Remote Sensing of Arctic and Boreal Atmospheric Composition from a Highly Elliptical Orbit

Ray Nassar¹, C. Tom McElroy², Kaley A. Walker³, Chris McLinden¹, Chris E. Sioris², Dylan B.A. Jones³, Randall V. Martin⁴, Yves Rochon¹, Louis Garand¹ and Alexander P. Trishchenko⁵

¹ Environment and Climate Change Canada, ² York University, ³ University of Toronto, ⁴ Dalhousie University, ⁵ Natural Resources Canada

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Boreal Forests
- Longer growing season and increase in disturbances may enhance or reduce their net CO₂ flux

Permafrost
- 1672 PgC, twice atm mass with potential for release of some fraction as CO₂, CH₄
- ~85 PgC by 2100 (0.8-1.1 PgC/yr) by extrapolation of Alaskan measurements (Schurr et al. 2009)
- Models: 104±37 PgC (Schaefer et al. 2011) and 9-114 PgC (Schneider von Deimling et al. 2012) by 2100

Satellite observations of CO₂ and CH₄ would be valuable
Anthropogenic Emissions North of ~45°N

- NO₂ sources
- SO₂ sources
- Lights
- Current/planned industrial projects

- Oil Sands
- Fracking
- Smelting
- Diamond mines
- Diamond mine (proposed)
- Coal-fired power plant

Satellite night light imagery from VIIRS http://earthobservatory.nasa.gov/Features/IntotheBlack/

Chris McLinden
A Few Current and Future GHG and AQ missions

- **GOSAT** launched in 2009 is a Japanese mission dedicated to measuring CO$_2$ and CH$_4$
- **OCO-2** is a NASA CO$_2$ mission successfully launched on July 2, 2014
- **TanSat** (China) CO$_2$ mission to launch in Aug 2016
- **GOSAT-2** scheduled to launch around 2018
- **OCO-3** on the Space Station in 2018
- **MicroCarb** CNES CO$_2$ mission to launch around 2020

- **TropOMI** will launch in Oct 2016
- Successor to **OMI** (Aura)
- Air quality mission along with CH$_4$
- Wide swath increases coverage

- **TEMPO** will launch around 2019 or later
- Air quality over US, southern Canada (<60°N) and parts of Central America

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**SRON, KNMI, NSO**

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[Logos of various organizations]
Common Satellite Orbits and Coverage

- **Low Earth Orbit (LEO)**
  - Below ~1000 km altitude
  - Near-polar plane
  - Can give global sampling, but typically observe a given point at constant local time of day

- **Geostationary Orbit (GEO)**
  - ~35,800 km altitude
  - Near-equatorial plane
  - Synchronized with Earth rotation with potential for ‘continuous’ sampling over selected area (<60°N/S)

Air Quality moving toward LEO + GEO (like meteorology), GHGs next? Neither LEO or GEO can give continuous observations over the Arctic
Highly Elliptical Orbit (HEO)

- WMO Vision for the Global Observing System (GOS) in 2025
- Conservation of angular momentum requires faster motion when close to Earth (perigee), slower motion when far from Earth (apogee)

- Example of a HEO is the Three Apogee (TAP) orbit:
  Period = 16 hr and Apogee altitude = 43,500 km

Other Highly Elliptical Orbits

• Numerous HEO possibilities by varying the orbital period and apogee altitude (40,000 - 48,500 km, so higher than GEO: 35,800 km)

Garand, Trishchenko, Trichtchenko, Nassar (2014), Physics in Canada, 70, 4, 247-254
Polar Communications and Weather (PCW)

- Canadian mission with 2 satellites in Highly Elliptical Orbit (HEO) configuration, under consideration for post-2020 launch

- Main objectives are to expand Arctic communications (National Defence) capabilities and provide meteorological observations (Environment and Climate Change Canada)

- Canadian Space Agency (CSA) also considered additional science instruments under the Polar Highly Elliptical Orbit Science (PHEOS) program

- The Weather, Climate and Air quality (WCA) mission concept is an atmospheric research option that completed Phase A in 2012 (PHEOS-WCA PI was Prof. Jack McConnell of York U)
PCW-PHEOS-WCA Instrument Configurations

- Fourier Transform Spectrometer (FTS)
- UV-Visible Spectrometer (UVS)

CSA Allocations

Size: 30 x 30 x 30 cm$^3$ (27 000 cm$^3$)

Mass: 50 kg
Power: 100 W

FTP (aperture 15 cm) with UVS, 85 kg
~103 800* cm$^3$

FTP (aperture 10 cm) with UVS, 45 kg
~35 128* cm$^3$

No O$_2$ A band or SWIR CO$_2$

“Lite”

All Bands Configuration

Compliant Configuration

O$_2$ A band and SWIR CO$_2$

*configuration volumes given with 20% contingency
### PCW-PHEOS-WCA Spectral Bands / Species

<table>
<thead>
<tr>
<th>Band (µm)</th>
<th>Band (cm⁻¹)</th>
<th>Resolution</th>
<th>Target species</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.7 – 14.2</td>
<td>700 - 1500</td>
<td>0.25 cm⁻¹</td>
</tr>
<tr>
<td>2</td>
<td>3.7 – 5.6</td>
<td>1800 - 2700</td>
<td>0.25 cm⁻¹</td>
</tr>
<tr>
<td>3a</td>
<td>1.66 - 1.67</td>
<td>5990 - 6010</td>
<td>0.25 cm⁻¹</td>
</tr>
<tr>
<td>3b</td>
<td>1.60 - 1.67</td>
<td>5990 - 6257</td>
<td>0.25 cm⁻¹</td>
</tr>
<tr>
<td>4</td>
<td>0.760-0.766</td>
<td>13060-13168</td>
<td>0.50 cm⁻¹</td>
</tr>
<tr>
<td>UVS</td>
<td>0.280-0.650</td>
<td>~ 1 nm</td>
<td>O₃, NO₂, aerosol, BrO, HCHO, SO₂, …</td>
</tr>
</tbody>
</table>

Widening band 4 would enable retrieval of chlorophyll fluorescence like GOSAT / OCO-2
What else could be measured? Snow, fires, other vegetation parameters, …

Designed and built ACE-FTS, CrIS and GOSAT interferometer
Designed and built MOPITT and ACE-MAESTRO (EMS Technologies)
FTS Imaging from Three Apogee Orbit

- 2 satellites, 8h apart in co-planar 16h orbit
- Apogee ~43,500 km, Perigee ~8100 km
- Observe 3 apogees/24 h (from 2 satellites)
- For apogee at local noon, observing ±4 h, so up to 8 h of data per day per region

Nassar, Sioris, Jones, McConnell (2014), JGR

- Quasi-geostationary viewing: 100 second scan of each small box with a 2D 56x56 array of 10x10 km² pixels, taking ~80 minutes to observe a region, repeat
- Viewing scenario for UVS would be somewhat different (~8x8 km² pixels)
Study on CO₂ observations from HEO Mission

- Generated 1-year of synthetic CO₂ observations from PHEOS-FTS and GOSAT accounting for orbits, instrument observing characteristics, sunlight, clouds, snow / surface properties, etc. in an Observing System Simulation Experiment (OSSE) to compare their ability to constrain Arctic and boreal CO₂ sources and sinks.

- Posterior Arctic / boreal land flux uncertainties from PHEOS-WCA were lower than from GOSAT by 30% annually and 45% in summer.

- Largest interannual variability and uncertainty in summer (boreal forest growing, disturbance and permafrost thaw) when PHEOS-FTS offers greatest potential constraints.

Take Home Message

• Highly Elliptical Orbit (HEO) satellite observations can greatly improve coverage over Northern regions, complementing planned international LEO and GEO missions (and ground-based data) for AQ, GHGs and meteorology

• PCW-PHEOS-WCA team (academia, government and industry) proposed a mission concept that completed Phase A study in March 2012, which could meet these needs but optimal instrument configuration requires CSA to relax mass/volume constraints

• What’s next?
Future Plans and Path Forward

- Will test PHEOS-FTS CO\textsubscript{2} and CH\textsubscript{4} imaging and pointing from a high altitude balloon (~35-40 km) to launch from New Mexico, late August / early September 2016 (PI: Tom McElroy)

- CSA providing funding to ABB for continual development of imaging FTS technology (2016-2017)

- Joint CSA - ECCC led opportunity for renewed mission concept studies for an “Air Quality and GHG mission focused on Northern Regions” includes consideration of a standalone HEO mission and instrument trade studies (2016-2017) with bids from multiple industry teams now under review

- Studies planned at ECCC (2016-2019) using currently available high latitude LEO satellite data (OMI, OCO-2, etc.) and modelling/assimilation systems to optimize observing characteristics for a HEO Air Quality and GHG mission