# Computationally Efficient Technique for Wide-Band Analysis of Grid-Like Spatial Shields for Protection Against LEMP Effects

**Andrzej Karwowski, Artur Noga, and Tomasz Topa**

Institute of Electronics
Silesian University of Technology (SUT), Gliwice, 44-100, Poland
andrzej.karwowski@polsl.pl, artur.noga@polsl.pl, tomasz.topa@polsl.pl

***Abstract*** **─** This paper introduces a heterogeneous CPU+GPU co-processing implementation of the method of moments (MoM) for broadband full-wave electromagnetic analysis of grid-like spatial shields for protecting structures against LEMP effects. Broadband capacity of the approach is achieved through supporting MoM by adaptive frequency sampling and implicit rational interpolation of the observed quantity via Stoer-Bulirsch algorithm. The overall application performance is increased by hardware acceleration, i.e., by employing CPU+GPU co-processing. Sample numerical results for a lightning protection system directly hit by lightning show that reliable rational interpolation can be done at substantially reduced computational effort compared to that of conventional uniform sampling, and the CPU+GPU co-processing offers additional noticeable speedup over the CPU single-thread implementation of the method.

***Index Terms*** **─** CPU+GPU co-processing, grid-like shield, lightning protection system, method of moments, rational interpolation, Stoer-Bulirsch algorithm.

## I. INTRODUCTION

Wire meshes in the form of spatial grid-like structures are widely used as lightning protection systems (LPS) designed to reduce aggressive high-intensity electromagnetic (EM) effects caused by lightning strikes. For effective design of LPS, prediction of its response to lightning induced electromagnetic excitation is of vital importance. Therefore, a considerable research effort has been devoted over the last years to the development of accurate and efficient techniques for EM analysis of complex LPSs. For spatial grid-like structures composed of arbitrarily arranged conductors, perhaps the best choice is the full-wave method of moments (MoM) formulated in the frequency domain (FD) [1]. When a wideband response of a structure is required, the investigation is usually carried out by point-by-point frequency swept computations, i.e., evaluation of samples of the required physical observable over a predefined set of uniformly spaced frequency nodes. The approach is computationally inefficient, since EM simulation must be performed repeatedly at many frequencies resulting in that the computation time can be unacceptably long for complex resonant structures. Among available approaches aimed at reducing the number of EM simulations needed for reconstruction of the system response, and thus, minimizing the overall processing time is the rational-function interpolation approach based upon the assumption that the system response can be represented by a rational polynomial [2]. The approach usually involves adaptive procedures for selecting the interpolation nodes and the rational interpolant order. In this study, we employ an adaptive frequency sampling (AFS) technique based upon interval halving (bisection) in combination with the rational interpolation implemented through Stoer-Bulirsch (SB) algorithm [3]. The details of the formulation are given in [4, 5].

Till the end of Pentium IV era, the possibility of MoM-based wide-band simulation of LPS structures on PC-based workstations was seriously limited. For example, the runtime needed for a wide-band simulation from 1 kHz to 20 MHz of a single-layer grid-like LPS type 1 (10 m × 10 m × 10 m) [6] discretized into 2224 wire segments was about one week [7]. The situation has changed dramatically with the introduction, about 2006, of powerful multi-core CPU technologies and the unified graphics and computing Graphics Processing Unit (GPU) architecture known as Nvidia CUDA (Compute Unified Device Architecture). Multi-core processors and CUDA-enabled GPUs offer an inexpensive massively parallel programmable hardware platform very attractive for use in scientific computing. It is now well known that by extending a traditional CPU-based computation model through adoption of the General-Purpose computing on GPU (GPGPU) paradigm, the performance of EM simulations can be remarkably increased.

In this paper, a CUDA-enabled heterogeneous CPU+GPU co-processing implementation of the method of moments supported by AFS and implicit rational interpolation for electromagnetic simulation of grid-like lightning shields over a wide frequency band is outlined.

*Submitted On: October 24, 2015*
*Accepted On: November 5, 2016*

The approach employs the technique described in [8] for mapping CPU sequential MoM procedures to parallel GPU platform. For consistence of presentation, we briefly summarize partial concepts of the overall approach including AFS-SB algorithm and CUDA-based CPU+GPU implementation of the relevant computer program. The potential of the approach is demonstrated by a numerical example involving grid-like LPS under direct strike.

The key components of a hardware platform engaged in this study were the Intel Core i7-3820 Quad-Core Processor and GeForce GTX 680 graphics card. Software tools included Intel Fortran, PGI Fortran, CULA and Intel MKL libraries. The overall approach constitutes an example of the integration of the advanced computational electromagnetics technique with modern architecture of a rather typical low-cost PC-style workstation for the purpose of increasing efficiency of the application-oriented EM simulator.

## II. METHOD

### A. Matrix approximant to the integral equation

The approach outlined in this paper adopts (for wires) the frequency-domain mixed-potential electric field integral equation (EFIE) formulation developed in [9] for analyzing an arbitrary configuration of conducting bodies and wires. For the sake of completeness, the formulation is briefly outlined here.

For a wire residing in a simple medium $(\varepsilon, \mu)$ and illuminated by an incident time-harmonic (exp (j$\omega t$)) EM field $(\mathbf{E}^i, \mathbf{H}^i)$, the EFIE for the total axial current $\mathbf{I}(l)$ excited on the wire can be written as [9]:

$$(j\omega\mathbf{A} + \nabla\phi)\cdot\mathbf{1}_l = \mathbf{1}_l\cdot\mathbf{E}^i, \tag{1}$$

with conventional notation $\mathbf{A}$ and $\phi$ employed for the magnetic vector potential and electric scalar potential, respectively, and $\mathbf{1}_l$ denoting the unit vector locally parallel to the wire axis. For the wire approximated by a series of broken line segments, the unknown current is expanded as a linear combination of one-dimensional (triangle) RWG-type functions:

$$\mathbf{I}(l) \cong \sum_{n=1}^{N} I_n \mathbf{T}_n(l), \tag{2}$$

where

$$\mathbf{T}_n(l) = \begin{cases} \mathbf{1}_n^+(l - l_{n-1})/\Delta_n^+ & \text{if} \quad l_{n-1} \le l \le l_n, \\ \mathbf{1}_n^-(l_{n+1} - l)/\Delta_n^- & \text{if} \quad l_n \le l \le l_{n+1}, \\ 0 & \text{otherwise}, \end{cases} \tag{3}$$

and

$$\Delta_n^+ = |\mathbf{r}_n - \mathbf{r}_{n-1}| \quad \text{and} \quad \Delta_n^+ = |\mathbf{r}_{n+1} - \mathbf{r}_n|, \tag{4}$$

with $l$ and $\mathbf{r}_i$ denoting the arc length along the wire axis and a position vector of the $i$-th point subdividing the wire into segments, respectively. The EFIE-MoM procedure leads to the matrix equation:

$$\mathbf{Z}(f)\mathbf{I}(f) = \mathbf{V}(f), \tag{5}$$

in which $\mathbf{Z}_{N\times N}$ denotes the MoM-generated system matrix with elements ($m$, $n$ = 1, 2, …, N):

$$\begin{aligned} Z_{mn} = j\omega\big[&\mathbf{A}_n(\mathbf{r}_{m-1/2})\cdot(\mathbf{r}_m - \mathbf{r}_{m-1/2}) \\ &+ \mathbf{A}_n(\mathbf{r}_{m+1/2})\cdot(\mathbf{r}_{m+1/2} - \mathbf{r}_m)\big] \\ &+ \phi_n(\mathbf{r}_{m+1/2}) - \phi_n(\mathbf{r}_{m-1/2}), \end{aligned} \tag{6}$$

where $\mathbf{A}_n(\mathbf{r})$ and $\phi_n(\mathbf{r})$ denote $\mathbf{A}$ and $\phi$ values from n-th basis function at the observation point specified by $\mathbf{r}$, respectively, with

$$\mathbf{r}_{m-1/2} = \frac{\mathbf{r}_{m-1} + \mathbf{r}_m}{2}, \quad \mathbf{r}_{m+1/2} = \frac{\mathbf{r}_m + \mathbf{r}_{m+1}}{2}. \tag{7}$$

The unknown current expansion coefficients constitute a column vector $\mathbf{I}_{N\times 1}$, and the elements of a column vector $\mathbf{V}_{N\times 1}$ representing the excitation are given by ($m$ = 1, 2, …, N):

$$\begin{aligned} V_m = &\mathbf{E}^i(\mathbf{r}_{m-1/2})\cdot(\mathbf{r}_m - \mathbf{r}_{m-1/2}) \\ &+\mathbf{E}^i(\mathbf{r}_{m+1/2})\cdot(\mathbf{r}_{m+1/2} - \mathbf{r}_m). \end{aligned} \tag{8}$$

The complex valued dense impedance matrix $\mathbf{Z}$ is frequency, $f(= \omega/2\pi)$, dependent and, therefore, the matrix equation must be set up and then solved repeatedly for each individual frequency within a set of discrete frequencies of interest. The Equation (5) can be solved by standard methods of linear algebra. In this paper, only the LU decomposition is considered in GPU context, since the technique is widely used in MoM simulations.

### B. Adaptive frequency sampling

An adaptive frequency sampling scheme employed in this study consists in performing repetitive bisection of each of initially chosen frequency intervals until a specified convergence criterion is met for the observable $H(f)$. The efficiency of sampling process is noticeably improved by way of interpolation of the quantity of interest by a rational function, $R(f)$, fitting the support point $\{f_i, H_i; i = 0, 1, 2, \cdots, N\}$. Such the function is defined as a quotient of polynomials $P_L(f)$ and $Q_M(f)$ of orders $L$ and $M$, respectively, that is

$$R_{L,M}(f) = \frac{P_L(f)}{Q_M(f)} = \frac{\sum_{i=0}^{L} p_i f^i}{1 + \sum_{j=1}^{M} q_j f^j}, \tag{9}$$

where $L + M = N$. Instead of constructing $R_{L,M}$ explicitly, we employ in this study a recursive tabular algorithm developed by Stoer and Bulirsch, which generates implicitly the so-called diagonal rational interpolant [3]. A combination of SB algorithm with bisectional AFS results in the AFS-SB adaptive frequency sampling scheme. This latter is controlled by error surrogates. To be precise, for the interval $[f_{i-1}, f_i]$, three approximate values for $H$: $\widehat{H}_m$, $\widehat{H}_m^+$ and $\widehat{H}_m^-$ are computed at the midpoint $f_m$ from three rational fitting models $R_{L,M}$, $R_{L+1,M-1}$ and $R_{L-1,M+1}$, respectively. Then, the absolute values of relative errors between $\widehat{H}_m^+$ and $\widehat{H}_m$, and $\widehat{H}_m^-$ and $\widehat{H}_m$, respectively, are computed for the purpose of controlling the AFS-SB process. When one of the errors (or both of them) exceed(s) the assumed convergence tolerance, δ, a new sample $H_m$ is computed at $f_m$ via MoM, the number of support points for the rational fitting model is thus increased by one, and the bisection process continues until the convergence criterion is met.

### C. GPU+CPU co-processing

As already mentioned in the introductory section, the GeForce GTX 680 CUDA-capable device has been used to accelerate the MoM solution process. The device has 4 GB of GDDR5 memory and 8 Kepler-based Streaming Multiprocessors (SMXs) comprised of 8×192 CUDA cores. Each SMX has access to 64 KB of on-chip memory configured as 48 KB of shared memory and 16 KB of L1 cache. The device has the capability to overlap kernel execution and data transfer between the device and host memory, offers fully IEEE-754 compliant single and double precision floating point operations, supports concurrent kernel execution, and employs a dynamic voltage and frequency scaling (DVFS) technique [10].

Solution of the integral equation via MoM involves two computationally intensive phases, i.e., assembling the system matrix $\boldsymbol{Z}$ and the solution of the linear system given by (5). Correspondingly, the CPU+GPU implementation of the MoM scheme has been divided into two relevant parts. The matrix assembly part is ported on the GPU device and handled by a highly optimized CUDA Fortran kernels [8]. To maximally exploit the compute capability of the device, blocks of 16×16 threads using 40 registers each are employed in computing the system matrix $\boldsymbol{Z}$. The SMX with 64 K register file accommodates six such blocks, resulting in thread capacity of 1536 threads in each SMX utilizing 61440 registers, that is, 94% of the register file.

For the solution of the linear system given by (5), the routine `cula_device_zgesv()` from a commercial library CULA Tools [11] is employed when the matrix $\boldsymbol{Z}$ fits into GPU memory. When the matrix is too big to reside in GPU memory, an out-of-core-like approach described in [12] is followed. In brief, the LU decomposition process of the $\boldsymbol{Z}$ matrix is divided into numerous tasks on top of blocks of its columns called panels. The panels are factorized on the CPU using a multi-core routine such as `zgetf2()` from the MKL library, while the trailing submatrices are updated on both the CPU and GPU with the use of highly optimized MKL/CUDA kernels. The pseudo-code for the proposed LU decomposition scheme is presented in Fig. 1. Note that four different CUDA streams are created to manage the computations (line 8). The initial data is assumed to be on the CPU, and when the GPU is executing the task, the data need to be copied from the host and sent back to be used for updating the impedance matrix. All data transfers are asynchronous, allowing the overlapping with kernel executions (line 16 and 19). To reduce CPU idle time, a concept known as a look-ahead is employed [13]. After performing LU factorization of the matrix, the backward substitution executed on the CPU yields a solution to the matrix equation (line 27).

Various aspects of GPU+CPU co-processing in solving dense linear algebra problems are discussed from general and CEM perspectives in [13, 14] and [15-17], respectively.

```
1.  ! Perform factorization and update panel size
2.  call set_size(nf0, nu1, nu2)
3.  nw = n  ! number of rows of the trailing submatrix
4.  ! Create CUDA streams and events to manage block LU
5.  ! decomposition and record the timings
6.  istat = cudaEventCreate()
7.  do i = 1, 4
8.   istat = cudaStreamCreate(nStream(i))
9.  end do
10. ! Update and factorize the impedance matrix
11. do while (i<n-n_d)
12.  call zgetf2(m-s*nf0/nw,nf0/nw)
13.  call ztrsm(nu1/nw, nu1/nw)
14.  call ztrsm(nb2,m-(i+1)*nu1/nw,nu1/nw)
15.  do i = 1, 4
16.   istat = cudaMemcpy2DAsync(d_cz(m1,n1), &
      (h_cz(n-s*nf0/nw,i+(i-1)*nu1/nw:i*nu1/nw),nStream(i))
17.   call cula_device_Ztrsm(n-s*nu2,nw,nu2/nw,nStream(i))
18.   call cula_device_Zgemm(n-(i+1)*nu2/nw), &
      n-(i+1)*nu2/nw,nu2/nw,nStream(i))
19.   istat = cudamemcpy2DAsync(h_cz(n-s*nf0/nw, &
      i+(i-1)*nu2/nw:i*nu2/nw),d_cz(m1,n1),nStream(i))
20.   istat = cudaStreamSynchronize()
21.  end do
22.  ! check the update order
23.  call upd_nw(nw) ! update nw
24.  i=i+incr(nw, nf0)
25. end do
26. ! Perform backward substitution
27. call zgetrs(h_cz,n,ipv,ci,n)
28. istat = cudaEventDestroy()
29. istat = cudaStreamDestroy()
```

Fig. 1. Pseudo-code for out-of-core-like LU decomposition of MoM matrix.

## III. RESULTS

To demonstrate the efficiency of the proposed approach, a lightning protection system directly hit by lightning is considered. The LPS, serving as a building shielding structure from the lightning electromagnetic pulse (LEMP), is modeled by a grounded wire-mesh cage. A perfectly electrically conducting (PEC) ground plane is assumed and taken into account by the method of images. The dimensions of the building are (length × width × height) 10 m × 10 m × 50 m. The model is based on the type 3 grid-like large volume shield considered in

[6]. The shield is assumed to be made of perfectly conducting wires of radius 4 mm forming a square mesh of 0.5 m × 0.5 m (see Fig. 2 (a)). The lightning is assumed to strike a corner of the building. The lightning channel is represented by a vertical lossy monopole antenna of the height 2 km and radius 5 cm, loaded with the distributed inductance of 4.5 μH/m in series with the resistance of 1 Ω/m [18]. The monopole is fed at its base by a delta-gap unit-voltage generator. The entire structure including LPS and lightning channel is discretized into linear segments of 1 m in length. The total number of segments is 18710, and the number of unknowns (basis functions) associated with the structure is 27109.

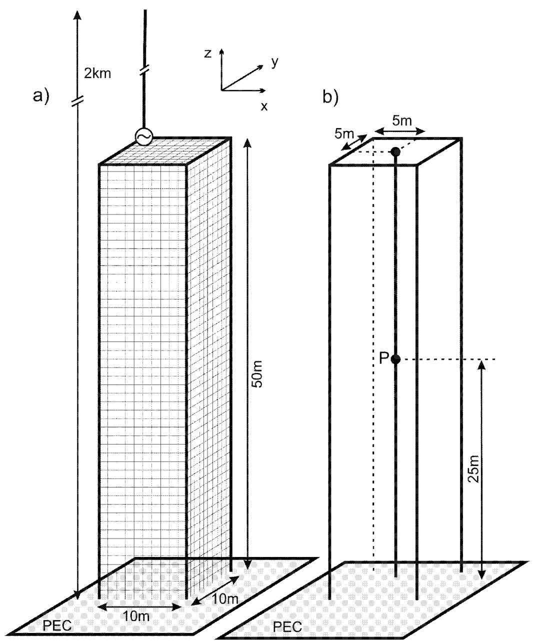


Fig. 2. Model of grid-like LPS with lightning channel and vertical wire located inside the protected volume.

As a numerical example, the electric field/current transmittance:

$$T_{E/I}(f) = |\mathbf{E}(f)|/|I_g(f)|, \quad (10)$$

where $\mathbf{E}(f)$ denotes the electric field intensity at the centre of the shielded volume ($x = 5\text{m}, y = 5\text{m}, z = 25\text{m}$) and $I_g$ is the current at the channel base (i.e., at the feed-point of the equivalent monopole antenna) has been computed. The resulting frequency run of the transmittance in the range from 1 kHz to 20 MHz is shown in Fig. 3 in the linear and logarithmic scales. The empty circles represent data points (EM samples) generated by the AFS-SB/GPU algorithm outlined in Section II. As can be seen, the AFS-SB/GPU results compare very well with those derived from FEKO [19].

The computations of $T_{E/I}$ were performed for the frequency range from 1 kHz to 20001 kHz with the initial frequency step $\Delta f = 2$ MHz and the convergence tolerance $\delta = 0.01$. The AFS-SB algorithm generated totally 149 non-uniformly spaced frequency samples of $T_{E/I}$ with the frequency step locally decreased to 3.90625 kHz. To achieve the same convergence level with uniform sampling, 5121 samples taken with $\Delta f = 3.90625$ kHz would be required so that the AFS-SB algorithm offers about 34.4x reduction of the number of EM samples. Moreover, engaging GPU device in both phases of MoM solution, that is, assembling the system matrix $\boldsymbol{Z}$ and solving the system of linear Equations (5), accelerates computations by a factor of 6.7 for each frequency sample. The total wall-clock simulation time was 16 h 16 min, and the improvement in performance with a speedup ratio of about 34.4×6.7 = 230x was achieved compared to a reference single-thread sequential CPU implementation of the uniform sampling scheme. When a parallel four-core CPU OpenMP version of the code is taken as a reference, the above figure drops to about 64x.

The knowledge of voltages induced in electrical circuits inside a protected volume/building is crucial for the design of LPS. To mimic the situation of interest, a long vertical cylindrical wire of radius 0.89 mm was placed in the protected volume parallel to the down conductors of the LPS system and connected directly between midpoints of the roof and the floor coinciding with PEC ground (see Fig. 2 (b)). The wire was discretized into 100 0.5-m segments resulting in that the total number of basis functions associated with the considered structure increased to 27210. The task was to calculate the voltage/current transmittance defined as:

$$T_{U/I}(f) = |U(f)/I_g(f)|, \quad (11)$$

where $U$ is the open-circuit voltage at point $P$ located in the middle of the wire (see Fig. 2 (b)) and $I_g$ denotes the current at the lightning channel base. Figure 4 shows the frequency run of the transmittance of interest in the range from 1 kHz to 20 MHz using a convention similar to that applied for $T_{E/I}$. Again, the AFS-SB/GPU results are in excellent agreement with the results derived from a commercial full-wave EM simulator FEKO [19]. This time the AFS-SB algorithm launched for the frequency range from 1 kHz to 20001 kHz with the initial $\Delta f$= 2 MHz and $\delta$ = 0.01 generated 70 non-uniformly spaced frequency samples of $T_{U/I}(f)$ with the frequency step locally refined to 31.25 kHz. This implies that 641 samples uniformly spaced at every 31.25 kHz would be required to achieve the same convergence level. Hence, the number of samples needed for reconstruction of $T_{U/I}(f)$ is reduced by a factor of about 9.2. The overall improvement in performance with a speedup ratio of about 17x was achieved compared to the four-core parallel OpenMP version of the code. The total wall-clock simulation time was 7 h 41 minutes.

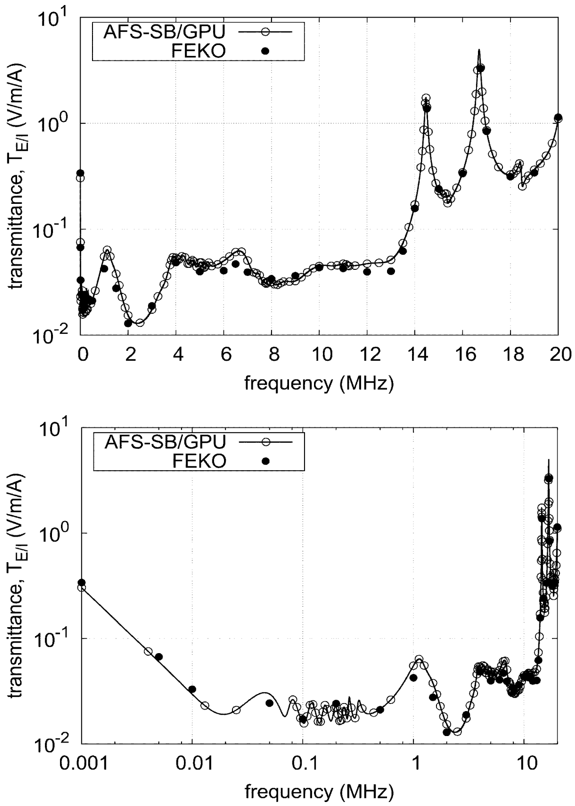


Fig. 3. Electric field/current transmittance $T_{E/I}$.

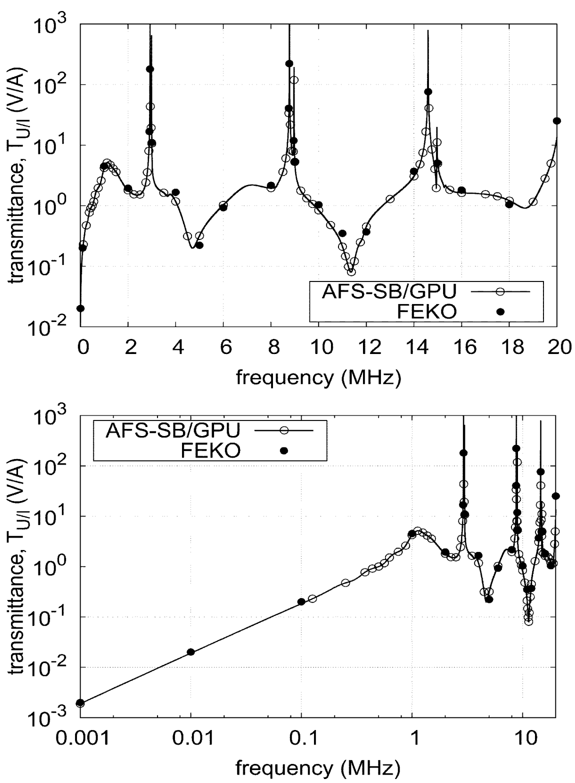


Fig. 4. Voltage/current transmittance $T_{U/I}$.

## IV. CONCLUSION

The fast technique based on method of moments for wideband analysis of lightning protection systems is presented in the paper. Broadband capability of the technique is attained through supporting MoM by the dynamic adaptive frequency sampling employing the interval halving scheme backed by the recursive tabular Stoer-Bulirsch rational interpolation algorithm. The approach offers significant reduction in the number of EM samples needed for reconstruction of the response of the system. Further speedup of numerical MoM-based simulations is achieved by GPU hardware acceleration. In case of GeForce GTX 680 CUDA-capable device used in this study, the improvement in performance with a speedup ratio of about 6.7x for each frequency sample is reached compared to the single-thread sequential CPU implementation of the algorithm. Numerical examples for the grid-like LPS directly hit by lightning are presented to illustrate the usefulness and efficiency of the approach. From a broader perspective, the approach described in this paper represents an example of utilizing the potential for technical computing provided by CPU+GPU architectures of low-cost PC-based workstations.

## ACKNOWLEDGMENT

This work was supported by the Ministry of Science and Higher Education Republic of Poland (decision no. 8686/E-367/S/2016).

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**Andrzej Karwowski** received the Ph.D. and D.Sc. degrees in Electronic Engineering from the Wrocław University of Technology (WUT), Wrocław, Poland, in 1976 and 1984, respectively. Since 1987, he has been with the Faculty of Automatic Control, Electronics and Computer Science, Silesian University of Technology (SUT), Gliwice, Poland, where he now holds a position of a Professor. His professional interests are mainly in antennas, electromagnetic compatibility, transmission lines, passive microwave components with emphasis on development and application of relevant CEM methods and tools. He is a Senior Member of the IEEE and a Member of the IET. He was the Founder of the Polish IEEE EMC Society Chapter and its first Chairperson. From 2010 to 2015 he served the European EMC community as a Member of the International Steering Committee EMC Europe.

**Artur Noga** received the M.Sc. and Ph.D. degrees in Electrical Engineering from the Silesian University of Technology, Gliwice, Poland, in 2002 and 2007, respectively. His professional interests are primarily in computational electromagnetics with applications in the field of antennas and electromagnetic compatibility.

**Tomasz Topa** received the M.Sc. and Ph.D. degrees in Electrical Engineering from the Silesian University of Technology, Gliwice, Poland, in 2002 and 2007, respectively. His professional interests are primarily in numerical simulation of electromagnetic fields with particular emphasis on parallel computing, high-performance computing, CPU-GPU hybrid and cooperative computing and multicore computing.