Progress of MIDAS and Challenges

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Background and Motivation

- Single-scattering properties of hydrometeors are fundamental for physical precipitation (and cloud) remote sensing (retrieval).
- Many solid and melting hydrometeors have *complex* and *non-convex* shapes.
- The assumption of *simple, convex* shapes causes inconsistency between active (radar) and passive (radiometer) retrievals.
  - Olson et al (2016; https://doi.org/10/f8h9qw)
- Generating the complex, non-convex hydrometeors and solving the associated EM scattering problems are computationally costly.
- Melting hydrometeors add the complication of **heterogeneous composition with high refractive contrast** between liquid and solid at lower microwave frequencies (≲ 35 GHz).

MIDAS in a Nutshell

- MIDAS: MoM (Method of Moments) Integral-equation Decomposition for Arbitrary Scatterers
- MIDAS can run in one of two modes
  1. full MoM mode: MIDAS-MOM, no approximation
  2. Characteristic Basis Function Method mode: MIDAS-CBFM, with SVD approximation
- In the integral-equation formulation, MoM and DDA are equivalent
  - The volume elements, or voxels, in MoM are just like the dipoles in DDA
- They require the same criterion, $|m|kd<0.5$, for accurate angular cross-sections where m is the refractive index, k the angular wave number, and d the dipole distance (voxel size).

MIDAS-MOM

The volume integral equation (VIE)

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_0(\mathbf{r}) + (k_0^2 + \nabla\nabla\cdot)\int_\Omega \chi(\mathbf{r}')G(\mathbf{r},\mathbf{r}')\mathbf{E}(\mathbf{r}')\,d\mathbf{r}'$$

$$\Rightarrow\ \Gamma\mathbf{E}(\mathbf{r}) = \mathbf{E}_0(\mathbf{r})$$

$$\Gamma = \mathbf{I} + (k_0^2 + \nabla\nabla\cdot)\int_\Omega \chi(\mathbf{r}')G(\mathbf{r},\mathbf{r}')\,d\mathbf{r}': \text{operator}$$

Ω: the spatial domain (grid cells when discretized) occupied by the scatterer

$\chi(\mathbf{r}) = (\epsilon(\mathbf{r})/\epsilon_0) - 1$: dielectric contrast between the scatterer and the free space

After discretizing the *bounding box* of Ω into a grid system of cubic cells, in which Ω occupies N cells, we arrive at a linear system of size $3N\times3N$

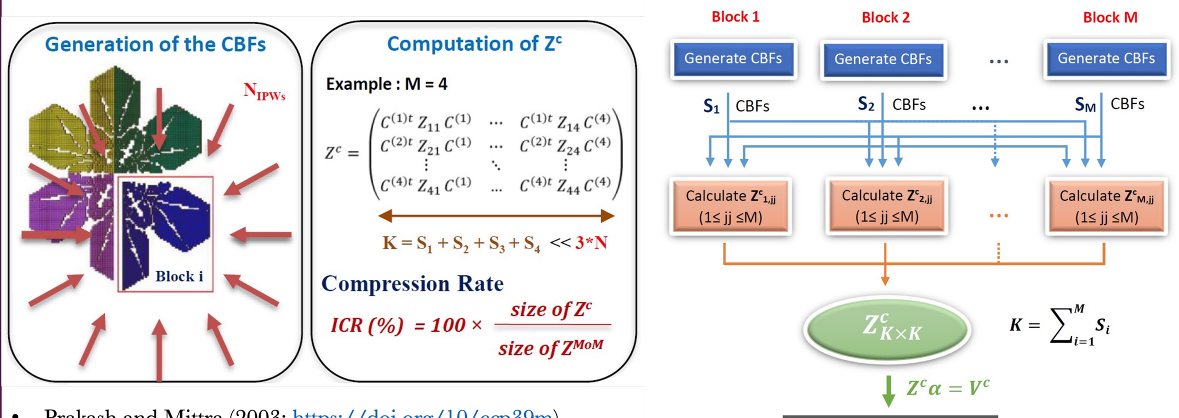
$$\sum_{n=1}^{N}\sum_{q=1}^{3} Z_{pq}^{mn}E_q^n = E_{0,p}^m$$

MIDAS-CBFM

In CBFM mode, MIDAS

- decomposes the container volume into several sub-volumes,
- formulates each sub-volume as a separate, local MoM problem with a set of incident waves,
- performs singular value decomposition (SVD) on the matrix of each local problem,
- applies a threshold to the singular values and constructs an approximate matrix by selecting only the components corresponding to those above the threshold,
- concatenates the local matrices, and
- solves the approximate problem.

MIDAS-CBFM Illustration

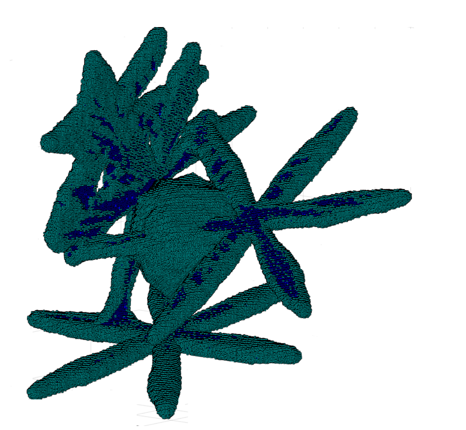


- Prakash and Mittra (2003; https://doi.org/10/ccp39m)
- Mittra and Du (2008; https://doi.org/10/c3wthc)
- Fenni et al (2018; https://doi.org/10.1109/TGRS.2017.2781625)

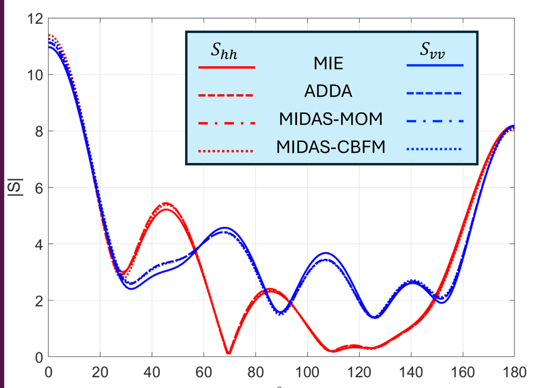
Challenge of Melting Hydrometeors

- Melting hydrometeors have a heterogeneous composition of ice and liquid water
- Starting around the Ka-band $|m|>4$ for liquid water, beyond the valid range of DDA
- Even when the DDA criterion, $|m|kd<0.5$, is strictly satisfied, we find significant uncertainties in Q_e, Q_s, and Q_b
- Large contrast in dielectric dipole size, $|m_w|/|m_i| \gtrsim 2.5$, at the liquid-solid interfacial boundaries

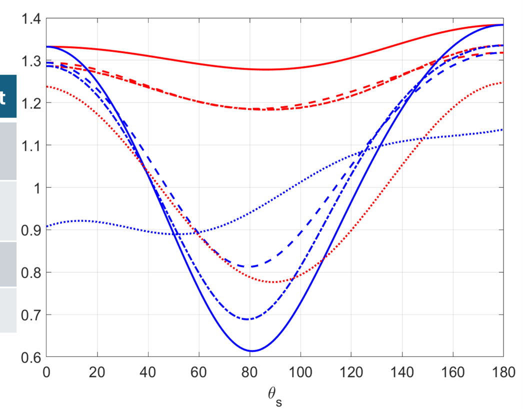
	13.5 GHz (Ku)	35 GHz (Ka)	94 GHz (W)
Water	6.26 + i 2.98	4.07+i 2.37	2.94 + i 1.39
Ice	1.79 + i 3.61 10⁻⁴	1.79 + i 9.13 10⁻⁴	1.79 + i 2.41 10⁻⁴
$\lvert m_w\rvert/\lvert m_i\rvert$	3.87	2.63	1.82



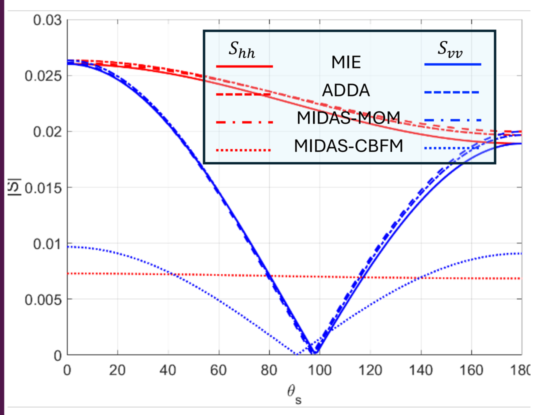
Homogeneous Liquid Sphere



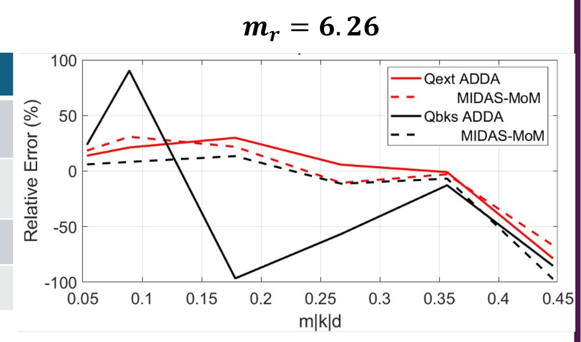
Left		Right
16	r (mm)	4
800	d (μm)	200
1.79	$\lvert m\rvert$	6.26
0.41	$\lvert m\rvert kd$	0.36



Findings:
1. The solution error is due mainly to high refractive index, not the contrast between them.
2. The $|m|kd \lesssim 0.5$ criterion is valid for $|m| = 1.79$, but insufficient for larger $|m|$.



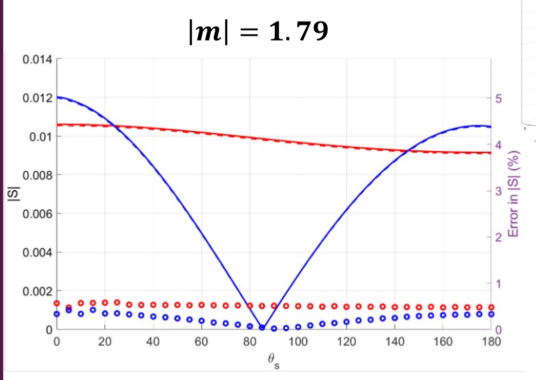
p	v
r (mm)	1
d (μm)	50
$\lvert m\rvert$	6.26
$\lvert m\rvert kd$	0.09

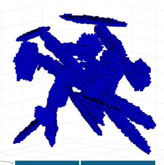


Findings:
3. Decreasing d, hence $|m|kd$, improves accuracies of ADDA and MIDAS-MoM for $|m|$=6.26
4. Higher resolution does not improve MIDAS-CBFM results.

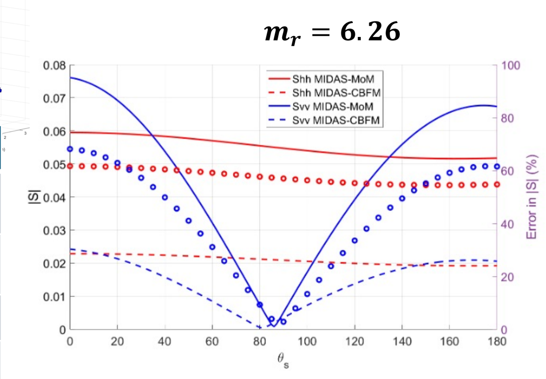
Homogeneous "Liquid Aggregate"

Comparing MIDAS-CBFM to -MOM (No Mie)





p	v
r_{eq} (mm)	1
d (μm)	50
$\lvert m\rvert$	6.26
$\lvert m\rvert kd$	0.09



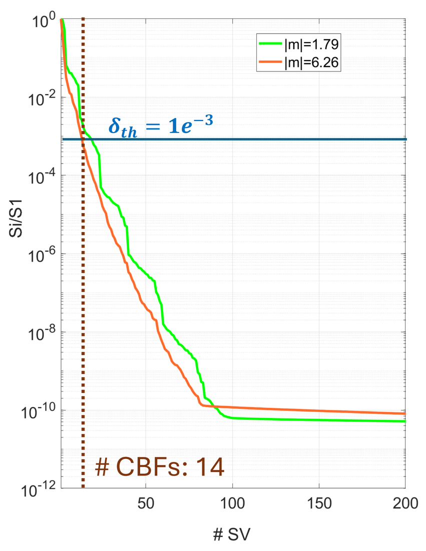
Finding:
5. It is not the shape of the particle.

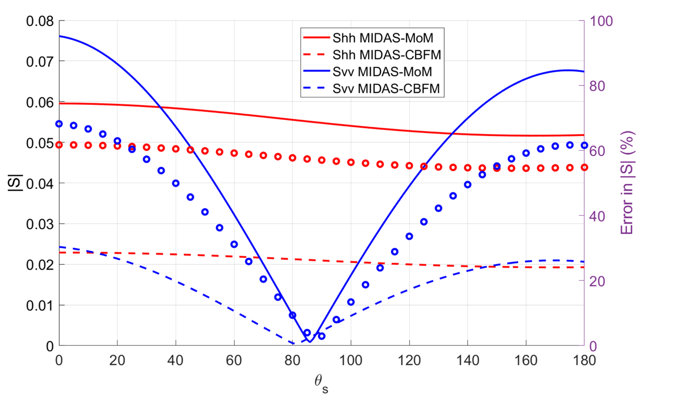
Recap

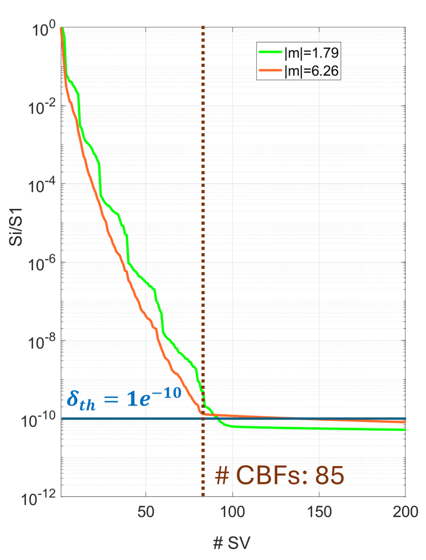
- Findings
  - We initially suspected it was due to the high contrast between the refractive indices of liquid water and ice.
    - Comparing to the Mie solution of a liquid sphere shows that It is mainly due to the high refractive index of liquid water
    - The discretization resolution, d, improves ADDA and MOM solutions but not CBFM
  - Results from a fictitious "liquid aggregate" indicate that particle shape has little or no impact.
- Since CBFM is an approximation to MOM with many tunable parameters, adjustment to some combination of these parameters may improve the approximation, e.g.,
  - the size (dimensions) of the CBFM blocks,
  - the number and type of the incident waves,
  - the quadrature used for integration, and
  - the threshold applied to the singular value decomposition (SVD).

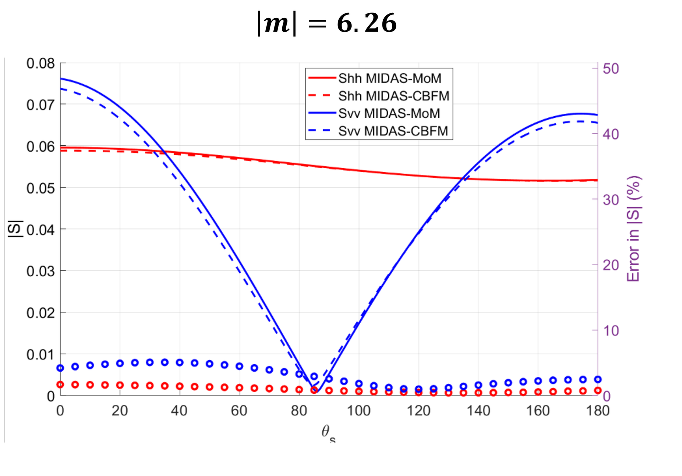
Homogeneous Liquid Sphere

The Role of SVD Threshold



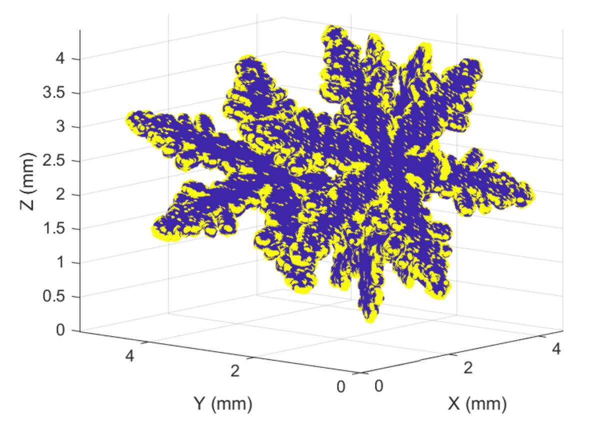






Background and Motivation

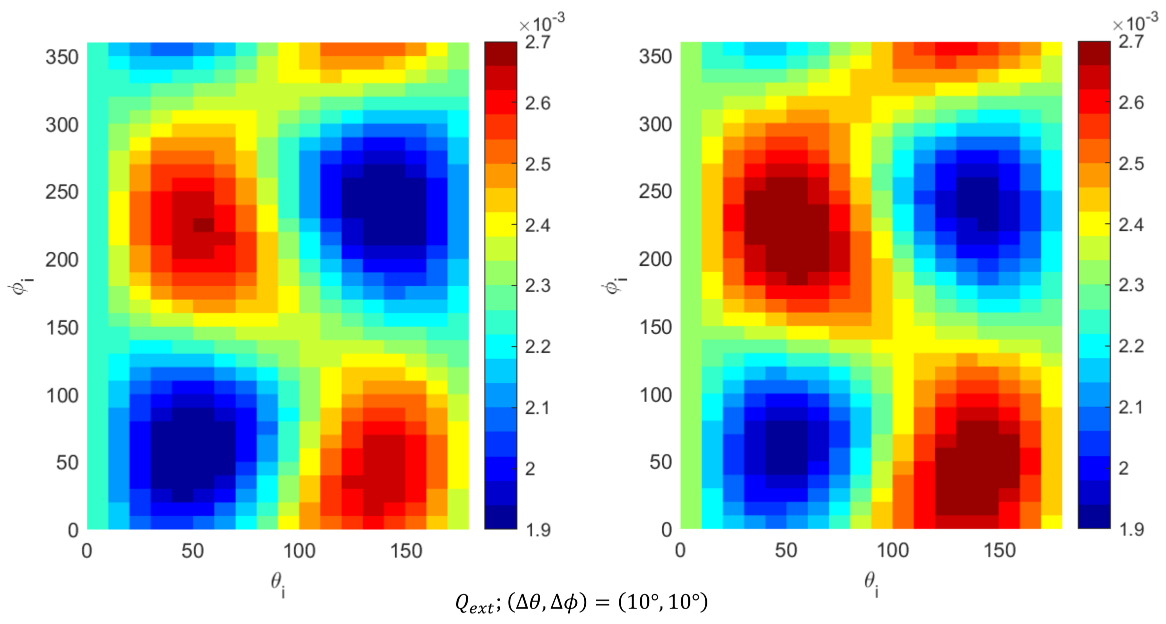
p	v
$\lvert m\rvert$	6.26
d (μm)	15
$\lvert m\rvert kd$	0.027
r_{eq} (mm)	0.834
D_{max} (mm)	5.32
LWF	3.285%



$|m|kd \cong 0.027 (\approx 0.5/20)$

- It takes ADDA ~4 minutes for each orientation and ~46 hours for 703 orientations!
- Even with significantly more CBFs, MIDAS has a large edge in time-to-solution!

10^{-3}	δ_{th}	10^{-8}
adaptive	Quadrature	spherical design
190	N_{iw}	482



~4.28	max. % Error w.r.t. ADDA	~-1.6
24.9	Compute Time in minutes (4 nods, 256 MPI tasks)	100.6

Conclusions

- Realistic scatterer geometry and composition are paramount for reducing uncertainties in physical particulate-matter retrievals, e.g., aerosol, cloud, and precipitation.
- For higher $|m|(\gtrsim 4)$, the accuracy of ADDA and MIDAS-MoM improves when a much finer discretization resolution is used, e.g., $|m|kd \lesssim 0.1$, but not MIDAS-CBFM
  - Higher discretization resolutions lead to higher computation demands!
- The **SVD threshold used** for selecting CBFs at local blocks plays the most crucial role in improving MIDAS-CBFM accuracy (after resolution refinement)
  - The number of incident waves and the degree of quadrature play important supporting roles.
  - MIDAS-CBFM is still significantly more computationally competitive than DDA.
- MIDAS characterization effort will continue to address the issue of predetermining the optimal parameter combination.

Acknowledgement

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