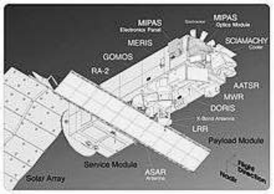
Jet Propulsion Laboratory
California Institute of Technology

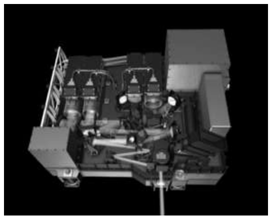
EPIC/DSCOVR as Pathfinder in Differential Oxygen Absorption Spectroscopy (DOAS) … from Space

Anthony B. Davis (JPL, Aerosol & Cloud Group)
Quentin Libois (CNRM, Météo-France, CNRS, U. de Toulouse, France)
Nicolas Ferlay (Laboratoire d'Optique Atmosphérique, Villeneuve d'Ascq, France)
Yuekui Yang and *Alexander Marshak* (NASA – GSFC)

DSCOVR Science Team Meeting, NASA – GSFC, Greenbelt, Md, Sept 28–30, 2021

DOAS from space: A brief history





Moderate spectral resolution, very low spatial resolution:

Global Ozone Monitoring Experiment (GOME) / ERS-2, 1995-2011

SCIAMACHY / Envisat, 2002-2012

GOME-2 / MetOp-A/-B/-C, launches 2006/2012/2018

Bi-spectral, multi-angle, low spatial resolution:

POLDER / ADEOS I, 1996-1997

POLDER-2 / ADEOS II, 2002-2003

POLDER-3 / PARASOL, 2004-2013

Bi-spectral (A- & B-bands), low spatial resolution:

EPIC / DSCOVR, launched 2015 (to Lagrange-1)

High spectral resolution, moderate spatial resolution:

OCO-2, launched 2014

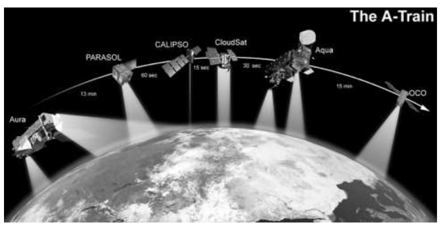
OCO-3 / ISS, launched 2019

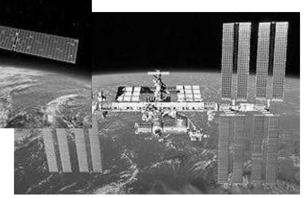
Future missions:

OCI+SPEC / PACE (*low spectral / moderate spatial resolutions*)

MAIA (*bi-spectral, multi-angle, moderate spatial resolution*)

AOS-polar spectrometer (*low spectral / moderate spatial resolutions*)





Journal of Quantitative Spectroscopy & Radiative Transfer 122 (2013) 141–149

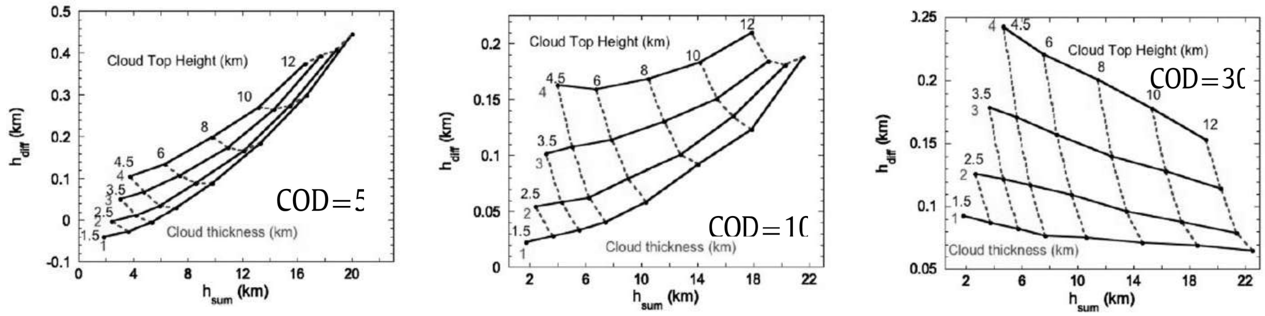
Contents lists available at SciVerse ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

A method of retrieving cloud top height and cloud geometrical thickness with oxygen A and B bands for the Deep Space Climate Observatory (DSCOVR) mission: Radiative transfer simulations

Yuekui Yang[a,b,*], Alexander Marshak[b], Jianping Mao[b,c], Alexei Lyapustin[b], Jay Herman[b,d]



- ✔ Axes are O_2 A- and B-band DOAS observations, recast as apparent cloud top heights
- ✔ Nakajima–King-type algorithm: 2 observations □ 2 cloud parameters
- ✔ Good “orthogonality” of constant parameter curves □ joint retrieval is feasible

- No account of observation error: Is h_{dif} obtainable at 0.05 to 0.10 km accuracy?
- Dark (water-like) surface

Journal of Quantitative Spectroscopy & Radiative Transfer 216 (2018) 6–16

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Cloud information content in EPIC/DSCOVR's oxygen A- and B-band channels: An optimal estimation approach

Anthony B. Davis[a,*], Guillaume Merlin[b], Céline Cornet[b], Laurent C. Labonnote[b], Jérôme Riédi[b], Nicolas Ferlay[b], Philippe Dubuisson[b], Qilong Min[c], Yuekui Yang[d], Alexander Marshak[d]

errors

sensor □

model □

not shown here: $\mathbf{S_y} = \mathbf{S_\varepsilon} + \mathbf{S_b}$

Bayes' theorem:

PDF of total cost function =

observations □

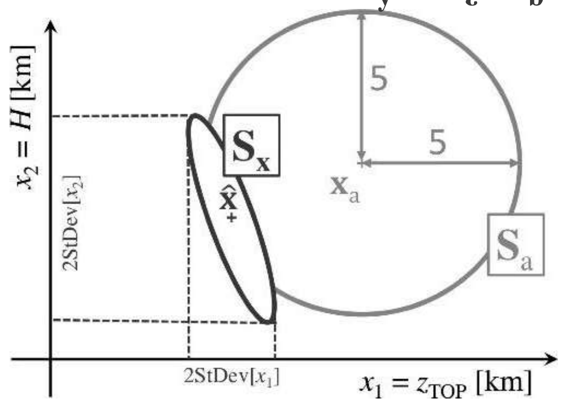
PDF of forward model prediction error on **y**

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

likelihood of y, given **x** — *prior* uncertainty on **x**

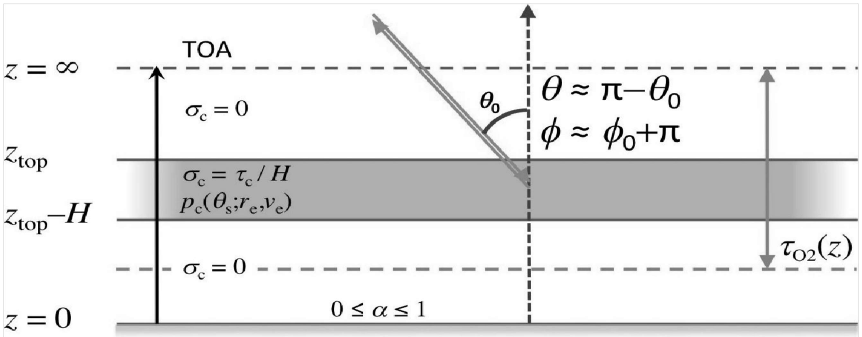
$$p(\mathbf{x}|\mathbf{y}) = p(\mathbf{y}|\mathbf{x})\, p(\mathbf{x}) / p(\mathbf{y})$$

posterior uncertainty on **x**, given **y** — unimportant



Shannon information content / gain

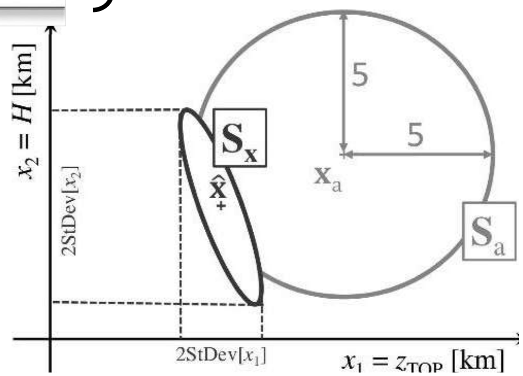
Information Content (IC) gain or Degrees-Of-Freedom (DOF) per cloud property = ratio of the areas of S_a and $S_{\mathbf{x}}$, projected onto one of the state/**x**-space axes



$\mathbf{x} = (z_{top}, H)$

$\mathbf{y} = (I_{abs,\lambda}/I_{ref,\lambda},$
λ = A-,B-bands)

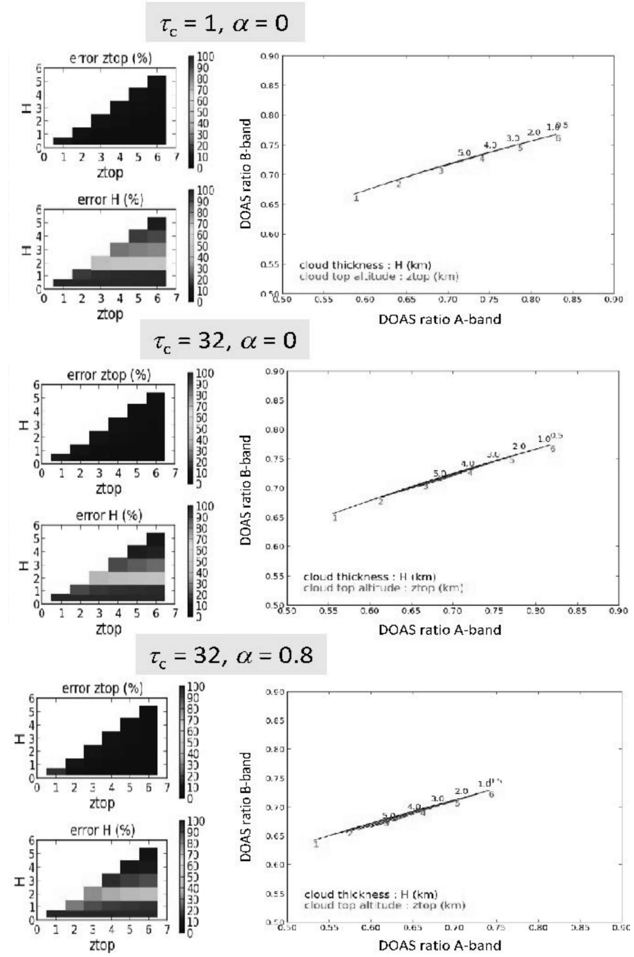
Total information content/gain = Ratios of ellipses areas |**S**|, i.e., of products of minor and major axes of the prior-to-posterior PDFs



Posterior uncertainty of the retrieved cloud properties

Errors expressed in %: 100 σ_i/x_i

“Nakajima-King” plots of DOAS ratios on (z_{top},H) look-up table (LUT)



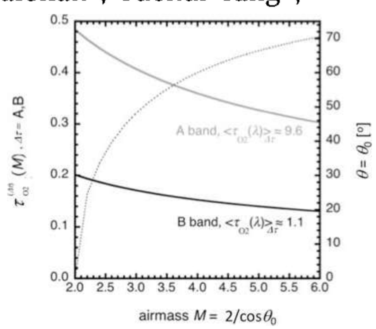
Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Cloud information content in EPIC/DSCOVR's oxygen A- and B-band channels: A physics-based approach

Anthony B. Davis[a,*], Nicolas Ferlay[b], Quentin Libois[c], Alexander Marshak[d], Yuekui Yang[d], Qilong Min[e]



use $\tau_{O_2}^{(\Delta\lambda)}(M)$ here

$$-\log r_\lambda(\mathbf{\Omega};\mathbf{\Omega}_0,\tau_c) \approx (1/\mu_0 + 1/\mu)\tau_{O_2}(\lambda; z_{top}) + (\mu+\mu_0)\left[\tau_{O_2}(\lambda;z)\right]_{z_{top}-H}^{z_{top}} \times (1 + C(\tau_c, g, \mu_0))$$

DOAS ratio

… and here

a pre-asymptotic correction term

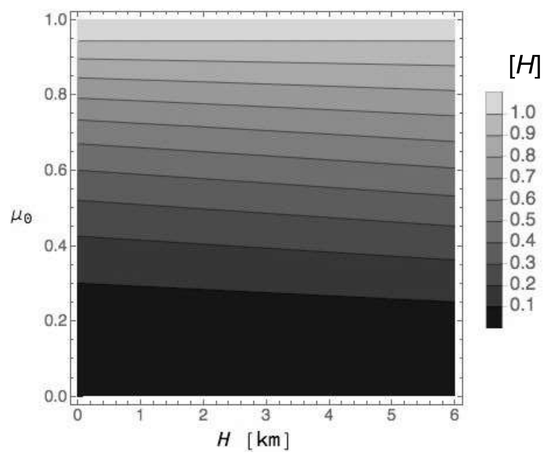
Gain physical insights …

e.g., retrieval bias from ignoring in-cloud path length

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

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

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.



Gain *more* physical insights …

5.2. A remarkable invariance property of mean path length

Before closing, we take note of a very interesting development in the optics of purely scattering media that relates directly to our present work with clouds and di-oxygen absorption, to diffuse optical tomography [29] in biomedical imaging [30], and to many other applications. Using thermodynamical and weak light absorption arguments Blanco and Fournier [31] showed theoretically that, in our notations,

$$\langle ct \rangle_F^{(\mathrm{all})} = 4V/S, \tag{24}$$

where:

- the superscript "(all)" means isotropic (Lambertian) illumination of the whole surface of the arbitrarily-shaped medium M, and we recall that the subscript "*F*" means integration over all escape angles to obtain hemispherical flux, in this case, perpendicular to the local outgoing normal, and averaging covers the whole boundary ∂M of the medium;
- V is the volume of M;
- S is the surface of M.

[31] Blanco S, Fournier R. An invariance property of diffusive random walks. EPL (Europhys Lett) 2003;61:168. doi:10.1209/epl/i2003-00208-x.

Surprisingly, the result does not depend on the details of the scattering phase function, nor on the opacity of the medium: it can be void of scatterers (i.e., the uniform extinction coefficient σ vanishes, hence only ballistic trajectories occur); or it can be very opaque ($\sigma V/S \gg 1$); or anything in between. This mean path invariance property was extended by Pierrat et al. to multiple scattering theory using both physical optics and time-dependent 3D radiative transfer [32]. Recently, Savo et al. [33] demonstrated its experimental validity in the laboratory.

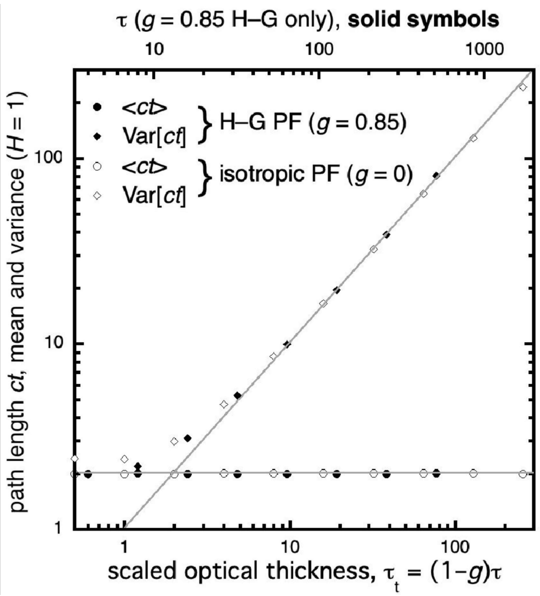
In our present study, we use plane-parallel media that can be viewed, e.g., as rectangular parallelepipeds of height H and square horizontal section of side $L \gg H$. We then have $V = HL^2$ and $S = 2L^2 + 4HL$, hence $4V/S = 2H/(1 + 2H/L)$ and $\lim_{L\to\infty} 4V/S = 2H$ is the corresponding prediction for

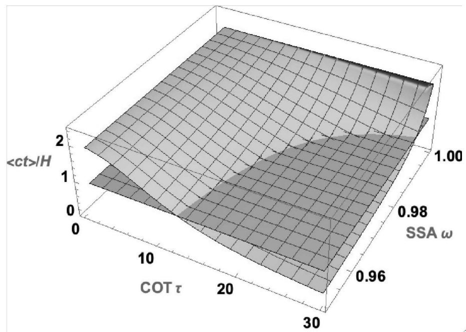
$$\langle ct \rangle_F^{(\mathrm{all})} = R\langle ct \rangle_R + T\langle ct \rangle_T, \tag{25}$$

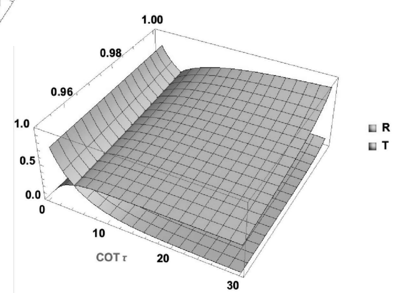
Gain *more* physical insights …

Coming soon to a journal near you:

- a new proof of <*ct*> = 4*V/S* in arbitrary geometry
- what about higher order moments?
- what about partially absorbing scatterers?







Summary

- EPIC has broken new ground in DOAS
  - extreme range at Langrange-1
  - combination of A- and B-band sensitivities
  - new applications to dust
    - Xu X, Wang J, Wang Y, Zeng J, Torres O, Yang Y, Marshak A, Reid J, Miller S. Passive remote sensing of altitude and optical depth of dust plumes using the oxygen A and B bands: First results from EPIC/DSCOVR at Lagrange-1 point. *Geophysical Research Letters.* **44**, 7544-7554 (2017).
- EPIC has inspired new algorithm development
  - pairing statistical and physical approaches
  - higher pathlength moments □ COT from DOAS