Jet Propulsion Laboratory
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Physics-Based Analysis of Cloud Information Content in EPIC/DSCOVR's O_2 A- and B-Band Channels

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Outline

- **Physics-based approach**
  - A.B. Davis, N. Ferlay, Q. Libois, A. Marshak, Y. Yang, and Q. Min. Cloud information content in EPIC/DSCOVR's oxygen A- and B-band channels: A physics-based approach. *J. Quant. Spectrosc. Rad. Transf.* **220**, 84-96 (2018). https://doi.org/10.1016/j.jqsrt.2018.09.006
- **Optimal estimation approach**
  - A.B. Davis, G. Merlin, C. Cornet, L. C.-Labonnote, J. Riédi, N. Ferlay, P. Dubuisson, Q. Min, Y. Yang, and A. Marshak. Cloud information content in EPIC/DSCOVR's oxygen A- and B-band channels: An optimal estimation approach. *J. Quant. Spectrosc. Rad. Transf.* **216**, 6-16 (2018). https://doi.org/10.1016/j.jqsrt.2018.05.007
- **Conclusions/outlooks**

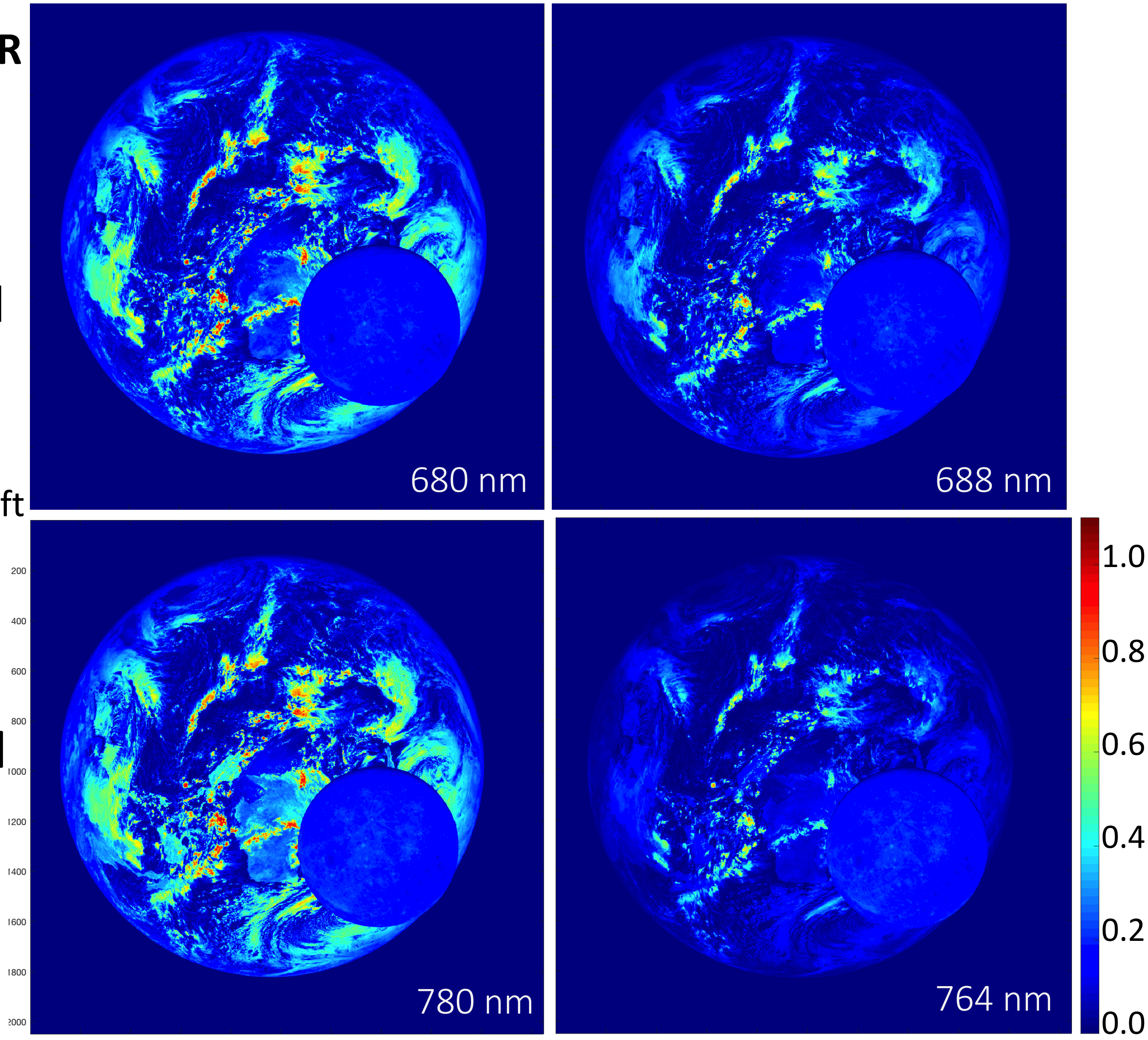
EPIC's A- and B-band channels, at Nov'17 new Moon

EPIC/DSCOVR
O_2 channels:

B-band
$\tau_{O2} \approx 0.3$

Reference on left
($\tau_{O2} = 0$)

A-band
$\tau_{O2} \approx 0.6$



2017-11-19

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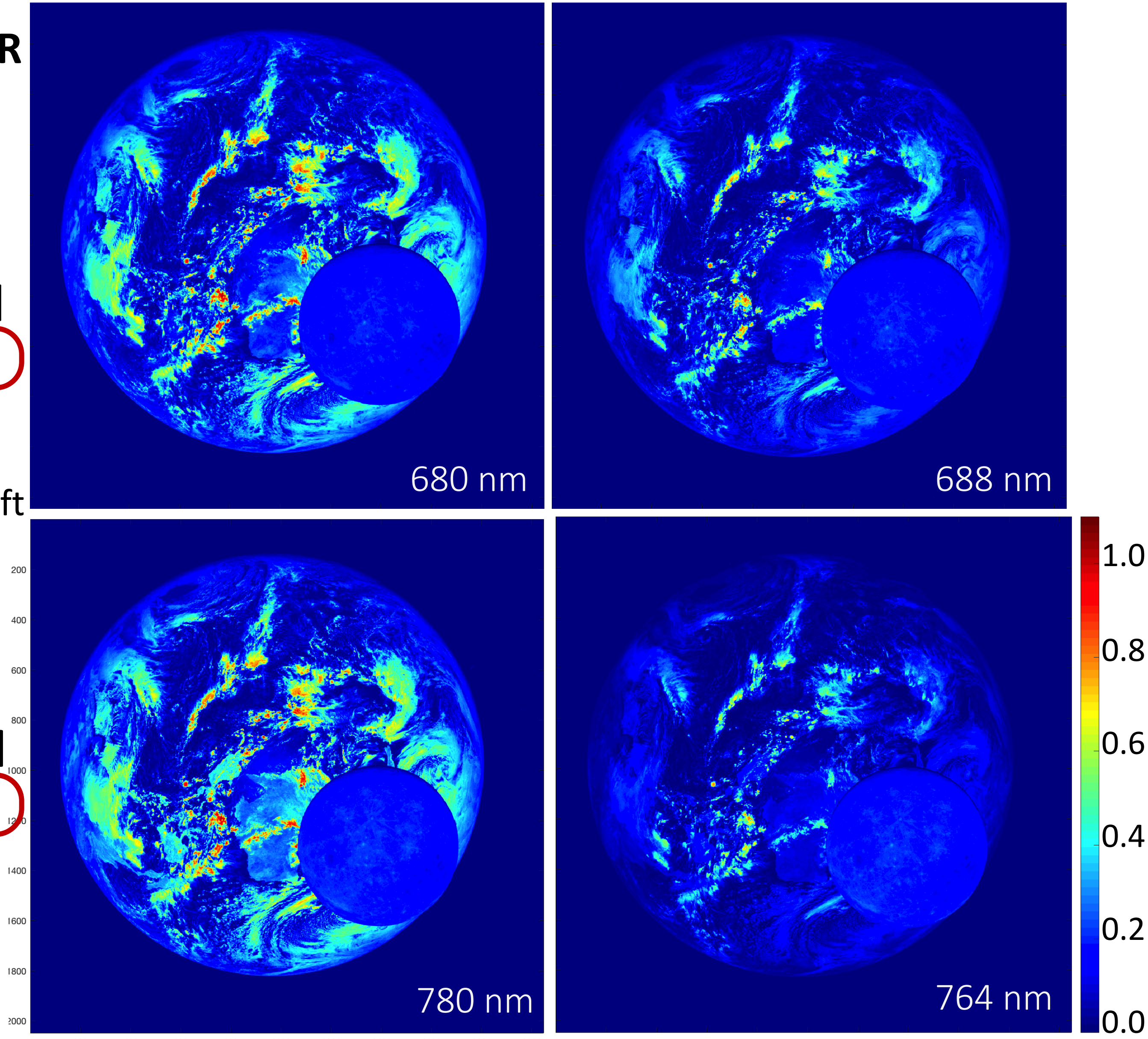
effective optical thicknesses



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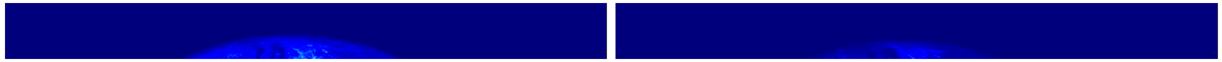
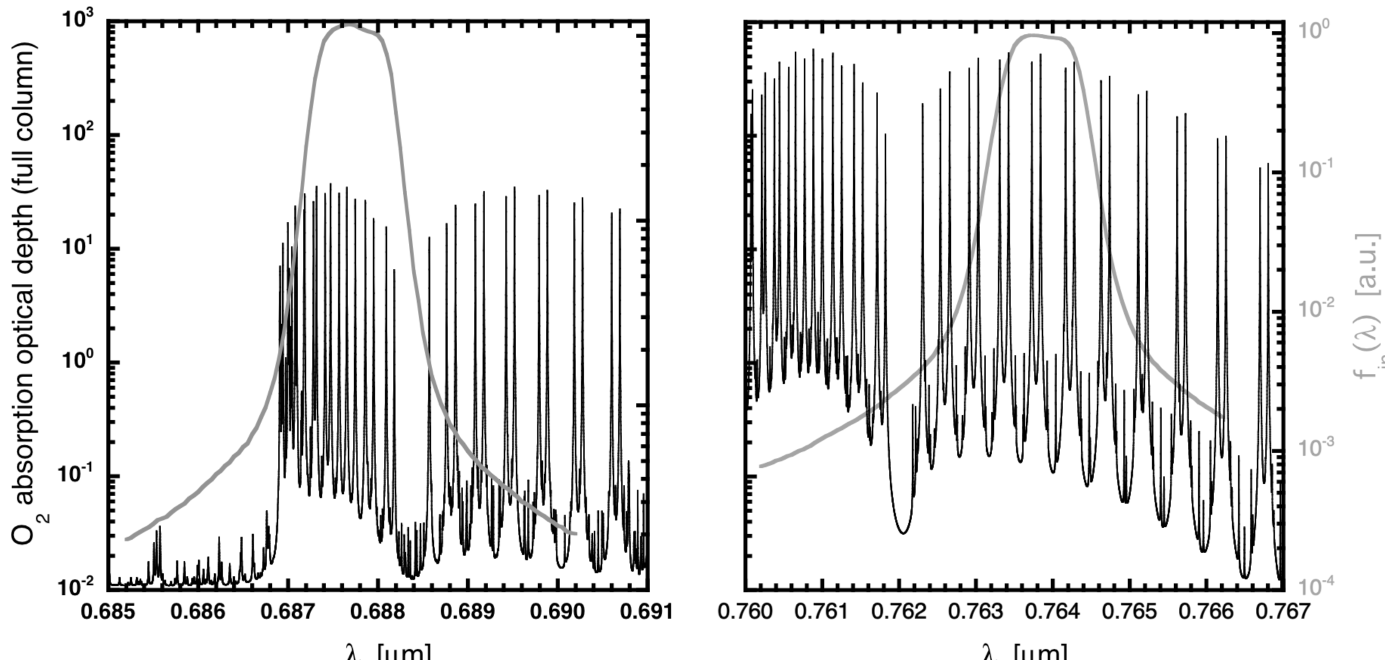
EPIC's A- and B-band channels, in full spectral detail

EPIC/DSCOVR
O_2 channels:





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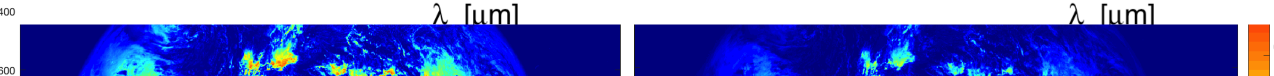
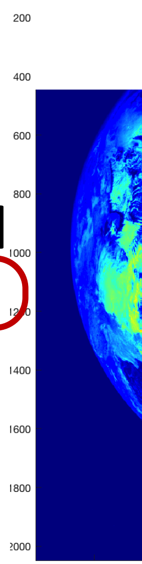




$$\tau_{O_2}^{(\Delta\lambda)}(M) = -\frac{1}{M}\log\left(\int_{\Delta\lambda}\exp[-M\tau_{O_2}(\lambda;0)]f_{\text{in}}^{\star}(\lambda)\mathrm{d}\lambda\right)$$

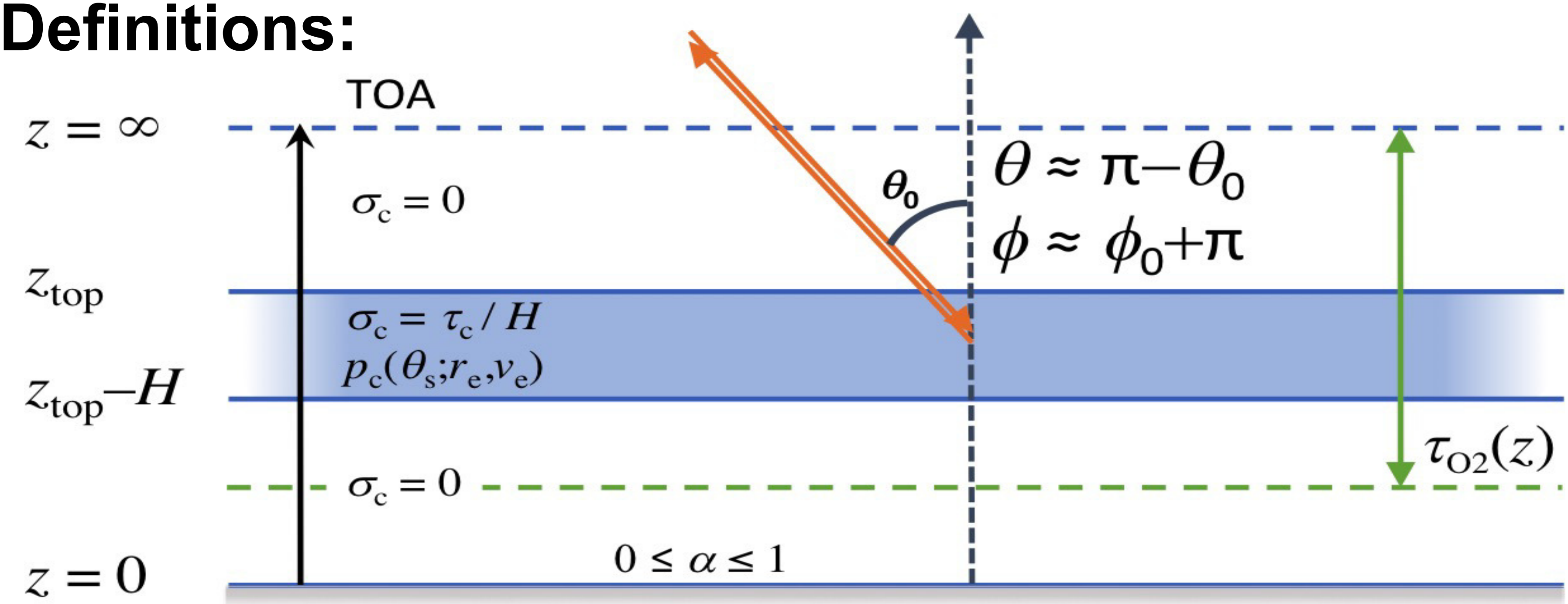
so-called "airmass" factor

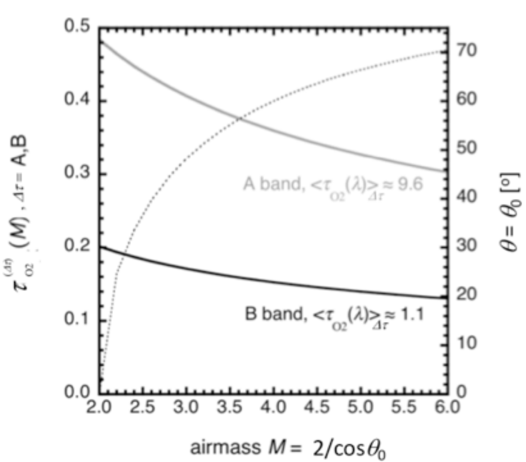
$$M = \frac{1}{\cos\theta_0} + \frac{1}{\cos\theta} = \frac{1}{\mu_0} + \frac{1}{\mu},$$

2017-11-19

Physics-based modeling approach

Definitions:





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Physics-based modeling approach

Assumptions:

- plane-parallel geometry (1D RT is OK)
- optical thick clouds (asymptotic/diffusion theory)
- dark surface (water)
- use exponential pressure profile, as needed:

$$p(z) = p(0)\exp[-z/H_{\mathrm{mol}}] \rightarrow \tau_{O2}(\lambda;z) = \tau_{O2}(\lambda;0)\exp[-z/H_{\mathrm{mol}}]$$

- use "effective" O_2 optical depth for each band …

… i.e., it's OK to use $\tau_{\mathrm{O}_2}^{(\Delta\lambda)}(M)$ here

$$\begin{aligned} -\log r_\lambda(\mathbf{\Omega};\mathbf{\Omega}_0,\tau_\mathrm{c}) &\approx (1/\mu_0+1/\mu)\overbrace{\tau_{\mathrm{O}_2}(\lambda;z_\mathrm{top})} \\ &+ (\mu+\mu_0)\left[\underbrace{\tau_{\mathrm{O}_2}(\lambda;z)}_{\text{… and here}}\right]_{z_\mathrm{top}-H}^{z_\mathrm{top}} \times (1+\underbrace{C(\tau_\mathrm{c},g,\mu_0)}_{\text{pre-asymptotic correction term}}) \end{aligned}$$

↑

DOAS ratios:

$I_{\mathrm{abs},\lambda}/I_{\mathrm{ref},\lambda}$, λ = A-,B-bands

(Differential Optical Absorption Spectroscopy)

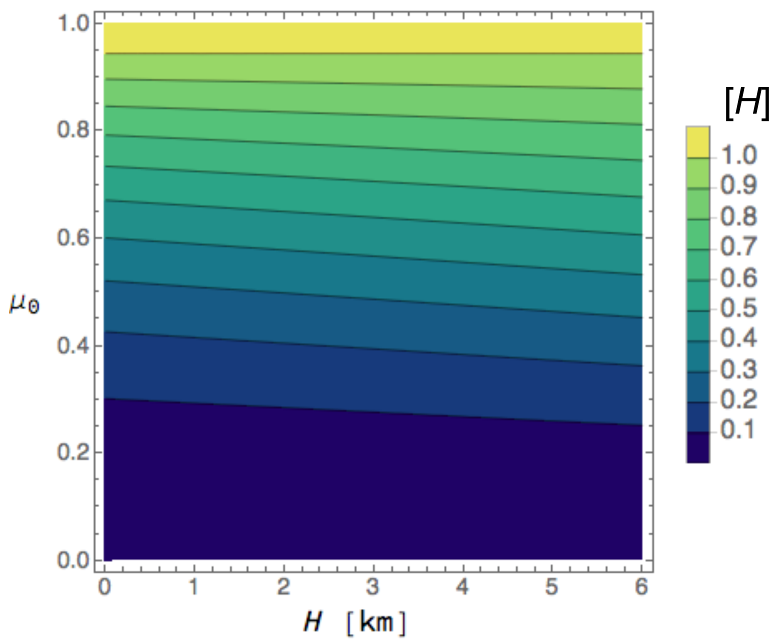
Physical insights …

retrieval bias from ignoring in-cloud path length

$$z_{\mathrm{top}}^{(\mathrm{app})} \approx z_{\mathrm{top}} \overbrace{- H_{\mathrm{mol}} \log\left[1 + \mu_0\mu\left(\mathrm{e}^{H/H_{\mathrm{mol}}} - 1\right) \times (1 + C(\tau_{\mathrm{c}}, g, \mu_0))\right]}$$

$$\approx -\mu_0\mu H \times (1 + C(\tau_{\mathrm{c}}, g, \mu_0))$$

Normalized CTH bias $\left(z_{\mathrm{top}} - z_{\mathrm{top}}^{(\mathrm{app})}\right)/H$ from (19) for EPIC ($\mu_0 = \mu$), and $H_{\mathrm{mol}} = 8$ km.

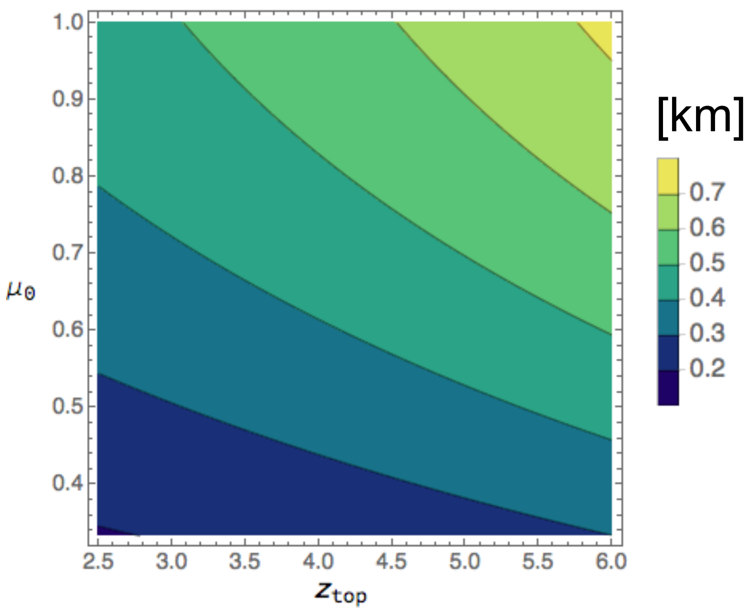


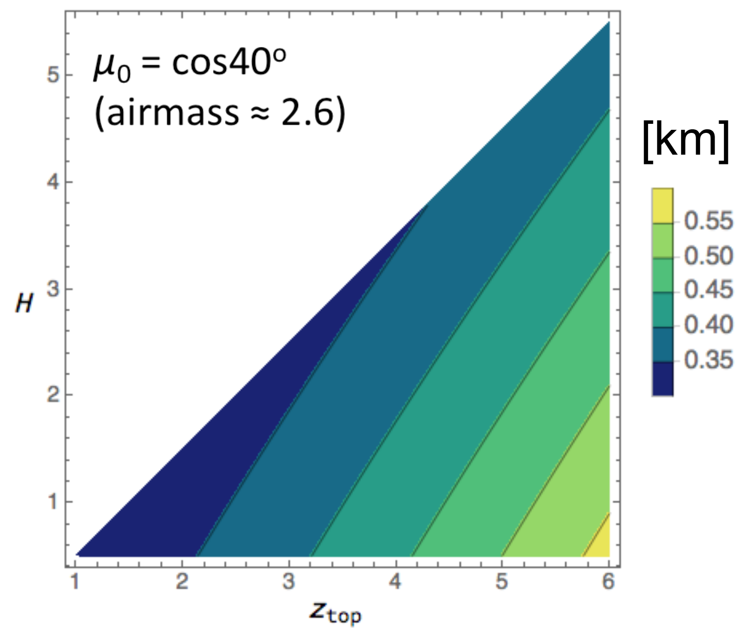
Physical insights …

random retrieval uncertainty resulting from sensor error, assuming 1.5% on DOAS ratio

$$\Delta z_{\text{top}}^{(\text{app})} \approx \frac{0.015\, H_{\text{mol}}}{\tau_{\text{O}_2}^{(\Delta\lambda)}} \times \frac{\mathrm{e}^{z_{\text{top}}/H_{\text{mol}}}}{2\mu_0 \left(\mu_0^{-2} + \mathrm{e}^{H/H_{\text{mol}}} - 1\right)}$$

$H = 2$ km





Statistical (optimal estimation) approach

Bayes' theorem:

PDF of total cost function =

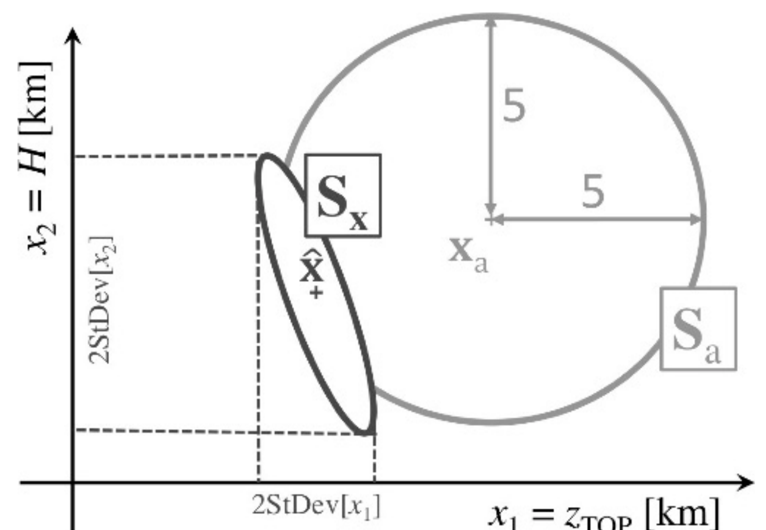
PDF of forward model prediction error on observations **y**

x PDF of prior uncertainty on state vector **x**

$$\underbrace{p(\mathbf{x}|\mathbf{y})}_{\textit{posterior}\text{ uncertainty on }\mathbf{x}\text{, given }\mathbf{y}} = \overbrace{p(\mathbf{y}|\mathbf{x})}^{\text{likelihood of y, given }\mathbf{x}}\ \overbrace{p(\mathbf{x})}^{\textit{prior}\text{ uncertainty on }\mathbf{x}} \underbrace{/\ p(\mathbf{y})}_{\text{unimportant}}$$

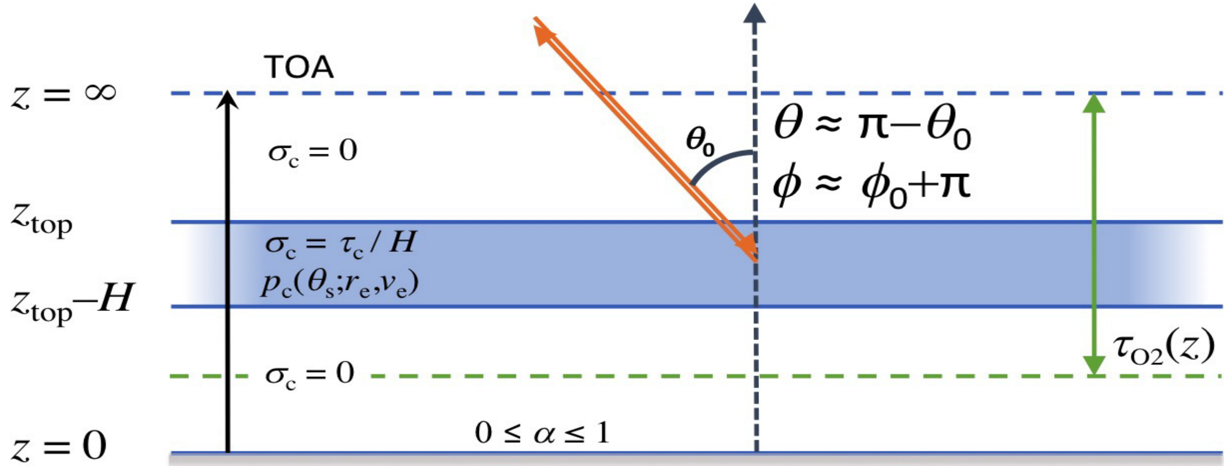
sensor ↓ model ↓

errors in **y** *space:* $\mathbf{S_y} = \mathbf{S_\varepsilon} + \mathbf{S_b}$



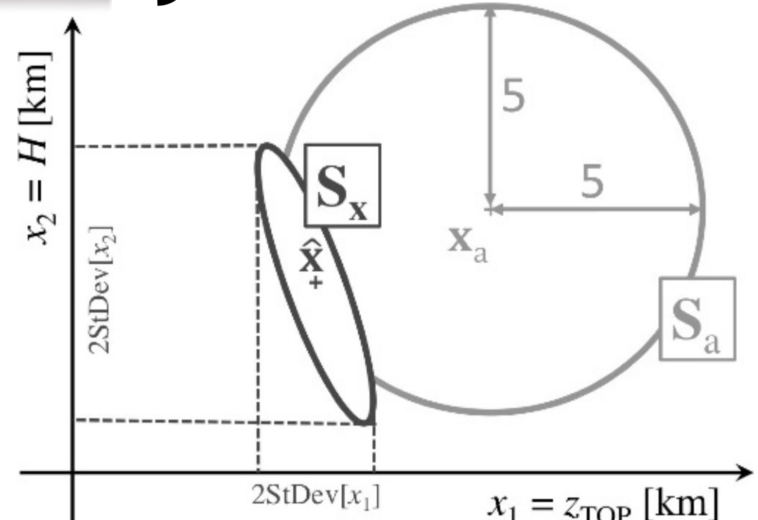
Shannon information content / gain

Information Content (IC) gain or Degrees-Of-Freedom (DOF) per cloud property = ratio of the areas of S_a and $S_{\mathbf{x}}$, projected onto one of the state/**x**-space axes



$$\left.\begin{array}{l} \mathbf{x}^T = (z_{top}, H) \\ \mathbf{y}^T = (I_{abs,\lambda}/I_{ref,\lambda}, \\ \quad \lambda = \text{A-,B-bands}) \end{array}\right.$$

Total information content/gain = Ratios of ellipses areas |S|, i.e., of products of minor and major axes of the prior-to-posterior PDFs



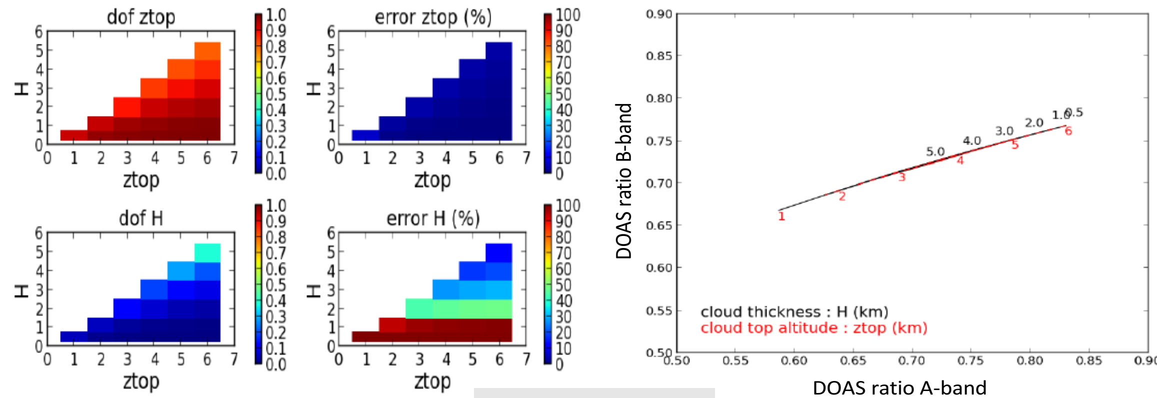
Posterior uncertainty of the retrieved cloud properties

$0 \le \mathrm{pDOF}_i \le 1$, for $i = 1,2$ (z_{top}, H) and $\sigma_{pi} = \sigma_{ai}(1 - \mathrm{DOF}_i)^{1/2}$ for the standard deviations.

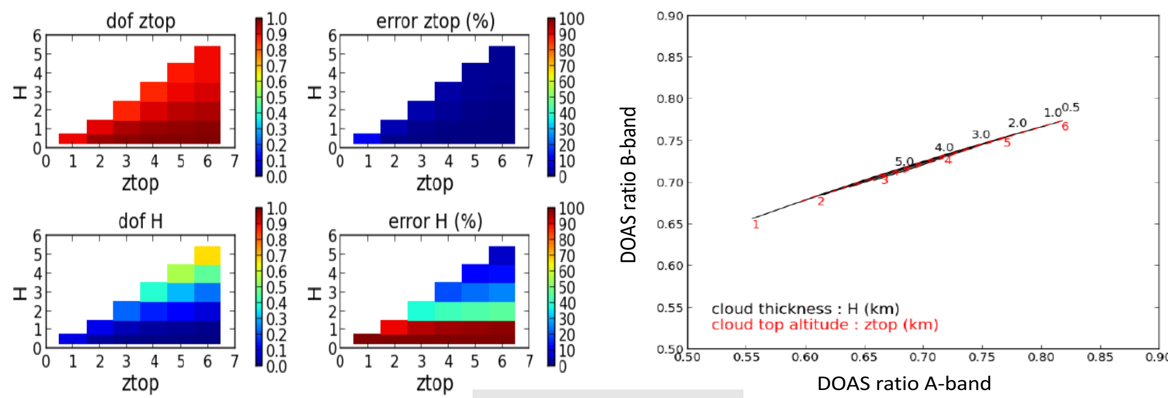
Errors expressed here in %: $100\, \sigma_i / x_i$

Nakajima/King-type plots of DOAS ratios

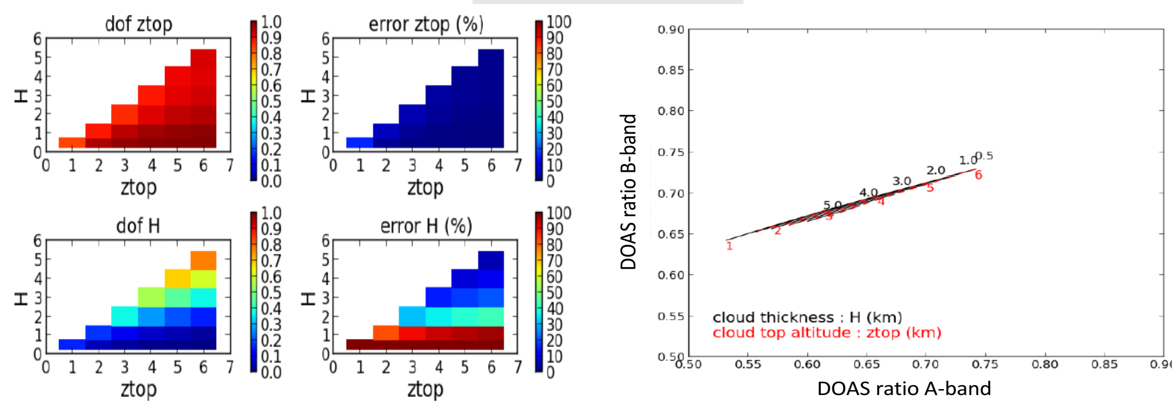
$\tau_c = 1,\ \alpha = 0$



$\tau_c = 32,\ \alpha = 0$



$\tau_c = 32,\ \alpha = 0.8$



Conflict with Yang et al. (2013)?

cloud optical thickness (COT) τ_c = 30

→ not really …

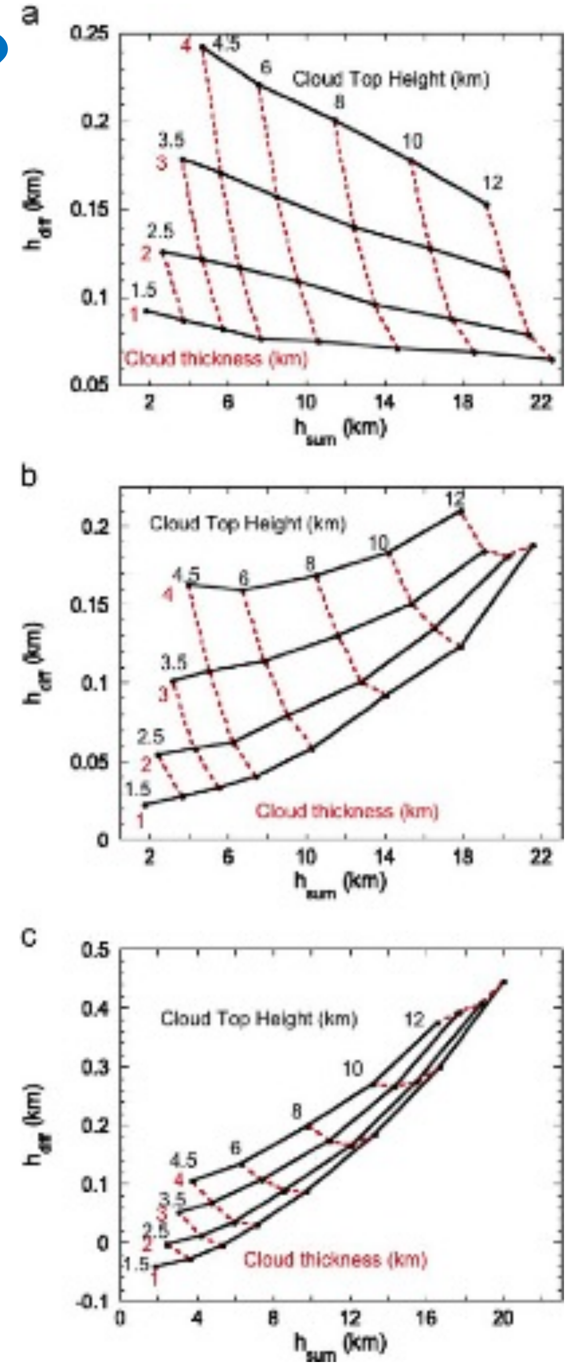
τ_c = 10

ECH: "effective" cloud height

$h_{diff,sum}$ = $CEH_A \pm CEH_B$

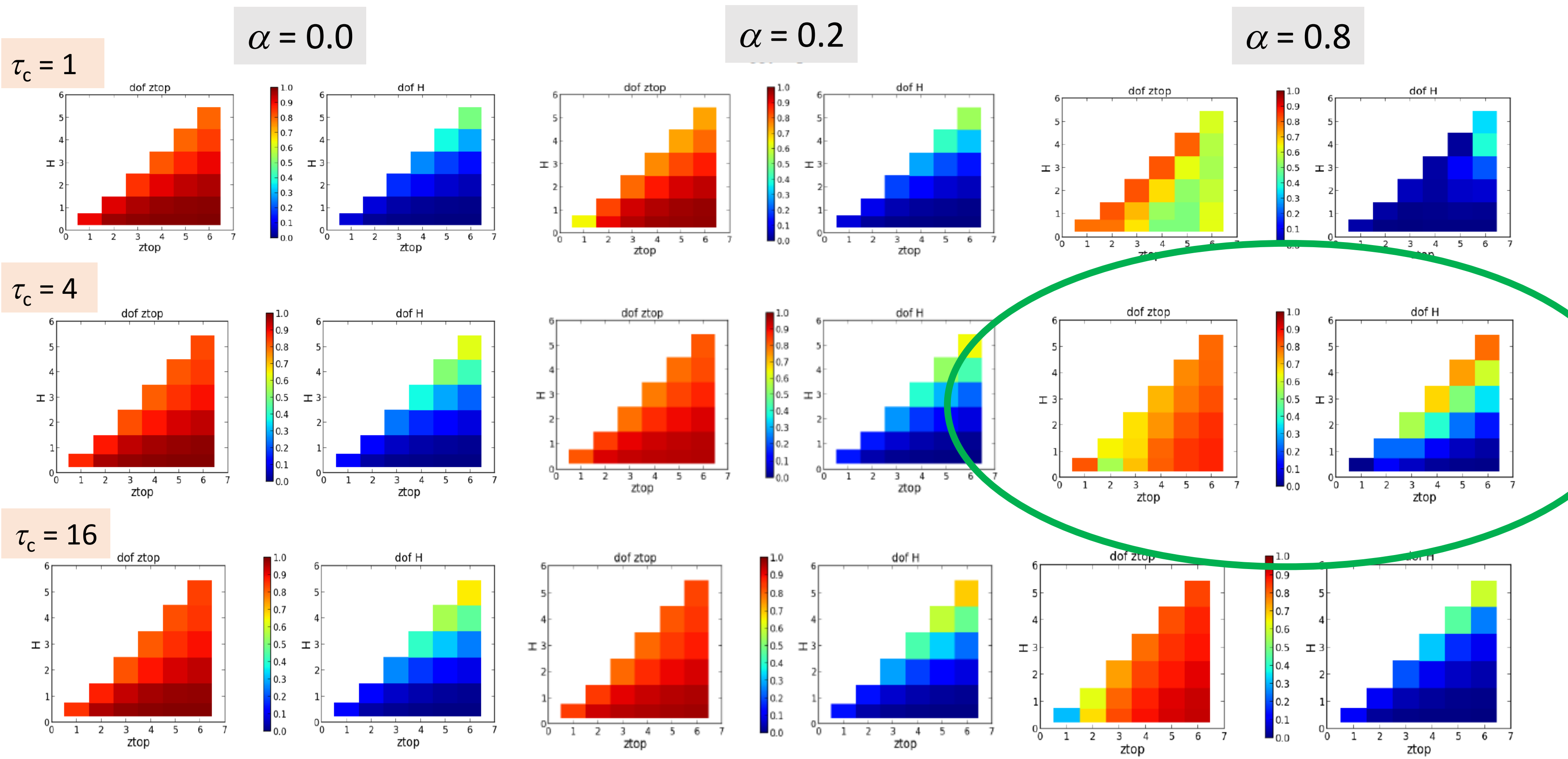
τ_c = 5

Factoring in sensor error,
uncertainty on h_{diff} is ~ vertical axes
uncertainty on h_{sum} is << horizontal axes



A sweet spot for z_{top} and H retrieval?

→ moderately opaque clouds over bright surfaces …



… a possible application to arctic clouds?

Summary/outlook

- **Optimal estimation approach**
  - computational (exact) 1D RT model
  - Rodgers' [2000] statistical formalism
- **Physics-based approach**
  - analytical (but approximate) 1D RT model
  - physical insights about biases and sensitivities
- **Both approaches …**
  - use derivatives of signals w.r.t. cloud properties (a.k.a. Jacobians)
  - account for sensor noise
  - lead to the conclusion that, under most circumstances, only the cloud top height can be reliably retrieved