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MIDAS : A Computationally Efficient Model for Multistatic Scattering from Complex-shape Hydrometeors

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Abstract—We have developed a MoM-based Integral equation Decomposition for Arbitrarily-shaped Scatterers (MIDAS), to overcome the computational efficiency issues plaguing the Discrete Dipole Approximation (DDA)-based available codes. Our ultimate goal is to provide the precipitation retrieval community with an efficient tool to mitigate the uncertainty in the physical single scattering properties (SSPs) of ice and mixed-phase hydrometeors, representing today a great challenge for the passive and active microwave remote sensing of precipitation.

Index Terms—Scattering by hydrometeors, Method of moments (MoM), EFIE, characteristic basis function method (CBFM).

I. INTRODUCTION

We have developed a 3D full-wave model for scattering by complex-shaped particles (MIDAS). The key idea behind this model is the use of a direct solver-based domain decomposition method, known as the Characteristic Basis Function Method (CBFM). Our model maintains the advantages of the Discrete Dipole Approximation (DDA) [1], namely full-wave solution to arbitrarily shaped scatterer with inhomogeneous composition, while significantly surpassing the DDA implementations in computational efficiency, particularly when considering a large number of particle orientations. A wide spectrum of enhancements is investigated to further optimize the numerical efficiency of our model MIDAS and to improve its accuracy.

II. CBFM APPLIED TO SCATTERING BY SNOW PARTICLES

The method developed to calculate the total field inside the complex-shape hydrometeor is based on a Method of Moments (MoM) solution of the volume integral equation (VIE). After dividing the 3D arbitrary geometry of the particle of N_c cubic cells into M blocks (see figure 1), the CBFM process [2] consists in generating S_i Characteristic Basis Functions (CBFs) for each block i in order to generate at the end a reduced matrix of size $K \times K$ where $K = \sum_{i=1}^M S_i$. This results in a substantial size-reduction of the MoM matrix and enables us to use a direct method for its inversion [3]. Next, the scattering amplitude matrix \mathbf{S} for each incident direction is derived from the scattered fields by using the definition of the scattering matrix adopted for DDScat in [4]. Then, the extinction, scattering and backscattering efficiency factors Q_{ext} , Q_{scat} and Q_{bks} are derived from the scattering amplitude matrices as detailed in [4].

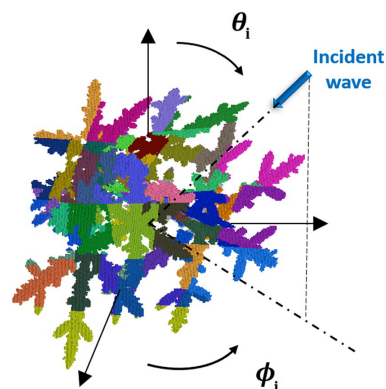


Fig. 1: Division into blocks of an ice aggregate from the OpenSSP database [5], accessible at <https://storm.pps.eosdis.nasa.gov/storm/OpenSSP.jsp>, and definition of the incident direction (θ_i, ϕ_i) .

The main achievements and current efforts (see figure 2) in terms of optimization of the accuracy and computational efficiency of MIDAS, for MoM Integral-equation Decomposition for Arbitrarily-shaped Scatterers, are:

- Reducing the computational expense, both time and memory requirements, when computing the scattering properties of electrically large hydrometeors for a large number of incident directions (θ_i, ϕ_i) (see figure 3). This point has been introduced and dealt with in [3].
- Accurately and efficiently determining orientation-averaged Single Scattering Properties (SSPs), after evaluating the efficacy of several quadrature schemes in minimizing the number of orientations, and hence computation resources, needed for an acceptably accurate orientation average. This point has been introduced and dealt with precisely in [6].
- Ensuring the accuracy of the MoM/CBFM solution when considering scattering from mixed-phase hydrometeors, featuring a problematic high dielectric contrast between ice and water. The present paper will show first promising results announcing an eventual new advantage of MIDAS over existing codes.

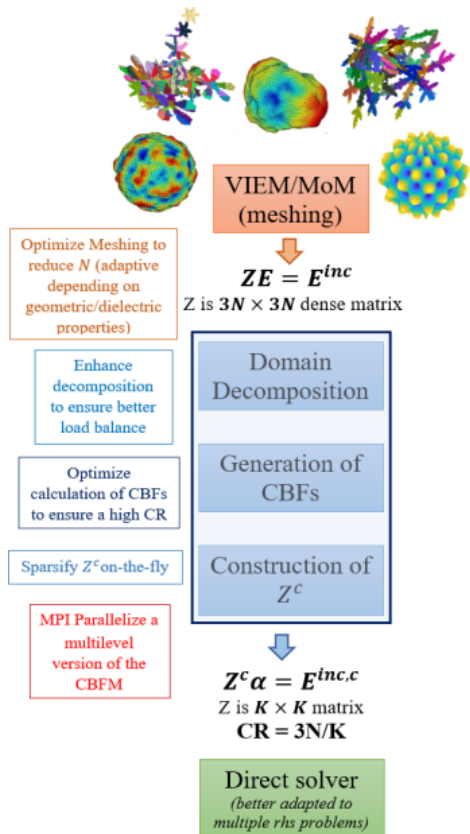


Fig. 2: MIDAS schematic diagram and achieved/potential enhancements

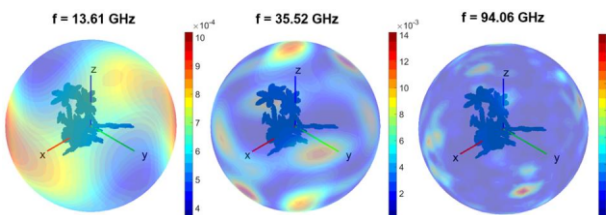


Fig. 3: Variation of the backscatter efficiency Q_{bks} of snow aggregate a0058 (from the OpenSSP database [5]) depending on the incident direction (θ_i, ϕ_i) .

III. SCATTERING BY COMPLEX-SHAPED MIXED-PHASE HYDROMETEORS

The mixed-phase melting hydrometeors represent the “final frontier” of comprehensive physical quantitative precipitation retrievals. Due to their complex structure, heterogeneous composition, usually larger size, and likely preferential orientation, solving the EM scattering problem for these hydrometeors poses an onerous computational challenge. Although the melting hydrometeors are mostly confined in the melting layer, their greatly enhanced reflectivity and extinction obfuscate the EM signal of rain from below when observed from satellites, amplifying uncertainty in the surface precipitation estimates that are paramount for hydrological applications. MIDAS, is promising in meeting this challenge completely, due to its computational efficiency and amenability to improvements.

In this context, recent studies [7] achieved interesting

progress in augmenting the OpenSSP database with realistic synthetic melting hydrometeors (see figure 4). The single Particle Melting Model (SPMM), and other strategies used for melting simulation of any arbitrary particle, is extensively described in [7]. The adopted ice and water refractive indices at Ku, Ka and W bands are shown in Table I.

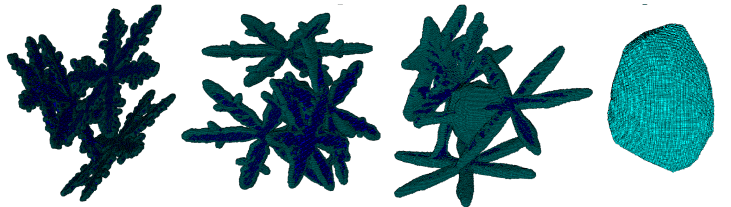


Fig. 4: A mixed-phase hydrometeor at different melting stages from [7]

	Ku	Ka	W
Water	$6.26 + j2.98$	$4.07 + j2.37$	$2.94 + j1.39$
Ice	$1.79 + j3.6110^{-4}$	$1.79 + j9.1310^{-4}$	$1.79 + j2.4110^{-3}$

TABLE I: refractive indices of liquid water and ice at -10°C for Ku, Ka and W bands [6]

Knowing that the discretization cell size, required to ensure the MoM accuracy, depends on the dielectric properties of the considered medium, the new objective is to integrate, in MIDAS, an adaptive mesh to reduce computational cost while maintaining good accuracy. The application of the CBFM on a non-uniform mesh for MIDAS will help solving the current issues of shape consistency and mass conservation through the melting process, while maintaining optimal computation efficiency. A mixed-resolution/adaptive mesh will also enable to finely model some geometrical features of a hydrometeor without over-meshing the entire particle. Particles with small-scale surface roughness, modeling graupel, a hailstone or an aerosol are typical examples. While a very fine discretization is required at the surface to accurately model the small-scale roughness, a much coarser discretization could be used in the inner part of the particle. The adaptive mesh is also practical to faithfully model the inner layers of a realistic hailstone with an optimized computational cost, as we can adapt the cell size to the dielectric properties of each layer. Figure 5 shows examples of adaptive meshes of a complex-shaped melting hydrometeor, and a 2-layer Chebyshev particle modeling a hailstone.

To evaluate the impact of adaptive mesh on both the computational efficiency and accuracy of MIDAS solution, we compute the scattering properties of a melting hydrometeor using a mixed-resolution (MR) mesh, namely cell sizes $d = 15$ and $d = 30 \mu\text{m}$ for water and ice parts respectively, and compare the results to those obtained with the high-resolution (HR) uniform mesh of cell size $d = 15 \mu\text{m}$. The simulated melting snow particle, generated as described in [7], has 25 melting stages with liquid water fraction (LWF) going from 0 to 1, corresponding to a maximum dimension D_{max} going from 5.34 to 1.86 mm. Figure 6a shows the numerical size of the particle with high and mixed resolution mesh, HR and MR respectively, and the resulting computing times. Figure

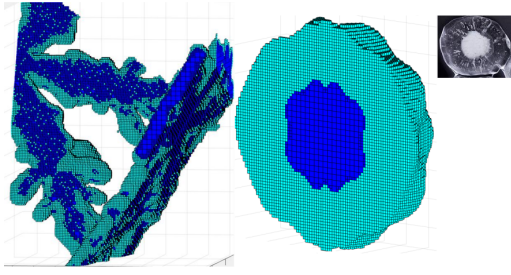
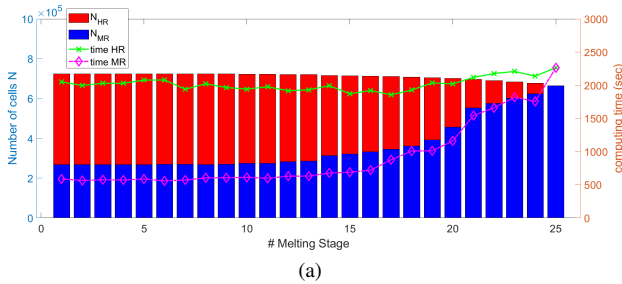
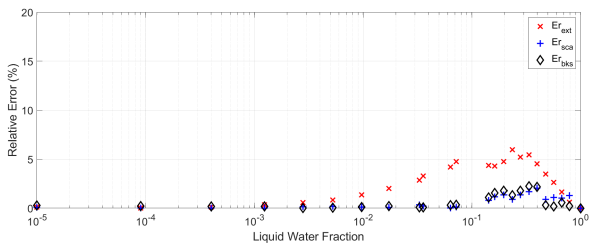


Fig. 5: Adaptive mesh applied to a melting hydrometeor and a Chebyshev particle modeling a hailstone



(a)



(b)

Fig. 6: (a) The number of cells with the high- and mixed resolution mesh, N_{HR} and N_{MR} , and the corresponding computing time in seconds (b) The relative error Er introduced in Q_{ext} , Q_{sca} and Q_{bks} , by the mixed-resolution (MR) mesh with reference to the uniform high-resolution (HR) mesh function of the incident wave direction defined by (θ_i, ϕ_i) . To allow an accurate comparison, we ran DDSCAT at exactly the same orientations as those used in MIDAS with the aq configuration.

6b plots the relative error observed in extinction, scattering and backscattering efficiency factors, Q_{ext} , Q_{sca} and Q_{bks} , obtained as $Er = 100 * |Q_{MR} - Q_{HR}| / Q_{HR}$ where Q_{MR} and Q_{HR} are the efficiency factors (extinction, scattering or backscattering) computed with mixed- and high-resolution mesh, respectively.

As can be seen in Figure 6 a mixed-resolution mesh with a factor of only two ($d = 15$ and $d = 30 \mu m$ for water and ice parts respectively) results in a significant reduction of the numerical size of the EM problem, and thus the computation cost, particularly throughout the first melting stages, without significantly impacting the accuracy of the EM solution.

Figure 7 compares the magnitude of scattering matrix elements S_{HH} , S_{VV} , S_{HV} and S_{VH} , obtained with the high- and mixed-resolution meshes, as function of scattering angle θ_s , when the particle is at the melting stage 17. It confirms that the computational cost reduction achieved by implementing the mixed-resolution mesh is associated with a satisfactory level of accuracy of the EM solution.

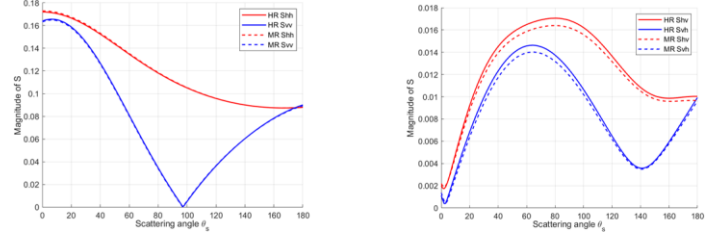
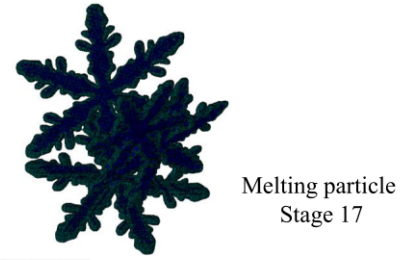


Fig. 7: variations of the scattering amplitude matrix elements as function of the scattering angle θ_s for the snow aggregate at melting stage 17 (LWF=0.23566) for the high- and mixed-resolution, HR and MR respectively, discretization

It is understandable that the gain in numerical size achieved by the adaptive mesh decreases as the LWF increases, as the portion of liquid water, meshed with the highest resolution, is getting dominant towards the end of the melting process. This spurs us to conduct an extensive study of the contribution of the adaptive mesh to the computational efficiency and its impact on the accuracy of the MoM then the CBFM separately, depending on the geometry and dielectric properties of the particle and on the frequency of interest.

IV. CONCLUSION

MIDAS has not only demonstrated significant advantage in computational efficiency over the DDA-based code DDSCAT, without compromising accuracy, but also great potential to address outstanding EM scattering challenges from solid and mixed-phase hydrometeors to comprehensively improve physical quantitative microwave precipitation retrievals.

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