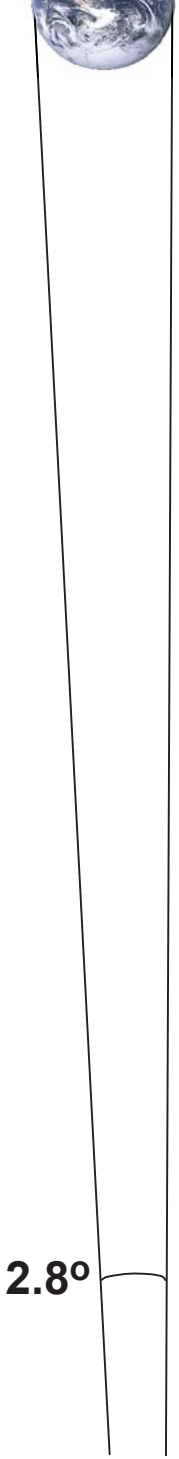
2011 Fall AGU Meeting, 5-9 December 2011, San Francisco, Ca
Special session on "Earth Observations from the L1 (Lagrangian Point No. 1)"

Cloud (and Aerosol) Information Content Analysis for EPIC/DSCOVR's Oxygen A- and B-band Channels

Anthony B. Davis
Suniti V. Sanghavi
Jet Propulsion Laboratory
California Institute of Technology

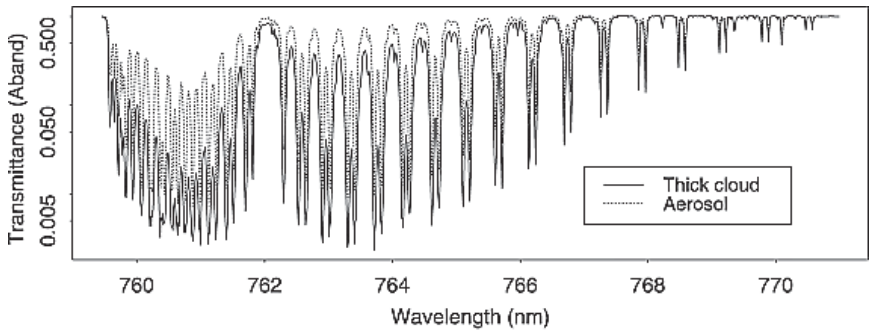


Outline

- **Simple/analytical forward RT model for space-based O_2 spectroscopy**
- **Application to EPIC pixels:**
  - ***Fully cloudy, over water***
  - ***Cloud-free, over water***
  - ***Partially cloudy, over water***
  - ***All of the above, over land***
- **Conclusions**
- **Recommendations**

The Earth seen from Apollo 17 (Dec 7–19, 1972) at 1023^2 pixels

Differential optical absorption spectroscopy (DOAS) at *high* spectral resolution



From: Min Q.-L., L. C. Harrison, P. Kiedron, J. Berndt, and E. Joseph, 2004: A high-resolution oxygen A-band and water vapor band spectrometer, *J. Geophys. Res.*, **109**, D02202, doi:10.1029/2003JD003540.

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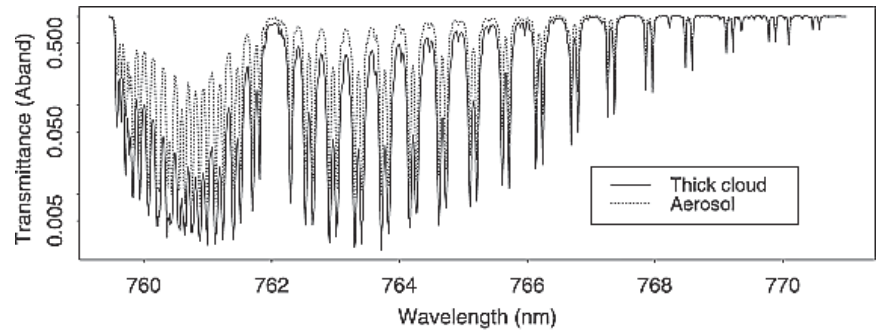

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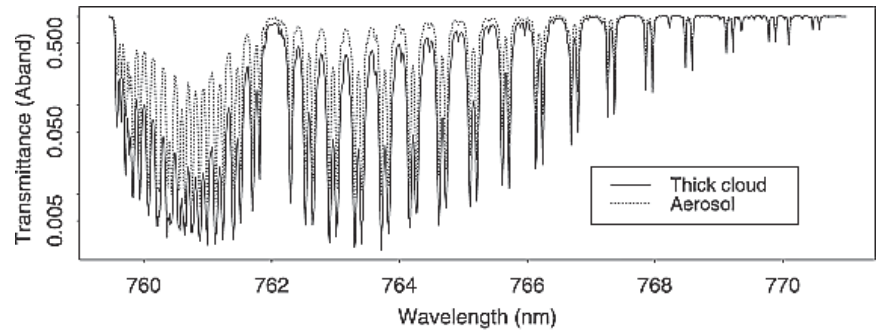
$$I(\nu)/I_0 = \exp[-\sigma_\nu \; n \; L]$$

x-section **density** **pathlength**

known/not :

- ? √ √ estimating molecular cross-sections in the laboratory
- √ ? √ monitoring amounts of chemical effluent in situ
- √ √ ? scattering/reflection diagnostics of media permeated with gas

Differential optical absorption spectroscopy (DOAS) at *high* spectral resolution



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$$I(\nu)/I_0 = \exp[-\underbrace{\sigma_\nu}_{\text{x-section}}\ \underbrace{n}_{\text{density}}\ \underbrace{L}_{\text{pathlength}}]$$

$$\text{known/not}: \begin{cases} ?\ \surd\ \surd & \text{estimating molecular cross-sections in the laboratory} \\ \surd\ ?\ \surd & \text{monitoring amounts of chemical effluent in situ} \\ \surd\ \surd\ ? & \text{scattering/reflection diagnostics of media permeated with gas} \end{cases}$$

$$I(\nu) = I(k_\nu) = I_0 \int_0^\infty p(L)\ \exp[-k_\nu L]\ \mathrm{d}L \ \text{(equivalence "theorem")} \Rightarrow \langle L^q \rangle = \frac{(-1)^q}{I_0}\left(\frac{\mathrm{d}^q I}{\mathrm{d}k_\nu^q}\right)_{k_\nu = 0}$$

A-band Cartoon - General Case

… in lieu of λ ↓

τ_{O_2} is short for $\tau_{O_2}(0,\infty)$

TOA

$$I_{TOA}(\tau_{O_2},\mu_0;Z_t,H,\tau,\mathrm{pf},\alpha) = \mu_0 F_0 R_{TOA}(\tau_{O_2},\mu_0;Z_t,H,\tau,\mathrm{pf},\alpha)/\pi$$

$\tau_{O_2}(Z_t,\infty)$

$$\tau_{O_2}(Z_1,Z_2) = \int_{Z_1}^{Z_2} \sigma_{O_2}(z)\,\mathrm{d}z = \int_{Z_1}^{Z_2} \sigma_{O_2}(P_z,T_z)\,\mathrm{d}z = \sigma_{O_2}^{\mathrm{ref}} \int_{Z_1}^{Z_2} \frac{P}{P_0} f(P_z,T_z)\,\mathrm{d}z$$

$$\approx \sigma_{O_2}^{\mathrm{ref}} \int_{Z_1}^{Z_2} \mathrm{e}^{-z/H_m}\,\mathrm{d}z = \tau_{O_2} \times \left(\mathrm{e}^{-Z_1/H_m} - \mathrm{e}^{-Z_2/H_m}\right) = \tau_{O_2} \frac{\Delta P}{P_0}$$

H_m 8 km

$Z_t = Z_b + H$

$\tau_{O_2}(Z_b,Z_t)$

scattering layer: extinction σ, thickness $H << H_m$

$Z_b = Z_t - H$

$\tau_{O_2}(0,Z_b)$

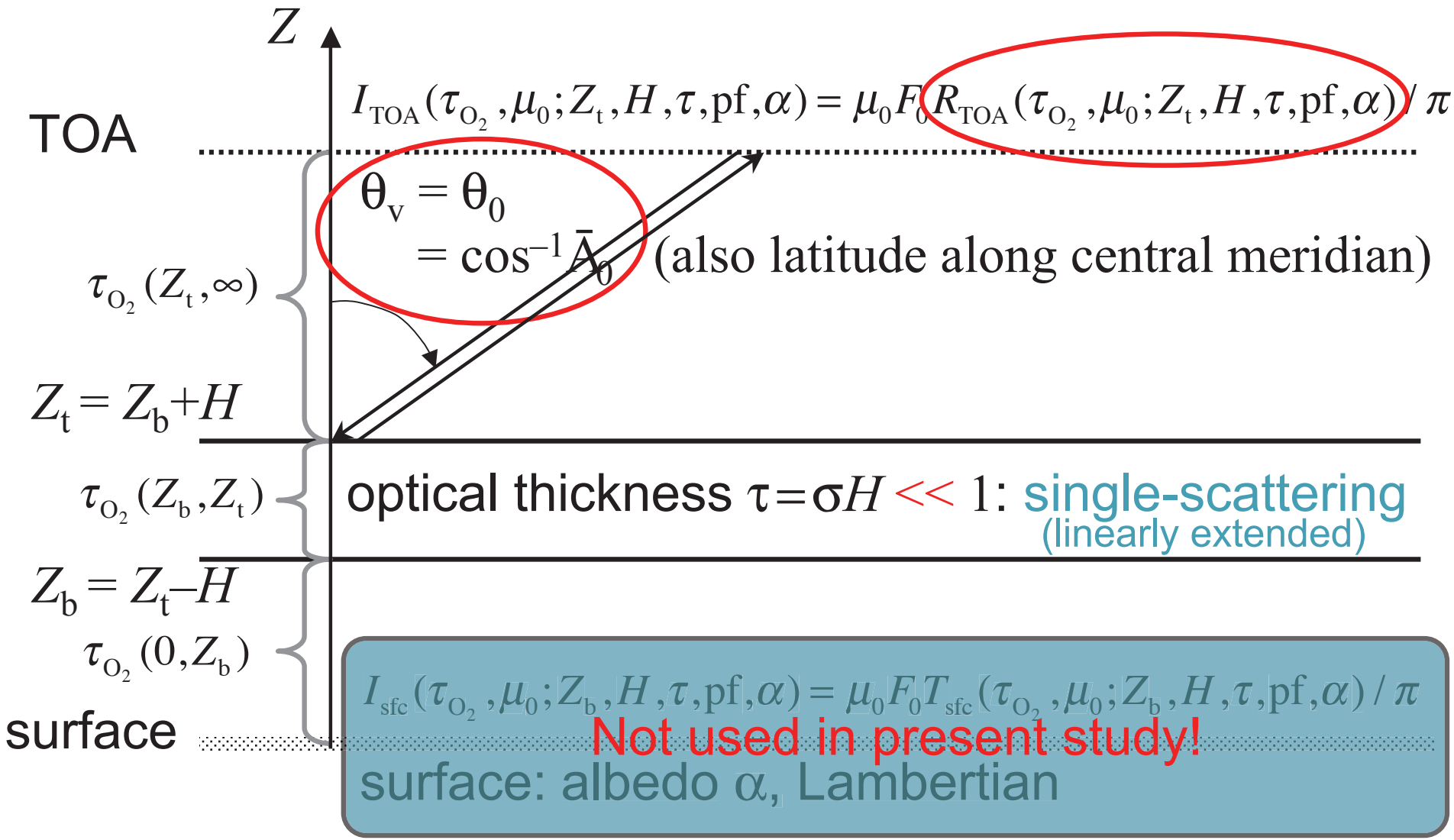
$$I_{sfc}(\tau_{O_2},\mu_0;Z_b,H,\tau,\mathrm{pf},\alpha) = \mu_0 F_0 T_{sfc}(\tau_{O_2},\mu_0;Z_b,H,\tau,\mathrm{pf},\alpha)/\pi$$

Not used in present study!

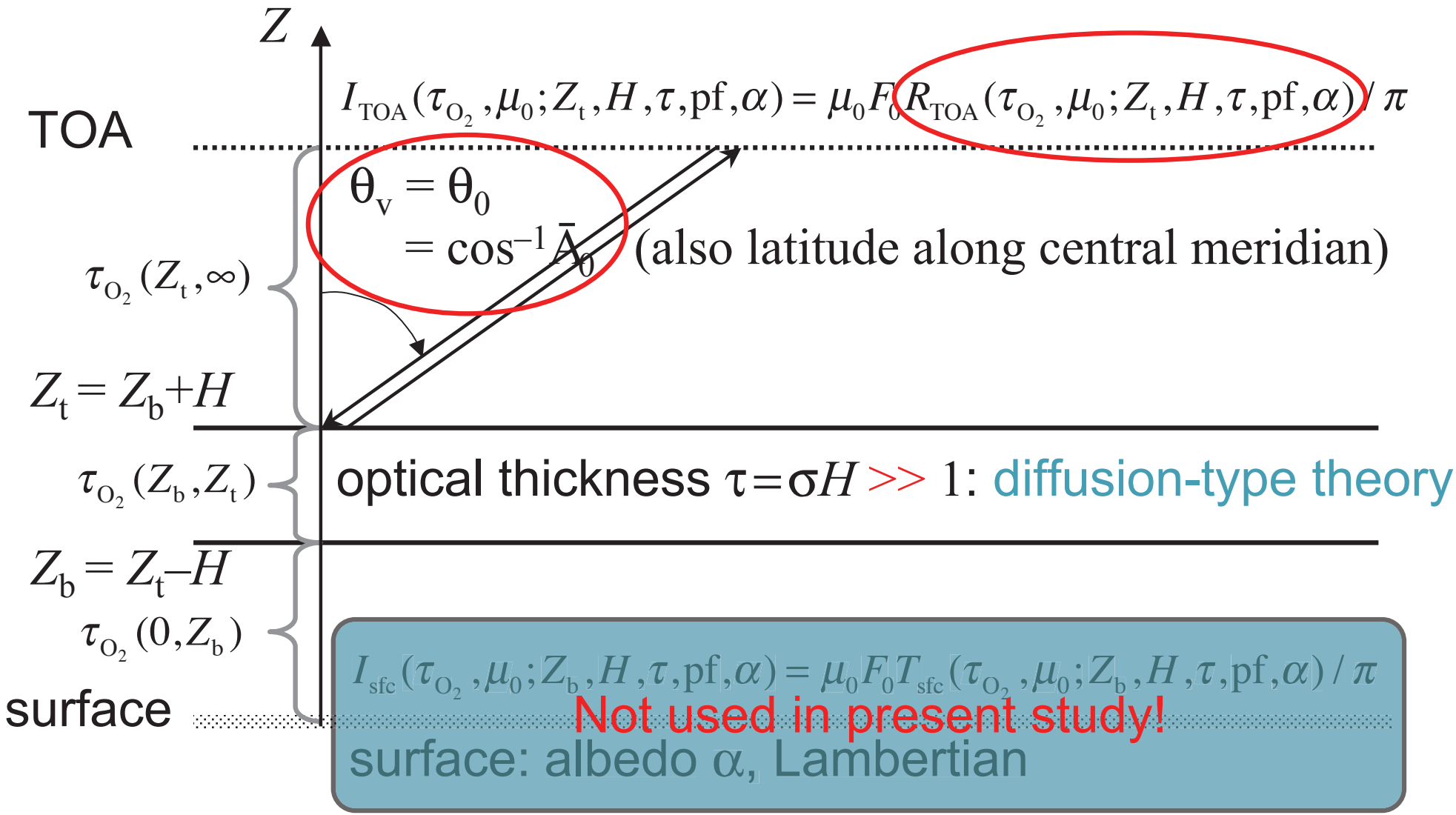
surface

surface: albedo α, Lambertian

Aerosol Case



Cloud Case


Z
TOA
$I_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)=\mu_0 F_0 R_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)/\pi$
$\theta_{\mathrm{v}}=\theta_0$
$=\cos^{-1}\bar{\mu}_0$ (also latitude along central meridian)
$\tau_{\mathrm{O}_2}(Z_{\mathrm{t}},\infty)$
$Z_{\mathrm{t}}=Z_{\mathrm{b}}+H$
$\tau_{\mathrm{O}_2}(Z_{\mathrm{b}},Z_{\mathrm{t}})$
optical thickness $\tau=\sigma H$ >> 1: diffusion-type theory
$Z_{\mathrm{b}}=Z_{\mathrm{t}}-H$
$\tau_{\mathrm{O}_2}(0,Z_{\mathrm{b}})$
$I_{\mathrm{sfc}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{b}},H,\tau,\mathrm{pf},\alpha)=\mu_0 F_0 T_{\mathrm{sfc}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{b}},H,\tau,\mathrm{pf},\alpha)/\pi$
surface
Not used in present study!
surface: albedo α, Lambertian

Forward model (space-based platform):

$$I_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)=\mu_0 F_0 R_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)/\pi$$

$$R_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)=\mathrm{e}^{-\tau_{\mathrm{O}_2}(Z_{\mathrm{t}},\infty)\left(\frac{1}{\mu_0}+\frac{1}{|\mu|}\right)}R_{\mathrm{t}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)$$

where $|\mu|=1$ and $\tau_{\mathrm{O}_2}(Z_{\mathrm{t}},\infty)=\tau_{\mathrm{O}_2}\times\left(P_{\mathrm{t}}/P_0\right)$

$$R_{\mathrm{t}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)=R_{\mathrm{col}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf})$$

$$+\left(T_{\mathrm{col}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf})T_{\mathrm{O}_2}(0,Z_{\mathrm{t}}-H)+\mathrm{e}^{-\frac{\tau+\tau_{\mathrm{O}_2}(0,Z_{\mathrm{t}})}{\mu_0}}\right)$$

$$\times\left(\frac{\alpha T_{\mathrm{O}_2}(0,Z_{\mathrm{t}}-H)T_{\mathrm{dif}}(\tau_{\mathrm{O}_2};Z_{\mathrm{b}},H,\tau,\mathrm{pf})}{1-\alpha T_{\mathrm{O}_2}(0,Z_{\mathrm{t}}-H)^2 R_{\mathrm{dif}}(\tau_{\mathrm{O}_2};Z_{\mathrm{b}},H,\tau,\mathrm{pf})}\right)$$

Not used in present study!

where $T_{\mathrm{O}_2}(0,Z_{\mathrm{t}}-H)=2\int_0^1 \mathrm{e}^{-\tau_{\mathrm{O}_2}(0,Z_{\mathrm{t}}-H)/\mu}\mu\,\mathrm{d}\mu=\mathrm{e}^{-x}\left(1-x-\mathrm{e}^{x}x^2 Ei(-x)\right)\Big|_{x=\tau_{\mathrm{O}_2}(0,Z_{\mathrm{t}}-H)}$

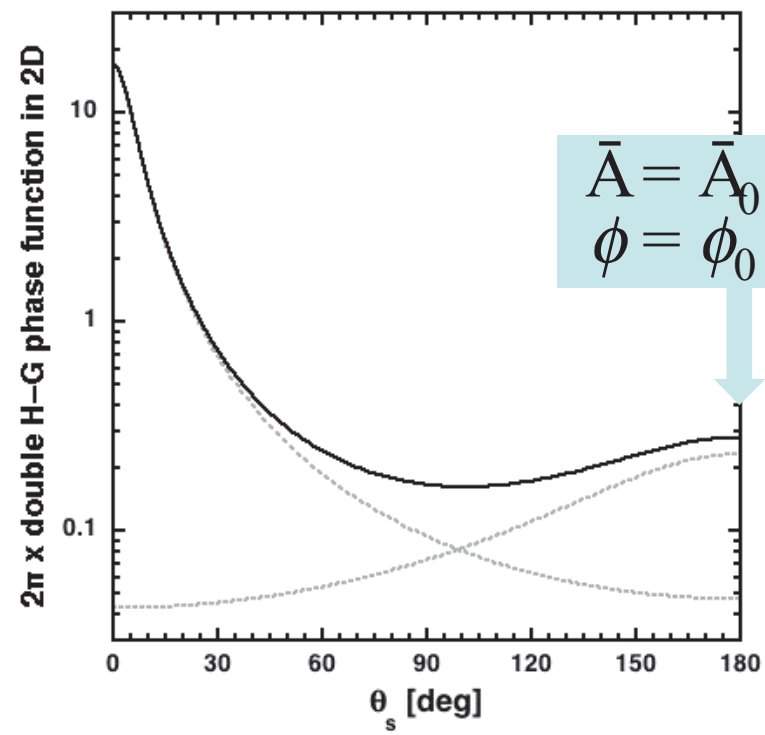
Typical Aerosol Phase Function

phase function (double Henyey-Greenstein) :

$$p(\mu_s; f_1, g_1, g_2) = \frac{1}{4\pi}\left(f_1 \frac{1-g_1^2}{\left(1+g_1^2-2g_1\mu_s\right)^{3/2}} + \left(1-f_1\right)\frac{1-g_2^2}{\left(1+g_2^2-2g_2\mu_s\right)^{3/2}} \right)$$

$$p(-1; f_1, g_1, g_2) = \frac{1}{4\pi}\left(f_1 \frac{1-g_1}{\left(1+g_1\right)^2} + \left(1-f_1\right)\frac{1-g_2}{\left(1+g_2\right)^2} \right)$$

$$\{f_1, g_1, g_2\} = \{0.8, +0.7, -0.4\}$$



Henyey, L. C., and J. L. Greenstein, 1941: Diffuse radiation in the galaxy. *Astrophys. J.*, **93**, 70-83.

White, R. L., 1979: Polarization in reflection nebulae. I - Scattering properties of interstellar grains. *Astrophys. J.*, **229**, 954-961.

Single scattering theory (reflection)

phase function (double Henyey-Greenstein) :

$$p(-1; f_1, g_1, g_2) = \frac{1}{4\pi}\left(f_1 \frac{1-g_1}{(1+g_1)^2} + (1-f_1)\frac{1-g_2}{(1+g_2)^2} \right)$$

since $\mu_0 = |\mu|$ and $\phi = \phi_0$, hence $\mu_s(\mu_0, |\mu|, \phi - \phi_0) = -1$

$$R_{\mathrm{col}}(\tau_{\mathrm{O}_2}, \mu_0; Z_{\mathrm{b}}, H, \tau, \mathrm{pf}) = \pi \varpi_0(\tau_{\mathrm{O}_2}; Z_{\mathrm{b}}, H, \tau) p(\mu_s; f_1, g_1, g_2) \frac{1 - \mathrm{e}^{-\tau\left(\frac{1}{\mu_0} + \frac{1}{|\mu|}\right)}}{\mu_0 + |\mu|}$$

$$\approx \pi \varpi_0(\tau_{\mathrm{O}_2}; Z_{\mathrm{b}}, H, \tau) p(\mu_s; f_1, g_1, g_2) \tau / \mu_0 |\mu| \text{ (works better!)}$$

where $\varpi_0(\tau_{\mathrm{O}_2}; Z_{\mathrm{t}}, H, \tau) = \dfrac{\tau}{\tau + \tau_{\mathrm{O}_2}^{(\mathrm{a})}}$, $\tau_{\mathrm{O}_2}^{(\mathrm{a})} = \tau_{\mathrm{O}_2}(Z_{\mathrm{t}} - H, Z_{\mathrm{t}})$

$T_{\mathrm{col}}(\tau_{\mathrm{O}_2}, \mu_0; Z_{\mathrm{t}}, H, \tau, \mathrm{pf}) = \ldots$

$R_{\mathrm{dif}}(\tau_{\mathrm{O}_2}, \chi; Z_{\mathrm{t}}, H, \tau, \mathrm{pf}) = \ldots$ — ... from diffusion-like theory, but with χ = 4/3

$T_{\mathrm{dif}}(\tau_{\mathrm{O}_2}, \chi; Z_{\mathrm{t}}, H, \tau, \mathrm{pf}) = \ldots$

Not used in present study!

Cloud/aerosol remote sensing (dark surface case)

$$I_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)=\mu_0 F_0 R_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf},\alpha)/\pi$$

becomes

$$I_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;P_{\mathrm{t}},\Delta P,\tau,\mathrm{pf},\alpha)=\mu_0 F_0 R_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;P_{\mathrm{t}},\Delta P,\tau,\mathrm{pf},\alpha)/\pi$$

where $Z_{\mathrm{t}}=H_{\mathrm{m}}\ln P_0/P_{\mathrm{t}}$ and $H\approx H_{\mathrm{m}}\Delta P/\left(P_{\mathrm{t}}+\Delta P/2\right)$ (recalling that $H_{\mathrm{m}}\approx 8$ km).

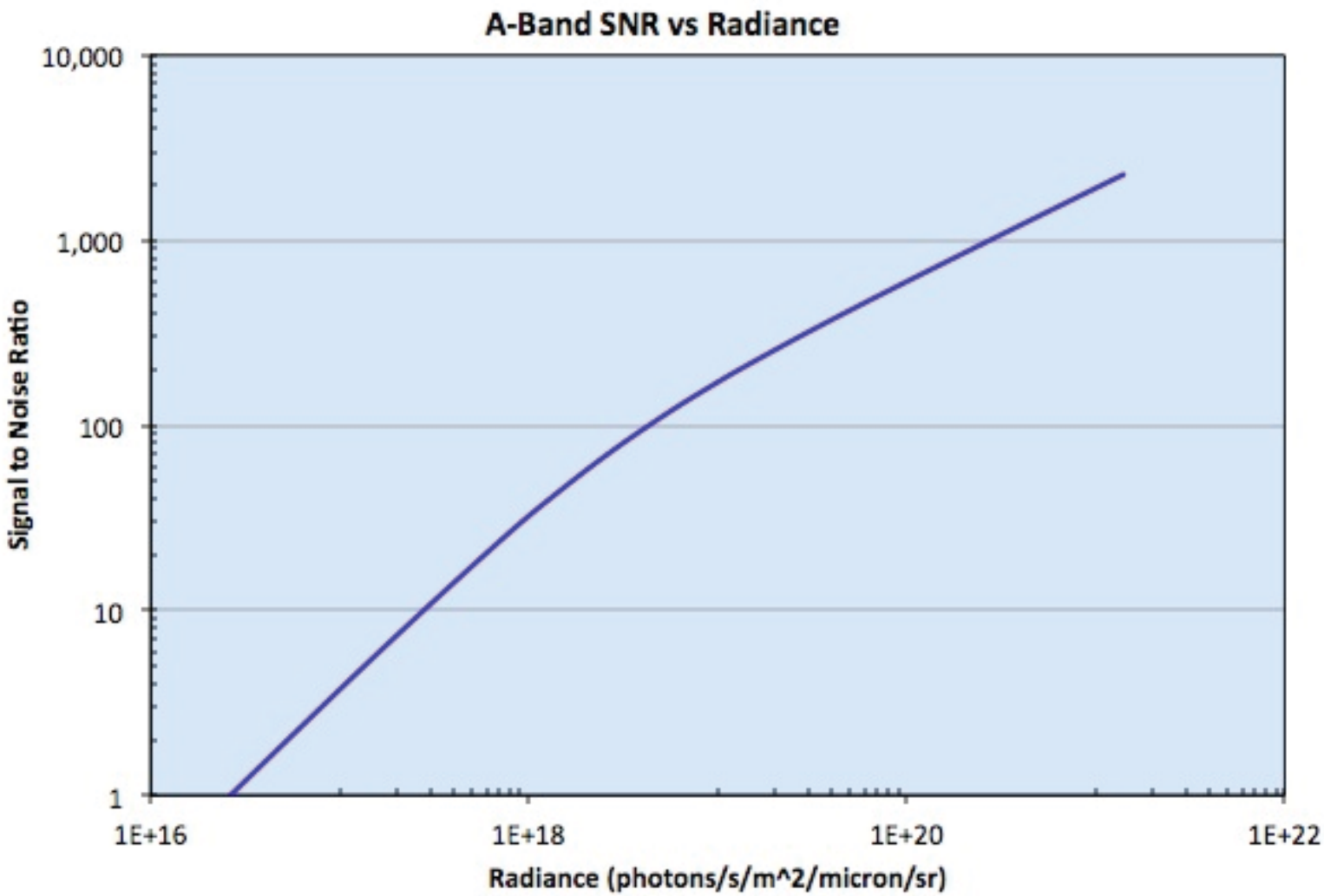
In this case,

$$R_{\mathrm{TOA}}(\tau_{\mathrm{O}_2},\mu_0;P_{\mathrm{t}},\Delta P,\tau,\mathrm{pf},0)=\mathrm{e}^{-\tau_{\mathrm{O}_2}\left(\frac{P_{\mathrm{t}}}{P_0}\right)\left(1+\frac{1}{\mu_0}\right)}R_{\mathrm{col}}\left(\tau_{\mathrm{O}_2}\left(\Delta P/\left(P_{\mathrm{t}}+\Delta P/2\right)\right),\mu_0;\tau,\mathrm{pf}\right)$$

For $R_{\mathrm{col}}(\cdots)$ with
- aerosols: a *previous* slide
- clouds: an *upcoming* slide

Typical SNR Estimation

OCO-2 [Randy Pollock, pers. comm.]



SNR ~ I (e-noise) **SNR ~ $\sqrt{I}$ (shot-noise)**

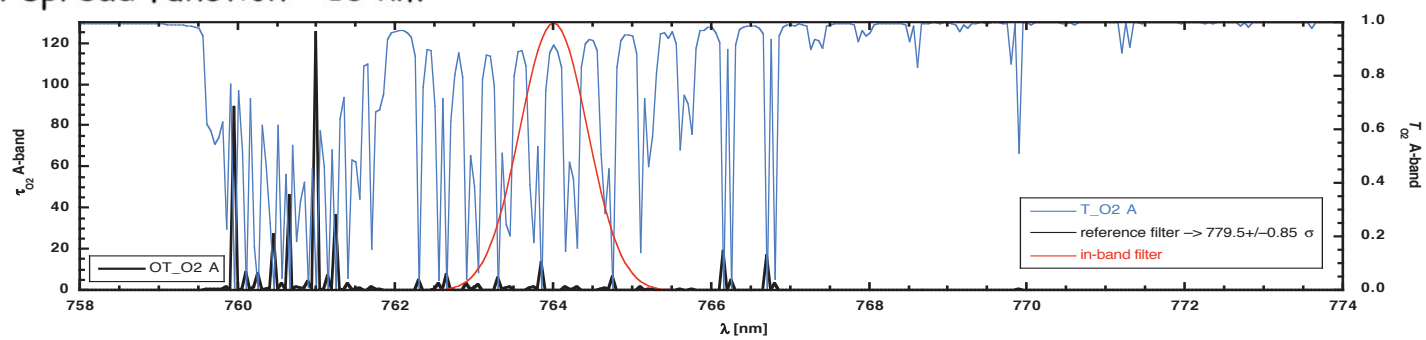
EPIC Filters

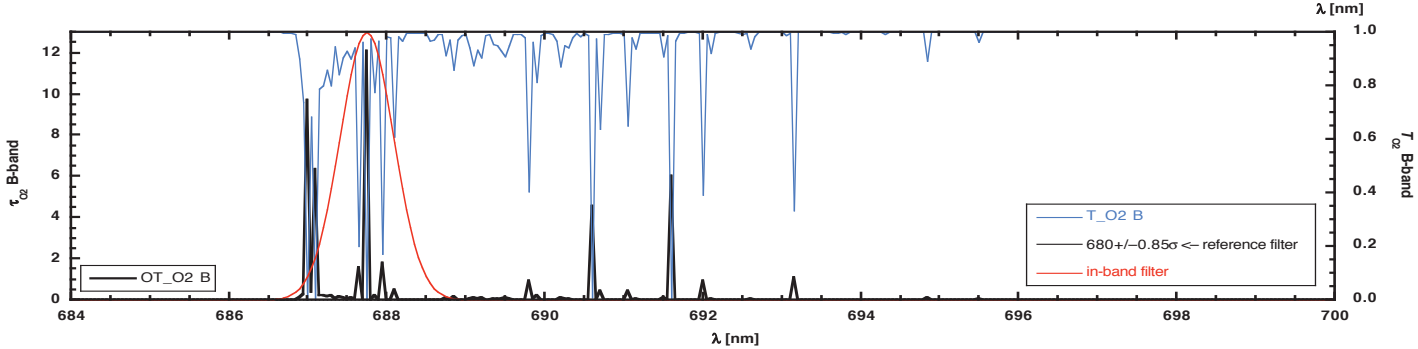
	λ (nm)	Δλ (nm) FWHM	Purpose
	317.5±0.1	1±0.2	Ozone
	325±0.1	2±0.2	Ozone
	340±0.3	3±0.6	Ozone, Aerosols, Clouds
	388±0.3	3±0.6	Aerosols, Clouds
	443±1	3±0.6	Aerosols
	551±1	3±0.6	Aerosols, Vegetation
B	680±0.2	2±0.4	Aerosol, Vegetation, Clouds, O_2 B-Band Reference
B	687.75±0.2	0.8±0.2	O_2 B-Band Cloud Height
A	764.0±0.2	1±0.2	O_2 A-Band Cloud Height, Aerosol Height
A	779.5±0.3	2±0.4	O_2 A-Band Reference, Vegetation

Estimated resolution including point spread function = 10 km

What are the *effective* O_2 optical depths?

σ_λ (nm)	0° 1	60° 1/2	70.53° 1/3	$\theta_v = \theta_0$ cosθ
0.849	0.693	0.599	0.534	$\langle T(\theta)^2\rangle_B$
0.340	0.184	0.128	0.105	$-\ln\langle\ldots\rangle_B/2$
0.425	0.465	0.328	0.250	$\langle T(\theta)^2\rangle_A$
0.849	0.383	0.279	0.231	$-\ln\langle\ldots\rangle_A/2$

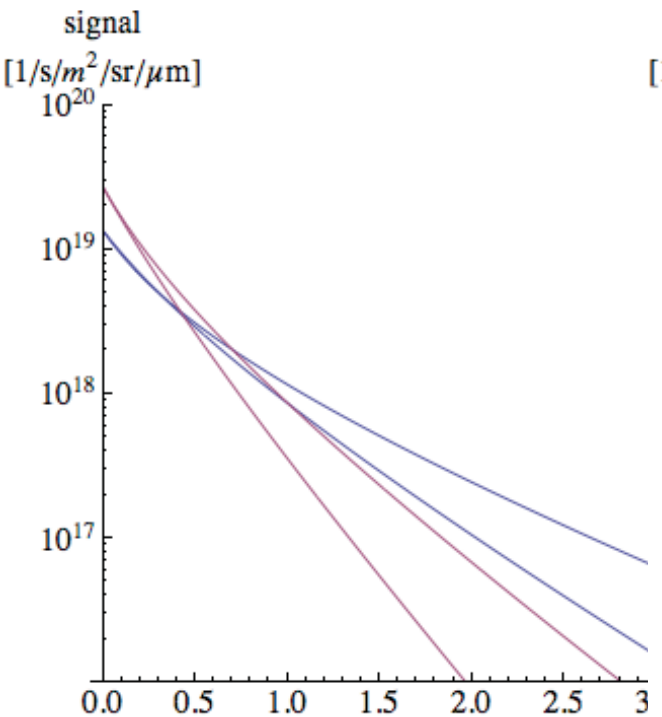




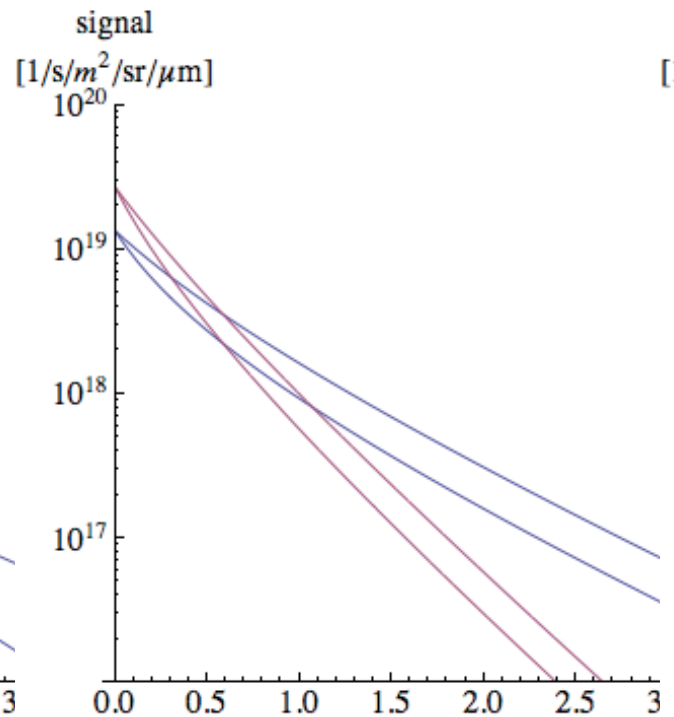
Aerosols: I_{TOA} vs τ_{O2} vs parameters

F_0 = ! 1.5 10^{21} ph/s/m^2/Ām; $\bar{A}_0$ = 1, 1/2; P_0 = 1013.25 mbar;
$\{f_1, g_1, g_2\} = \{0.8, +0.7, -0.4\}$

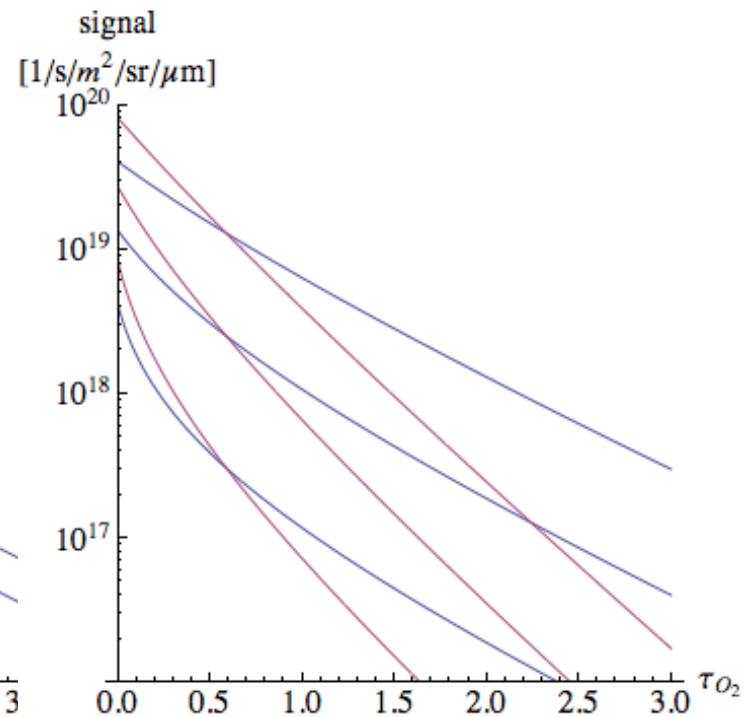
$\tau = 0.1$, $\Delta P = 200$ mbar,
$P_t = \{800, 500\}$



$\tau = 0.1$, $P_t = 700$ mbar,
$\Delta P = \{100, 300\}$



$P_t = 700$ mbar, $\Delta P = 200$ mbar,
$\tau = \{0.03, 0.1, 0.3\}$



Z_t $\{1.9, 5.7\}$ [km]
$\rightarrow H$ $\{1.8, 2.7\}$ [km]

H $\{1.1, 2.4\}$ [km]
at Z_t 3.0 [km]

at Z_t 3.0, H 2.0 [km]

N.B. Typically, no signal left for τ_{O2} > ~3.

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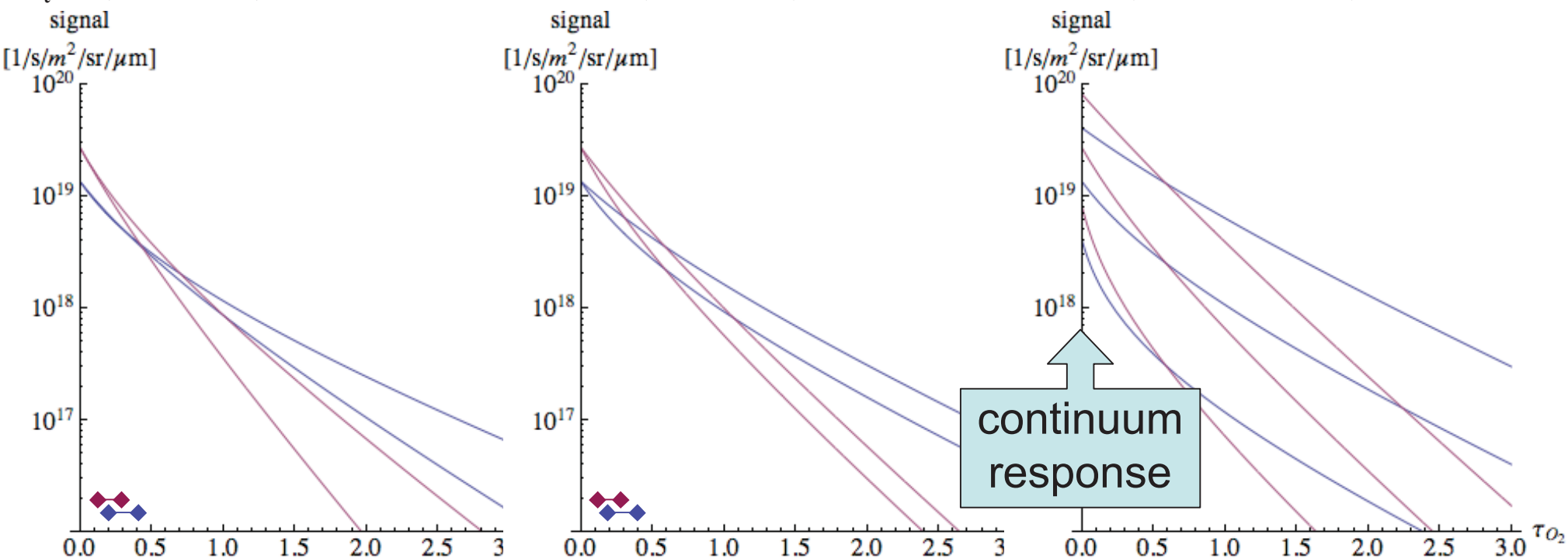
$P_t = 700$ mbar, $\Delta P = 200$ mbar, $\tau = \{0.03, 0.1, 0.3\}$



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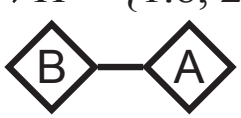

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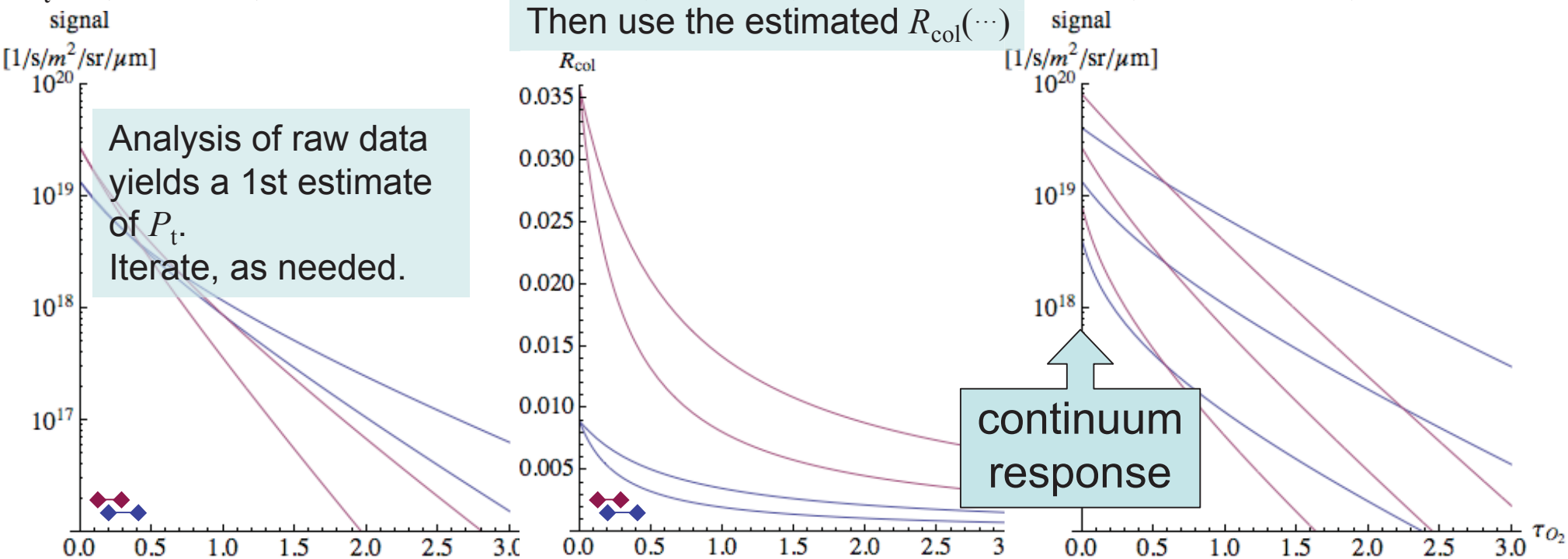
$\tau = 0.1$, $\Delta P = 200$ mbar, $P_t = \{800, 500\}$

$\tau = 0.1$, $P_t = 700$ mbar, $\Delta P = \{100, 300\}$

$P_t = 700$ mbar, $\Delta P = 200$ mbar, $\tau = \{0.03, 0.1, 0.3\}$

Then use the estimated $R_{col}(\cdots)$



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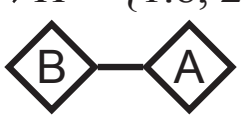


N.B. Typically, no signal left for τ_{O2} > ~3.

Diffusion / 2 stream-type theory, 1: Isotropic boundary source

Radiance reduced to :

$$I(z,\mu) \approx \frac{1}{4\pi}\left[J(z) + 3F(z)\mu\right]$$

phase function (δ-scaled Eddington model) :

$$p(\mu_s; f, g') \approx \frac{1}{4\pi}\left[f 2\delta(1-\mu_s) + (1-f)(1+3g'\mu_s)\right]$$

with $f = g^2, g' = \dfrac{g}{1+g} \approx 0.46$, with $g \approx 0.85$ and $\tau' = \tau(1-g)/(1-g') \approx 0.28\tau$

where $\mu_s(\mu,\phi \to \mu',\phi') = \mu\mu' + \sqrt{1-\mu^2}\sqrt{1-\mu'^2}\cos(\phi'-\phi)$

Define $\sigma_{tr} = \tau_{tr}/H = (1-g)\sigma$ & $\sigma_a = \tau_{O2}(Z_b,Z_t)/H$

Solve $\begin{cases} dF/dz = -\sigma_a J \\ dJ/dz = -3(\sigma_{tr}+\sigma_a)F \end{cases}$, subject to BCs: $J + 3\chi F\big|_{z=0} = 4,\ J - 3\chi F\big|_{z=H} = 0.$

$$\left.\begin{aligned} R_{dif}(\tau_{O_2},\chi;Z_t,H,\tau,\mathrm{pf}) &= J(0)/2 - 1 = \left(\tau_{O_2}^{(c)}\left(1-3\chi^2\right) + \tau_{tr}\right)\sqrt{3\tau_{O_2}^{(c)}\left(\tau_{O_2}^{(c)}+\tau_{tr}\right)} \\ T_{dif}(\tau_{O_2},\chi;Z_t,H,\tau,\mathrm{pf}) &= J(H)/2 \quad = 6\chi\tau_{O_2}^{(c)}\left(\tau_{O_2}^{(c)}+\tau_{tr}\right)/\sinh\left(\sqrt{3\tau_{O_2}^{(c)}\left(\tau_{O_2}^{(c)}+\tau_{tr}\right)}\right) \end{aligned}\right\}$$

$$\div\left[\left(\tau_{O_2}^{(c)}\left(1+3\chi^2\right)+\tau_{tr}\right)\sqrt{3\tau_{O_2}^{(c)}\left(\tau_{O_2}^{(c)}+\tau_{tr}\right)} + 6\chi\tau_{O_2}^{(c)}\left(\tau_{O_2}^{(c)}+\tau_{tr}\right)\coth\left(\sqrt{3\tau_{O_2}^{(c)}\left(\tau_{O_2}^{(c)}+\tau_{tr}\right)}\right)\right]$$

where $\tau_{O_2}^{(c)} = \tau_{O_2} \times \left(\Delta P / P_0\right)$, $\tau_{tr} = (1-g)\tau$, and $\chi = 2/3$ for clouds (4/3 for aerosols).

Diffusion / 2 stream-type theory, 2: Anisotropic (collimated) internal source, *T*

Solve $\begin{cases} \mathrm{d}F/\mathrm{d}z = -\sigma_{\mathrm{a}} J + \sigma \mathrm{e}^{-(\sigma+\sigma_{\mathrm{a}})z/\mu_0} \\ \mathrm{d}J/\mathrm{d}z = -3(\sigma_{\mathrm{tr}} + \sigma_{\mathrm{a}})F + 3\mu_0 g \sigma \mathrm{e}^{-(\sigma+\sigma_{\mathrm{a}})z/\mu_0} \end{cases}$, subject to $\boxed{J + 2F\big|_{z=0} = J - 2F\big|_{z=H} = 0}$

$$T_{\mathrm{col}}(\tau_{\mathrm{O}_2}, \mu_0; Z_{\mathrm{t}}, H, \tau, \mathrm{pf}) = J(H)/2 =$$

$$\Bigg(3\,\mu_0\,\tau\,e^{-\frac{\tau_{\mathrm{O}_2}^{(c)}+\tau}{\mu_0}}\Bigg(\Bigg(e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}-1\Bigg)\Bigg((\mu_0\,(g\,(3\,\mu_0+2)+2)+1)\,\tau_{\mathrm{O}_2}^{(c)\,2}\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}+\tau_{\mathrm{tr}}\,\tau\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\Bigg)-$$

$$\tau\,\tau_{\mathrm{O}_2}^{(c)}\Bigg(-(3\,\mu_0+2)\,\tau_{\mathrm{tr}}\Bigg(-2\,e^{\frac{\tau_{\mathrm{O}_2}^{(c)}+\tau}{\mu_0}+\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}+e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}+1\Bigg)+\left(3\,(g-1)\,g\,\mu_0^2+g-2\,\mu_0-2\right)\Bigg(e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}-1\Bigg)\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\Bigg)-$$

$$\tau\,(g\,(3\,\mu_0\,(2\,(g-1)\,\mu_0+g)+2)-6\,\mu_0-4)\,\tau_{\mathrm{O}_2}^{(c)\,2}\Bigg(-2\,e^{\frac{\tau_{\mathrm{O}_2}^{(c)}+\tau}{\mu_0}+\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}+e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}+1\Bigg)+$$

$$(3\,\mu_0\,(2\,g\,\mu_0+g+1)+2)\,\tau_{\mathrm{O}_2}^{(c)\,3}\Bigg(-2\,e^{\frac{\tau_{\mathrm{O}_2}^{(c)}+\tau}{\mu_0}+\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}+e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}+1\Bigg)\Bigg)\Bigg)\Bigg)\Big/$$

$$\Bigg(\left(\tau_{\mathrm{O}_2}^{(c)}\left(1-3\,\mu_0^2\right)+\tau\right)\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\Bigg(\Bigg(-1+e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\Bigg)\left(7\,\tau_{\mathrm{O}_2}^{(c)}+3\,\tau_{\mathrm{tr}}\right)+4\Bigg(1+e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\Bigg)\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\Bigg)\Bigg)$$

where $\tau_{\mathrm{O}_2}^{(c)} = \tau_{\mathrm{O}_2} \times \left(\Delta P / P_0\right)$ and $\tau_{\mathrm{tr}} = (1-g)\tau$.

Diffusion / 2 stream-type theory, 2: Anisotropic (collimated) internal source, *R*

$$R_{\mathrm{col}}(\tau_{\mathrm{O}_2},\mu_0;Z_{\mathrm{t}},H,\tau,\mathrm{pf}) = J(0)/2 =$$

$$\Bigg(3\,e^{-\frac{\tau_{\mathrm{O}_2}^{(c)}+\tau}{\mu_0}-\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\,\tau\,\mu_0$$

$$\Bigg(2\,e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\left(\tau_{\mathrm{tr}}+\tau_{\mathrm{O}_2}^{(c)}\right)\left((3\,\mu_0\,(-2\,\mu_0\,g+g+1)-2)\,\tau_{\mathrm{O}_2}^{(c)}+\tau\,(3\,\mu_0-2)\right)\tau_{\mathrm{O}_2}^{(c)}+$$

$$e^{\frac{\tau_{\mathrm{O}_2}^{(c)}+\tau}{\mu_0}+3\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\left(-\tau\left(\left(6\,\mu_0+g\left(-6\,(1-g)\,\mu_0^2-3\,g\,\mu_0+2\right)-4\right)\tau_{\mathrm{O}_2}^{(c)}+\left(-3\,(1-g)\,g\,\mu_0^2+2\,\mu_0+g-2\right)\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\right)\tau_{\mathrm{O}_2}^{(c)}+\right.$$

$$\left(6\,g\,\mu_0^2-3\,(g+1)\,\mu_0+2\right)\tau_{\mathrm{O}_2}^{(c)\,3}+\tau_{\mathrm{tr}}\,\tau\left((2-3\,\mu_0)\,\tau_{\mathrm{O}_2}^{(c)}+\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\right)+\left(3\,g\,\mu_0^2-2\,(g+1)\,\mu_0+1\right)\tau_{\mathrm{O}_2}^{(c)\,2}\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\Bigg)+$$

$$e^{\frac{\tau_{\mathrm{O}_2}^{(c)}+\tau}{\mu_0}+\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\left(\tau\left(\left(-6\,\mu_0+g\,(3\,\mu_0\,(-2\,\mu_0\,g+g+2\,\mu_0)-2)+4\right)\tau_{\mathrm{O}_2}^{(c)}+\left(-3\,(1-g)\,g\,\mu_0^2+2\,\mu_0+g-2\right)\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\right)\tau_{\mathrm{O}_2}^{(c)}+\right.$$

$$\left.\left.\left(6\,g\,\mu_0^2-3\,(g+1)\,\mu_0+2\right)\tau_{\mathrm{O}_2}^{(c)\,3}-\tau_{\mathrm{tr}}\,\tau\left((3\,\mu_0-2)\,\tau_{\mathrm{O}_2}^{(c)}+\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\right)+\left(\mu_0\,(-3\,\mu_0\,g+2\,g+2)-1\right)\tau_{\mathrm{O}_2}^{(c)\,2}\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\right)\right)\Bigg)\Bigg/$$

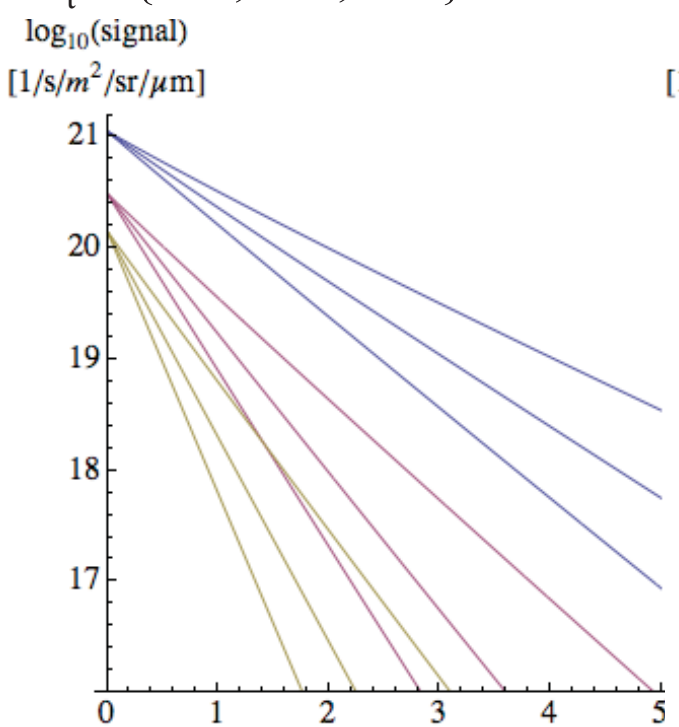
$$\left(\left(\tau_{\mathrm{O}_2}^{(c)}\left(1-3\,\mu_0^{\,2}\right)+\tau\right)\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\left(\left(-1+e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\right)\left(7\,\tau_{\mathrm{O}_2}^{(c)}+3\,\tau_{\mathrm{tr}}\right)+4\left(1+e^{2\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}}\right)\sqrt{3\,\tau_{\mathrm{O}_2}^{(c)}\left(\tau_{\mathrm{O}_2}^{(c)}+\tau_{\mathrm{tr}}\right)}\right)\right)$$

where $\tau_{\mathrm{O}_2}^{(c)} = \tau_{\mathrm{O}_2} \times \left(\Delta P / P_0\right)$ and $\tau_{\mathrm{tr}} = (1-g)\tau$.

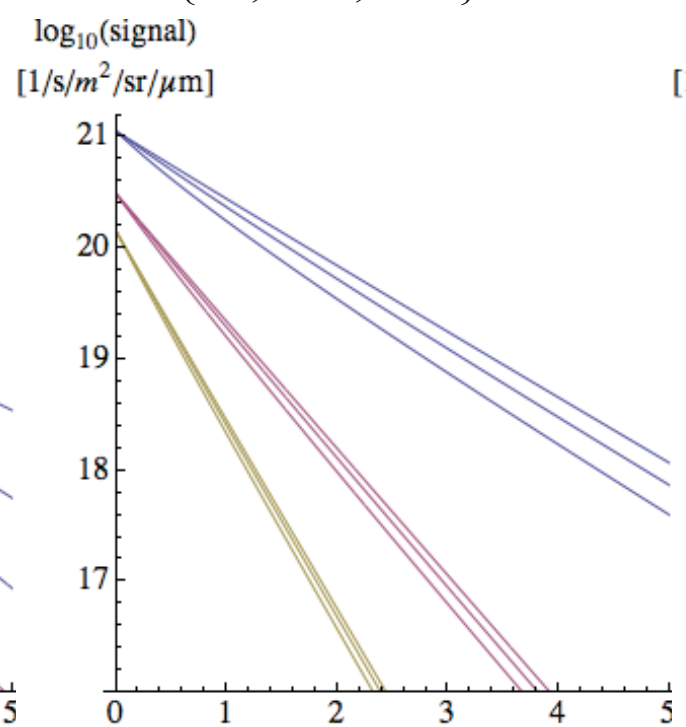
Clouds: I_{TOA} vs τ_{O2} vs parameters

F_0 = ! 1.5 10^{21} ph/s/m^2/Ām; $\bar{A}_0$ = 1, 1/2, 1/3; P_0 = 1013.25 mbar;
g = 0.85, hence g' = 0.46

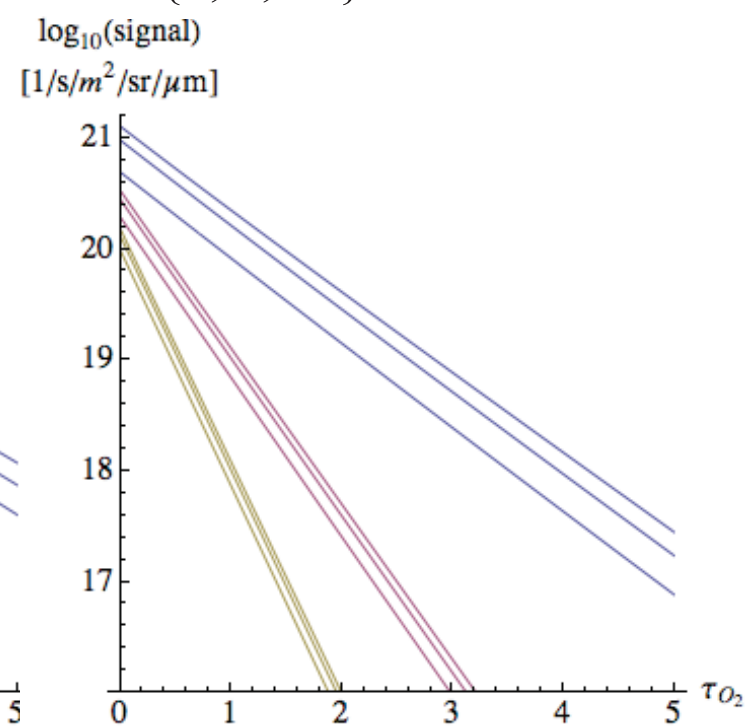
τ' = 10, ΔP = 100 mbar,
P_t = {900, 700, 500}



τ' = 10, P_t = 650 mbar,
ΔP = {50, 150, 450}



P_t = 800 mbar, ΔP = 100 mbar,
τ' = {2, 6, 18}



Z_t {0.95, 3.0, 5.7} [km]
$\rightarrow H$ {0.84, 1.1, 1.5} [km]

H {0.6, 1.6, *4.1*} [km]
at Z_t 3.6 [km]

$\tau \approx$ {7, 21, 64}
at Z_t 1.9, H 0.95 [km]

N.B. Typically, no signal left for τ_{O2} > ~5.

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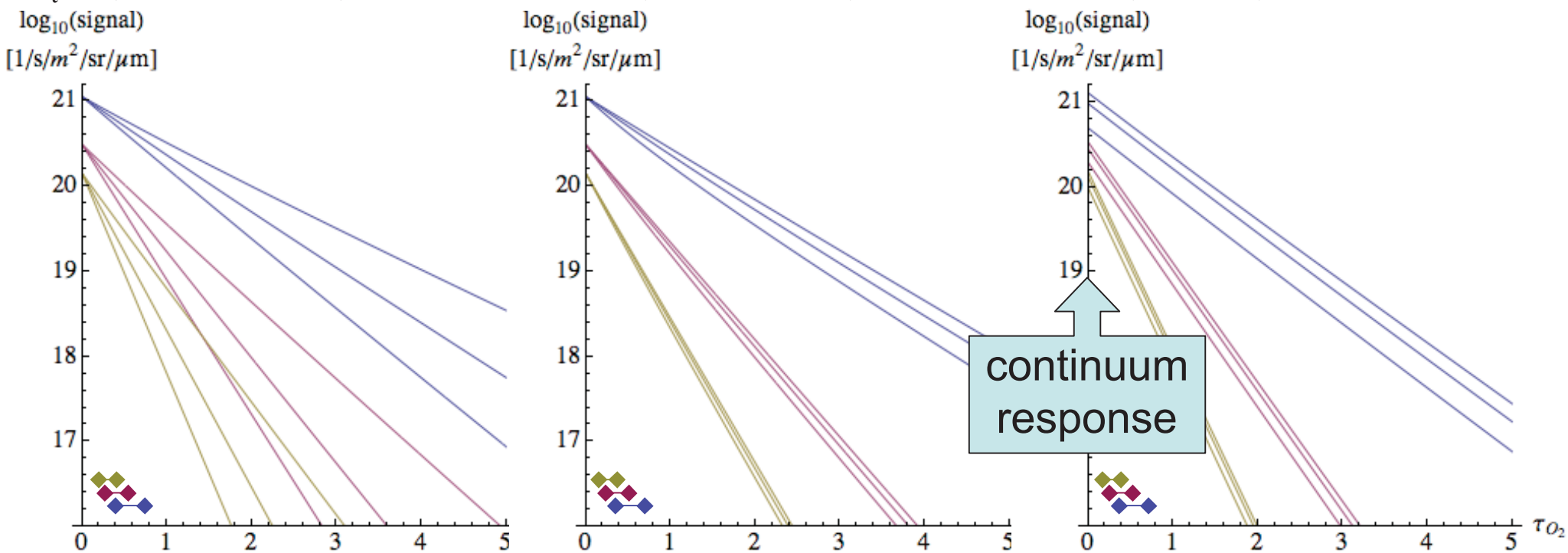
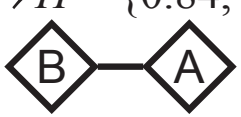


Z_t {0.95, 3.0, 5.7} [km]
$\rightarrow H$ {0.84, 1.1, 1.5} [km]

H {0.6, 1.6, *4.1*} [km]
at Z_t 3.6 [km]

$\tau \approx$ {7, 21, 63}
at Z_t 1.9, H 0.95 [km]



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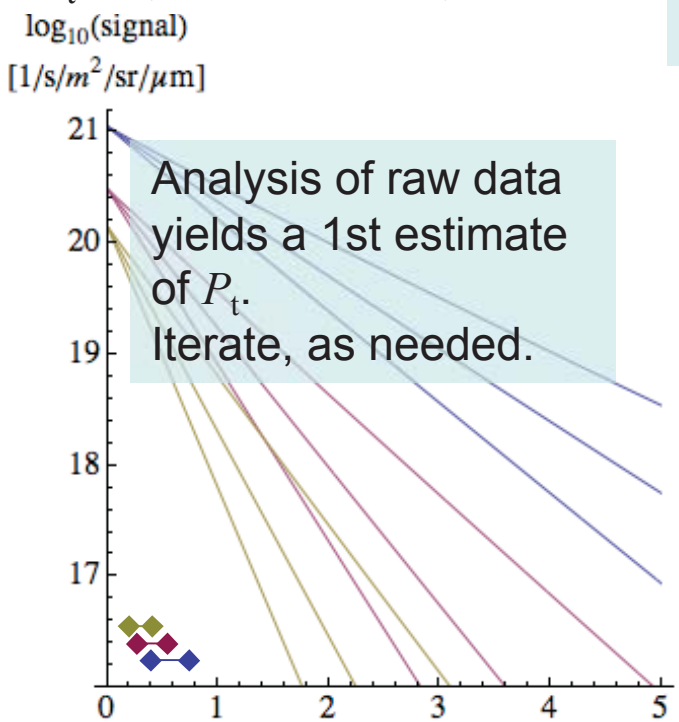
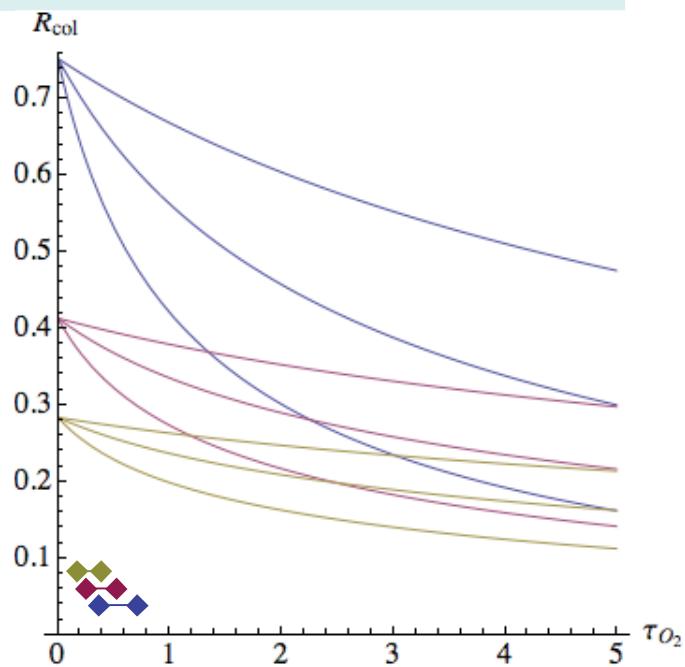
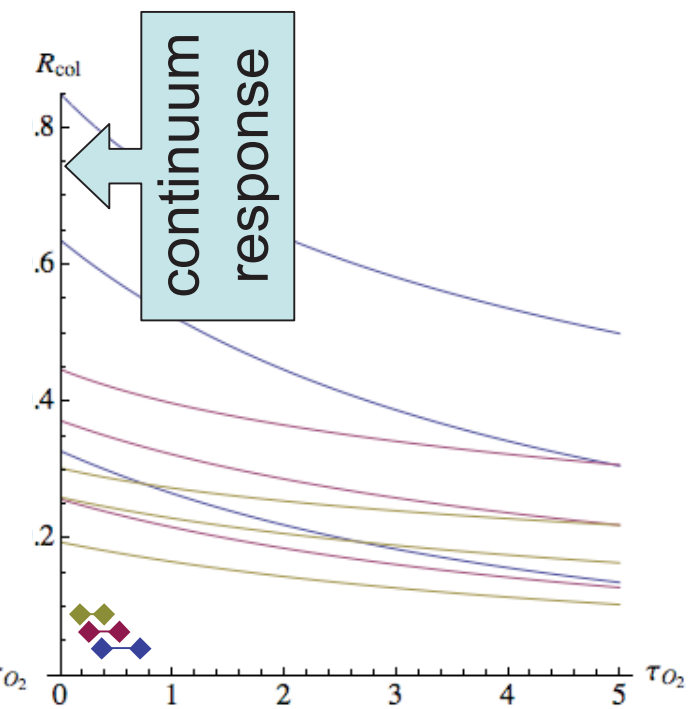
Then use the estimated $R_{col}(\cdots)$







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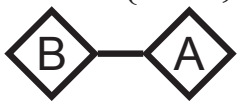

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Conclusions

- EPIC's (A+B)-band suite offers promising results for coarse (parameterized) profiling of clouds & aerosols
- Simplified 1D RT good for:
  - Tutorial purposes
  - Dissecting signal (physics-based information content analysis)
  - 1st guess for inversion scheme based on more rigorous 1D RT

Next …

- Incorporate SNR (*vertical* error bars)
- Implement nonlinear averaging for $\Delta\lambda$ effects of $\tau_{O2}(\lambda)$
- Study reflective surface cases, especially for aerosols
- Study partial cloudiness cases (linear a/c mixtures)
- Correct for time-domain 3D RT effects on sunlight paths

… coming in 2013: NASA will launch the Orbiting Carbon Observatory “reflight” (OCO-2), which will have imaging (pixels Ā2 km) A-band spectroscopy at very high resolution.

Recommendations

- **Leverage OCO-2’s A-band**
- **Polarization? May help:**
  - **Tropospheric ozone?**
  - **Aerosol case**
  - **Partial cloudiness**
- **Golden opportunity for applied 3D RT:**
  - **Ānadir … subpixel-scale effects (stochastic RT models)**
  - **Ālimb … pixel adjacency effects (multi-pixel retrievals?)**

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Thank you! ***Questions?***

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