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A Novel Algorithm for Deriving Aerosol Optical Depth over Cities using the Building Shadows of High-resolution Satellite Imagery

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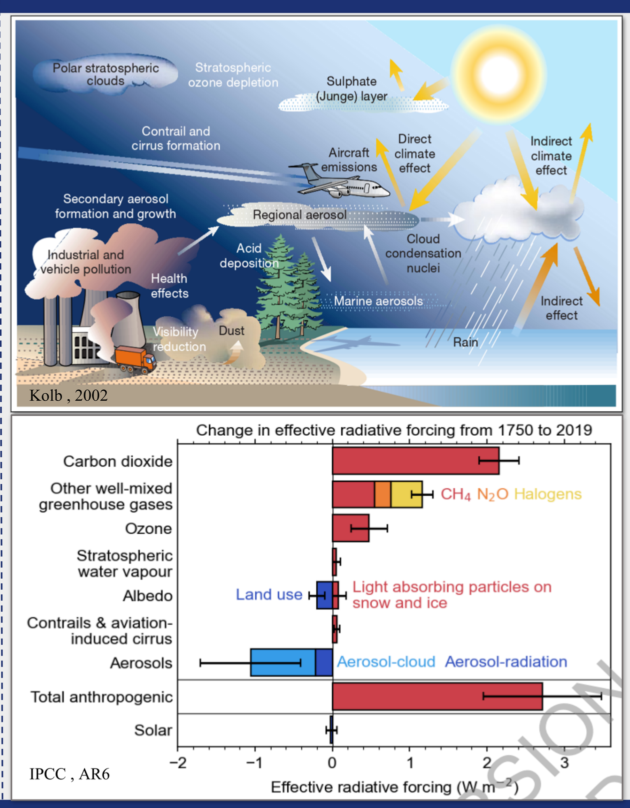
ABSTRACT

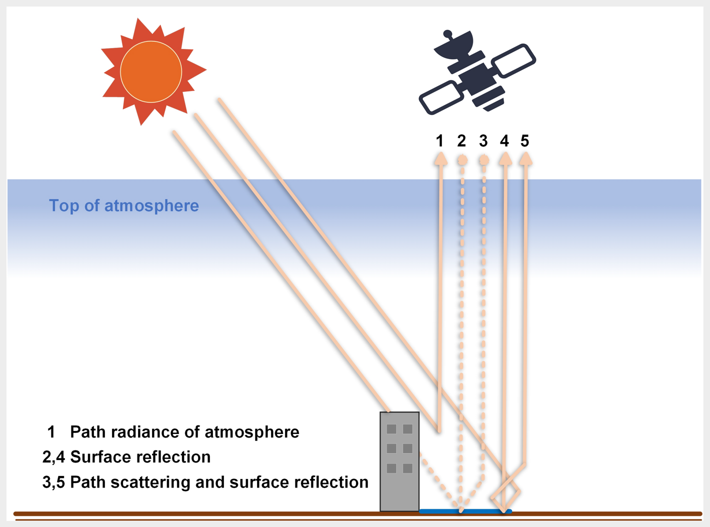
Current satellite-based methods for measuring aerosols require uniform surfaces and accurate pre-assumed albedo, unsuitable for diverse urban areas. Advances in high-resolution satellites allow identifying building shadows in images. A new algorithm suggests retrieving aerosol optical depth (AOD) and ground albedo (ALB) using shaded building pixels and sunlit adjacent pixels. Using the GF2 satellite images for algorithm testing, the AOD and ALB values near the Beijing Olympic Center were successfully retrieved. The AOD from shadow method closely matched ground-based photometers measurements, mostly differing by <±0.03, indicating the shadow method can accurately retrieve aerosol data over megacities.



INTRODUCTION

Aerosols have substantial impacts on climate, environment, and human health. They affect climate by scattering light directly or modifying clouds indirectly. However, accurately estimating their climate effects, especially indirect ones, remains challenging due to uncertainties. Aerosols also emerge as major pollutants in regions like East Asia, leading to smog, acid rain, and health risks. In the context of space remote sensing for gases and Earth surfaces, prior aerosol information is crucial for accurate correction via radiative transfer modeling due to their strong scattering interference. Satellite remote sensing is the primary method for deriving aerosol optical properties due to its coverage advantages. Algorithms like Dark Target (DT) and Deep Blue (DB) are commonly used, but they face uncertainties due to inaccurate assumptions about surface properties and aerosol models, affecting retrieved aerosol optical depth accuracy. Recent high-resolution satellite advances have driven innovative methods for aerosol information extraction, exemplified by Duan et al.'s method based on cloud-shadowed and sunlit pixels, inspiring a new algorithm for AOD and ALB retrieval using building shaded pixels and sunlit adjacent pixels in urban areas. The proposed algorithm's efficacy was demonstrated with GF2 images near the Beijing Olympic Center, compared against MODIS aerosol products and CE-318 sun photometers measurements.

MATERIALS AND METHODS



The radiance received by satellite in the visible and near-infrared bands can be expressed as:

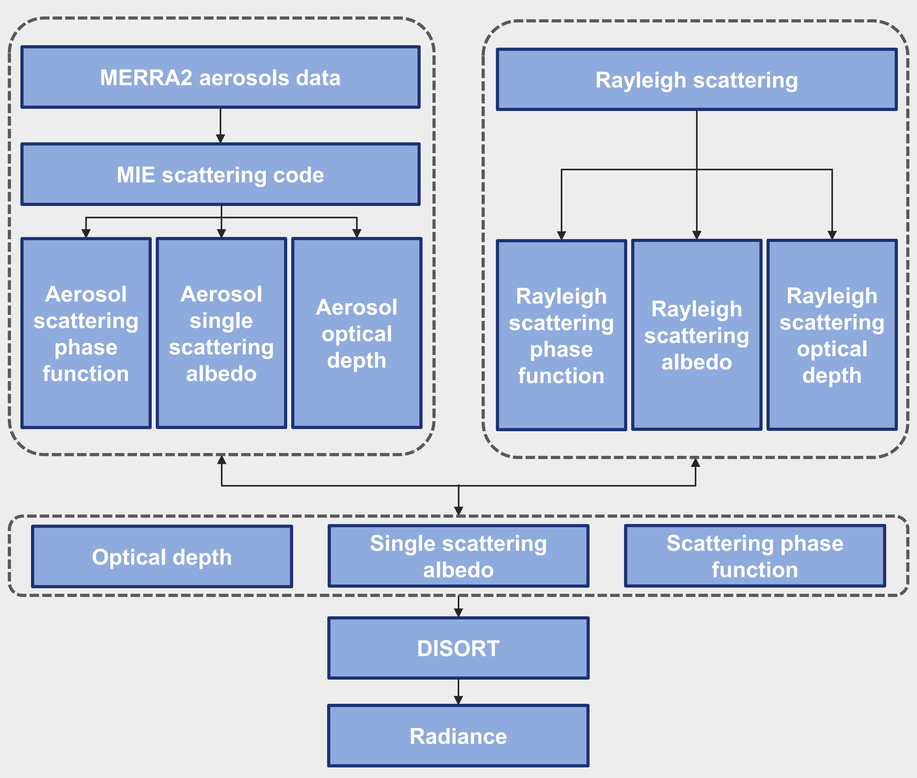
$$I_b = I_{path} + \frac{E_0\mu_0\left(e^{-\tau/\mu_0} + t_{dif}(\mu_0)\right)T(\mu_v)A}{\pi(1-AS)}$$

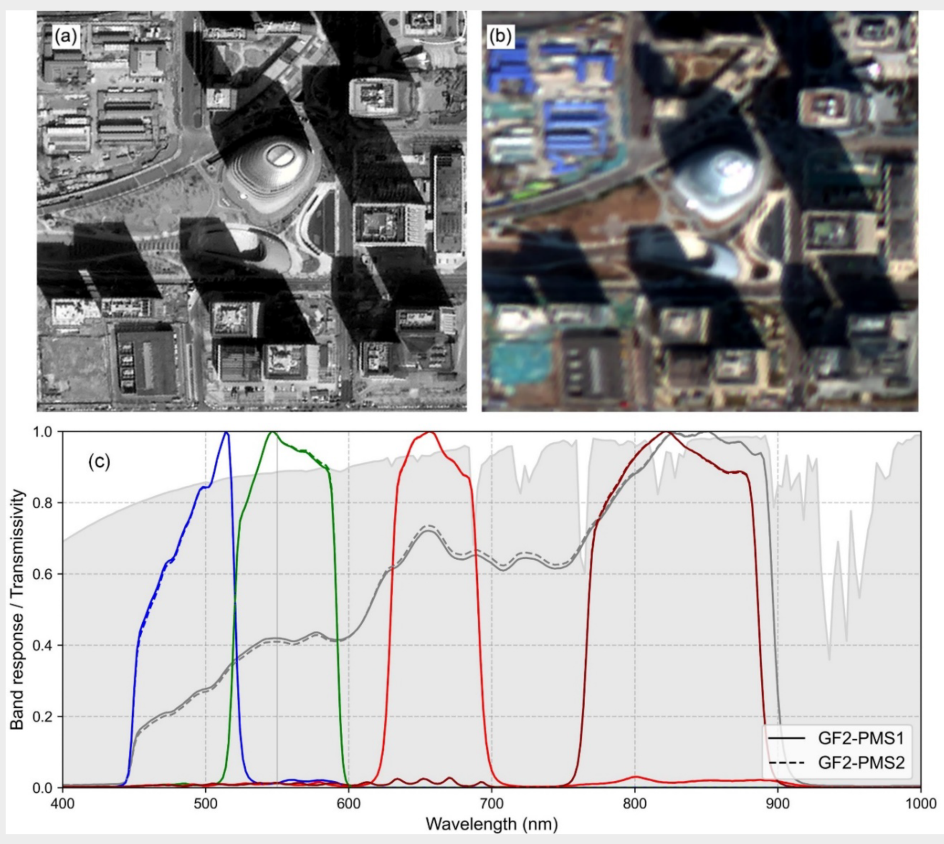
For shaded pixels, the direct sunlight is blocked by tall building:

$$I_s = I_{path} + \frac{E_0\mu_0 t_{dif}(\mu_0)T(\mu_v)A}{\pi(1-AS)}$$

By combining the two equations above, we solve for two unknown parameters: optical thickness τ and ground albedo A. The atmospheric path scattering, direct radiation reaching the Earth's surface, and diffuse radiation are calculated using radiative transfer models. The radiance values for dark and bright pixels reaching the microsensor are obtained from GF2 satellite imagery.

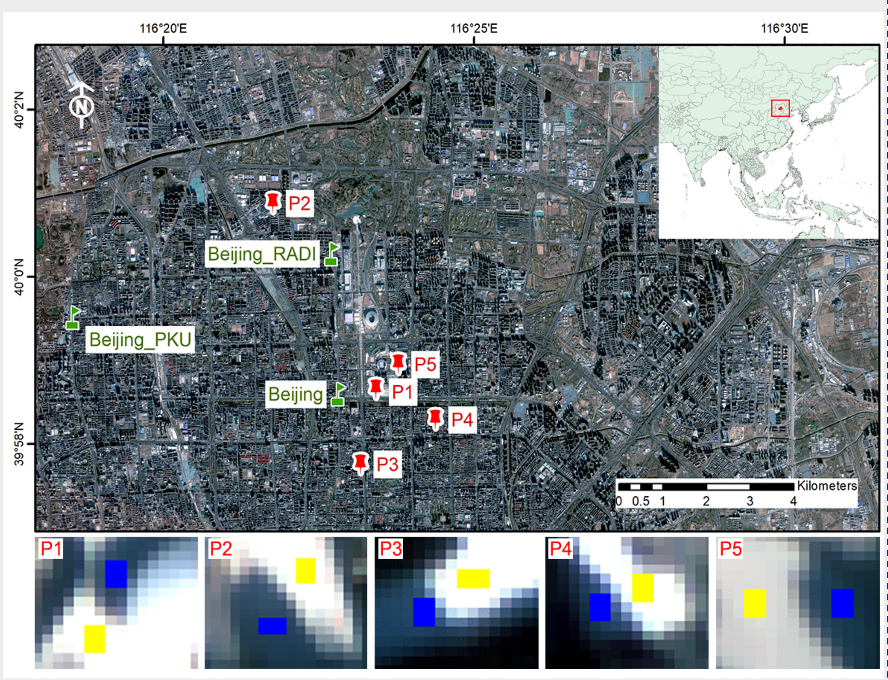
Forward Model Structure



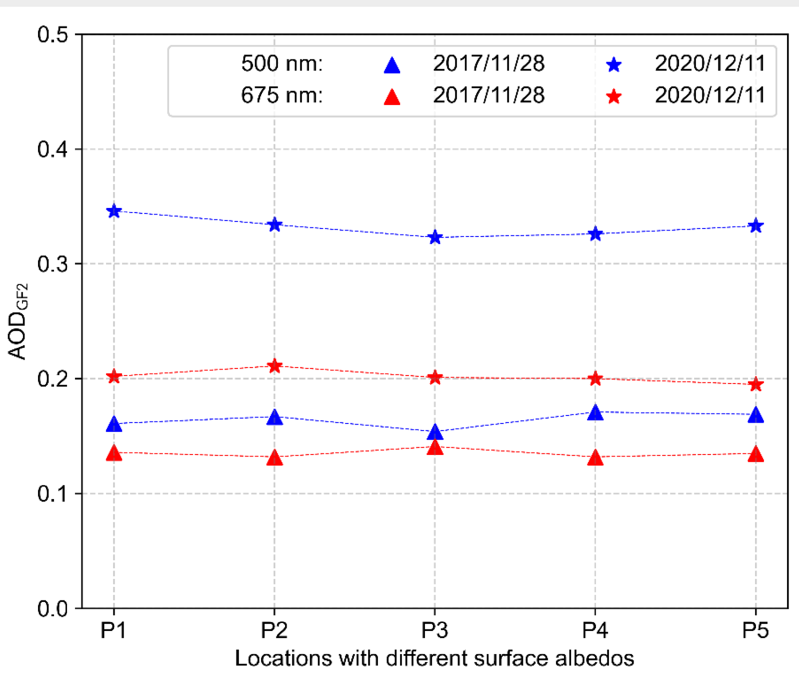


RESULTS

High spatial resolution images from PMS/GF2 around the Beijing Olympic Center were used, and several high-rise building shadow areas were selected to test this shadow-based method. To facilitate the verification of inversion results, the selected shadow areas are located near three AERONET sites (Beijing, Beijing_RADI, Beijing_PKU).



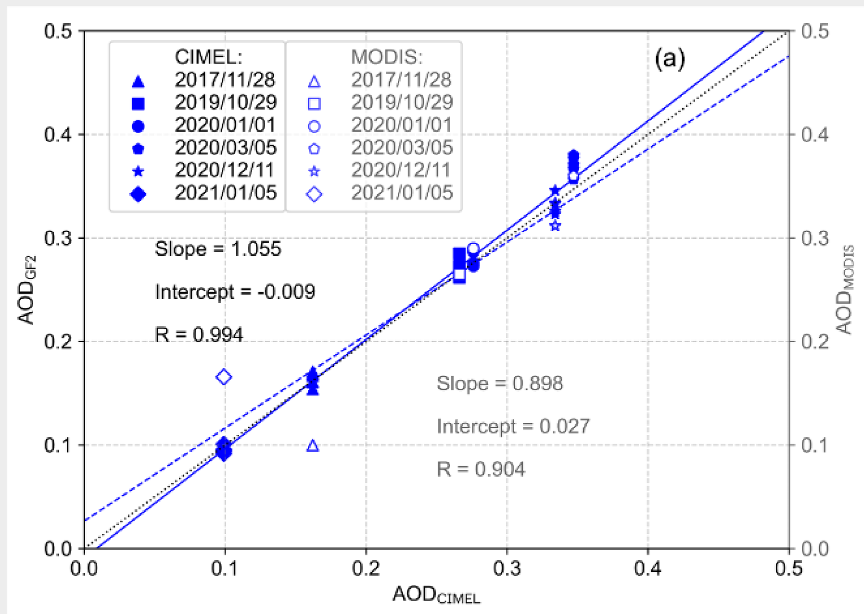
- Compared to the MODIS aerosol products, the AOD retrieved by the shadow method are closer to the ground measurements, with correlation coefficients of 0.99 and 0.95 for 500 nm and 675 nm, respectively, and the differences mostly within ±0.03.
- A larger disparity between the AOD retrieved on March 5, 2020, the small panel shows notable fluctuations in the AOD at 675 nm, as measured by CE-318 during the GF2 transit time, indicating the atmospheric environment during this period is unstable, which may be the reason for the larger difference.

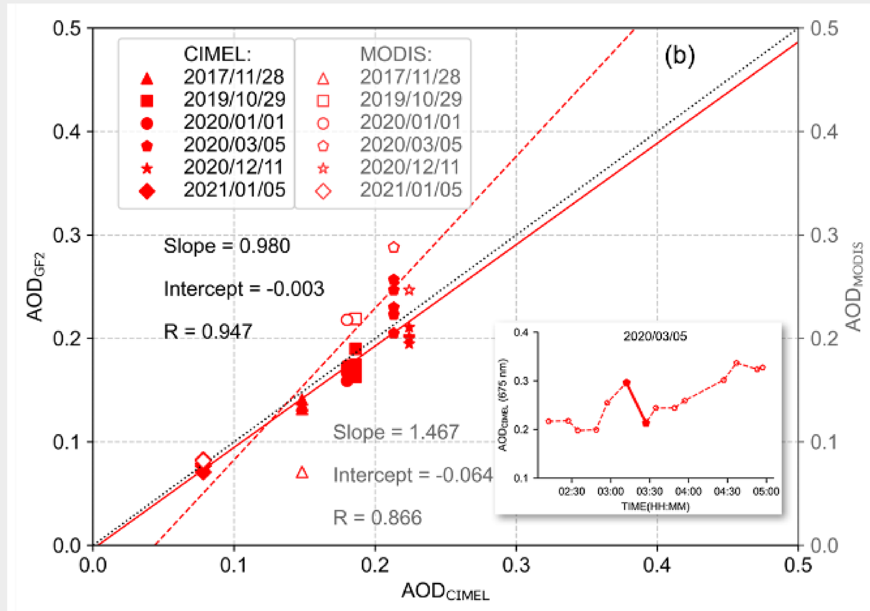


The AOD at 500 and 675 nm retrieved from GF2 satellite images captured on November 28, 2017, and December 11, 2020. Numbers on the horizontal axis correspond to specific locations on imagery that share similar atmospheric conditions. Although lacking ground data, the AOD retrieved by the shadow method were consistent. This suggests that the method can estimate AOD in urban areas with diverse surfaces.

The AOD and ALB retrieved from GF2, and the differences with the AOD provided by AERONET (AOD_{GF2}-AOD_{CIMEL}).

Band	PART	20171128 AOD	20171128 ALB	20191029 AOD	20191029 ALB	20200101 AOD	20200101 ALB	20200305 AOD	20200305 ALB	20201211 AOD	20201211 ALB	20210105 AOD	20210105 ALB
500 nm	P1	0.160 (-0.002)	0.220	0.278 (+0.012)	0.305	0.295 (+0.019)	0.190	0.435 (+0.021)	0.200	0.347 (+0.013)	0.130	0.099 (+0.000)	0.200
	P2	0.168 (+0.006)	0.185	0.286 (-0.020)	0.205	0.280 (+0.004)	0.195	0.439 (+0.025)	0.210	0.338 (+0.004)	0.200	0.105 (+0.006)	0.200
	P3	0.151 (-0.011)	0.235	0.279 (+0.013)	0.205	0.296 (+0.020)	0.285	0.422 (+0.008)	0.260	0.323 (-0.011)	0.165	0.095 (-0.004)	0.250
	P4	0.175 (+0.013)	0.155	0.273 (+0.007)	0.220	0.276 (+0.000)	0.195	0.452 (+0.038)	0.225	0.326 (-0.008)	0.215	0.095 (-0.004)	0.190
	P5	0.164 (+0.002)	0.165	0.269 (+0.003)	0.220	0.270 (-0.006)	0.200	0.420 (+0.006)	0.225	0.326 (-0.008)	0.165	0.091 (+0.008)	0.155
675 nm	P1	0.134 (-0.014)	0.275	0.171 (-0.015)	0.350	0.163 (-0.017)	0.225	0.223 (-0.042)	0.245	0.198 (-0.026)	0.175	0.075 (-0.003)	0.280
	P2	0.133 (-0.015)	0.235	0.190 (+0.004)	0.190	0.168 (-0.012)	0.185	0.230 (-0.035)	0.270	0.211 (-0.012)	0.265	0.082 (+0.004)	0.265
	P3	0.140 (-0.008)	0.290	0.168 (-0.021)	0.240	0.155 (-0.025)	0.330	0.205 (-0.060)	0.300	0.200 (-0.024)	0.165	0.079 (+0.001)	0.315
	P4	0.131 (-0.017)	0.215	0.161 (-0.025)	0.215	0.168 (-0.012)	0.230	0.278 (+0.013)	0.185	0.195 (-0.029)	0.180	0.071 (-0.007)	0.190
	P5	0.134 (-0.014)	0.210	0.176 (-0.010)	0.280	0.153 (-0.027)	0.245	0.310 (-0.055)	0.280	0.194 (-0.030)	0.210	0.078 (+0.000)	0.205





Comparison of AOD retrieved from GF2 images and those from MODIS and AERONET at (a) 500 nm, (b) 675 nm.

CONCLUSIONS

In this study, a method for retrieving AOD and ALB from building shadows on high spatial resolution satellite images was developed and validated by GF2 images. The AOD inversion results were found to be consistent with the ground sun photometers measurements.

The shadow method largely reduces the need for accurate pre-assumed ground parameters, improving satellite aerosol retrieval accuracy over urban regions. In areas with insufficient ground-based aerosol observation equipment, this algorithm could potentially provide relatively accurate aerosol information. Moreover, it offers us a method for the acquisition of small-scale aerosol information within megacities, where often shows much inhomogeneity due to human activities.

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