# Replies to comments by reviewer 2

**Comment:** This paper shows the results of a study on the detection of geoengineering with solid particles at a rate of 5 Tg per year using a simulation of satellite solar occultation measurements and aerosol extinction retrievals on SOCOL-AERv2 model output. The detection criteria considers both measurement uncertainty and natural variability during a "near-background" period. The study is interesting and relevant, and fits well within the scope of AMT. However, there are a few shortcomings in the design of the study and the assumptions in the simulations that need to be addressed:

**Reply:** We thank the reviewer for his/her constructive and helpful comments. We tried to answer every comment in an appropriate way.

**Comment:** Line 2.2.2: What is the rational for a 30% a priori variance? Are the covariance terms (off-diagonal) assumed to be zero? How sensitive are the results to this assumption? Similarly, the assumed instrument SNR seems to be a critical element of this study, and the sensitivity to this assumption needs to be addressed. For example, how similar is this value to the current standard satellite occultation measurements, for example from SAGE II, or SAGE III/ISS, or even SCIAMACHY? The authors also need to compare their retrieval uncertainty to the uncertainties reported by a typical (real) occultation instrument.

**Reply:** Thank you for the comments. The a priori variance of 30% was chosen as a 'loose' constraint. This is because, on the one hand, it must allow the retrieved state sufficient freedom to deviate from the a priori (background) profile, which is necessary as the SAI signal considered here differs from the background by up to several orders of magnitude. On the other hand, the a priori covariance ensures regularisation of the inverse problem, thereby preventing unphysical, oscillating solutions. The value of 30% thus reflects a standard methodological choice balancing these two requirements.
The off-diagonal elements of the a priori covariance matrix are not assumed to be zero. The off-diagonal elements of the a priori covariance matrix are defined as:

$$S_a^{i,j} = \sigma^2 \exp\left(-\frac{|z_i - z_j|}{r_c}\right) \tag{1}$$

where $\sigma$ is the a priori variance, $z_i, z_j$ are the altitudes corresponding to element (i,j) of the covariance matrix, and $r_c$ is the correlation radius, which was set to 3.3 km in this study.
The maximum SNR of 1000 (at TH = 60 km) used in this study is based on Meyer et al. (2005), as cited in the manuscript, who report SNRs for SCIAMACHY solar occultation measurements of above 1000 throughout the visible and near-infrared range for a sufficiently high TH. The value used here therefore represents a conservative choice relative to the SNR reported for a real solar occultation instrument rather than an optimistic assumption. Please also note, that we used a TH-dependent SNR, as described in the manuscript.
To put the retrieval uncertainties into context with real satellite solar occultation instruments, we compare them to reported uncertainties for SAGE III/ISS. Wrana et al. (2021) report an extinction measurement uncertainty at 20 km altitude of 5.66% at 520 nm, averaged over the period from June 2017 to December 2019 (SAGE III/ISS Level 2 solar aerosol product). The retrieval uncertainties

obtained in our retrievals at the injection altitude ($\approx$ 20 km) range from 3 – 7% for alumina and 2 – 4% for calcite, which is of the same order of magnitude as the SAGE III/ISS uncertainties.

We added the following to the manuscript:

- The a priori variance of 30 % allows the retrieval state sufficient freedom to deviate from the a priori and ensures regularisation of the inverse problem, thereby preventing unphysical, oscillating solutions.

- The off-diagonal elements of the a priori covariance matrix are defined as follows:

$$S_a^{i,j} = \sigma^2 \exp\left(-\frac{|z_i - z_j|}{r_c}\right) \tag{2}$$

where $\sigma$ is the a priori variance, $z_i, z_j$ are the altitudes corresponding to element (i,j) of the covariance matrix, and $r_c$ is the correlation radius, which is set to 3.3 km in this study.

- The estimated retrieval uncertainties at the injection altitude of $\approx$ 20 km (3 – 7 % for alumina and 2 – 4% for calcite) are comparable to the uncertainties reported for the SAGE III/ISS Level 2 solar aerosol product. Wrana et al. (2021) reported an extinction measurement uncertainty of 5.66 % at 20 km altitude for 520 nm, averaged over June 2017 – December 2019.

**Comment:** Section 3.1: At several points, the authors mention the "relevant altitude range". This needs to be more thoroughly supported with at least some discussion of a tropopause definition with justification. It is mentioned later in the discussion around Fig 3, that SAGE II tropopause altitudes were used for the optical depth calculation but that this limits the analysis to 55 S to 55 N. This seems to be an unneeded limitation – tropopause altitudes are readily available from a large number of sources, including almost certainly from the SOCOL-AERv2 model output.

**Reply:** Thank you for the comments. In line with reviewer 1 we added the tropopause heights to the Figs. 2 and 5. The tropopause heights shown now in Figs. 2 and 5 are taken from the SOCOL-AERv2 reference simulation. For the SAOD calculations (Figs. 3, 6) and the natural variability analysis (Sect. 3.3), SAGE II tropopause heights (2000–2004) were used, to ensure consistency with the SAGE II-based natural variability estimate. Furthermore, we added: "The tropopause heights from SAGE II were chosen to ensure consistency with the following discussion on the natural variability, which is likewise based on the SAGE II data.".

**Comment:** Section 3.3: What is the justification for using only "near-background" levels of stratospheric aerosol to characterize natural variability? Stratospheric aerosol levels have been highly variable over the last two decades with perturbations from both minor to moderately sized volcanic eruptions and increasingly frequent forest fire smoke.

**Reply:** We agree that stratospheric aerosol levels have been highly variable over the last two decades. The SAGE II period 2000–2004 was chosen because it represents one of the closest approximations to near-background conditions. We do not claim that this period is entirely free of variability. The standard deviation shown in Fig. 8 already illustrates the year-to-year variability even within this comparatively quiet period.

We consider the analysis of the detectability under such near-background conditions a necessary baseline case, as it represents the most conservative scenario for detectability. Characterising detectability against a volcanically perturbed background would raise a different question, since a major volcanic eruption would likely lead to an adaptation or temporary suspension of the SAI deployment strategy (e.g. Quaglia et al., 2024). In this case, "background" and "signal" could no longer be clearly separated, and disentangling the volcanic perturbation, an adapted SAI signal, and residual natural variability would require a dedicated analysis beyond the present study.

Furthermore, we note that the injection rate of 5 Tg per year considered here corresponds to an all-sky radiative forcing on the order of -1 W m$^{-2}$ (now added to the manuscript), i.e. a large-scale climate intervention that would require coordinated, large-scale deployment rather than a small-scale or clandestine application. Such a coordinated deployment can plausibly be expected to be actively monitored and adapted in response to volcanic eruptions, further supporting the argument above that a volcanically perturbed background would need to be considered jointly with a correspondingly adapted SAI strategy, rather than as an independent source of natural variability against an unchanged SAI signal.

We added the following to the manuscript: "Near-background conditions were chosen, as this represents the most conservative case for detectability. A background disturbed by volcanic activity, for example, would very likely require an SAI strategy adapted to the volcanic eruption, which would mean that the background and the signal would no longer be clearly distinguishable and a separate analysis would be required.".

Quaglia, I., Visioni, D., Bednarz, E. M., MacMartin, D. G., & Kravitz, B. (2024). The potential of Stratospheric Aerosol Injection to reduce the climatic risks of explosive volcanic eruptions. Geophysical Research Letters, 51, e2023GL107702. https://doi.org/10.1029/2023GL107702.

**Comment:** Section 4: The conclusions from this study are somewhat limited due to the small scope of the study: only one injection scenario (5 Tg per year) and one set of instrument/retrieval parameters. It would be much for useful if the authors could identify a limit of detection in terms of both injection rate and instrument SNR (for example).

**Reply:** The injection rate of 5 Tg per year was not chosen arbitrarily. This injection rate results in an all-sky radiative forcing on the order of -1 W m$^{-2}$ (now added to the manuscript), representing a physically motivated, policy-relevant reference scenario for solid-particle SAI. Extending the analysis to a range of injection rates would require additional SOCOL-AERv2 simulations with the corresponding solid-particle microphysics at each rate, which are currently not available and are beyond the scope of the present study.

We agree that detectability is specific to the assumed instrument performance, and our conclusions apply to an idealised instrument with characteristics comparable to current solar occultation instruments, as described in Sect. 2.2.1 and 2.2.2. We note that the manuscript already addresses this point: "When interpreting the results presented here, the underlying assumptions must be taken into account. It is not the aim of this study to make general statements about the detection capabilities of all satellite solar occultation instruments, but rather to assess the detectability of SAI scenarios based on solid particles within a consistent simulation framework based on typical satellite solar occultation measurements." Furthermore: "It is worth noting that at significantly higher injection rates than the 5 Tg $yr^{-1}$ considered here, the zero-transmission problem, i.e. very low transmissions from the perspective of the satellite solar occultation instrument, could become relevant for solar occultation retrievals, potentially limiting the detectable range of SAI scenarios (Lange et al., 2026). Within the injection rates examined in this study, however, this effect is not expected to play a role.". We consider a systematic sensitivity analysis across injection rates and instrument SNRs as a valuable direction for future work.

**Comment:** Technical corrections:
Line 71: Are these really "Mie" calculations? Better to say something like "Scattering cross-section calculations. . . "

**Reply:** Changed to "The scattering and absorption cross sections for the solid particles were calculated using a semi-empirical code..."

**Comment:** Lines 82=85: At this point the discussion shifts from discussing Vattioni et al., 2025, to the current work and it's somewhat confusing. For example, what does "Based on" and "are analysed" mean in this context?

**Reply:** Changed to "The SOCOL-AERv2 model output provided by Vattioni et al. (2025) is used to derive the vertical profiles of the extinction coefficients, covering altitudes from 10 to 27 km, for alumina and calcite in the 440 – 690 nm wavelength band. In the present study, these profiles are calculated as zonal means at latitudes ranging from 85° S to 85° N in 10° steps.".

**Comment:** Line 97: Does the vertical field of view, quoted in Table 1, account for the forward scattering of the aerosol into the "instrument" line of sight? If not, how is this relevant?

**Reply:** Thank you for the question. The vertical field of view does not account for forward scattering of radiation into the "instrument's" line of sight. As described in the manuscript (Sect. 2.2.1), the transmission calculations are performed in the transmission modelling mode (solar occultation mode), in which only the directly transmitted solar radiation through the spherical Earth's atmosphere is simulated, including the effects of atmospheric refraction. Under the injection rates considered here (5 Tg per year), the resulting increase in aerosol extinction does not lead to highly reduced transmission values, such that the directly transmitted solar radiation can be expected to dominate over the forward-scattered contribution.

**Comment:** Figs 2,3,5,6: The "total error" is potentially confusing. The plot actually shows the range of uncertainty about the retrieved profile, not the total error. Please consider changing to shading on the plot and a different terminology.

**Reply:** Thank you, we've reworded it to 'retrieval uncertainty range'.