Internship 3 (E099980): report
Summer internship at Keysight Technologies Belgium BV

Robin Wydaeghe

31 October 2020

1 Company description

Keysight Technologies is a S&P 500 [1] American company that is most known for manufacturing electronic test and measurement equipment. The company also develops electronic design automation software in the PathWave design division. As market leader in many of their enterprises [2], they have generated 4.3 billion USD in fiscal year 2019 with over 14000 employees and 15 R&D sites[1] worldwide [3, 4]. Keysight is most active in the communications, aerospace, defense, government, electronic industrial and service provisions industries but are also present in the automotive, energy, semiconductor and education industries [5].

Keysight's history starts in 1939 with the founding of Hewlett-Packard in a Silicon Valley garage [6]. Catalyzed by the Walt Disney's request for help on the 1940 animated movie *Fantasia*, the company quickly grew into a multinational corporation for test and measurement instrumentation, being regarded as the symbolic founder of Silicon Valley [7]. In 1999, the measurement, electronic components, chemical analysis, and medical businesses division of HP spun-off into Agilent Technologies. A further field narrowing occurred in 2014 when Agilent decided to separate in two public companies, one comprising the life sciences, diagnostics and applied markets businesses, which retained the Agilent name, and the second consisting of the electronic measurement business [8]. The name Keysight was given, a blend of *key* and *insight*, chosen to convey the company's ability to unlock key insights [9].

Keysight Technologies Belgium BV has two offices in Rotselaar and Ghent [10]. The first is part of the Keysight Research Laboratory site, dedicated to applied research of test and measurement solutions such as ASICs, FPGAs and measurement concepts [11]. The second is part of the PathWave Design division, which is where my internship took place. The team in Ghent of roughly 20 software development and R&D engineers are specialized in electronic simulation and design software. Most individuals have a MSc or PhD computer science, electrical engineering or applied physics profile. The software packets ADS, RFPro and EMPro – amongst others – are used to simulate analog RF and high-speed digital designs. Their activities can be further divided in engineers working on cloud solutions (where the simulation task is handled entirely by Keysight computing servers) and people developing and researching advances in simulation tools. The scope of my internship lies within the latter, as explained in the next section.

2 Internship goals

The ever-increasing complexity and decreasing size of electronic components, require 3D full-wave electromagnetic solvers for simulating the emitting far-fields and the study of EMI and EMC problems, which is an active area of research [12]. For the latter, both the time domain simulation tools (FDTD) and frequency domain simulation tools (FEM & MoM) are useful and therefore available in Keysight's software suite. Especially the ability of FDTD to model transient far-field phenomena is interesting for EMI applications. However, frequency domain solvers offer advantages in accuracy, the modelling of inhomogeneous materials and the use of unconditionally stable, flexible and complex meshes. My internship supervisor Jan

[1] with more than 50 R&D engineers

Van Hese proposed the idea of researching the use of the Fourier transformation to convert far-field results to the time domain. This allows us to harness the advantages of frequency domain solver while being able to simulate transient phenomena. A similar conversion is already available in Keysight's EMPro software, called TDR/TDT analysis. This is a well-established tool based on circuit results inside the component. As we were both unaware to which extent any research had been conducted on this idea for far-fields, the goal would be made flexible to allow *any meaningful time domain result* and a feasibility study to be deemed satisfactory. In the opposite case, a stable add-on could be programmed by a script to the software packet RFPro or EMPro, which would allow viewing transient phenomena as an output of a frequency domain simulation. During the literature study of the internship, it became apparent that the topic was largely unexplored and the focus did shift to assessing feasibility.

3 Technical description

To conclude my internship, I held a 30 minute presentation for the R&D Keysight team in Ghent. My internship promotor prof. dr. ir. Dries Vande Ginste said in the meeting discussing the realisation of this report that attaching this 42 slide long presentation as an appendix suffices for the complete technical description. The PDF is appended to this document.

4 Personal evaluation

Since I was a teenager, I have had an unexplainably great interest for all things related to physics simulation. This prompted me to pursue an education in Engineering Physics where I became familiar with Keysight's (and parent companies Agilent Technologies and Hewlett-Packard) equipment in the university's electronic labs as well as some of their simulation and design tools. I contacted this specific company amongst many for an internship due to the shared interest. It comes as no surprise that the contents of the internship were very exciting and fulfilling. The overall experience was also particularly educational on three important aspects. First, I learned to apply my knowledge in a practical setting with direct tangible benefits. Concretely, I used assumptions based on what is usual in practice, did not dwell on details of mathematical formalism, formulated a plan of attack myself and had regular meetings with company staff. Second, I was happy to learn that a lot of the competences acquired in my education could be directly applied to the project. I gained a lot of time by not having to study various techniques used in the software packet. I appreciated the research nature of the project. Finally, I learned social skills essential in the corporate world such as writing a CV, doing a solicitation meeting and discussing my progress during and at the end of the internship.

The internship's technical conclusion was that it isn't feasible to use the (inverse) Fourier transform to convert the results to transients with the current state-of-the-art tools. In a way, this is saddening, but a negative result is still a scientific result. I have laid down some ideas to maybe achieve it anyways for future work (maybe in the form of a master thesis). Another unfortunate negative is the COVID-19 pandemic making work in the office impossible during the entire six weeks. This sometimes prevented me from asking very small questions, although instant-messaging platforms were used to alleviate this problem. Solving IT technical issues was also not as easy. The whole team does operate fully online for several months now and I was surprised by how well they handled the it regardless of the tough pandemic circumstances.

I would like to especially thank my internship supervisor dr. ir. Jan Van Hese for his thorough and continued support during the internship. He was always open to answer any questions I had and provided helpful guidance in a professional manner when I did not know what the next step was. I would also like to thank the entire R&D team in Ghent for all the other questions or troubles I had.

References

[1] Witkowski W., 2018, *Keysight Technologies to replace CA on S&P 500*, Marketwatch, viewed 31 October 2020, <https://www.marketwatch.com/story/keysight-technologies-to-replace-ca-on-sp-500-2018-10-30>.

[2] Frost Sullivan, 2014, *Frost & Sullivan 2014 Global Instrumentation Software Market Leadership Award*, viewed 31 October 2020, <https://www.keysight.com/be/en/assets/7018-04649/article-reprints/5992-0310.pdf>

[3] Keysight Technologies, 2019, *Keysight Technologies at a Glance*, viewed 31 October 2020, <https://about.keysight.com/en/companyinfo/Keysight_FactSheet.pdf>.

[4] Fortune 500, 2019, *Keysight Technologies: company information*, viewed 31 October 2020, <https://fortune.com/company/keysight-technologies/fortune500/>.

[5] Keysight Technologies, 2020, *Industries*, viewed 31 October 2020, <https://www.keysight.com/be/en/industries.html>.

[6] Keysight Technologies, 2020, *Keysight Technologies: Our history*, viewed on 31 October 2020, <https://www.keysight.com/be/en/about/timeline.html>.

[7] Silicon Valley Historical Association, 2008, *Hewlett-Packard*, viewed on 31 October 2020, <https://www.siliconvalleyhistorical.org/hewlett-packard-history>.

[8] Agilent Technologies, 2020, *Company History Timeline - 2010s*, viewed on 31 October 2020, <https://www.agilent.com/about/companyinfo/history/timeline_2010s.html>.

[9] Geary E., 2018, *Keysight and Aunt Gilda: How we didn't name the company*, Keysight Blogs, viewed 31 October 2020, <https://blogs.keysight.com/blogs/keys.entry.html/2018/09/25/keysight_and_auntgi-DpAC.html>.

[10] Keysight Technologies, 2020, *Keysight in Belgium*, viewed on 31 October 2020, <https://jobs.keysight.com/go/Keysight-in-Belgium/8003600/>.

[11] Keysight Techonologies, 2020, *Keysight Laboratories*, viewed on 31 October 2020, <https://about.keysight.com/en/companyinfo/labs/>.

[12] Vande Ginste D. et al, -, *Electromagnetic Compatibility, Signal and Power Integrity (EMC/SI/PI)* , viewed on 31 October 2020, <https://www.ugent.be/ea/idlab/en/research/electromagnetics-rf-and-high-speed-circuits-and-systems/emc-si-pi.htm>

EM Modelling in the Time Domain using Frequency Domain Far Field Data

A SIX-WEEK INTERNSHIP

Robin Wydaeghe | *2020.09.08*

Supervised by Jan Vanhese

KEYSIGHT TECHNOLOGIES

Problem statement

TD Techniques (FDTD)

- Computationally more efficient
- Non-linear anisotropic materials
- Broadband simulation
- Courant limit (explicit methods)
- Transient phenomena
- EMI/EMC

FD Techniques (FEM/Momentum)

- Generally more accurate
- Inhomogeneous materials
- Flexible and complex meshes

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“

Can we say anything meaningful about transients given the frequency domain spectrum?

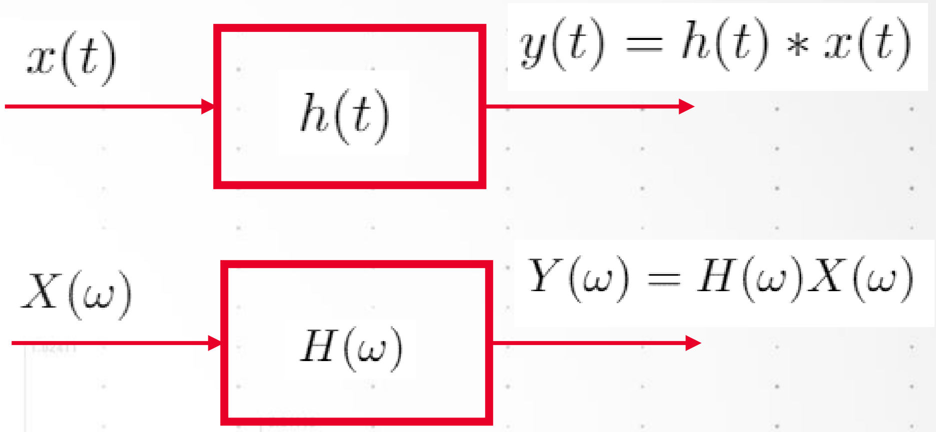
Literature

- TDR/TDT
  - Circuit result
  - Well-known
  - EMPro: windowed non-uniform inverse FFT
- Far fields
  - Never done to my knowledge
  - Academic problem
    - 1D scalar wave equation error estimates [1]

Basic assumptions

- Keep it simple
- Causal BIBO stable LTI system [2]
  - Only non-dispersive, linear [3], local materials
- IO system *for each angle and field component*
- Far field approximation
  - Independent of bounding box size
  - PML

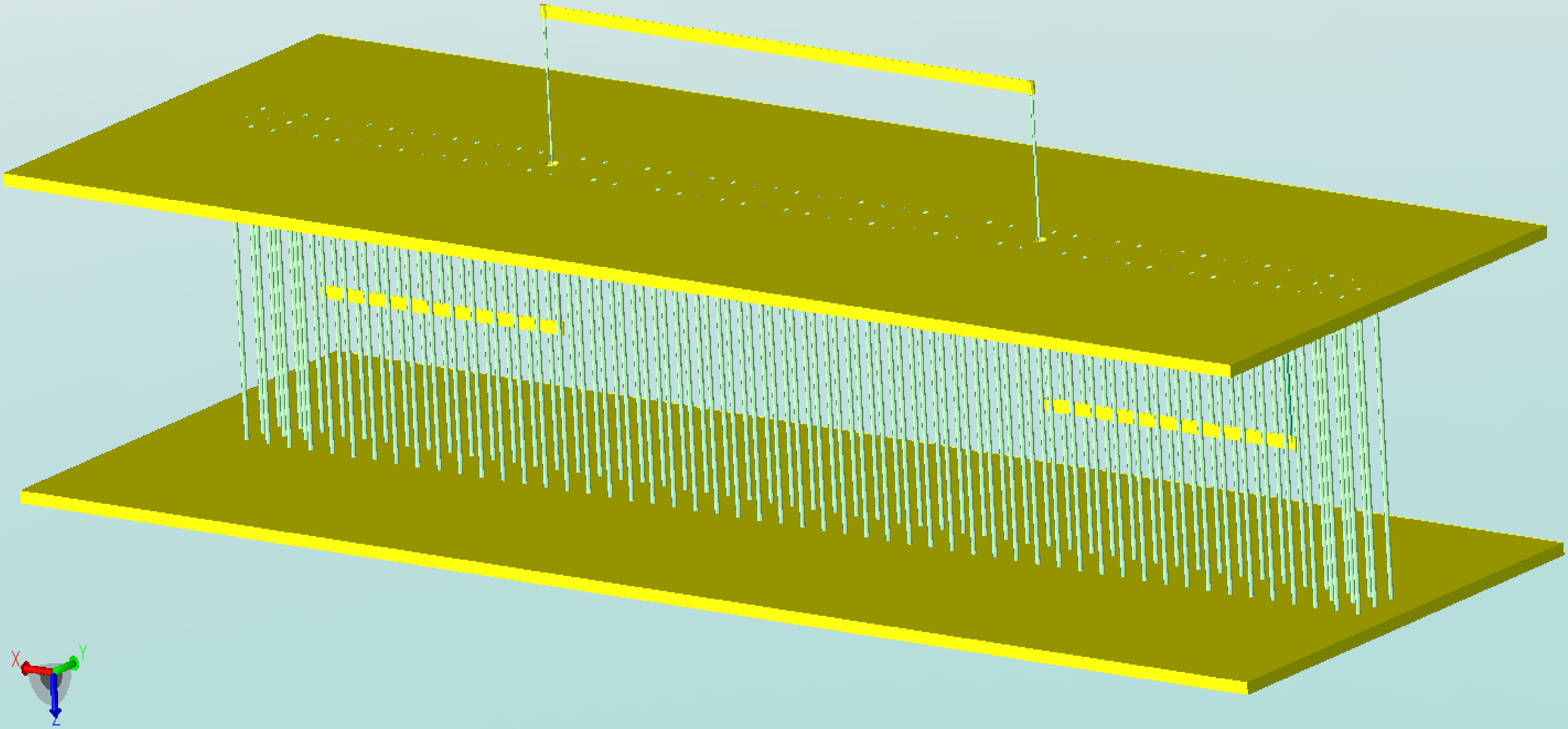
$$r \geq \frac{2d^2}{\lambda}$$



Practical approach

- Choose good source signal
- FFT the source transient
- Achieve convergence within each solver
- Multiply by FEM spectrum
  - Compare with FFT of far field transients from FDTD
- Inverse FFT this result
- Time shift by
  - Source timeshift
  - Bounding box & far field travel distance

KEYSIGHT TECHNOLOGIES


X
Y
Z

Choose good source signal

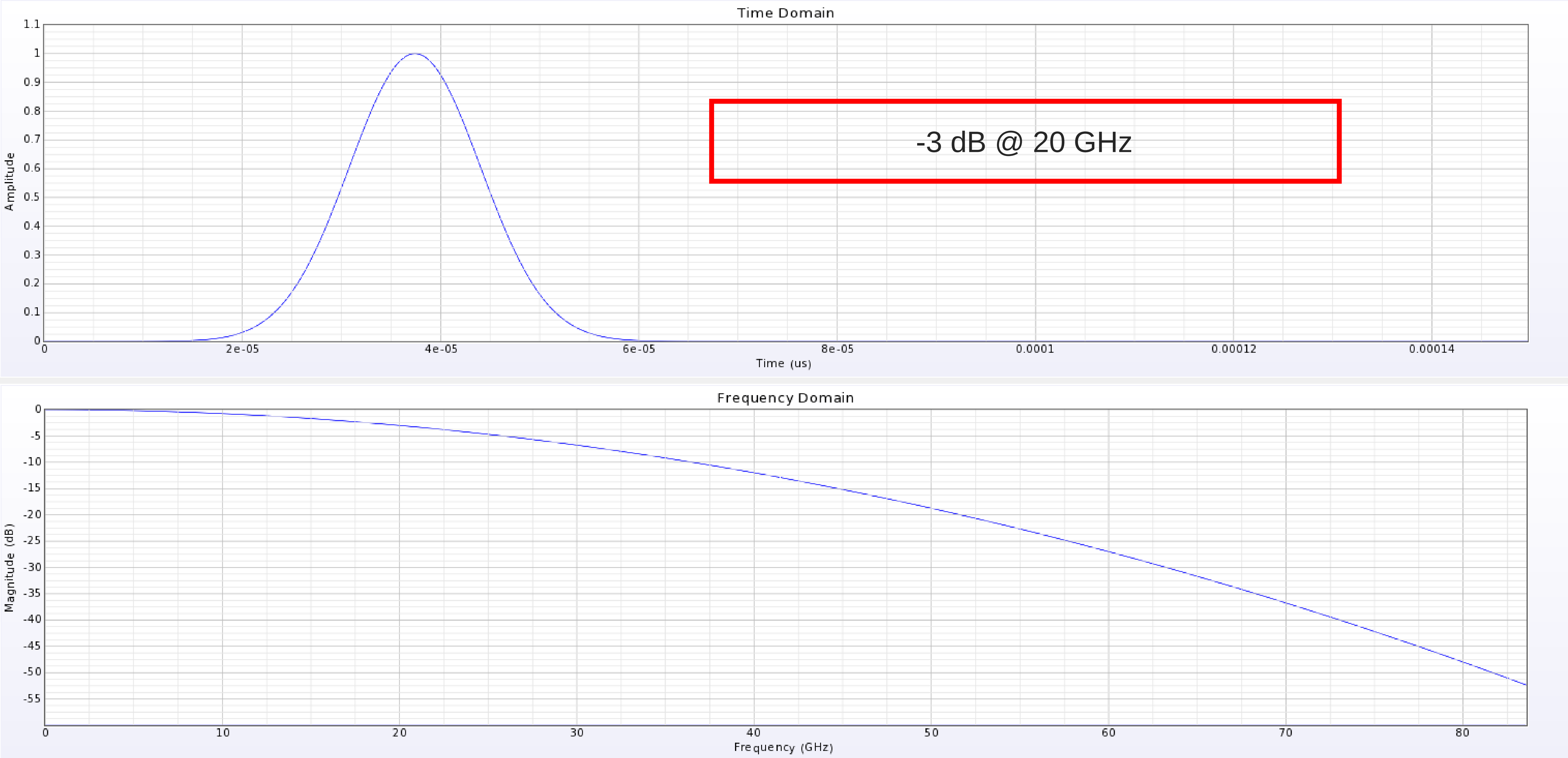
- One port
- Reasonable BW
- Reasonable signal length
- FDTD: input signal starts at rest
  - FD→TD: rigorously implements any (generalized) function!

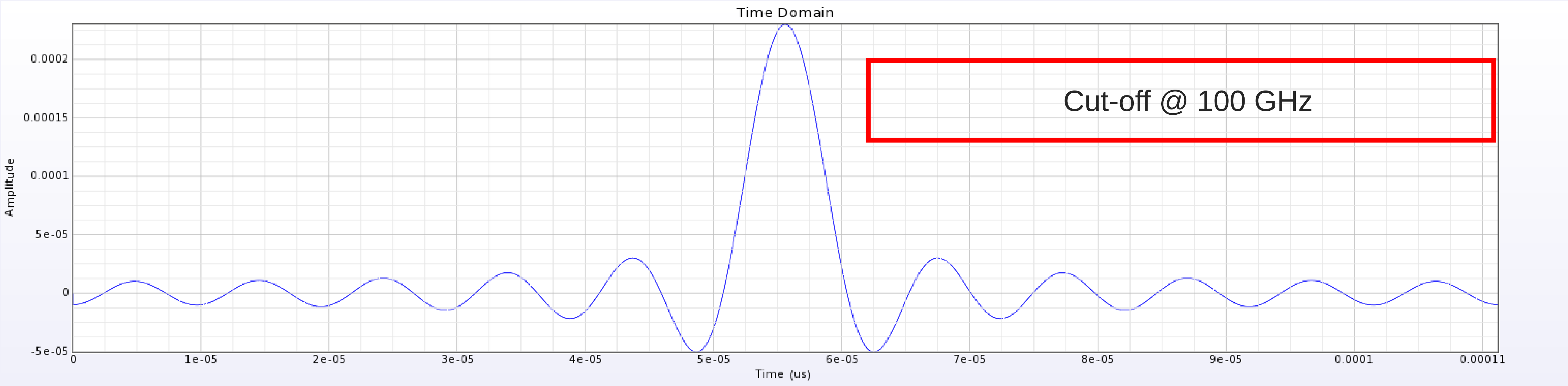
Choose good source signal

- Gaussian → Gaussian
  - ≥ 99.7% spectral content for frequencies ≤ 3/sigma
  - Multiply/divide by nearly zero
  - Time shift by 5 sigma
- Good test: Sinc function → Boxcar window
  - Less high frequency FEM evaluations
  - More accurate inverse fourier transform
  - Also needs time shift
- Time shift: $e^{j\omega T_{\text{shift}}}$

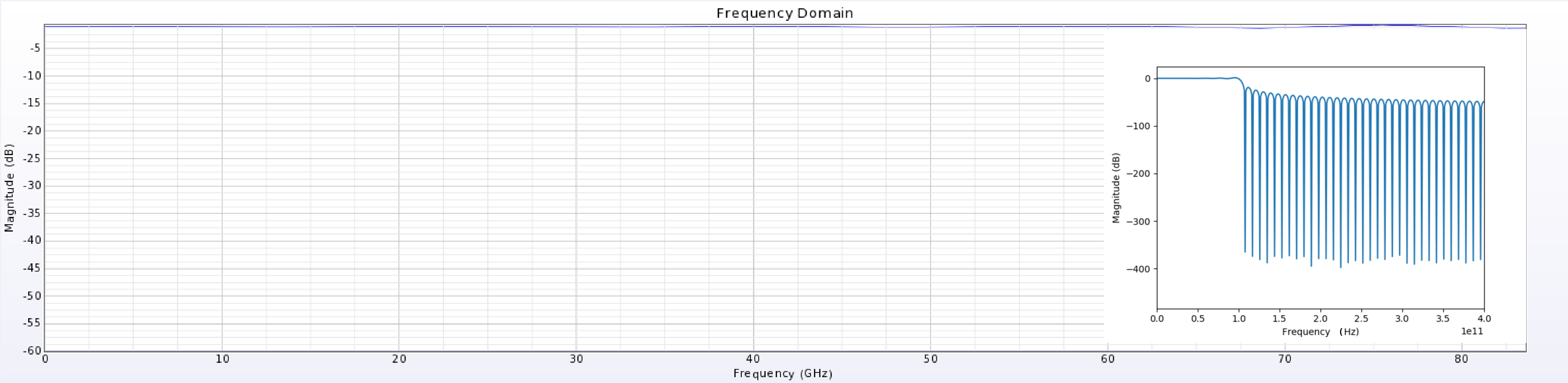
FFT the source signal

- Generate the Gaussian or sinc in Python
- Import to EMPro


Time Domain
-3 dB @ 20 GHz
Amplitude
Time (us)
Frequency Domain
Magnitude (dB)
Frequency (GHz)



Time Domain
Cut-off @ 100 GHz
Amplitude
0.0002
0.00015
0.0001
5e-05
0
-5e-05
0
1e-05
2e-05
3e-05
4e-05
5e-05
6e-05
7e-05
8e-05
9e-05
0.0001
0.00011
Time (us)



Frequency Domain
Magnitude (dB)
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
0
10
20
30
40
50
60
70
80
Frequency (GHz)
0
−100
−200
−300
−400
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Frequency (Hz)
1e11

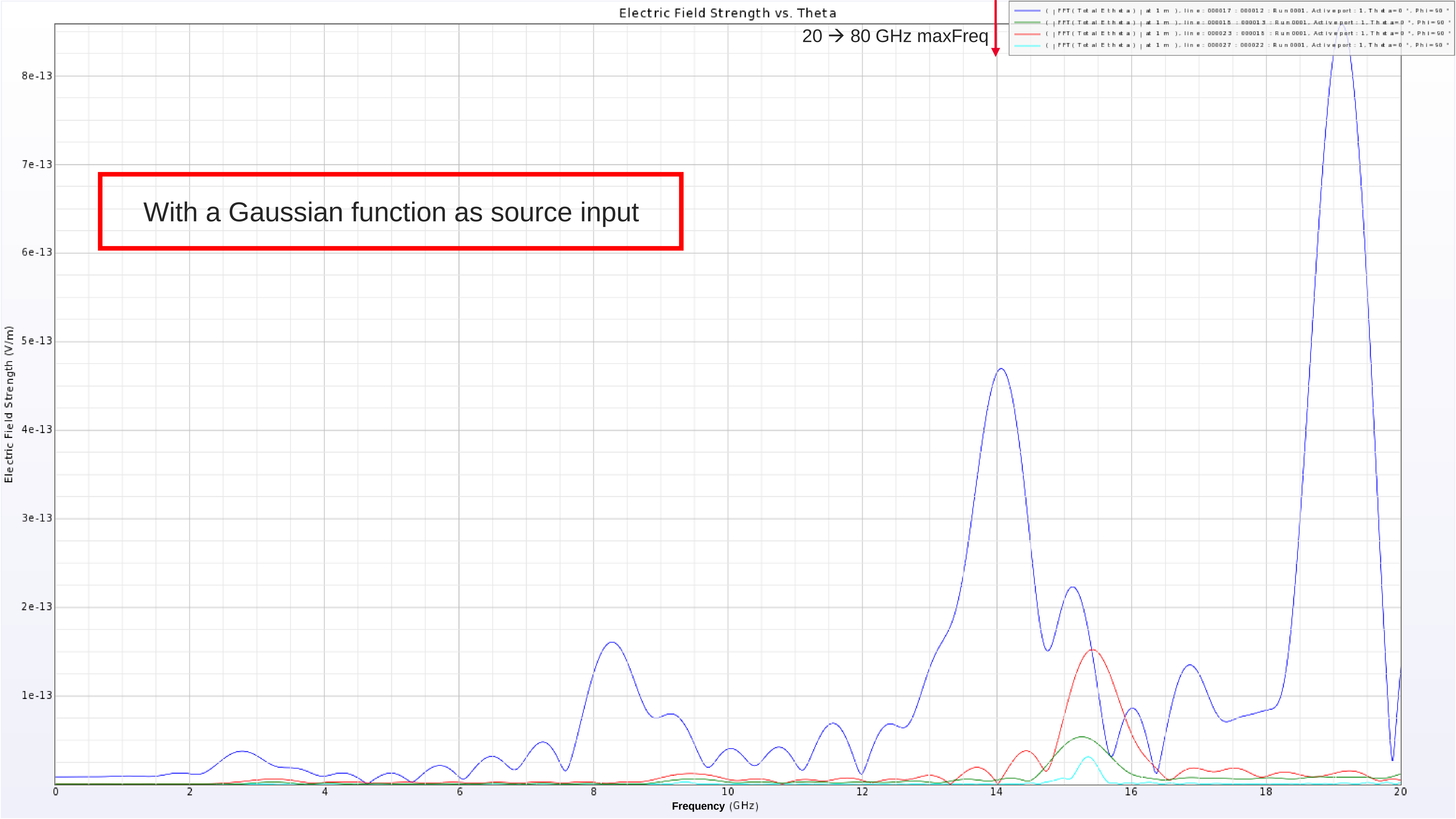
Achieve convergence within each solver

FEM

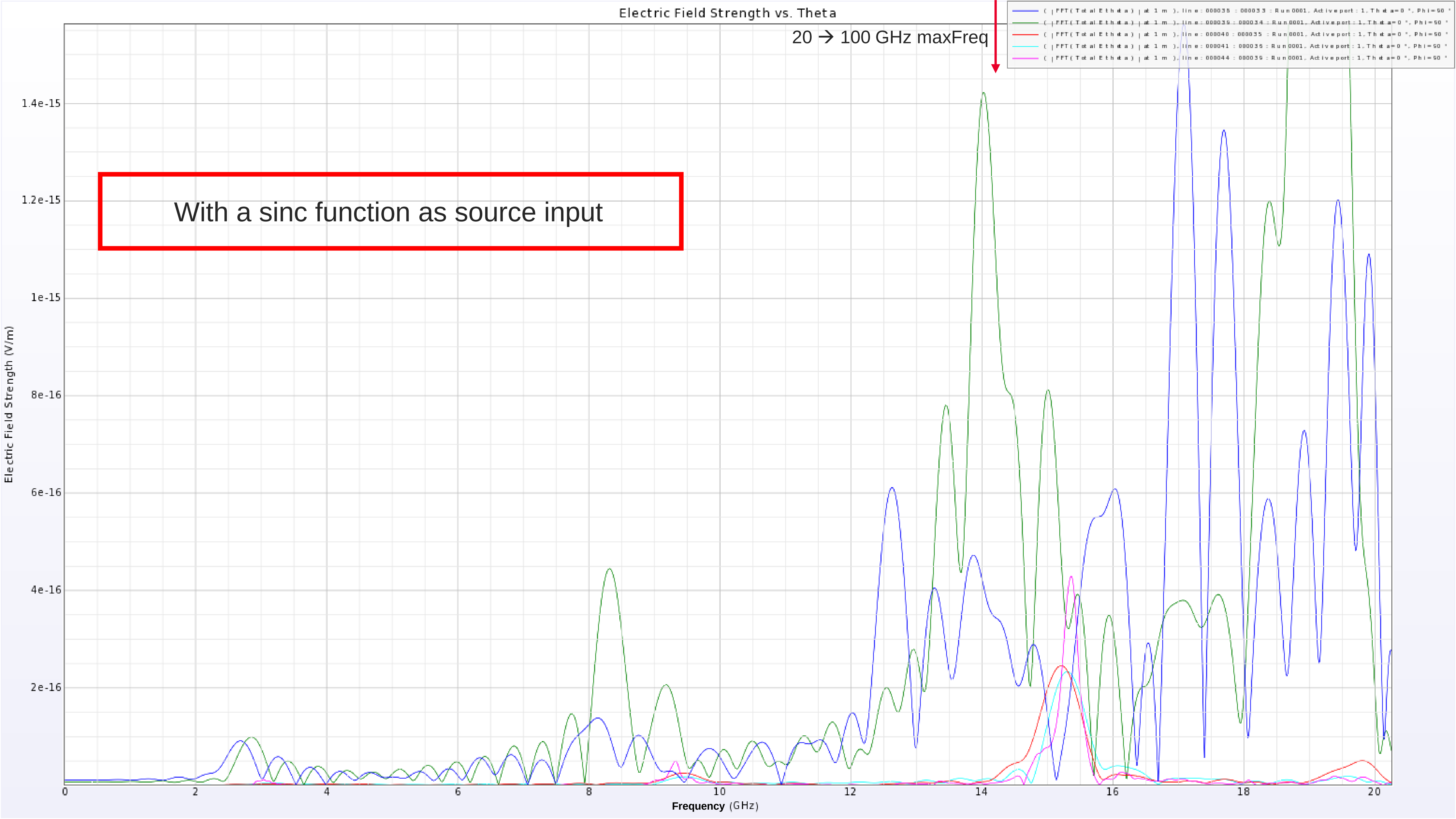
- Cpw = 20 unchangeable
- Convergence detection is already implemented for one frequency
  - Good for S-parameters, but also for far fields?
- Increase delta error and # of steps
- Bottleneck: memory, mesh convergence

FDTD

- Signal must die out
  - *Detect convergence* not always reliable
- Strong unphysical ultra high frequency components make it difficult
- Increase maxFreq, not manually the cpw
- Bottleneck: time



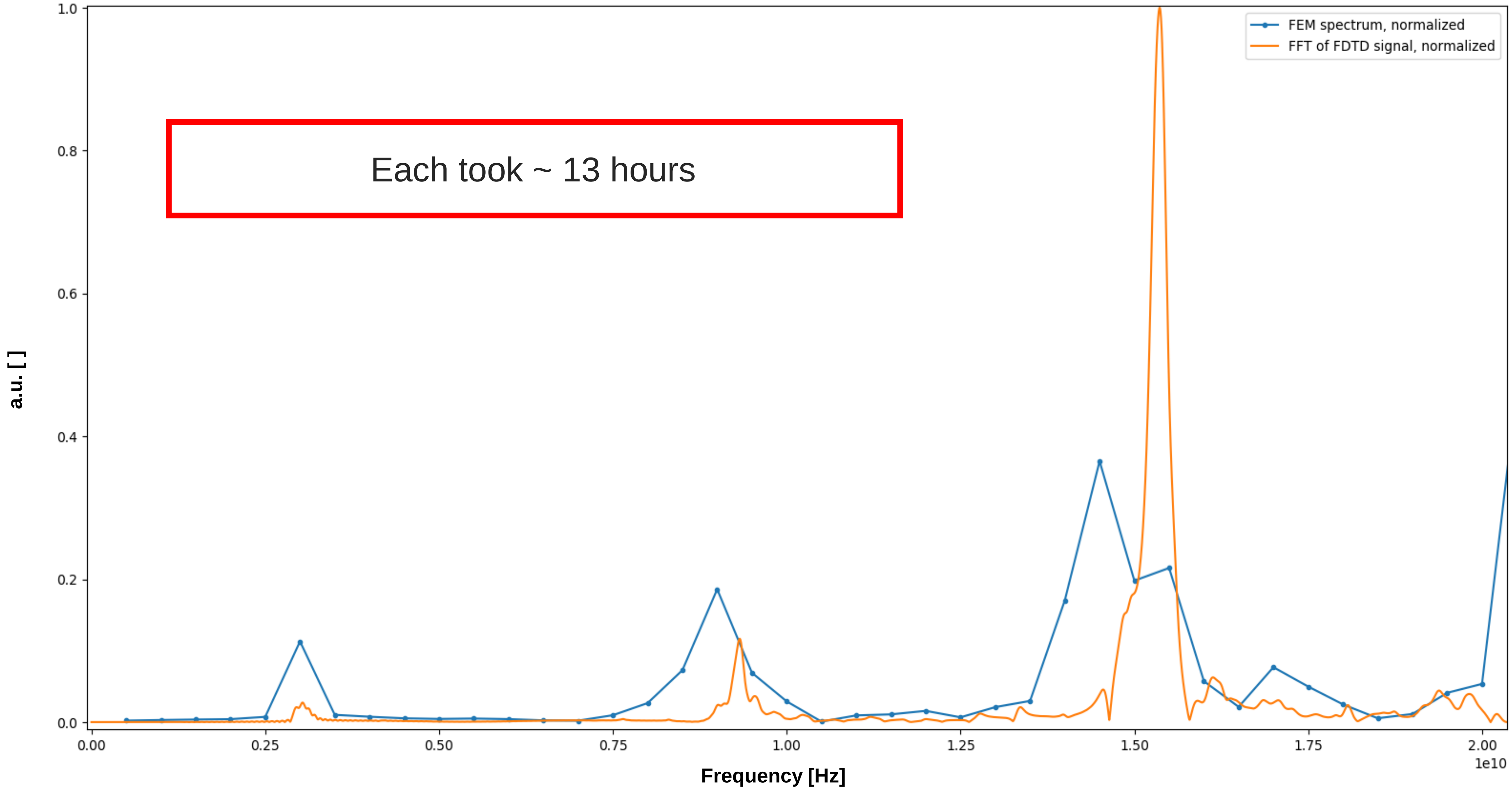
Electric Field Strength vs. Theta
20 → 80 GHz maxFreq
With a Gaussian function as source input
(|FFT(Total Etheta)| at 1 m), line: 000017 : 000012 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
(|FFT(Total Etheta)| at 1 m), line: 000018 : 000013 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
(|FFT(Total Etheta)| at 1 m), line: 000023 : 000018 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
(|FFT(Total Etheta)| at 1 m), line: 000027 : 000022 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
Electric Field Strength (V/m)
8e-13
7e-13
6e-13
5e-13
4e-13
3e-13
2e-13
1e-13
0
2
4
6
8
10
12
14
16
18
20
Frequency (GHz)



Electric Field Strength vs. Theta
20 → 100 GHz maxFreq
(|FFT(Total Etheta)| at 1 m).line: 000038 : 000033 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
(|FFT(Total Etheta)| at 1 m).line: 000039 : 000034 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
(|FFT(Total Etheta)| at 1 m).line: 000040 : 000035 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
(|FFT(Total Etheta)| at 1 m).line: 000041 : 000036 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
(|FFT(Total Etheta)| at 1 m).line: 000044 : 000039 : Run0001, Activeport: 1, Theta=0 °, Phi=90 °
With a sinc function as source input
Electric Field Strength (V/m)
1.4e-15
1.2e-15
1e-15
8e-16
6e-16
4e-16
2e-16
0
2
4
6
8
10
12
14
16
18
20
Frequency (GHz)

Multiply by FEM spectrum

- Export ffio file, read in Python
- For loop over angles, components, frequencies
- Interpolate where needed
- Compare with spectrum from FDTD
- Later work: use directivity from FDTD to improve fit
  - Needs ffio EMPro for all angles

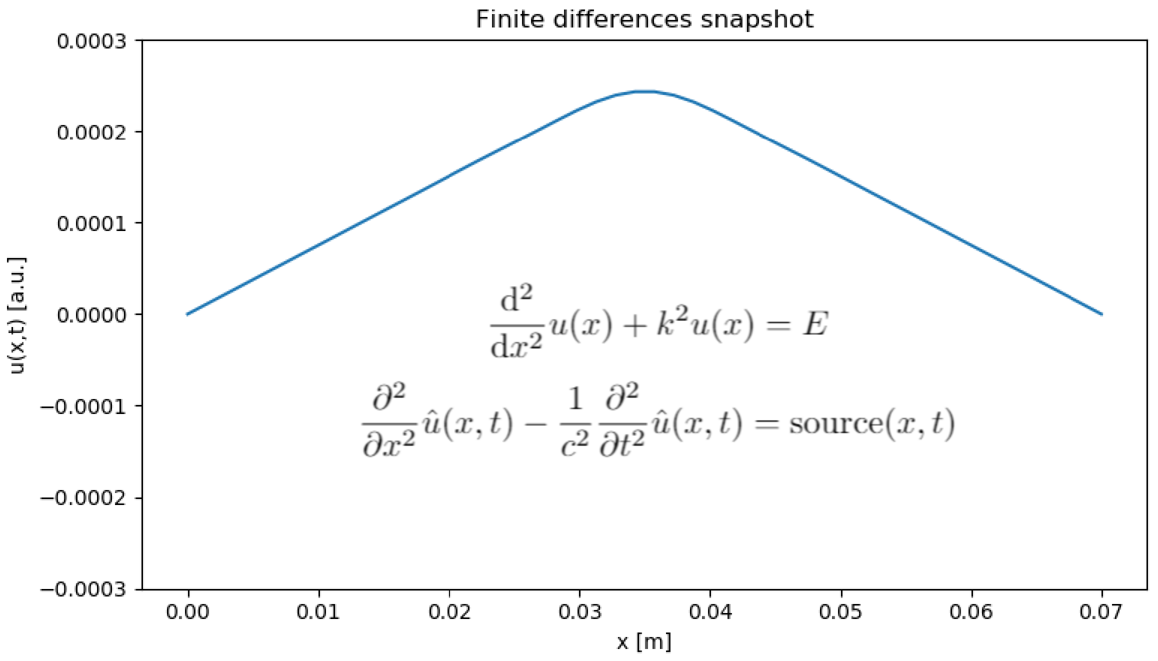

Each took ~ 13 hours
FEM spectrum, normalized
FFT of FDTD signal, normalized
a.u. [ ]
Frequency [Hz]
1e10
0.0
0.2
0.4
0.6
0.8
1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

What now?

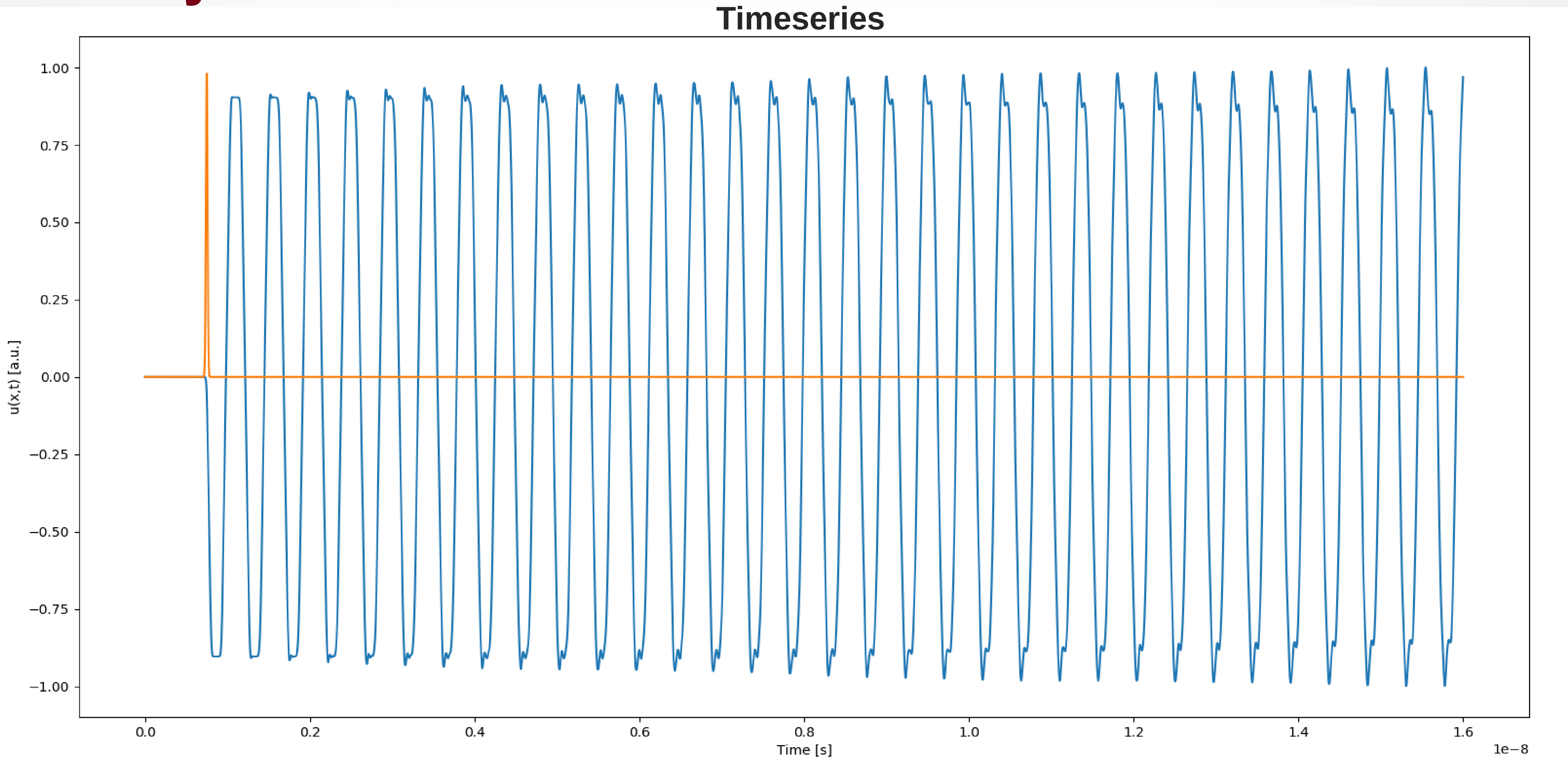
- Study problems on much more simple simulations
  - Less computation time, good convergence
  - Very broad Gaussian as source
  - Easier troubleshooting, testing assumptions
  - Eliminate travelling timeshift
  - Exact solution available (magnitude and **phase**)
- ‘Dummy’ simulations in Python
  - 1D
  - Helmholtz equation
  - Dirichlet boundaries
  - Vacuum

Dummy simulation: methods

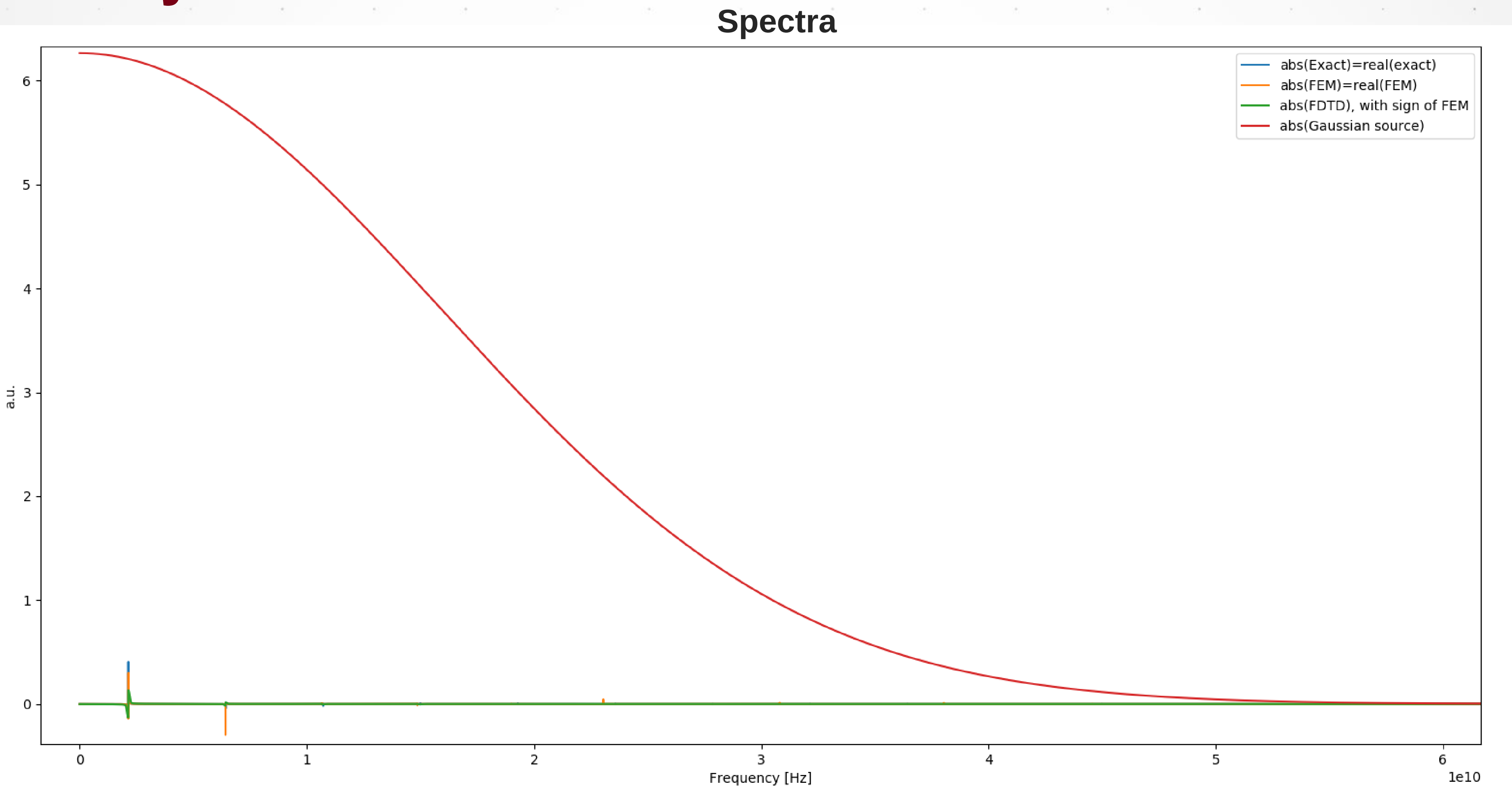
- FEM
  - $$\mathbf{A}\begin{pmatrix} U_1 \\ U_2 \\ \vdots \\ U_{m-1} \end{pmatrix} = \mathbf{F}^* = \begin{pmatrix} h^2F_1 - U_{\mathrm{BC},0} \\ h^2F_2 \\ \vdots \\ h^2F_{m-1} - U_{\mathrm{BC},m} \end{pmatrix} \quad , \quad \mathbf{A} = \begin{pmatrix} -2 & 1 & & \\ 1 & \ddots & \ddots & \\ & \ddots & \ddots & 1 \\ & & 1 & -2 \end{pmatrix} + k^2h^2\mathbf{I}$$
- Finite differences
  - $$u_m^{n+1} = r^2\left(u_{m+1}^n - 2u_m^n + u_{m-1}^n\right) + 2u_m^n - u_m^{n-1}$$
  - Soft source
  - BCs
  - Timeshifted broad Gaussian source
- Exact
  - $$\frac{E}{k^2}\left(\sin(kx)\frac{\cos(kx_{\max})-1}{\sin(kx_{\max})} - \cos(kx) + 1\right)$$



Dummy simulation: results



Dummy simulation: results



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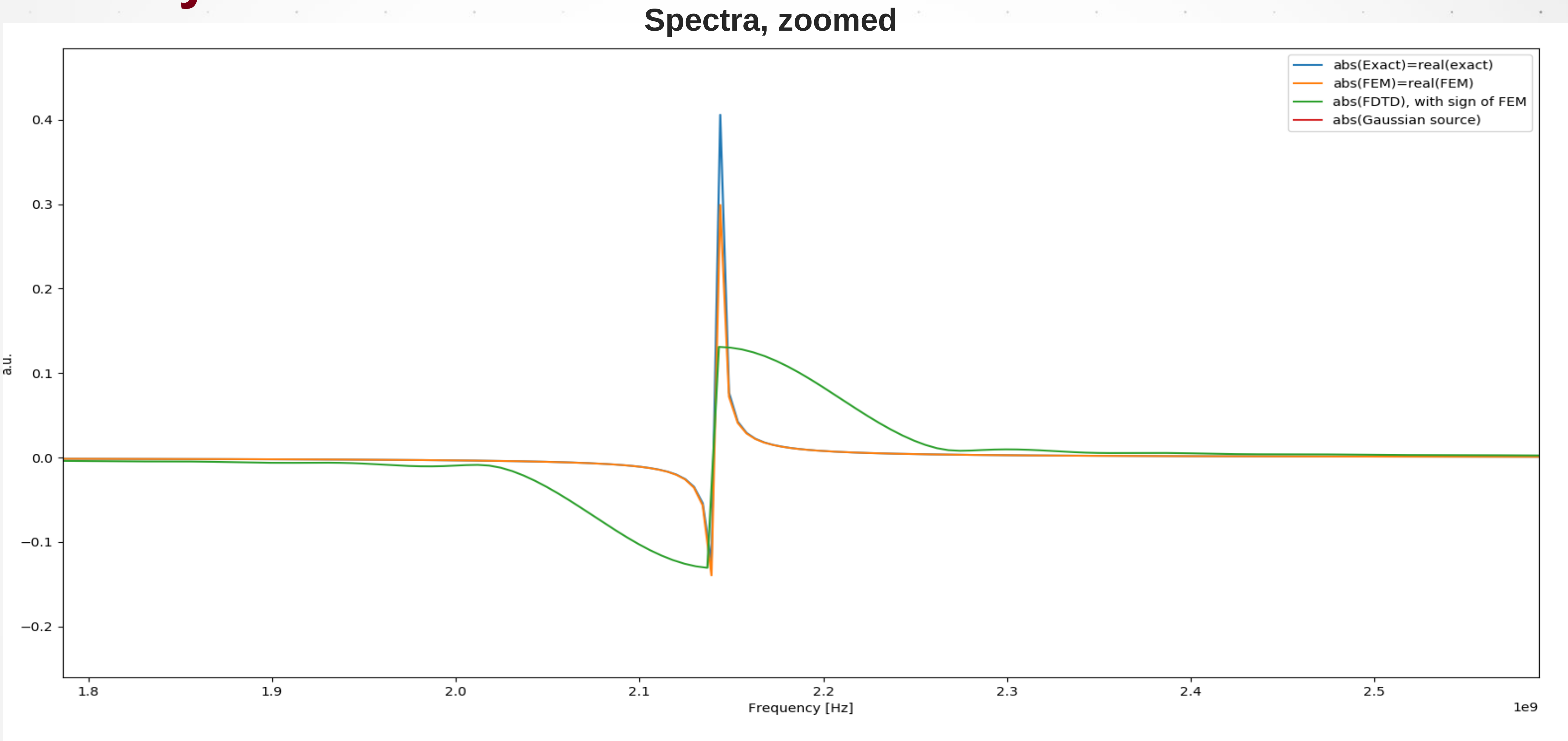
Dummy simulation: results



Intermezzo: the influence of phase on signal reconstruction

- Consider time shifted Gaussian signal and its (continuous!) phase function

$$G(\omega) = \mathcal{F}\left[\exp\left(-\frac{1}{2}\left(\frac{t-T}{\sigma}\right)\right)^2\right](\omega) = \sigma\exp\left(-\frac{1}{2}(\sigma\omega)^2\right)\exp(i\omega T)$$

$$P(\omega) = \frac{G(\omega)}{|G(\omega)|} = \exp(i\omega T)$$

- Add white noise perturbation on phase

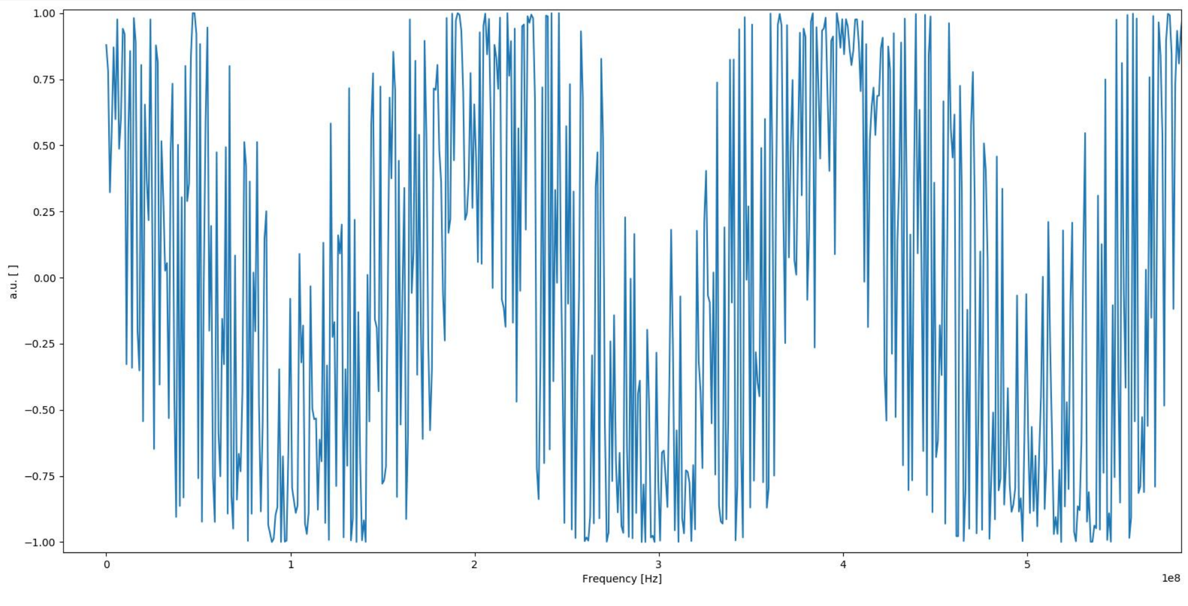
$$P'(\omega) = P(\omega)\exp(i2\pi \cdot b \cdot \mathrm{random}(-0.5, 0.5))$$
$$G'(\omega) = G(\omega)\exp(i2\pi \cdot b \cdot \mathrm{random}(-0.5, 0.5))$$

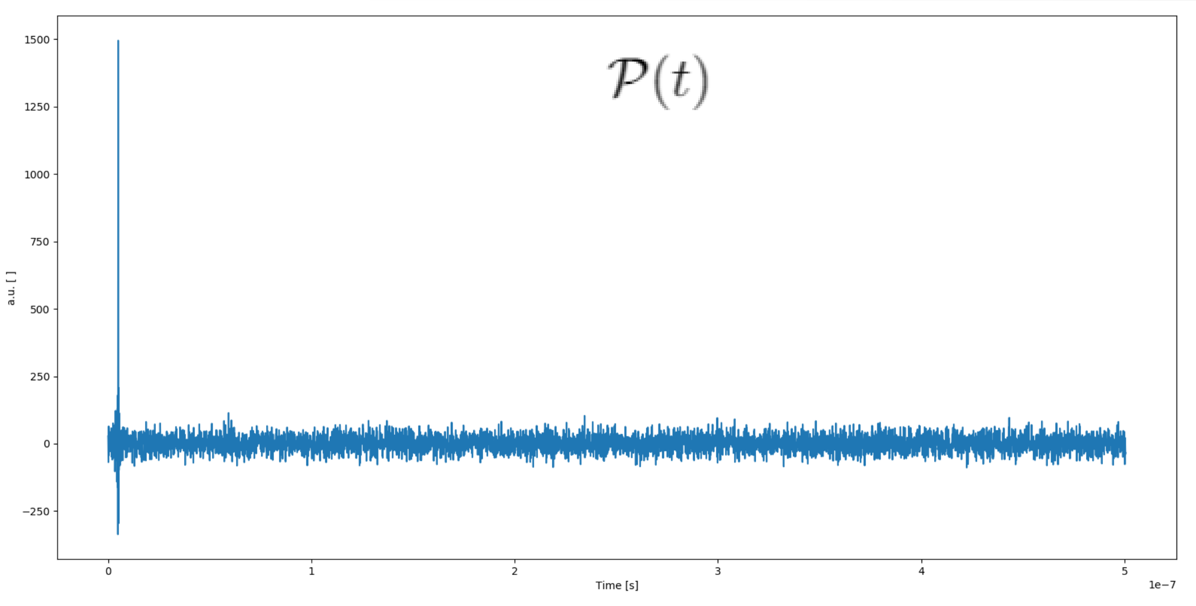
- Reconstruct signal for b = 0 → 1

$$\mathcal{P}(t) = \mathcal{F}\left[P'(\omega)\right](t)$$
$$\mathcal{G}(t) = \mathcal{F}\left[G'(\omega)\right](t)$$

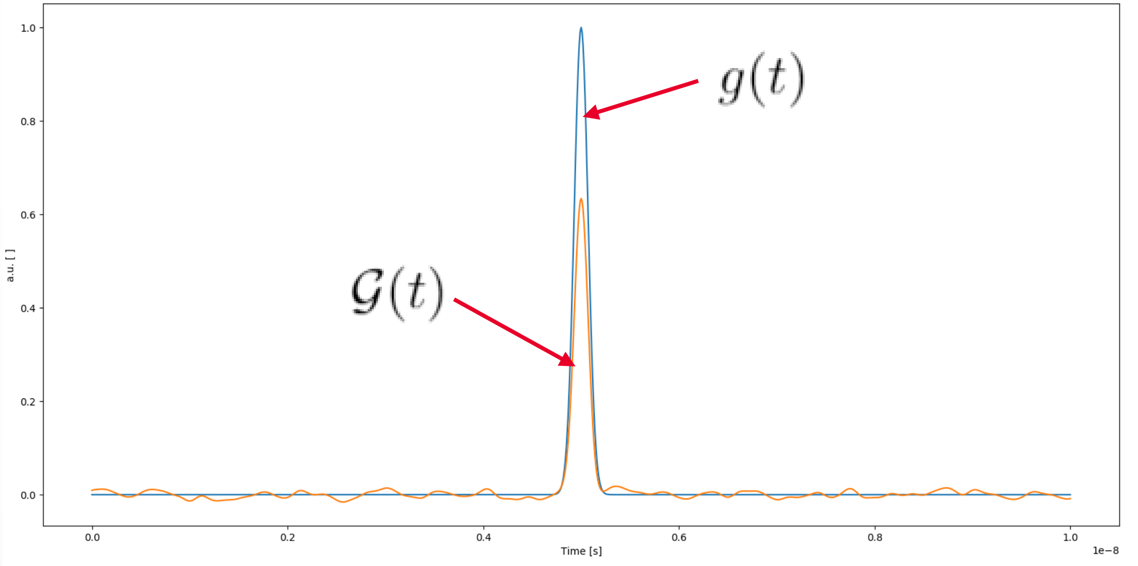
Intermezzo: the influence of phase on signal reconstruction

$\Re(P'(\omega))$



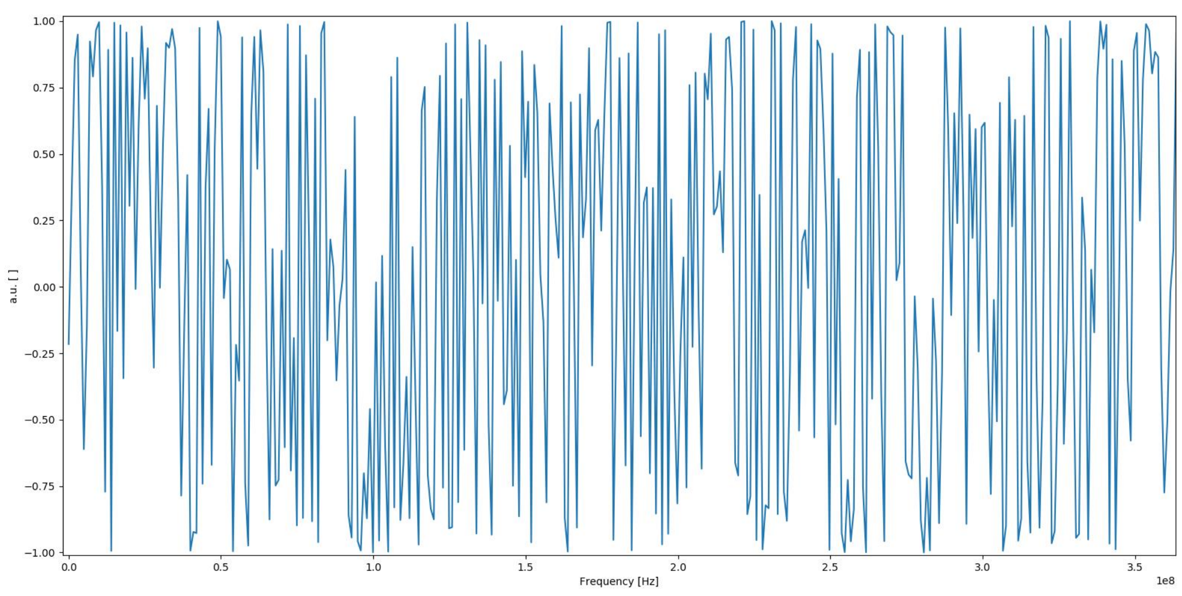


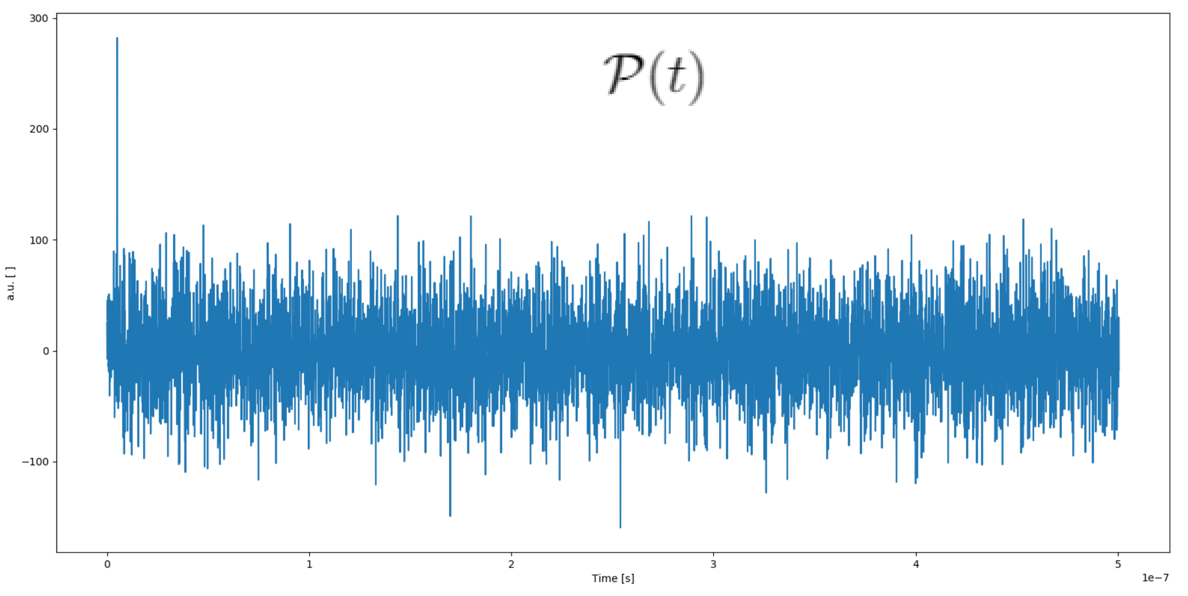
$$\boxed{b = 0.5}$$



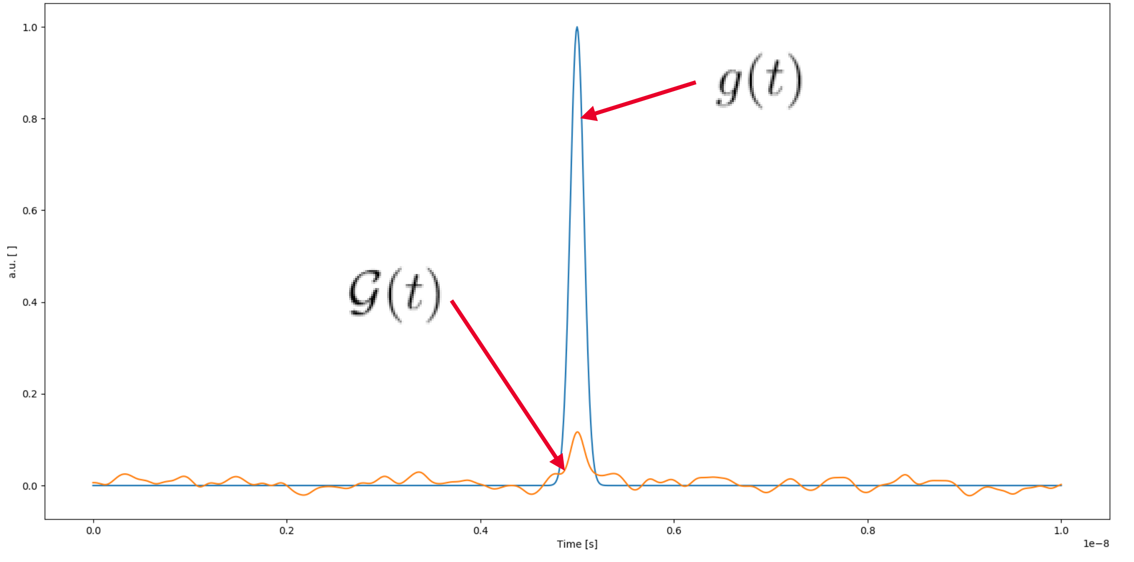
Intermezzo: the influence of phase on signal reconstruction

$\Re\mathfrak{e}(P'(\omega))$





$b = 0.9$



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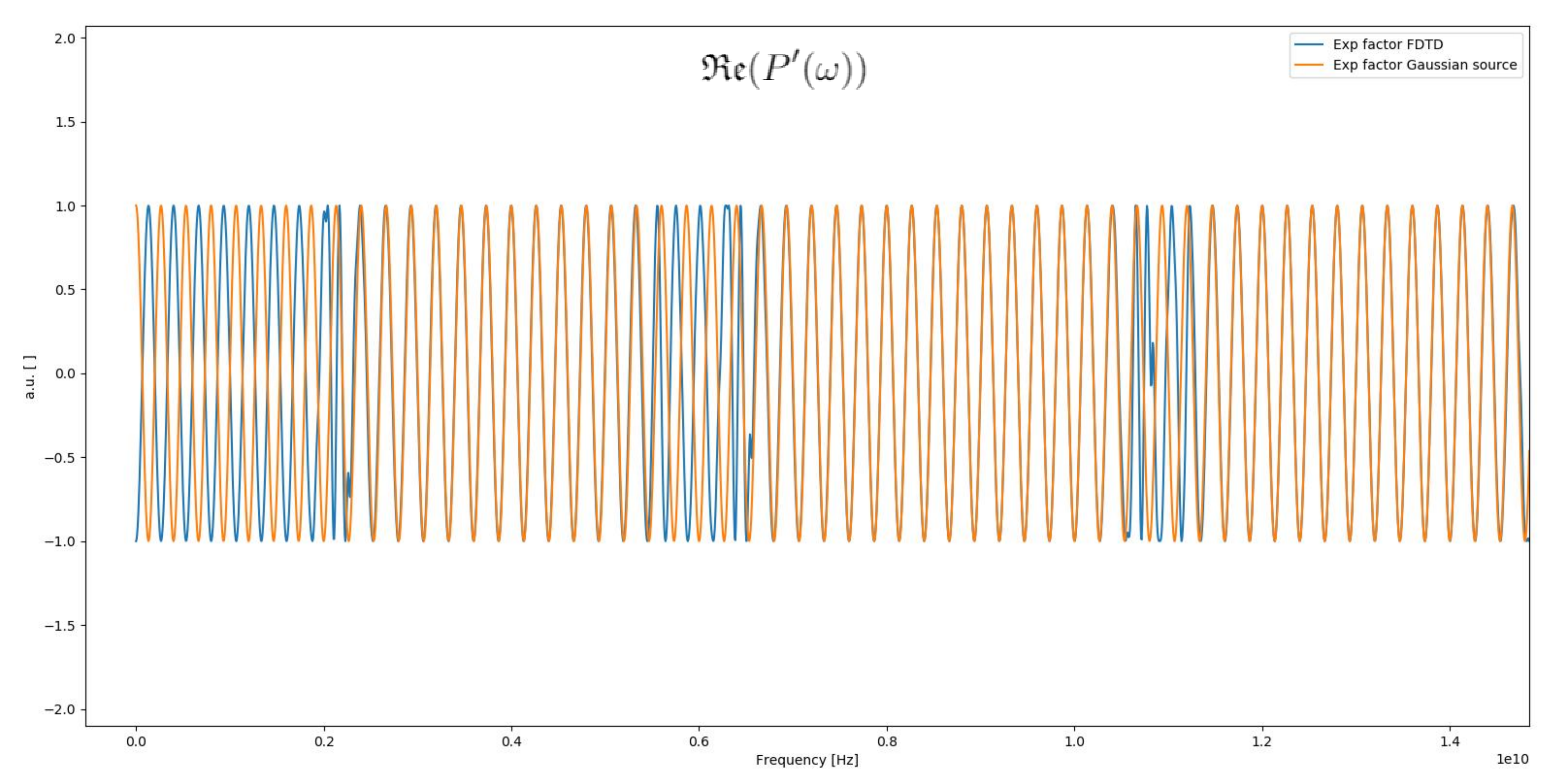
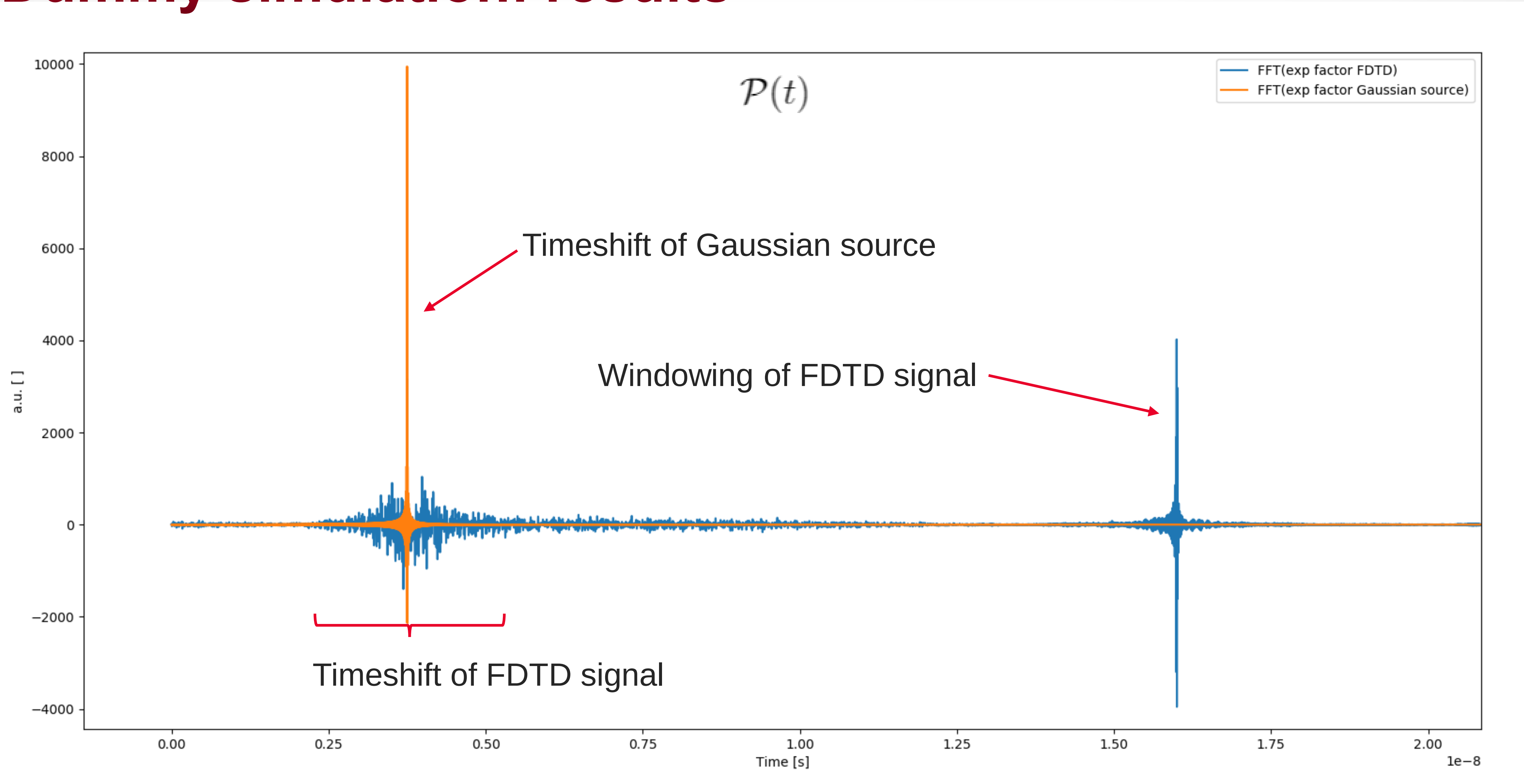
Dummy simulation: results

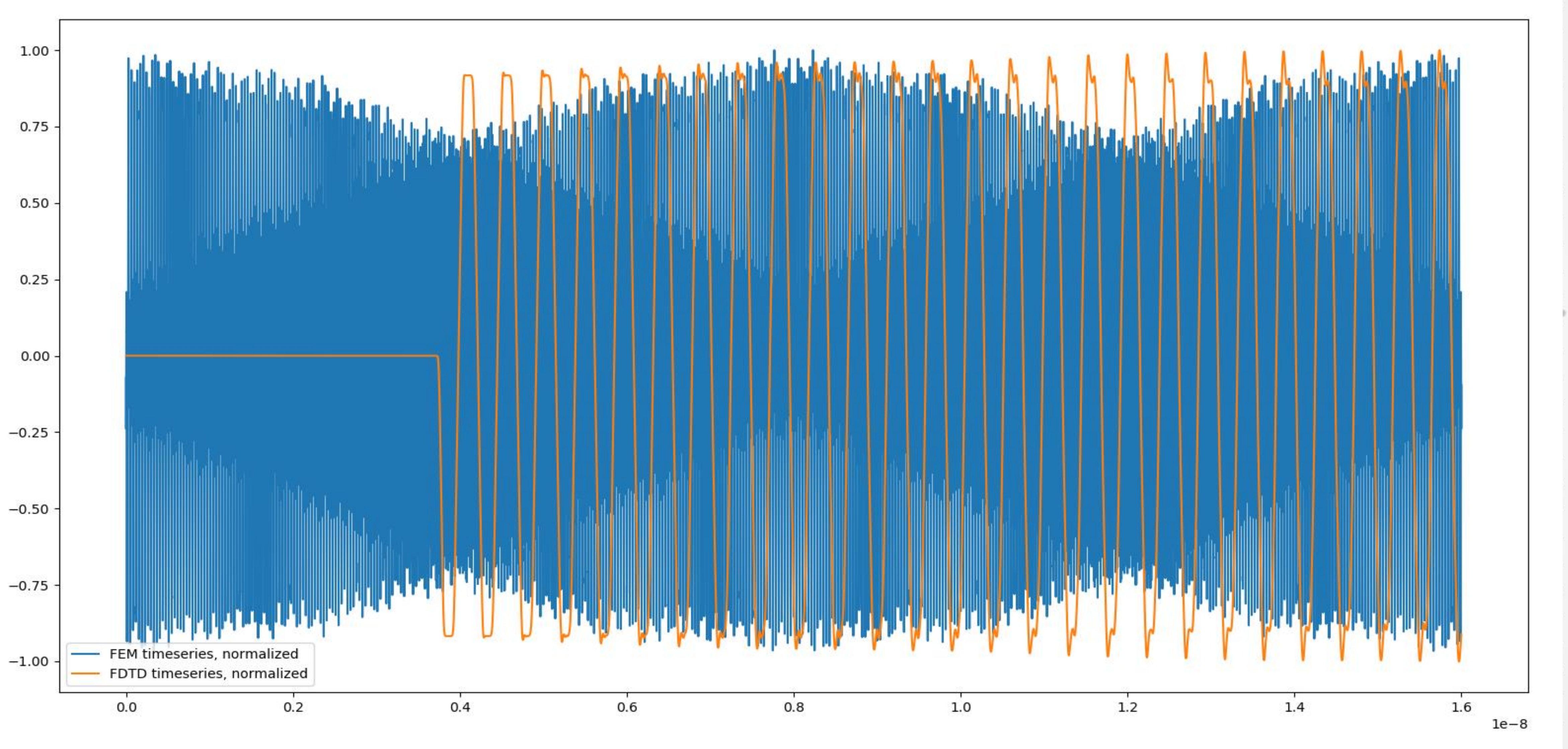


Dummy simulation: results



KEYSIGHT TECHNOLOGIES

Dummy simulation: results



Dummy simulation: conclusion

- Windowing makes comparison hard
  - Deconvolve the boxcar window
    - Extrapolation
    - Von-Cittert algorithm [4]
    - CLEAN algorithm [5]
    - Phase retrieval algorithms
  - Signal must die out
    - Absorption
    - Periodic BCs
    - **PML**
- Influence of boundaries → not far field?
  - **PML**
- Phase is crucial

$$\hat{u}_{\text{windowed}}(x,t) = \hat{u}(x,t) \cdot \hat{w}(t)$$

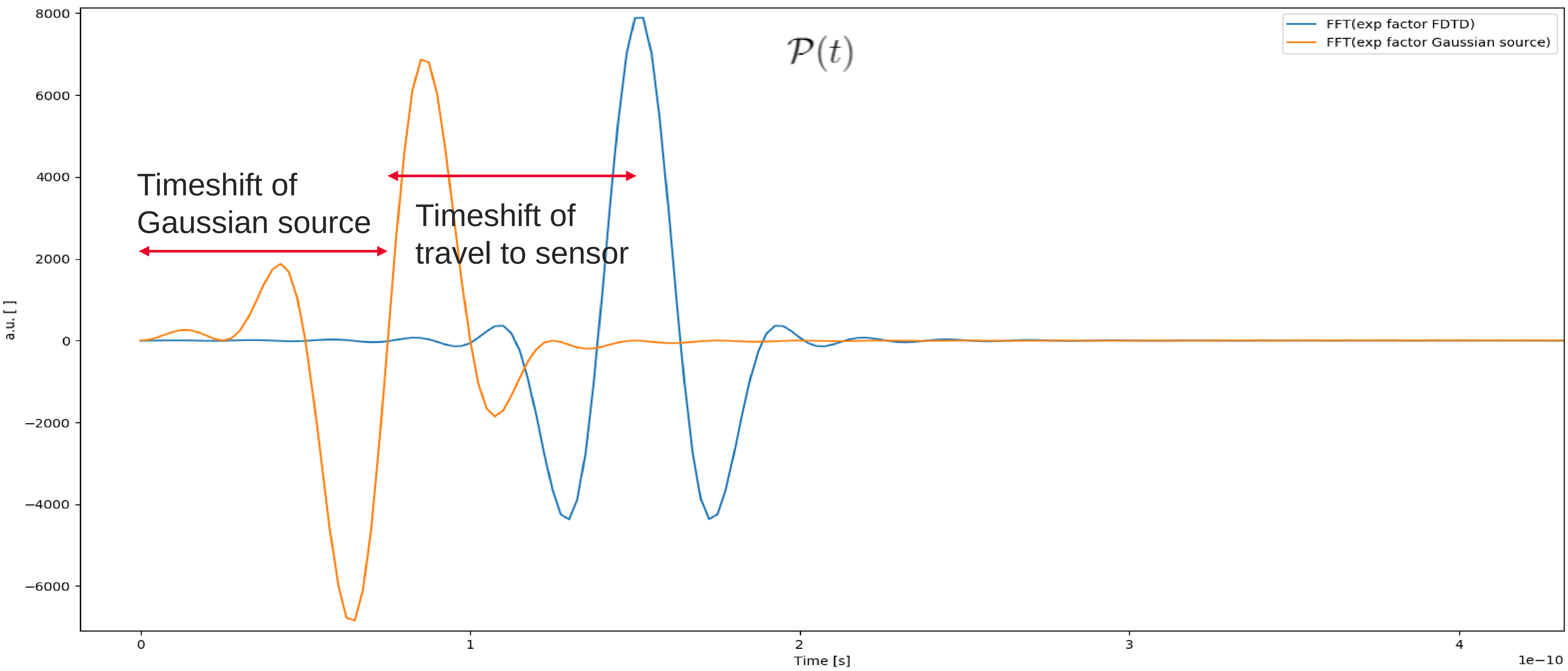
$$u_{\text{windowed}}(x,\omega) = u(x,\omega) * w(\omega)$$

$$\hat{u}(x,t) = \text{IFFT}(\text{deconvolve}(u_{\text{windowed}}(x,\omega), w))$$

Dummy simulation: PML addition

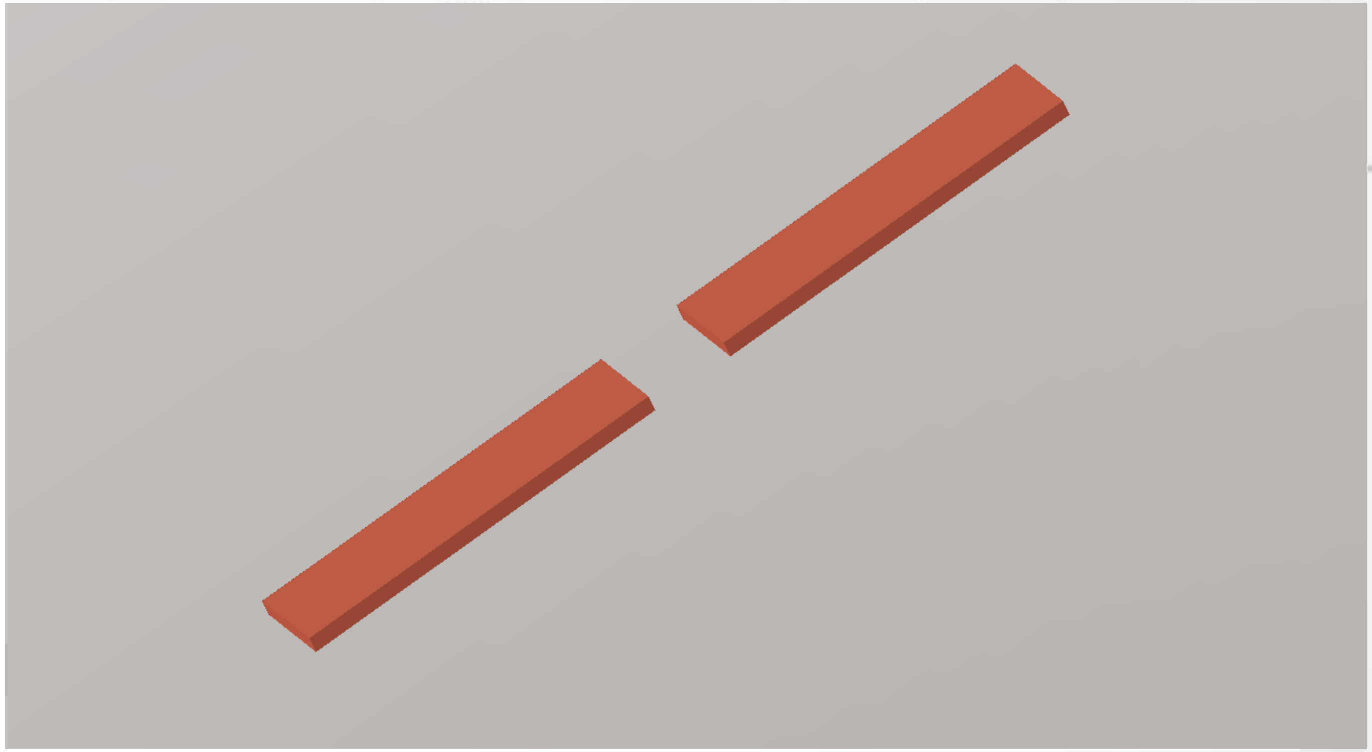
- FEM
  - Stretched coordinate PML [6]
  - $\tilde{x}(x,\omega) = x + \frac{\mathrm{i}}{\omega}\int_0^x \xi(s)\,\mathrm{d}s$ → $\Lambda_\omega(v,w) = -\omega^2 \int_\Omega v(x)\overline{w(x)}\tilde{\xi}(x,\omega)\,\mathrm{d}x + \int_\Omega \frac{\partial v(x)}{\partial x}\overline{\frac{\partial w(x)}{\partial x}}\frac{1}{\tilde{\xi}(x,\omega)}\,\mathrm{d}x.$
- Finite differences
  - Mur ABC for 1D: $u_N^{m+1} = u_{N-1}^m + \frac{r-1}{r+1}(u_{N-1}^{m+1} - u_N^m)$
- Exact
  - Available through Green's function [6]
- Only sure of correct implementation finite differences
  - Future work
  - Does the PML influence the phase?

Dummy simulation: PML addition

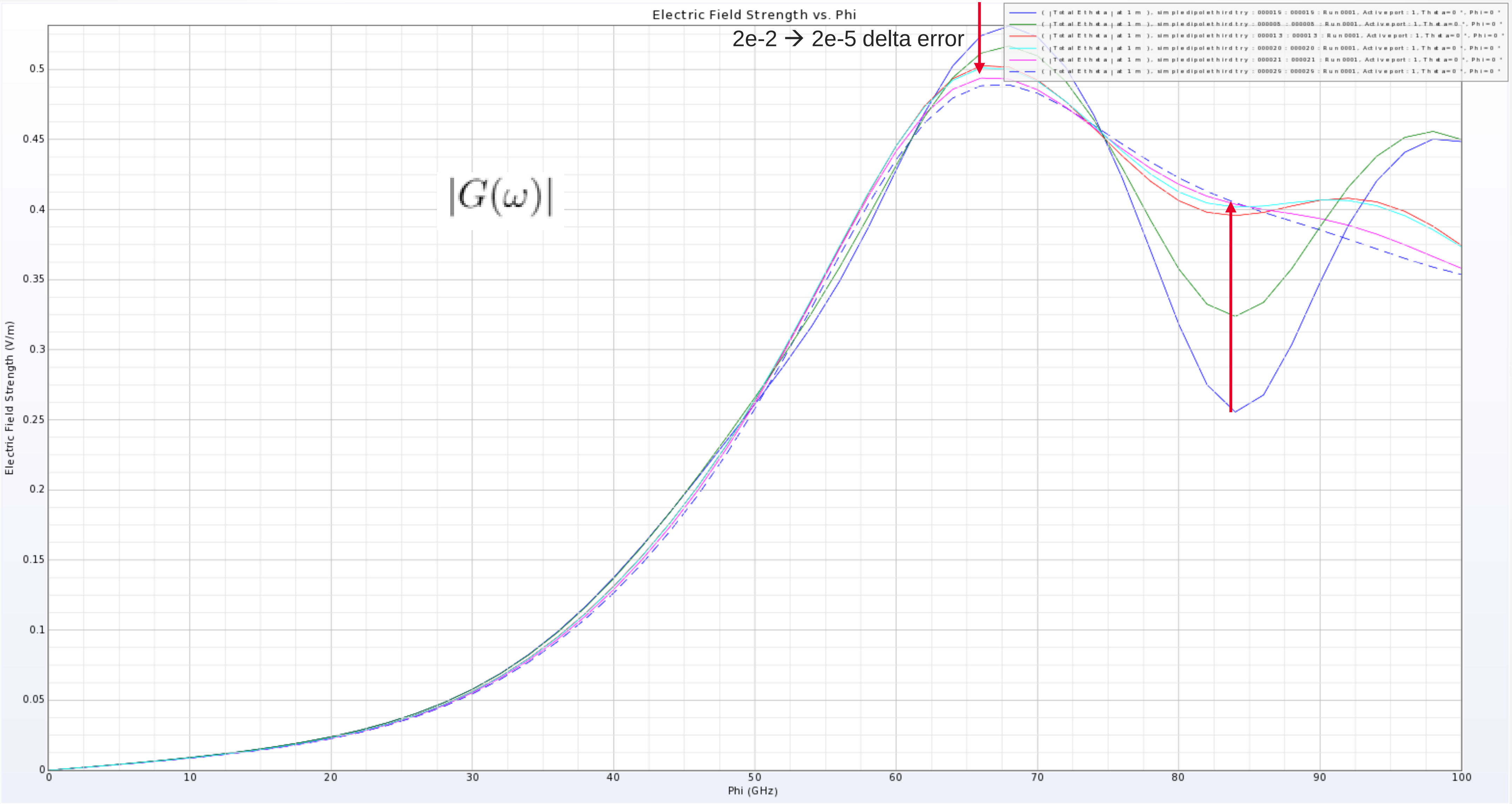


Simple dipole simulation

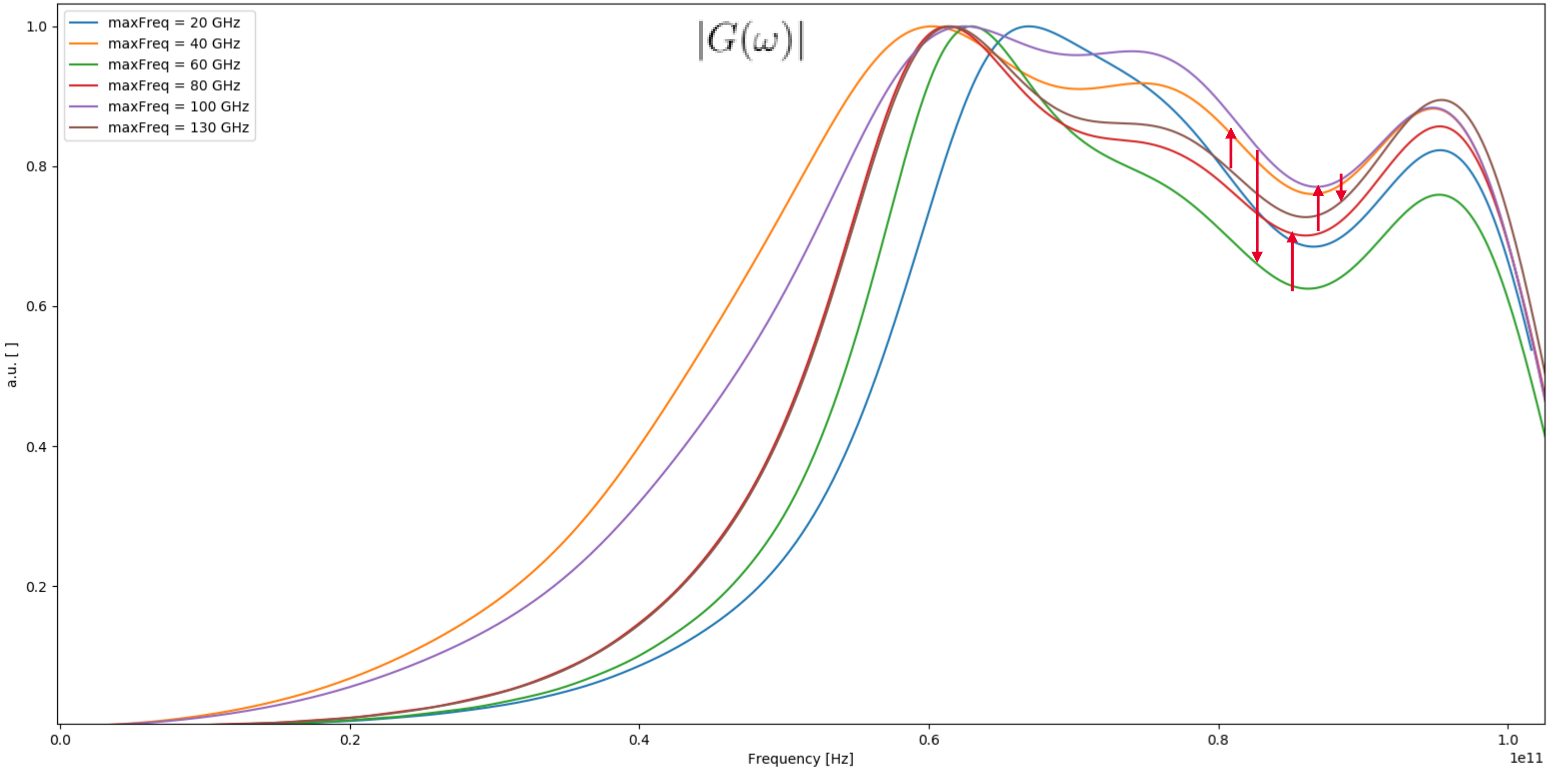
- 1 mm strips → resonance @ 75 GHz
- Very short to half-wavelength dipole
- Simple spectrum
- Much quicker computation times
- FEM converges much better
- FDTD converges better



Simple dipole simulation: FEM convergence



Simple dipole simulation: FDTD convergence



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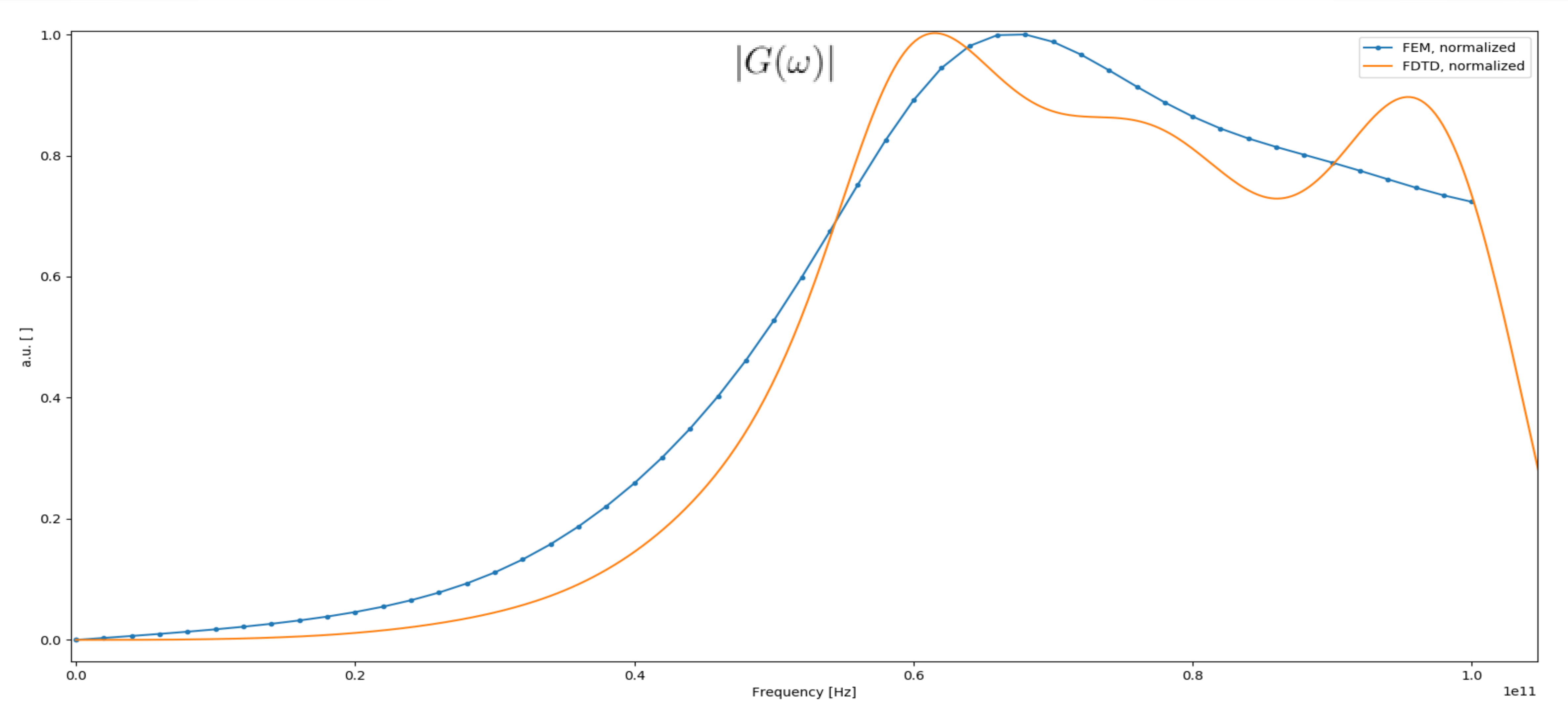
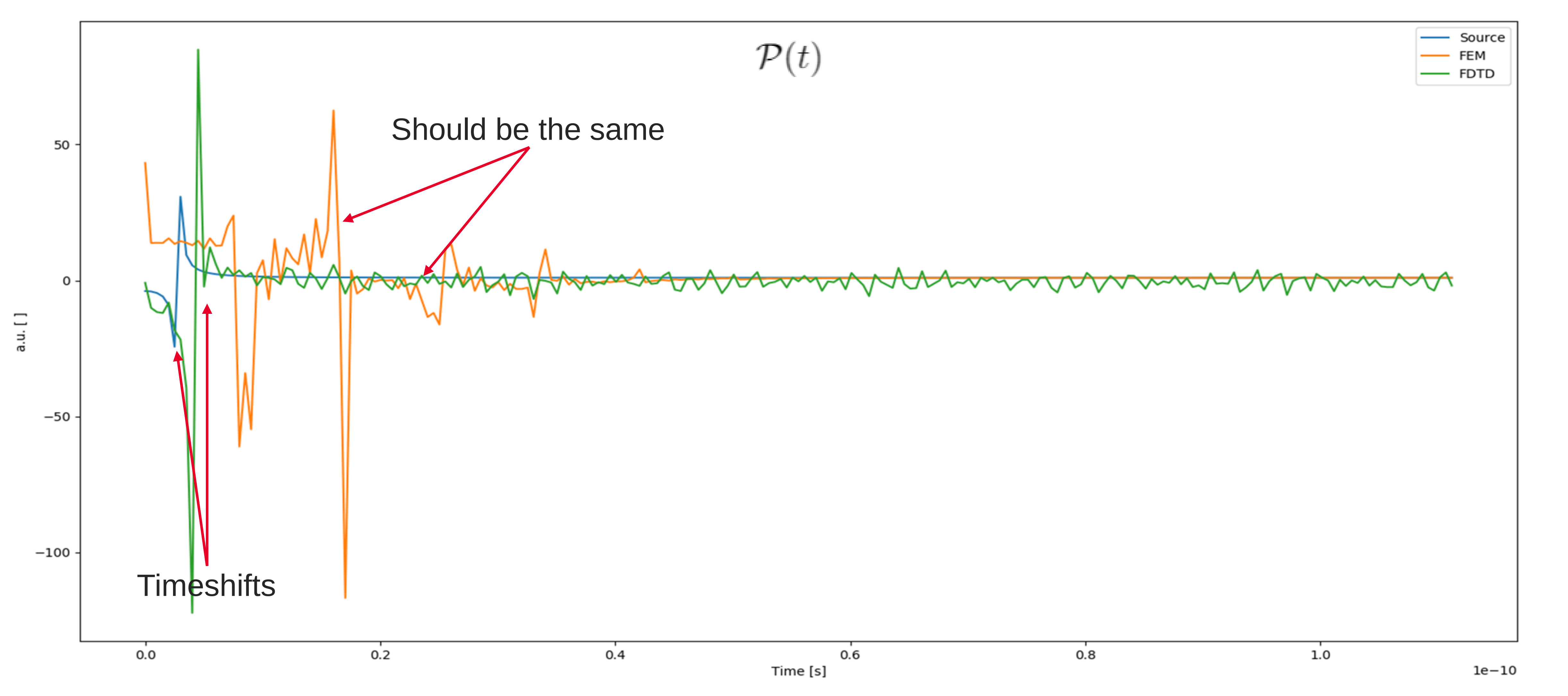
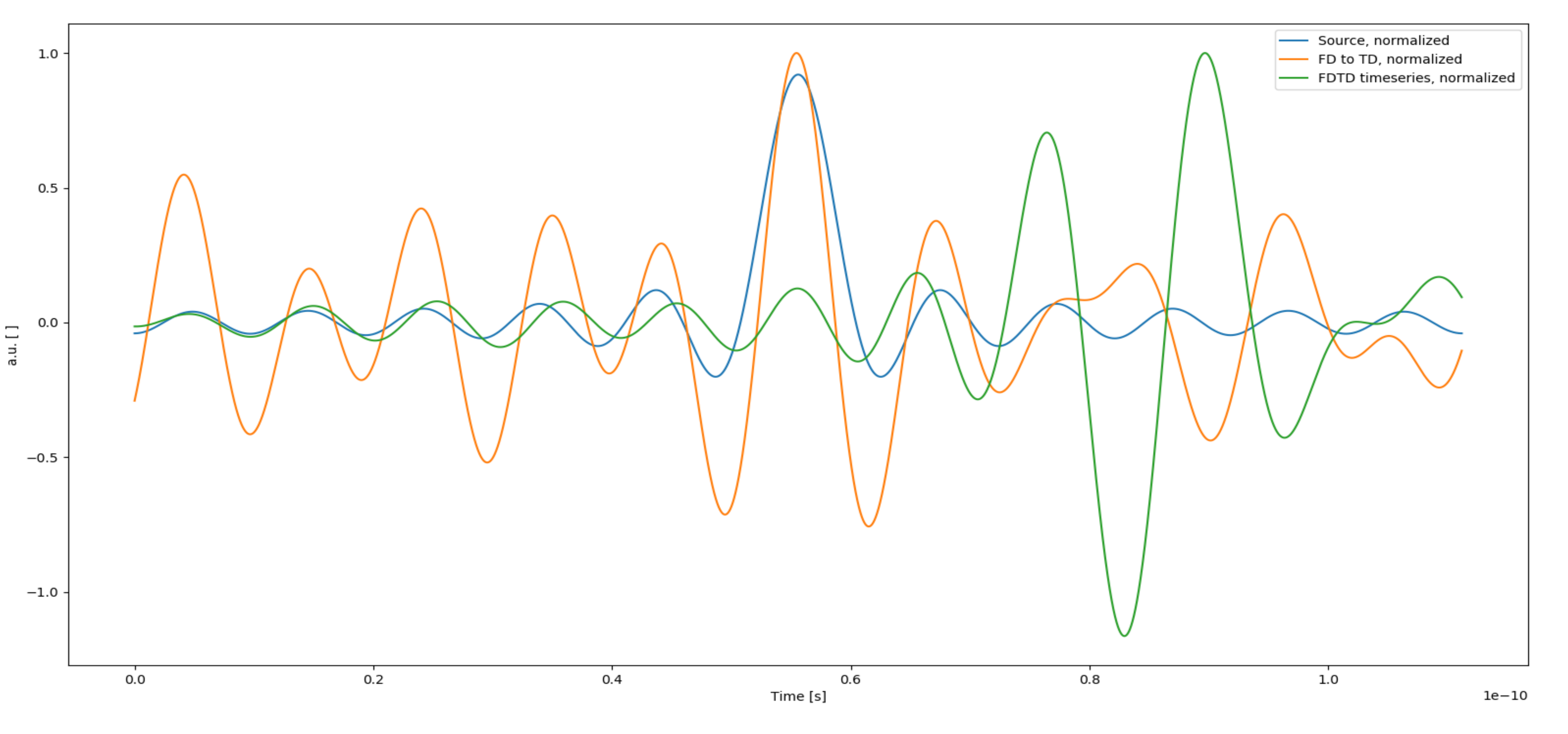
Simple dipole simulation: comparison



Simple dipole simulation: timeshift analysis



Simple dipole simulation: final result



Final thoughts & further work

- Almost always validation is through absolute values
  - University courses
  - Various papers
- Phase is hard to find
  - Substract timeshift by source and sensor
  - Correctly model $e^{-\jmath kr}$ and other phasedistribution
  - Examine convergence
  - Study numerical dispersion errors of each solver
- May need radically novel approach
  - Lead: possible by frequency and space FFT of near fields?
- Not a versatile tool
  - Convergence
  - Restrictions

$$\mathbf{a}(\mathbf{r}) = \mu_0 \int_V G\left(|\mathbf{r}-\mathbf{r}'|\right)\mathbf{j}\left(\mathbf{r}'\right)\mathrm{d}V' = \frac{\mu_0}{4\pi}\int_V \frac{e^{-\jmath k|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}\mathbf{j}\left(\mathbf{r}'\right)\mathrm{d}V'$$

$$\lim_{kr\to\infty}\mathbf{a}(\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{e^{-\jmath kr}}{r}\int_V e^{\jmath k\mathbf{u}_r\cdot\mathbf{r}'}\mathbf{j}\left(\mathbf{r}'\right)dV'$$

$$\lim_{kr\to\infty}\hat{\mathbf{a}}(\mathbf{r},t) = \frac{\mu_0}{8\pi^2}\int_{-\infty}^{+\infty}\frac{e^{-\jmath kr}}{r}\int_V e^{\jmath k\mathbf{u}_r\cdot\mathbf{r}'}\mathbf{j}\left(\mathbf{r}'\right)dV' e^{\jmath\omega t}\mathrm{d}\omega$$

Thank you for your attention

Questions or comments?

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