NIR Solar Reference Spectrum Algorithm for the Orbiting Carbon Observatory (OCO)

Hartmut Bösch and Geoffrey Toon
Jet Propulsion Laboratory, California Institute of Technology
OCO Mission

Global, space-based observations of atmospheric CO\textsubscript{2} with precision, resolution, and coverage needed to monitor sources and sinks:

- Spectra of reflected/scattered sunlight in NIR CO\textsubscript{2} and O\textsubscript{2} bands used to estimate $X_{\text{CO}_2}$ with large sensitivity near surface
- A-train orbit (1:26 PM polar sun sync)
- NASA ESSP (Earth Space System Pathfinder) scheduled for Sept 2008 launch; 2 yrs lifetime
OCO Instrument

- **3 bore-sighted, high resolution, grating spectrometers**
  - O$_2$ 0.765 μm A-band
  - CO$_2$ 1.61 μm band
  - CO$_2$ 2.06 μm band

- **Similar optics and electronics**
  - Common 200 mm f/1.9 telescope
  - Resolving Power ~18,000/21,000
  - Spectrometers cooled to < 0 °C
  - Common electronics for focal planes

- **Observation Modes**
  - Science Modes: Nadir, Glint, Target
  - Calibration Modes: Solar, Dark, Lamp etc.
Motivation

- OCO measures reflected/scattered sunlight:
  - analysis must correctly account for imprinted solar spectrum

- OCO measures solar spectra every orbit:
  - OCO spectra are not sufficiently oversampled
  - ratioing of radiance spectrum with measured solar spectrum will result in spectral artifacts

- OCO approach:
  - Empirical solar reference spectrum algorithm enables us to compute high-resolution solar spectrum
Measured NIR Solar Spectra

- Sources of NIR high-resolution spectra (all FTS) for derivation of solar linelist:
  - MkIV balloon, 1989 - 2004, 32 - 41 km, (650 - 5650 cm\(^{-1}\))
  - Kitt Peak ground-based (500 - 25,000 cm\(^{-1}\))
  - Park Falls/Lauder ground-based (3,900 - 15,500 cm\(^{-1}\))
  - LPMA balloon (13,000 - 13,200 cm\(^{-1}\))
  - Denver University balloon, July 2000, 33 km (12,839 - 13,334 cm\(^{-1}\))
  - ILAS spectrometer on board ADEOS satellite

- Kitt Peak is most important source
  - Continuous coverage from 500 - 25,000 cm\(^{-1}\)
  - Disk-integrated and disk-centered spectra
  - High altitude (but still significant atmospheric interference from O\(_2\) and CO\(_2\) in OCO spectral ranges)

- Continuum parameterization from space-based low resolution calibrated observations, e.g. SIM, SOLSPEC
Example: Fit to DU O₂ A-Band Spectrum

/spt/zdu20000707.7940  ψ = 79.40°  Z_T = 33.20km  σ_{rms} = 0.9597%  \int dz = 3.807 \pm 0.150 \times 10^{22}
Comparison with Synthetic Solar Spectra (Kurucz Model)

O$_2$ A-Band Region

1.61 $\mu$m CO$_2$ Band Region
Fit to SCIAMACHY Solar Spectrum

- Space-borne grating spectrometer on board ESA/Envisat satellite.
- Provides radiometric calibrated, spectrally resolved solar spectrum
Summary

• OCO will provide solar spectra in narrow 0.76, 1.61 and 2.06 um regions with spectral resolving power of ~20000, which are calibrated only pre-launch

• Since OCO will need high-resolution solar spectrum, we have developed empirical, linelist-based solar reference spectrum algorithm:
  - Disk-center linelist covers 600 - 15,700 cm⁻¹ region
  - Disk-integrated linelist covers OCO spectral region

• Empirical Solar reference spectrum algorithm needs further validation with calibrated solar irradiance spectra from measurements and models

• Description of variability of Fraunhofer lines with solar activity cycle?
Solar Model Approach

- We don’t have a high-resolution, TOA atmospheric solar spectrum
- We have calibrated low-resolution TOA solar spectra (e.g. SCIAMACHY, SOLSPEC, SIM)
- We have un-calibrated high-resolution ground- and balloon-based solar spectra (e.g. Kitt Peak), but these are contaminated by atmospheric absorptions
- Identification of Fraunhofer lines:
  - Use airmass-behavior of telluric absorptions; Fraunhofer lines have constant depth
  - Use HITRAN linelist to fit the atmospheric absorptions. Whatever is left in the residuals must be solar.
SOLAR Reference Algorithm

We have developed a solar linelist, containing 20,000+ lines, each assumed to have an absorption shape of the form:

\[
P(\nu - \nu_0) = S \times \exp\left(\frac{(\nu - \nu_0)^2}{\sqrt{d^4 + [y \times (\nu - \nu_0)]^2}}\right)
\]

where

- \(S\): line-center optical thickness (dimensionless)
- \(\nu_0\): line-center frequency (cm\(^{-1}\))
- \(y\): 1/e folding width (cm\(^{-1}\))
- \(d\): Doppler width (cm\(^{-1}\))

For \(y \ll d\), this becomes straightforward Doppler lineshape.
Comparison with Synthetic Solar Spectra (Kurucz Model)

**O₂ A-Band Region**

**1.61 μm CO₂ Band Region**
Fit to DU A-Band Spectrum

\[ /spt/zdu20000707.9067 \quad \psi = 90.67^\circ \quad Z_T = 32.77 \text{km} \quad \sigma_{\text{rms}} = 1.1992\% \quad \int dz = 4.089 \pm 0.150 \times 10^{22} \]

Transmittance

\[ 1.295 \times 10^4 \quad 1.300 \times 10^4 \quad 1.305 \times 10^4 \quad 1.310 \times 10^4 \quad 1.315 \times 10^4 \quad 1.320 \times 10^4 \]

Frequency (cm\(^{-1}\))

\text{other solar, O}_2