Mid IR Coherent Remote Sensing of Chemicals

…using QCLs, of course

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Outline

- Introduction
- Coherent (heterodyne) advantages
- Historical perspective
- Coherent systems
  - Passive laser heterodyne radiometer
  - Active coherent laser spectrometer
  - Chirped laser dispersion spectrometer
- Conclusion

Introduction

Observational requirements in remote sensing

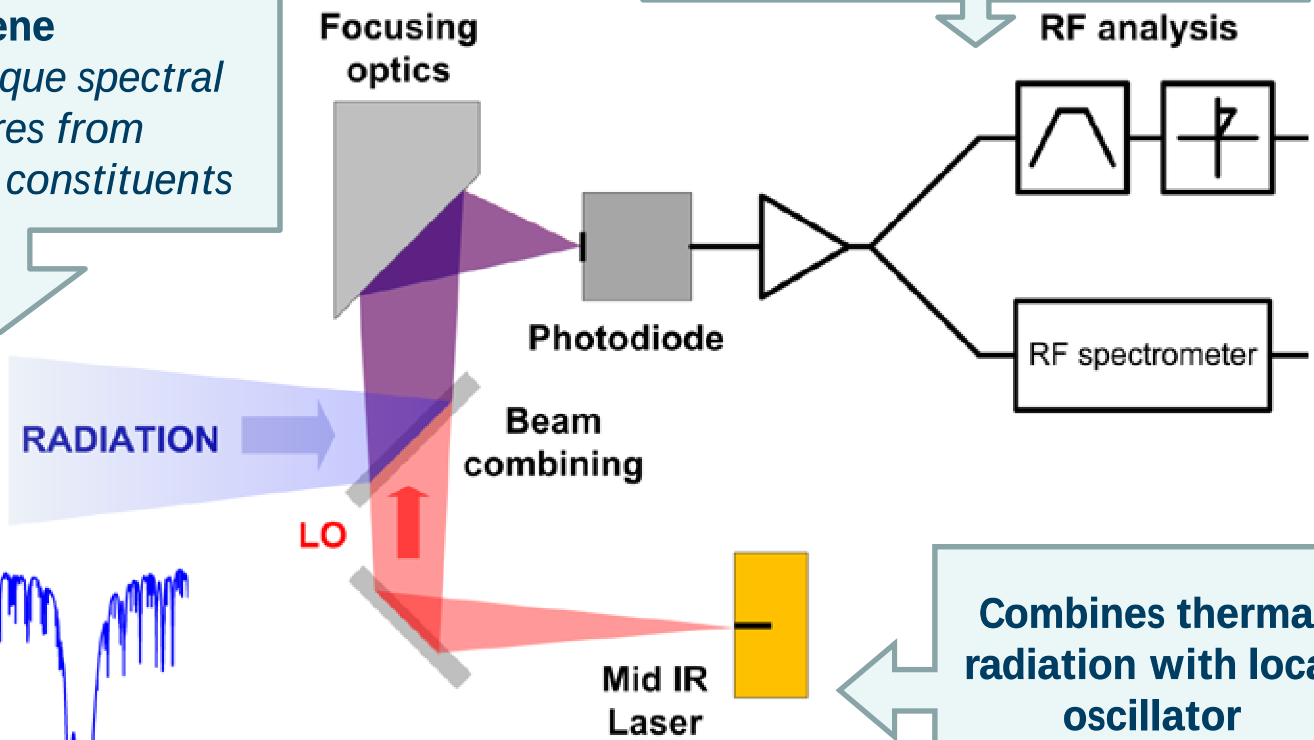
- Remote sensing of our environment
  - Atmospheric composition information
    - Setting model constraints
    - Model validation
  - Ground-based, airborne, spaceborne
- Requirements for remote sounders
  - Driven by the need of fine meshes for models
    - Higher geographical resolution
    - Higher altitudinal resolution
    - Higher sensitivity and traceability

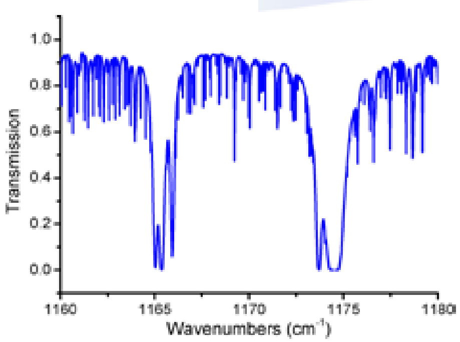
Optical Heterodyne Spectroscopy

Basic principles

Collects radiation from the scene
contains unique spectral signatures from atmospheric constituents

Non linear mixing
Down conversion into RF domain





Combines thermal radiation with local oscillator
Laser

Advantages in Remote Sounding

Merits	Figures	Remote sounding benefits
High sensitivity Shot noise limited	**NEP = 4.10^{-16} W** (10µm -1s) **NESR = 120 nW/cm^{-2}.sr.cm^{-1}**	**Detection of ultra-low concentration traces** **High accuracy - Heterodyne gain**
High spectral resolution Set by electronic filters	**Resolving power > 10^6** Resolution down to **~10 MHz** Highest in the thermal IR	**Full lineshape resolution** **Deconvolution of altitudinal information** **Usage of spectral micro-windows**
High spatial resolution Coherent FoV	10 cm aperture gives **FoV = 0.13 mrad = 27 arcsec** Þ ~50 m LEO , ~4km GEO	**Ultrafine geographical coverage** **Higher altitude resolution (limb)** **Less cloud interferences - Localized emission**
Electrical definition of **Instrument Lineshape**	**Directly measureable** to a high level of accuracy	**No ILS artefact** **ILS stability with sounding configuration**
Miniaturization Enabled by QCLs	**0.01 m3 – few kg – 30 W**	**Deployment on small satellites, piggy-backing, UAVs, HALE, ground networks…**
Phase information		**Interferometry** **Dispersion measurements**

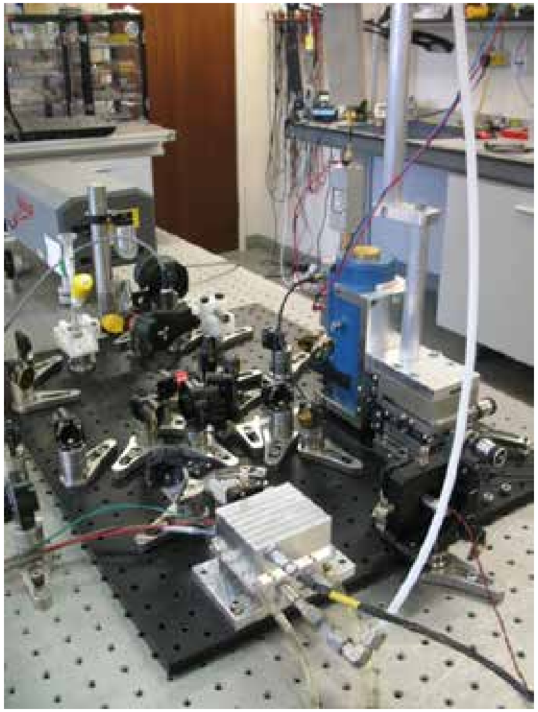
Optical Laser Heterodyne Spectroscopy
Historical Perspective (Mid IR)

- High accuracy molecular resonance frequencies

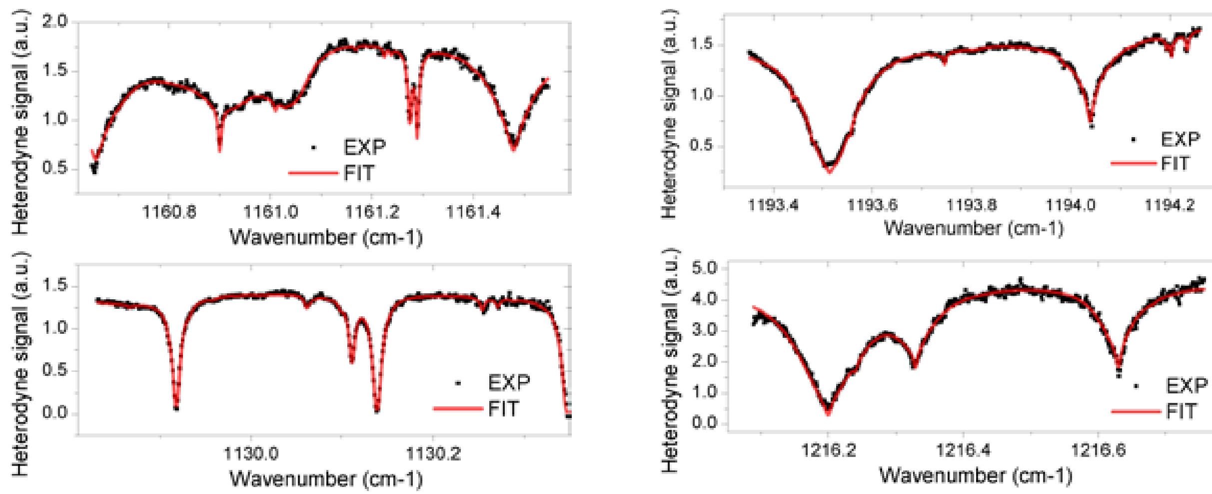
- Atmospheric applications
  - Ground based observation (Menzies, 1974)
    - Pollution, stratospheric chemistry, …
  - Space based planned (shuttle)

- Ground-based Astronomy
  - Titan stratospheric winds (Kostiuk, 2005)
  - Gain amplification on Mars and Venus (Mumma, 1981)
  - Shoemaker Levi collision with Jupiter
    - NH_3 temporal behaviour (Fast 2005)
  - Mount Wilson infrared interferometer

Laser Heterodyne Spectro-Radiometer



Atmospheric transmission in several narrow windows



Full lineshape information recovered

- contains the integrated altitudinal lineshapes

Narrow spectral windows (< 1cm^{-1})

- can be optimized to increase information content
- limits interference
- Better control on error propagation

Faster retrievals

60 MHz (0.002 cm^{-1})

1/40 solar disk

8-9 µm

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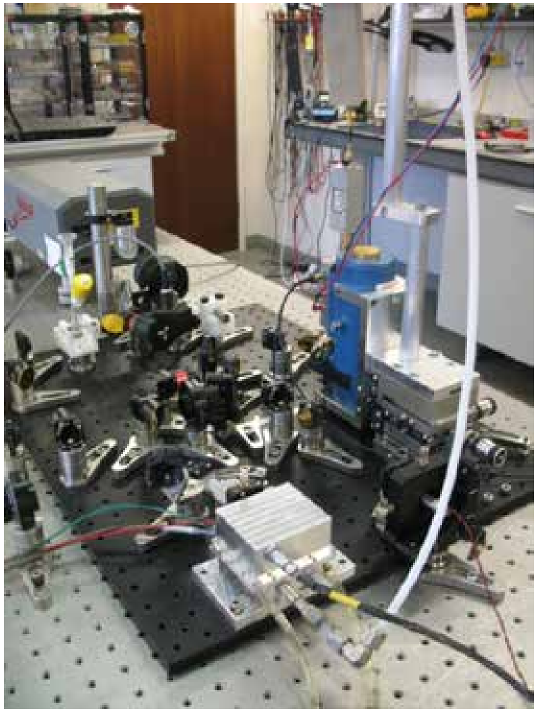
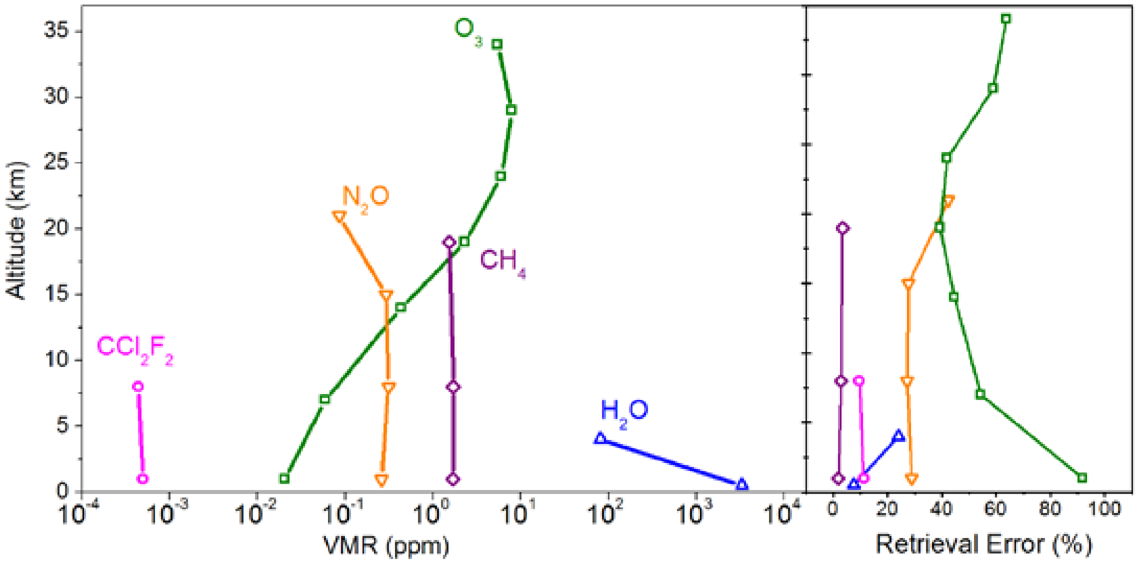
Laser Heterodyne Spectro-Radiometer



Atmospheric altitudinal distribution



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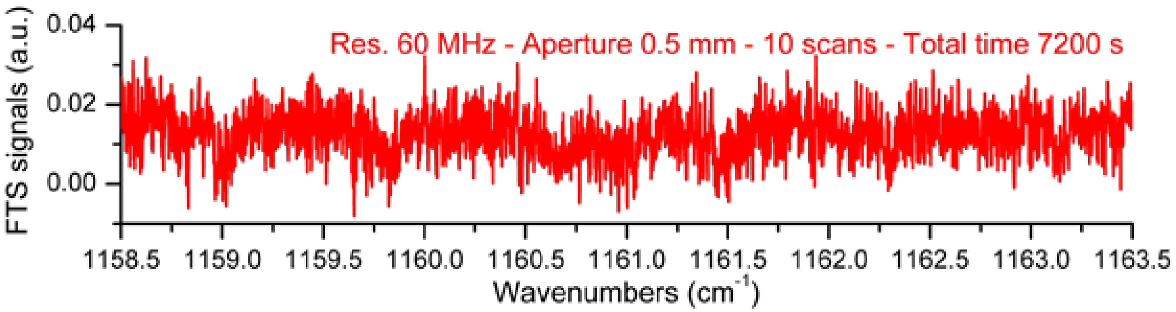
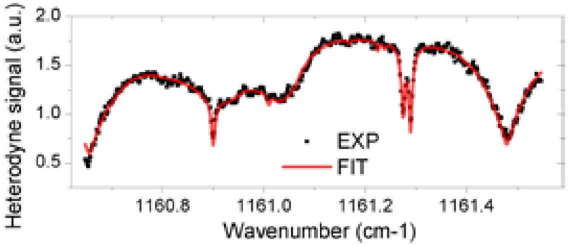
FTIR / LHR Side by Side Comparison

Identical resolution 60 MHz and field of view

Bruker IFS 125HR - 4m x 2m

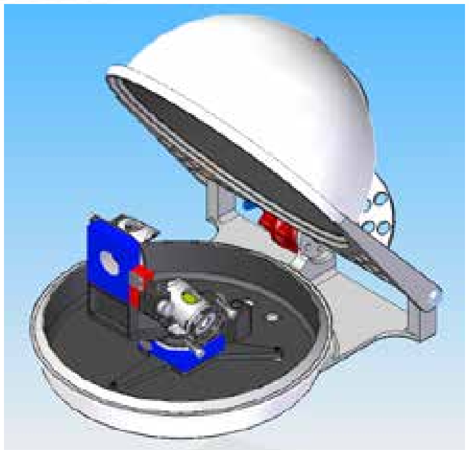
Bench top LHR - 1m² – 1min acquisition

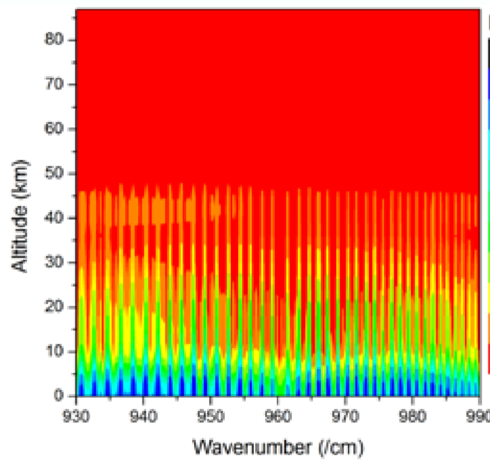


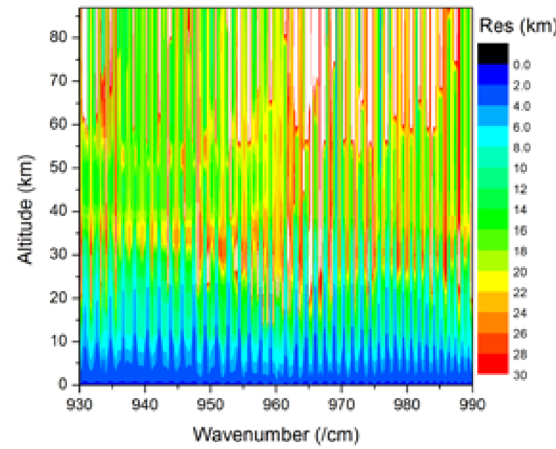


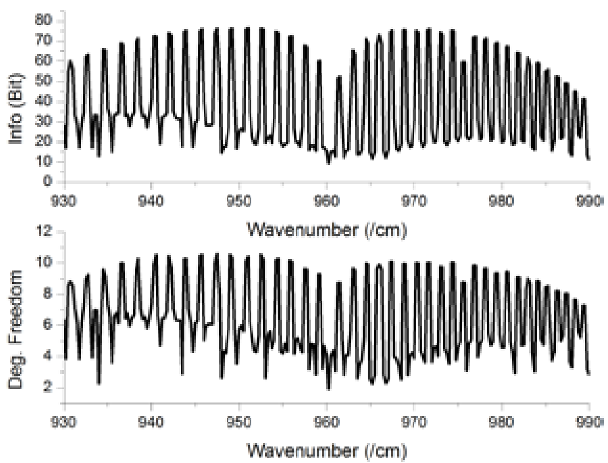
Carbon Dioxide Sensing Programme

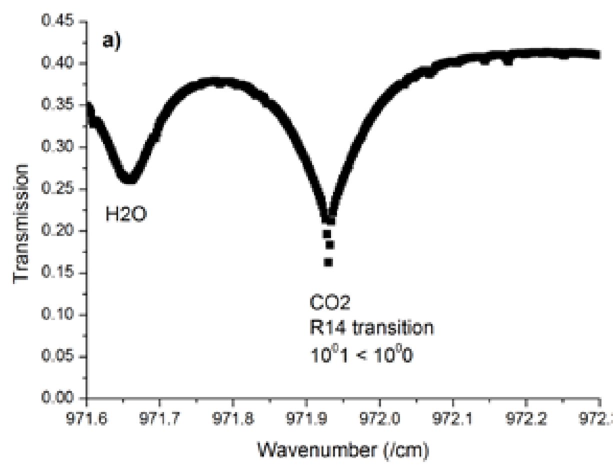
On- going work on ground based LHR

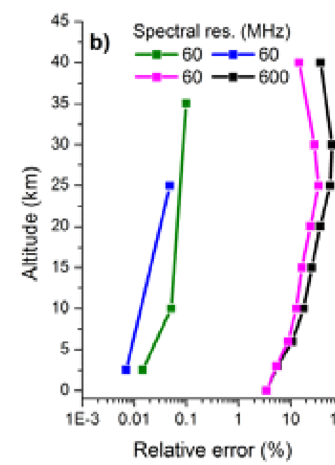












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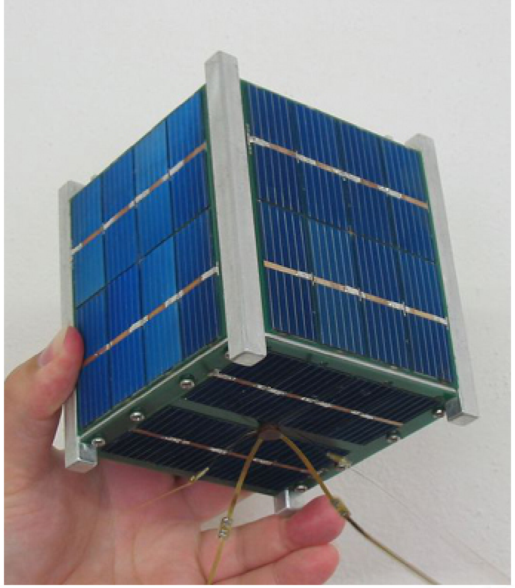
Miniaturization / Ruggedization

Rationale

Ø Easing deployment in any field through
- Reduction of mass
- Reduction of volume
- Increased robustness

Ø Ultimately cost reduction is the prime target
- Launch between $4k-$30k per kilo
- Up to few $M for piggy-backing
- Cost of space qualification

Ø Also new environmental sounding opportunities
- Novel airborne platforms (UAVs, HALE)
- Development of micro- and nano-satellites (1-10 and 10-100 kg resp.)
- Piggy backing
- Dense ground network



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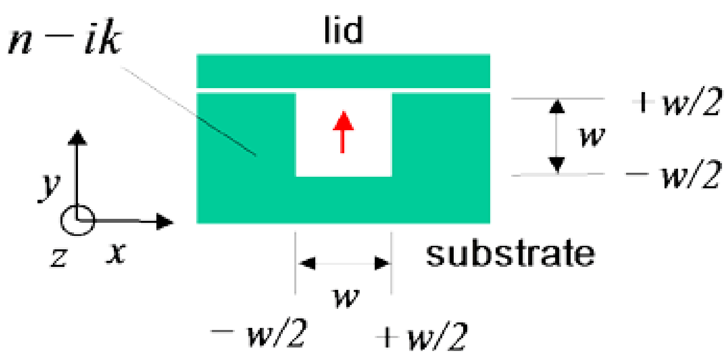
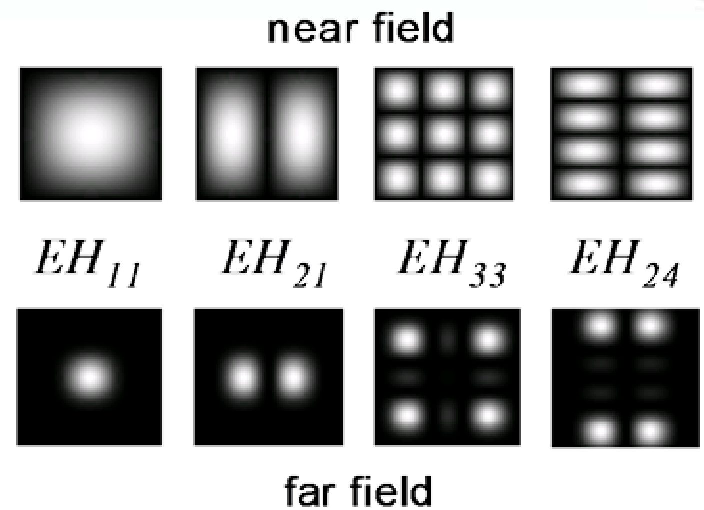
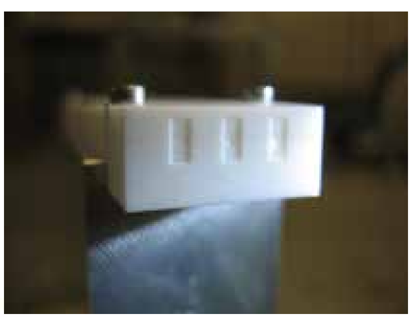
Multimode Hollow Waveguide





$$T_{pq_{dB}} = -4.35 \frac{\lambda^2}{w^3} \left[p^2 \, Re\left(\frac{1}{\left\{ (n-ik)^2 - 1 \right\}^{1/2}} \right) + q^2 \, Re\left(\frac{(n-ik)^2}{\left\{ (n-ik)^2 - 1 \right\}^{1/2}} \right) \right]$$

Hollow waveguide channels



Prof. Mike Jenkins

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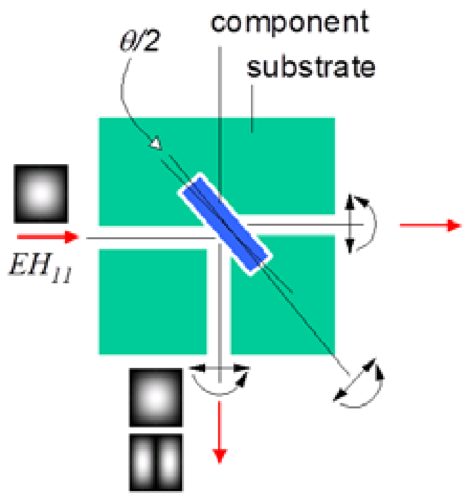
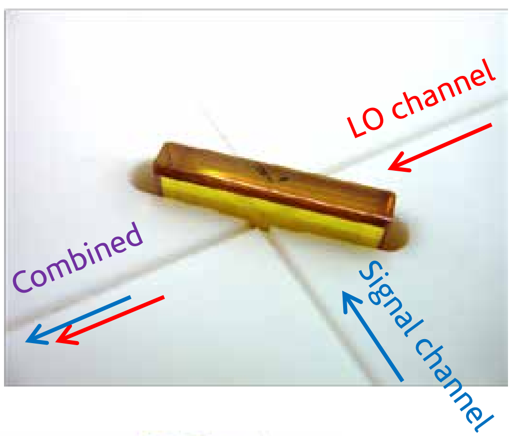
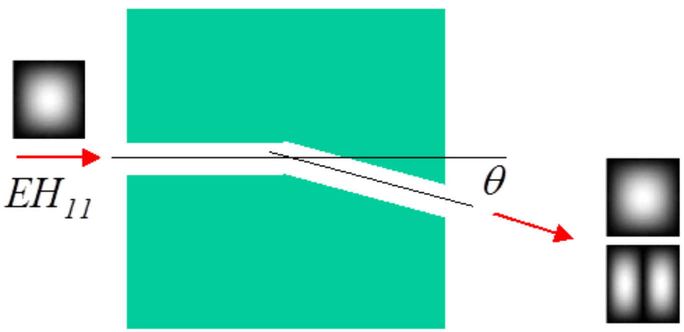
Optical Integration & Tolerancing

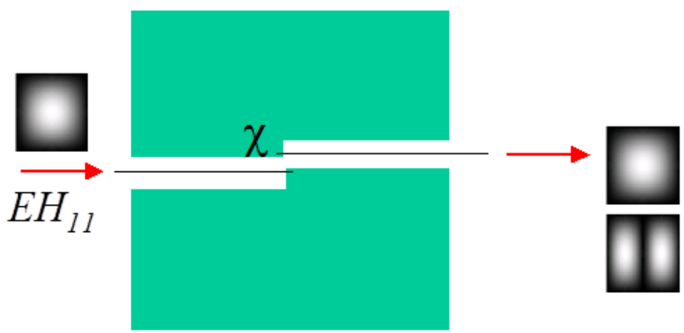




angular misalignment



lateral misalignment



design criteria

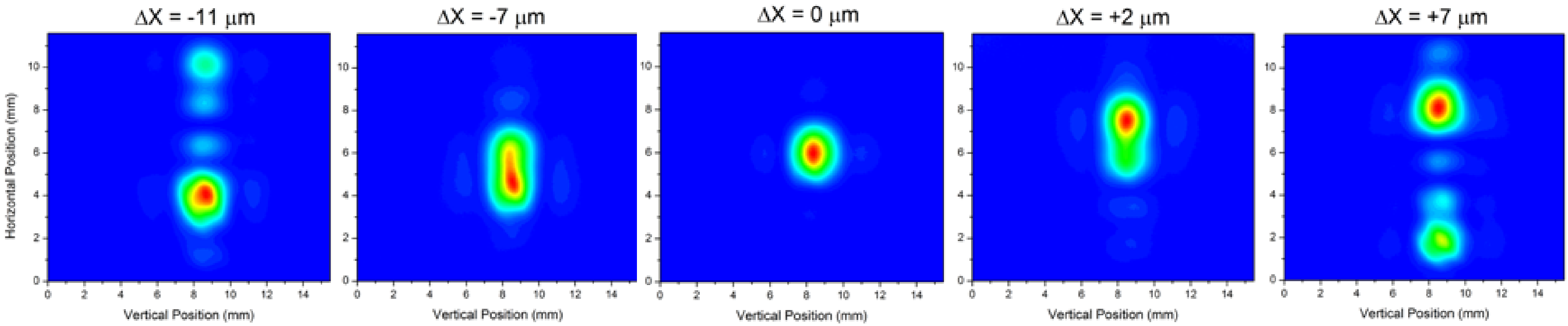
$$\boxed{\theta \leq \frac{\lambda}{5w}}$$

$$\boxed{\chi \leq \frac{w}{15}}$$

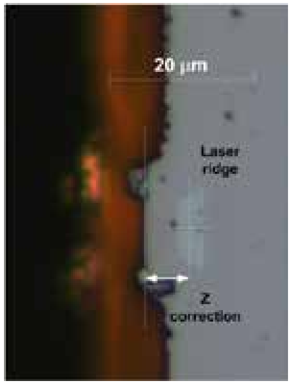
Optimum Coupling Assessment

Far field profiles (0.750 mm guide width)

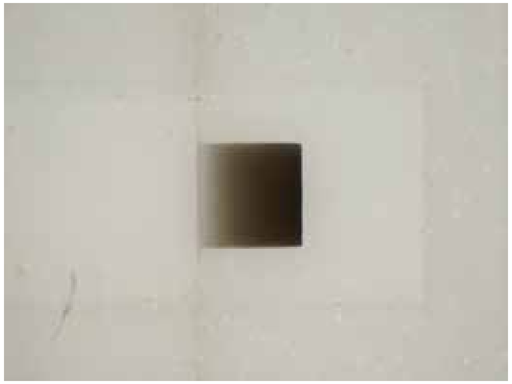
Lateral coupling : sensitivity < 2 µm



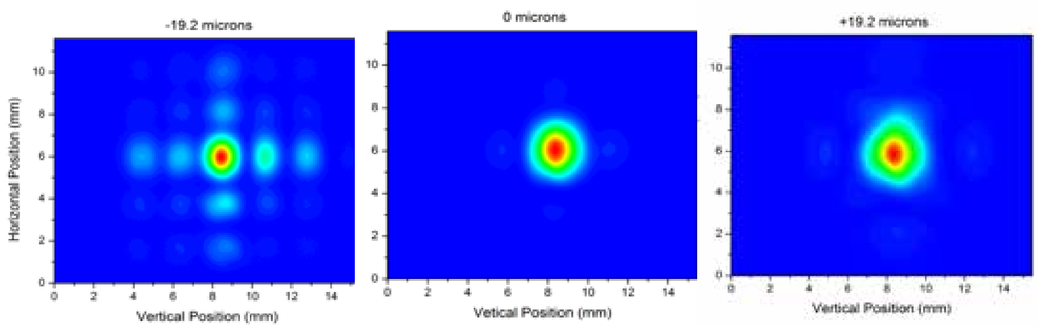
QCL output 4x10 µm²



HW input ~0.75x0.75 mm²

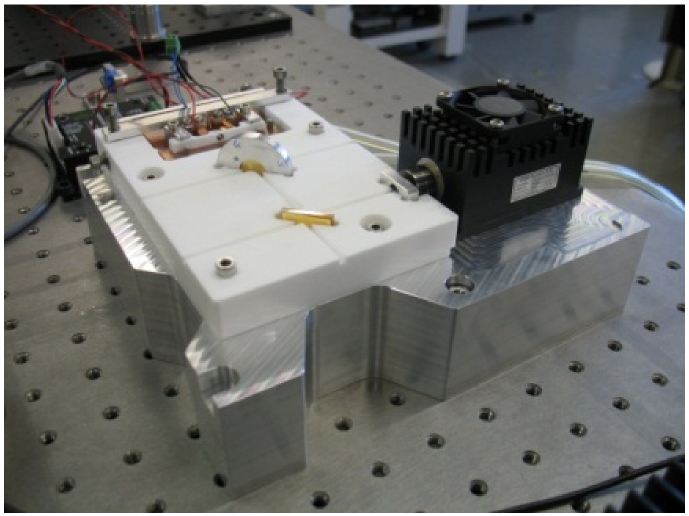


Waist position sensitivity < 10 µm

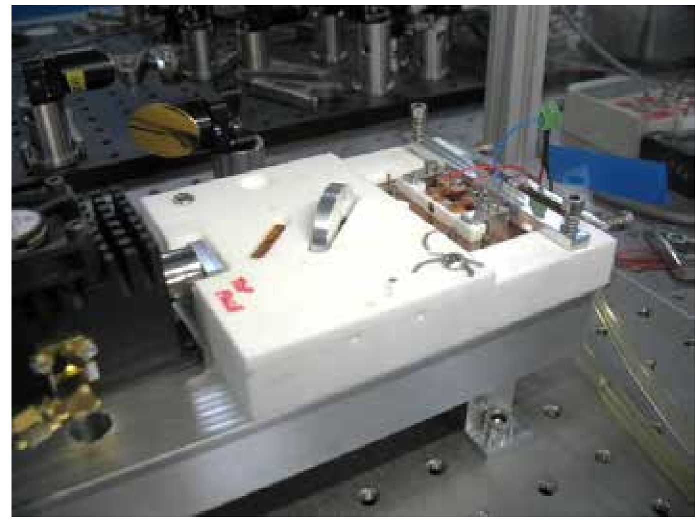


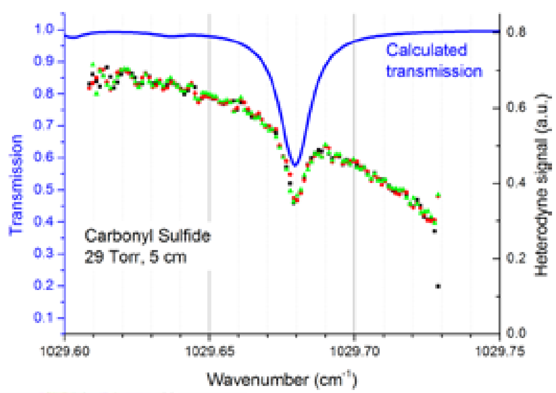
First Miniature LHR Demonstration
Carbonyl sulphide absorption

Iteration 1



Iteration 2 – size further reduced





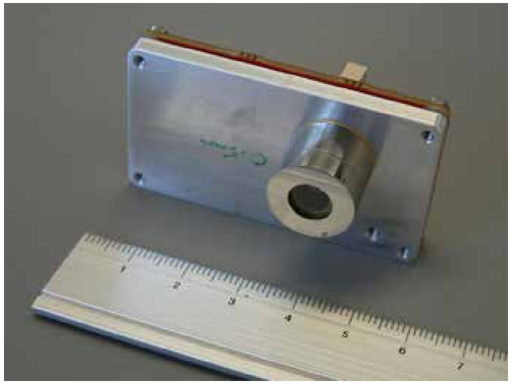
Level of performance achieved almost identical to "open space" traditional LHR using LN2 cooled detector

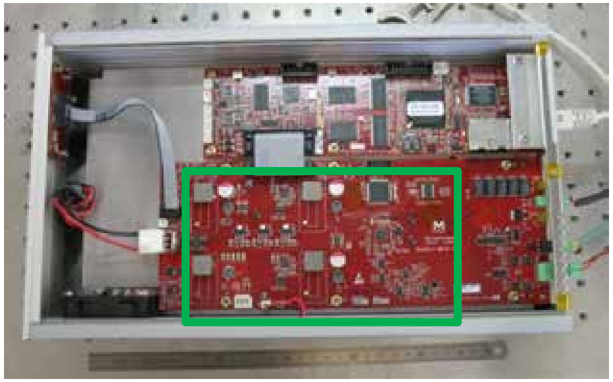
Still issue with the focusing on the detector -> understood and addressable

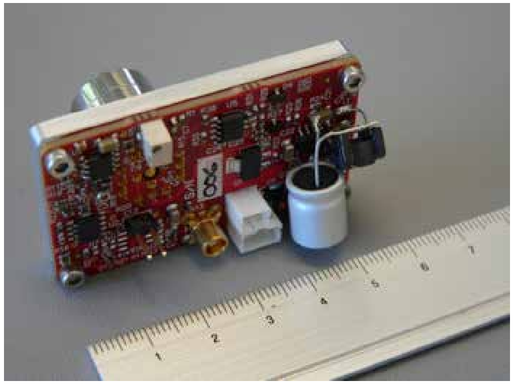
Miniaturization of Control Electronics

QCL Driver – Photomixer

- Miniaturization QCL control
  - 10 x 20 cm board
  - While power efficiency X2
  - While stability X4
- Miniaturisation of detector electronics
  - T control and preamp







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Active Version of LHR

- Ø Passive system well suited for long range TIR and FIR remote sounding
  - – Such as GEO, LEO, HAP
  - – Need thermal contrast
- Ø For terrestrial activities such as
  - – Highly localized emissions
    - Seeps of gas – Emissions
  - – Low concentration – low vapour pressure
  - – Short plume
- Ø An “active” version of the LHR was developed
  - – Active Coherent Laser Spectrometer (ACLaS)
  - – Mid infrared spectroscopic heterodyne lidar

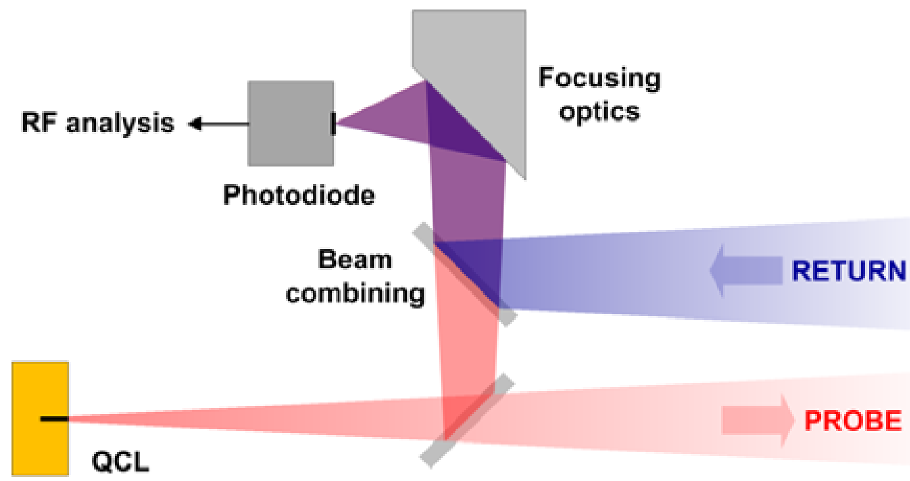
Benefits of ACLaS

Inherit advantages of LHR + new ones

High detection sensitivity (femtoWatts)

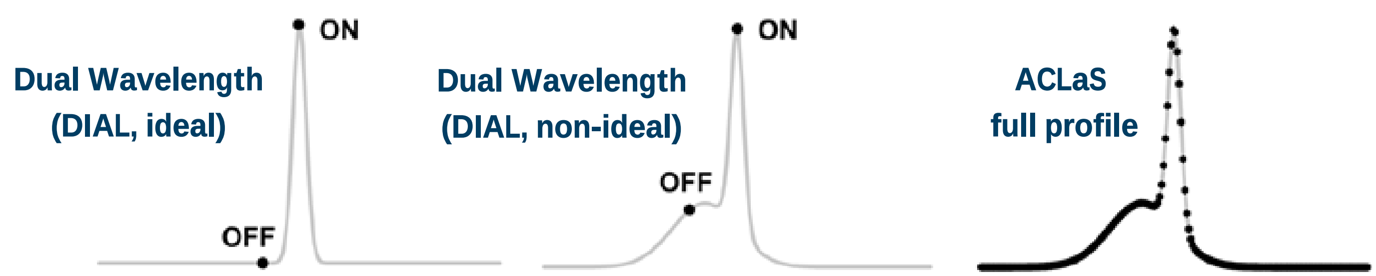
Ultra high spectral resolution: ~1MHz !!! (0.00003 cm^{-1})

- Can match the 1 MHz laser linewidth
- Immune to laser frequency noise
- Full profile information



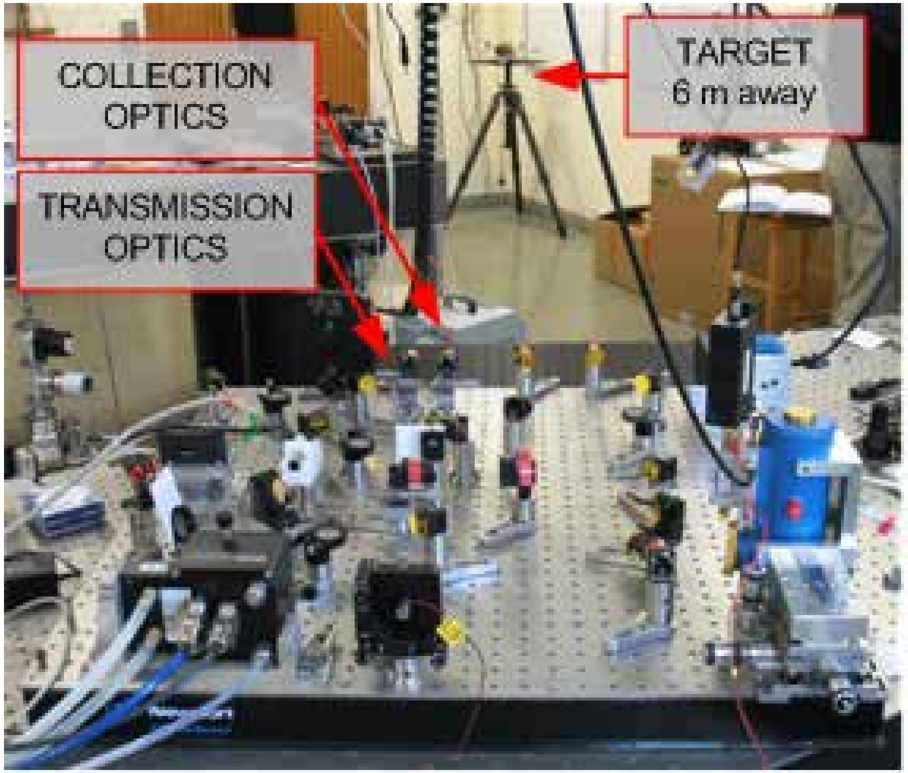
High spatial resolution (narrow FoV)

- Identification of highly localized releases before dispersion
- Potential for high resolution imaging

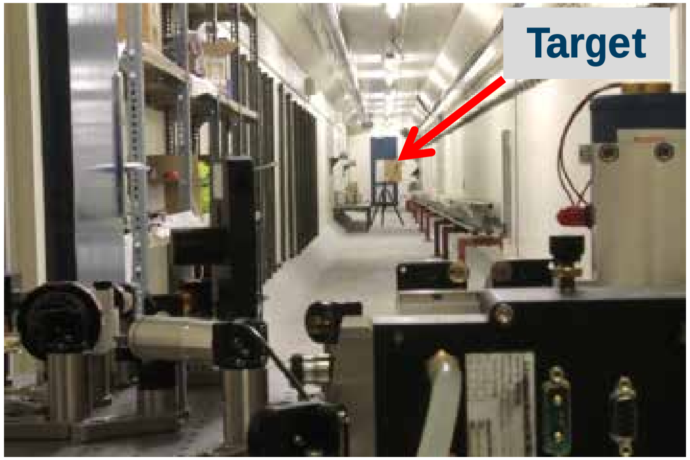


Bench Top Demonstrator of ACLaS

Short range tests 1 – 6 m

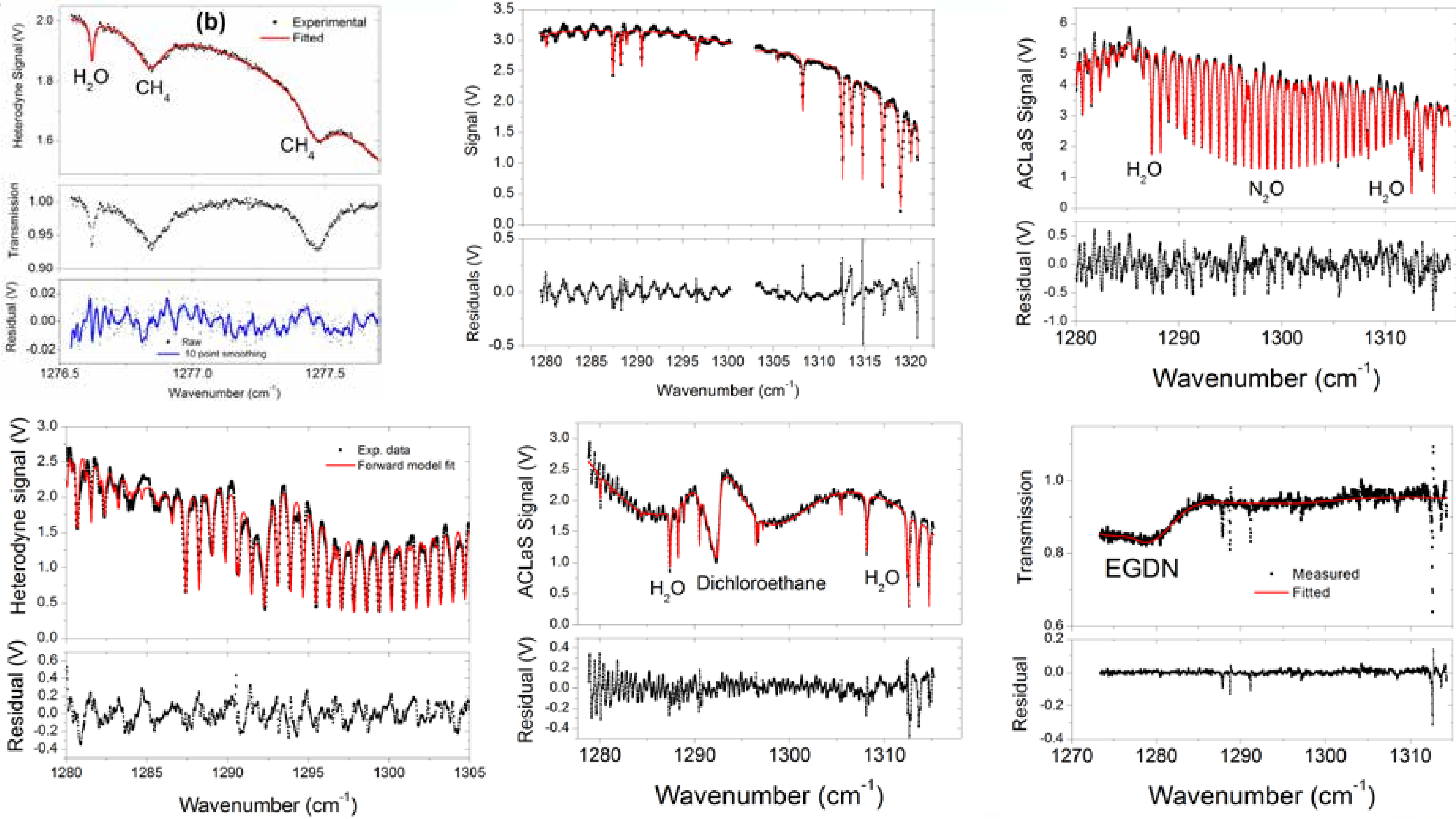


Medium range, up to 65 m



Some Results

H2O, CH4, N2O, H2O2, DCE, EGDN



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ACLaS Limits of Detection

Normalized to 1 m plume and 1s acquisition

Experimental data

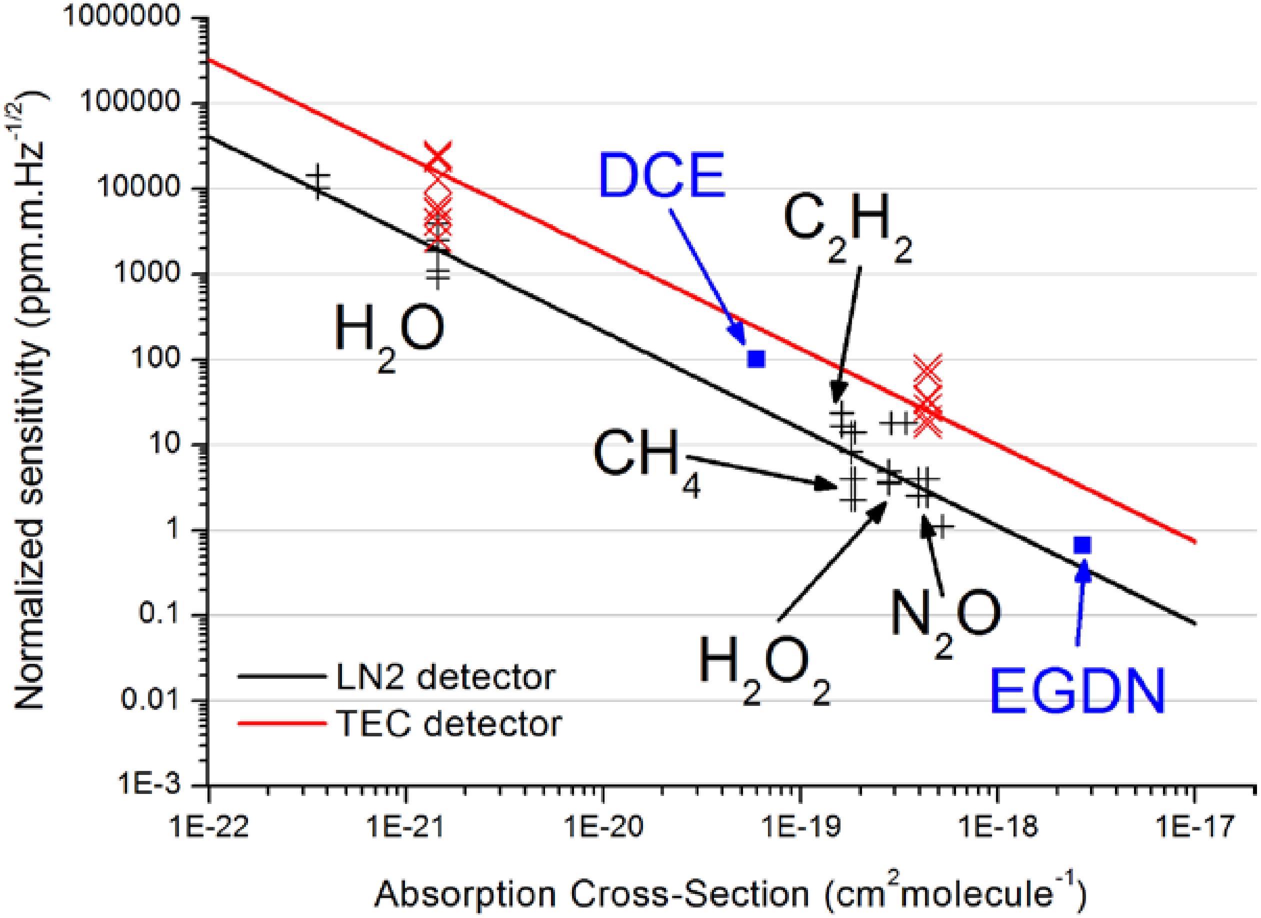
- 6 to 12 m standoff range
- ~20mW laser illumination
- EC-QCL degrades sensitivity by ~one order of magnitude

Projected improvements

- 200 mW still well eye safe -> 10X smaller LoD

10^4 improvement SNR

- Compared to ultimate limit
- Speckle reduction needed



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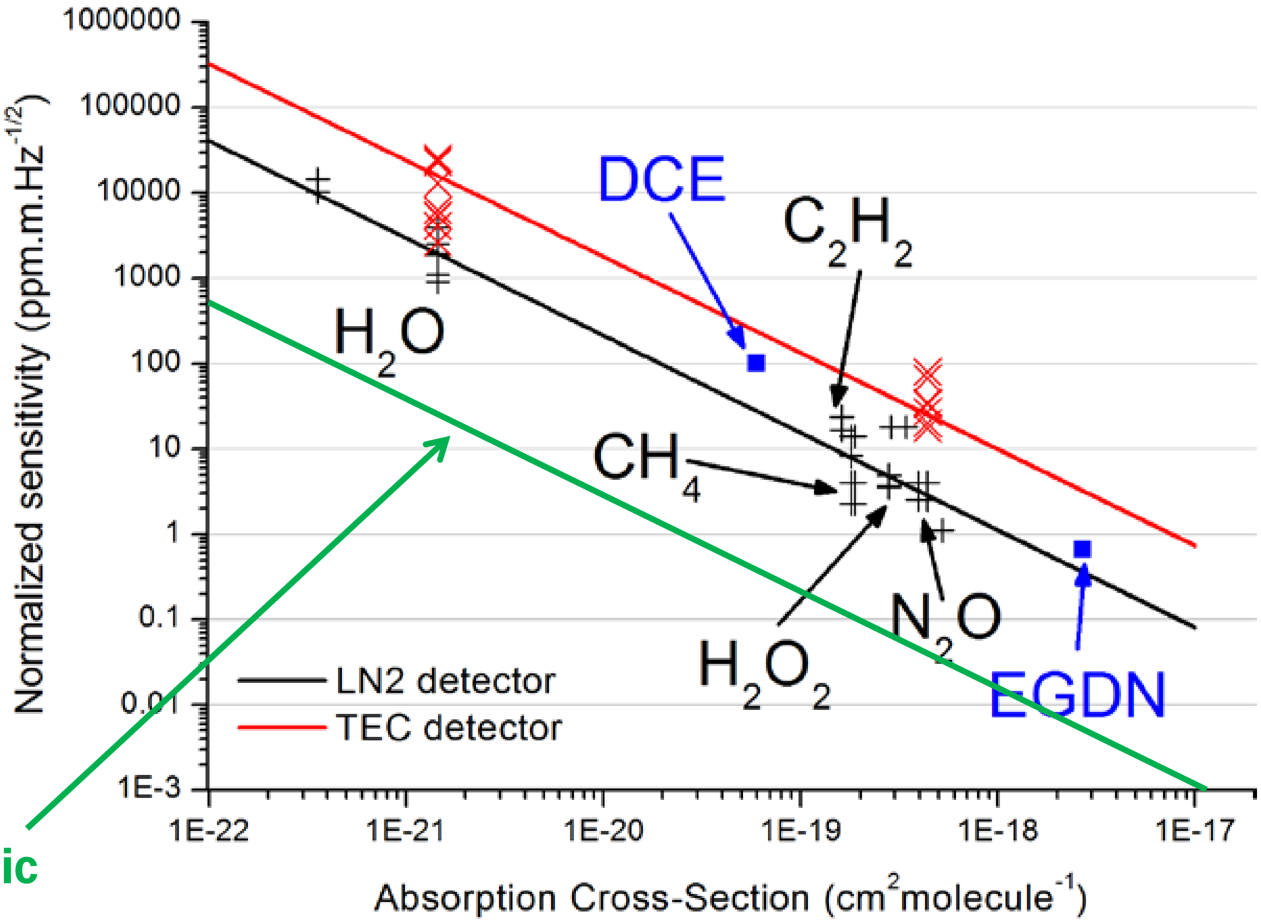
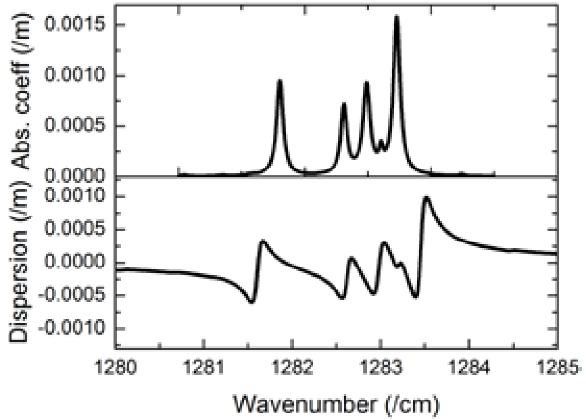


100X improvement realistic

Measuring Molecular Dispersion

Chirped Laser Dispersion Spectrometer (CLaDS)

Atmospheric methane



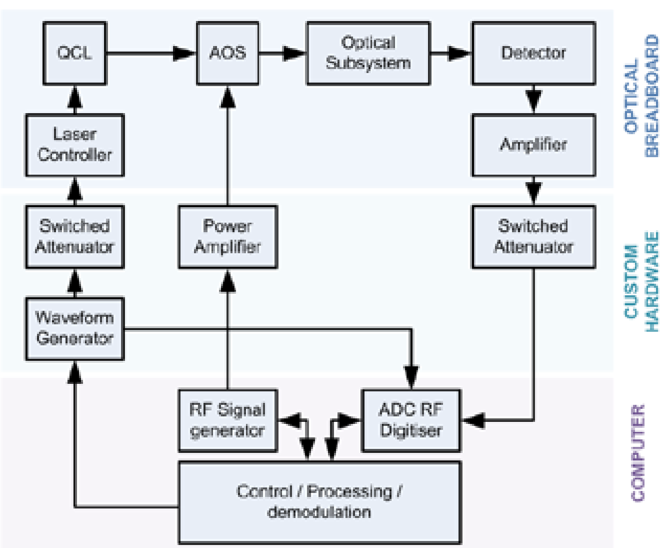
Phase measurement

- Real part of refractive index
- Access to molecular dispersion

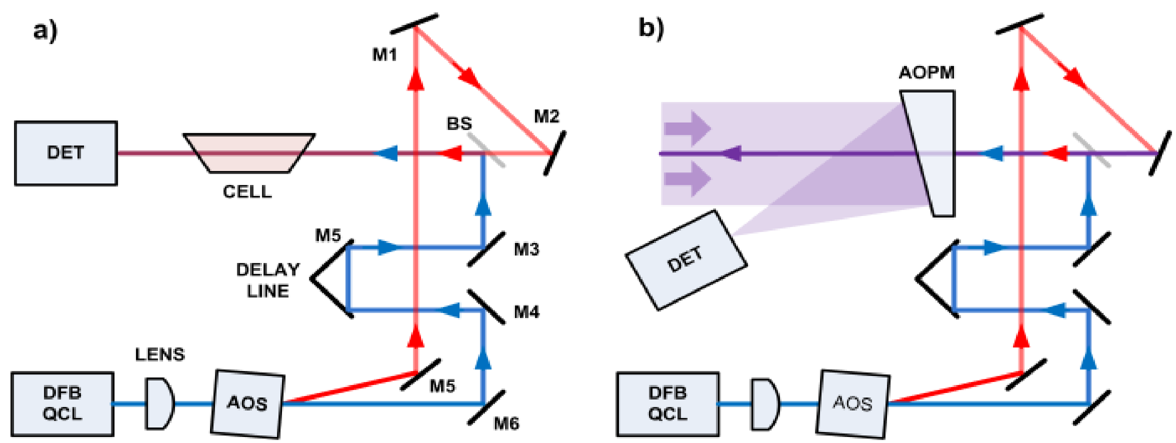
Dispersion signal

- Baseline free
- Linear

Be-spoke Demodulator & analyser



Optical layout



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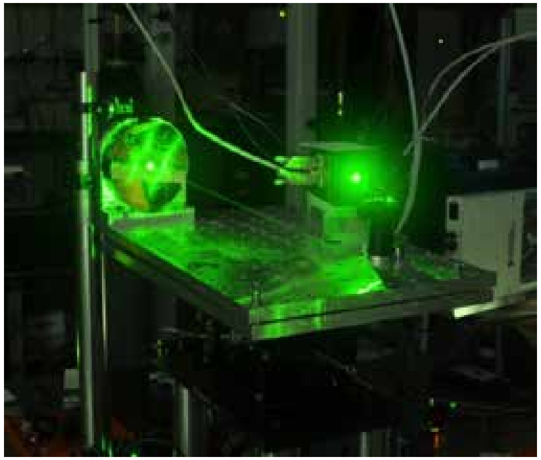
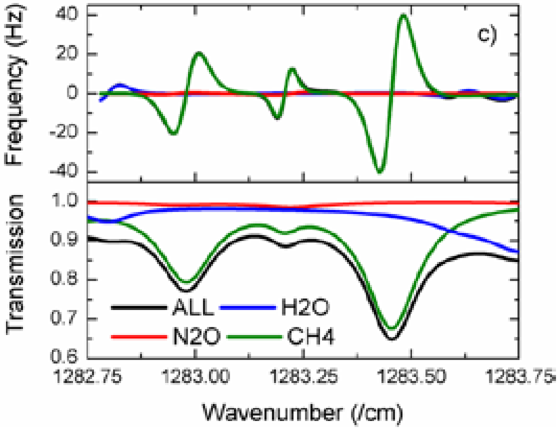
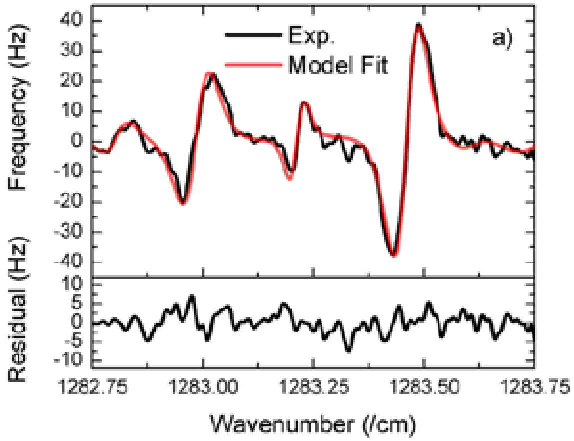
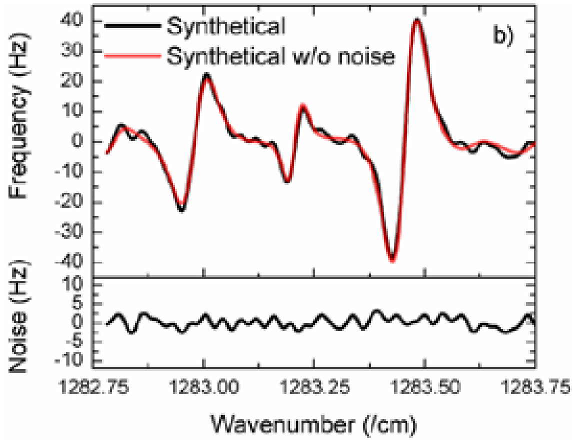
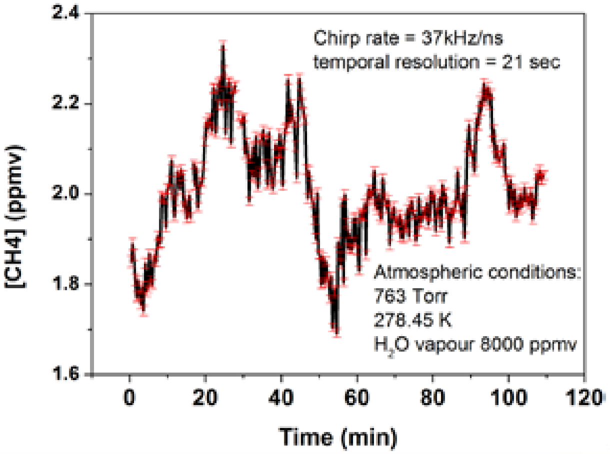
Open-Path Methane Monitoring











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Collaborators

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