Tropospheric Methane Retrievals from GOSAT Thermal Infrared Soundings

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Greenhouse gases Observing SATellite

- Thermal and Near Infrared sensor for carbon Observation - Fourier Transform Spectrometer (TANSO-FTS) & Cloud and Aerosol Imager (CAI)
- Global measurements: April 2009 - present
- IFOV = 10.5 km, Swath = 750 km, Repeat cycle = 3 days

### Band Spectral Range (µm)
<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Range (µm)</th>
<th>Spectral Sampling (cm⁻¹)</th>
<th>SNR (pre-launch)</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75 - 0.77</td>
<td>0.2</td>
<td>&gt;340</td>
<td>Solar Irradiance Deep Space, Lunar, Diode Laser</td>
</tr>
<tr>
<td>2</td>
<td>1.56 - 1.72</td>
<td>0.2</td>
<td>&gt;320</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.92 - 2.08</td>
<td>0.2</td>
<td>&gt;410</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4.5 - 14.3 (700 - 2000cm⁻¹)</td>
<td>0.2</td>
<td>&gt; 280</td>
<td>Deep Space, On-board Blackbody</td>
</tr>
</tbody>
</table>
Motivation

- Tropospheric methane (CH₄) retrievals from nadir thermal infrared measurements - AIRS (Xiong et al., 2008), IASI (Razavi et al., 2009, Crevoisier et al., 2009) & TES (Payne et al., 2009, Worden et al., 2012)
- **Thermal Infrared (TIR) measurements -> complement shortwave Infrared (SWIR) retrievals**
  - maximum TIR sensitivity in mid-troposphere -> provides additional information of tropospheric gas concentrations
  - GOSAT TIR & SWIR sample the same air mass -> avoid uncertainties in combining information from different sensors (e.g. combining GOSAT & IASI)
- Combination of SWIR -TIR information -> potential for increase in DFS & better vertical representation of tropospheric methane

**Vertical sensitivity of GOSAT SWIR and TIR**

- **TIR:** mid- & upper-troposphere sensitivity
- **SWIR:** near surface sensitivity
Thermal Infrared Spectra

- Current version of GOSAT Level 1b data (V1.60+) -> optimised TIR spectral calibration (polarisation & blackbody emissivity)
- Uncertainties in pre-launch calibration -> TIR spectra a) are likely systematically biased (based on JAXA/NIES - U. Wisconsin TIR calibration campaigns) & b) low signal-to-noise ratio

Calibration errors (A. Kuze, 2015):
- Internal blackbody temperature & pointing mirror
- Produces different spectral response across methane spectral band

Reference: Kuze et al, 2015, GOSAT TIR WG.
UOL GOSAT TIR Processor

GOSAT SWIR Pre-Processing:
- CH₄ (MACC+TOMCAT)
- H₂O + TEM (ERA Interim) a priori
- Surface pressure & (SRTM DEM) topography

Cloud Filtering:
Land*: SWIR O₂ A-band cloud pressure retrieval
Ocean*: CAI cloud mask (channels 0.66 μm, 0.87 μm, 0.38 μm, 1.60 μm)

Surface: CIMSS MODIS
High Spectral Resolution Emissivity
ECWMF Skin Temperature

Profiles: Slimcat N₂O & Initial Guess (IG2) climatological species

OUTPUT:
XCH₄ (total column, concentration profiles, a posteriori uncertainties (with TEM, H₂O, SFC-TEM)

OE Retrieval V1.60 TIR L1B
(Oxford Reference Forward Model, Levenberg Marquardt iterations)

Instrument: Line Shape and Radiometric Noise

Line & Cross Sections: HITRAN 2012 Spectroscopy

* State Vector: [CH₄, H₂O, TEM, SFC-TEM, SPECTRAL SHIFT]
* 1240 – 1305 cm⁻¹ and NESR: 50 nWcm².sr.cm⁻¹ (SNR <70)
* Retrieval levels 40 equidistant pressure levels

* Extract TIR brightness temperature differences for TIR cloud mask using clear-sky thresholds (not yet implemented)
XCH4: GOSAT TIR: November 2009

GOSAT TIR

Methane [ppbv]

1620.00 1661.67 1703.33 1745.00 1786.67 1828.33 1870.00

XCH4: Total Column

AT PROXY XCH4 (SWIR)
http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/CRDP_REG/
XCH4: GOSAT TIR: June 2011

AT PROXY XCH4 (SWIR)
http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/CRDP_REG/

XCH4: Total Column
UoL GOSAT TIR XCH4 V1.0
Aircraft Inter-comparisons
HIAPER Pole-to-Pole Missions

- NOAA Gulfstream V aircraft -> transects across Pacific Ocean from 85° N to 85° S with vertical profiles every ~ 2.2° latitude
  - Surface to tropopause, pole to pole CH₄ measurements
  - ideal for validation of TIR mid/upper troposphere sensitivity

<table>
<thead>
<tr>
<th>HIPPO mission</th>
<th>Dates</th>
<th>Number of Profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2008 Dec - 2009 Jan</td>
<td>138</td>
</tr>
<tr>
<td>2</td>
<td>2009 Oct - 2009 Nov</td>
<td>148</td>
</tr>
<tr>
<td>3</td>
<td>2010 Mar - 2010 Apr</td>
<td>136</td>
</tr>
<tr>
<td>4</td>
<td>2011 Jun - 2011 Jul</td>
<td>175</td>
</tr>
<tr>
<td>5</td>
<td>2011 Aug - 2011 Sep</td>
<td>190</td>
</tr>
</tbody>
</table>

File:HIPPO_profiles_100m_intervals_20140519.tbl

http://www.eol.ucar.edu/field_projects/hippo

Wofsy et al, 2011
GOSAT & HIPPO inter-comparisons

- ± 300km, ± 6 hours
- HIPPO profiles are merged with a priori methane profiles above top altitude
- Application of co-located averaging kernel and pressure weighting function

\[ x_{\text{truth}} = x_{\text{apriori}} + A_{\text{gosat}} (x_{\text{truth-highres}} - x_{\text{apriori}}) \]
GOSAT TIR vs. HIPPO XCH4: Zonal Average

Zonal average = GOSAT measurements across HIPPO flight transect
GOSAT vs. HIPPO XCH4

Mean Difference: 13.347 ppbv
Median Difference: 8.737 ppbv
Sigma: 11.280 ppbv
Correlation: 0.94

Mean Difference | NH [ppbv] | Tropics [ppbv] | SH [ppbv] |
--- | --- | --- | --- |
18.27 | 7.84 | 9.63 |
24.58 | 7.04 | 8.00 |
34.41 | 30.69 | 21.41 |
15.18 | 9.05 | 9.14 |
0.65 | 0.92 | 0.88 |

GOSAT TIR
HIPPO
MACC TM5
• We have performed GOSAT TIR methane profile retrievals (2009 to 2011) that show a good agreement with UoL GOSAT (SWIR) proxy XCH4 and MACC TM5 model
  • Capture large-scale features and north-south gradient
  • Positive bias in XCH4 compared to in-situ HIPPO measurements: $25 \pm 15$ ppbv in the Northern hemisphere
  • Likely causes a combination of TIR CH$_4$ spectroscopy, instrument calibration and interfering species

• Further Improvements:
  • Testing TIR spectral bias correction with JAXA to improve spectra prior to retrieval
  • “Proxy”-type retrieval using co-retrieved N$_2$O profiles correct CH$_4$ profile (to remove systematic errors that affect both CH$_4$ and N$_2$O) has shown promise (improved agreement with TM5) but requires information on TIR bias correction
  • CH$_4$ & N$_2$O spectroscopy updates (particularly line mixing)
  • GEOS-Chem (Edinburgh) model inversions assimilating both GOSAT SWIR & TIR data
Thank you
Extra Slides
A priori taken from MACC-II NOAA assimilation run.

Uses monthly mean TOMCAT stratospheric model run (University of Leeds) to improve stratospheric a priori stratospheric.

TOMCAT run is just monthly mean run.

MACC is daily and assimilates surface network.

TOMCAT has many more stratospheric level but constant troposphere.

MACC is coarse in stratosphere but has good troposphere.

Complement each other well.

Not massively dissimilar in stratosphere anyway.

Above 50 hPa we replace MACC profile with TOMCAT profile.

Weight the percentage of each profile for a smooth transition between the two.
Degrees of freedom signal: 0.6 - 0.8 mid-latitude, 0.8 - 1.2 tropics

Average chi-square ~ 1.2

A posteriori error < 3%

Residual = real - simulated GOSAT spectra

GOSAT V1.60 spectra
Nov 2009

Average Residual
50° North to 50° South

CH₄ spectral sensitivity in GOSAT band 4
Razavi et al., (2009), Worden et al. (2012) have shown that TIR CH4 can benefit from proxy type N2O correction

- Minimise impact of systematic effects on retrieval (water vapour continuum, instrumental..)
- Can assume errors affect CH4 also affect co-retrieved N2O

“Proxy” type retrieval

\[ XCH_4 = \frac{XCH_4}{XN_2O} \times N_2O \]

Kuze, A., 20150527

GOSAT N2O vs. HIPPO N2O

Kuze, A., 20150527
**UoL GOSAT SWIR Retrieval**

- **Algorithm:** OCO (ACOS) Full Physics Optimal Estimation algorithm

- **L1B files:**
  - Spectra and calibration provided by NIES/JAXA
  - Noise estimated from spectra

- **Full-Physics Retrieval:**
  - Fit to O₂ A Band, 1.61μm & 2.06μm bands
  - Retrieved parameters: CO₂, H₂O, CH₄, temperature, surface Pressure, albedo, dispersion, O₂ zero level offset, aerosol and cirrus

- **Proxy Retrieval (CH₄/CO₂):**
  - Fit to CO₂ Band at 1.61μm + 1.65 μm CH₄ Band
  - Retrieved parameters: CO₂ and CH₄, H₂O, temperature, albedo and dispersion
  - CO₂ acts as a “proxy” for the light-path and allows majority of scattering effects to ratio out.

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Key Contacts: Robert Parker & Hartmut Boesch, Leicester, UK
- Small bias of 4.8 ppb (0.27%)
- Single-sounding precision of 13.4 ppb (0.74%)
- The station-to-station bias (a measurement of the relative accuracy) is found to be 4.2 ppb
- For the first time the $X_{CH_4}/X_{CO_2}$ ratio component of the Proxy retrieval is validated:
  - Bias of 0.014 ppb/ppm (0.3%)
  - Single-sounding precision of 0.033 ppb/ppm (0.72%).
Greenhouse gAs Uk and Global Emissions (GAUGE): Quantifying UK anthropogenic GHG emissions

Inter-calibrated atmospheric GHG measurements

Cutting-edge models of atmospheric transport

Estimating posterior emissions by combining measurements and models

Inputs: 1) Measurements and uncertainty and 2) prior emissions uncertainty

Single model inversion

Output: Posterior emission estimates and uncertainty

Facilitating better decisions: ensemble of emissions estimates provide uncertainty
XCH4: Emissivity effects

- UOL GOSAT TIR retrieval: V1.01 used CIMSS baseline emissivity database. Updated to high spectral resolution emissivity database (Knuteson, Borbas et al.)

Baseline Emissivity

High spectral Resolution Emissivity

Emissivity effects

- Most significant improvements observed: Saharan desert, Australia
# Cloud Filtering

<table>
<thead>
<tr>
<th>Mn</th>
<th>CAI Cloud Fraction</th>
<th>SWIR Delta PSURF [hPa]</th>
<th>SWIR Clouds Hit [%]</th>
<th>SWIR Clear pixels Hit [%]</th>
<th>SWIR Missed Cloud [%]</th>
<th>SWIR False Alarm [%]</th>
<th>TIR Clouds Hit [%]</th>
<th>TIR Clear pixels Hit [%]</th>
<th>TIR Missed Cloud [%]</th>
<th>TIR False Alarm [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>03</td>
<td>0.2 - 1.0</td>
<td>30.0</td>
<td>80.9</td>
<td>71.9</td>
<td>19.1</td>
<td>28.0</td>
<td>78.5</td>
<td>81.3</td>
<td>21.5</td>
<td>18.6</td>
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<tr>
<td>04</td>
<td>0.2 - 1.0</td>
<td>30.0</td>
<td>83.3</td>
<td>70.3</td>
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<td>82.3</td>
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<tr>
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<td>88.3</td>
<td>84.9</td>
<td>11.6</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Inter-comparison of SWIR cloud mask and TIR cloud mask vs. CAI cloud mask
XCH4: GOSAT TIR vs. GEOS-Chem (Edinburgh)
XCH4: GOSAT TIR vs TCCON
Vertical Cross Section: GOSAT TIR - TM5