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AOD fusion based on pixel-level uncertainty using geostationary satellite instruments: GEMS, AMI, and GOCI-II

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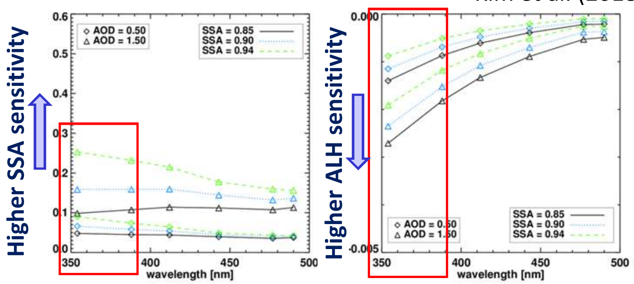
Remote sensing synergy of multiple sensors

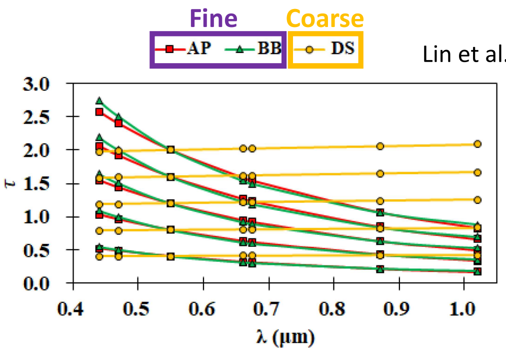
- **Sensor spectral range affects sensitivity & spatial coverage of aerosol retrieval**

Kim et al. (2018)



! UV: sensitive to aerosol absorption & height

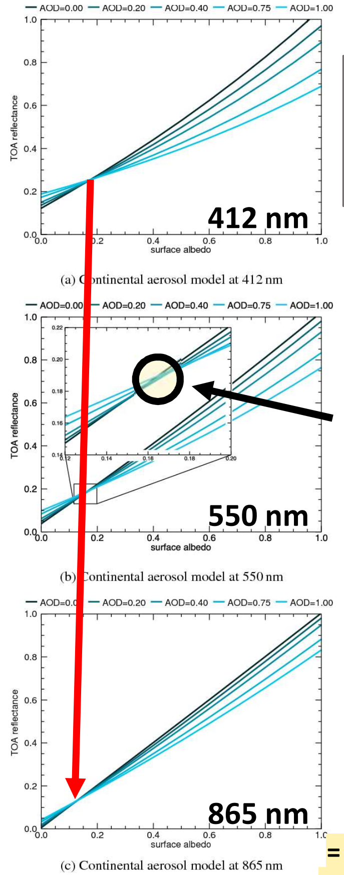
Lin et al. (2021)



! VIS-NIR: sensitive to aerosol size

- High sensitivity = retrieval of the optical property.
- Low sensitivity = **robust retrieval against the optical property**.
  - different uncertainty characteristics

Seidel et al. (2011)



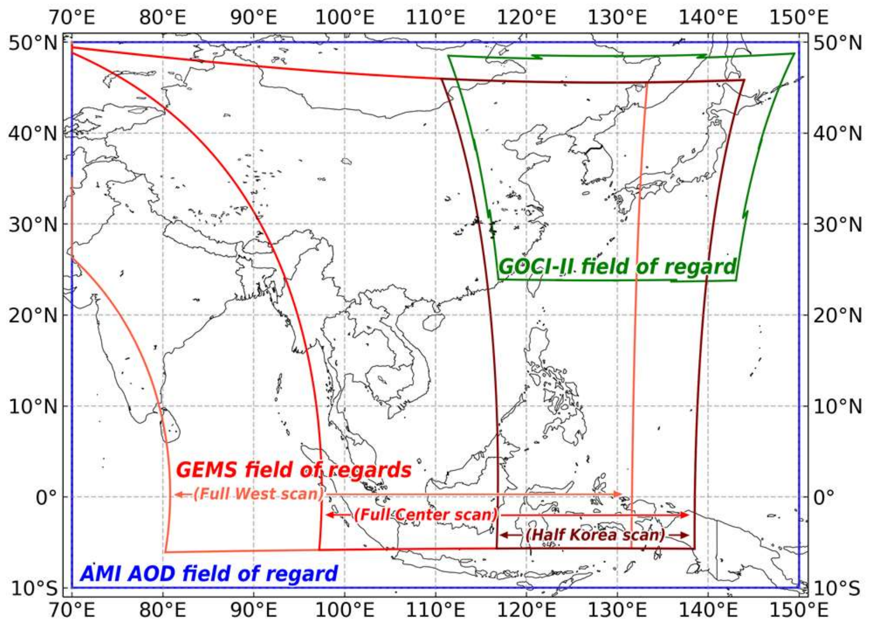
- Observation at shorter wavelength
= low land surface albedo
= broader coverage of AOD

No AOD sensitivity
(critical albedo)
= AOD retrieval only at surface with lower reflectance than critical albedo

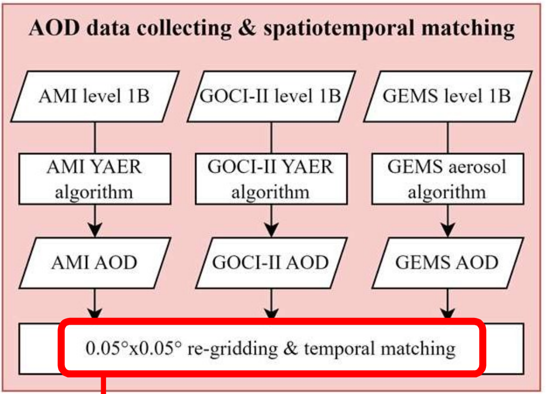
Longer wavelength
= Lower critical albedo
= Smaller AOD coverage

GK-2A, -2B / GEMS, AMI, GOCI-II aerosol algorithm

	AMI	GEMS	GOCI-II
Satellite	GeoKompsat-2A (GK-2A)	GeoKompsat-2B (GK-2B)	
Purpose	Meteorology monitoring	Environment monitoring	Ocean color monitoring
Spectral range	VIS~**IR** (0.47-13.3 μm) 16 **band**	**UV**~VIS (300-500 nm) 0.6 nm res. **hyperspectral**	VIS-NIR (0.38-0.86 μm) 13 **bands**
Field of regard	**Full-disk**, East Asia, Korean local area	East Asia (5˚S~45˚N, 75˚E~145˚E)	Korean local area
Spatial resolution	0.5 km (Red), 1 km (Green, Blue), 2 km (IR)	3.5 km × 8 km	**250 m**
Temporal resolution	**10 min.** (Full-disk), 2 min. (EA, KLA)	1 hour (8 times during daytime)	1 hour (10 times during daytime)
Aerosol product	Yonsei aerosol retrieval (YAER) algorithm 6 km res.	GEMS V2 operational algorithm 3.5 km × 8 km res.	Yonsei aerosol retrieval (YAER) algorithm 2.5 km res.



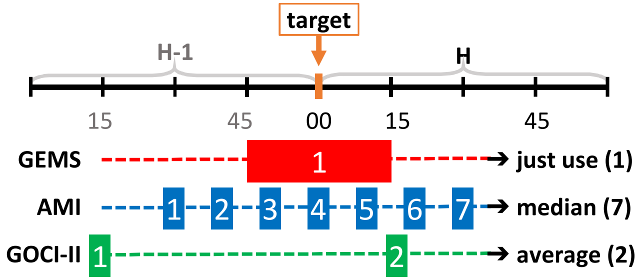
L2 AOD fusion strategy

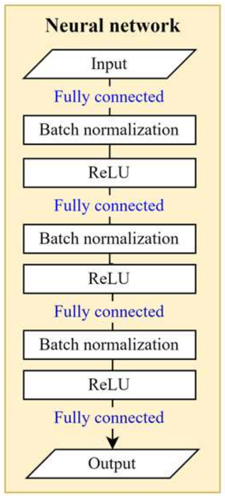


- **Spatial matching**

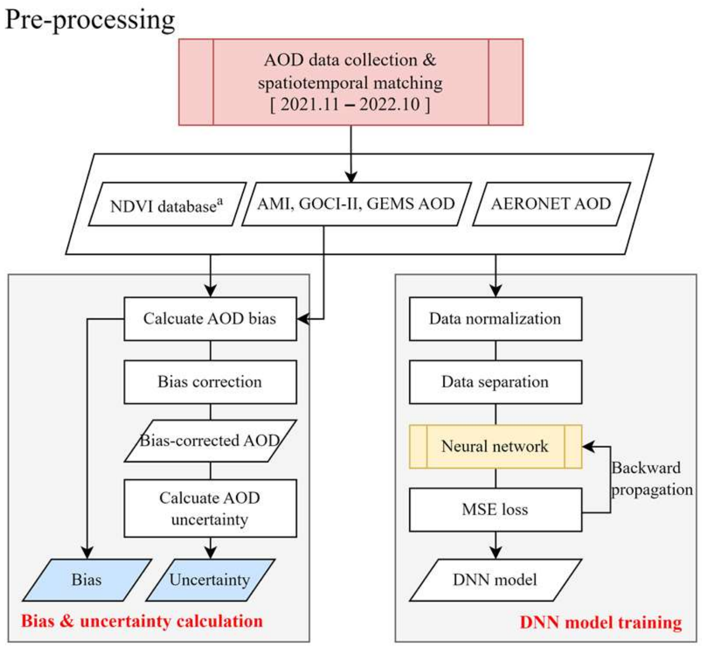
GEO coordinate ➔ 0.05° ×0.05° grid
Inverse distance weighting of maximum 3 neighboring pixels of each grid points.

- **Temporal matching**

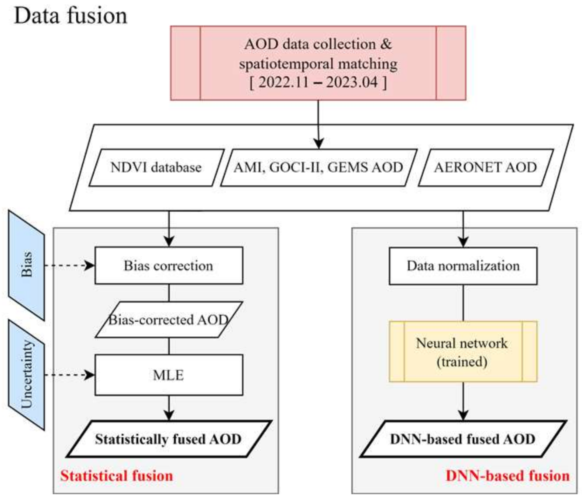




<Uncertainty estimation with 1-year data>
: used AERONET V3 LEV2.0

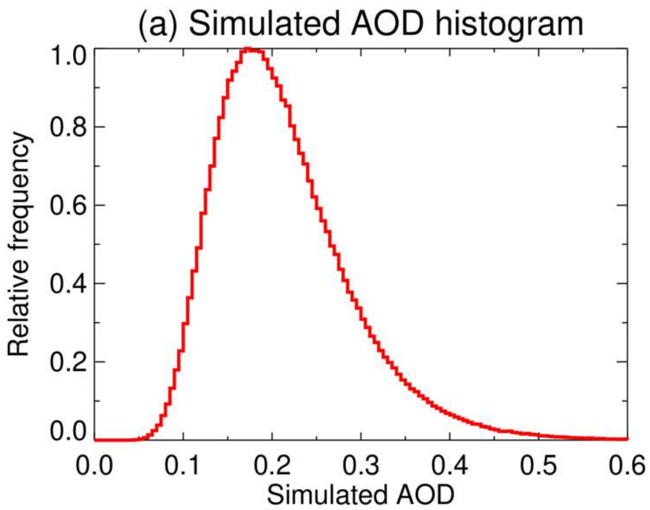


<Data fusion for 6 months>
: validated with AERONET V3 LEV1.5

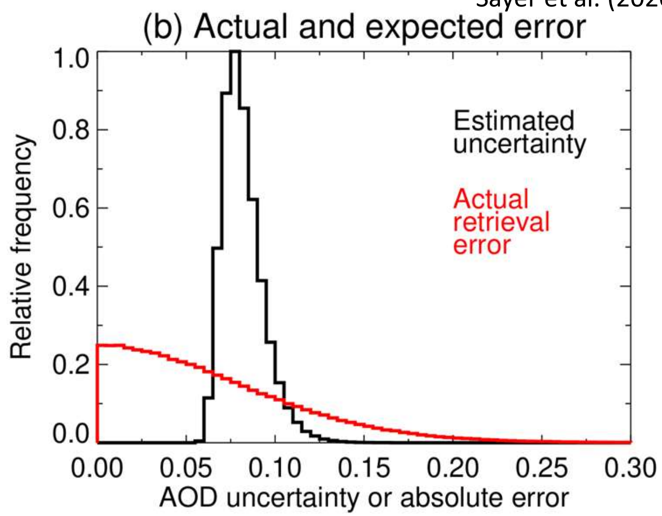


Statistical fusion: ① bias correction

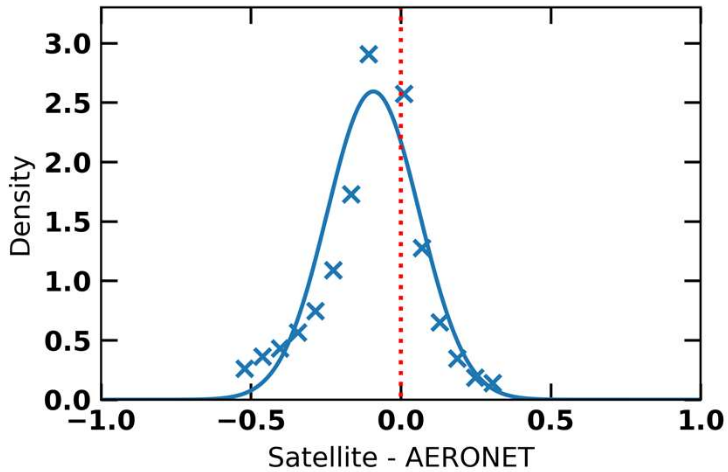
Sayer et al. (2020)



< Typical AOD distribution (log-normal) >



< Typical AOD error distribution (Gaussian) >



< GEMS AOD error distribution >

Typical AOD has Gaussian error distribution (mean of **zero**, standard deviation of **unity**)

⇨ Gaussian fitting with actual retrieval data returns **non-zero** mean, and **non-unity** standard deviation.

⇨ **non-zero** mean = bias / **non-unity** standard deviation = uncertainty

⇨ A likelihood function of the MLE fusion is based on the assumption of unbiased satellite retrieval.

⇨ Retrieval bias needs correction.

Statistical fusion: ② Maximum Likelihood Estimation

- **Maximum Likelihood Estimation**

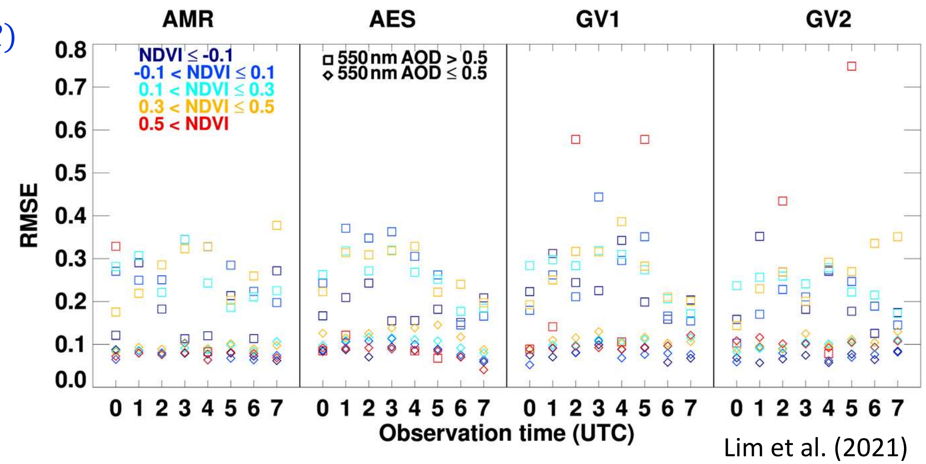
A likelihood function that assumes a **Gaussian error** having $\boldsymbol{\mu = 0, \sigma = uncertainty(R)}$

$$\rho(x) = \sum_i \frac{1}{R\sqrt{2\pi}} \left(-0.5 \frac{\tau_{MLE} - \tau_i}{R_i}\right),$$

- $\boldsymbol{\rho(x)}$: likelihood function
- $\boldsymbol{\tau_{MLE}}$: target(fused) AOD
- $\boldsymbol{\tau_i}$: AOD of instrument i
- $\boldsymbol{R_i}$: uncertainty (RMSE)

τ_{MLE} maximizing the likelihood function

$$\tau_{MLE} = \frac{\sum \tau_i R_i^{-2}}{\sum R_i^{-2}},$$



Lim et al. (2021)

- **Why consider "pixel-level" uncertainty?**

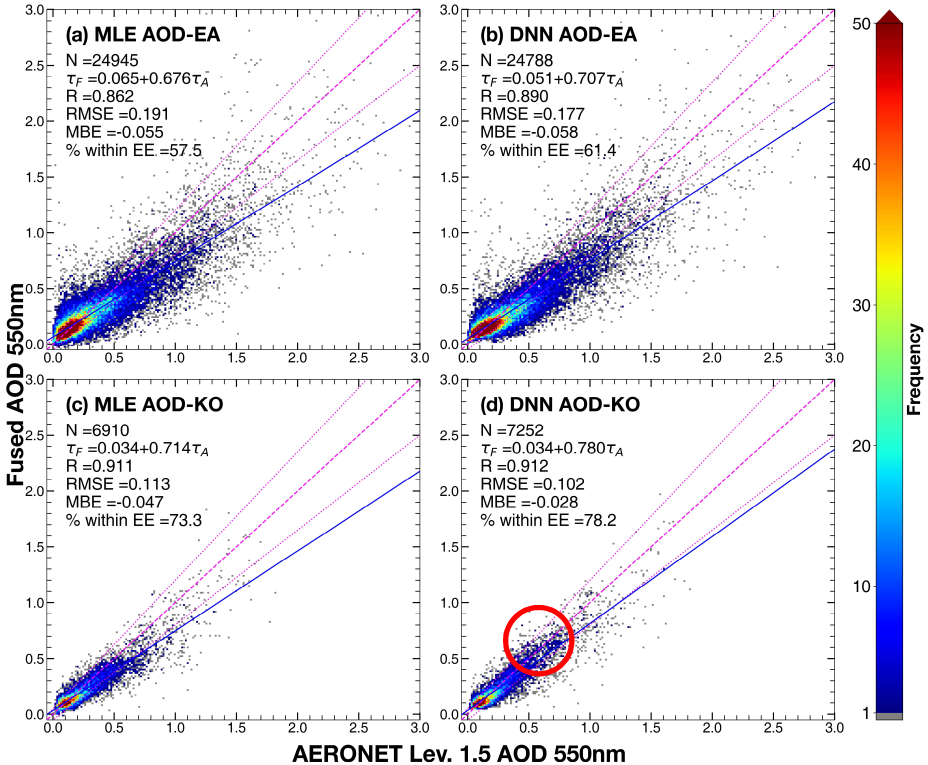
Satellite AOD retrieval have different uncertainty characteristics based on various error sources such as **(a)surface condition, (b)light path, (c)aerosol loading, (d)aerosol type**.

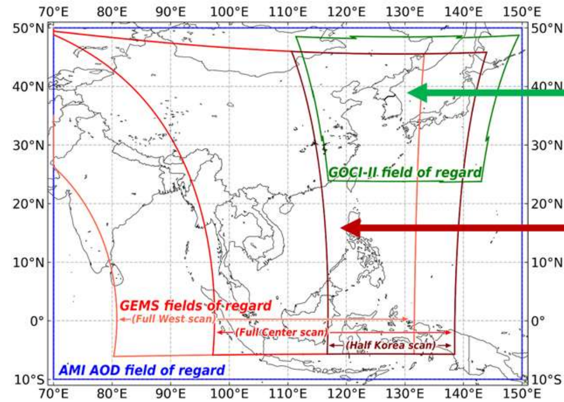
Uncertainty that reflects retrieval condition of each pixel is needed.

- **How?**

Calculate uncertainty(RMSE) at different (a)NDVI, (b)observation time, (c)AOD, (d)aerosol type

Validation with ground-based (AERONET) AOD





Fused AOD near Korean peninsula:
"AOD-KO"
: within GOCI-II domain

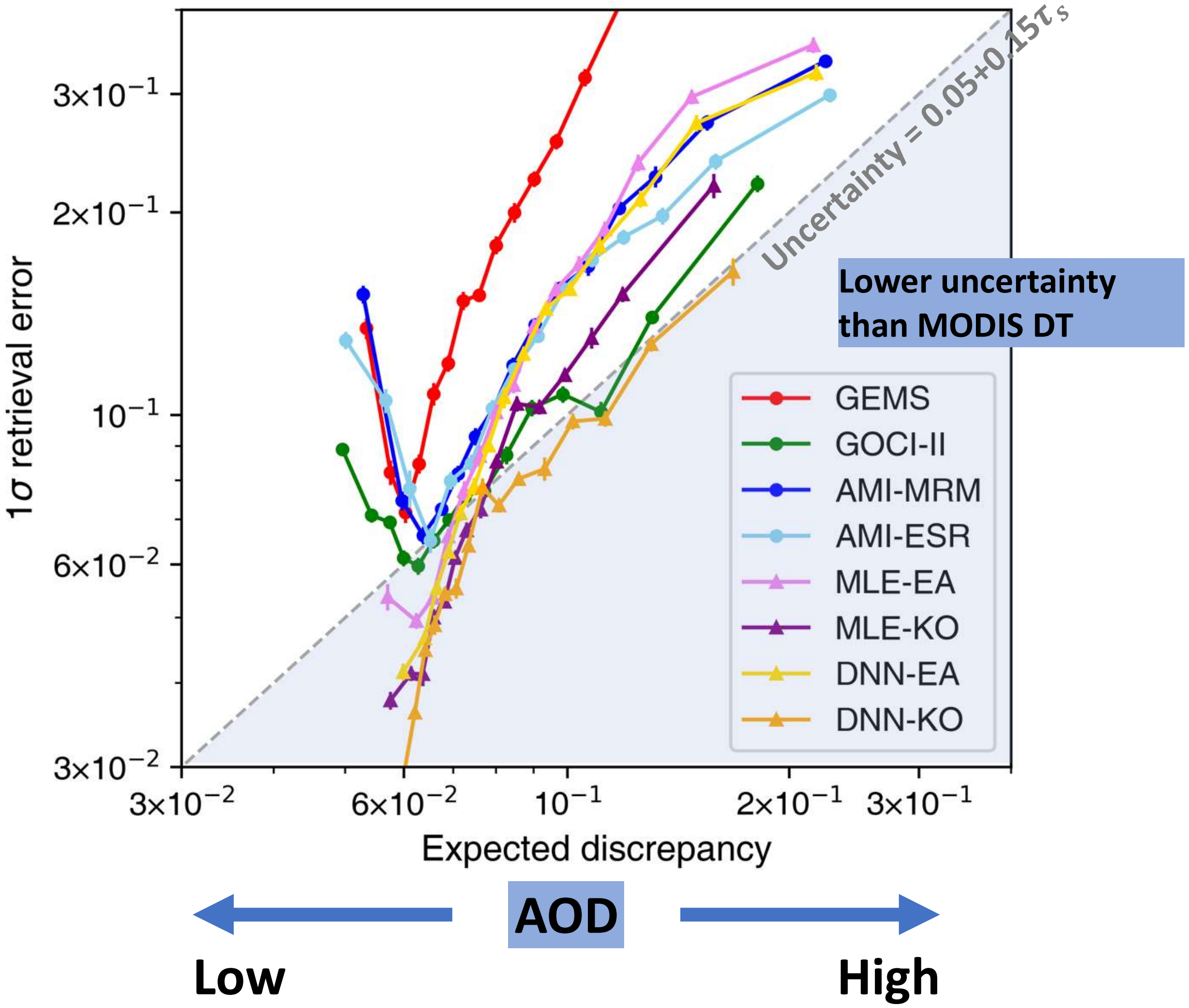
Fused AOD in East Asia:
"AOD-EA"
: within GEMS domain

Expected error (EE) envelope: 0.05+0.15τ_s

	AMI-MRM	AMI-ESR	GEMS	MLE-EA	DNN-EA	GOCI-II	MLE-KO	DNN-KO
N	23690	23531	18034	24945	24788	7321	6910	7252
R	0.833	0.860	0.800	**0.862**	**0.890**	0.903	**0.911**	**0.912**
RMSE	0.201	0.187	0.282	**0.191**	**0.177**	0.119	**0.113**	**0.102**
MBE	-0.045	-0.045	-0.154	**-0.055**	**-0.058**	-0.045	**-0.047**	**-0.028**
% EE	52.1	53.1	39.5	**57.5**	**61.4**	65.1	**73.3**	**78.2**

- **Underestimation** of high aerosol loading affects MLE AOD.
  - Better fusion result is expected after version update of GEMS aerosol algorithm.
  - Using neural network mitigates the problem.
- Bias correction enhances **low AOD accuracy** of MLE AOD.
  - High MLE-KO AOD's % within EE.
  - % within EE of DNN-KO AOD is much higher due to better quality at higher AOD

Performance Evaluation with MODIS DT expected error

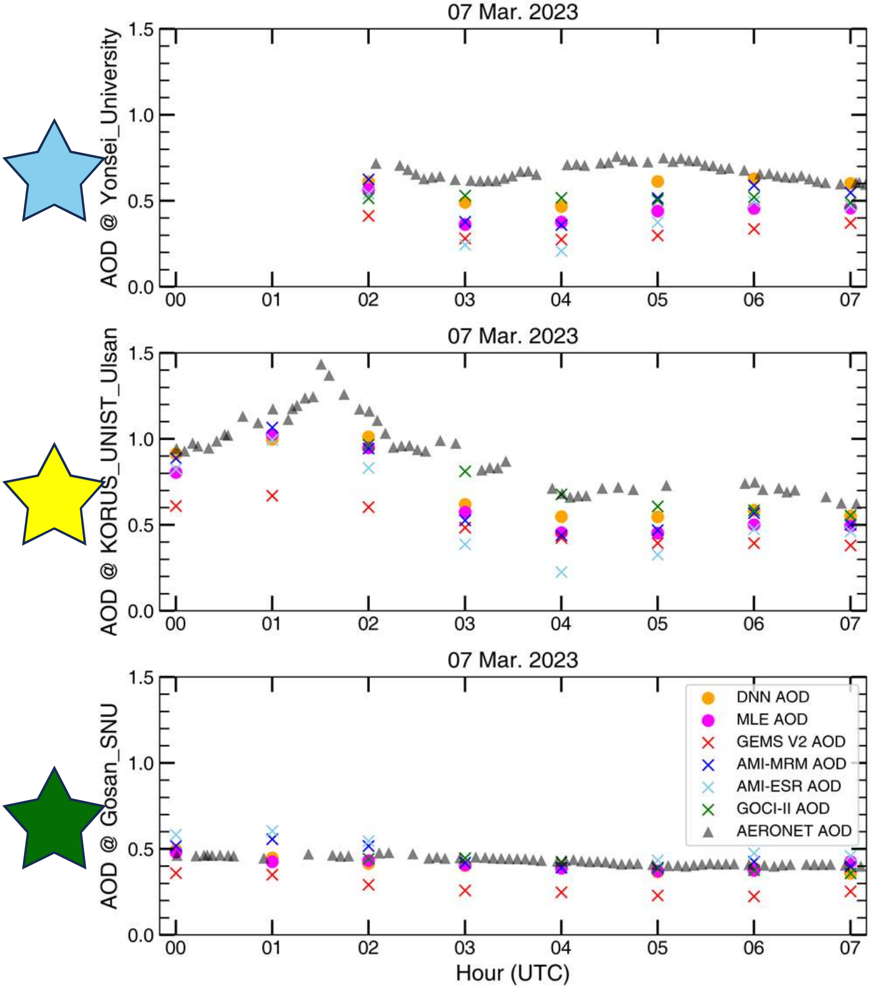


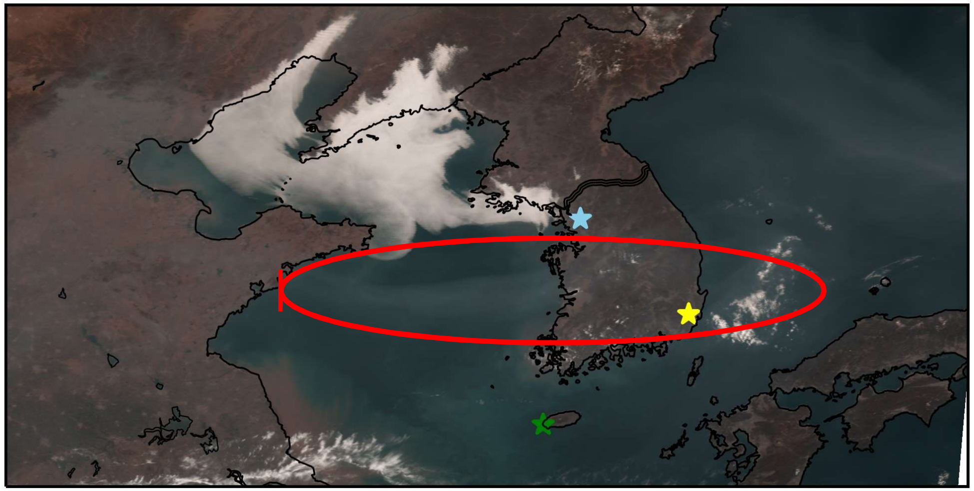
- "Expected discrepancy": **AOD uncertainty** estimated based on MODIS DT expected error (EE: 0.05+0.15τ_s)
- Expected discrepancy is linearly related to AOD.
- Compare AOD uncertainty with one standard (MODIS DT).

- Within –EA region, MLE and DNN uncertainties are similar.
  - Merging GEMS + AMI-MRM + AMI-ESR, the uncertainty result at high AOD is similar to AMI-MRM.
  - Uncertainty of fused AOD products are low at low AOD.

- DNN-KO AOD has the lowest uncertainty.

Performance Evaluation with MODIS DT expected error





- (Yonsei_University) all AOD products were underestimating.
  - AOD value of DNN AOD is closer to AERONET, but diurnal variation is better captured with MLE AOD
- (KORUS_UNIST_Ulsan) AOD > 1.0 is observed with AERONET.
  - Both MLE and DNN AOD well captured high AOD.
- (GOSAN_SNU) Diurnal error variation of AMI-MRM, AMI-ESR AOD
  - Wrong diurnal AOD variation of AMI is mitigated after fusion.

Summary

- Bias and RMSE of GEMS, AMI, GOCI-II AOD products are calculated from **Nov. 2021 to Oct. 2022**.
- Three AOD products are fused **from Nov. 2022 to Apr. 2023**.
- Compared to EE based on MODIS DT, **fused AOD performs better at low aerosol loading**.
- At higher AOD, DNN algorithm works better than statistical fusion.
- **Underestimation of AOD at higher aerosol loading** affects fused AOD product.
- **Aerosol data fusion stabilizes diurnal error variation.**

Reference

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