

High-Performance Computing in Electromagnetics

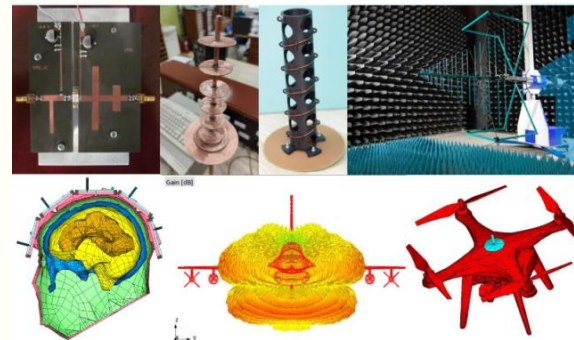
Group for Electromagnetics, Antennas and Microwaves

School of Electrical Engineering, University of Belgrade

Presenter: Dragan Olcan, Professor (olcan@etf.bg.ac.rs)

Contributors:

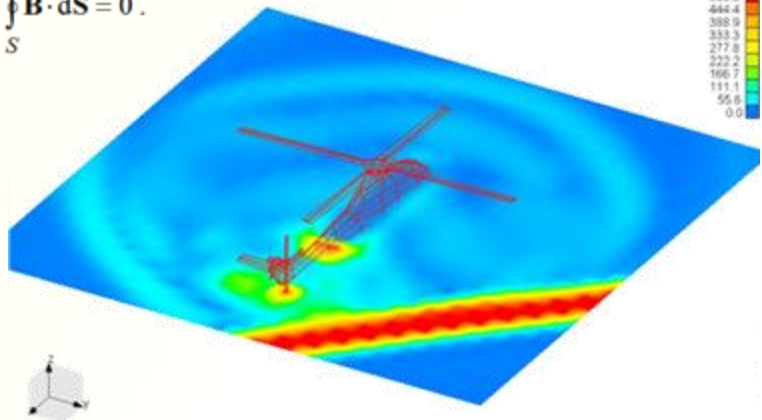
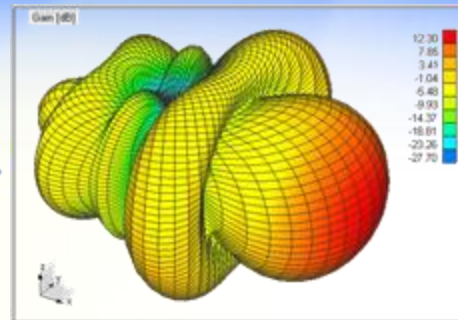
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Electromagnetics in General

- ~150 years ago J.C. Maxwell
A Treatise on Electricity and Magnetism
- Equations rewritten by Oliver Heaviside
- Computational model of all electric devices (on macroscopic level)
 - Kirchhoff's circuit laws are a special case
- Examples: light bulbs, mobile phones, microwave ovens, antennas, motors, computers, drones, radars, etc.
- The microscopic level (light & semiconductors) included by quantum electrodynamics ~1950

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = - \int_S \frac{d\mathbf{B}}{dt} \cdot d\mathbf{S},$$
$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \int_S \left(\mathbf{J} + \frac{d\mathbf{D}}{dt} \right) \cdot d\mathbf{S},$$
$$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_v \rho dv,$$
$$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0.$$



Computational Electromagnetics

- Solving Maxwell's equations **analytically** is possible only for very simple structures (integral and differential equations)
- Computers made a revolution in EM about 70 years ago
- **Computational electromagnetics** = using computers to design and analyze EM sources & fields
- Linear EM system is transformed into a set of linear equations (MoM or FEM): solutions are coefficients in approximation of charges, currents or electromagnetic fields
- **Linear** CEM problem = Integration + linear algebra @ full steam
 - LAPACK library, <https://www.netlib.org/lapack/>
 - INTEL Math Kernel Library (MKL), <https://www.intel.com/content/www/us/en/developer/tools/oneapi/onemkl.html>
 - NVIDIA cuBLAS, CUDA , <https://developer.nvidia.com/cublas>
- Solving **nonlinear** CEM problem = heuristics
- PhD in CEM = EM + programming + high-performance computing

The image displays two screenshots of web pages. The top screenshot is the LAPACK website, titled 'LAPACK — Linear Algebra PACKage'. It features a 'Menu' section with links to 'Presentation', 'Software', 'Licensing', 'Standard C language APIs for LAPACK', 'LAPACK for Windows', 'GIT Access', 'Support', 'Contributors', 'Documentation', 'Release Notes', 'Improvements and Bugs', 'FAQ', 'Browse, Download LAPACK routines with on-line documentation browser', 'Users' Guide', 'Manuals', 'LAPACK Working Notes', and 'Release History'. The bottom screenshot is the Intel oneAPI Math Kernel Library (oneMKL) website. It has a navigation bar with 'Overview', 'Download', and 'Documentation & Resources'. Below the navigation bar is a section titled 'Get Intel® oneAPI Math Kernel Library (oneMKL)' with a 'Download' button. The main content area describes the library as an 'Offline' library that 'Accelerate math processing routines, increase application performance, and reduce development time.' It also mentions that for the most current functional and security features, users should update to the latest version. There is a 'Download' section with a link to 'Register your product to receive update notifications plus hand-curated technical articles, tutorials, and training opportunities to help you optimize your code.' Below this is a section for 'cuBLAS' titled 'Basic Linear Algebra on NVIDIA GPUs'. It includes buttons for 'Download', 'Documentation', 'Samples', 'Support', and 'Feedback'. The text below these buttons states: 'NVIDIA cuBLAS is a GPU-accelerated library for accelerating AI and HPC applications. It includes several API extensions for providing drop-in industry standard BLAS APIs and GEMV APIs with support for fusions that are highly optimized for NVIDIA GPUs. The cuBLAS library also contains extensions for batched operations, execution across multiple GPUs, and mixed- and low-precision execution with additional tuning for the best performance.' At the bottom, it says 'The cuBLAS library is included in both the NVIDIA HPC SDK and the CUDA Toolkit.'

Just as we speak in IEEE AP

- Benchmarking CEM codes
 - Accuracy and
 - Speed
- Standard
 - EM Problems
 - Computers

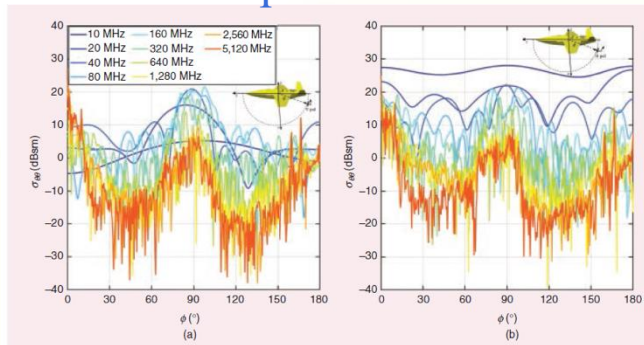
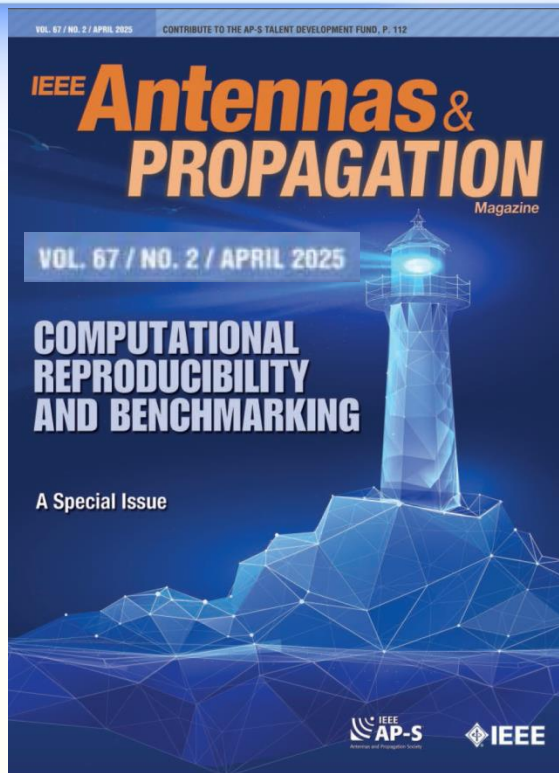


FIGURE 7. The reference monostatic (a) VV- and (b) HH-polarized RCS patterns of the L ≈ 49-ft-long PRIME aircraft calculated using method 2 at every 0.5° in azimuth with the denser meshes shown in Figure 2(d). As computing the reference results with the denser mesh was infeasible at 5,120 MHz, the RCS patterns shown are those generated using mesh FF instead.

May 20th, 2025



EuroCC4SEE Workshop in Belgrade

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4/20

Machine Precision in CEM (Conversion to Linear Equations)

- Numerical solutions down to machine precision
- 64-bit yields max. 15 significant digits
- Novel algorithms for numerical integration are developed

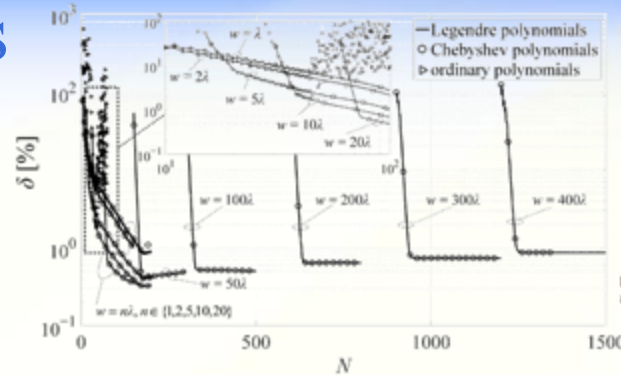


Fig. 16. Estimates of the maximum error δ for curvilinear strips of various lengths of the cross-section contour for three sets of basis functions.

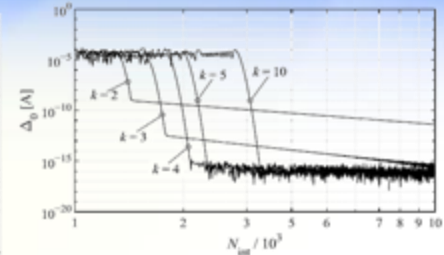


Fig. 8. Estimation of the absolute error of the integral for a curvilinear strip and $w = 400l$, and the order of Legendre polynomial $q = 200$.

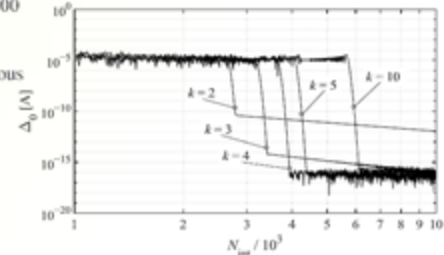


Fig. 9. Estimation of the absolute error of the integral for a curvilinear strip and $w = 400l$, and the order of Legendre polynomial $q = 1350$.

J. G. Perović, D. I. Olćan, B. M. Kolundžija and A. R. Djordjević, "A Singularity Cancellation Transformation for Entire-Domain Analysis of 2-D Structures With High-Precision Integration," *IEEE Transactions on Antennas and Propagation*, 2019, doi: 10.1109/TAP.2019.2891401

High Accuracy: 24hrs on Desktop PC

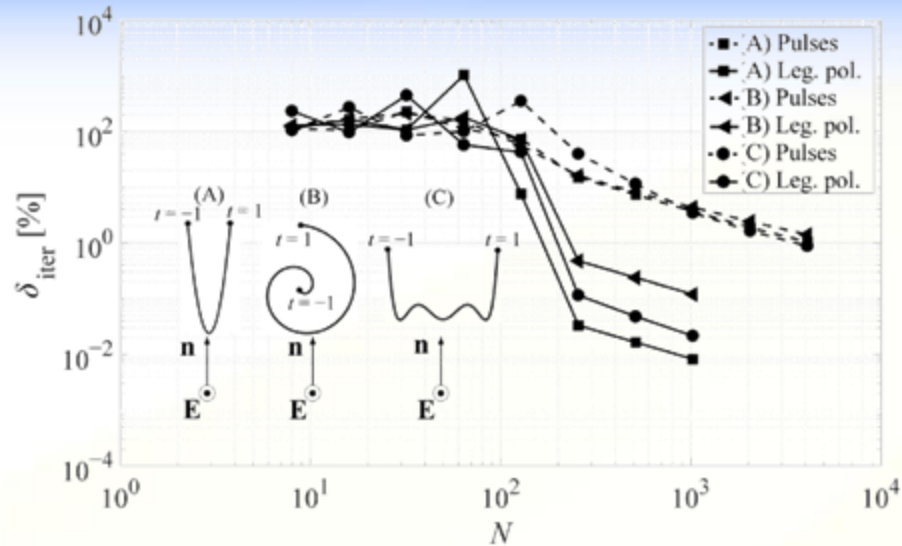


Fig. 17. Improvement of the approximation of currents on three strips with different opened cross sections in the case of pulses (dotted lines) and Legendre polynomials (bold lines).

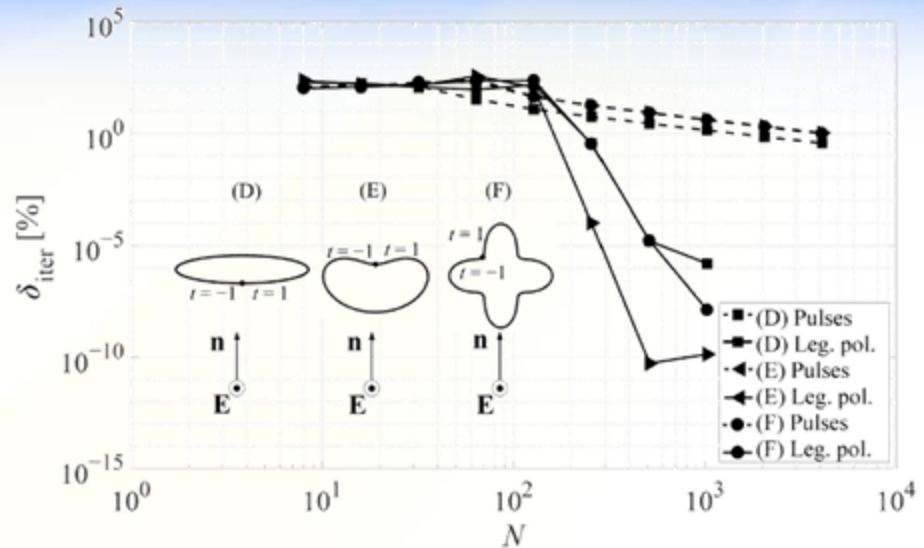
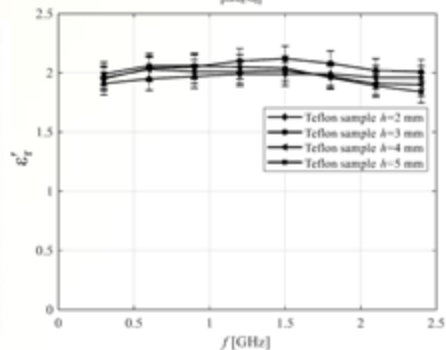
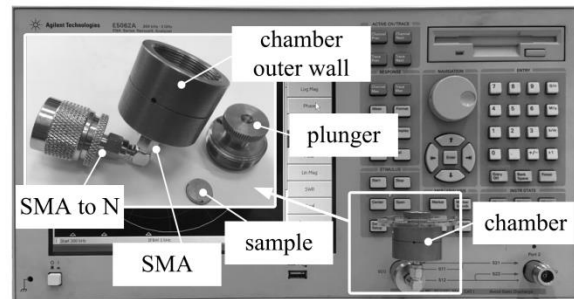
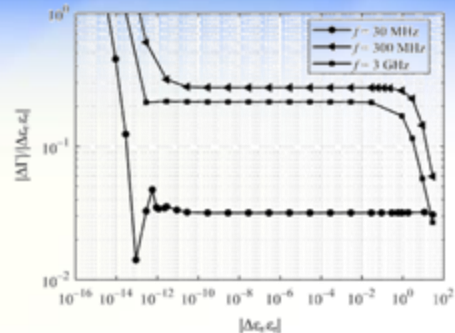
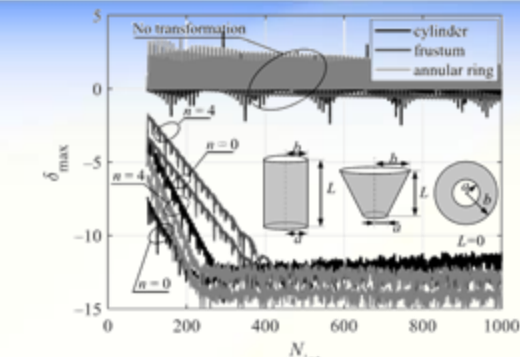


Fig. 18. Improvement of the approximation of currents on three strips with different closed cross sections in the case of pulses (dotted lines) and Legendre polynomials (bold lines).

EM Parameters of Materials

- Extraction of EM parameters of materials
- Step 1: measurements
- Step 2: accurate EM ~2 days of simulation
- Step 3: extraction from steps 1 & 2



J. G. Petrović, D. I. Olćan, N. N. Obradović and A. R. Djordjević, "High-Precision Method of Moments Applied to Measurement of Dielectric Parameters at Microwave Frequencies," *IEEE Transactions on Microwave Theory and Techniques*, 2022, doi: 10.1109/TMTT.2021.313629

Antenna Design Needs HPC!

- IRA: Impulse radiating antenna
- Design, prototype & measurements
- 2 weeks of design using HPC cluster: 48 CPUs+256 GB RAM + 4 GPUs

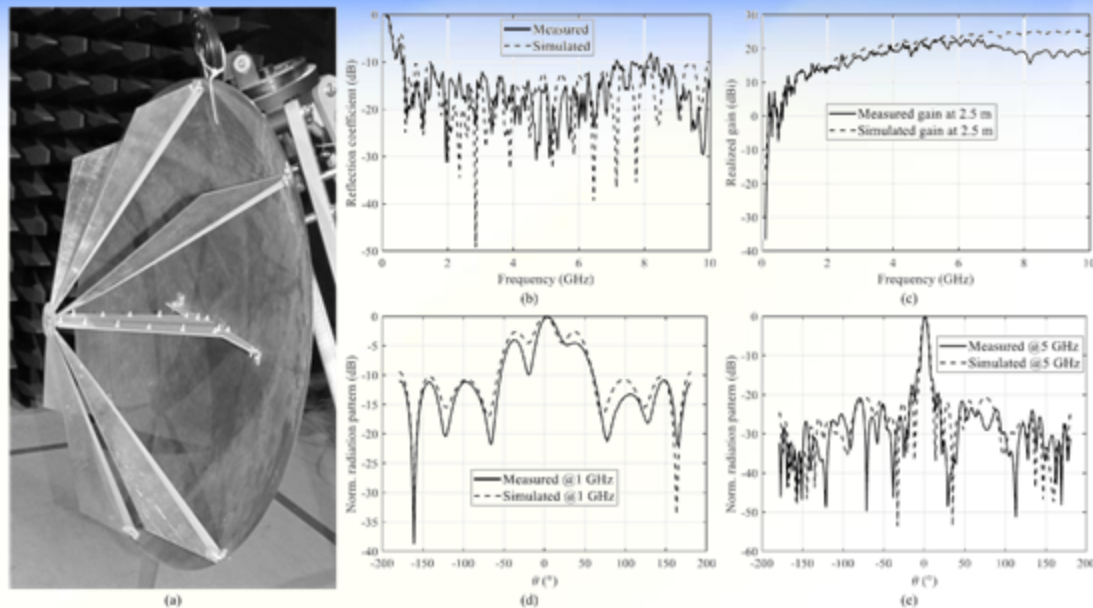
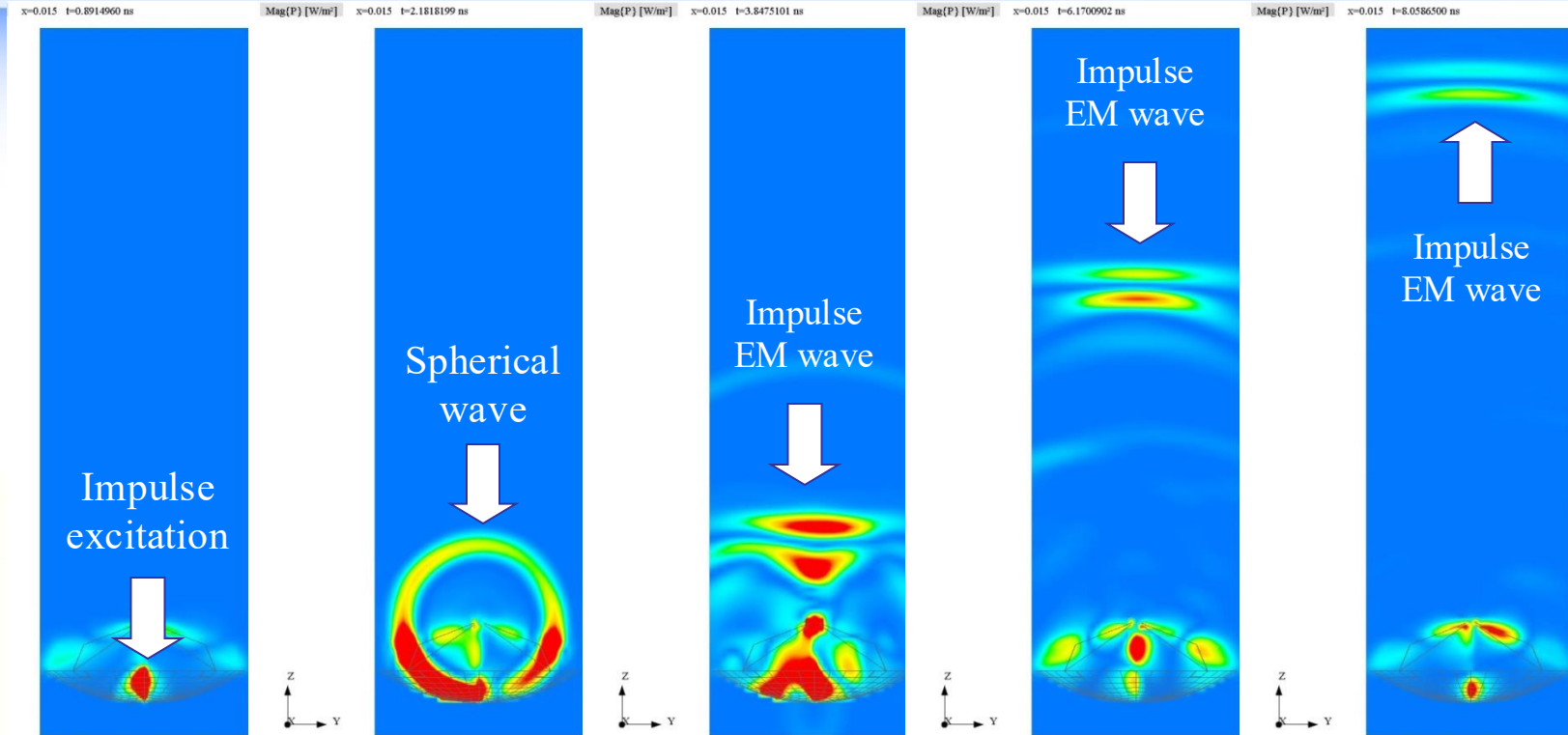


Fig. 15. (a) Photograph of the fabricated prototype and comparison of the measured and calculated results of (b) reflection coefficient, (c) realized gain, (d) normalized radiation pattern in the E-plane at 1 GHz, and (e) normalized radiation pattern in the E-plane at 5 GHz.

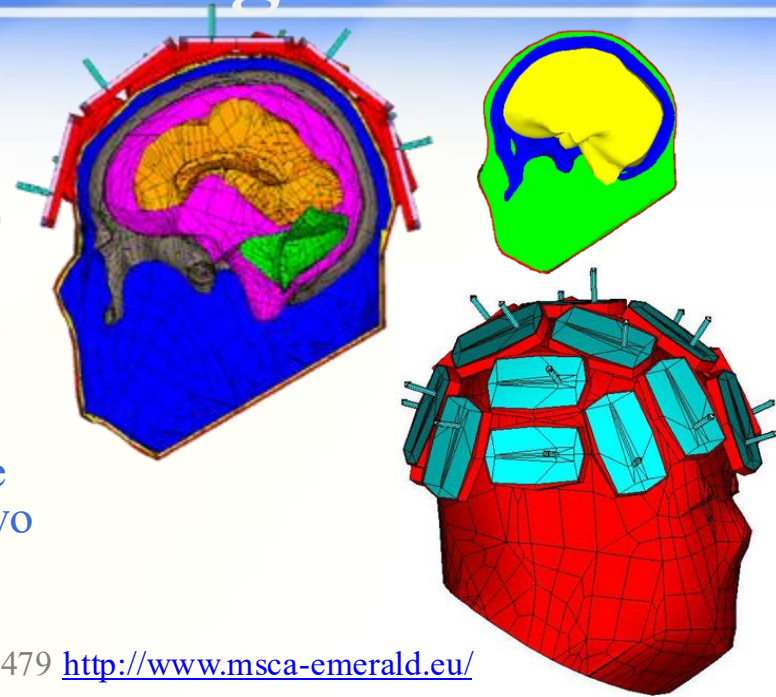
M. F. Miletić and D. I. Olćan, "Impulse Radiating Antenna With Six Feeding Arms and a Tapered Balun," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 8, pp. 6414-6422, 2022, doi: 10.1109/TAP.2022.3161572

For every pixel: CEM+DFT=12hrs



Microwave Imaging: Non-invasive Medical Diagnostics

- 3D Distorted Born iterative method for brain imaging (brain tumor detection)
- 7 head tissues are estimated in 20 iterations using coarser grid (60 minutes each) and additional 10 iterations using finer grid (105 minutes each)
- Intel Core i7-9700 CPU @3 GHz 8 cores, whole analysis lasted about 37.5 hours
- Child phantoms: about 5 hours of simulation time per phantom with 4 tissues on a computer with two Intel® Xeon® Gold 6342 CPU @2.80 GHz (96 threads in total) and 1024 GB of RAM.

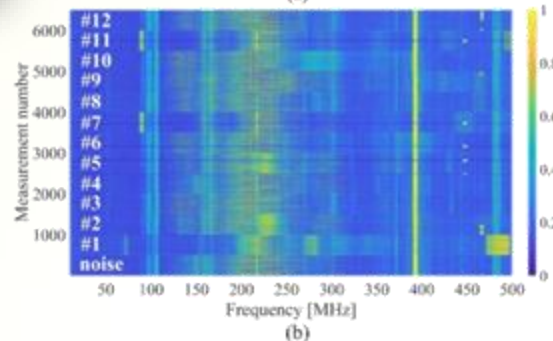
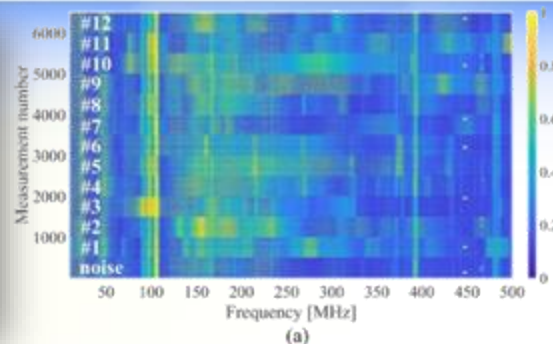
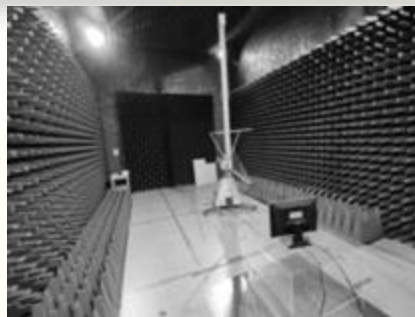


EU Horizon 2020: EMERALD Grant agreement ID: 764479, DOI 10.3030/764479 <http://www.msca-emerald.eu/>

T. Singh, D. M. Ninkovic, B. M. Kolundzija and M. N. Stevanovic, "Smooth Polynomial Approach for Microwave Imaging in Sparse Processing Framework," *IEEE Access*, vol. 10, pp. 120616-120629, 2022, doi: 10.1109/ACCESS.2022.3217221

AI-Assisted Identification of Monitors

- Identifying monitor state & type based on emanated EM fields
- Technique based on (MLP) neural networks
- 12 monitors measured: 30,000 frequency spectrums with 501 components each
- Trained ANNs identify monitor with the accuracy of 99%!
- Training of 100 ANNs lasted 19.5 hours using Intel Core i7-9700 CPU @3 GHz with 8 cores



D. M. Ninković and D. I. Olćan, "AI-Assisted Identification of State and Type of Flat-Panel Monitors in the Presence of EM Noise," *IEEE Transactions on Electromagnetic Compatibility*, 2024, doi: 10.1109/TEMPC.2024.3370653

Machine Learning and AI for Antenna Modeling

- ML models to model highly nonlinear relations (EM output vs. parameters)
- Large datasets (100 million) Yagi-Uda antennas for training: 2 weeks of run time @ Intel® Xeon® Gold 6342 CPU / 96threads 1TB of RAM

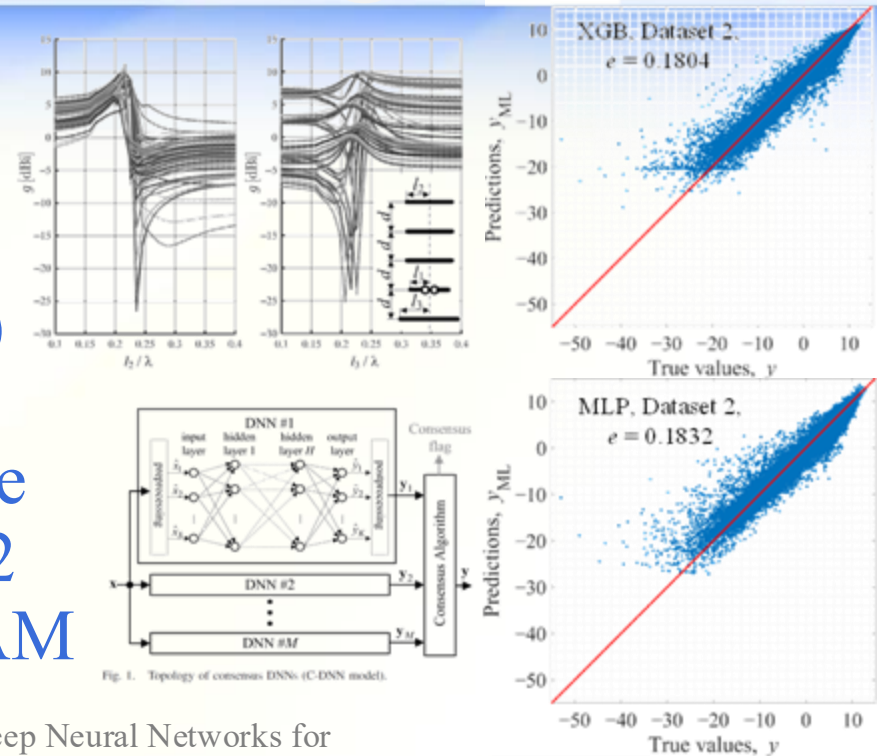
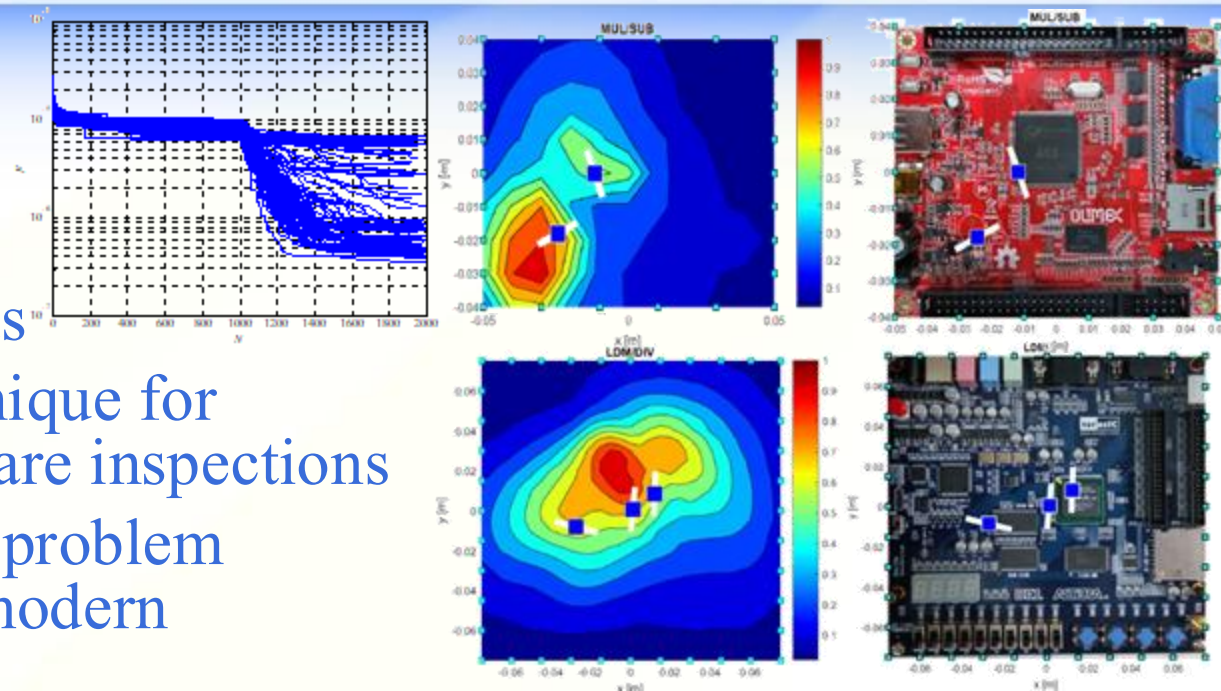


Fig. 1. Topology of consensus DNNs (C-DNN model).

Localization of Field Sources due to Instruction Execution in Processor

- Finding executed instruction in a processor based on EM fields
- Noninvasive technique for hardware & software inspections
- Nonlinear inverse problem utilizing CEM + modern heuristics to solve

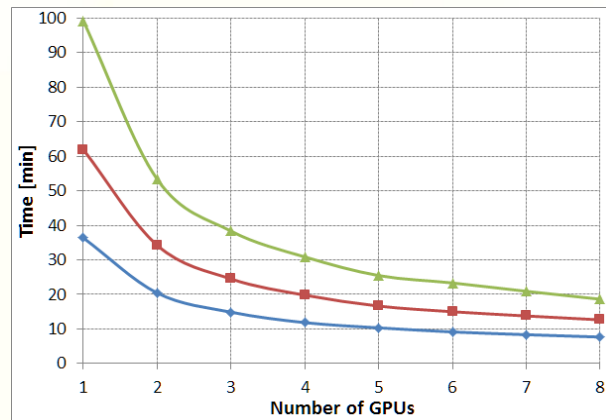
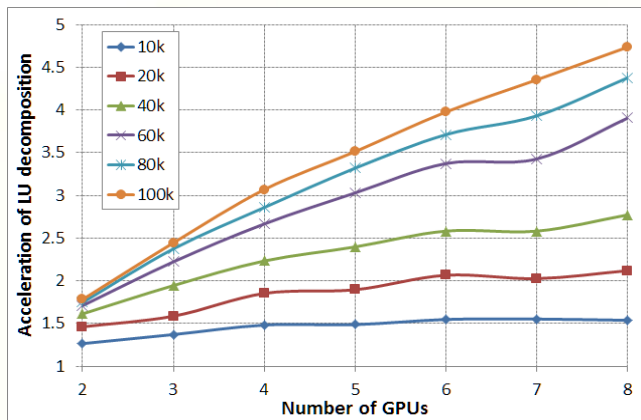


F. Werner, D. Chu, A. Djordjević, D. Oléan, M. Prvulovic and A. Zajić, "A Method for Efficient Localization of Magnetic Field Sources Excited by Execution of Instructions in a Processor," *IEEE Transactions on Electromagnetic Compatibility*, 2018, doi: 10.1109/TEMPC.2017.2742501

GPU Solver: Large Problems

- Computer configuration
 - Intel Xeon CPU E5-2660 v2 @2.2GHz (2 processors) + 256 GB of RAM
 - 4 SATA HDDS (~100MB/s RW speed)
 - 8 identical GPUs GeForce GTX 680
 - GPUs are placed in the Cubix XPRM-G3-82A GPU Xpander

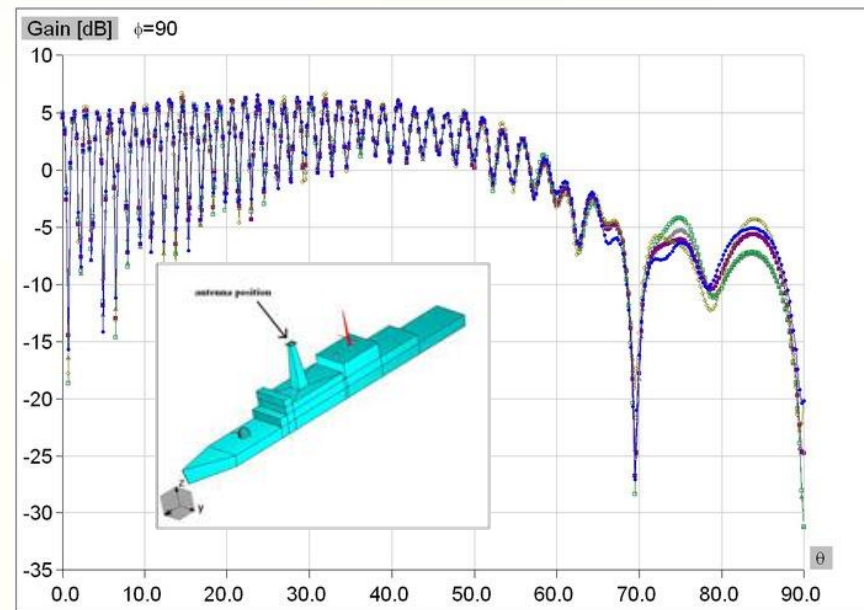
Acceleration for 10k to 100k problems Simulation time for 100k to 140k problem



Large Structure: Smart Reduction

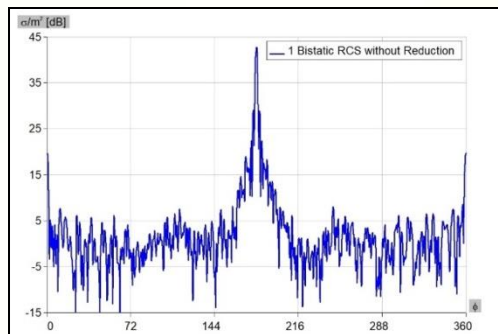
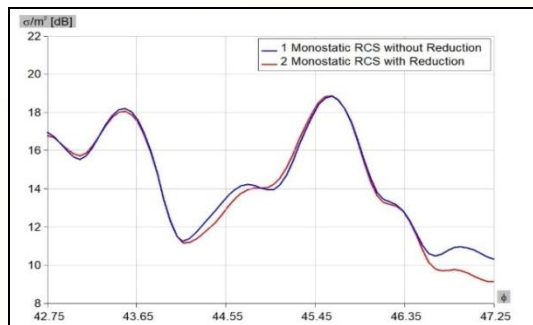
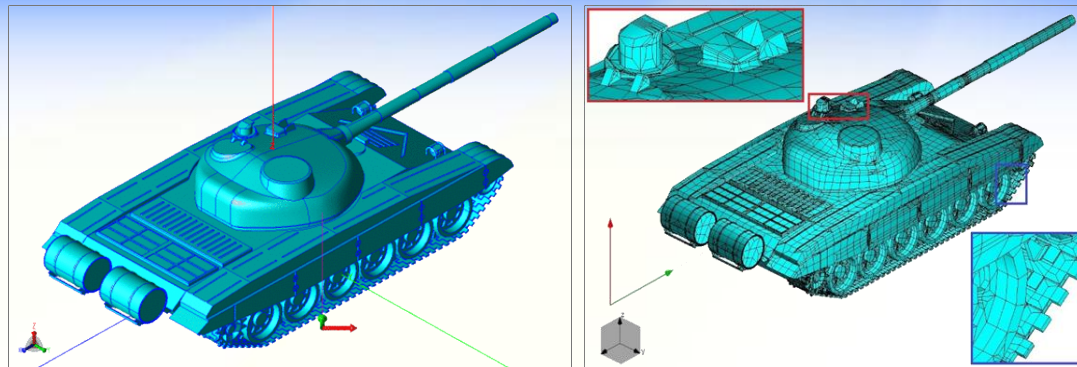
- Frigate warship, 117 m long and 12.6 m wide
 - A monopole antenna is placed on top of a 24 m high comm. tower
 - The frigate is around 100λ long
- **Significant reduction in number of unknowns and simulation times**
 - Negligible discrepancies in the calculated radiation pattern

Number of unknowns	Memory [GB]	Sim. time CPU	Sim. time GPU
86 894	56.3	8.39 h	1.12 h
64 147	30.7	3.88 h	31 min
51 844	20	1.6 h	11.4 min
40 125	12	45 min	6.4 min
33 564	8.4	26.6 min	4.7 min



Amazon Cloud Server: RCS of Tank

- **Bistatic RCS** at 1,801 directions (20.8 hrs)
- **Monostatic RCS** at 70 directions (6.9 hrs)
- Frequency of **3.6 GHz**
- Reduction of ref. frequency and total shadow
- Matrix fill-in and output results - CPU
- Matrix inversion - GPU



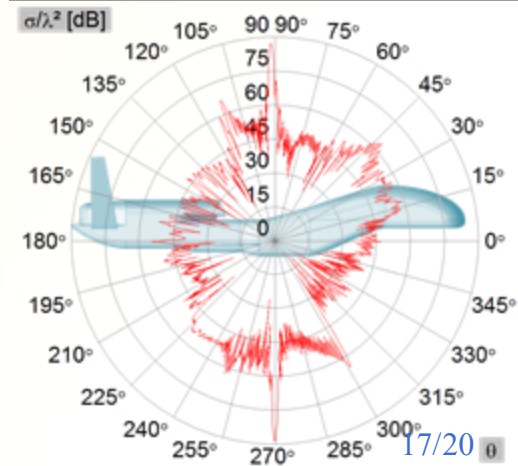
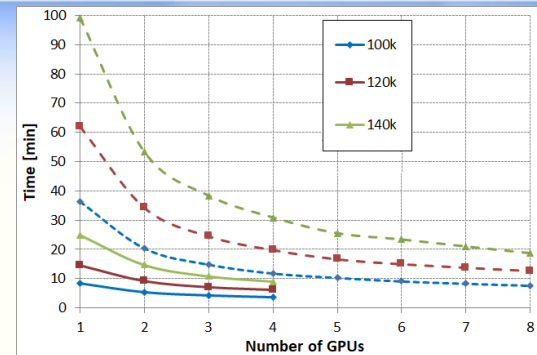
- **Amazon cloud server**
- CPU: Intel Xeon E5-2686 v4 @ 2.3 GHz (2 processors)
- **64 threads**, RAM: 488 GB
- HDD: 3 Hard disks, 1000 MB/s
- GPU: **8 x Tesla V100**

GPU Cluster: Large Problems

- Acceleration of all phases of an EM simulation
- Arbitrary number of:
CPU threads, GPUs, GPU cluster nodes
- Matrix solve time for 100 – 140k unknowns:
3.7 minutes for 100k unknowns on 4 GPUs

Global hawk – Monostatic RCS (8.2 hours)

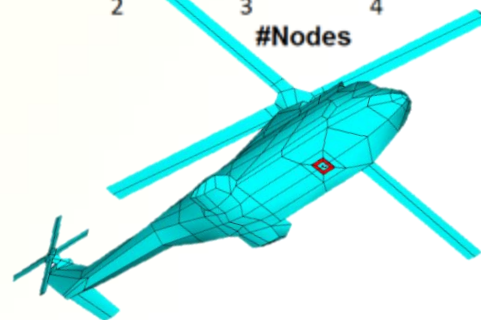
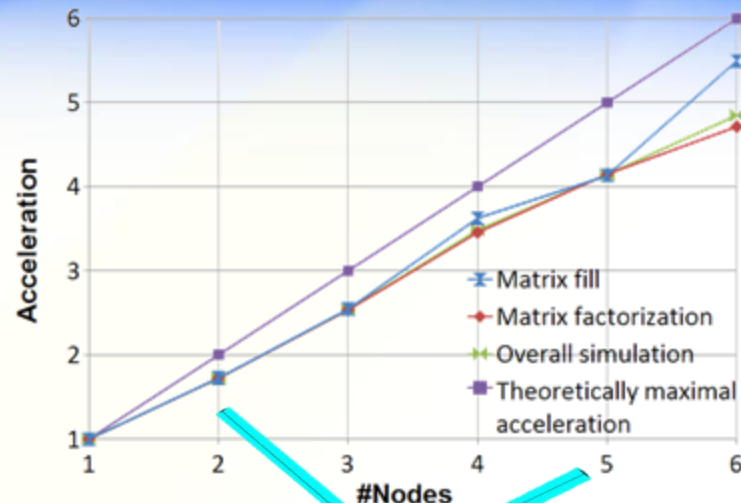
- Unknowns: 546k $f = 5$ GHz
- Wing span: 36 m (600λ)
- **Cluster:** 8 nodes x 2 GPUs each
(GeForce GTX 680 GPU card)



GPU Cluster: Solver Scalability

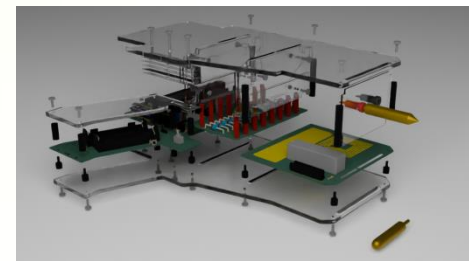
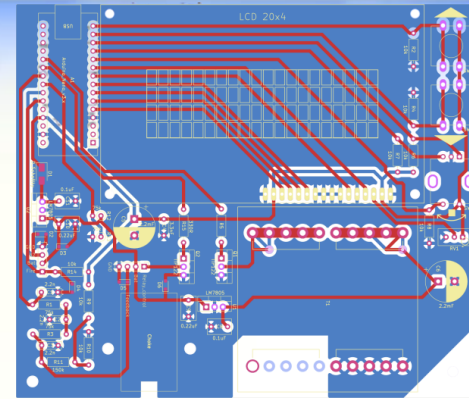
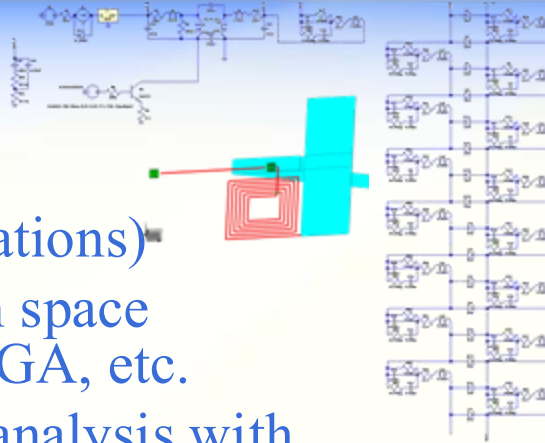
- Helicopter with one microstrip patch antenna on the fuselage at 1.8 GHz
- Efficiency: (achieved acc.)/(max acc.)
- Matrix fill efficiency > 83%
- Matrix factorization efficiency 79%
- **Overall simulation efficiency > 80%**

#Nodes	Matrix fill			Matrix factorization			Overall Simulation		
	Time [s]	Acc.	Eff. [%]	Time [s]	Acc.	Eff. [%]	Time [s]	Acc.	Eff. [%]
1	3726	-	-	15338	-	-	19064	-	-
2	2160	1.73	86	8914	1.72	86	11074	1.72	86
3	1465	2.54	85	6053	2.53	84	7518	2.54	85
4	1028	3.62	91	4440	3.45	86	5468	3.49	87
5	902	4.13	83	3697	4.15	83	4599	4.15	83
6	678	5.50	92	3254	4.71	79	3932	4.85	81



Optimizations (Heuristics) in Design

- Running one CEM analysis is just a beginning
- Design = multiple iterations in the design space (optimizations)
- Modern heuristics for design space searches: GA, DE, PSO, NSGA, etc.
- Transient non-linear circuit analysis with ~200 elements = 2GB of data on HDD
- Optimal route for drilling holes in PCB
165 drilling holes: $165! = 5.4 \cdot 10^{295}$ paths to search
- Running @ 200PFlops $\sim 1.7 \cdot 10^{273}$ years of calculations!



Horizon Europe, NGI Zero Core: Open-Hardware for Electrostatic Discharge Testing (O-ESD) 2024-2025, <https://o-esd.etf.bg.ac.rs>

Conclusions

- High-performance computing is **indispensable tool** in computational electromagnetics
- **State-of-the-art research** in EM (and electrical engineering) is **entangled with high-performance computing**
- Changes in industry and academia: desktop computers used for preparing models but actual computations done at HPC installations
- Challenges ahead:
 - running existing CEM codes on emerging HPC hardware
 - efficient implementation of CEM algorithms on HPC architectures
 - managing HPC resources (technical + economics aspects)
 - minimizing power consumptions
 - capital expenditures (capex) & operational expenditures (opex)