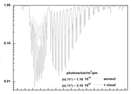
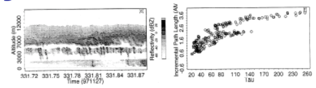
Oxygen A-Band Spectroscopy as a Remote Sensing Capability for Clouds

… from Both Sides!



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ARM Atmospheric Radiation Measurement

SUMMARY

Differential Optical Absorption Spectroscopy (DOAS) of oxygen in its "A" band (~760 nm) has been demonstrated theoretically and observationally (e.g., IOPs at the SGP ARM facility) as an sensitive diagnostic of spatial complexity in cloudiness. "Complexity" captures here any mix of multiple and/or horizontally broken layers, the essence of large-scale cloud "3D-ness." This makes O_2-DOAS a powerful diagnostic of cloud-radiation interactions in the solar spectrum for the most challenging scenarios, e.g., for GCM shortwave radiation schemes. This has lead ARM to invest in the development of fieldable high-resolution A-band instruments, though both Science Team and SBIR efforts.

Overlooked in this development is the opportunity for O_2-DOAS to become a new modality in cloud property remote sensing, either stand-alone or in synergy with other cloud probing sensors.

The basic radiative transfer physics for the cloud 3D-ness detection and remote sensing is the same. O_2-DOAS is used to infer low-order moments of the integrated paths that sunlight takes between its source and its detection, either above or below the cloud. The length of this path is random, with a distribution determined primarily by the number of scatterings suffered in the clouds.

For a single unbroken deck, reasonably well approximated by a plane-parallel slab, low-order moments of solar photon path length are known quantities. In diffusion regimes (cloud optical thickness > ~10), we have analytical functions of cloud thickness and optical depth. The present author has recently added to these expressions the effects of

- solar zenith angle, with delta-Eddington scaling [here, and Davis et al., 2009],
- an overall internal gradient in cloud opacity [Davis, 2008, Davis et al., 2009],
- small-scale random fluctuations of droplet concentration [ibid.], and
- gross deviations from slab geometry [unpublished work, cylinders and spheres].

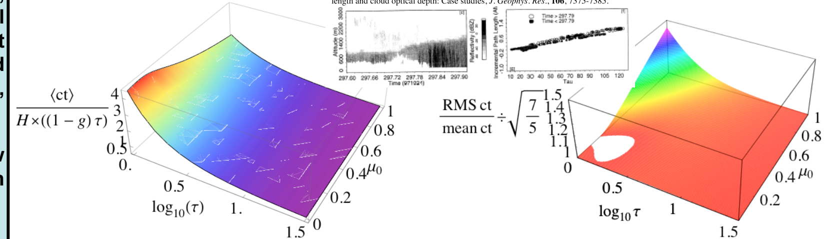
We demonstrate that, for ground-based O_2-DOAS, one can confidently infer cloud thickness knowing its optical depth, or vice-versa. Therefore, when ARM acquires continuously operating A-band instruments, they will (1) enable stringent testing of GCM shortwave schemes vis-à-vis the cloud complexity problem, and (2) add robustness to its cloud profiling (ARSCL/micro-ARSCL) and optical depth products.

In contrast, from above, using diffusely reflected rather than transmitted light, stand-alone cloud property remote sensing is a possibility since various path-length moments bring new pieces of information. We are therefore excited about the 2013 reflight of NASA's Orbiting Carbon Observatory (OCO), which has its own reasons for having hi-res O_2-DOAS capability. It could be a potent cloud probe as well as an exquisite CO_2 monitor.

Photon pathlength statistics, such as moments, are the first-level products of O_2-DOAS. Let $\langle (ct)^q \rangle_F$ be the q^{th}-order moment of pathlength in **transmission** ($F = T$) or **reflection** ($F = R$) from a single stratiform cloud layer. Cloud optical depth is τ, and its thickness H.

Transmitted sunlight, germane to ARM's current and future A-band instruments:

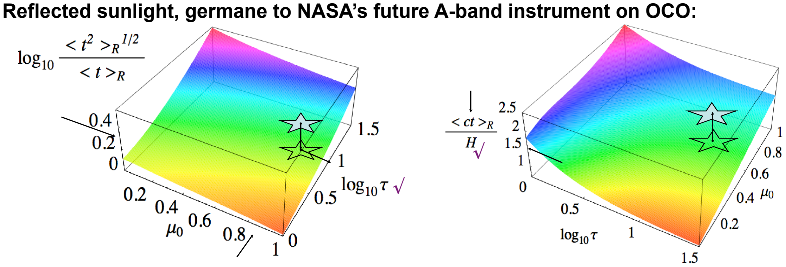
Min, Q.-L., L. C. Harrison, and E. E. Clothiaux (2001), Joint statistics of photon path length and cloud optical depth: Case studies, *J. Geophys. Res.*, **106**, 7375-7385.



The left-hand panel shows the ratio of $\langle ct \rangle_T$ to the product of cloud thickness H and scaled optical thickness of the cloud, $(1-g)\tau$ [$= (1-g')\tau'$], as function of the cosine of the SZA (μ_0) and $\log_{10}\tau$, $g = 0.85$ [$g' = g/(1+g) = 0.46$] is the [δ-scaled] scattering phase function's asymmetry factor. Knowing any two, one can compute the 3[rd] quantity in the ratio, e.g., H from MMCR or τ from MFRSR.

The right-hand panel shows the non-dimensional ratio of the root-mean-square (RMS) path, $\langle (ct)^2 \rangle_T^{1/2}$, to its mean $\langle ct \rangle_T$, further divided by its asymptotic (large τ) value $(7/5)^{1/2} \approx 1.18$. We see that the mean is a very good predictor of the RMS, so no new cloud parameter can be gleaned from higher moments for ground-based O_2-DOAS, at least in this simple cloud geometry.

Reflected sunlight, germane to NASA's future A-band instrument on OCO:



These plots show $\log_{10}\langle (ct)^2 \rangle_R^{1/2} / \langle ct \rangle_R$ and $\langle ct \rangle_R / H$ vs. μ_0 and $\log_{10}\tau$. The former ratio of O_2-DOAS observables can now be used to derive τ, knowing g and μ_0. Knowing τ, one can then derive H from the observed value of $\langle ct \rangle_R$. Therefore, reflected O_2-DOAS can, in principle, be used as a stand-alone cloud probing modality from air or from space. It can therefore add robustness to existing methods, at least during daytime.

Attention! Entering geek's corner … 1+1D RT in $0<z<H$:

$$\left[c^{-1}\partial_t + \mu\partial_z + \sigma(z)\right] I = \sigma_s(z)\int_{4\pi} p(z,\Omega\cdot\Omega') I(t,z,\Omega')\,\mathrm{d}\Omega' + q(t,z,\Omega)$$

$$q(t,z,\Omega) = F_0 \exp[-\int_0^z \sigma(z')\,\mathrm{d}z'/\mu_0]\,\sigma_s(z)\, p(z,\Omega\cdot\Omega_0)\,\delta(t - z/\mu_0 c)$$

$$c^{-1}\partial_t J + \partial_z F = -\cancel{\sigma_a} J + F_0\sigma_s \exp(-\sigma z/\mu_0)\,\delta(t - z/\mu_0 c)$$

$$c^{-1}\cancel{\partial_t F} + \boxed{\partial_z J/3} \approx -\sigma_t F + g' F_0 \sigma_s \exp(-\sigma z/\mu_0)\,\delta(t - z/\mu_0 c)$$

subject to BCs $\left(J + 2F\right)\big|_{z=0} = \left(J - 2F\right)\big|_{z=H} = 0$

$\xrightarrow{\text{Laplace Transform}}$

$$\mathrm{d}F^*/\mathrm{d}z = -(s/c + \cancel{\sigma_a}) J^* + F_0\sigma_s \exp[-(s/c + \sigma) z/\mu_0]$$

$$\mathrm{d}J^*/\mathrm{d}z \approx -3\sigma_t F^* + 3g' F_0 \sigma_s \exp[-(s/c + \sigma) z/\mu_0]$$

subject to BCs $\left(J^* + 2F^*\right)\big|_{z=0} = \left(J^* - 2F^*\right)\big|_{z=H} = 0$

Diffusion limit: once-or-more scattered radiance
$I(t,z,\mu) \approx [J(t,z) + 3\mu F(t,z)]/4\pi$,
along with $p(\mu_s) \approx f 2\delta(1-\mu_s) + (1-f)(1+3g'\mu_s)/4\pi$

$$\begin{cases} J(t,z) = 2\pi\int_{-1}^{+1} I(t,z,\mu)\,\mathrm{d}\mu \\ F(t,z) = 2\pi\int_{-1}^{+1} \mu I(t,z,\mu)\,\mathrm{d}\mu \end{cases}$$

Fick's law, with
transport extinction coefficient
$\sigma_t = (1-g')\sigma_s + \cancel{\sigma_a}$

$$R^*(s) = \tfrac{1}{4}[J^* - 2F^*]_{z=0} = J^*(s,0)/2\mu_0 F_0$$
$$\{T^*(s) = \tfrac{1}{4}[J^* + 2F^*]_{z=H} = J^*(s,H)/2\mu_0 F_0\} + \mathrm{e}^{-\sigma H/\mu_0}$$

$$\begin{pmatrix} I_\lambda(0,-1) \approx \mu_0 F_0 R^*(s)/\pi|_{s=k(\lambda)} \\ I_\lambda(H,+1) \approx \mu_0 F_0 T^*(s)/\pi|_{s=k(\lambda)} \end{pmatrix}$$

$F = F^*(0)$ with $F = R,T$ and
$$\begin{cases} \langle ct \rangle_F = (-c/F^*)\,\partial F^*/\partial s|_{s=0} \\ \langle (ct)^2 \rangle_F = (+2c^2/F^*)\,\partial^2 F^*/\partial s^2|_{s=0} \end{cases}$$

Davis, A. B. (2008), Multiple-scattering lidar from both sides of the clouds: Addressing internal structure, *J. Geophys. Res.*, **113**, D14S10, doi:10.1029/2007JD009666.

Davis, A.B., I.N. Polonski, & A. Marshak (2009): Space-time Green functions for diffusive radiation transport, in application to active and passive cloud probing, *Light Scattering Reviews*, **4**, 169–292.