{c^2}\frac{\partial\Phi}{\partial t}\right)^2$$

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t};$$

$$\mathbf{B} = \nabla \times \mathbf{A};$$

$$C = \nabla\bullet\mathbf{A} + \frac{1}{c^2}\frac{\partial\Phi}{\partial t};$$

$$\nabla \times \mathbf{B} - \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} - \nabla C = \mu\mathbf{J};$$

$$\nabla\bullet\mathbf{E} + \frac{\partial C}{\partial t} = \frac{\rho}{\varepsilon}.$$

ε= permittivity, μ=permeability (homogeneous, not vacuum)

Reference: D.A. Woodside, *Am. J. Phys.* 77, 438-446 (2009)

EED is provably unique

Wave Equation for $\mathbf{A}$

$$C = \nabla \bullet \mathbf{A} + \varepsilon\mu \frac{\partial \Phi}{\partial t}$$

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\nabla \times \mathbf{B} - \varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} - \nabla C = \mu \mathbf{J}$$

Substitute first three equations into Ampere's law:

$$\nabla \times \nabla \times \mathbf{A} - \varepsilon\mu \frac{\partial}{\partial t}\left(-\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} \right) - \nabla\left(\nabla \bullet \mathbf{A} + \varepsilon\mu \frac{\partial \Phi}{\partial t} \right) = \mu \mathbf{J}$$

$$\nabla\nabla \bullet \mathbf{A} - \nabla^2 \mathbf{A} + \varepsilon\mu \frac{\partial^2 \mathbf{A}}{\partial t^2} - \nabla\nabla \bullet \mathbf{A} = \mu \mathbf{J}$$

$$\Box^2 \mathbf{A} = \mu \mathbf{J}$$

Wave Equation for $\mathbf{B}$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \times \left(\nabla \times \mathbf{B} - \varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} - \nabla C = \mu \mathbf{J} \right)$$

$$\nabla \times \nabla \times \mathbf{B} - \varepsilon\mu \frac{\partial \nabla \times \mathbf{E}}{\partial t} - \nabla \times \nabla C = \mu \nabla \times \mathbf{J}$$

$$\nabla \nabla \bullet \mathbf{B} - \nabla^2 \mathbf{B} - \varepsilon\mu \frac{\partial}{\partial t} \left(-\frac{\partial \mathbf{B}}{\partial t} \right) = \mu \nabla \times \mathbf{J}$$

$$\square^2 \mathbf{B} = \mu \nabla \times \mathbf{J}$$

Wave Equation for C

$$\varepsilon\mu \frac{\partial}{\partial t}\left(\nabla \bullet \mathbf{E} + \frac{\partial C}{\partial t} = \frac{\rho}{\varepsilon} \right) \Rightarrow \varepsilon\mu \nabla \bullet \frac{\partial \mathbf{E}}{\partial t} + \varepsilon\mu \frac{\partial^2 C}{\partial t^2} = \mu \frac{\partial \rho}{\partial t}$$

$$\nabla \bullet \left(\nabla \times \mathbf{B} - \varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} - \nabla C = \mu \mathbf{J} \right) \Rightarrow -\varepsilon\mu \nabla \bullet \frac{\partial \mathbf{E}}{\partial t} - \nabla \bullet \nabla C = \mu \nabla \bullet \mathbf{J}$$

Sum last two equations: $\varepsilon\mu \frac{\partial^2 C}{\partial t^2} - \nabla^2 C = \mu \frac{\partial \rho}{\partial t} + \mu \nabla \bullet \mathbf{J}$

$$\Box^2 C = \mu \left(\frac{\partial \rho}{\partial t} + \nabla \bullet \mathbf{J} \right)$$

Wave Equation for $\mathbf{E}$

$$\nabla \bullet \mathbf{E} + \frac{\partial C}{\partial t} = \frac{\rho}{\varepsilon} \Rightarrow \nabla \bullet \mathbf{E} = -\frac{\partial C}{\partial t} + \frac{\rho}{\varepsilon}$$

$$\nabla \times \mathbf{B} - \varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} - \nabla C = \mu \mathbf{J} \Rightarrow \nabla \times \mathbf{B} = \varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} + \nabla C + \mu \mathbf{J}$$

$$\nabla \times \left(\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} \right) = 0$$

$$\nabla \nabla \bullet \mathbf{E} - \nabla^2 \mathbf{E} + \frac{\partial \nabla \times \mathbf{B}}{\partial t} = 0$$

$$\nabla \left(-\frac{\partial C}{\partial t} + \frac{\rho}{\varepsilon} \right) - \nabla^2 \mathbf{E} + \frac{\partial}{\partial t} \left(\varepsilon\mu \frac{\partial \mathbf{E}}{\partial t} + \nabla C + \mu \mathbf{J} \right) = 0$$

$$\square^2 \mathbf{E} = -\frac{\nabla \rho}{\varepsilon} - \mu \frac{\partial \mathbf{J}}{\partial t}$$

Wave Equation for Φ

$$C = \nabla \bullet \mathbf{A} + \varepsilon\mu \frac{\partial \Phi}{\partial t}$$

$$\mathbf{E} = -\nabla \Phi - \frac{\partial \mathbf{A}}{\partial t}$$

$$\nabla \bullet \mathbf{E} + \frac{\partial C}{\partial t} = \frac{\rho}{\varepsilon}$$

$$\nabla \bullet \left(-\nabla \Phi - \frac{\partial \mathbf{A}}{\partial t} \right) + \frac{\partial}{\partial t} \left(\nabla \bullet \mathbf{A} + \varepsilon\mu \frac{\partial \Phi}{\partial t} \right) = \frac{\rho}{\varepsilon}$$

$$-\nabla^2 \Phi + \varepsilon\mu \frac{\partial^2 \Phi}{\partial t^2} = \frac{\rho}{\varepsilon}$$

$$\Box^2 \Phi = \frac{\rho}{\varepsilon}$$

Momentum Balance

$$\frac{\mathbf{B}}{\mu}\left(\nabla\bullet\mathbf{B}=0\right)\Rightarrow 0=\frac{\mathbf{B}\nabla\bullet\mathbf{B}}{\mu}$$

$$\varepsilon\mathbf{E}\times\left(\nabla\times\mathbf{E}+\frac{\partial\mathbf{B}}{\partial t}=0\right)\Rightarrow\varepsilon\mathbf{E}\times\frac{\partial\mathbf{B}}{\partial t}=-\varepsilon\mathbf{E}\times\left(\nabla\times\mathbf{E}\right)$$

$$\left(\nabla\times\mathbf{B}-\varepsilon\mu\frac{\partial\mathbf{E}}{\partial t}-\nabla C=\mu\mathbf{J}\right)\times\left(-\frac{\mathbf{B}}{\mu}\right)\Rightarrow\varepsilon\frac{\partial\mathbf{E}}{\partial t}\times\mathbf{B}+\frac{\left(\nabla C\right)\times\mathbf{B}}{\mu}+\mathbf{J}\times\mathbf{B}=-\frac{\mathbf{B}\times\left(\nabla\times\mathbf{B}\right)}{\mu}$$

$$\frac{C}{\mu}\left(\nabla\times\mathbf{B}-\varepsilon\mu\frac{\partial\mathbf{E}}{\partial t}-\nabla C=\mu\mathbf{J}\right)\Rightarrow-\varepsilon C\frac{\partial\mathbf{E}}{\partial t}+\frac{C\nabla\times\mathbf{B}}{\mu}=\mathbf{J}C+\frac{\nabla C^2}{2\mu}$$

$$-\varepsilon\mathbf{E}\left(\nabla\bullet\mathbf{E}+\frac{\partial C}{\partial t}=\frac{\rho}{\varepsilon}\right)\Rightarrow-\varepsilon\mathbf{E}\frac{\partial C}{\partial t}+\rho\mathbf{E}=\varepsilon\mathbf{E}\nabla\bullet\mathbf{E}$$

$$\text{Sum: }\varepsilon\mu\frac{\partial}{\partial t}\left(\frac{\mathbf{E}\times\mathbf{B}}{\mu}-\frac{C\mathbf{E}}{\mu}\right)+\rho\mathbf{E}+\frac{C\nabla\times\mathbf{B}}{\mu}+\left(\frac{\nabla C}{\mu}+\mathbf{J}\right)\times\mathbf{B}=\mathbf{J}C+\frac{\nabla C^2}{2\mu}+\nabla\bullet\overleftrightarrow{\mathbf{T}}$$

Momentum Balance: $\overleftrightarrow{\mathrm{T}}$

$$\nabla\left(\mathbf{F}\bullet\mathbf{G}\right)=\mathbf{F}\times\left(\nabla\times\mathbf{G}\right)+\mathbf{G}\times\left(\nabla\times\mathbf{F}\right)+\left(\mathbf{F}\bullet\nabla\right)\mathbf{G}+\left(\mathbf{G}\bullet\nabla\right)\mathbf{F}$$

$$\Rightarrow\nabla\mathbf{F}^2=2\mathbf{F}\times\left(\nabla\times\mathbf{F}\right)+2\left(\mathbf{F}\bullet\nabla\right)\mathbf{F}\Rightarrow-\mathbf{F}\times\left(\nabla\times\mathbf{F}\right)=\left(\mathbf{F}\bullet\nabla\right)\mathbf{F}-\frac{\nabla \mathrm{F}^2}{2}$$

$$\Rightarrow\mathrm{RHS}=\frac{\mathbf{B}\nabla\bullet\mathbf{B}}{\mu}-\frac{\mathbf{B}\times\left(\nabla\times\mathbf{B}\right)}{\mu}+\varepsilon\mathbf{E}\nabla\bullet\mathbf{E}-\varepsilon\mathbf{E}\times\left(\nabla\times\mathbf{E}\right)+\frac{\nabla C^2}{2\mu}$$

$$\Rightarrow\mathrm{RHS}=\frac{1}{\mu}\left[\mathbf{B}\nabla\bullet\mathbf{B}+\left(\mathbf{B}\bullet\nabla\right)\mathbf{B}-\frac{\nabla \mathrm{B}^2}{2}\right]+\varepsilon\left[\mathbf{E}\nabla\bullet\mathbf{E}+\left(\mathbf{E}\bullet\nabla\right)\mathbf{E}-\frac{\nabla \mathrm{E}^2}{2}\right]+\frac{\nabla C^2}{2\mu}$$

$$\Rightarrow\mathrm{RHS}=\nabla\bullet\left[\frac{\mathbf{BB}-\overleftrightarrow{\mathbf{I}}\mathrm{B}^2/2}{\mu}+\varepsilon\left(\mathbf{EE}-\overleftrightarrow{\mathbf{I}}\mathrm{E}^2/2\right)+\frac{\overleftrightarrow{\mathbf{I}}C^2}{2\mu}\right]\equiv\nabla\bullet\overleftrightarrow{\mathbf{T}}$$

$$\Rightarrow\overleftrightarrow{\mathbf{T}}\equiv\frac{\mathbf{BB}-\overleftrightarrow{\mathbf{I}}\mathrm{B}^2/2}{\mu}+\varepsilon\left(\mathbf{EE}-\overleftrightarrow{\mathbf{I}}\mathrm{E}^2/2\right)+\frac{\overleftrightarrow{\mathbf{I}}C^2}{2\mu}$$

Energy Balance

$$\frac{C}{\mu}\left(\nabla\bullet\mathbf{E}+\frac{\partial C}{\partial t}=\frac{\rho}{\varepsilon}\right)\Rightarrow\frac{1}{2\mu}\frac{\partial C^2}{\partial t}+\frac{C\nabla\bullet\mathbf{E}}{\mu}=\frac{\rho C}{\varepsilon\mu}$$

$$\frac{\mathbf{B}}{\mu}\bullet\left(\nabla\times\mathbf{E}+\frac{\partial\mathbf{B}}{\partial t}=0\right)\Rightarrow\frac{1}{2\mu}\frac{\partial \mathrm{B}^2}{\partial t}+\frac{\mathbf{B}\bullet\nabla\times\mathbf{E}}{\mu}=0$$

$$-\frac{\mathbf{E}}{\mu}\bullet\left(\nabla\times\mathbf{B}-\varepsilon\mu\frac{\partial\mathbf{E}}{\partial t}-\nabla C=\mu\mathbf{J}\right)\Rightarrow\varepsilon\frac{\partial \mathrm{E}^2}{\partial t}-\frac{\mathbf{E}\bullet\nabla\times\mathbf{B}}{\mu}+\frac{\mathbf{E}\bullet\nabla C}{\mu}+\mathbf{J}\bullet\mathbf{E}=0$$

$$\text{Sum: }\frac{\partial}{\partial t}\left(\frac{\mathrm{B}^2}{2\mu}+\frac{C^2}{2\mu}+\varepsilon\mathrm{E}^2\right)+\nabla\bullet\left(\frac{\mathbf{E}\times\mathbf{B}}{\mu}+\frac{C\mathbf{E}}{\mu}\right)+\mathbf{J}\bullet\mathbf{E}=\frac{\rho C}{\varepsilon\mu}$$

Relativistic Covariance

$$\partial_\nu = \left(\partial / \partial ct, \nabla\right); \partial^\nu = \left(\partial / \partial ct, -\nabla\right); A^\eta = (\Phi / c, \mathbf{A}); J^\eta = (\rho c, \mathbf{J})$$

$$C = \partial_\nu A^\nu = \varepsilon\mu \partial\Phi / \partial t + \nabla \bullet \mathbf{A}$$

Scalar wave equation for Φ: $\square^2 \Phi = \rho / \varepsilon$

3-vector wave equation for **A**: $\square^2 \mathbf{A} = \mu \mathbf{J}$

4-vector wave equation for A^η: $\partial_\nu \partial^\nu A^\eta = \square^2 A^\eta = \mu J^\eta$

$$\nabla \bullet \nabla \times \mathbf{B} = 0 = \nabla \bullet (\nabla \times \nabla \times \mathbf{A}) = \nabla \bullet (\nabla\nabla \bullet \mathbf{A} - \nabla^2 \mathbf{A})$$

$$\nabla \bullet \nabla^2 \mathbf{A} = \nabla^2 \nabla \bullet \mathbf{A}$$

$$\partial_\eta \partial_\nu \partial^\nu A^\eta = \partial_\nu \partial^\nu \partial_\eta A^\eta = \partial_\nu \partial^\nu C = \mu \partial_\eta J^\eta$$

Wave equation for C comes from 4-vector wave equation for A^η

4-vector relativistic covariance.

SLW Attenuation in Conductive Media

$$\mathbf{B}=0 \Rightarrow \Box^2\mathbf{B}=\mu\nabla\times\mathbf{J}=0 \Rightarrow \nabla\times\nabla\times\mathbf{J}=0=\nabla(\nabla\bullet\mathbf{J})-\nabla^2\mathbf{J}=0 \Rightarrow \nabla(\nabla\bullet\mathbf{J})=\nabla^2\mathbf{J}$$

$$\nabla\left(\frac{\partial\rho}{\partial t}+\nabla\bullet\mathbf{J}=0\right) \Rightarrow \nabla\dot{\rho}=-\nabla(\nabla\bullet\mathbf{J})=-\nabla^2\mathbf{J}$$

$$\frac{\partial}{\partial t}\left(\Box^2\mathbf{E}=-\mu\frac{\partial\mathbf{J}}{\partial t}-\frac{\nabla\rho}{\varepsilon}\right) \Rightarrow \Box^2\dot{\mathbf{E}}=-\mu\frac{\partial^2\mathbf{J}}{\partial t^2}-\frac{\nabla\dot{\rho}}{\varepsilon}=-\mu\frac{\partial^2\mathbf{J}}{\partial t^2}+\frac{\nabla^2\mathbf{J}}{\varepsilon}=-\frac{\Box^2\mathbf{J}}{\varepsilon}$$

$$\mathbf{J}=\sigma\mathbf{E} \Rightarrow \Box^2\left(\dot{\mathbf{E}}+\frac{\mathbf{J}}{\varepsilon}\right)=\Box^2\left(\dot{\mathbf{E}}+\frac{\sigma\mathbf{E}}{\varepsilon}\right)=0$$

$$\dot{\mathbf{E}}+\frac{\sigma\mathbf{E}}{\varepsilon}=0 \Rightarrow \mathbf{E}=\mathbf{E_o}e^{-\sigma t/\varepsilon}$$

$$\mathbf{E}=\mathbf{E_o}(r)e^{-j\omega t} \Rightarrow \Box^2\mathbf{E}=0 \Rightarrow \text{lossless propagation in } \textit{linear} \text{ conductive media}$$

No SLW Attenuation in Conductive Media

$$\nabla^2\left(\dot{\mathbf{E}}+\frac{\sigma\mathbf{E}}{\varepsilon}\right)=0,\ \text{with}\ \sigma\text{=}\sigma(\mathrm{E})\equiv\sigma(|\mathbf{E}|)\Rightarrow\nabla^2\left(-j\omega+\frac{\sigma}{\varepsilon}\right)\mathbf{E}+\frac{\mathbf{E}}{\varepsilon}\frac{\partial\sigma}{\partial\mathrm{E}}\nabla^2\mathrm{E}=0$$

$$\text{For spherical wave, E=E}_r\Rightarrow\left(-j\omega+\frac{\sigma}{\varepsilon}\right)\nabla^2\mathrm{E}_r\hat{\mathbf{r}}+\mathrm{E}_r\hat{\mathbf{r}}\frac{\partial\left(-j\omega+\sigma/\varepsilon\right)}{\partial\mathrm{E}_r}\nabla^2\mathrm{E}_r=0$$

$$\Rightarrow\left[\left(-j\omega+\frac{\sigma}{\varepsilon}\right)+\mathrm{E}_r\frac{\partial\left(-j\omega+\sigma/\varepsilon\right)}{\partial\mathrm{E}_r}\right]\hat{\mathbf{r}}\nabla^2\mathrm{E}_r=0$$

$$\text{One solution for: }\nabla^2\mathrm{E}=0,\ \text{as before (E=E}_r)$$

$$\text{Second solution for: }-j\omega\varepsilon+\sigma+\mathrm{E}\frac{\partial\left(-j\omega\varepsilon+\sigma\right)}{\partial\mathrm{E}}=0:$$

$$\int\frac{d\mathrm{E}}{\mathrm{E}}=-\int\frac{d\left(-j\omega\varepsilon+\sigma\right)}{\left(-j\omega\varepsilon+\sigma\right)}\Rightarrow\ln\left(\frac{\mathrm{E}_2}{\mathrm{E}_1}\right)=-\ln\left(\frac{-j\omega\varepsilon_2+\sigma_2}{-j\omega\varepsilon_1+\sigma_1}\right)=\ln\left(\frac{-j\omega\varepsilon_o\varepsilon_1'+\omega\varepsilon_o\varepsilon_1''}{-j\omega\varepsilon_o\varepsilon_2'+\omega\varepsilon_o\varepsilon_2''}\right)$$

$$\frac{\mathrm{E}_2}{\mathrm{E}_1}=\frac{-j\varepsilon_1'\left(1+j\varepsilon_1''/\varepsilon_1'\right)}{-j\varepsilon_2'\left(1+j\varepsilon_2''/\varepsilon_2'\right)}=\frac{\varepsilon_1'}{\varepsilon_2'}\frac{1+j\tan\delta_1}{1+j\tan\delta_2};\tan\delta=\frac{\varepsilon''}{\varepsilon'}\Rightarrow\text{loss in media with }\sigma=\sigma(|\mathbf{E}|)$$

P_{OUT}(SLW) from Linear Monopole Antenna

$$\mathbf{J} = \frac{\hat{\mathbf{z}} I \delta(x)\delta(y) e^{-j\omega t}(\cos kz - \cos kL)}{(1-\cos kL)}; \rho = \frac{jI\delta(x)\delta(y)e^{-j\omega t}\sin kz}{c(1-\cos kL)}$$

$$\mathbf{A} = \frac{\mu}{4\pi}\int \frac{\mathbf{J}(\mathbf{x}',t')d^3x'}{|\mathbf{x}-\mathbf{x}'|} = \frac{\mu I \hat{\mathbf{z}} e^{j(kr-\omega t)}}{4\pi kr(1-\cos kL)}\left[\begin{array}{l} \dfrac{e^{-jkL\cos\theta}(\sin kL - j\cos\theta\cos kL) + j\cos\theta}{\sin^2\theta} \\ -\dfrac{j\cos kL}{\cos\theta}\left(e^{-jkL\cos\theta} - 1\right) \end{array}\right]$$

$$\Phi = \frac{1}{4\pi\varepsilon}\int \frac{\rho(\mathbf{x}',t')d^3x'}{|\mathbf{x}-\mathbf{x}'|} = \frac{I e^{j(kr-\omega t)}}{4\pi c\varepsilon kr(1-\cos kL)}\left[\frac{e^{-jkL\cos\theta}(-j\cos kL + \cos\theta\sin kL) + j}{\sin^2\theta}\right]$$

Retarded potentials are evaluated for $t'=t-|x-x'|/c$ and $(kr)^{-1} \ll 1$ (far field) in spherical coordinates, $\hat{\mathbf{z}} = \hat{\mathbf{r}}\cos\theta - \hat{\boldsymbol{\theta}}\sin\theta$.

$$C = \nabla \bullet \mathbf{A} + \frac{1}{c^2}\frac{\partial\Phi}{\partial t} = \frac{\mu I e^{j(kr-\omega t)}}{4\pi r}; \mathbf{E} = -\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t} = \frac{c\mu I e^{j(kr-\omega t)}\left[\hat{\mathbf{r}} - \hat{\boldsymbol{\theta}} f(\theta)\right]}{4\pi r}$$

$$P_{OUT} = \left\langle \frac{C\mathbf{E}}{\mu} \right\rangle = \frac{I^2}{2(4\pi r)^2}\sqrt{\frac{\mu}{\varepsilon}}$$

Derivation of irrotational (longitudinal) fields

$$\mathbf{A}^L = \nabla\alpha \Rightarrow \mathbf{B} = \nabla\times\mathbf{A}^L = \nabla\times\nabla\alpha = 0,\ \text{or}\ \mathbf{A}^L = \nabla\alpha \Rightarrow \mathbf{B} = 0. \quad (1)$$

$$\mathbf{B}^T = 0 = \nabla\times\mathbf{A}^L \Rightarrow \mathbf{A}^L = \nabla\alpha,\ \text{or}\ \mathbf{B}^T = 0 \Rightarrow \mathbf{A}^L = \nabla\alpha. \quad (2)$$

$$\nabla\times\nabla\times\mathbf{A}^L = \nabla\times\nabla\times\nabla\alpha = 0 = \nabla(\nabla\bullet\mathbf{A}^L) - \nabla^2\mathbf{A}^L \Rightarrow \nabla(\nabla\bullet\mathbf{A}^L) = \nabla^2\mathbf{A}^L = \nabla^2\nabla\alpha = \nabla\nabla^2\alpha. \quad (3)$$

$$\Box^2\mathbf{A}^L = \Box^2\nabla\alpha = \nabla\Box^2\alpha = -\mu\mathbf{J} \Rightarrow \mathbf{J}^L = \nabla\kappa,\ \text{or}\ \mathbf{A}^L = \nabla\alpha \Rightarrow \mathbf{J}^L = \nabla\kappa. \quad (4)$$

The EED form of Ampere's law can then be decomposed into:

$$\nabla\times\mathbf{B}^T - \frac{1}{c^2}\frac{\partial\mathbf{E}^T}{\partial t} = \mu\nabla\times\mathbf{G}^T \Rightarrow \nabla\times\left(\mathbf{B}^T - \mu\mathbf{G}^T\right) + \frac{\partial^2\mathbf{A}^T}{\partial c^2 t^2} = 0; \quad (5)$$

$$-\frac{1}{c^2}\frac{\partial\mathbf{E}^L}{\partial t} - \nabla C = \mu\ \nabla\kappa \Rightarrow \frac{\partial^2\mathbf{A}^L}{\partial c^2 t^2} = \nabla\left(-\frac{1}{c^2}\frac{\partial\Phi}{\partial t} + C + \mu\kappa\right). \quad (6)$$

$$\mathbf{J}^L = \nabla\kappa \Rightarrow \mathbf{A}^L = \nabla\alpha. \quad (7)$$

Combining these equations gives: $\mathbf{A}^L = \nabla\alpha \Leftrightarrow \mathbf{B}^T = 0 \Leftrightarrow \mathbf{J}^L = \nabla\kappa.$ (8)

3. Peer-reviewed work by others (4): SLW

- C. Monstein and J.P. Wesley, Europhys. Lett. **59**, 514-520 (2002); *Europhys. Lett.* **66**, 155 (2004).
- F. J. Butterworth, C. C. Allison, D. Cavazos, and F. M. Mullen, J. Sci. Explor. **27**, 12 (Spring 2013).

Comparison of tests by Monstein/Wesley and Butterworth et al.	
Feature in Monstein and Wesley (2002)	Feature in Butterworth et al. (2013)
Aluminum-sphere diameter: 6 cm	Aluminum-sphere diameter: 7.62 cm
Antennas on 4.3 m and 4.7 m high stanchions	Antennas on 2m high stanchions
f = 433.59 MHz (λ = 69.2 cm)	f = 446 MHz (λ = 67.3 cm)
Signal on and off for calibration purposes	No mention of on/off signal for calibration
Outdoor, north-south test (Rhine River bank)	Indoor-hallway/outdoor tests (east-west)
Use of ball antennas only	Ball and half-wave-dipole antennas
No mapping of ball-antenna radiation pattern	Radiation pattern vs angle from ball apex
Transmitter-to-receiver distance: 13-700 m	Transmitter-to-receiver distance, 2-90 m
Test-to-theory match: minima at 24, 40 m	Test-to-theory match: minimum at ~30 m
Longitudinal wave from dipolar polarizer	wave polarization shift by $\pi/2$ radians

Bottom line: neither test shows clear evidence for SLW

Inadequacies in Previous Experiments and Suggested Improvements	
Inadequacy in previous experiments	**Ways to avoid inadequacies**
a) Frequency too low (433-446 MHz)	Frequency of $\geq$2 GHz for lab test
b) Poorly controlled, test environment	Controlled, lab environment
c) Image charge in conductive ground	Eliminate return charge by balun
d) Image current@ conductive ground	Eliminate return current: balun
e) Imprecise measurements	Modern digital instrumentation
f) Longitudinal polariz'n: dipole array	Modern digital instrumentation
g) Transmitter-receiver distance: $\pm$5m	Position measurement < $\pm$1mm
h) No statistical analysis	Statistics: experiment vs theory

Experiment by Podkletnov and Modanese*

- Impulse gravity generator (IGG) used low-density plasma discharge
- YBCO superconducting electrode charged to 2-4 MV
- Arc discharge in high **B**-field produced collimated longitudinal wave
- Wave deflected pendulums ($\leq$1000 g's), positioned 1211m from IGG
- Wave also sensed by piezoelectric sensors at the same distance
- Wave speed measured by synchronous rubidium atomic clocks
- IGG-to-sensor time was 63$\pm$1ns, giving propagation speed of (64$\pm$1)c
- *Jane's Defence Weekly* claimed unattenuated wave to 200km
- Podkletnov is very secretive about IGG details (no diagram of device)

Reference:

*E. Podkletnov and G. Modanese, "Study of light interaction with gravity impulses and measurements of the speed of gravity impulses," Chapter 8 (pages 169-182) in Gravity-Superconductors Interactions: Theory and Experiment, Bentham Science Publ. (2012)

Magrav physics of IGG: Gertsenshtein effect (GE)*

- Nonlinearity in Einstein's general-relativistic field equations cause…
- Resonant coupling of electromagnetic (EM)-to-gravity waves (GW)
- Photons passing through a strong magnetic field generate GW
- Propagation of one wave type generates the other
- Coupling is *tiny* under CED, because scalar field is absent
- My suspicion: large coupling under general-relativistic EED

Reference:

*M.E. Gertsenshtein, "Wave resonance of light and gravitational waves," Sov. Phys. JETP 14, 84-85 (1962)

Comment on dark matter (27%) & dark energy (68%)

"…our current cosmological model…is…very successful in matching observations, but implies the existence of both dark matter and dark energy. These signify that our understanding of physics is incomplete. We will likely need a new idea as profound as general relativity to explain these mysteries…"

(Labels: dark matter/dark energy are *placeholder* names)

Reference: D.N. Spergel, "The dark side of cosmology: dark matter and dark energy," *Science* 347, 1100-1102 (2015).

Comment on quantum physics (1)

"The shell game that we play…is technically called 'renormalization.' But no matter how clever the word, it is what I would call a dippy process! Having to resort to hocus-pocus has prevented us from proving that the theory of quantum electrodynamics is mathematically self-consistent. It's surprising that the theory still hasn't been proved self-consistent one way or the other by now; I suspect that renormalization is not mathematically legitimate."

Reference: R. Feynman, QED—The strange theory of light and matter, Princeton University Press (1985), page 128. (1965 Nobel Prize in physics)

Comment on quantum physics (2)

"There is one further question. If superconductivity does not require an explicit Higgs in the Hamiltonian to observe a Higgs mode, might the same be true for the 126 GeV mode? As far as I can interpret what is being said about the numbers, I think that is entirely plausible. Maybe the Higgs boson is fictitious!"

Reference: P.W. Anderson, "Higgs, Anderson and all that," *Nature Phys.* 11, 93 (2015). (1977 Nobel Prize in physics)

Comment on quantum physics (3)

Freeman Dyson showed that the perturbation expansions in QED have a zero radius of convergence. That is, all power-series expansions in QED are divergent after renormalization, making the results meaningless.

Reference: F.J. Dyson, "Divergence of perturbation theory in quantum electrodynamics," *Phys. Rev.* 85, 631 (1952).

See FAQs for more comments on current problems in physics; a copy of these FAQs is available on request

Planck Scale*

- Defined on the basis of five universal physical constants:

c=speed of light in vacuum=2.99792458×10^8 m/s
G=gravitational constant=6.67408(31)×10^{-11} $m^3/kg/s^2$
$\hbar \equiv h/2\pi$=reduced Planck constant = 1.054571800(13)×10^{-34} Js
$(4\pi\varepsilon_0)^{-1}$=coulomb constant=8.9875517873681764×10^9 kg $m^3/s^4/A^2$
k_B=Boltzmann constant=1.38064852(79)×10^{-23} J/K

- Planck units can then be obtained by dimensional analysis:

ℓ_P=Planck length$\equiv \sqrt{\frac{\hbar G}{c^3}}$ =1.616229(38)×10^{-35} m

t_P=Planck time$\equiv \sqrt{\frac{\hbar G}{c^5}}$ =5.39116(13)×10^{-44} s

- Quantum effects of gravity probably dominate here (and below)

*M. Planck, *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin* 5, 440–480 (1899).