Laser Heterodyne Spectrometers for CO_2 Sounding

Damien Weidmann, Alex Hoffmann, Marko Huebner, Jerome Bredin, Neil Macleod

RAL Space

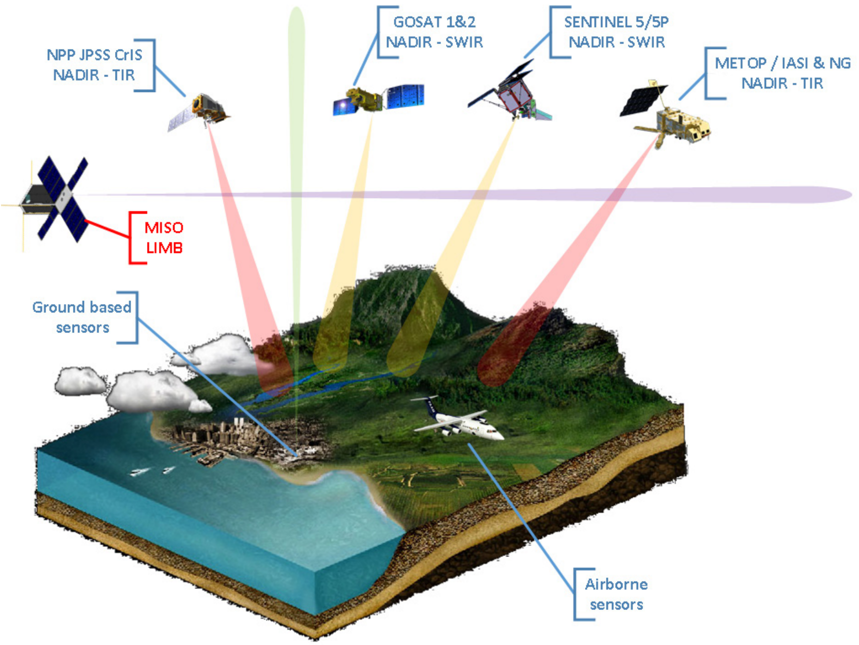
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Rationale

- Climate change and associated services
  - Scientific understanding and evidences
  - Modelling, projecting, informing
  - Attributing, monitoring, mitigating, enforcing

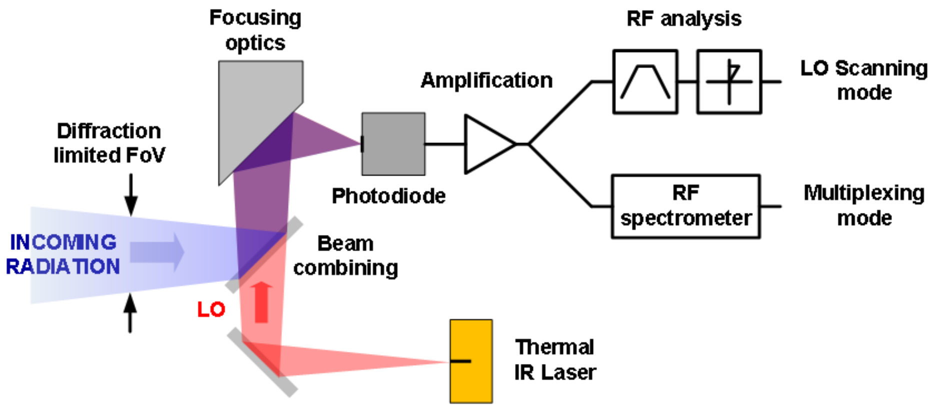
- Development of GHG EO system
  - Ground-based
  - Airborne (inc. balloons & UAVs)
  - Spaceborne

- CO_2 sensing systems enhancement
  - Miniaturization
  - Affordability
  - Performance

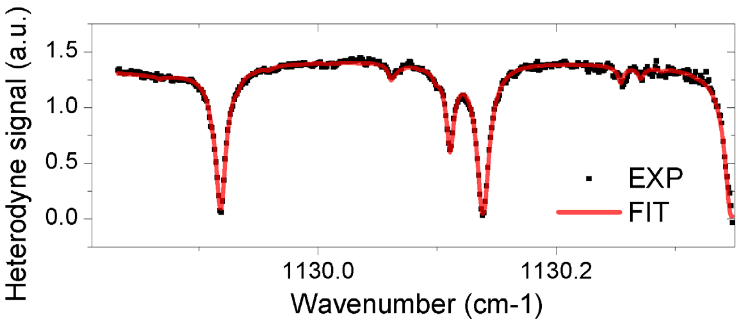


LHR Architecture & Benefits

- LHR architecture
  - Thermal IR
  - Ultra-high spectral resolution
  - Narrow FoV
  - Shot noise limited detection
  - Scalability

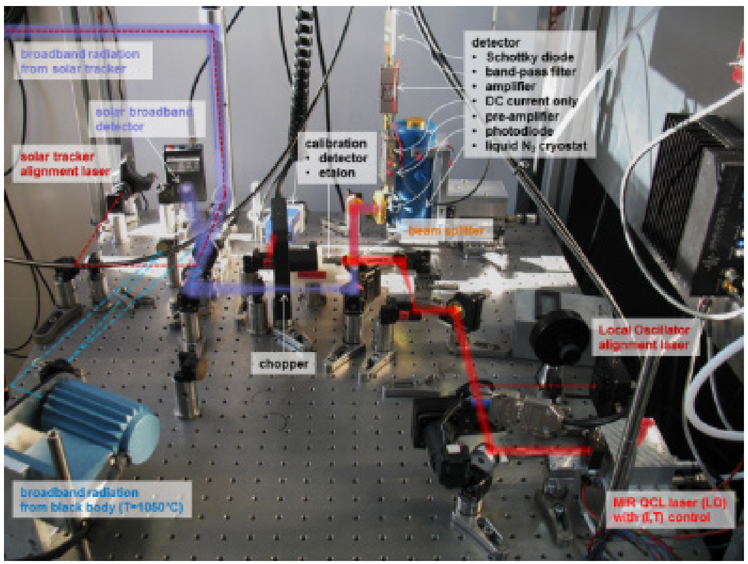


- Benefit for EO
  - Large trace gas target versatility
  - Upper atmosphere sounding (sub-Doppler resolution)
  - Interference discrimination
  - High spatial resolution
  - Radiometric sensitivity
  - Very small payload



Initial Lab Demonstrator

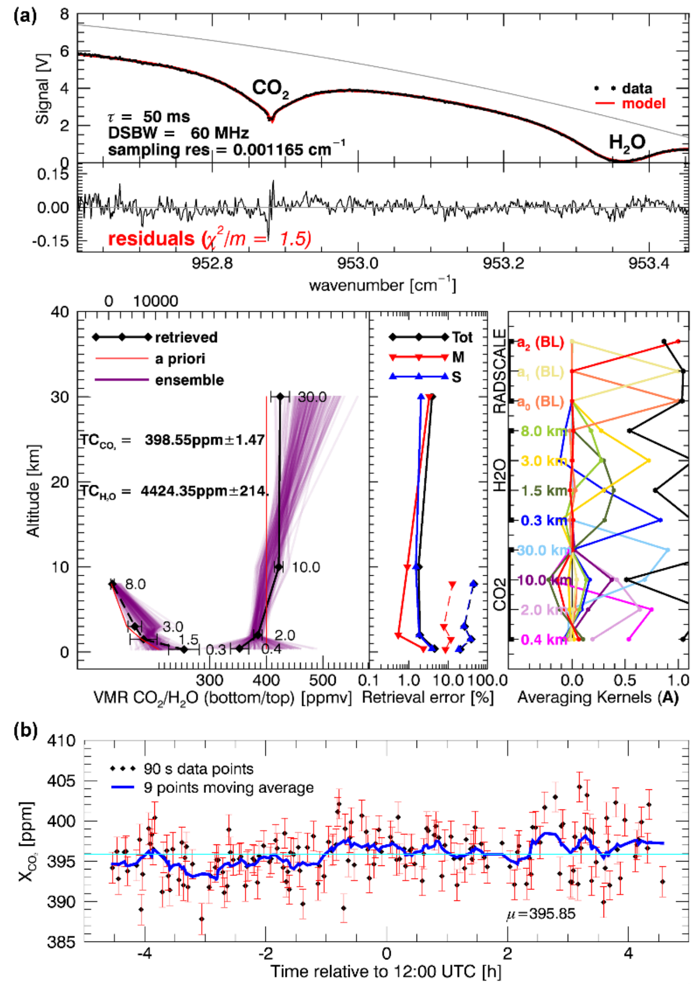
Ground-based solar occultation zenith



Thermal infrared laser heterodyne spectroradiometry
for solar occultation atmospheric CO2 measurements

Alex Hoffmann, Neil A. Macleod, Marko Huebner, and Damien Weidmann

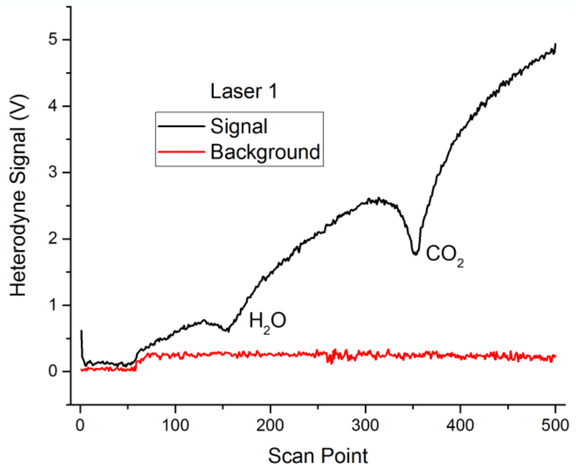
Atmos. Meas. Tech., 9, 5975–5996, 2016, doi: 10.5194/amt-9-5975-2016



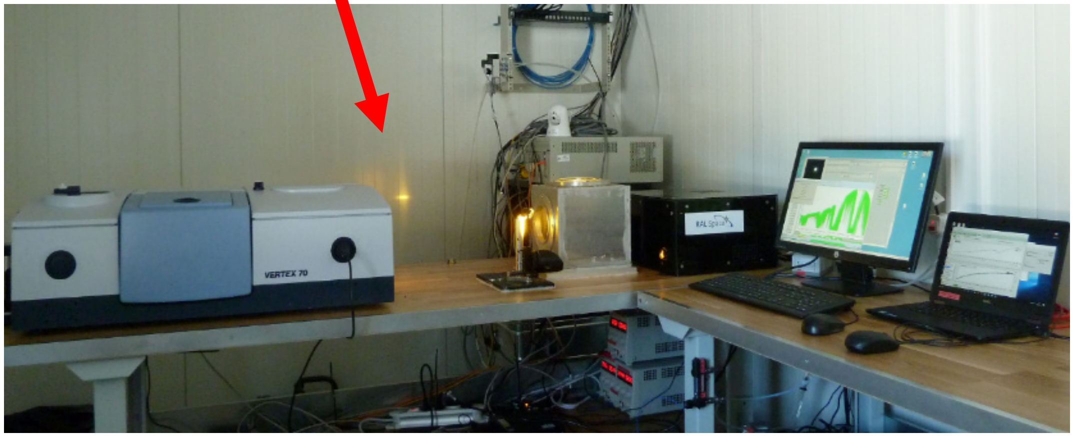
Deployable GHG LHR – ESA FRM4GHG

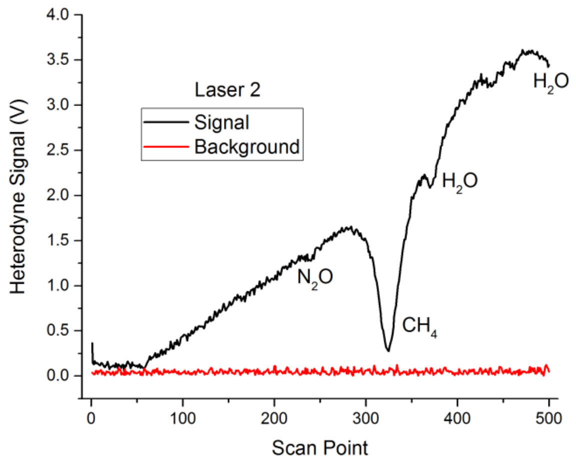
Intercomparison – validation campaign

Container Lab at Finnish Arctic Research Station

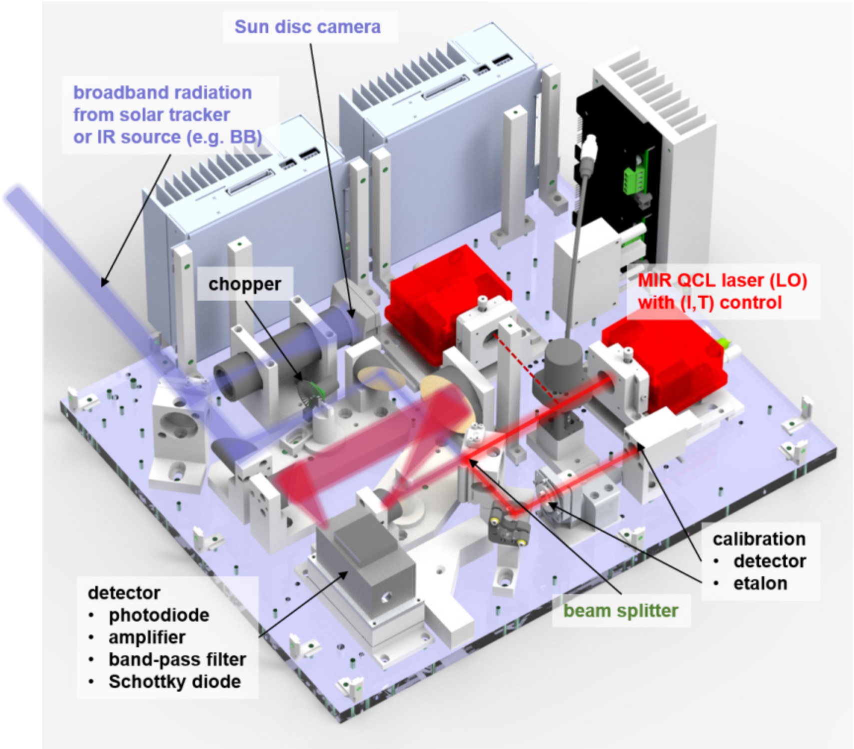


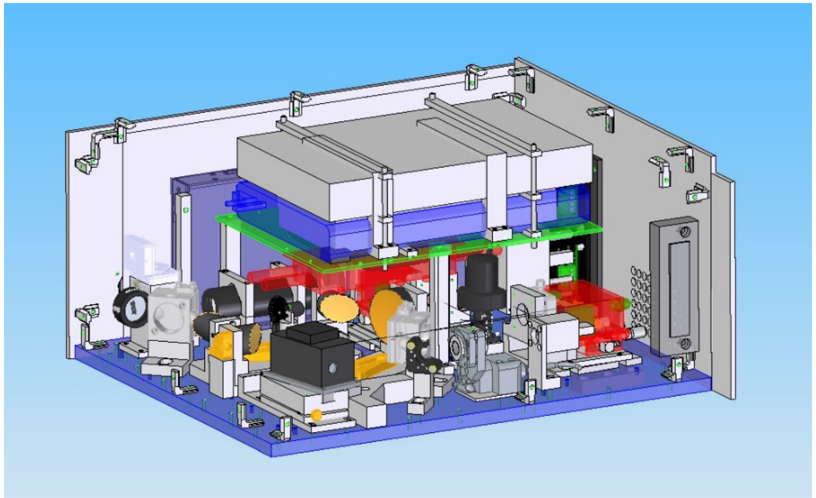
40x40x20 cm^3 LHR installed inside

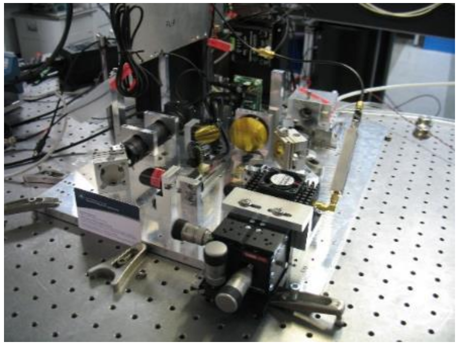




Deployable GHG LHR – ESA FRM4GHG

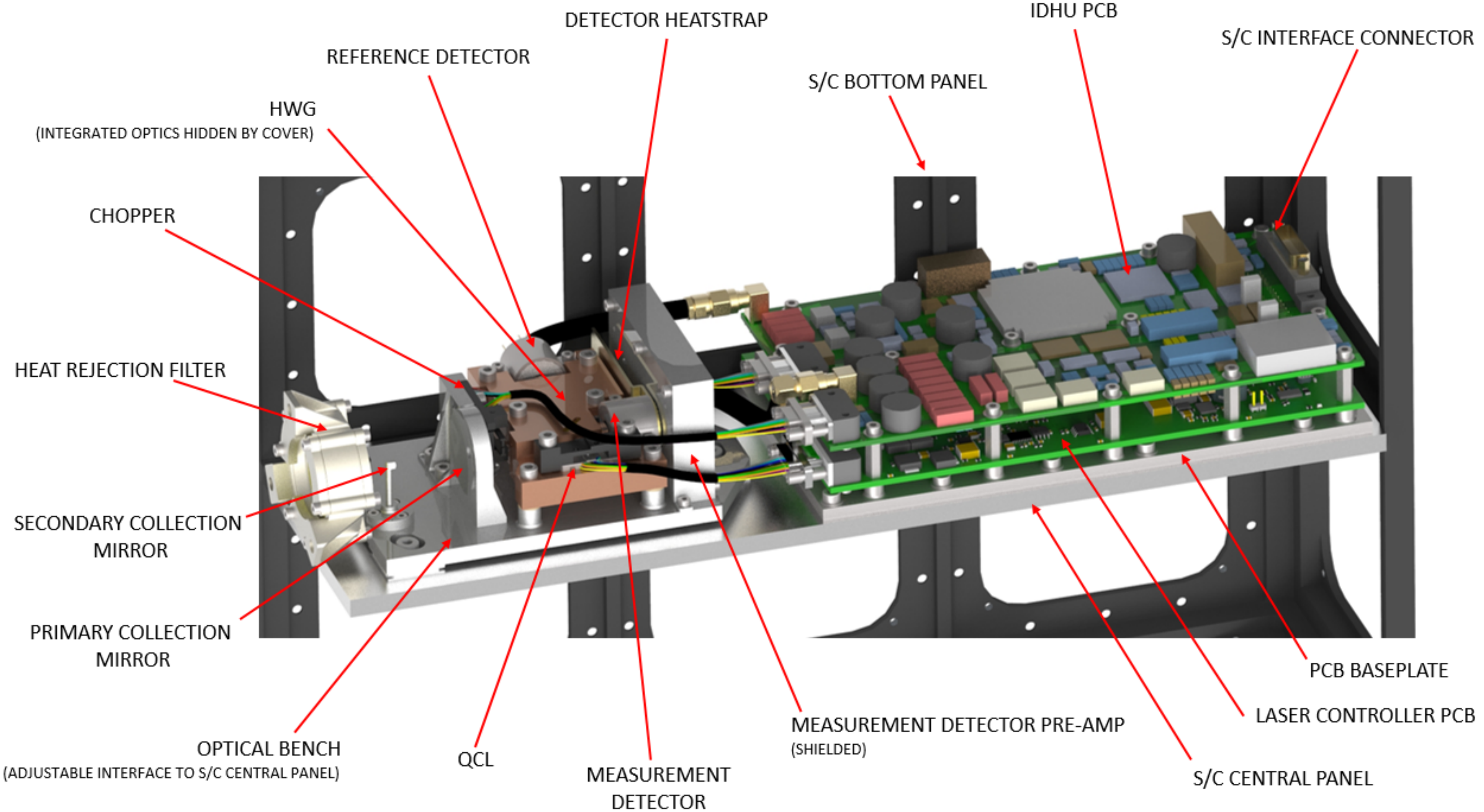






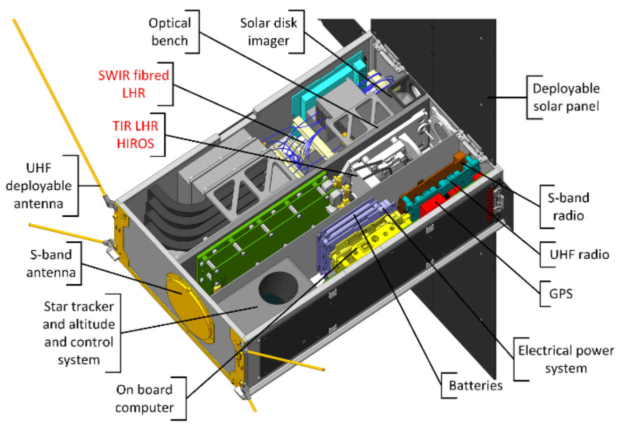
Embedded camera for sun tracking
Fully automated
Remotely operable

Ultra-miniaturized LHR



Missions

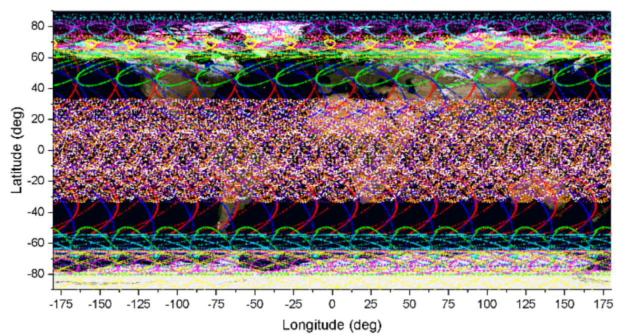
MISO
In orbit demonstration mission
3U cubesat type package
Augmenting Nadir infrastructure monitoring GHG



The Methane Isotopologues by Solar Occultation (MISO) Nanosatellite Mission: Spectral Channel Optimization and Early Performance Analysis
Damien Weidmann, Alex Hoffmann, Neil Macleod, Kevin Middleton, Joe Kurtz, Simon Barraclough, and Doug Griffin

Remote Sens. 2017, 9, 1073, doi: 10.3390/rs9101073

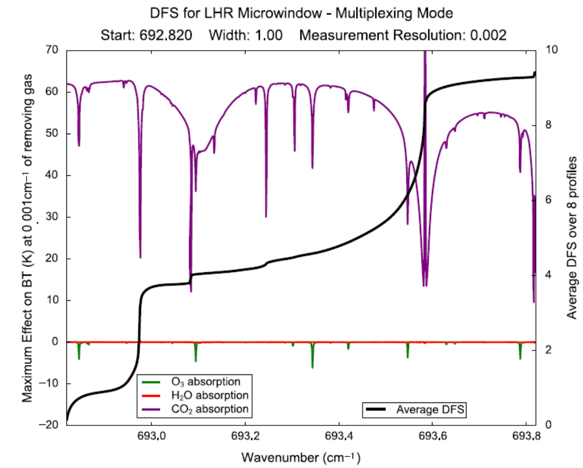
CAIROS
12 small sat constellation
Modular coverage and payloads
Middle atmosphere science



Studying the changing middle atmosphere at unprecedented resolutions - CAIROS – Constellation of Atmospheric hIgh Resolution Occultation Spectrometers
Damien Weidmann, Sophie Godin-Beekmann, William Bell, Bernd Funke, Michaela Hegglin, Brian Kerridge, Miyazaki Kazuyuki, William Randel, Keith Shine, Christopher Sioris, Michiel Van Weele, Vincent-Henri Peuch, Peter Hoor,

ESA EE10 Proposal, CEE10/021, 2018

LHR for Met
Small sat demonstrator
Upper atmosphere sounding
T and water vapour

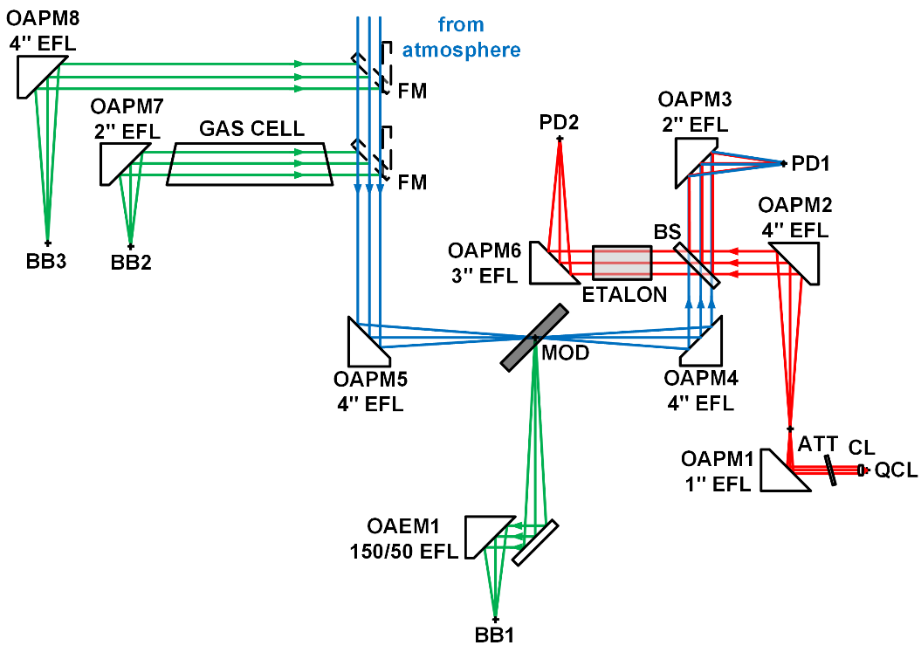


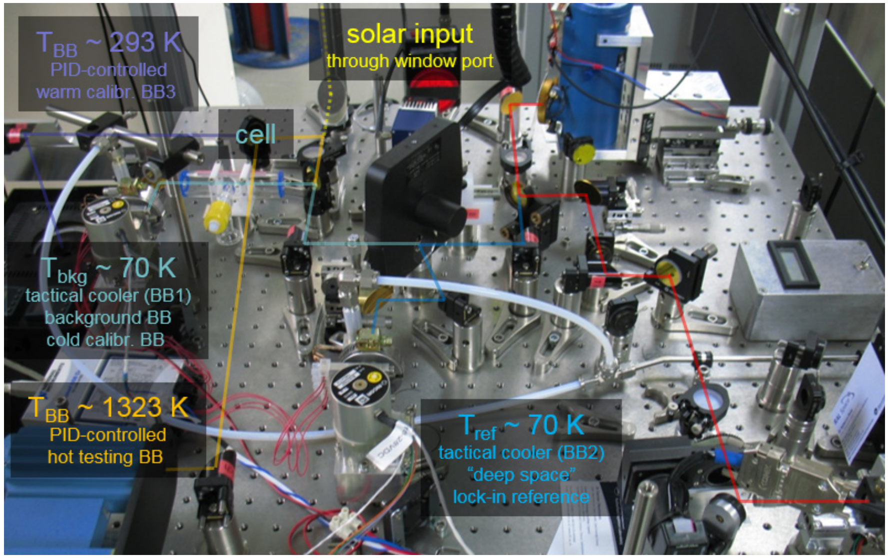
Evaluation of laser heterodyne radiometry for numerical weather prediction applications
F Smith, S Havemann, A Hoffmann, W Bell, D Weidmann, S Newman

Q J R Meteorol Soc., 1–20, 2018, doi: 10.1002/qj.3365

LHR for Emission Sounding

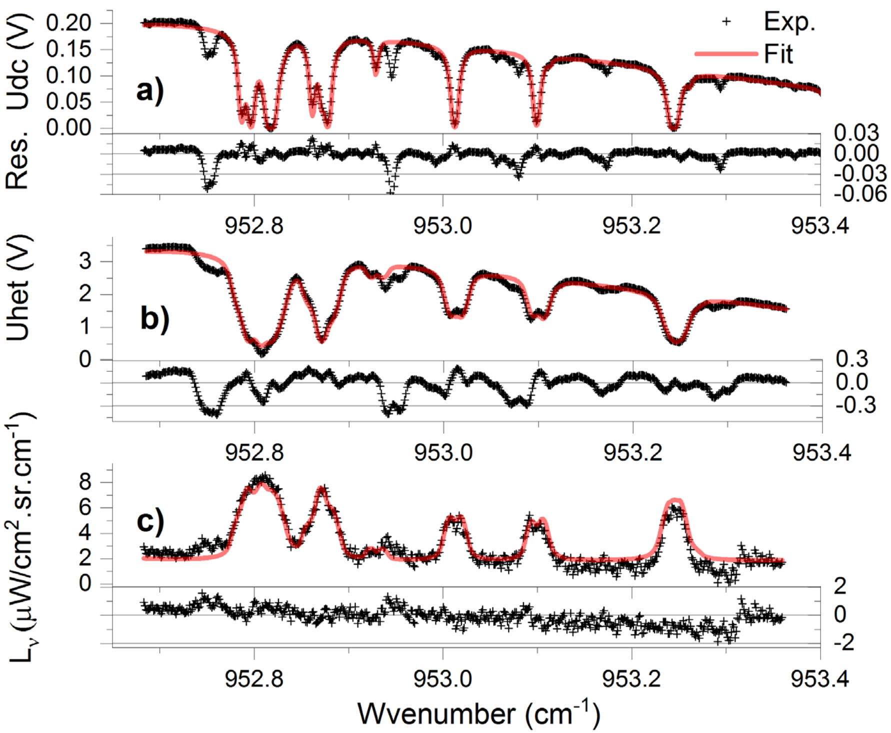
- Pathfinder CEOI project
- Evolve LHR to limb and nadir emission sounding
- Demonstrate LTE atmospheric molecular emission



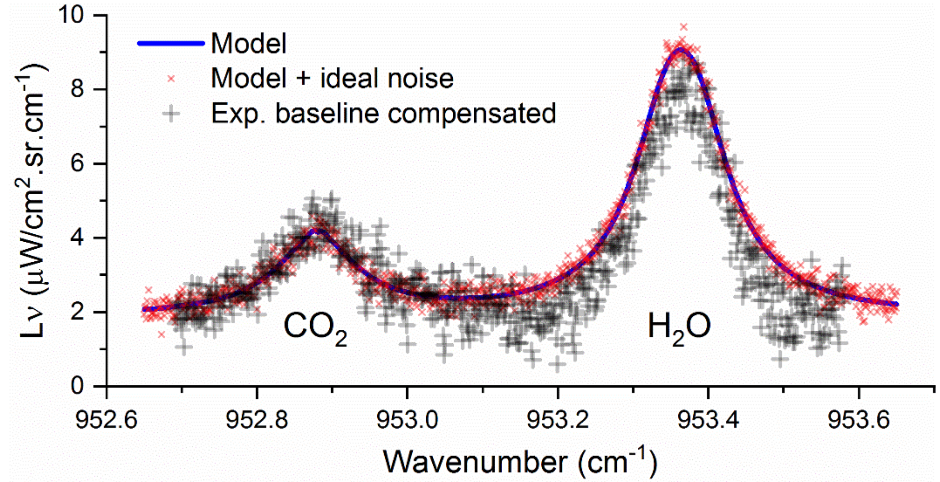


Spectrally Resolved Thermal Emission

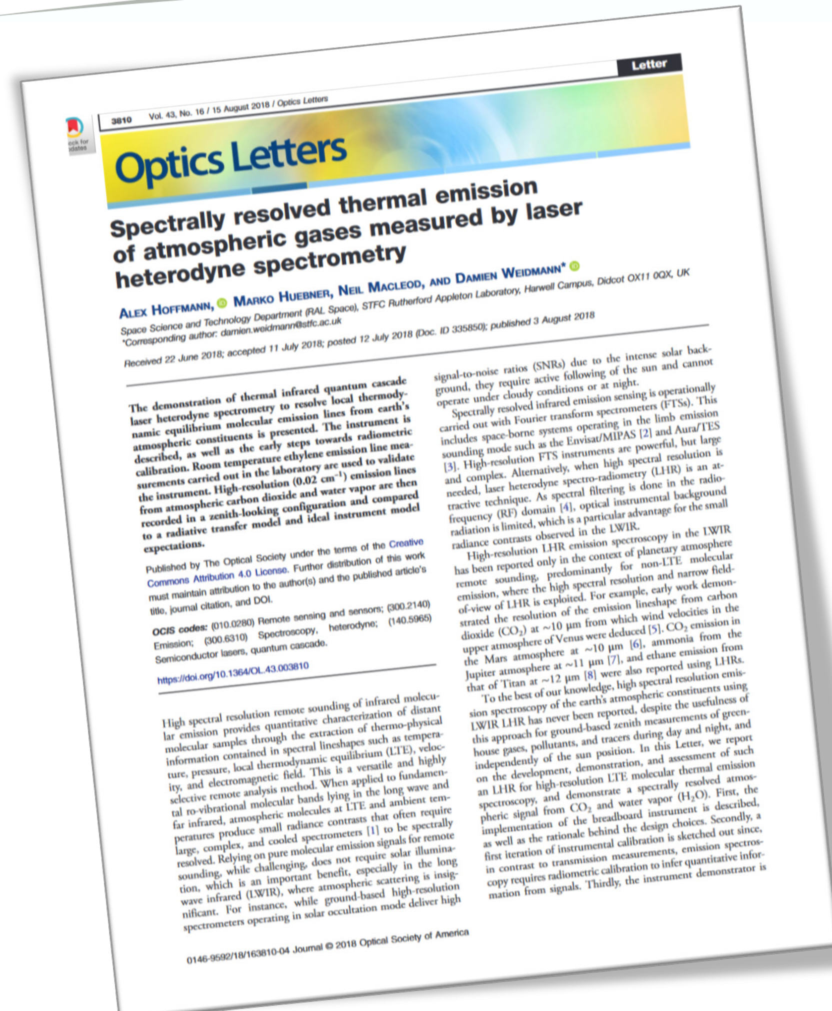
Laboratory demonstration
30 mbar of pure Ethylene at room temperature



Atmospheric emission demonstration
Zenith looking instrument
23 August - ~13:00



Publications



3810 Vol. 43, No. 16 / 15 August 2018 / Optics Letters

Letter

Optics Letters

Spectrally resolved thermal emission of atmospheric gases measured by laser heterodyne spectrometry

Alex Hoffmann, Marko Huebner, Neil Macleod, and Damien Weidmann*

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The demonstration of thermal infrared quantum cascade laser heterodyne spectrometry to resolve local thermodynamic equilibrium molecular emission lines from earth's atmospheric constituents is presented. The instrument is described, as well as the early steps towards radiometric calibration. Room temperature ethylene emission line measurements carried out in the laboratory are used to validate the instrument. High-resolution (0.02 cm^{-1}) emission lines from atmospheric carbon dioxide and water vapor are then recorded in a zenith-looking configuration and compared to a radiative transfer model and ideal instrument model expectations.

OCIS codes: (010.0280) Remote sensing and sensors; (300.2140) Emission; (300.6310) Spectroscopy, heterodyne; (140.5965) Semiconductor lasers, quantum cascade.

https://doi.org/10.1364/OL.43.003810

High spectral resolution remote sounding of infrared molecular emission provides quantitative characterization of distant molecular samples through the extraction of thermo-physical information contained in spectral lineshapes such as temperature, pressure, local thermodynamic equilibrium (LTE), velocity, and electromagnetic field. This is a versatile and highly selective remote analysis method. When applied to fundamental ro-vibrational molecular bands lying in the long wave and far infrared, atmospheric molecules at LTE and ambient temperatures produce small radiance contrasts that often require large, complex, and cooled spectrometers [1] to be spectrally resolved. Relying on pure molecular emission signals for remote sounding, while challenging, does not require solar illumination, which is an important benefit, especially in the long wave infrared (LWIR), where atmospheric scattering is insignificant. For instance, while ground-based high-resolution spectrometers operating in solar occultation mode deliver high signal-to-noise ratios (SNRs) due to the intense solar background, they require active following of the sun and cannot operate under cloudy conditions or at night.

Spectrally resolved infrared emission sensing is operationally carried out with Fourier transform spectrometers (FTSs). This includes space-borne systems operating in the limb emission sounding mode such as the Envisat/MIPAS [2] and Aura/TES [3]. High-resolution FTS instruments are powerful, but large and complex. Alternatively, when high spectral resolution is needed, laser heterodyne spectro-radiometry (LHR) is an attractive technique. As spectral filtering is done in the radio-frequency (RF) domain [4], optical instrumental background radiation is limited, which is a particular advantage for the small radiance contrasts observed in the LWIR.

High-resolution LHR emission spectroscopy in the LWIR has been reported only in the context of planetary atmosphere remote sounding, predominantly for non-LTE molecular emission, where the high spectral resolution and narrow field-of-view of LHR is exploited. For example, early work demonstrated the resolution of the emission lineshape from carbon dioxide (CO_2) at ~10 μm from which wind velocities in the upper atmosphere of Venus were deduced [5]. CO_2 emission in the Mars atmosphere at ~10 μm [6], ammonia from the Jupiter atmosphere at ~11 μm [7], and ethane emission from that of Titan at ~12 μm [8] were also reported using LHRs.

To the best of our knowledge, high spectral resolution emission spectroscopy of the earth's atmospheric constituents using LWIR LHR has never been reported, despite the usefulness of this approach for ground-based zenith measurements of greenhouse gases, pollutants, and tracers during day and night, and independently of the sun position. In this Letter, we report on the development, demonstration, and assessment of such an LHR for high-resolution LTE molecular thermal emission spectroscopy, and demonstrate a spectrally resolved atmospheric signal from CO_2 and water vapor (H_2O). First, the implementation of the breadboard instrument is described, as well as the rationale behind the design choices. Secondly, a first iteration of instrumental calibration is sketched out since, in contrast to transmission measurements, emission spectroscopy requires radiometric calibration to infer quantitative information from signals. Thirdly, the instrument demonstrator is

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Spotlight Summary by Simone Lolli

Spectrally resolved thermal emission of atmospheric gases measured by laser heterodyne spectrometry

The matter constituting the universe continuously interacts with electromagnetic radiation; each molecule in thermal equilibrium with its environment emits a spectrum of electromagnetic radiation (the so-called *thermal radiation*) that peaks towards shorter wavelengths as the temperature grows (the famous Wien's displacement law). The blackbody spectrum is modulated for each gas by its absorptivity, so that thermal emission spectra can be used to identify molecules. In their study, Hoffmann and coauthors aim to fully characterize Earth's thermal infrared radiation of atmospheric gases at very high spectral resolution. This would permit quantitative assessment of important thermo-physical information on the atmospheric gases: temperature, pressure, local thermodynamic equilibrium (LTE), and velocity. For the first time, the authors of this *Optics Letters* article applied the laser heterodyne spectro-radiometry (LHR) technique to measure LTE emission lines of terrestrial atmospheric gases with high-spectral resolution (up to 0.02 cm^{-1}). The LHR spectroscopy technique was previously used only to resolve predominantly non-LTE gas emissions in the atmospheres of other planets and never on Earth—this despite its operational advantages, as the LHR spectroscopy technique doesn't require solar illumination, so that it can operate both at night and under a cover of clouds. This innovative development is an elegant solution, and cheaper with respect to the complex and large cooled spectrometers used until now to resolve the spectral lines with poor radiance contrast emitted by atmospheric molecules at LTE.

Article Reference

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Opt. Lett. **43**(16) 3810-3813 (2018) View: Abstract | HTML | PDF

Article Information

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Conclusion

- Miniaturized GHG-LHR is ready for IOD
  - Assessing biases through long term ground based campaigns
- First ever demonstration of spectrally resolved atmospheric emission
  - Path to nadir and emission limb sounding
- Next steps
  - Implement novel nanoantenna's mixers
  - Demonstrate spectral multiplexing
  - Demonstrate spatial multiplexing

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