# Investigating the effects of smoke masking on satellite retrievals of carbon monoxide in fresh biomass burning plumes

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## 1. Introduction

The Biomass Burning Fluxes of Trace Gases and Aerosols (BB-FLUX) field campaign was carried out during the summer of 2018 with the primary goal of quantifying emission fluxes of trace gases by mass balance of actual wildfires. To characterize these fluxes, the University of Colorado Airborne Solar Occultation Flux (CU AirSOF) instrument was flown below biomass burning plumes to measure vertical trace gas columns, such as CO, along the direct solar beam at mid-infrared wavelengths. The Sentinel-5 Precursor satellite, which houses the TROPOspheric Monitoring Instrument (TROPOMI), provides a unique opportunity to quantify and validate emission fluxes from space. Through daily observations of area sources such as wildfires, TROPOMI provides measurements of trace-gas maps in the Ultraviolet-Visible (UV-Vis.) and shortwave-IR (SWIR) spectral regimes (e.g. CO, using the first overtone vibrational band). We first present radiative transfer modeling (RTM) calculations of air mass factors (AMFs) from both the aircraft and satellite perspectives for varying aerosol optical depths (AODs). In the SWIR, TROPOMI measures backscattered solar photons, which we show through RTM simulations to be advantageous in reducing aerosol effects.

## 2. Methods

- RTM in McArtim 3: fully-spherical, Monte Carlo-based algorithm. Gaussian plume centered at 2.0 km altitude, with a FWHM of 0.5 km
- Calculated Box Air Mass Factors, or a measure of the sensitivity to photons from a specific altitude
- Investigated effect of different viewing geometries (e.g. satellite and aircraft measurement perspectives

**Table 1. RTM Inputs to McArtim 3**

| Variable | Parameter | 355 nm | 2337.5 nm |
|---|---|---|---|
| Geometry | Solar Zenith Angle (SZA) | 30.0⁰ | |
| | Solar Azimuth Angle | 136.12⁰ | |
| | Approximated Elevation Angle | Satellite: Nadir<br>Aircraft: Zenith | |
| Sensor Altitude | Altitude | Satellite: 750.0 km<br>Aircraft: 1.0 km | |
| Atmosphere | Surface Albedo | 0.05 | 0.20 |
| | Absorbers | $O_3$, $O_4$, $H_2O$, $NO_2$, Aerosol | $CH_4$, $H_2O$, CO, Aerosol |
| Aerosol | Phase Function | Henyey-Greenstein | |
| | SSA, Asymmetry | 0.80, 0.76 | 0.95, 0.70 |

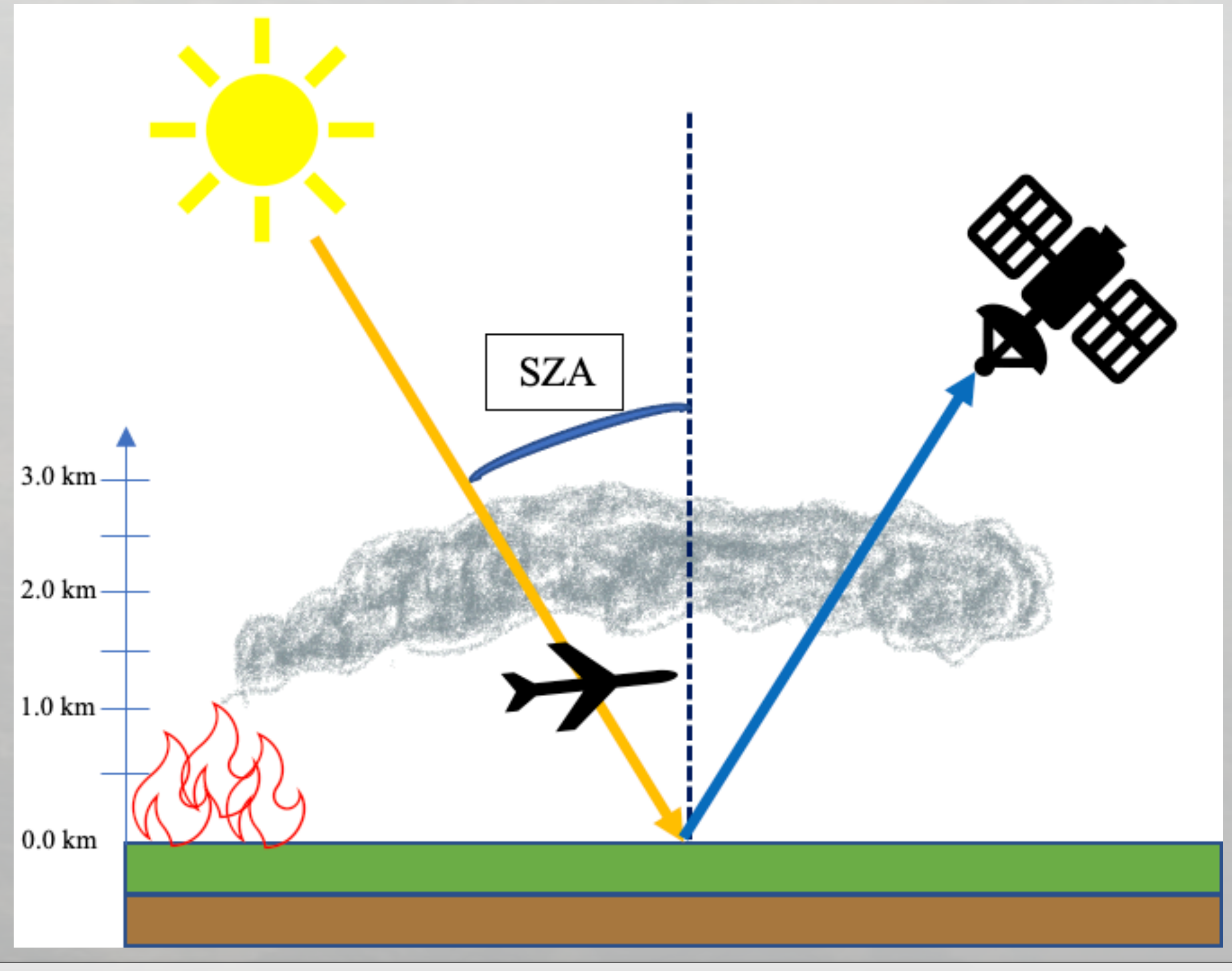

Figure 1. Schematic of the aircraft and satellite viewing geometries for biomass burning plume sampling. The aircraft measures along the direct solar beam, and a solar zenith angle correction is used to convert to a vertical column density. The position of the sun relative to the zenith, also known as the solar zenith angle (SZA), is shown. The satellite measures scattered photons along the slant column. Information on the AMF is required to convert the satellite SCD into a VCD, such that VCD = SCD / AMF. Once the AMF is known, the corresponding slant column can be converted to a vertical column, allowing for the comparison between the satellite and aircraft.

## 3. Results

- ~2-3x greater box air mass factors at & above simulated plume peak, indicating increased sensitivity in SWIR at plume peak
- UV to SWIR wavelength transition results in ~20x lower optical depth, indicating higher transparency through the plume
- Greater sensitivity in SWIR through plume depth, but sensitivity through entire plume decreases fast near surface
- Masking of the satellite air mass factor is reduced at longer wavelengths

**Table 2. BB-FLUX Research Flights & AirSOF Codes, where PUN_C-## stands for a plume underpass, and the respective occurrence of that underpass. The preceding sequence of numbers indicates the flight section and event occurrence within that section. All codes are preceded by RF##-. Displayed flights are chosen where spatial and temporal overlap between the aircraft and satellite is comparable, usually within ~1hr of the S5P overpass. Green shading are promising flights for comparison, yellow are possible, and red are unlikely.**

| RF | Date | BB-FLUX Flight Code and Sampling Time [UTC] | TROPOMI Overpass Time [UTC] |
|---|---|---|---|
| 5 | 2018-08-02 | No underpasses chosen for comparison | 20:30:00 |
| 9 | 2018-08-08 | No underpasses chosen for comparison | 20:20:00 |
| 11 | 2018-08-12 | -02-16-PUN_C-07 19:59:47 - 20:05:14<br>-02-17-PUN_C-08 20:07:04 - 20:14:44 | 20:45:00 |
| 13 | 2018-08-15 | -02-02-PUN_C-01 20:30:45 - 20:39:18<br>-02-04-PUN_C-02 20:40:50 - 20:49:43<br>-02-06-PUN_C-03 20:56:32 - 21:04:26<br>-02-09-PUN_C-04 21:08:09 - 21:17:22<br>-02-09-PUN_C-05 21:23:46 - 21:33:07 | 21:30:00 |
| 14 | 2018-08-19 | -02-02-PUN_C-01 17:22:14 - 17:33:01<br>-02-06-PUN_C-02 18:06:00 - 18:07:47<br>-02-12-PUN_C-03 18:43:30 - 18:49:01 | 20:05:00 |
| 15 | 2018-08-19 | -02-06-PUN_C-02 21:50:16 - 21:55:01<br>-02-08-PUN_C-03 21:58:22 - 22:03:12 | 21:54:00 |
| 21 | 2018-08-25 | -02-19-PUN_C-05 20:04:32 - 20:10:18<br>-02-21-PUN_C-06 20:13:04 - 20:20:03<br>-02-23-PUN_C-07 20:20:50 - 20:27:36 | 20:00:00 |
| 22 | 2018-08-25 | -02-03-PUN_C-01 22:32:29 - 22:40:25<br>-02-06-PUN_C-02 22:42:40 - 22:48:52 | 21:40:00 |

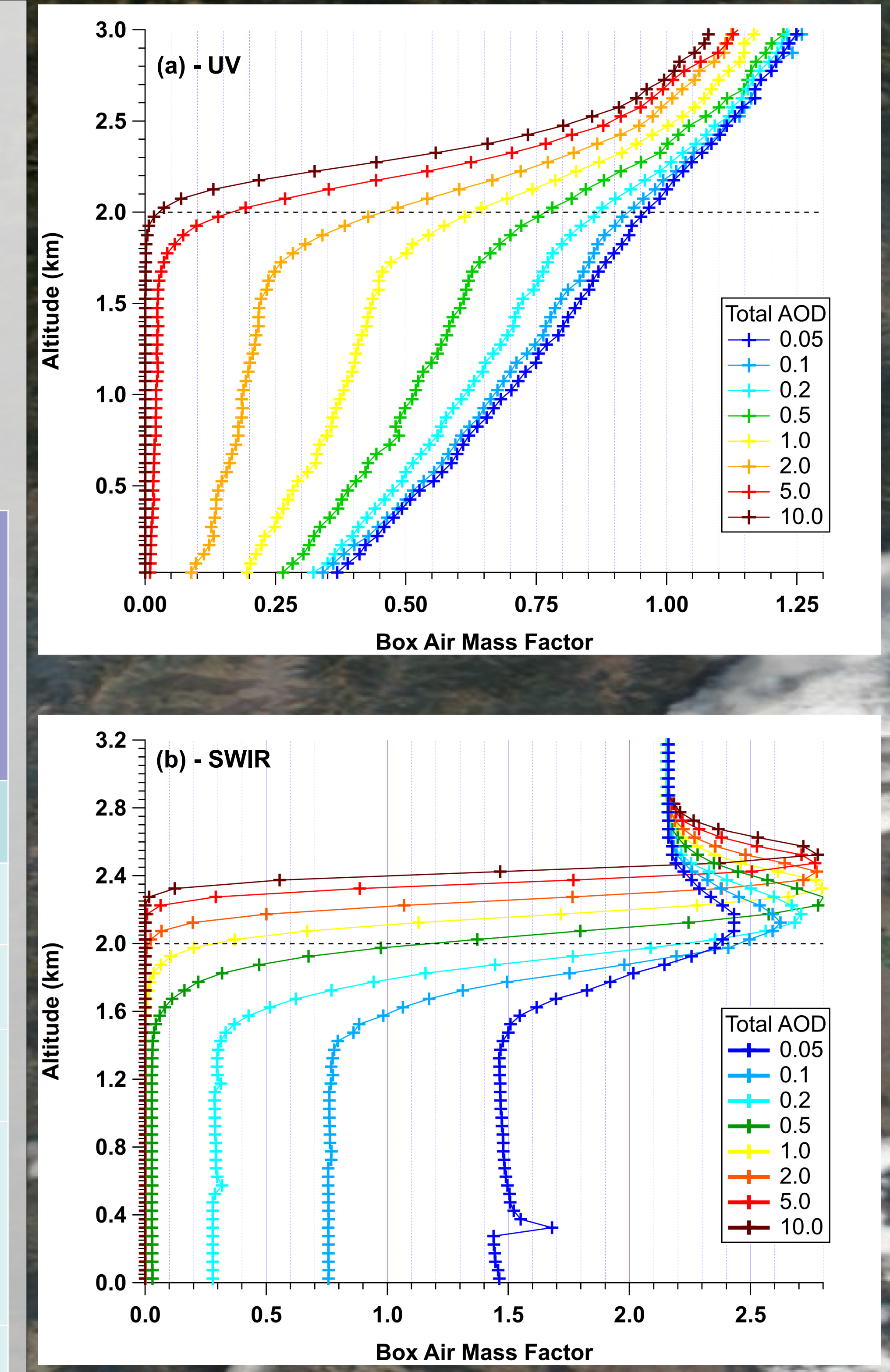

Figure 2. Box Air Mass Factors (BoxAMFs) for the satellite in the (a) UV and (b) SWIR regimes. The UV case is simulated for HONO detections [1] in biomass burning plumes, and the SWIR for CO detections. RTM plots follow the inputs in Table 1. The effective SWIR AOD is scaled as ~5% of UV AOD. Dashed line at 2.0 km marks the plume center height, and is modeled with a FWHM of 0.5 km as discussed in the methods section.

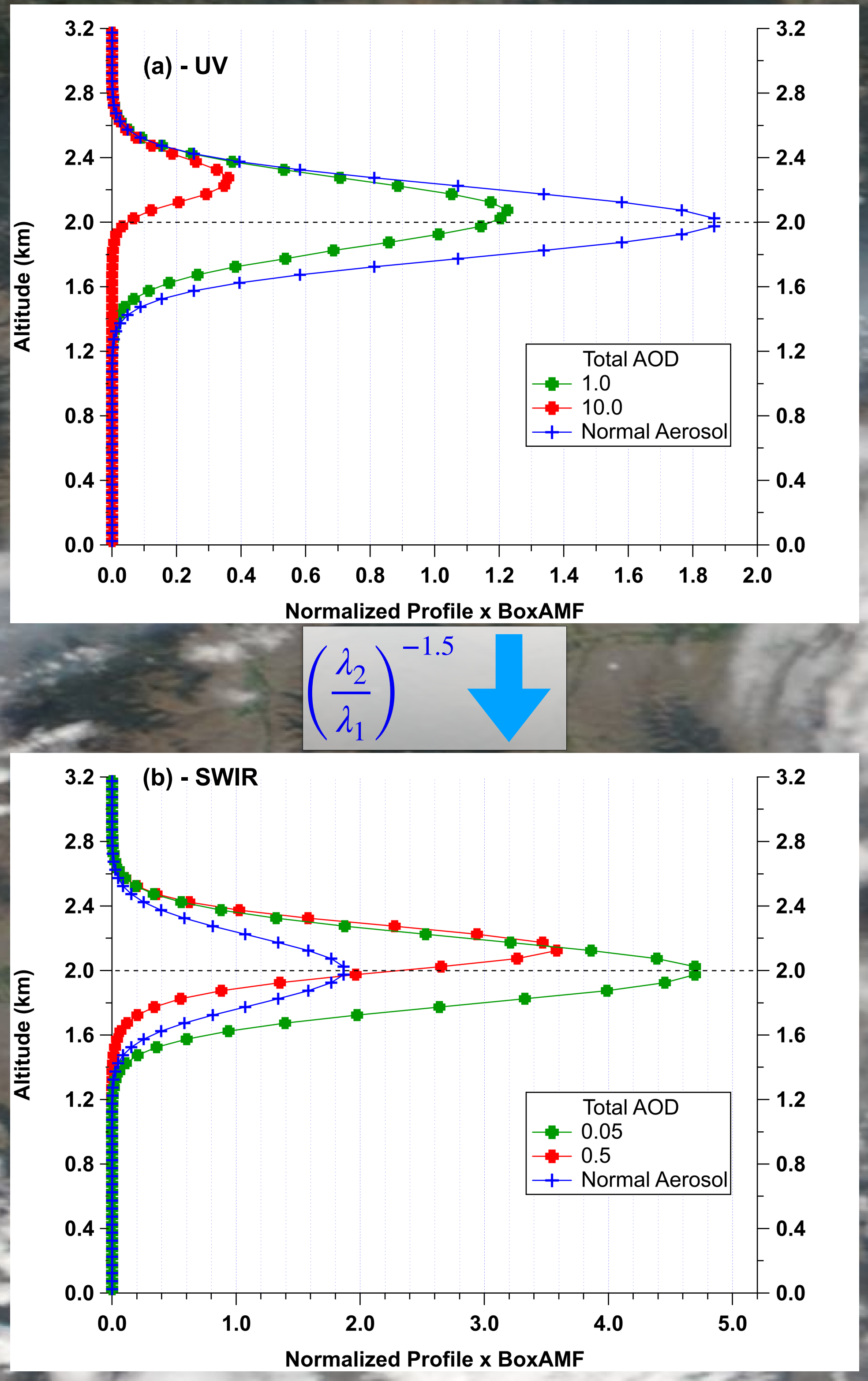

Figure 3. (a) UV and (b) SWIR satellite BoxAMFs by a unit Gaussian aerosol profile to illustrate the vertical sensitivity through the biomass burning plume. An Angstrom exponent of 1.5 is used to scale the UV aerosol extinction profile to the respective wavelength in the SWIR regime. Dashed line at 2.0 km marks the plume center height, with a FWHM of 0.5 km. We suspect the enhanced BoxAMF is a result of two photon passes through the plume.

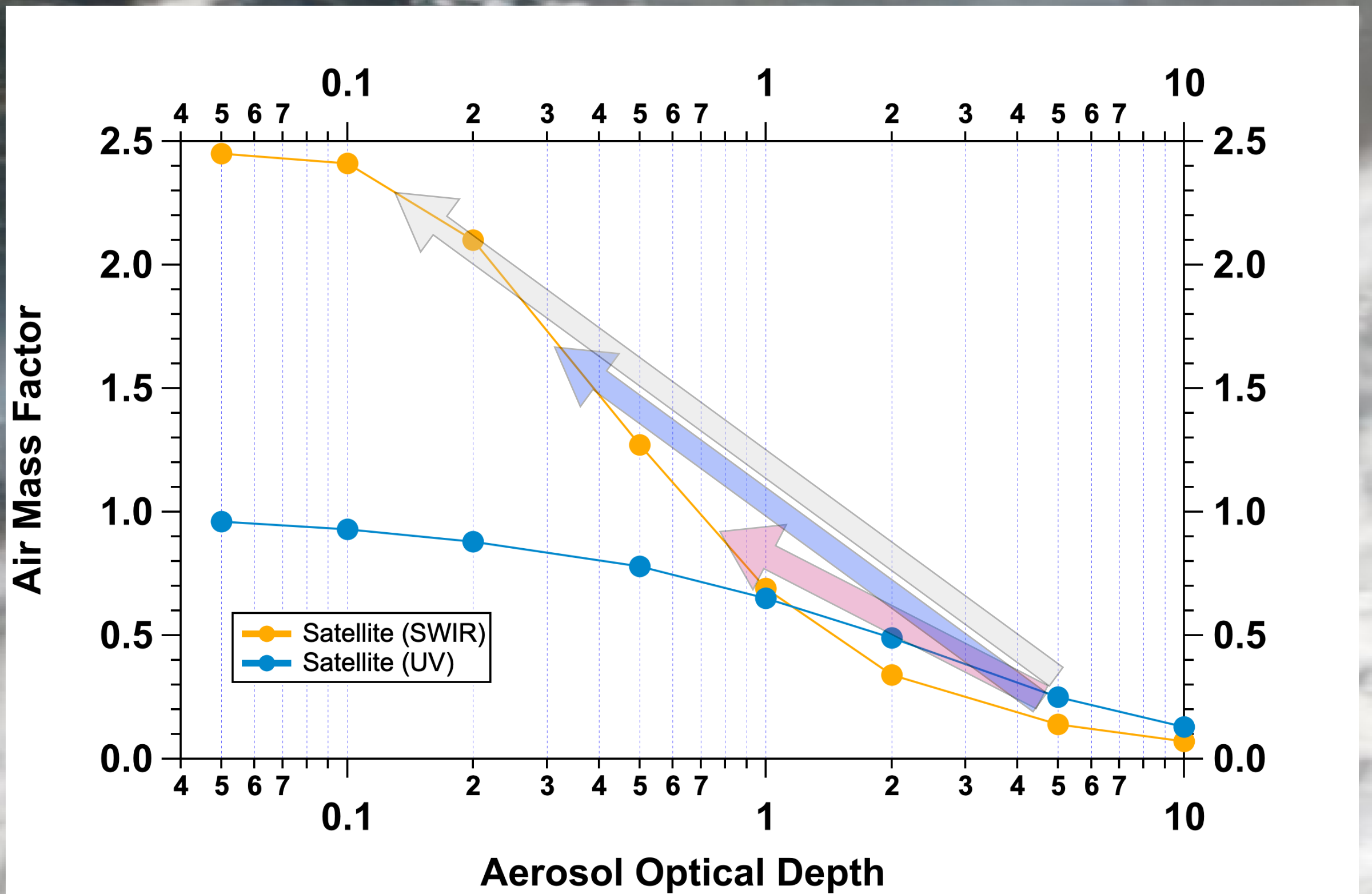

Figure 4. Calculated AMFs for the UV and SWIR regimes for a Gaussian aerosol profile of varying UV AOD. Transparent arrows illustrate the change in AMF by extending to the SWIR, which are dependent on the Angstrom exponent used to scale the true UV AOD of 5.0 to the SWIR. The new effective SWIR AOD is shown with arrows:
Red: Angstrom Exponent of 1.0 (SWIR AOD: 0.76, AMF: 0.95)
Blue: Angstrom Exponent of 1.5 (SWIR AOD: 0.30, AMF: 1.65)
Grey: Angstrom Exponent of 2.0 (SWIR AOD: 0.12, AMF: 2.30)

## 4. Conclusions & Outlook

- In estimating the effect of aerosol scattering for carbon monoxide, we found our measurement sensitivity improves greatly through the plume, as well as factor increases in the SWIR AMFs relative to the original UV case study. For strong wavelength dependencies on the AMF, the plume in the SWIR is still fairly transparent
- **We plan to compare integrated differential VCDs between the aircraft and satellite and conduct a RTM sensitivity study to understand the effect and magnitude of smoke masking**
- **The RFs from Table 2 will be used to compare CU AirSOF CO VCDs to TROPOMI and assess the aerosol scene and range of AODs found in biomass burning plumes**

## Acknowledgements

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[1] Theys, N., R. Volkamer, J.-F. Müller, K. J. Zarzana, N. Kille, L. Clarisse, I. De Smedt, C. Lerot, H. Finkenzeller, F. Hendrick, T. K. Koenig, C. F. Lee, C. Knote, H. Yu, and M. Van Roozendael: **Global nitrous acid emissions and levels of regional oxidants enhanced by wildfires**, *Nat. Geosci.*, 13, 681-686, doi:10.1038/s41561-020-0637-7, 2020.