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Progress towards a Polarized CRTM

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Abstract: In this presentation we summarize the progress in the development of a polarized CRTM version for the release REL-3.0. The CRTM is a fast and accurate scalar radiative transfer model [1] specifically developed for satellite radiance data assimilation in numerical weather models. For this purpose, the CRTM includes specific tangent-linear, adjoint, and Jacobian (K-matrix) functions in addition to the baseline forward model. In order to extend the CRTM to compute a subset or all elements of the Stokes vector two new radiative transfer models currently stand in competition. The first model is a straightforward extension of the current default scalar Advanced Doubling-Adding model of the CRTM [2] developed by Dr. Quanhua Liu and the second model is a Small-Angle Approximation code [3] developed at Texas A&M University. Other issues to extend the CRTM towards polarized radiation are the computation of Müller matrices for the hydrometeor and aerosol scattering properties and the provision of new polarized surface emissivities.

1. Motivation

The Community Radiative Transfer Model (CRTM) is a fast scalar radiative transfer model optimized for satellite data assimilation applications in the MW and IR. Sacrificing operational speed by including more than one Stokes-vector component is an important consideration and the considerable development effort needs to be justified. Generally speaking, a polarized CRTM provides improved accuracy and flexibility for the following assets:

- Many current and future polarimetric remote sensing missions, such as POLDER, GMI, AirMSPI, PACE, MAIA, ACE, and 3MI.
- Active sensors, such as radar and lidar in conjunction with the Community Active Sensor Module.
- Instruments with UV channels for e.g. atmospheric chemistry
- Novel, combined UV and active sensors, such as the ATHENA-OAWL and AEOLUS wind lidars.

2. Theory

As in the scalar case, a polarized CRTM scattering solver would need to solve the radiative transfer equation (1) for a 1D atmospheric geometry. Scattering objects, such as clouds are represented as infinite horizontal slabs, as illustrated in Fig. 1. The only difference to the scalar case is that instead of the scalar radiance, the 4-element Stokes vector is computed, and light scattering is governed by the 4-by-4 Müller matrix, instead of the scalar phase function.

$$\mu \frac{dI(\tau,\Omega)}{d\tau} = -I(\tau,\Omega) + \frac{\varpi}{4\pi}\int_{4\pi} P(\tau,\Omega,\Omega' \cdot I(\tau,\Omega')\,d\Omega' + S(\tau,\Omega,\Omega_0) \quad (1)$$

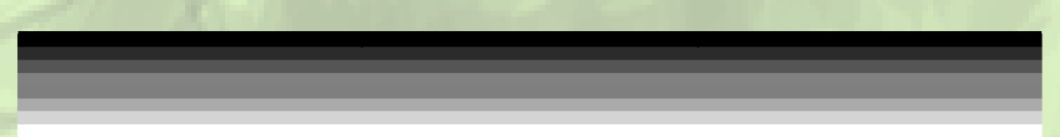


Fig. 1 (right): Conceptual sketch of a 1D slab model of a scattering atmospheric cloud layer. Each layer is characterized by its optical thickness, scattering albedo, and Müller matrix expansion coefficients. Furthermore, the problem is characterized by the instrument viewing geometry and the surface emissivity and reflectance (assumed to be Lambertian in the sketch for simplicity)

3. Scattering Solver Implementation

Selecting an appropriate RT solver is crucial to fulfill the requirements of operational speed, accuracy, but also simplicity for the sake of code maintainability and development of tangent-linear, adjoint, and Jacobian (K-matrix) solvers:

$$K = \frac{\partial I_{ch}}{\partial X} \qquad (2)$$

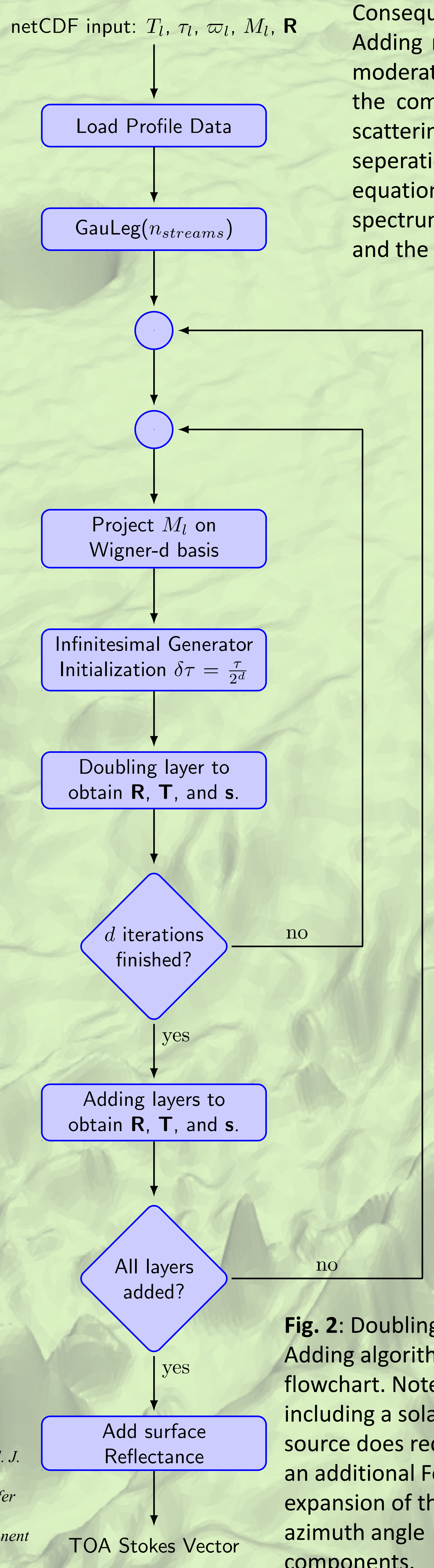
Scattering algorithms that are easy to implement included Monte Carlo methods and the Invariant Imbedding approach. However, both approaches suffer from slow calculation times.

References

[1] *Ding, S., P. Yang, F. Weng, Q. Liu, Y. Han, P. Van Delst, J. Li, and B. Baum, 2011: Validation of the community radiative transfer model. J. Quant. Sp. Rad. Trans. 112, 1050-1064.*

[2] *Liu, Q., and C. Cao, 2019: Analytic expressions of the Transmission, Reflection, and source function for the community radiative transfer model. J. Quant. Sp. Rad. Trans. 226, 115-126.*

[3] *Sun, B., and G. W. Kattawar, 2017: An Improved Small-Angle Approximation for Forward Scattering and Its Use in a Fast Two-Component Radiative Transfer Method. J. Atm. Sci. 74, 1959-1987.*



netCDF input: T_l, τ_l, ϖ_l, M_l, $\mathbf{R}$

Load Profile Data

GauLeg($n_{streams}$)

Project M_l on Wigner-d basis

Infinitesimal Generator Initialization $\delta\tau = \frac{\tau}{2^d}$

Doubling layer to obtain **R**, **T**, and **s**.

d iterations finished?

no

yes

Adding layers to obtain **R**, **T**, and **s**.

All layers added?

no

yes

Add surface Reflectance

TOA Stokes Vector

Fig. 2: Doubling-Adding algorithm flowchart. Note that including a solar source does require an additional Fourier expansion of the azimuth angle components.

Consequently, it makes sense to implement a variation of the existing scalar Doubling-Adding method as illustrated in Fig. 2. This algorithm is generally sufficiently fast for moderate optical thicknesses **τ**. Additionaly, the algorithm can be modified to increase the computational speed in certain situations, e.g. by exploiting symmetries of the scattering matrix. A more interesting recent development published in [3] is the seperation of the forward- and diffuse part of the Stokes vector and split Eq. (1) in two equations. This is advantageous for highly peaked phase functions in the NIR-to-UV spectrum, as the forward equation can be solved using a small-angle approximation and the diffuse equation requires less Legendre expansion terms.

3. Scattering Properties

The light scattering properties of the CRTM Release 2.3.x and below are only available in scalar form (i.e. only phase function expansion coefficients are saved in the CRTM coefficient files) and conversely the entire set of bulk scattering properties for the CRTM needs to be re-computed. Current efforts focus on scattering property sets for hydrometeors at 89 and 189 GHz for solver validation purposes.

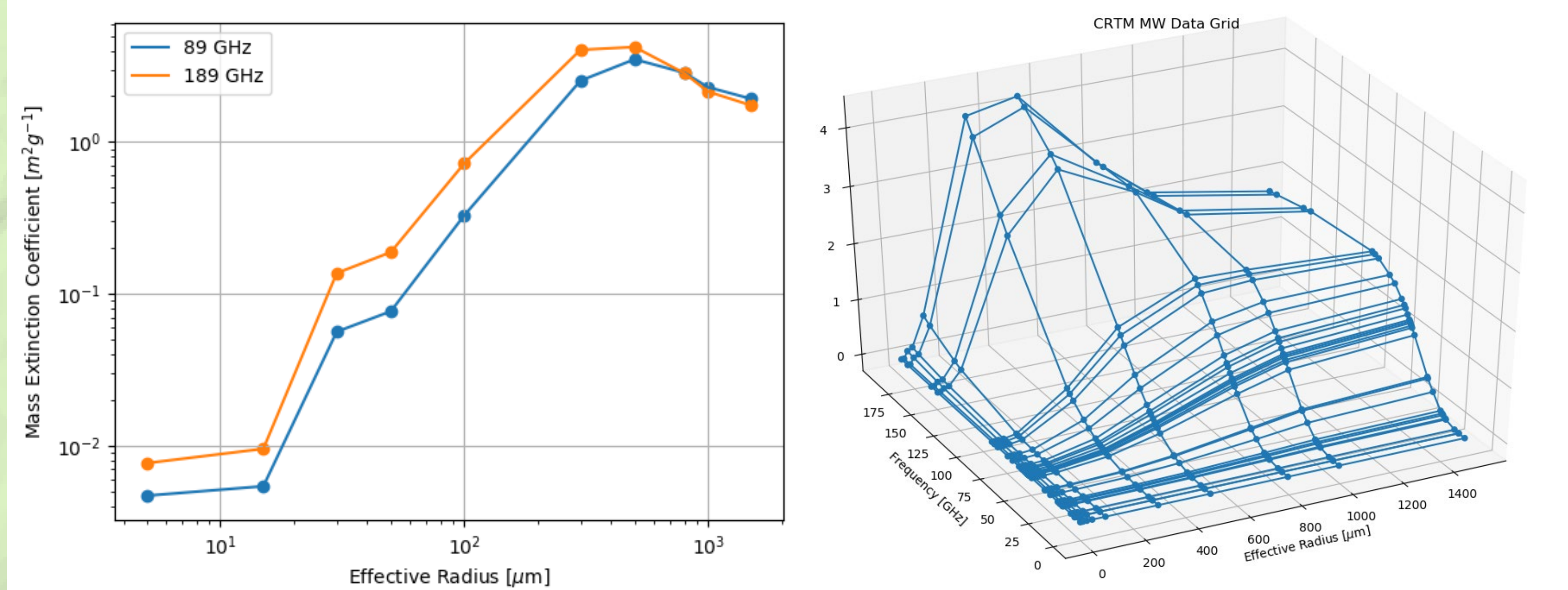


Fig. 2: CRTM MW hydrometeor extinction coefficient data as a function of particle effective radius and instrument frequency.

For the application in the RT solver itself, the computed bulk scattering solvers are projected on a basis of Wigner-d functions (see Fig. 4), analogous to the Legendre function basis in the scalar case.

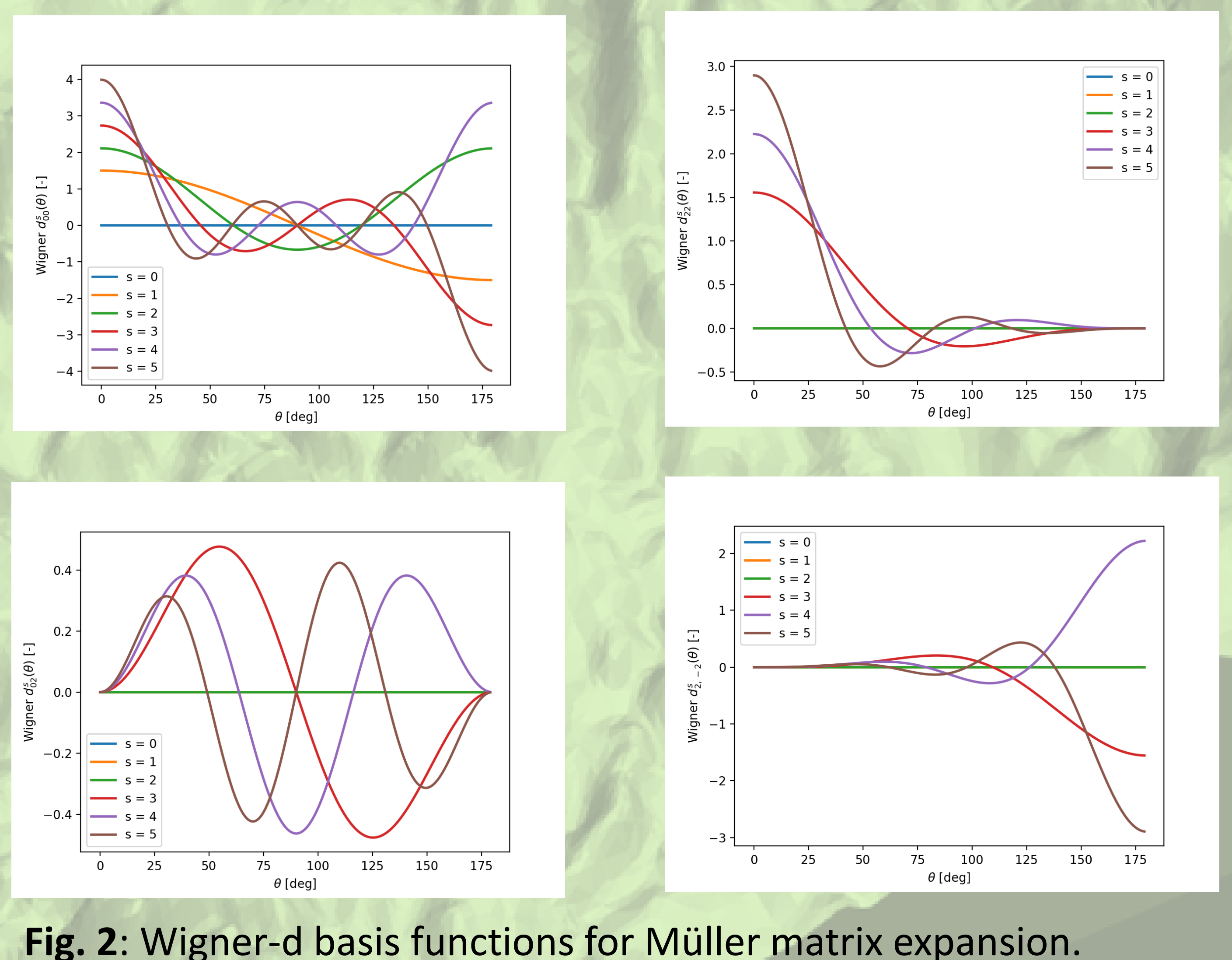


Fig. 2: Wigner-d basis functions for Müller matrix expansion.