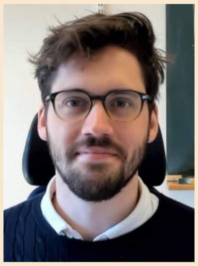
Characteristic Modes Special Interest Group

Newsletter, Volume 5, Number 3, 1st September 2025

In This Issue:

Scholar Spotlight:



Johan Lundgren is an assistant professor at Lund University. His research interests are in electromagnetic scattering, wave propagation, computational electromagnetics, characteristic modes, functional structures, meta-surfaces, inverse scattering problems, imaging, and measurement techniques.

Mats Gustafsson is a professor at Lund University. He co-founded the company Phase Holographic Imaging AB in 2004. His research interests are in scattering and antenna theory and inverse scattering and imaging. He has written over 100 peer-reviewed journal papers and over 100 conference papers. Prof. Gustafsson received the IEEE Schelkunoff Transactions Prize Paper Award 2010, the IEEE Uslenghi Letters Prize Paper Award 2019, and best paper awards at EuCAP 2007 and 2013. He served as an IEEE AP-S Distinguished Lecturer for 2013-15.

Featured Article

Degrees of Freedom and Characteristic Modes: Estimates for radiating and arbitrarily shaped objects

by Johan Lundgren, Mats Gustafsson

How many significant characteristic modes can a structure support for a given physical size? This question lies at the core of understanding the performance limits of antennas and scatterers. In our recent work, we explore this question by examining the number of significant characteristic modes, their connection to bandwidth and degrees of freedom (NDoF), as well as their relationship to other intuitive, physically measurable quantities.

Resonant characteristic modes are important in antenna design. Figure 1 shows the modal significances, $|t_n|$, of modes from a loop structure for various electrical sizes ka (or equivalently, increasing frequency). In practice, modes close to resonance are also useful, and these are referred to as significant characteristic modes. Here, we define them as the modes satisfying $|t_n|^2 \geq 1/2$, with the shaded region in Fig. 1 marking the modes that meet this criterion.

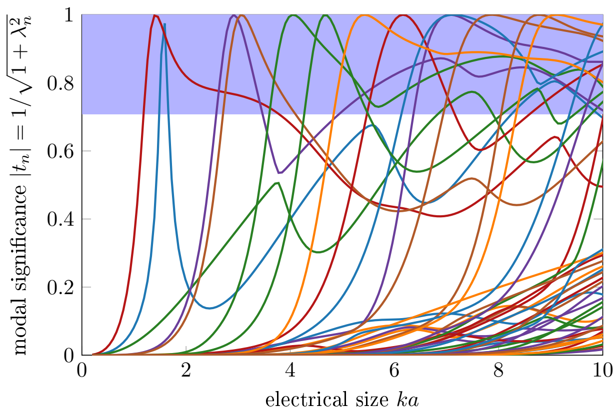


Figure 1: Modal significances, $|t_n|$, of a loop structure plotted versus electrical size ka. The shaded region highlights modes with $|t_n|^2 \geq 1/2$, which we define as significant characteristic modes near resonance.

A direct approach is to numerically simulate the structure and identify which modes satisfy the significance criterion. Figure 2 illustrates this for several examples: three planar geometries (patch, meander, and loop) and a convex three-dimensional object (sphere). The solid lines show the number of significant modes obtained numerically. Despite the different shapes, all curves follow a similar trend, sketched as dashed lines. In the paper, we show that these dashed lines correspond to a simple analytical expression that estimates the number of significant modes. For the planar cases, the expression is

$$N \approx \frac{2\pi A}{\lambda^2}$$

where λ is the wavelength and A is the physical area of the planar object.

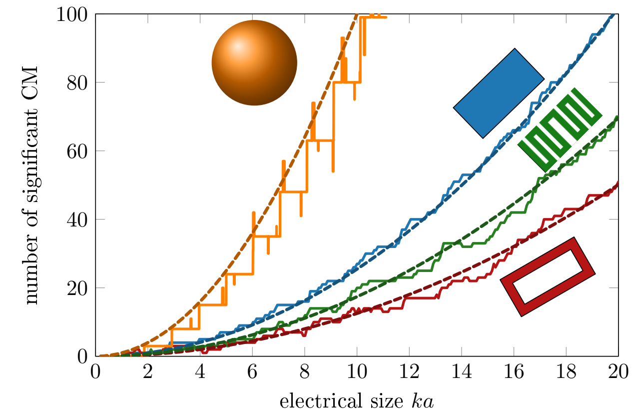


Figure 2: Number of significant characteristic modes versus electrical size for various geometries: planar patch, meander, loop, and a sphere. Solid lines show numerical results. Dashed lines indicate the analytical estimates based on the average shadow area.

However, this is only a particular case valid for planar structures. For general three-dimensional objects, the definition of "area" is less useful, particularly for arbitrary non-convex geometries. In the paper we show that the same form of the expression holds if A from the planar object is replaced by $2\langle A_s \rangle$, where $\langle A_s \rangle$ is the average shadow area the object casts when illuminated from all possible directions. To illustrate this quantity Fig. 3 shows a non-convex object and the three shadows it casts when illuminated from directions perpendicular to the shown planes. Averaging such shadows over all possible orientations of the object gives $\langle A_s \rangle$.

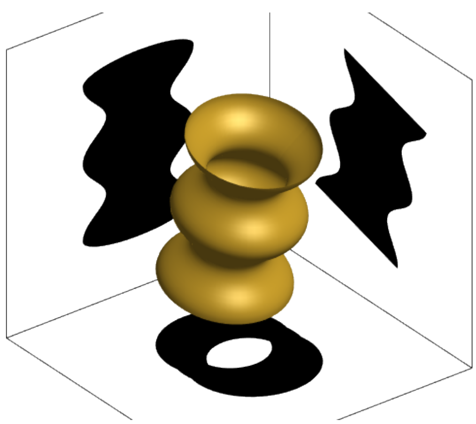


Figure 3: Example of a non-convex 3D object and its shadows cast when illuminated from three different directions perpendicular to the shown planes. The average shadow area $\langle A_s \rangle$ over all illumination angles can estimate the number of significant CM for arbitrary shapes.

These average shadow area estimates hold better for larger structures, but in the paper, we also explore small objects. For electrically small objects, N is reduced by resonant and polarizability constraints, while for electrically large objects, it increases proportionally to physical size. Additionally, the forward scattering sum rule imposes fundamental limits on the number of significant characteristic modes that can be efficiently excited within a given bandwidth. This introduces a trade-off between spatial and temporal diversity, showing that increasing operational bandwidth reduces the number of modes that can remain resonant and effective. Together, these insights unify the counting of significant characteristic modes with the well-known concept of degrees of freedom and tie it directly to physically measurable quantities.

This connection is not only of theoretical interest. In antenna engineering, it allows quick feasibility checks, for instance, to determine whether a given design is already size limited or if additional modes could be exploited. In MIMO systems, it links achievable spatial diversity directly to the object's physical extent. And when finite bandwidth is considered, as we do in the full paper, it shows how the effective number of modes is reduced in a predictable way.

In summary, while the number of significant characteristic modes can be found from detailed numerical simulations, it often follows simple physical limits set by the structure's average shadow area. This provides a bridge between characteristic mode theory, scattering theory, and the broader framework of spatial degrees of freedom.

For full derivations, bandwidth effects, and additional examples, see the article: M. Gustafsson and J. Lundgren, "Degrees of Freedom and Characteristic Modes: Estimates for radiating and arbitrarily shaped objects," in *IEEE Antennas and Propagation Magazine*, vol. 66, no. 6, pp. 18-28, Dec. 2024, doi: 10.1109/MAP.2024.3389451.

News and Events

1. **The Fourth Edition of the European School of Antenna (ESoA) Course on "Characteristic Modes: Theory and Applications"** was successfully held at **Lund University** (Lund, Sweden) during **9-13 June 2025**. The instructors were Miloslav Capek (CTU in Prague, Czech Republic), Dirk Manteuffel (Leibniz University Hannover, Germany), Eva Antonino-Daviu (Universitat Politècnica de València, Spain), Buon Kiong Lau and Johan Lundgren (both Lund University, Sweden). It was a truly fantastic experience for everyone involved. The instructors were electrified by the great enthusiasm of the keen learners. We look forward to **the next Edition in Prague in 2027**!


2. Characteristic mode analysis (CMA) continues to be an interesting topic at the recent 2025 IEEE International Symposium on Antennas and Propagation and INC/USNC-URSI Radio Science Meeting (AP-S/INC-USNC-URSI) in Ottawa, Canada, 13-18 July 2025. Some 10 papers were found using simple search of key words, and the papers were on both traditional and newer areas, the latter included its use in the analysis of composite nanostructures, diagnostics of faulty array and quantum sensing of two-body targets.

Recent Articles on CM Theory

- D. Zhang, Y. Chen, H. Li and S. Yang, "In-Band Scattering Suppression for Compact and Low-Profile Linear Antenna Arrays Using Periodic Characteristic Mode Analysis," in IEEE Transactions on Antennas and Propagation, vol. 73, no. 8, pp. 5468-5480, Aug. 2025, doi: 10.1109/TAP.2025.3558583.
- Z. Wang, F. Fan, R. Li, Y. Mo, J. Li and X. Zhao, "A Dual-Band Wideband U-Slot Resonant Metasurface Antenna Array for Millimeter-Wave Applications Using Characteristic Mode Analysis," in IEEE Transactions on Antennas and Propagation, vol. 73, no. 8, pp. 5217-5222, Aug. 2025, doi: 10.1109/TAP.2025.3564005.

Resources

Open Source Tools for CMA:

- FEKO-student edition
- CM MATLAB Software
- AToM Antenna Toolbox

Webinars:

- Our webinars on YouTube
- Our webinars on Bilibili
- Webinars from FEKO

Available Courses:

- Courses offered by ESoA

Past Special Issues on CMA:

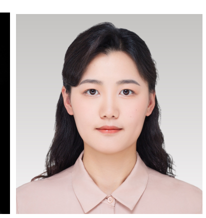
- July 2016 issue of IEEE Trans. Antennas Propag.
- April 2022 issue of IEEE Antennas Propag. Mag.

Past Issues of CM-SIG Newsletter:

- CM-SIG Newsletter

Contact Information (Editors):
Adam Narbudowicz
DTU Space
Technical University of Denmark
Lyngby, Copenhagen, Denmark
adana@dtu.dk

Li-Ying Nie
School of Computer Science and Information Engineering
Hefei University of Technology
Hefei, China, 230601
liyingnie@hfut.edu.cn

About CM-SIG: Characteristic Modes-Special Interest Group was initiated at the Special Session on CMs during the 2014, IEEE International Symposium on Antennas and Propagation in Memphis, TN, on 10 July 2014. CM-SIG was formed as a platform to promote technical activities in the field of CMs. For more information, please visit our website: http://www.characteristicmodes.org/.