Will OCI's O_2 A-band channels contain the information needed to infer the height & thickness of an optically thin layer of absorbing aerosols? If not, can a MAP help?

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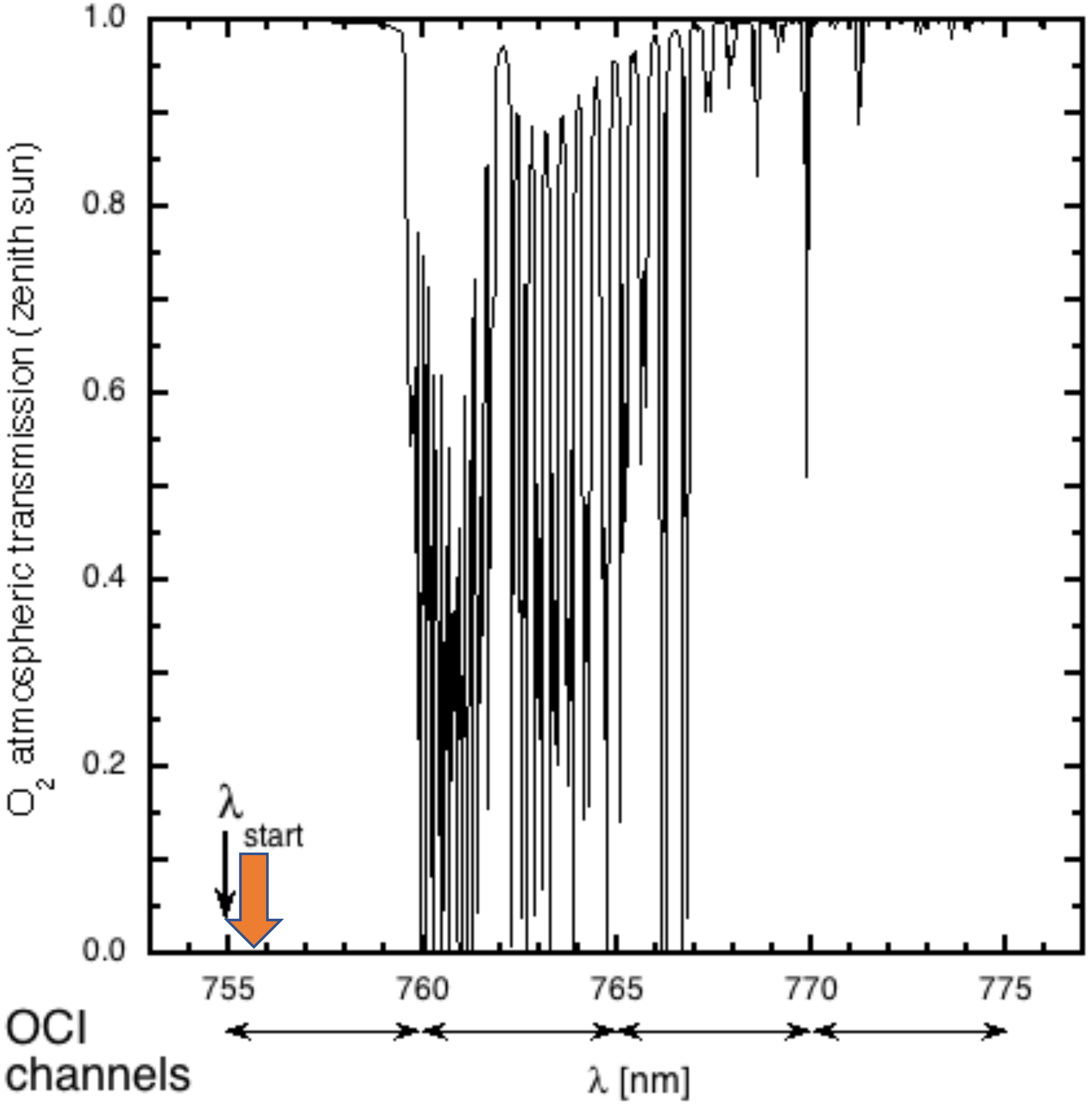
NO AUDIO. Please take time to read.

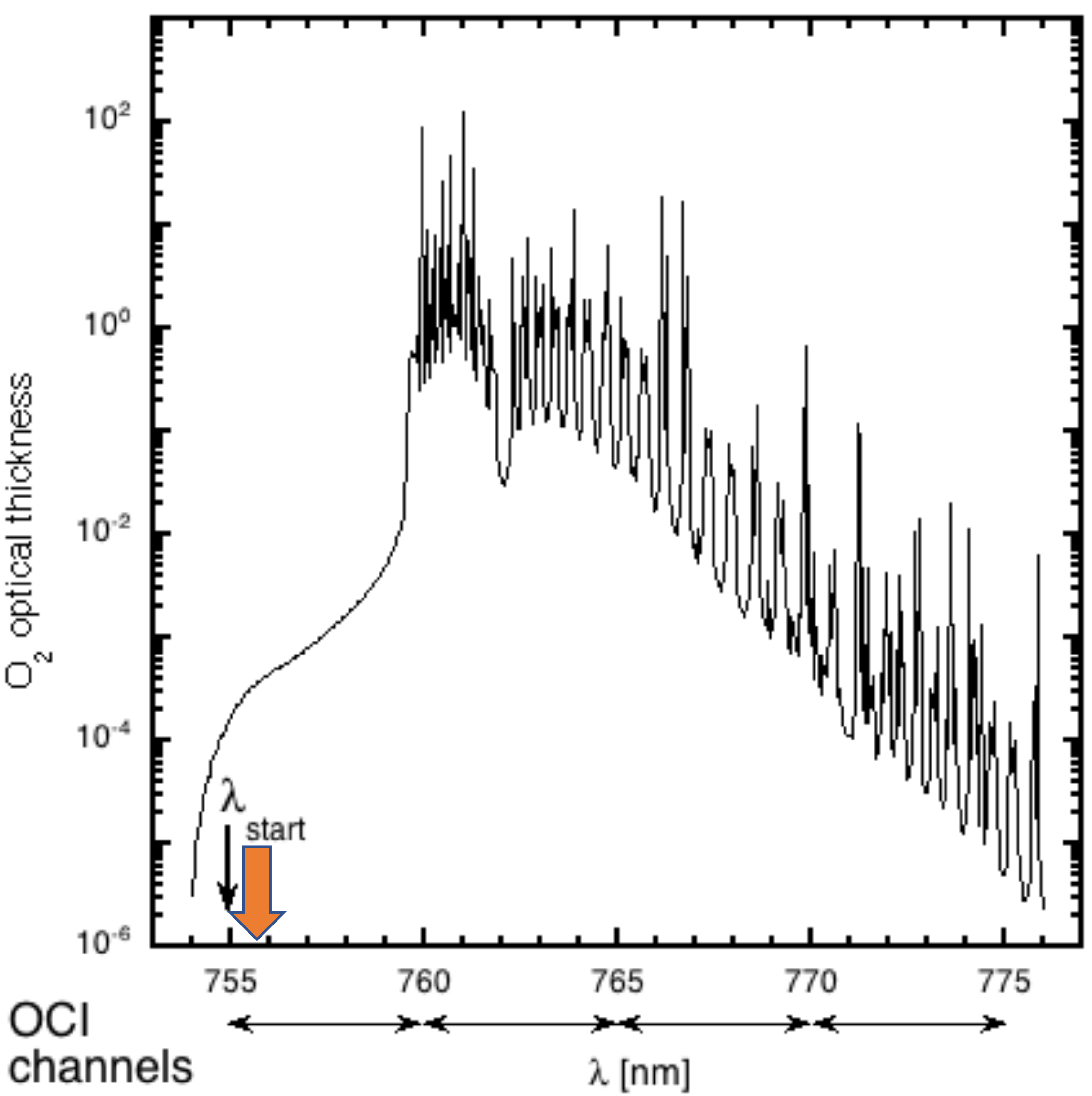
PACE STM, Harbor Branch, Florida, January 17-19, 2017

Contents

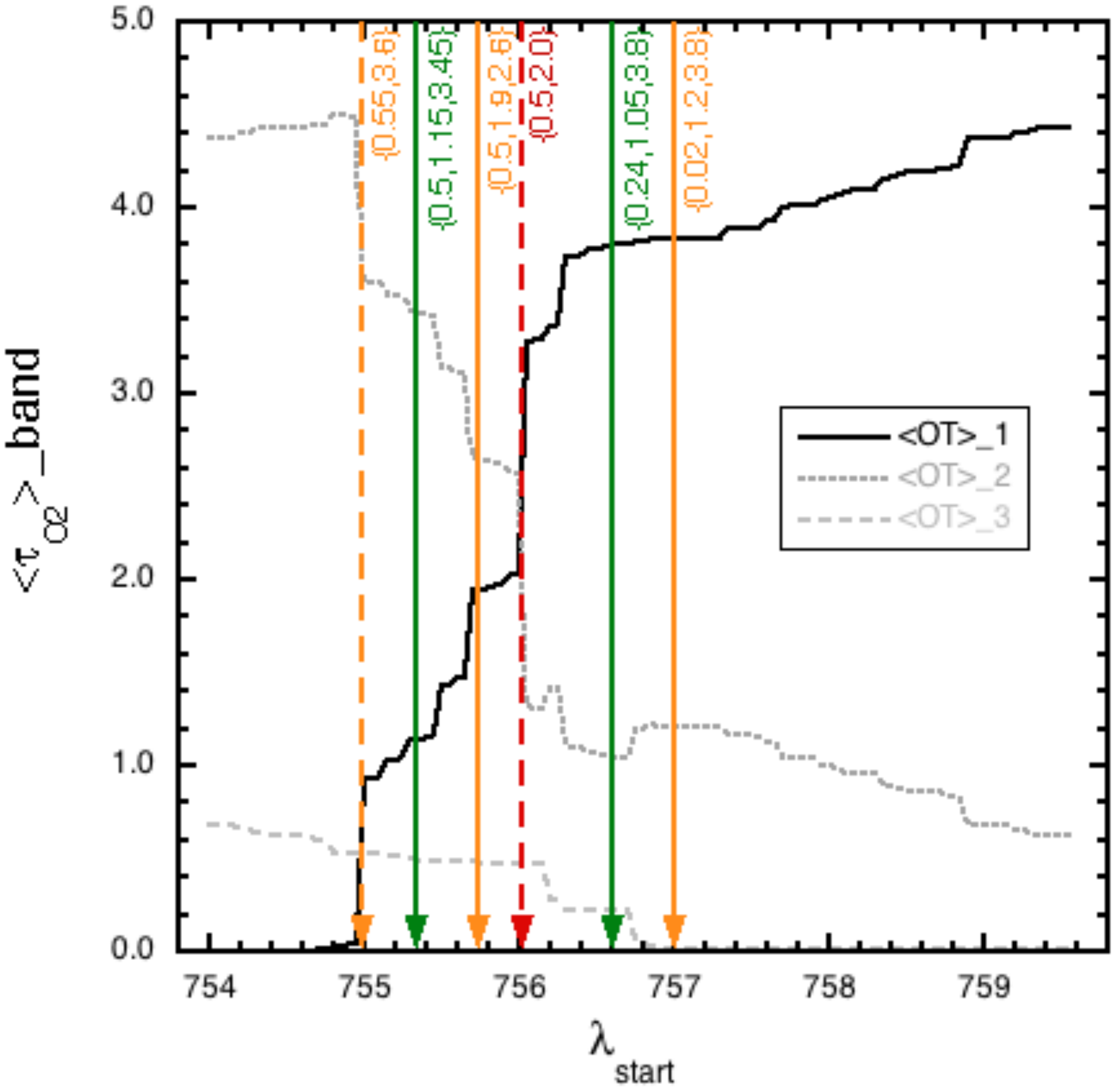
- Motivation:
  - ➢UV water-leaving radiance is critical to oceanographic remote sensing.
  - ➢Atmospheric correction in the UV calls for knowledge of the height z_{top} and thickness Δz of any absorbing aerosol layer that may be present.
- Methodology
  - Forward signal model for molecular oxygen DOAS
  - Bayesian framework for estimating joint retrieval error for $\{z_{top}, \Delta z\}$
- Information Content Analysis
  - Dark surface case
  - Slightly reflective surface
- Conclusions/recommendation

OCI’s spectral sampling of Oxygen A-band





OCI’s spectral sampling of Oxygen A-band



N.B. “Box-car” slit function $f(\lambda)$, for simplicity.

O2 optical thickness sampling?

Nice separation

OK separation

Bad separation

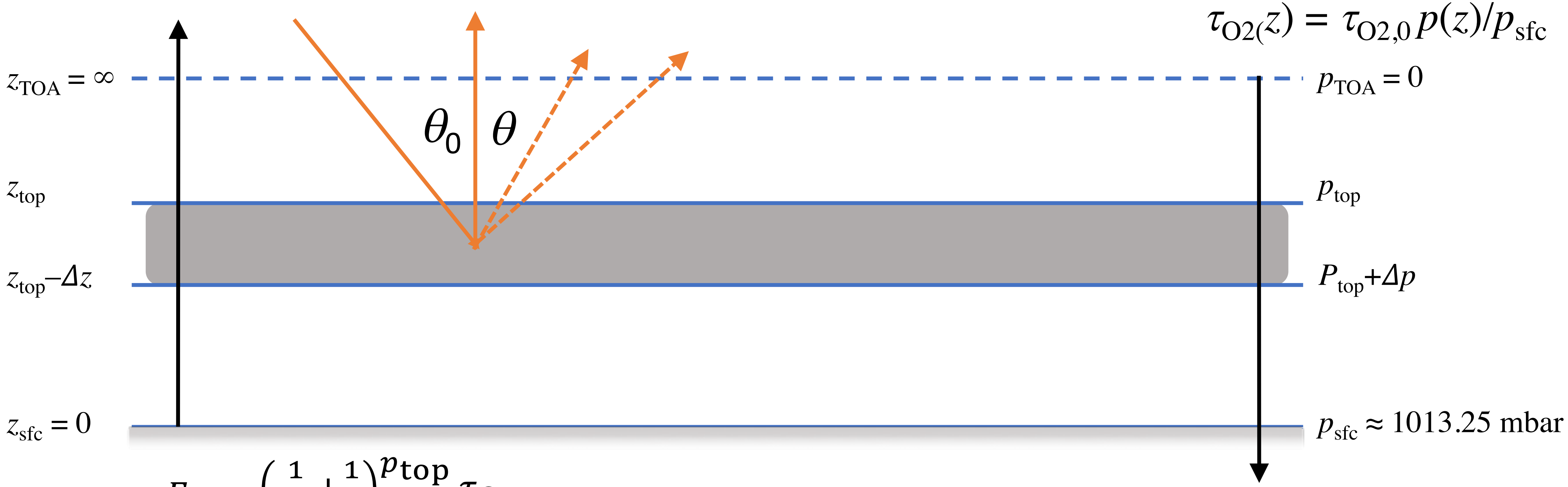
$$\langle\tau_{O2}\rangle_{band} = \int_{\lambda_{min}}^{\lambda_{max}} \tau_{O2}(\lambda) f(\lambda) d\lambda \Big/ \int_{\lambda_{min}}^{\lambda_{max}} f(\lambda) d\lambda$$

$$\lambda_{min} = \lambda_{start}$$
$$\lambda_{max} = \lambda_{min} + 5 \text{ [nm]}$$

Forward signal model: Dark surface

$p(z) \approx p_{sfc}\, e^{-z/8}$

$\tau_{O2}(z) = \tau_{O2,0}\, p(z)/p_{sfc}$



$$I = \frac{\mu_0 F_0}{\pi} e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\frac{p_{top}}{p_{sfc}}\tau_{O2,0}} R(\mu_0, \mu, \varphi; \mathbf{b}, \mathbf{x}), \text{ with } \mu = \cos\theta$$

$$R(\mu_0, \mu, \varphi; \mathbf{b}, \mathbf{x}) = \omega_{tot} \mathrm{pf_a}(\mu_0, \mu, \varphi) \frac{1 - e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_{tot}}}{4(\mu_0 + \mu)}$$

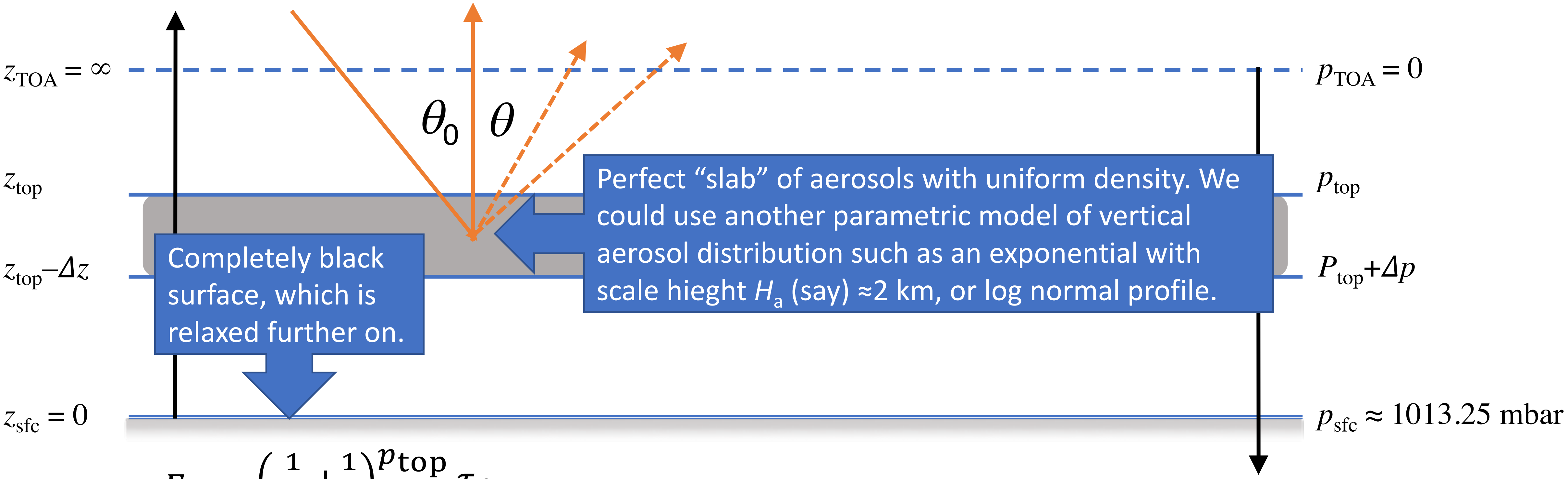
where $\tau_{tot} = \tau_a + \tau_{O2,0}\Delta p/p_{sfc}$

$\omega_{tot} = \omega_a \tau_a / \tau_{tot}$

retrieved: $\mathbf{x} = (p_{top}, \Delta p)^T$

not retr'd: $\mathbf{b} = (\tau_a, \omega_a, \mathrm{pf_a})^T$

Forward signal model: Representativeness, 1



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$$R(\mu_0, \mu, \varphi; \mathbf{b}, \mathbf{x}) = \omega_{tot} \mathrm{pf_a}(\mu_0, \mu, \varphi) \frac{1 - e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_{tot}}}{4(\mu_0 + \mu)}$$

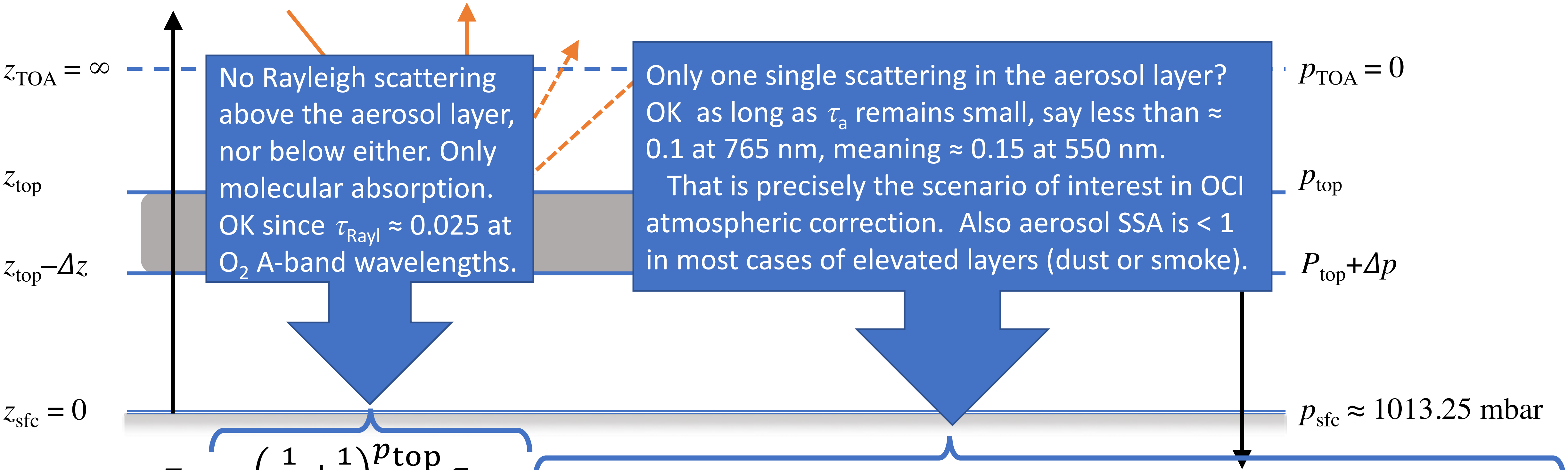
retrieved: $\mathbf{x} = (p_{top}, \Delta p)^T$

not retr'd: $\mathbf{b} = (\tau_a, \omega_a, \mathrm{pf_a})^T$

where $\tau_{tot} = \tau_a + \tau_{O2,0}\Delta p / p_{sfc}$

$\omega_{tot} = \omega_a \tau_a / \tau_{tot}$

Forward signal model: Representativeness, 2



$$I = \frac{\mu_0 F_0}{\pi} e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\frac{p_{top}}{p_{sfc}}\tau_{O2,0}} R(\mu_0, \mu, \varphi; \mathbf{b}, \mathbf{x}), \text{ with } \mu = \cos\theta$$

$$R(\mu_0, \mu, \varphi; \mathbf{b}, \mathbf{x}) = \omega_{tot} \mathrm{pf_a}(\mu_0, \mu, \varphi) \frac{1 - e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_{tot}}}{4(\mu_0 + \mu)}$$

where $\tau_{tot} = \tau_a + \tau_{O2,0} \Delta p / p_{sfc}$

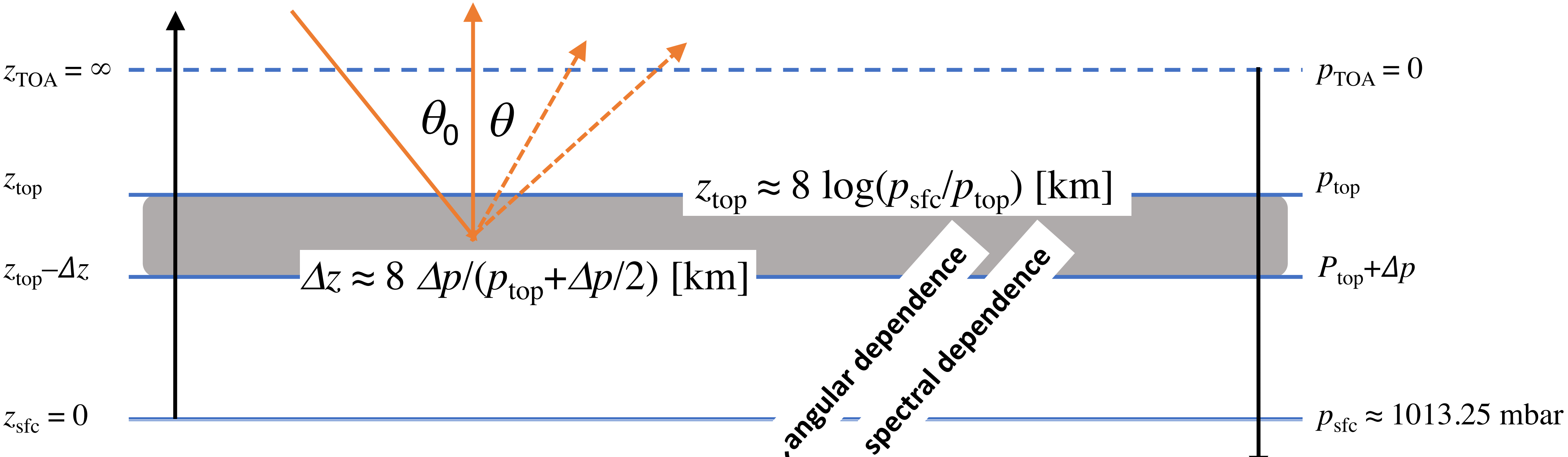
$\omega_{tot} = \omega_a \tau_a / \tau_{tot}$

retrieved: $\mathbf{x} = (p_{top}, \Delta p)^T$

not retr'd: $\mathbf{b} = (\tau_a, \omega_a, \mathrm{pf_a})^T$

Cannot be separated in 1-scattering limit.

Forward signal model: Dark surface



Differential Optical Absorption Spectroscopy (DOAS) ratio …

$$\mathbf{f}(\mathbf{x};\mathbf{b}) = \frac{I(\cdots;\tau_{O2})}{I(\cdots;0)} = \underbrace{e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_{O2,0}\frac{p_{top}+\Delta p}{p_{sfc}}}}_{\text{dominant term}} \underbrace{\frac{e^{\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\left(\tau_a+\tau_{O2,0}\Delta p/p_{sfc}\right)}-1}{e^{\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_a}-1}\,\frac{\tau_a}{\tau_a+\tau_{O2,0}\Delta p/p_{sfc}}}_{\text{only quadratic in arguments of exp}(\cdots)}$$

dominant term

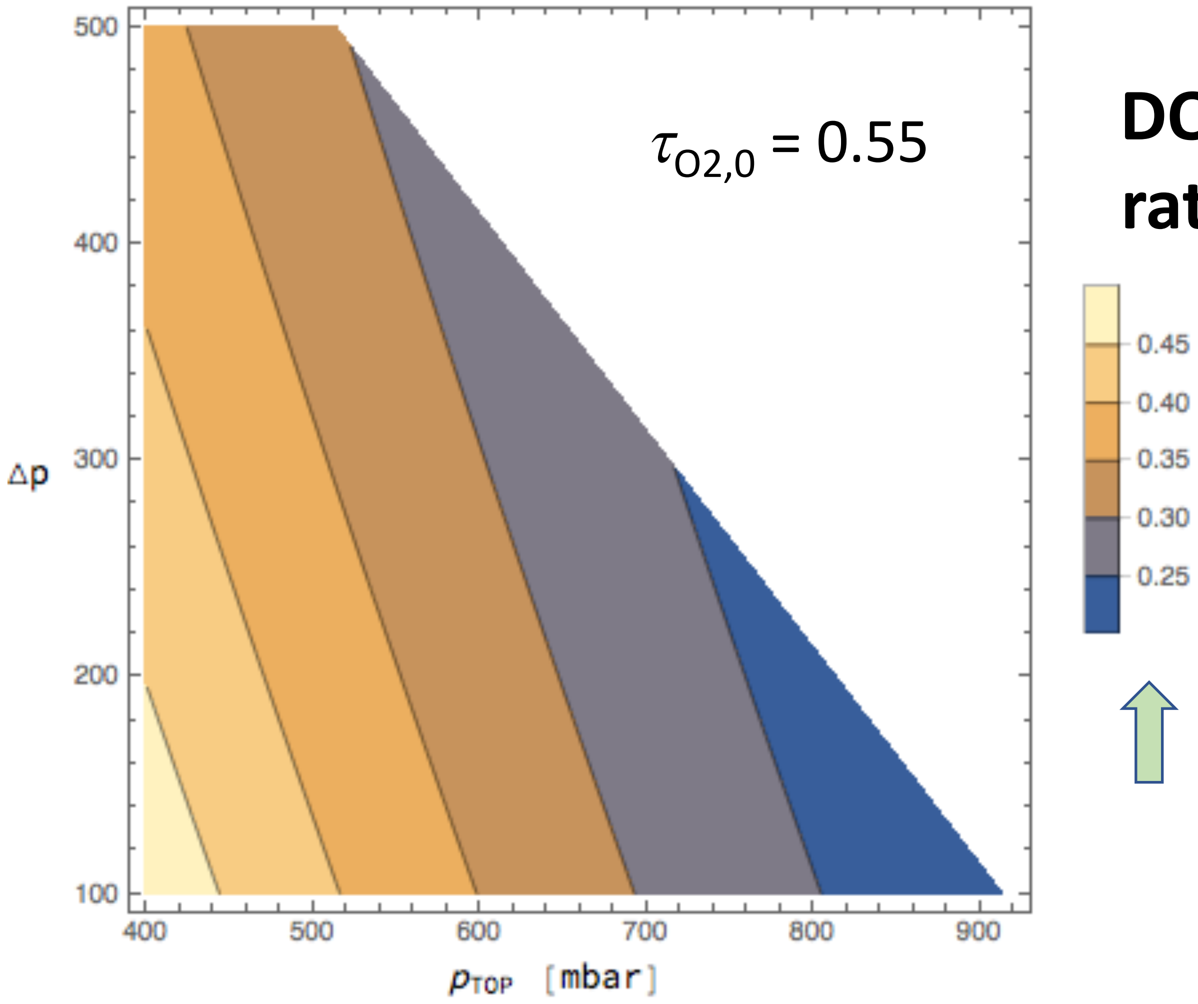
only quadratic in arguments of exp(⋯)

retrieved: $\mathbf{x} = (p_{top}, \Delta p)^T$

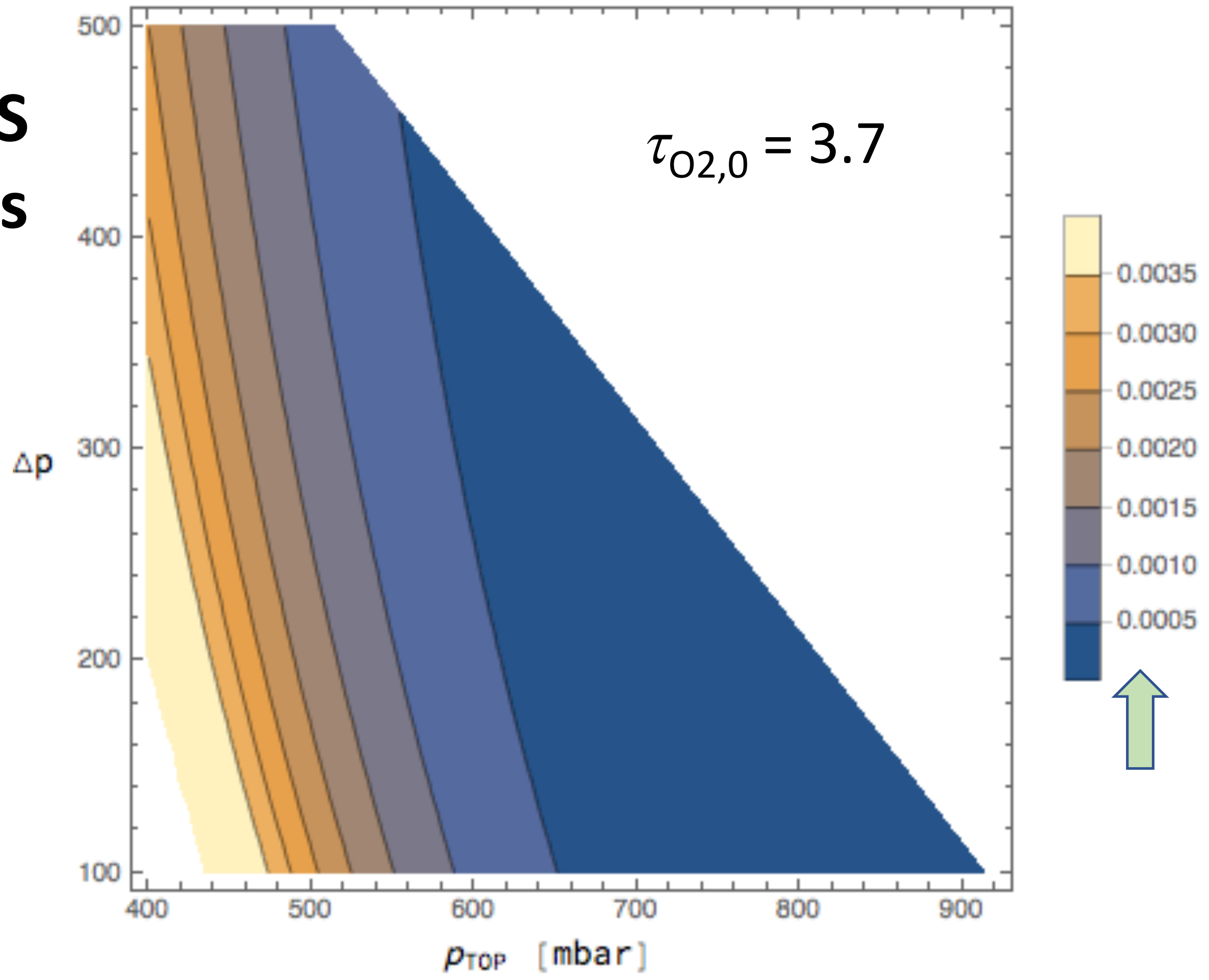
not retr'd: $\mathbf{b} = \tau_a$ ← Just one … pleasent surprise!

Forward signal model: Dark surface

$\mu_0 = ½, \mu = 1; \tau_a = 0.1, p_{top} = 800, \Delta p = 200$ (aerosols in PBL)



DOAS ratios



Bayesian/Rodgers-like Estimation of Posterior/Retrieval Error & Retrievability

$\mathbf{y} = [\mathrm{DOAS}_{0.5}, \mathrm{DOAS}_{1.9}, \mathrm{DOAS}_{2.6}]^{\mathrm{T}}$ are data, where subscript is $\tau_{\mathrm{O_2},0}$ ($\lambda_{\mathrm{start}} \approx 755.75$ nm) with $\mu = 1$ ($m = 3$).

$\mathbf{S_y} = \mathrm{diag}[(0.015 y_i)^2]$ is measurement $m \times m$ error (co)variance matrix.

$\mathbf{S}_\mathrm{a} = \mathrm{diag}[250^2, 150^2]$ is $n \times n$ "apriori" uncertainty (co)variance matrix in mbar^2 for $\mathbf{x} = [p_{\mathrm{top}}, \Delta p]^{\mathrm{T}}$ ($n = 2$). ← **Key to this approach!**

$\mathbf{S_b} = (\mathrm{Max}[0.025, 0.15\ \tau_\mathrm{a}])^2$ is 1×1 uncertainty (variance) on non-retrieved parameter τ_a.

$\mathbf{f}(\mathbf{x}, \mathbf{b}; \cdots)$ is the forward model for the DOAS ratio.

$\mathbf{K} = \dfrac{\partial \mathbf{f}}{\partial \mathbf{x}}, \mathbf{K_b} = \dfrac{\partial \mathbf{f}}{\partial \mathbf{b}}$ are Jacobian matrices for retrieved ($m \times 2$) and non-retrieved ($m \times 1$) quantities.

$\mathbf{S_f} = \mathbf{K_b S_b K_b^{\mathrm{T}}}$ is forward model error $m \times m$ covariance matrix, from uncertainty on non-retrieved properties.

$\mathbf{S}_\varepsilon = \mathbf{S_y} + \mathbf{S_f}$ is total covariance error matrix for estimation of cost function: $(\mathbf{y} - \mathbf{f}(\mathbf{x}))^{\mathrm{T}} \mathbf{S}_\varepsilon^{-1} (\mathbf{y} - \mathbf{f}(\mathbf{x}))/2$.

$\mathbf{S_x} = (\mathbf{K}^{\mathrm{T}} \mathbf{S}_\varepsilon^{-1} \mathbf{K} + \mathbf{S}_\mathrm{a})^{-1}$ is the "posterior" error estimate for retrieved quantities in mbar^2.

For dark surface, max-eigenvalue of $\mathbf{S_f}$ ~ that of $\mathbf{S}_\varepsilon/10$

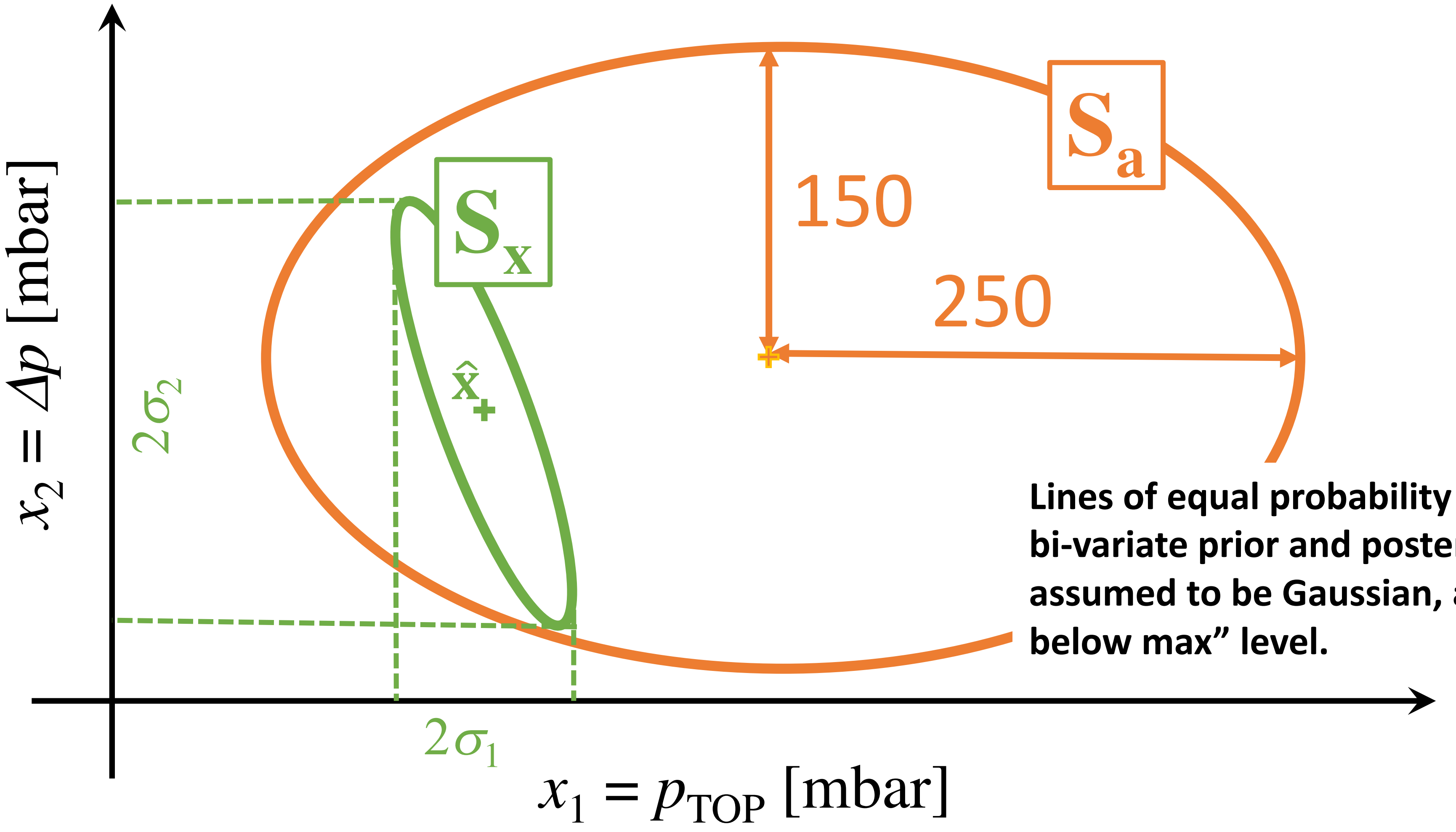
From there, uncertainty on each retrieved quantity is: $\sigma_i = \sqrt{S_{ii}}$ ($i = 1, \ldots, n$) in mbar.

A non-dimensional counterpart is the "Degree of Freedom" (DoF) for each quantity: A_{ii} ($i = 1, \ldots, n$) from $\mathbf{A} = \mathbf{I} - \mathbf{S_x S_a^{-1}}$. Note that DoF $\in [0,1]$ measures what the observations do to improve on the prior info.

A_{ii} > ≈0.7 is OK

Bayesian/Rodgers-like Estimation of Posterior/Retrieval Error & Retrievability

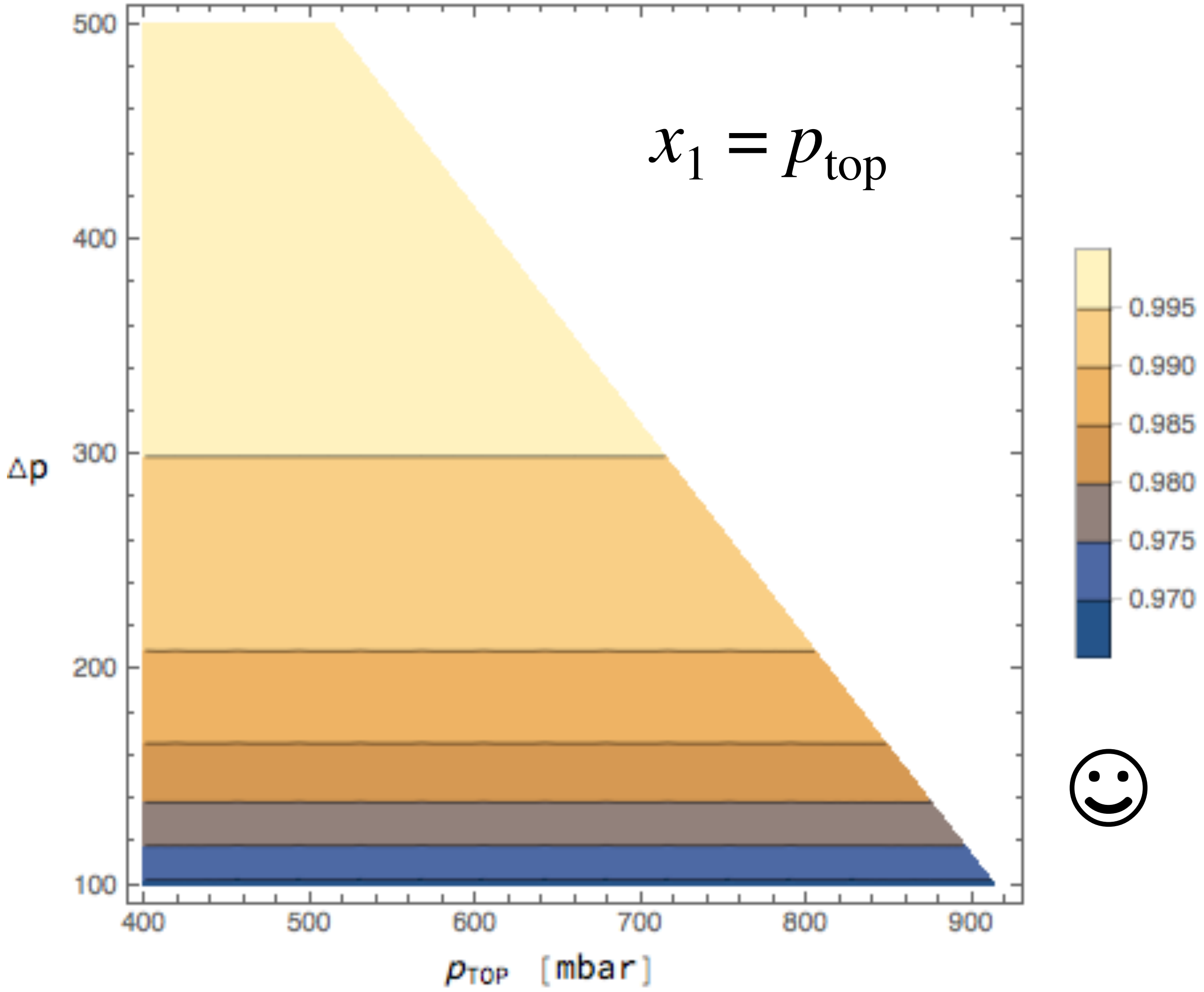
… geometric interpretation in **x**-space: before & after observations

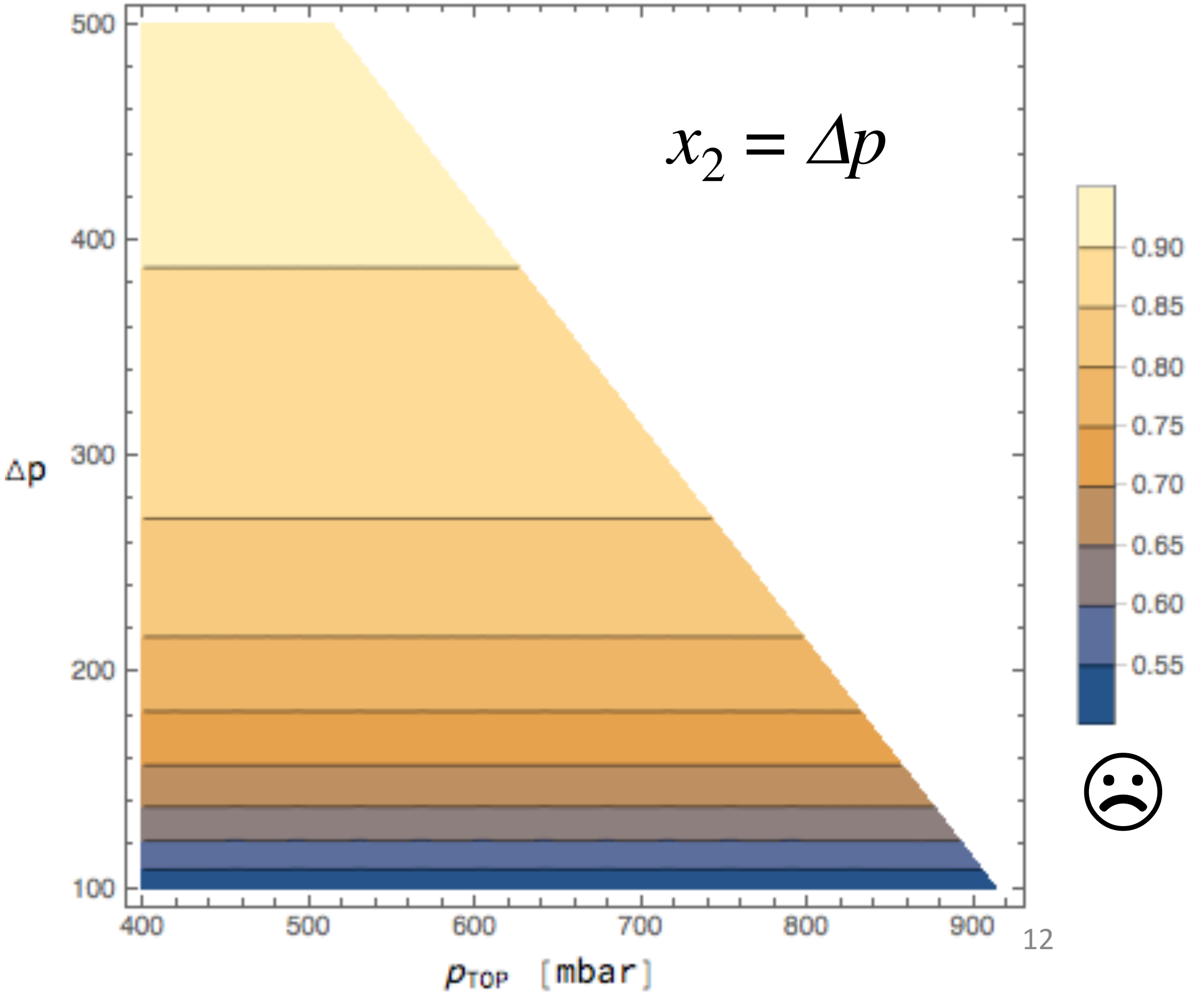


Lines of equal probability density for bi-variate prior and posterior PDFs, assumed to be Gaussian, at the "1/e below max" level.

DoFs of $\mathbf{x}$, for Ocean Color Imager (OCI) only

$\mu_0 = ½$, $\mu = 1$ ($\theta = 0°$); $\tau_{O2,0} = 0.5, 1.9, 2.6$; $\tau_a = 0.1$





DoFs of $\mathbf{x}$, for OCI+MAP (Multi-Angle Polarimeter)

μ_0 = ½, {μ = 1 (θ = 0°); $\tau_{O2,0}$ = 0.5, 1.9, 2.6}; {θ = 0°,30°,60°; $\tau_{O2,0}$ = 1.5}, τ_a = 0.1

$$\underbrace{\left[\mathrm{DOAS}_{0.5}, \mathrm{DOAS}_{1.9}, \mathrm{DOAS}_{2.6}\right]^{\mathrm{T}}}$$ are data, where subscript is $\tau_{\mathrm{O}_2,0}$ with $\mu = 1$ ($m = 3$).

$$\mathbf{y} = [\cdots, \underbrace{DOAS\_0, DOAS\_30, DOAS\_60}]^{\mathrm{T}}$$ are more data, where subscript is θ with $\tau_{\mathrm{O}_2,0} = 1.5$ ($m = 6$, SPEX-like).

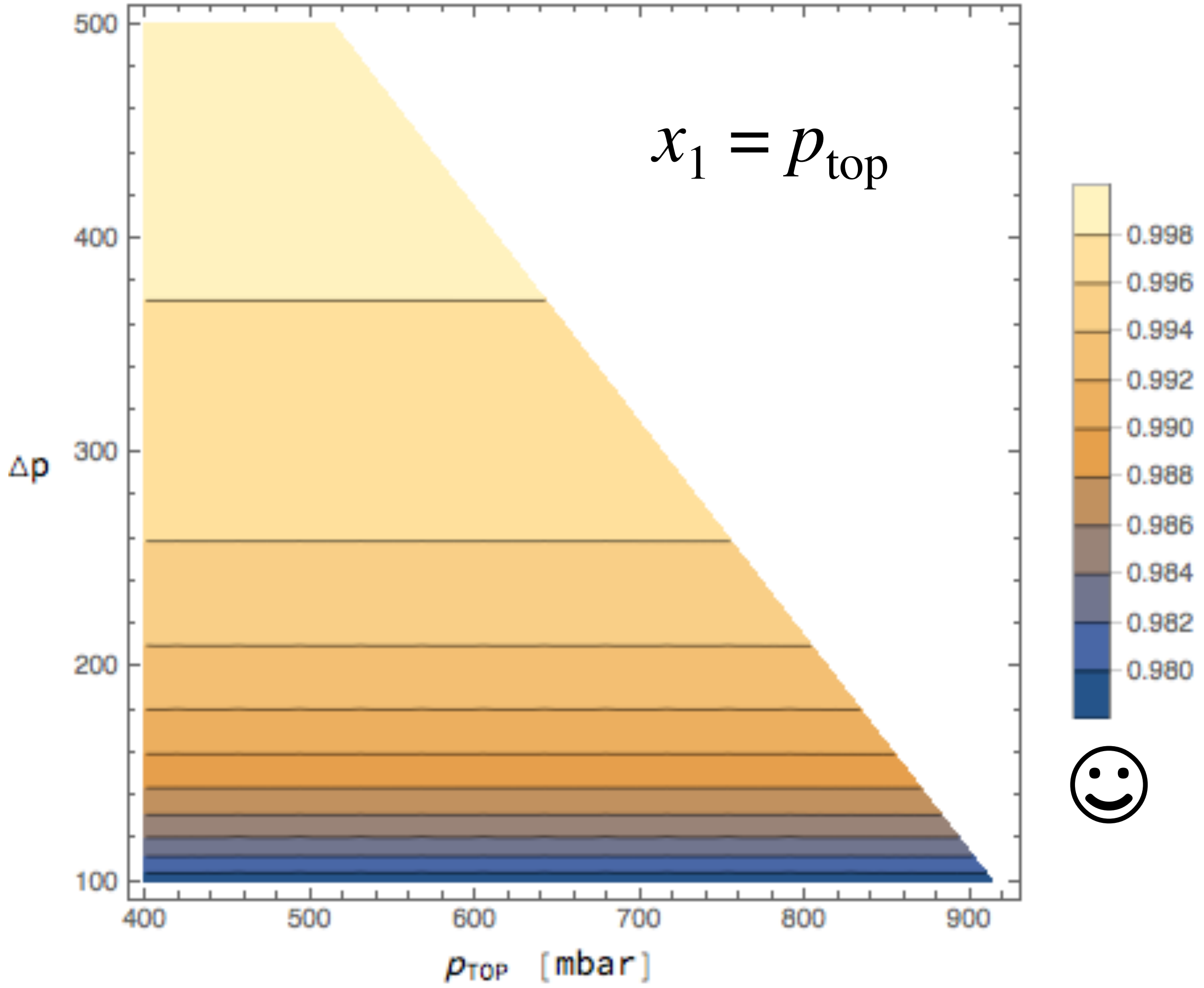
We assume a simple (MSPI2/MAIA-like) two-channel take on the A-band:

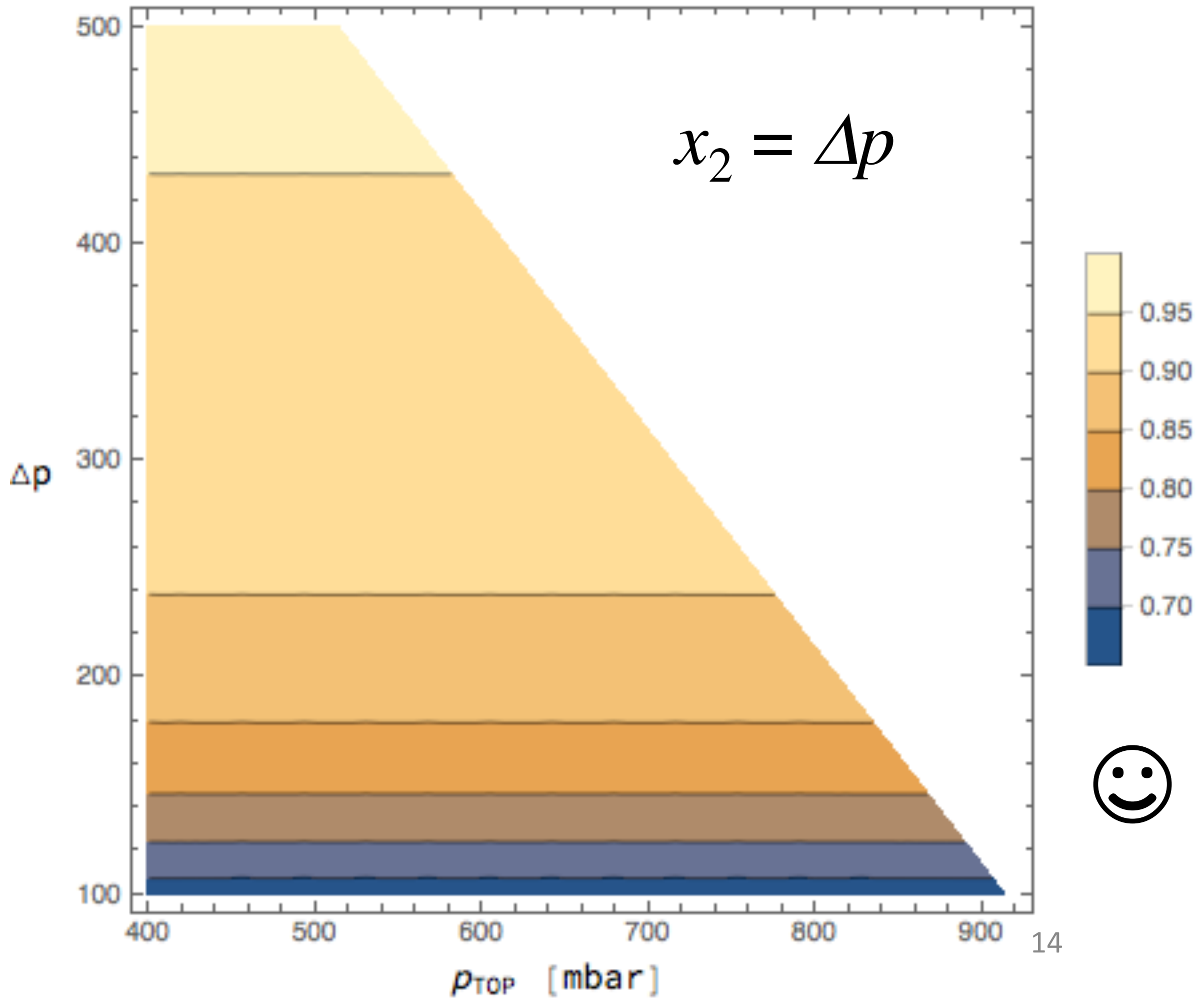
- one “in-band” channel;
- one “reference” channel near the A-band.

Note that multi-angle capability enables in principle a stereographic determination of z_{top}. However, for optically thin layers, smoothly distributed over horizontal directions, it may be hard to find a robust “feature” to track between views.

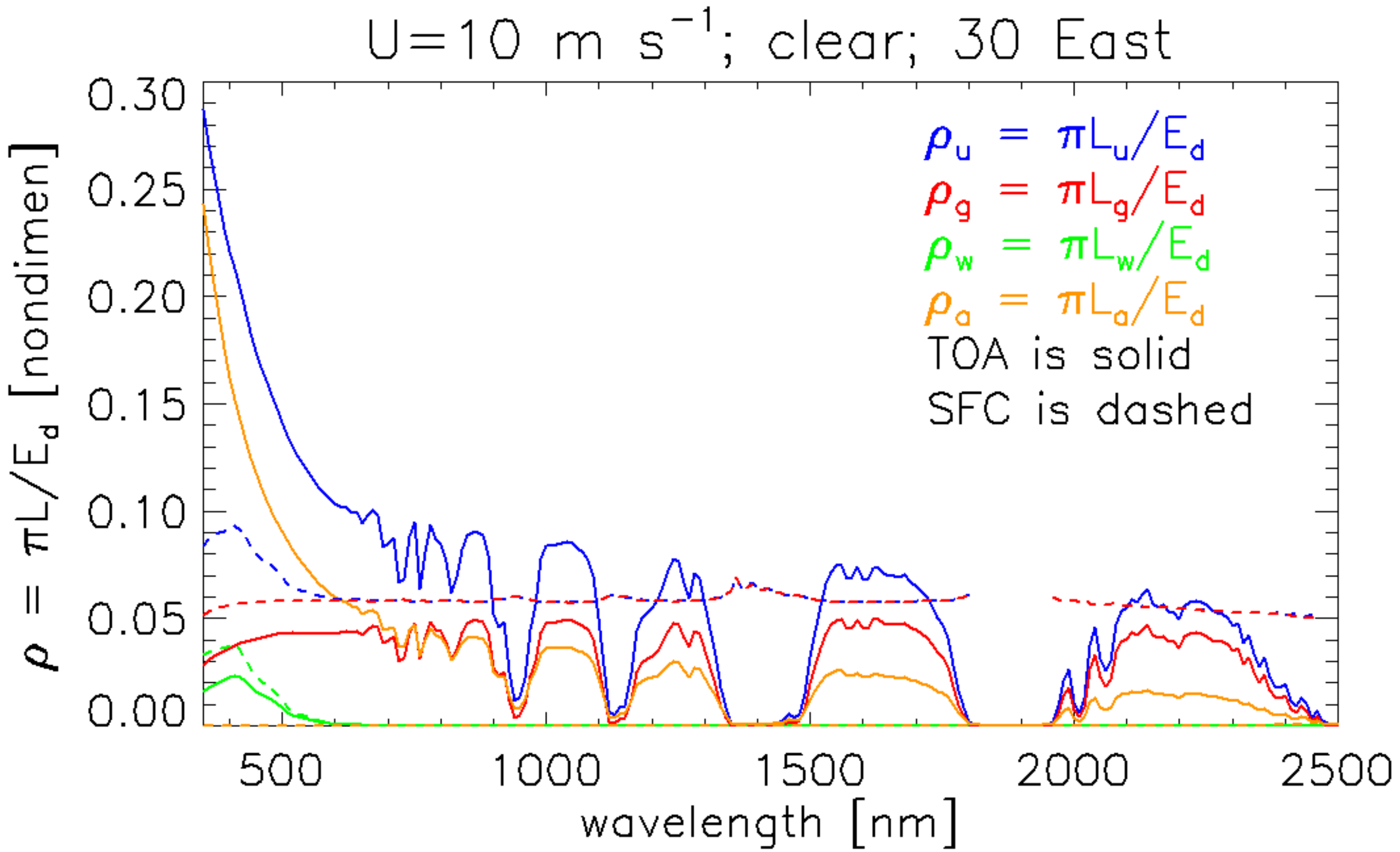
DoFs of $\mathbf{x}$, for OCI+MAP (Multi-Angle Polarimeter)

μ_0 = ½, {μ = 1 (θ = 0°); $\tau_{O2,0}$ = 0.5, 1.9, 2.6}; {θ = 0°,30°,60°; $\tau_{O2,0}$ = 1.5}, τ_a = 0.1



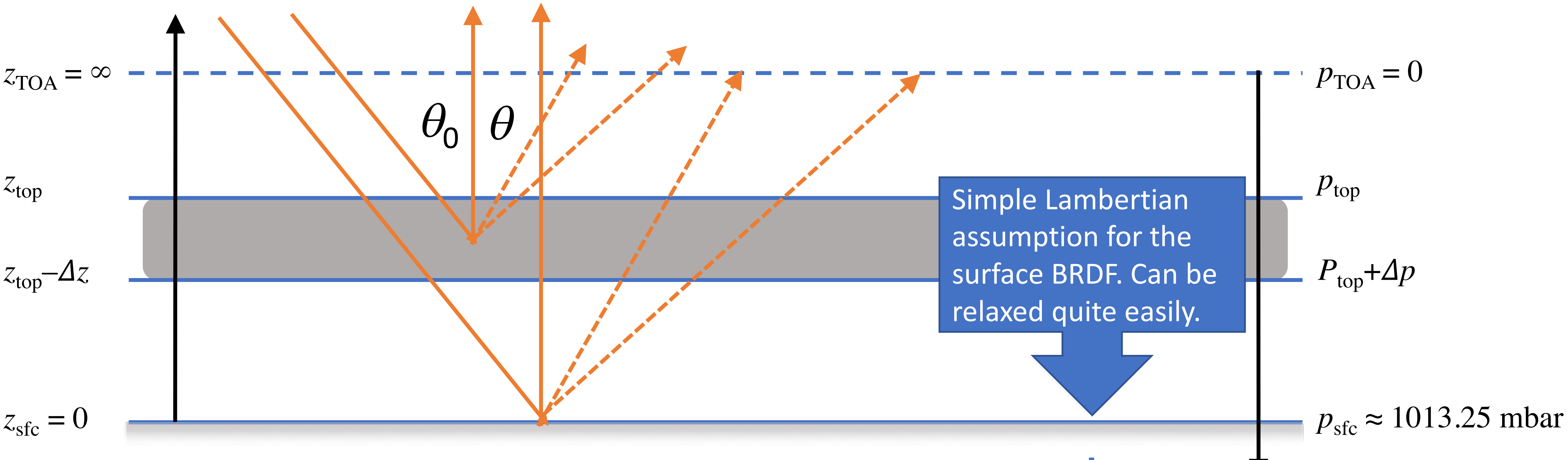


Forward signal model: Partially reflective surface



From Curtis Mobley, Principal Author of:
http://www.oceanopticsbook.info/view/remote_sensing/the_atmospheric_correction_problem

Forward signal model: Partially reflective surface



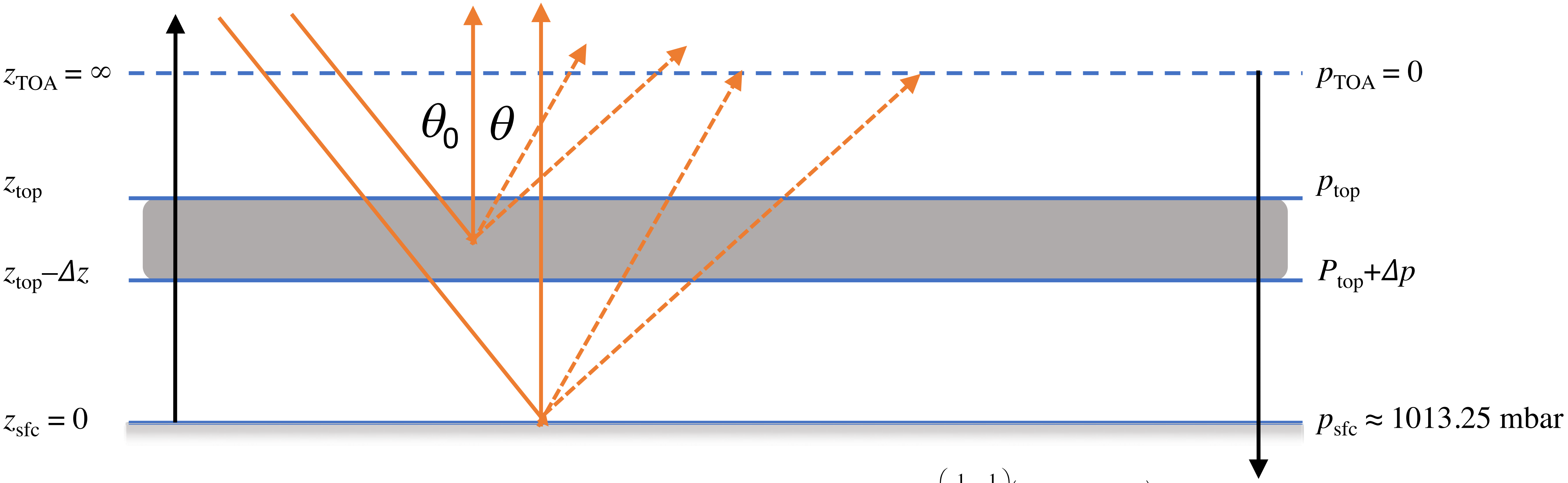
$$I = \frac{\mu_0 F_0}{\pi}\left[e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\frac{p_{top}}{p_{sfc}}\tau_{O2,0}} R(\mu_0,\mu,\varphi;\tau_a,\omega_a,\mathrm{pf}_a;\mathbf{x}) + e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)(\tau_a+\tau_{O2,0})}\mathrm{brf}\right]$$

retrieved: $\mathbf{x} = (p_{top}, \Delta p)^T$

not retr'd: $\mathbf{b} = (\tau_a, \omega_a, \mathrm{pf}_a, \mathrm{brf})^T$

Only one surface reflection, and no interaction with the aerosol layer! OK since water surface BRF is small (outside of glint) and AOT is small as well.

Forward signal model: Partially reflective surface



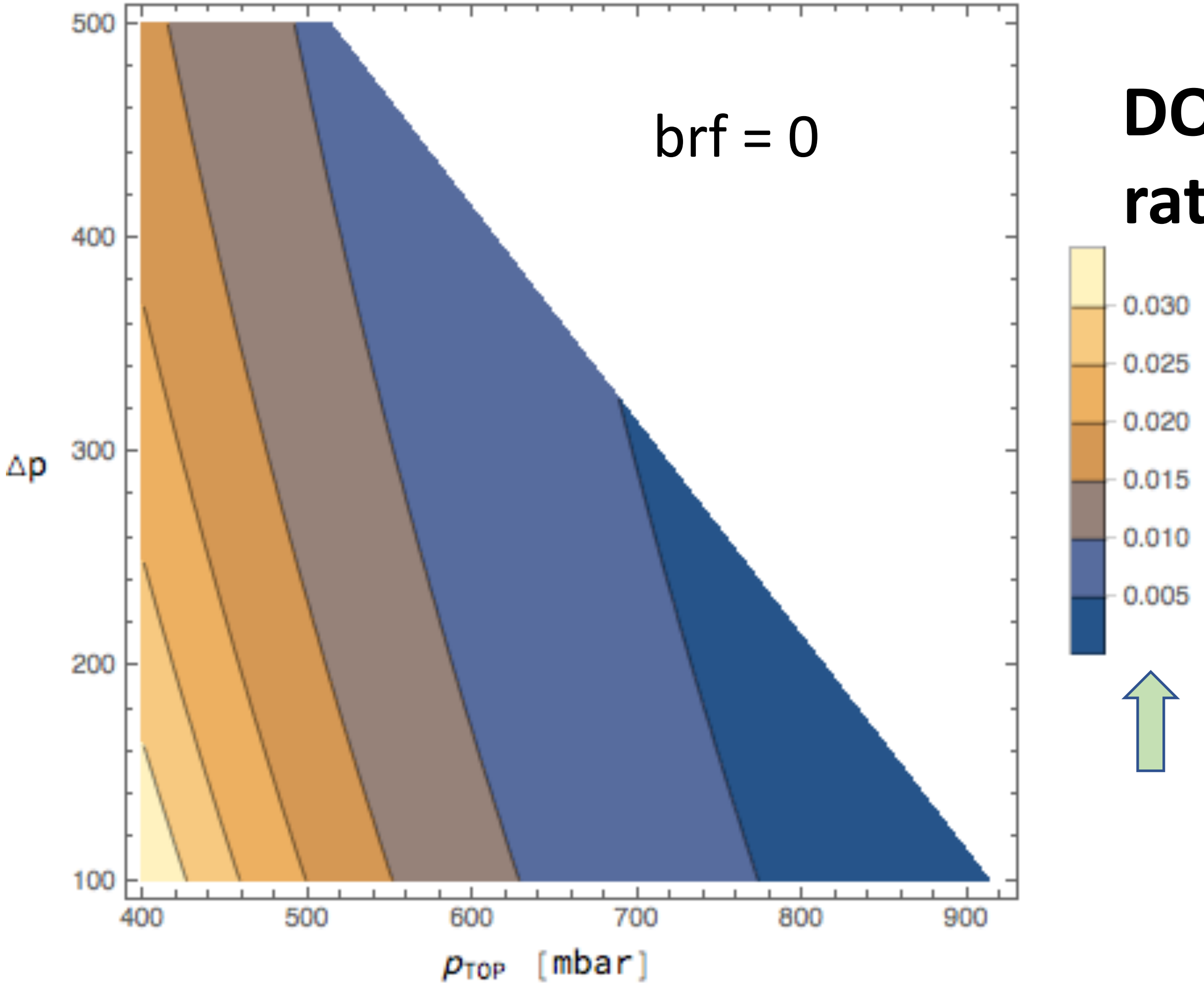
$$\mathbf{f}(\mathbf{x};\mathbf{b}) = \frac{I(\cdots;\tau_{O2,0})}{I(\cdots;0)} = \frac{e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_{O2,0}\frac{p_{top}+\Delta p}{p_{sfc}}} \frac{\omega_a \tau_a}{\tau_a + \tau_{O2,0}\Delta p / p_{sfc}} \mathrm{pf}_a \frac{1-e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\left(\tau_a+\tau_{O2,0}\Delta p/p_{sfc}\right)}}{4(\mu_0+\mu)} + \mathrm{brf}\, e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\left(\tau_a+\tau_{O2,0}\right)}}{\omega_a \mathrm{pf}_a \frac{1-e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_a}}{4(\mu_0+\mu)} + \mathrm{brf}\, e^{-\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)\tau_a}}$$

retrieved: $\mathbf{x} = (p_{top}, \Delta p)^T$

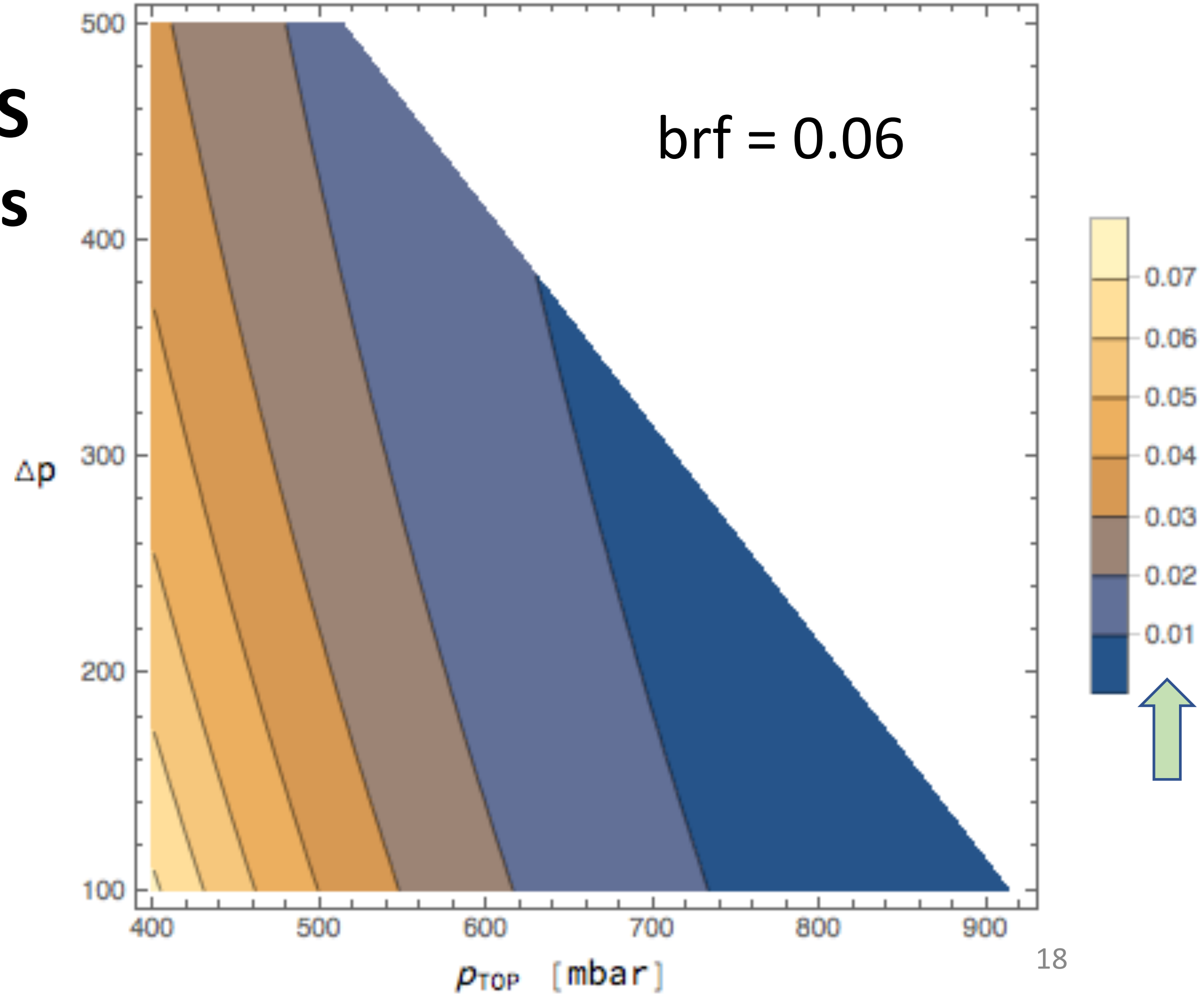
not retr'd: $\mathbf{b} = (\tau_a, \omega_a, \mathrm{pf}_a, \mathrm{brf})^T$

Forward signal model: Dark vs non-dark surface

$\mu_0 = ½$, $\mu = 1$; $\tau_a = 0.1$, $\omega_a = 0.9$, $pf_a = 1$, $p_{top} = 800$, $\Delta p = 200$; $\tau_{O2,0} = 2$



DOAS ratios



DoFs of $\mathbf{x}$, for OCI+MAP: Slightly reflective surface

μ_0 = ½, {μ = 1 (θ = 0º); $\tau_{O2,0}$ = 0.5, 1.9, 2.6}; {θ = 0º,30º,60º; $\tau_{O2,0}$ = 1.5};

τ_a = 0.1, ω_a = 0.9, pf_a = 1; brf = 0.06

Here, the max-eigenvalue of $\mathbf{S_f}$ is ~ that of $\mathbf{S_y}$. Need to include!

DoF plots for p_{top} and Δp should be finished for face-to-face STM. (Code is taking too long to run!) We anticipate somewhat reduced DoF values because the non-informative but uncertain surface contribution rivals the aerosol signal in magnitude. We may need more viewing angles in MAP to compensate for loss of information about aerosol layer thickness. Please ask about outcome at F2F.

Summary

- **Will OCI's O_2 A-band channels contain the information needed to infer the height & thickness of an optically thin layer of absorbing aerosols?**
  - Over a dark surface, aerosol layer top pressure p_{top} can be retrieved with confidence, from which altitude z_{top} can be derived.
  - Probably true also for a weakly reflective surface, such as turbid water.
- **If not, can a MAP help?**
  - Over a dark surface, aerosol layer pressure thickness Δp will call for a MAP under most circumstances; geometric thickness Δz can be derived from Δp and p_{top}.
  - Need to extend to weakly reflective surfaces (e.g., turbid water).
- **This theoretical prediction of retrieval error was based on:**
  - Forward modeling with 1D linearized RT in the single-scattering/reflection limit;
  - Realistic characteristics for OCI and a notional MAP;
  - A Rodgers-like Bayesian framework for optimal estimation used to quantify the (posterior) uncertainty on retrieved properties, assuming proper convergence (no bias error) and Gaussian statistics for errors and prior, and accounting for uncertainty on non- or otherwise retrieved properties, such as AOT.