



**AToM**  
ANTENNA TOOLBOX FOR MATLAB

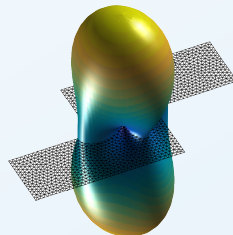
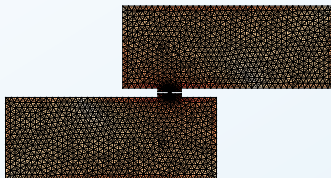
# Antenna Toolbox for MATLAB

A Versatile MATLAB Tool for Antenna Synthesis

Miloslav Capek, Pavel Hazdra, Viktor Adler, Petr Kadlec, Vladimir Sedenka, Martin Marek, Michal Masek, Vit Losenicky, Martin Strambach, Milos Mazanek, Jaroslav Rymus

April 11, 2018

1. Background of the Project
2. AToM Features
3. Matrix Operators in AToM
4. Benchmark Activity: Characteristic Modes of Spherical Shell
5. Conclusion



Project started from **September 2014**.

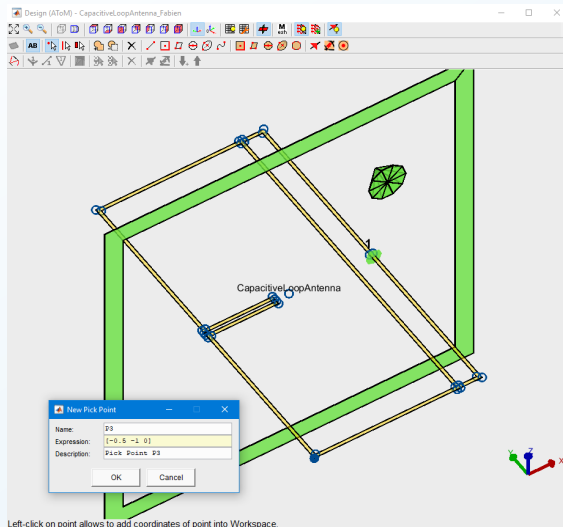
- ▶ We wanted to develop unique tool allowing further research,
  - ▶ base point for *attack on the problem of antenna synthesis*.
- ▶ We wanted to share our know-how with commercial partner.
  - ▶ Previously, our knowledge in characteristic modes offered to CST.
  - ▶ Knowledge transferred to CEM One of ESI as tool Visual Antenna.
  - ▶ Nowadays, fruitful cooperation with MECAS ESI s.r.o., a subsidiary of ESI.

Reasons:

- ▶ Commercial packages are sometimes not documenting the implementation details (quadrature order, singularities, feeding, export of data,...),
- ▶ scalability of the code, independence from embedded solution,
- ▶ possibility to swiftly implement new features, versatility,...

## Motto

“Draw the antenna interactively, visualize mesh grid, feeding scenarios, and boundary conditions. Take the advantage of AToM Workspace.”



Left-click on point allows to add coordinates of point into Workspace.

AToM Design Viewer with a capacitive loop antenna and active pick-point tool. The PEC symmetric plane is enabled and highlighted by green color.

## Motto

“Create own variables and use them freely throughout the AToM to parametrize all your models. AToM Workspace is the primary gateway between variables in MATLAB workspace and AToM.”

Workspace (AToM) - CapacitiveLoopAntenna\_Fabien

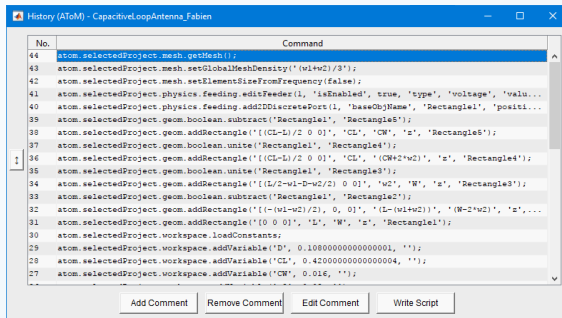
	Name	Expression	Description	Value	Class	Size	Status
1	CL	0.420000000000000004		0.42	double	1x1	OK
2	CW	0.016		0.016	double	1x1	OK
3	D	0.108000000000000001		0.108	double	1x1	OK
4	L	1	antenna length	1	double	1x1	OK
5	P1	[-L/2 W/2 0]	Pick Point P1	[-0.5 1 0]	double	1x3	OK
6	P2	[L/2 W/2 0]	Pick Point P2	[0.5 1 0]	double	1x3	OK
7	W	2	antenna width	2	double	1x1	OK
8	Z0	376.73031346177066	impedance of free space	376.7303135	double	1x1	OK
9	a	norm(P1-P2)/2	radius of circm. sphere	0.5	double	1x1	OK
10	c0	299792458	speed of light	299792458	double	1x1	OK
11	ep0	8.854187817620389...	permittivity of vacuum	8.854187818e-12	double	1x1	OK
12	mu0	1.256637061435917...	permeability of vacuum	1.256637061e-06	double	1x1	OK
13	w1	0.02		0.02	double	1x1	OK
14	w2	0.02		0.02	double	1x1	OK
15							

Delete Variable    Load Constants    Assign in Matlab

List of user-defined AToM variables which parametrize the capacitive loop antenna.

## Motto

“Rely on automatic  
MATLAB-executable record of  
your AToM session. Modify it,  
send it, share it.”



History (AToM) - CapacitiveLoopAntenna\_Fabien

No.	Command
44	atom.selectedProject.mesh.getMesh();
43	atom.selectedProject.mesh.setGlobalMeshDensity('(w1+w2)/3');
42	atom.selectedProject.mesh.setElementSizeFromFrequency(false);
41	atom.selectedProject.physics.feeding.editFeeder(1, 'isEnabled', true, 'type', 'voltage', 'valu...
40	atom.selectedProject.physics.feeding.add2DDiscretePort(1, 'baseObjName', 'Rectangle1', 'positi...
39	atom.selectedProject.geom.boolean.subtract('Rectangle1', 'Rectangle5');
38	atom.selectedProject.geom.addRectangle('[(CL-L)/2 0 0]', 'CL', 'CW', 'z', 'Rectangle5');
37	atom.selectedProject.geom.boolean.unite('Rectangle1', 'Rectangle4');
36	atom.selectedProject.geom.addRectangle('[(CL-L)/2 0 0]', 'CL', '(CW+2*w2)', 'z', 'Rectangle4');
35	atom.selectedProject.geom.boolean.unite('Rectangle1', 'Rectangle3');
34	atom.selectedProject.geom.addRectangle('[(L/2-w1-D-w2/2) 0 0]', 'w2', 'W', 'z', 'Rectangle3');
33	atom.selectedProject.geom.boolean.subtract('Rectangle1', 'Rectangle2');
32	atom.selectedProject.geom.addRectangle('[-(w1-w2)/2, 0, 0]', 'L-(w1+w2)', '(W-2*w2)', 'z',...
31	atom.selectedProject.geom.addRectangle('[0 0 0]', 'L', 'W', 'z', 'Rectangle1');
30	atom.selectedProject.workspace.loadConstants;
29	atom.selectedProject.workspace.addVariable('D', 0.10800000000000001, '');
28	atom.selectedProject.workspace.addVariable('CL', 0.42000000000000004, '');
27	atom.selectedProject.workspace.addVariable('CW', 0.016, '');

Buttons: Add Comment, Remove Comment, Edit Comment, Write Script

Record of AToM History for capacitive loop antenna.

## Motto

“Have a full control of the AToM workflow. Access all powerful low-level functions and features. Combine freely AToM commands and other MATLAB commands.”

```

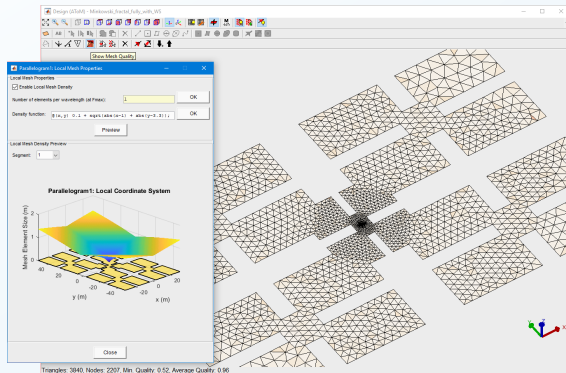
1  % (sample of code calculating presented antenna):
2  fList = models.utilities.constants.c0/(2*2*2*(L+W)) * linspace(1/2, 5, F);
3  atom.selectedProject.physics.setFrequencyList(fList);
4
5  % Solver requests
6  atom.selectedProject.solver.MoM2D.setProperties('resultRequests', ...
7  'basisFcns, iVec, mesh, vVec, zInActive, zInMutual, zMat, zMatD');
8
9  % Start solver (with default options)
10 atom.selectedProject.solver.MoM2D.solve;
11
12 % Process results:
13 R = atom.selectedProject.solver.MoM2D.results;
14 Zin = R.zInActive.data;
15
16 figure;
17 plot(fList, real(Zin), fList, imag(Zin));
18

```

Segment of MATLAB code with AToM-executable commands (start of MoM solver and acquisition of the results).

## Motto

“Use fast and versatile AToM mesher. Set up local density functions. Enjoy various settings of uniform mesh grid and full support of symmetries.”

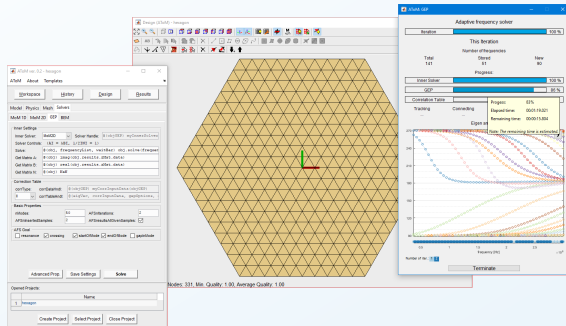


Complex fractal body discretized using local density function (discretization is finer where high amplitudes of current density are expected).



## Motto

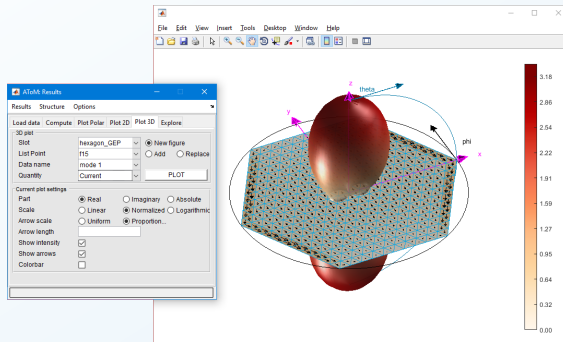
“Try out the far most advanced characteristic modes decomposition package. Adaptive tracking, accurate decomposition, symmetry based-tracking, scalable GEP definitions... all at your disposal.”



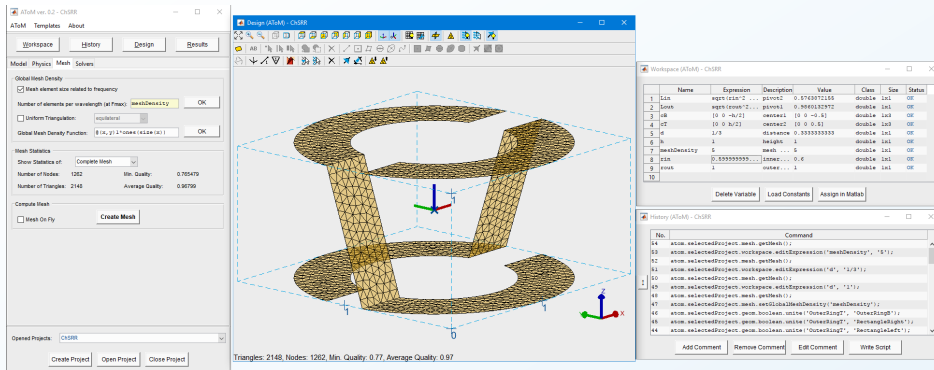
Characteristic mode decomposition of hexagon with perfectly symmetrical mesh grid.

## Motto

“Analyze your results swiftly with standalone AToM Results Browser or dig directly into the deep study with underlying elementary functions.”



Radiation pattern of dominant characteristic mode on hexagon.

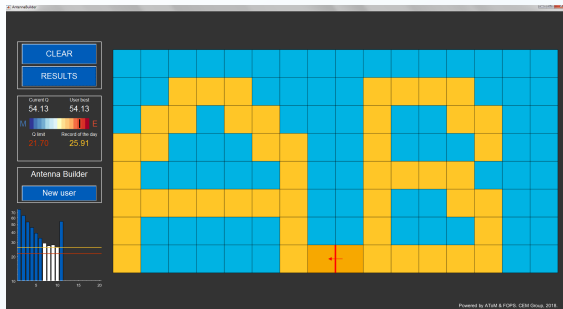


Screenshot of typical AToM working session.

- In the conference paper, circularly polarized antenna is completely designed starting from the modal study and including measuring.

Download for free from: [antennatoolbox.com](http://antennatoolbox.com)

Watch overview on YouTube: [youtube.com/watch?v=WUQs5ustPzk](https://youtube.com/watch?v=WUQs5ustPzk)



Code lines: **214 928**.

MATLAB functions: **4 645**.

- ▶ All written in MATLAB,
- ▶ OOP heavily used.

Antenna Builder – Designing antennas as a tablet game.



**AToM**  
ANTENNA TOOLBOX FOR MATLAB



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## AToM v. 1.1: New version released

Geometry save/load, some bugs fixed.

Increased stability of mesh generator.

Mesh of unified objects: bug fixed.

Added new part of the documentation.

Examples in MoM2D revisited.

Visit [Order](#) for more information...



**AToM**  
ANTENNA TOOLBOX FOR MATLAB




NEWS



**AToM V1.1**

The new version of AToM was released and it is available for [download](#). List of changes follows: ...

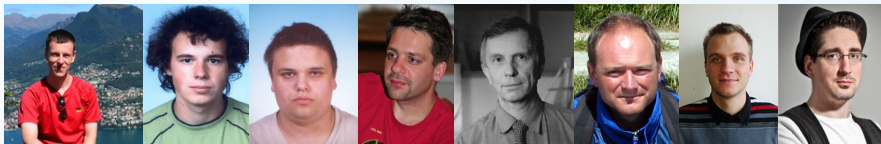
[MORE](#)



**ANTENNA BUILDER**

New addon for AToM: [Antenna Builder](#) is free to download.

[MORE](#)



► And many other colleagues helped with their advices and support.

Usage of (finite) discretization of the source region  $\Omega$  leads to

$$\mathbf{J}(\mathbf{r}) \approx \sum_{n=1}^N I_n \psi_n(\mathbf{r}), \quad (1)$$

where  $\mathbf{I} = [I_n] \in \mathbb{C}^{N \times 1}$  are expansion coefficients,  $\psi_n$  are the basis functions.

All analytical formulas transferred into algebraic forms (*i.e.*, matrices and vectors)

$$\mathbf{p} \approx \frac{1}{2} \mathbf{I}^H \mathbf{L} \mathbf{I} \quad \text{with} \quad L_{mn} \equiv \int_{\Omega} \psi_m \cdot \mathcal{L} \{ \psi_n \} d\mathbf{r}. \quad (2)$$

The impedance matrix is constructed (from normalized data) as

$$\mathbf{Z} = \mathbf{R} + j\mathbf{X} = jZ_0 a^2 \left( ka (\mathbf{Z}^{M,k} + \mathbf{Z}^{M,0}) - \frac{1}{ka} (\mathbf{Z}^{E,k} + \mathbf{Z}^{E,0}) \right), \quad (3)$$

where individual elements of the defining matrices are

$$Z_{mn}^{M,k} = \frac{1}{a^3} \int_{\Omega} \int_{\Omega} \boldsymbol{\psi}_m(\mathbf{r}) \cdot \boldsymbol{\psi}_n(\mathbf{r}') \frac{e^{-jkR} - 1}{4\pi R} dS dS', \quad (4)$$

$$Z_{mn}^{M,0} = \frac{1}{a^3} \int_{\Omega} \int_{\Omega} \boldsymbol{\psi}_m(\mathbf{r}) \cdot \boldsymbol{\psi}_n(\mathbf{r}') \frac{1}{4\pi R} dS dS', \quad (5)$$

$$Z_{mn}^{E,k} = \frac{1}{a} \int_{\Omega} \int_{\Omega} \nabla \cdot \boldsymbol{\psi}_m(\mathbf{r}) \nabla' \cdot \boldsymbol{\psi}_n(\mathbf{r}') \frac{e^{-jkR} - 1}{4\pi R} dS dS', \quad (6)$$

$$Z_{mn}^{E,0} = \frac{1}{a} \int_{\Omega} \int_{\Omega} \nabla \cdot \boldsymbol{\psi}_m(\mathbf{r}) \nabla' \cdot \boldsymbol{\psi}_n(\mathbf{r}') \frac{1}{4\pi R} dS dS'. \quad (7)$$



The analytical differentiation of  $\mathbf{Z}$  with respect to  $\omega$  (normalized by  $\omega$ ) is

$$\omega \frac{\partial \mathbf{Z}}{\partial \omega} = jZ_0 a^2 \left( ka (\mathbf{Z}^{M,k} + \mathbf{Z}^{M,0} - jka \mathbf{T}^M) + \frac{1}{ka} (\mathbf{Z}^{E,k} + \mathbf{Z}^{E,0} + jka \mathbf{T}^E) \right), \quad (8)$$

where individual elements of the defining matrices are

$$T_{mn}^M = \frac{1}{a^4} \int_{\Omega} \int_{\Omega} \boldsymbol{\psi}_m(\mathbf{r}) \cdot \boldsymbol{\psi}_n(\mathbf{r}') \frac{e^{-jkR}}{4\pi} dS dS', \quad (9)$$

$$T_{mn}^E = \frac{1}{a^2} \int_{\Omega} \int_{\Omega} \nabla \cdot \boldsymbol{\psi}_m(\mathbf{r}) \nabla' \cdot \boldsymbol{\psi}_n(\mathbf{r}') \frac{e^{-jkR}}{4\pi} dS dS', \quad (10)$$

and

$$R = |\mathbf{r} - \mathbf{r}'|, \quad a = \max_{\mathbf{r}, \mathbf{r}' \in \Omega} \left\{ \frac{R}{2} \right\}, \quad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}. \quad (11)$$

Many matrices available ( $\mathbf{X}_m$ ,  $\mathbf{X}_e$ ,  $\hat{\mathbf{Z}}$ ,  $\mathbf{R}_\Omega$ ,  $\mathbf{S}$ ,  $\mathbf{F}$ ,  $\mathbf{U}$ ,  $\mathbf{N}_{m/e}$ ,  $\mathbf{M}$ ,  $\mathbf{P}$ )...

Discretization grid and RWG basis functions:

Listing 1: atom\_code1\_mesh.m

```
% Frequency
f = atom.selectedProject.physics.getFrequencyListValues;
% or manually specified by user:
f = 1e9; % 1 GHz

% (It is expected that MoM requests are correctly set up.)
Res = atom.selectedProject.solver.MoM2D.results;

Mesh = Res.mesh;          % mesh grid
BF    = Res.basisFcns;    % basis functions

% Or without running MoM solver directly from AToM:
Mesh = atom.selectedProject.mesh.getMeshData2D();
BF    = models.solvers.MoM2D.basisFcns.getBasisFcns(Mesh);
```

Impedance matrix(-related) operators  $\mathbf{Z}$ ,  $\mathbf{W}$ ,  $\mathbf{Z}^{M,k}$ ,  $\mathbf{Z}^{M,0}$ ,  $\mathbf{Z}^{E,k}$ ,  $\mathbf{Z}^{E,0}$ ,  $\mathbf{T}^M$ ,  $\mathbf{T}^E$ :

Listing 2: atom\_code1\_MoM1.m

```
% Impedance matrix
Z = Res.zMat.data;

omega = 2*pi*f;
% Stored energy matrix
W = omega*imag(Res.zMatD.data); % omega*DZ!

% Individual parts of impedance matrix:
ZMk = Res.zMatMk.data;
ZM0 = Res.zMatM0.data;
ZEK = Res.zMatEk.data;
ZE0 = Res.zMatE0.data;
TE = Res.tMatE.data;
TM = Res.tMatM.data;
```

All results known analytically<sup>1</sup>.

- ▶ No feeding – enormous simplification.
- ▶ The only input is impedance matrix.
- ▶ Various aspects studied.

Characteristic numbers:

$$\lambda_n^{\text{TE}} = -\frac{ka y_n(ka)}{ka j_n(ka)}, \quad (12)$$

$$\lambda_n^{\text{TM}} = -\frac{(n+1)y_n(ka) - ka y_{n+1}(ka)}{(n+1)j_n(ka) - ka j_{n+1}(ka)}. \quad (13)$$

Spherical shell of radius  $a$ .

Modal surface current densities  $\mathbf{J}_n(\mathbf{r})$  and far-fields  $\mathbf{F}_n(\hat{\mathbf{r}})$  can be compared as well.

<sup>1</sup>M. Capek, V. Losenicky, L. Jelinek, *et al.*, “Validating the characteristic modes solvers,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 8, pp. 4134–4145, 2017. DOI: 10.1109/TAP.2017.2708094

1. *Select a real life example.*
2. *Create a simple and canonical version of the example.*
3. *Try to identify an analytical solution at the reference.*
4. *Compare the software results against the reference.*
5. *Identify potential shortcomings.*
6. *Bring this to the attention of community and software vendors.*
7. *Make this as an example to be archived for others to test their codes.*
8. *Be clear that this is your best effort and take no responsibility.*

(Copy-pasted from 2017 AP-S talk given by Yahya Rahmat Samii.)

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► Notice there are IEEE standards<sup>2</sup> for validation of CEM software.

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<sup>2</sup> 1597.1-2008 – IEEE standard for validation of computational electromagnetics computer modeling and simulations, IEEE, 2008. DOI: [10.1109/IEEESTD.2008.4957854](https://doi.org/10.1109/IEEESTD.2008.4957854)  
 1597.2-2010 – IEEE recommended practice for validation of computational electromagnetics computer modeling and simulations, IEEE, 2011. DOI: [10.1109/IEEESTD.2011.5721917](https://doi.org/10.1109/IEEESTD.2011.5721917)

## Benchmark of Characteristic Mode Decomposition - Spherical Shell

- Introduction
- Proposal of Benchmark Tests
- Analytical Solution and Reference Results
- Test #1 - Characteristic Numbers
- Test #2 - Tracking Algorithm
- Test #3 - Characteristic Currents
- Test #4 - Characteristic Far-Fields
- Matlab Codes and Structure of FTP
- Errors in Model
- Precise Evaluation of Real Part of Impedance Matrix (will be added soon)

### Annotation:

This webpage has been created as a reaction on the recent [paper](#) we wrote, mainly since we have realized that further effort in CM benchmarking is needed to compare and synchronize results available across the community.

Precise synthetic benchmarks are proposed to test the contemporary software packages, both commercial and in-house ones. All tests are based on example of spherical shell, for which all results are derived analytically and majority of numerical errors can be tracked down. Although canonical shape of simple geometry, spherical shell has surprisingly complex behaviour (internal resonances, eigenspectrum degeneracy, non-conformity of the surface with triangular mesh grid,...). The goal is to provide open benchmark and store the results.

Are you interested in helping us with the benchmarking or in providing your own results? Just read the instructions below! :-)

Contact: [miloslav.capek@fel.cvut.cz](mailto:miloslav.capek@fel.cvut.cz)

### Materials:

**NEW:** [Presentation](#) about Benchmarking from APS 2017, San Diego (it is recommended to download the presentation and open it in Adobe Reader)

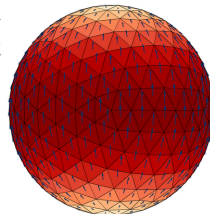
**NEW:** [Manuscript](#) "Validation of Characteristic Modes Solvers" (IEEE Trans. Antennas and Propagation)

[Presentation](#) about Spherical Shell, Lund University 29/12/2016, CM mini-workshop

**FTP:** [elmag.fel.cvut.cz](ftp://elmag.fel.cvut.cz), username: [cuser](#), password will be provided (by request)

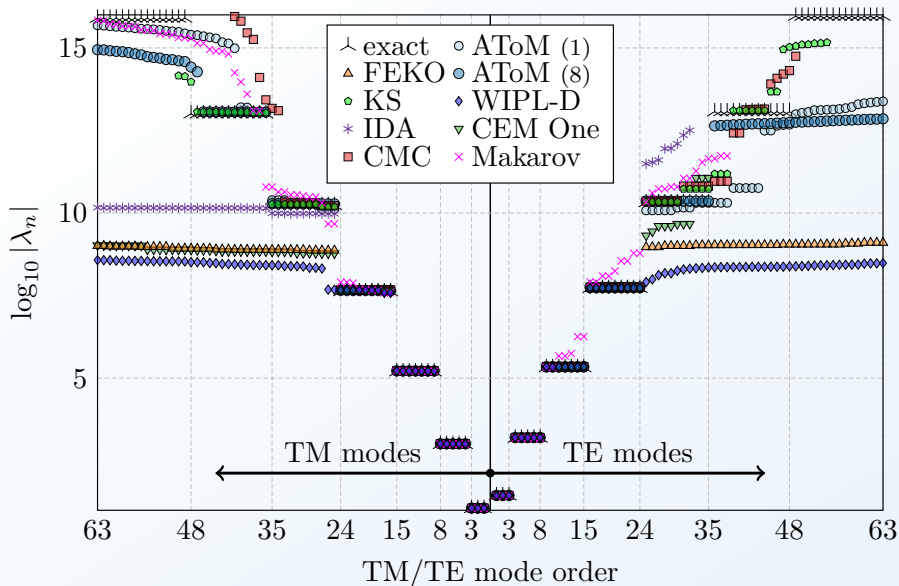
**SIG:** [Special Interest Group on Theory of Characteristic Modes](#)

**Mesh grids** (Matlab): 500 and 2220 triangles

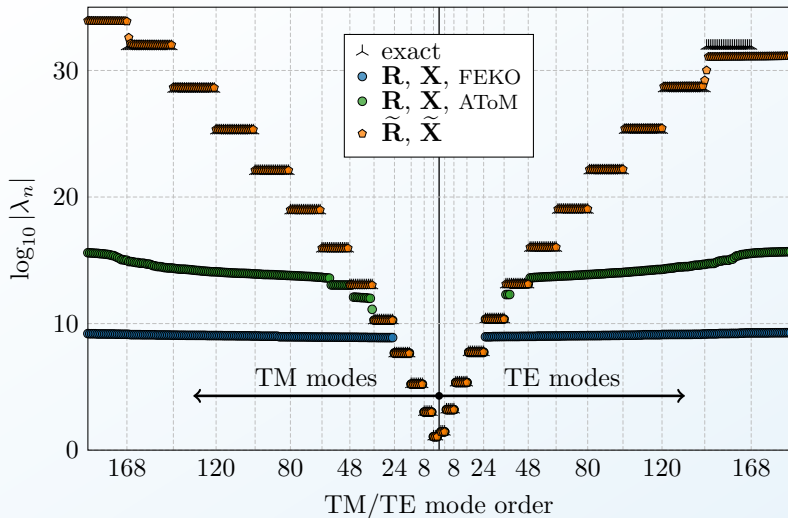


Characteristic mode associated with  $TM_{10}$  mode.

# Benchmark of CM Solvers: Spherical Shell, $ka = 1/2$



<sup>3</sup>See [elmag.fel.cvut.cz/CMbenchmark](http://elmag.fel.cvut.cz/CMbenchmark)



<sup>4</sup>D. Tayli, M. Capek, L. Akrou, *et al.*, “Accurate and efficient evaluation of characteristic modes,” , 2017, submitted, arXiv:1709.09976. [Online]. Available: <https://arxiv.org/abs/1709.09976>



AToM finished

- ▶ available for download ([antennatoolbox.com](http://antennatoolbox.com)),
- ▶ used extensively for the research activities.

Benchmark finished ([elmag.org/CMbenchmark](http://elmag.org/CMbenchmark))

- ▶ Joint-activity within Special Interested Group (Yikai Chen).
- ▶ To repeat with new versions of software?
- ▶ To maintain the (existing) FTP site?

(Idealistic) questions remained:

- ▶ How detailed should the documentary be?
- ▶ Shall the vendors share immediate results (*e.g.*, impedance matrix)?

# Questions?

For a complete PDF presentation see

► [capek.elmag.org](http://capek.elmag.org)

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