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Advanced Infrared Laser Sources for Trace Gas Detection and Chemical Analysis

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OUTLINE

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- Motivation, Design, and Technology Issues
- Infrared Diode and QC Laser Based Gas Sensors
- Performance Characteristics of Compact IR Sensors
- Selected Applications of Trace Gas Detection
- Outlook and Summary

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Applications of Trace Gas Detection

- Urban and Industrial Emission Measurements
  - Industrial Plants
  - Combustion Sources
  - Automobile
- Rural Emission Measurements
  - Agriculture
- Environment Monitoring
  - Atmospheric Chemistry
  - Volcanic Emissions
- Spacecraft and Planetary Surface Monitoring
  - Crew Health Maintenance & Life Support
- Chemical Analysis and Process Control
  - Semiconductor Industry
- Medical Applications

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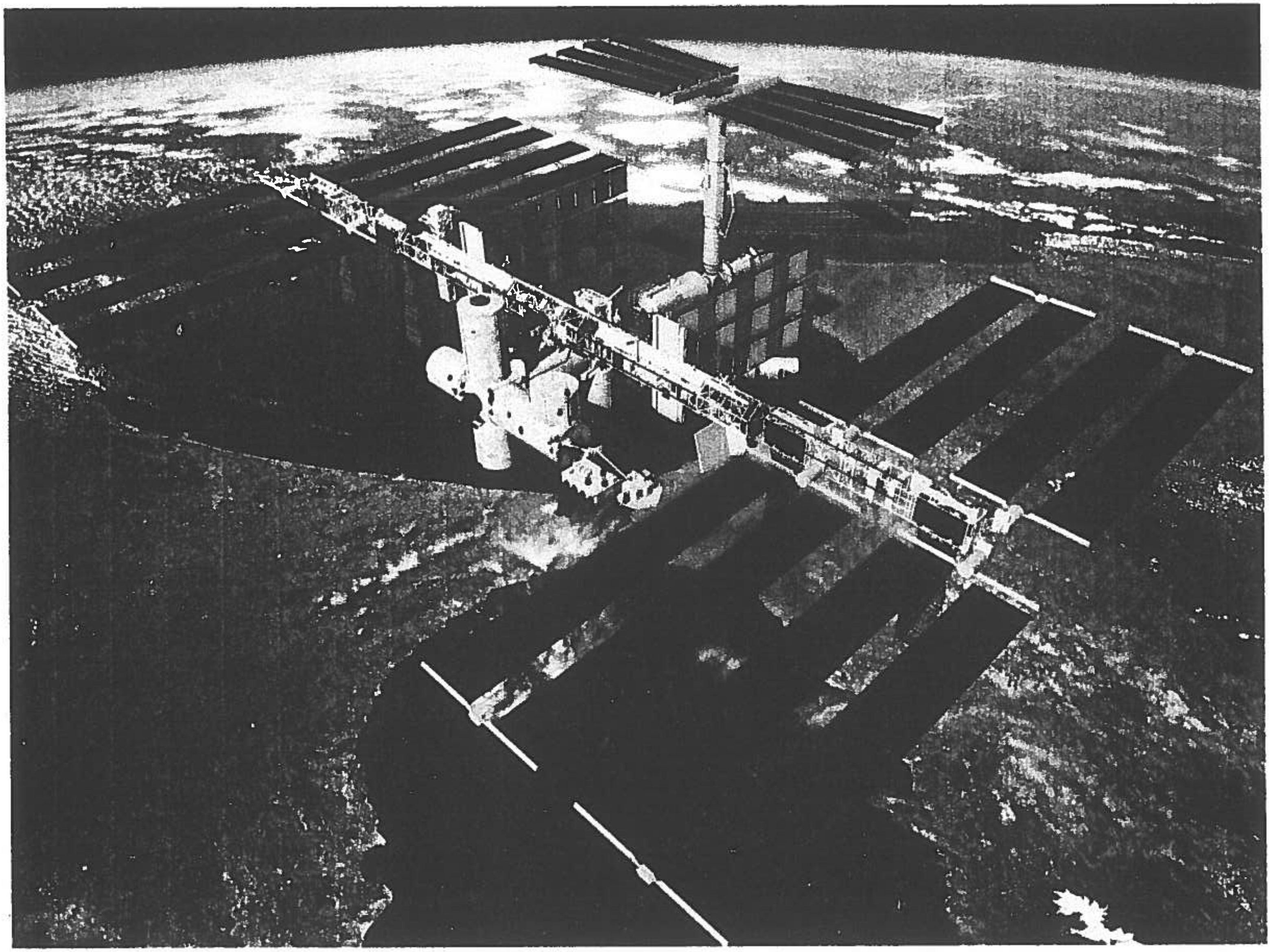
International Space Station



Air Composition

Main Components		Trace Components	
Nitrogen	78%	Methane	1.7 ppm
Oxygen	21%	CO	0.4 ppm
Water	0.8%	N_2O	0.3 ppm
CO_2	0.03 %	O_3	0.03 ppm
		…	

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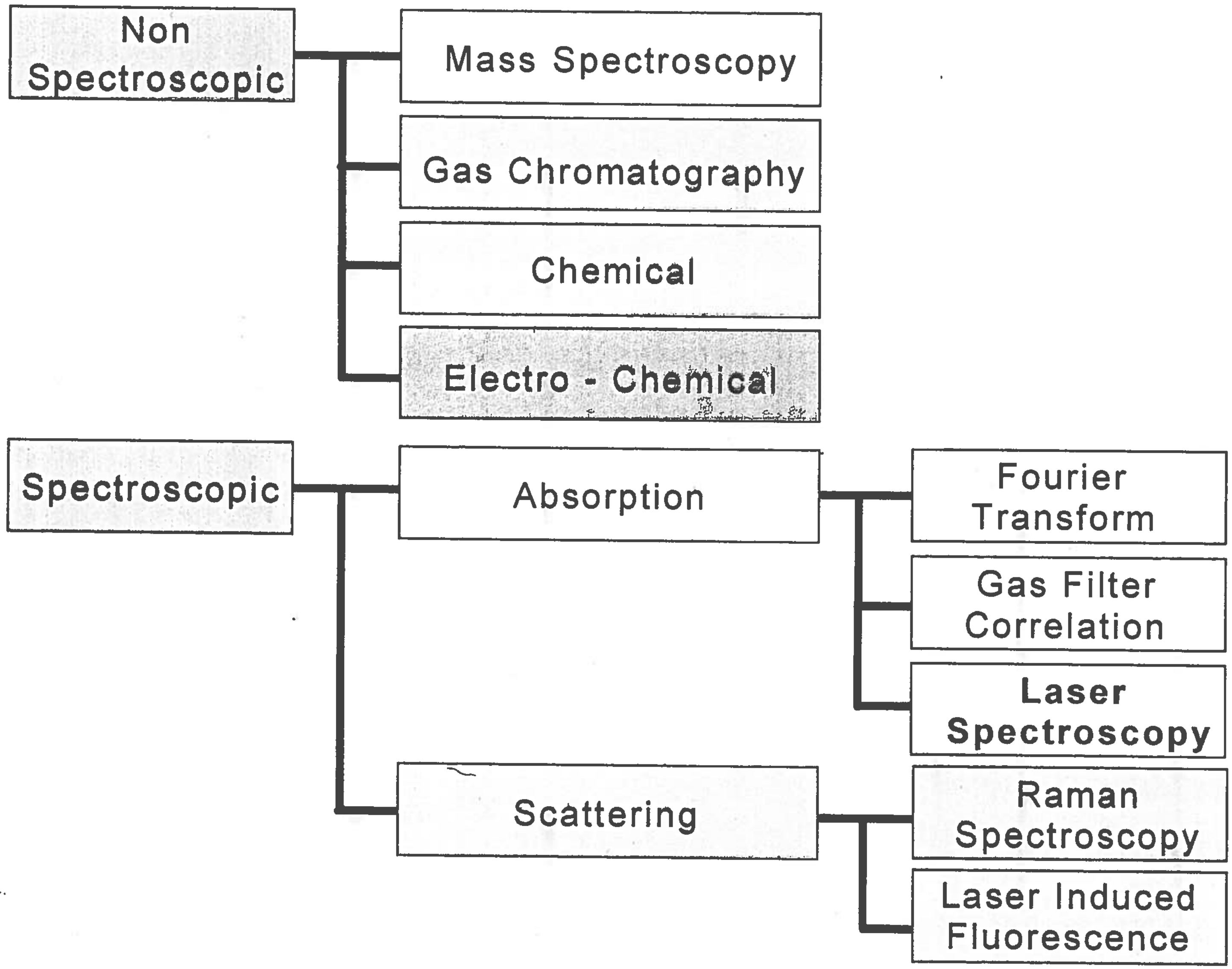
Existing Techniques for Trace Gas Detection



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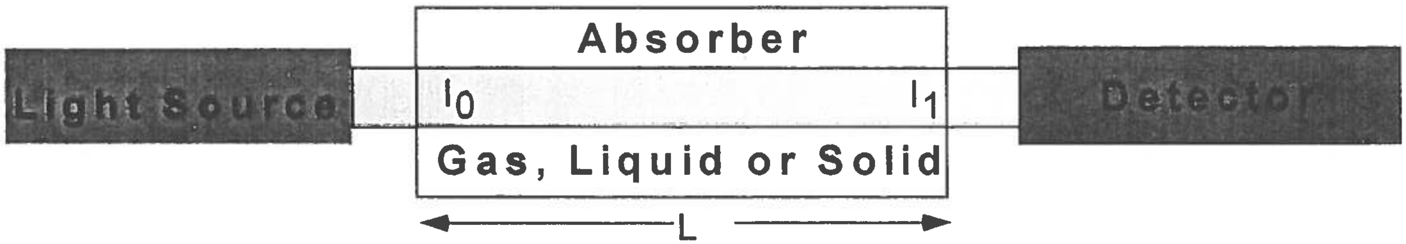
Absorption Spectroscopy



Beer's Law

$$I_1(\nu)=I_0 \cdot e^{-\alpha(\nu)\cdot L}$$

$\alpha(\nu)$-absorption coefficient (cm^{-1}), L- path length (cm), ν - frequency (cm^{-1})

Molecular Absorption Coefficient

$$\alpha(\nu)=C\cdot\frac{S}{\Delta\nu}\cdot g(\nu)$$

C-gas concentration (cm^{-3}), S - absorption line strength (cm), $\Delta\nu$ – linewidth (cm^{-1})

g (ν) - line shape function: Gaussian, Voigt, or Lorentzian profile

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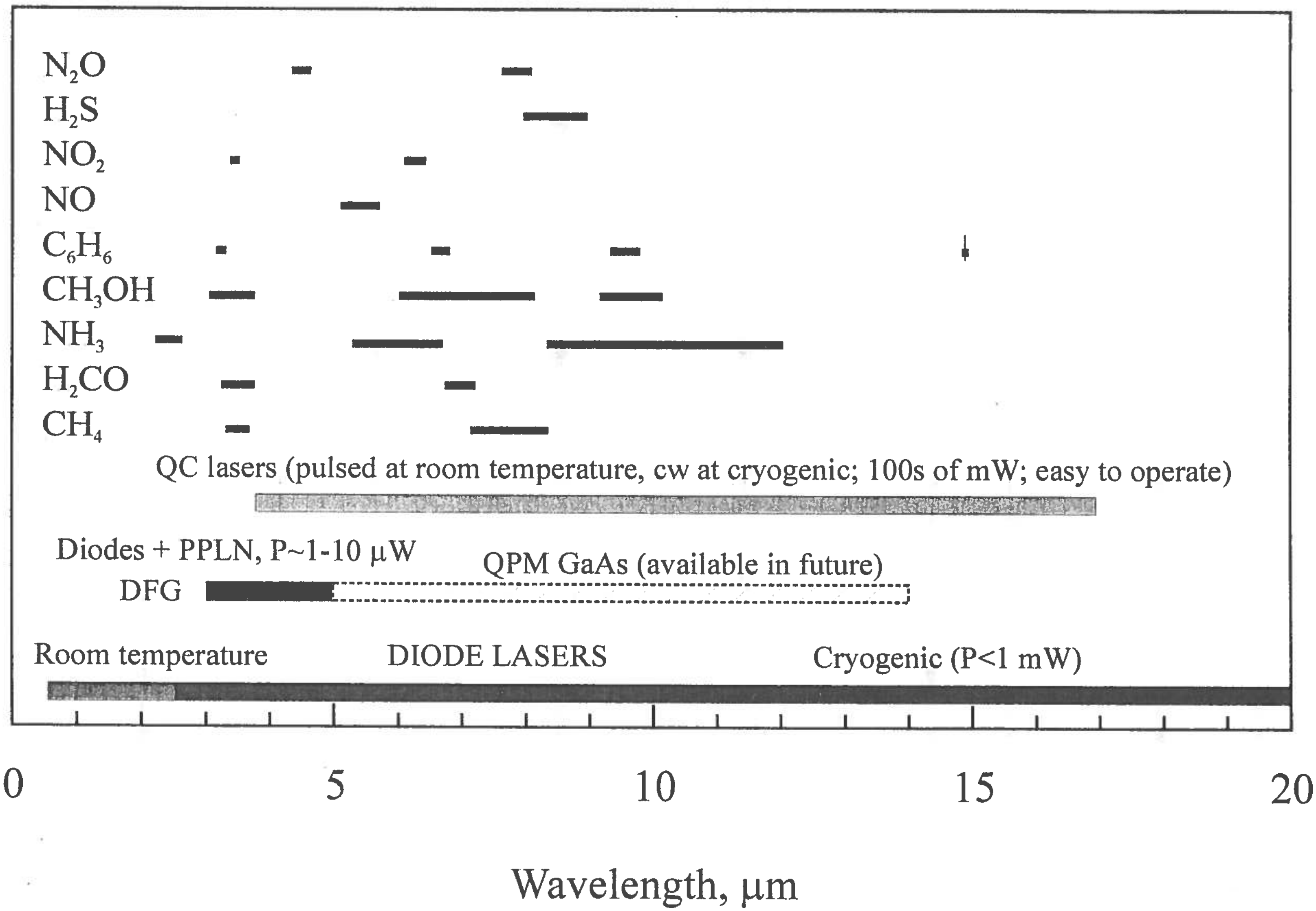
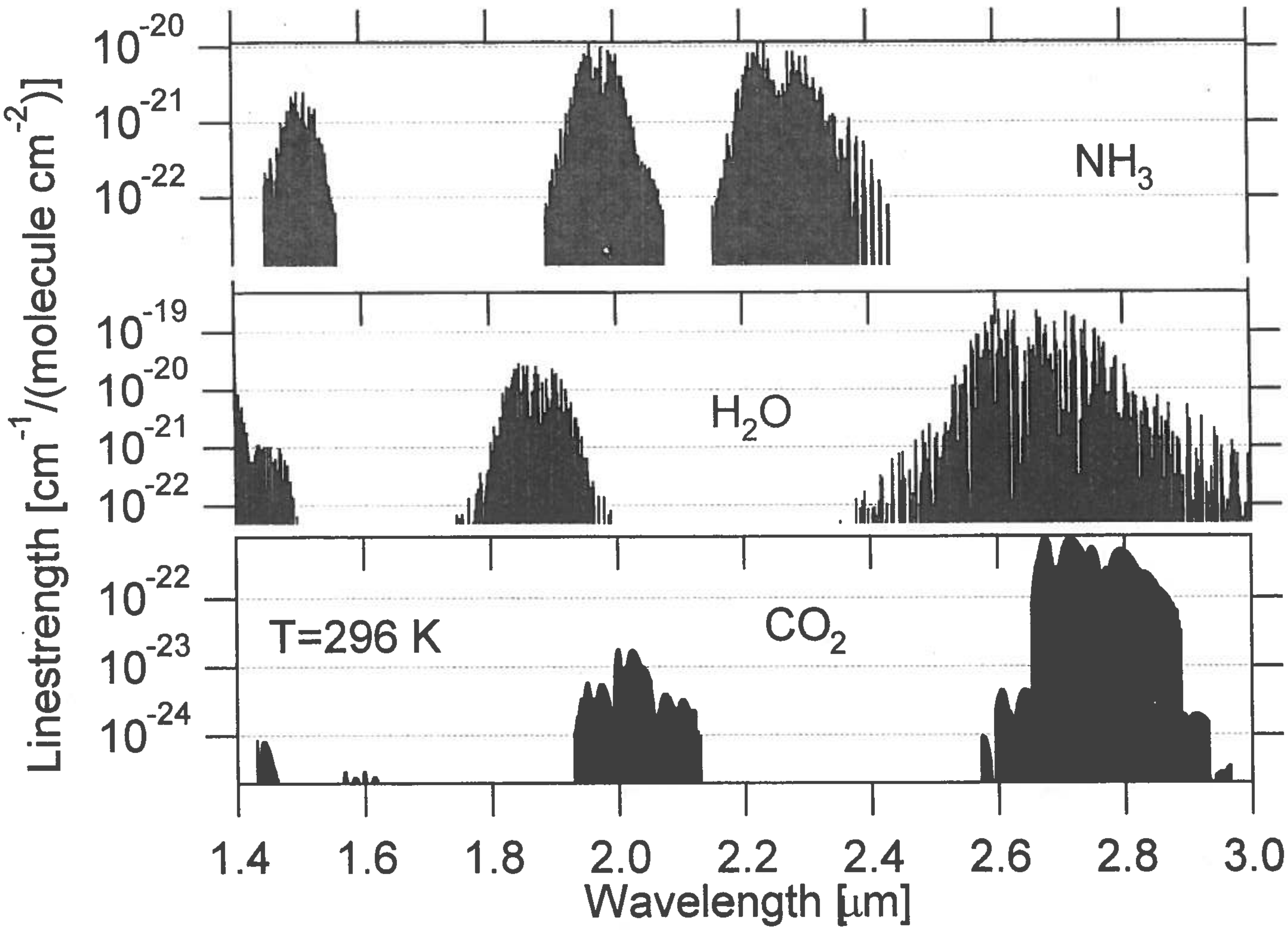
DFG Source Requirement for Spectroscopy

SOURCE	**REQUIREMENTS**
•**Power**	•**Sensitivity**
•**Line Width**	•**Specificity**
•**Tunable**	•**Multi-gas Components**
•**Beam Quality**	•**Directionality**
•**Response**	• **Rapid Data Acquisition**

Spectral Coverage by Diode/QC Lasers



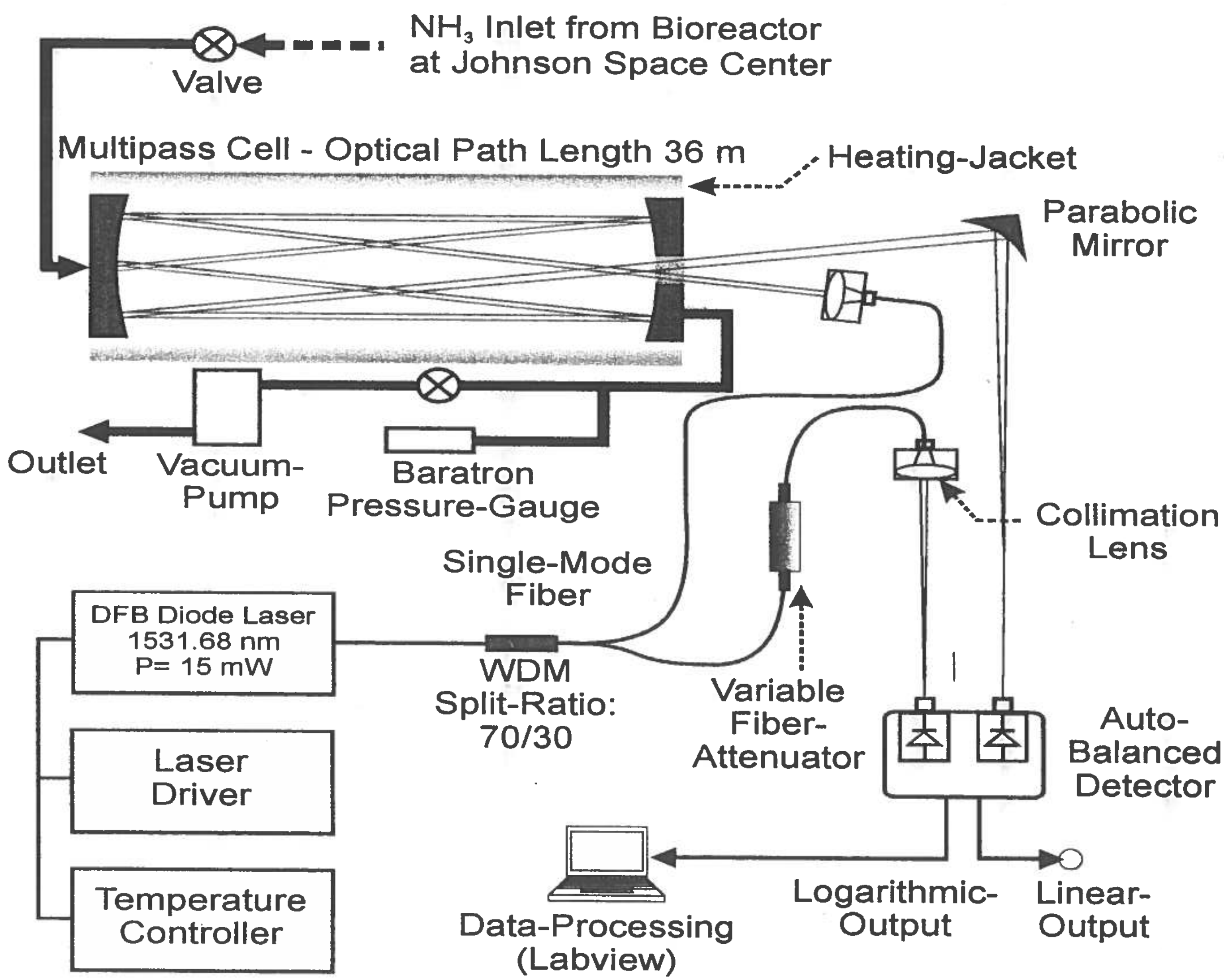
NIR Spectra of NH_3,CO_2 & H_20



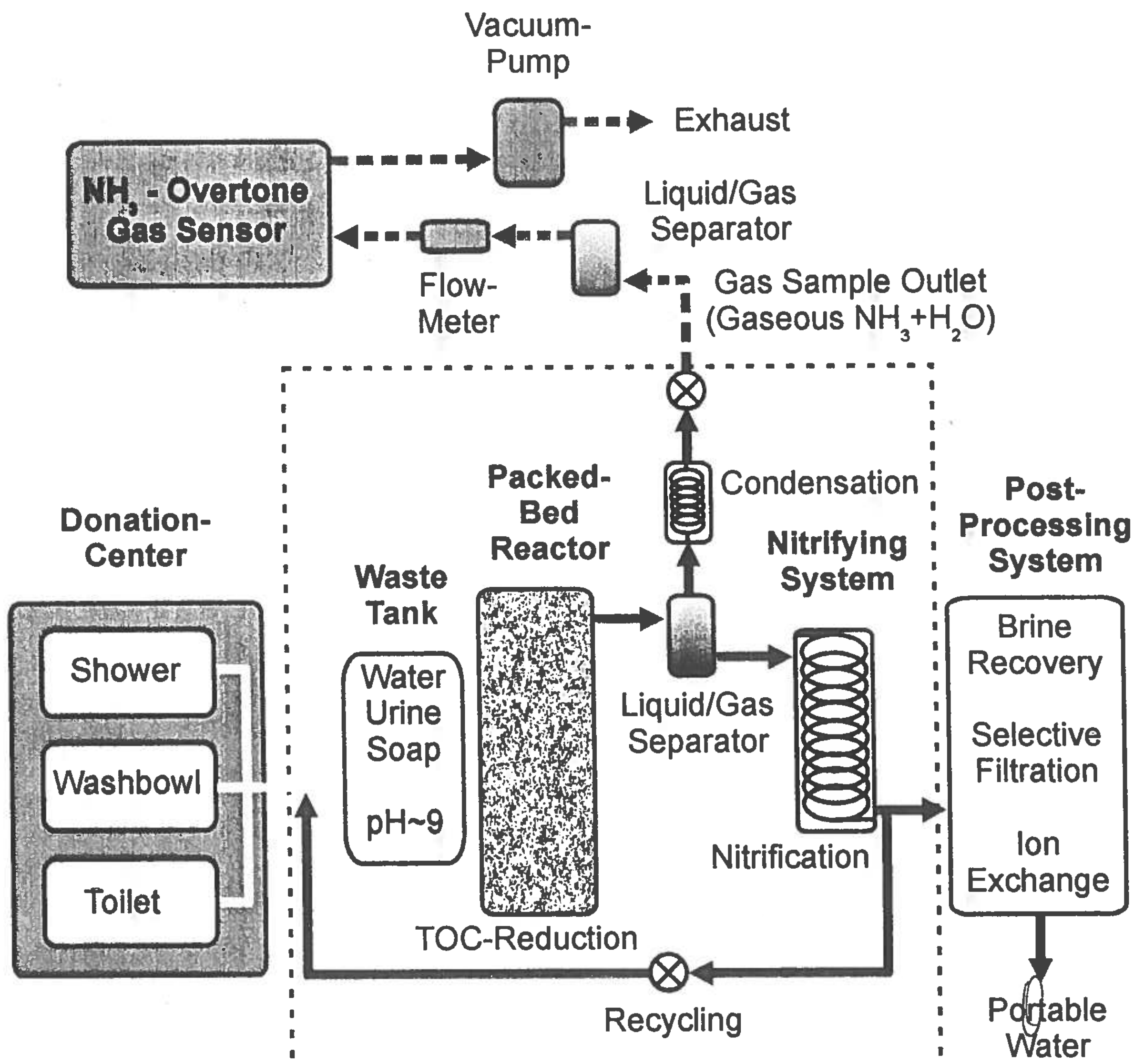
Motivation

- Monitoring NH_3 concentration after De-NO_x process of exhaust pipes in a power station
- Pollutant gas monitoring
- Atmospheric chemistry
- Space craft related gas monitoring
- Semiconductor Processing
- Medical diagnostics (kidney)

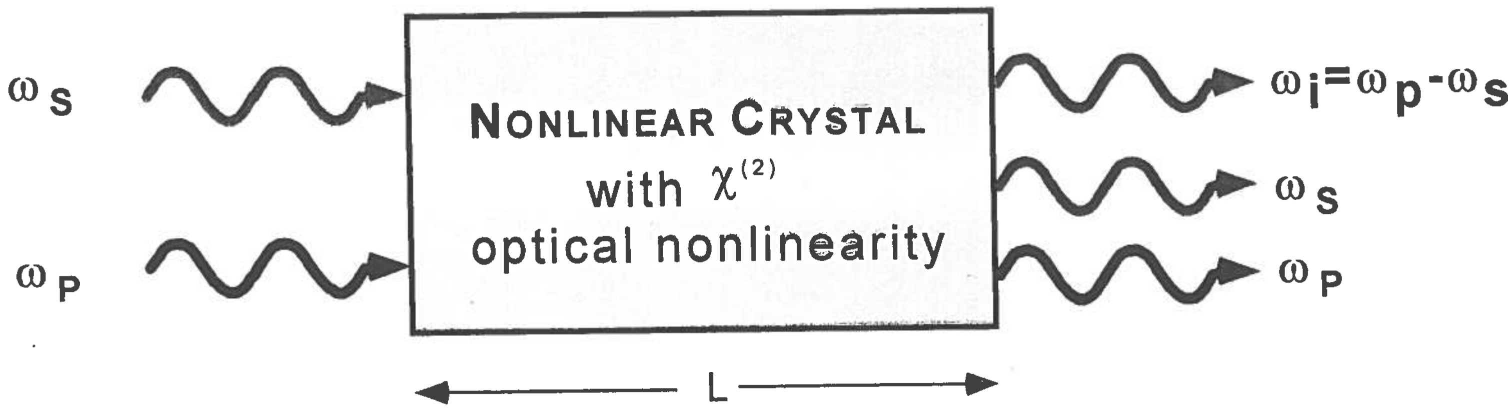
NH_3 Diode Laser Based Sensor



NASA Water Recovery System



Difference Frequency Generation



MID-IR POWER: $P_i \sim C \cdot P_{PUMP} \cdot P_{SIGNAL} \cdot L\, h(\zeta,\mu)$

$C = (\omega_i\, d_{eff})^2$, $\mu = k_s/k_p$, $\zeta = L/b$

EXAMPLE: FOR PPLN AT 3.5 μM

C~450 μW / cm $\cdot$ W^2

~3 μW for 6mW and 540mW LD pump sources

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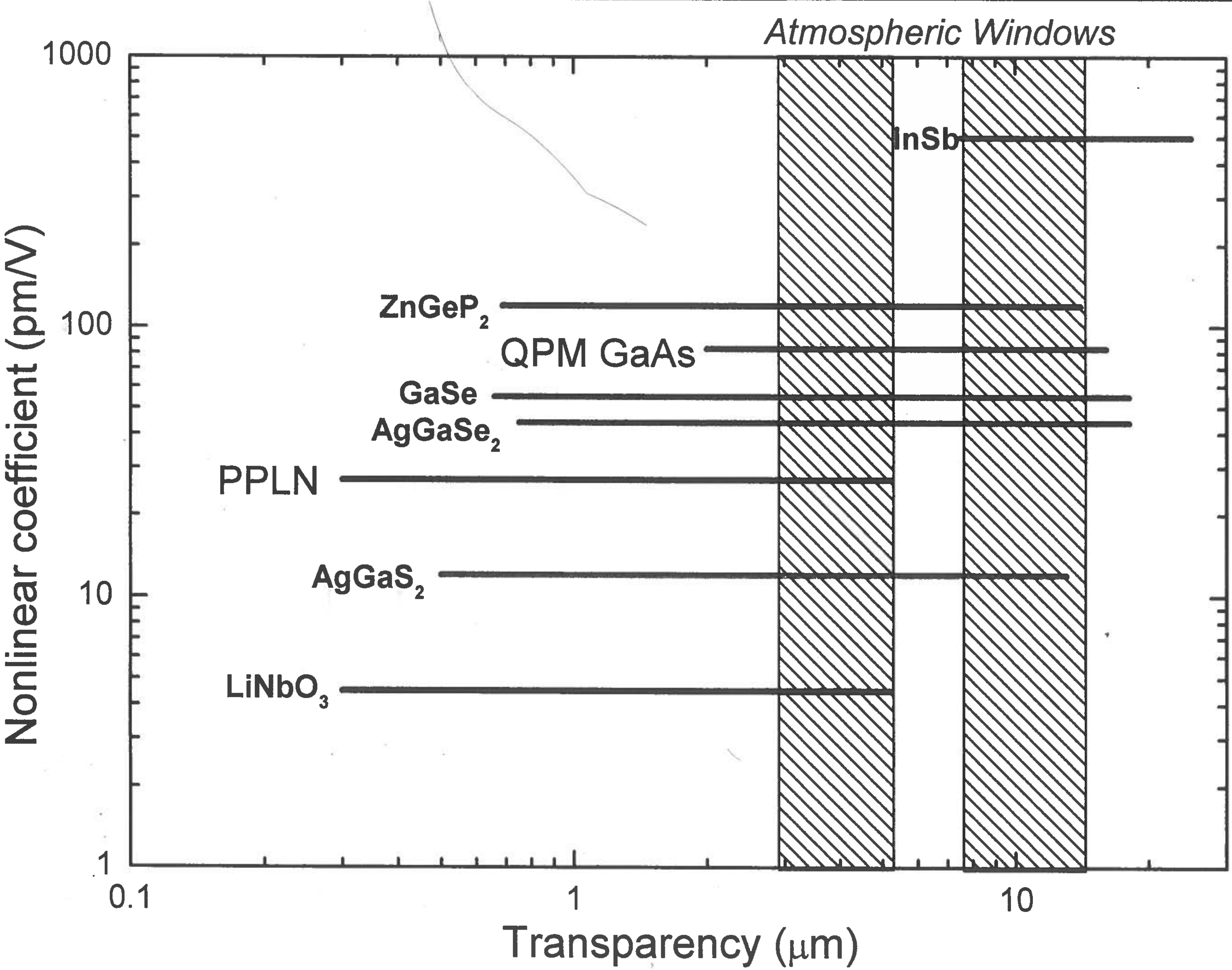
Characteristics of Mid-IR Nonlinear Optical Crystals



Advantages of Diode Laser Pump Sources

- Broad wavelength coverage (630nm to 2 μm, with gaps)
  - Tunability (0.3 nm / C, or 2 MHz / μA typical)
  - High efficiency ($\eta_{elec} \leq 30\%$, 0.1-1 W/A)
  - FP, DBR, DFB, ECDL, Multi-section DFB-DBR, VCSEL, DPFL, DPSSL
- CW single mode power (1 to 500 mW)
  - With amplification: ≥ 1W (MOPA, Fiber)
- Narrow linewidth (≤ 15 MHz)
- Amplitude and frequency stability
- Direct frequency modulation
- Room temperature or TE cooled operation
- Convenient fiber pigtailing
- Reliability (>10,000 hrs.), small size, low cost

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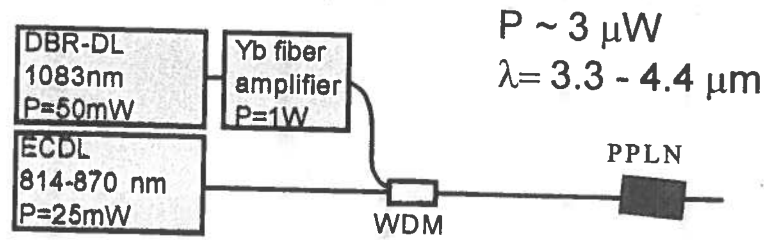
Two DFG Based Gas Sensing Approaches

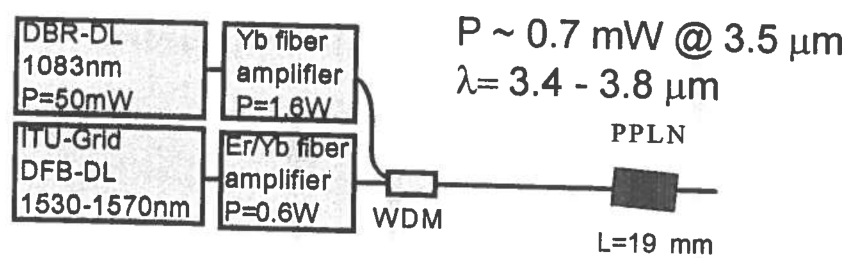
Multi-species detection:

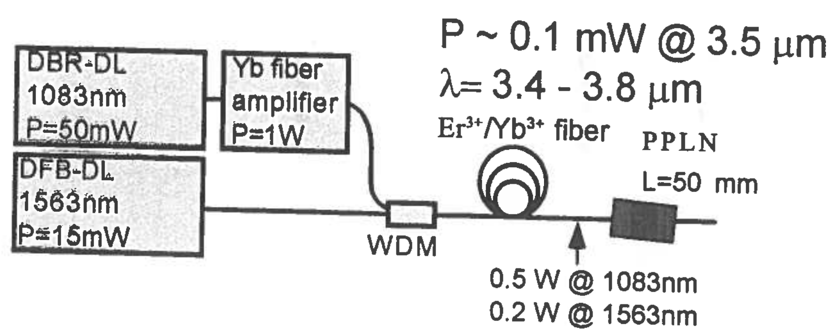
- widely tunable:3.3-4.4μm
- moderate DFG power
- good sensitivity



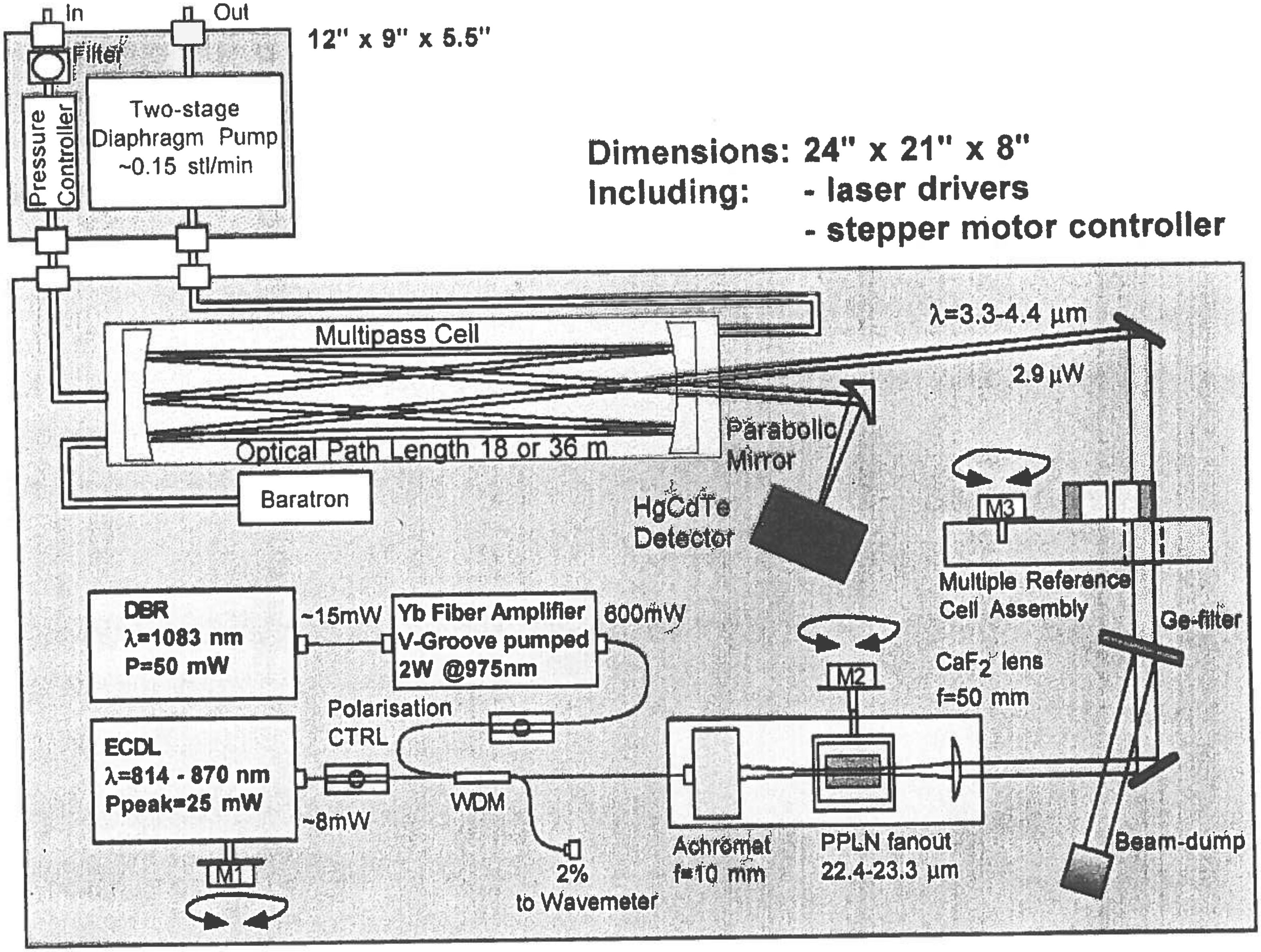
Single-species detection:

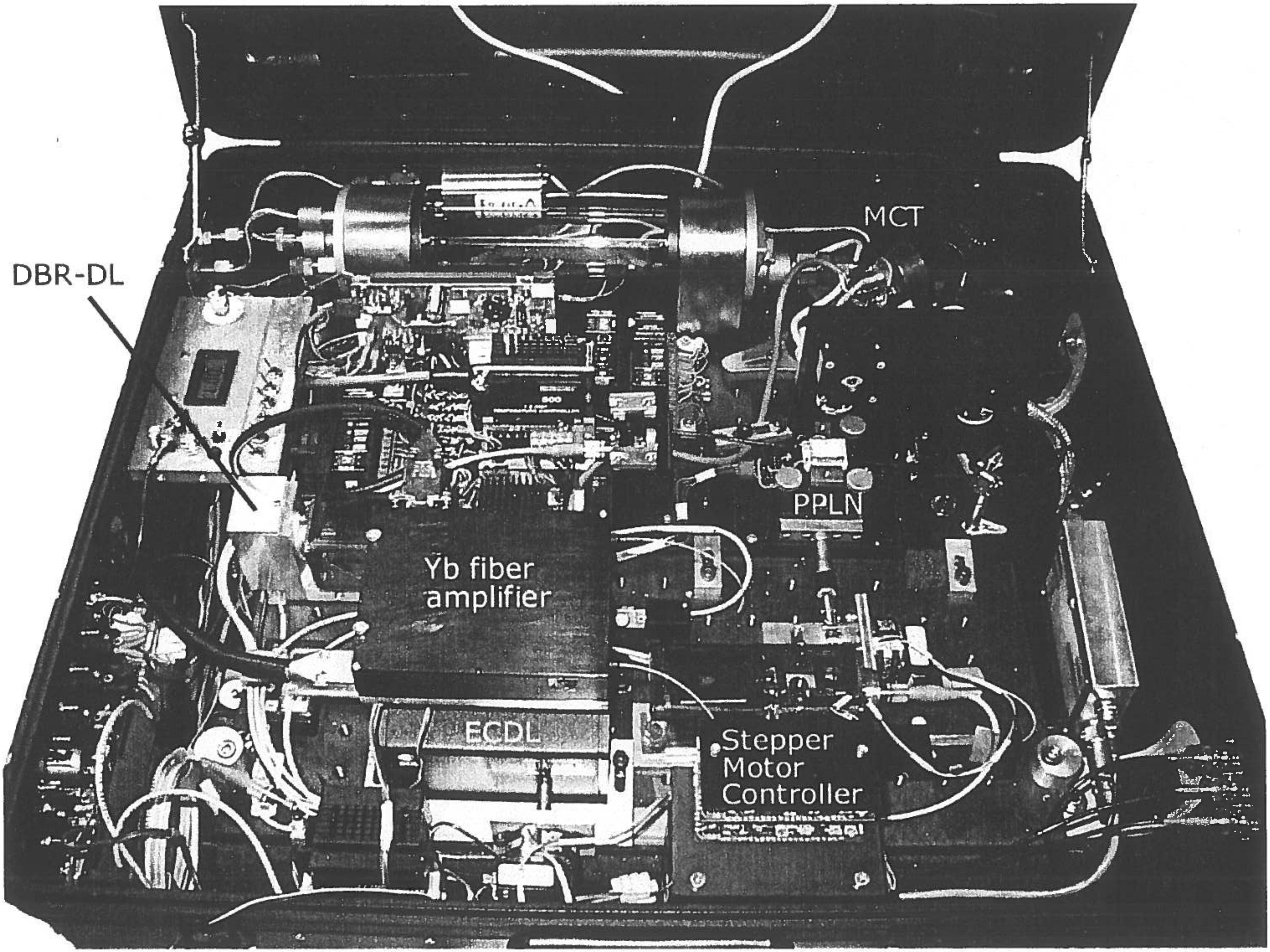
- ITU-diode laser selection
- high DFG power
- high sensitivity





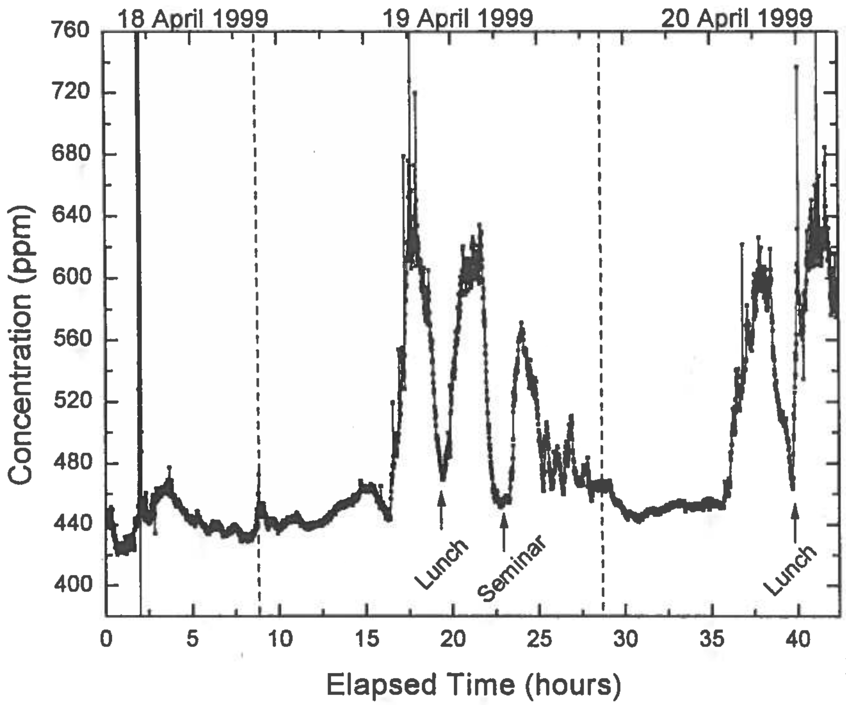
▶ Schematic of DFG based gas sensor





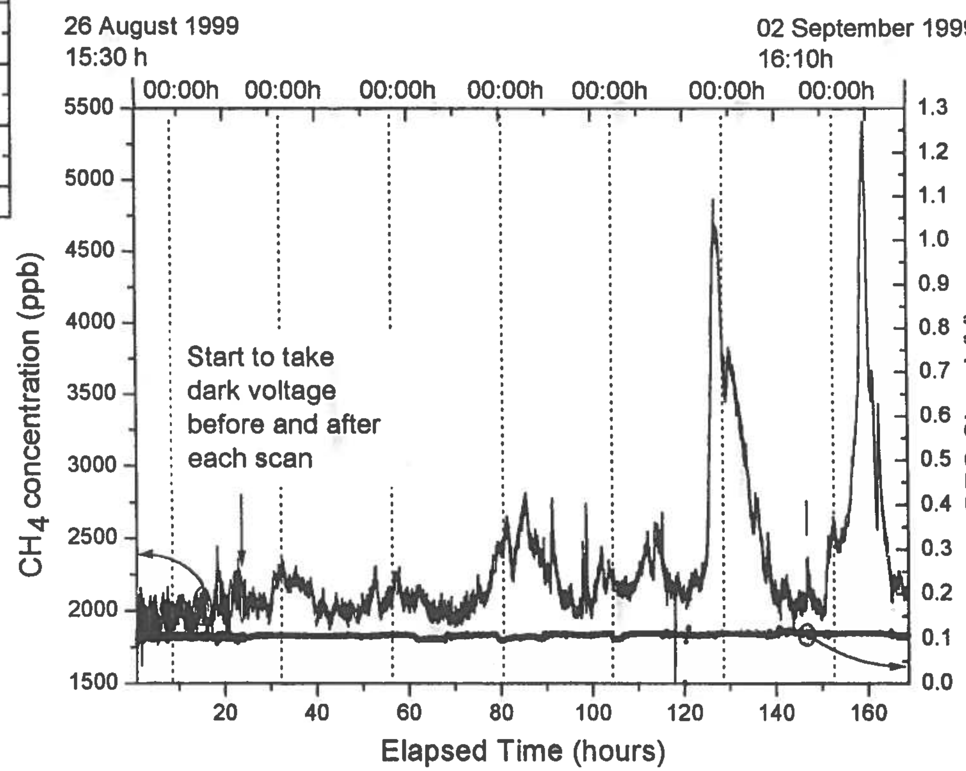
DBR-DL
MCT
PPLN
Yb fiber
amplifier
ECDL
Stepper
Motor
Controller

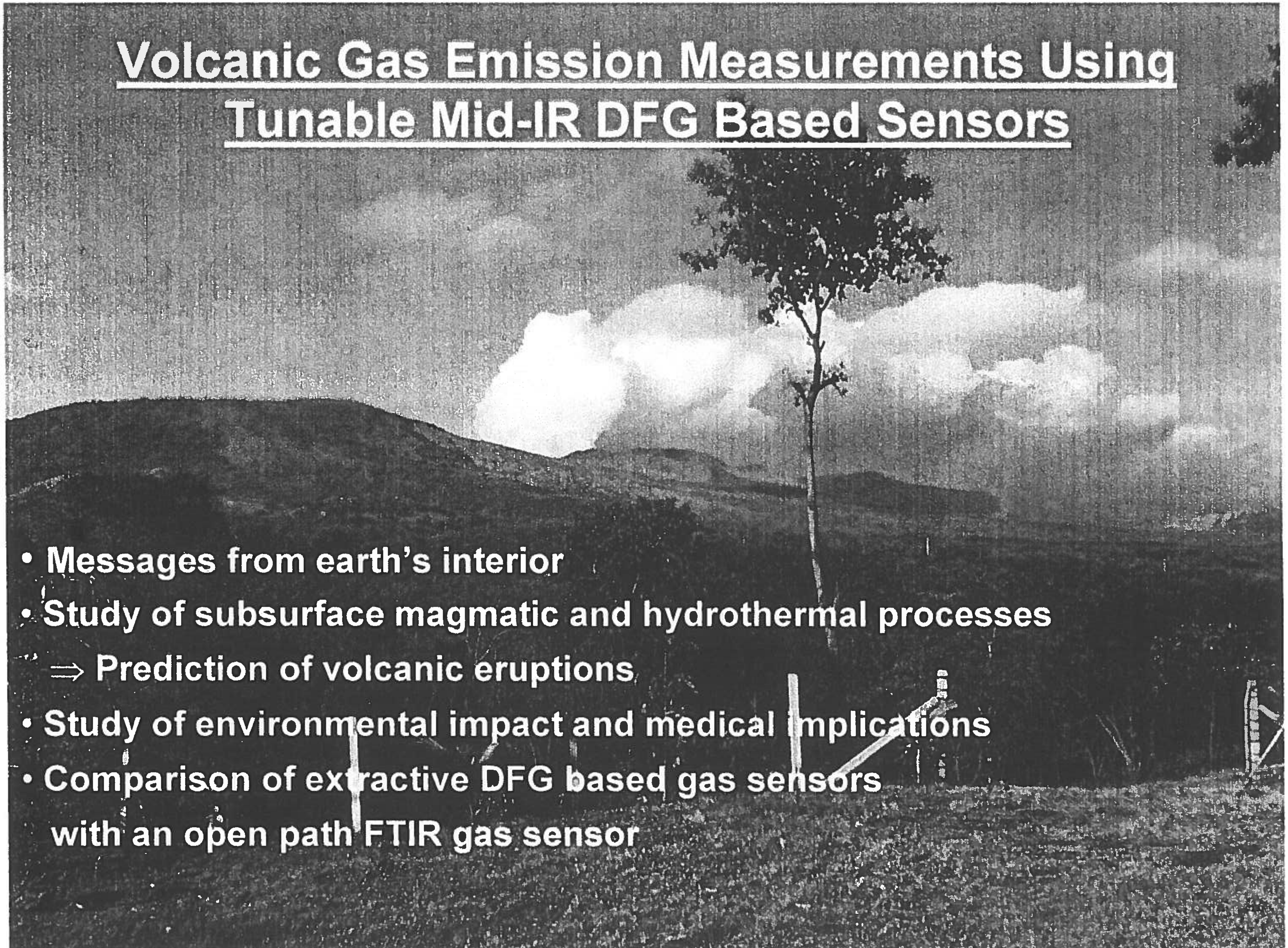
Long-term Gas Detection



CO_2 (in ambient room air):
3 day period

CH_4 (in ambient room air):
7 day period

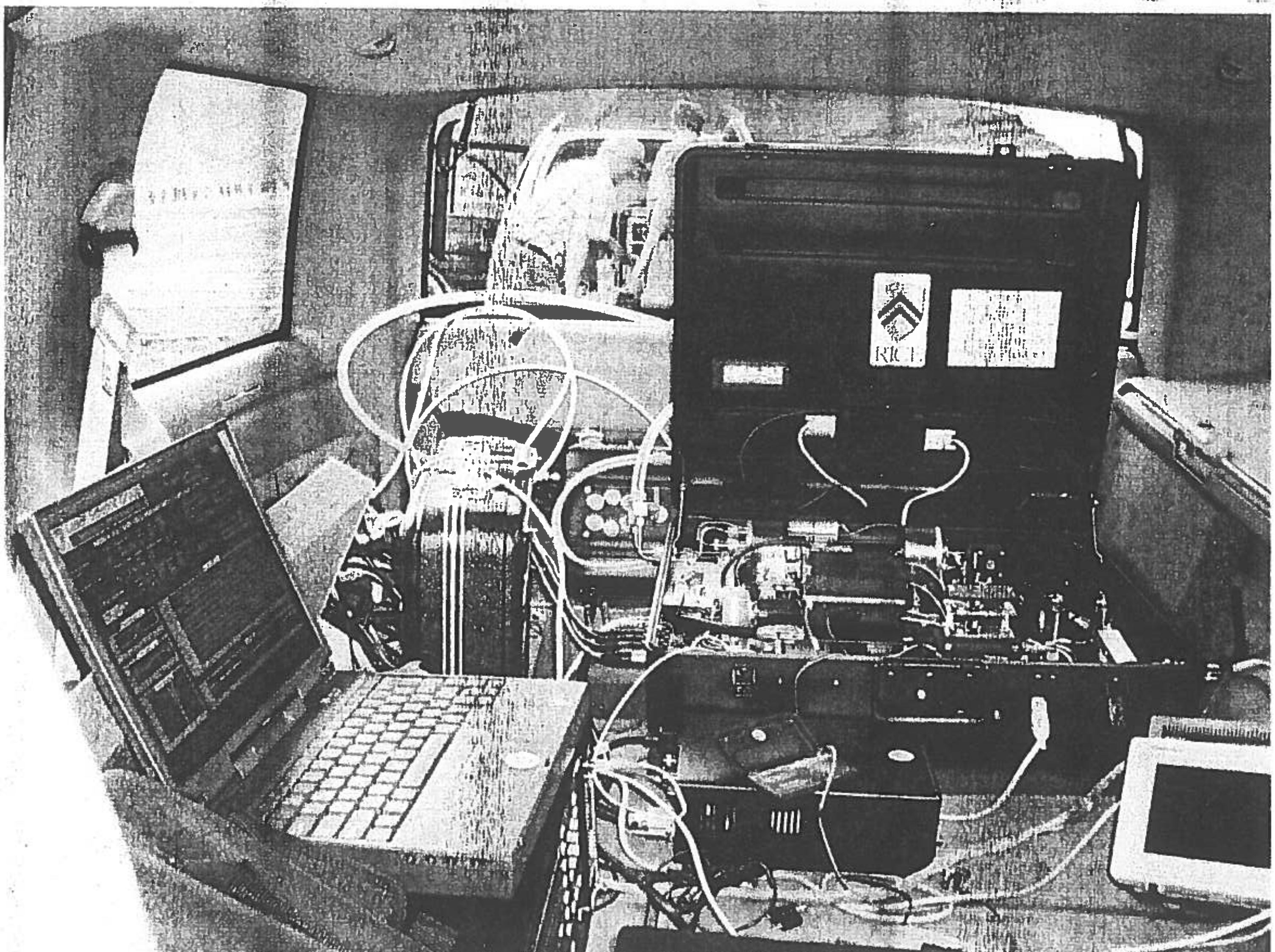




Volcanic Gas Emission Measurements Using Tunable Mid-IR DFG Based Sensors

- Messages from earth's interior
- Study of subsurface magmatic and hydrothermal processes
  ⇒ Prediction of volcanic eruptions
- Study of environmental impact and medical implications
- Comparison of extractive DFG based gas sensors with an open path FTIR gas sensor

Masaya Volcano Emissions Campaign April 2000



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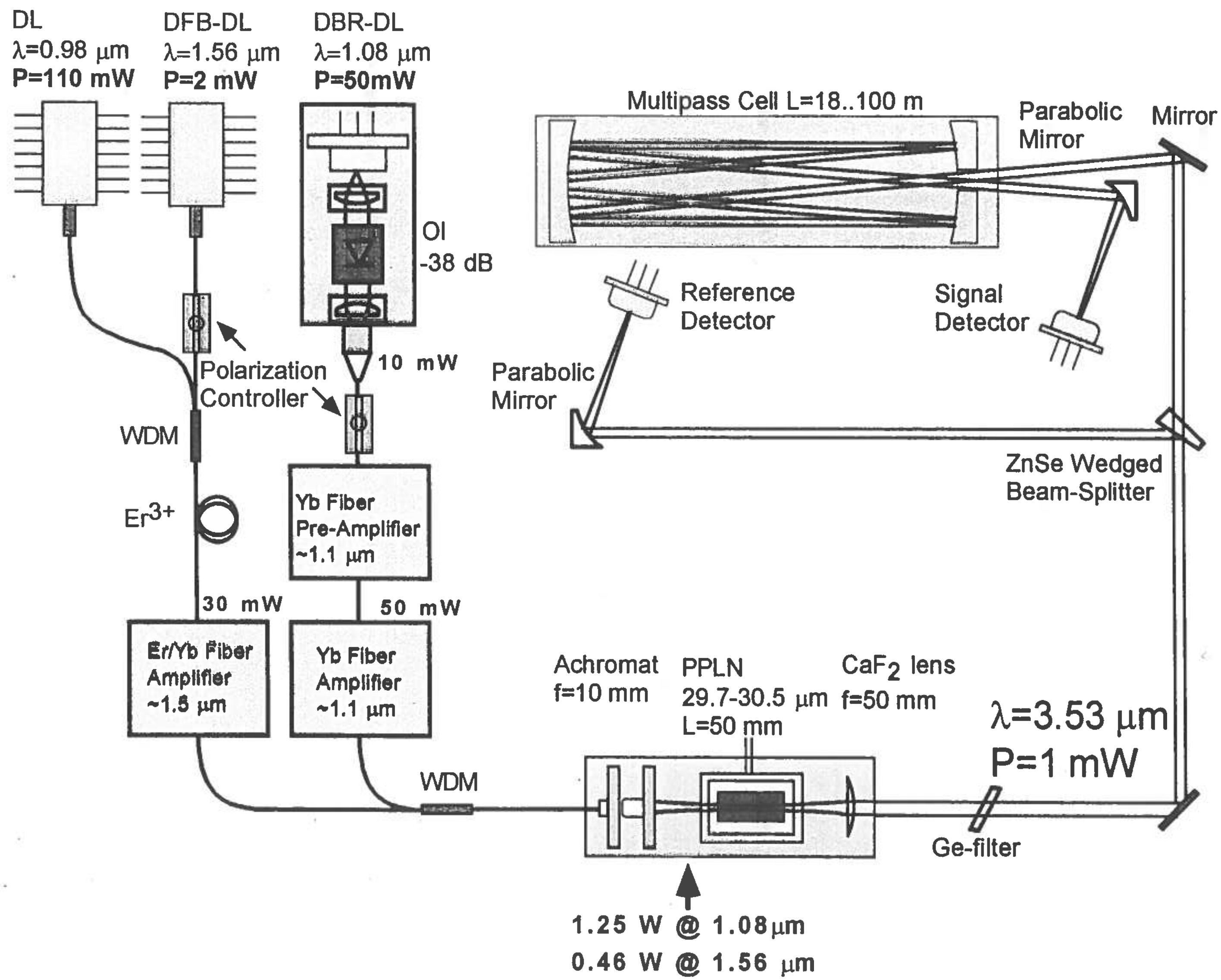
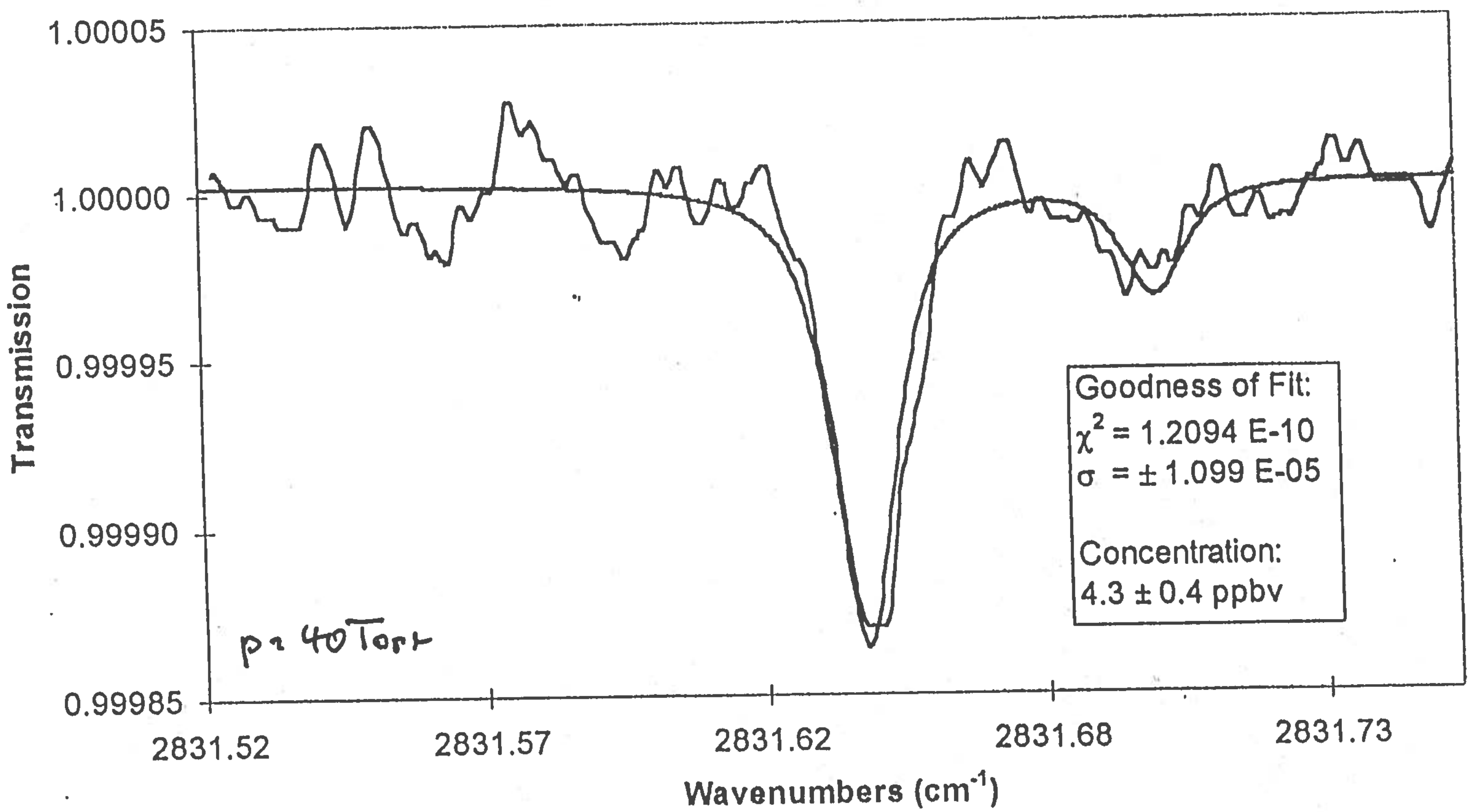
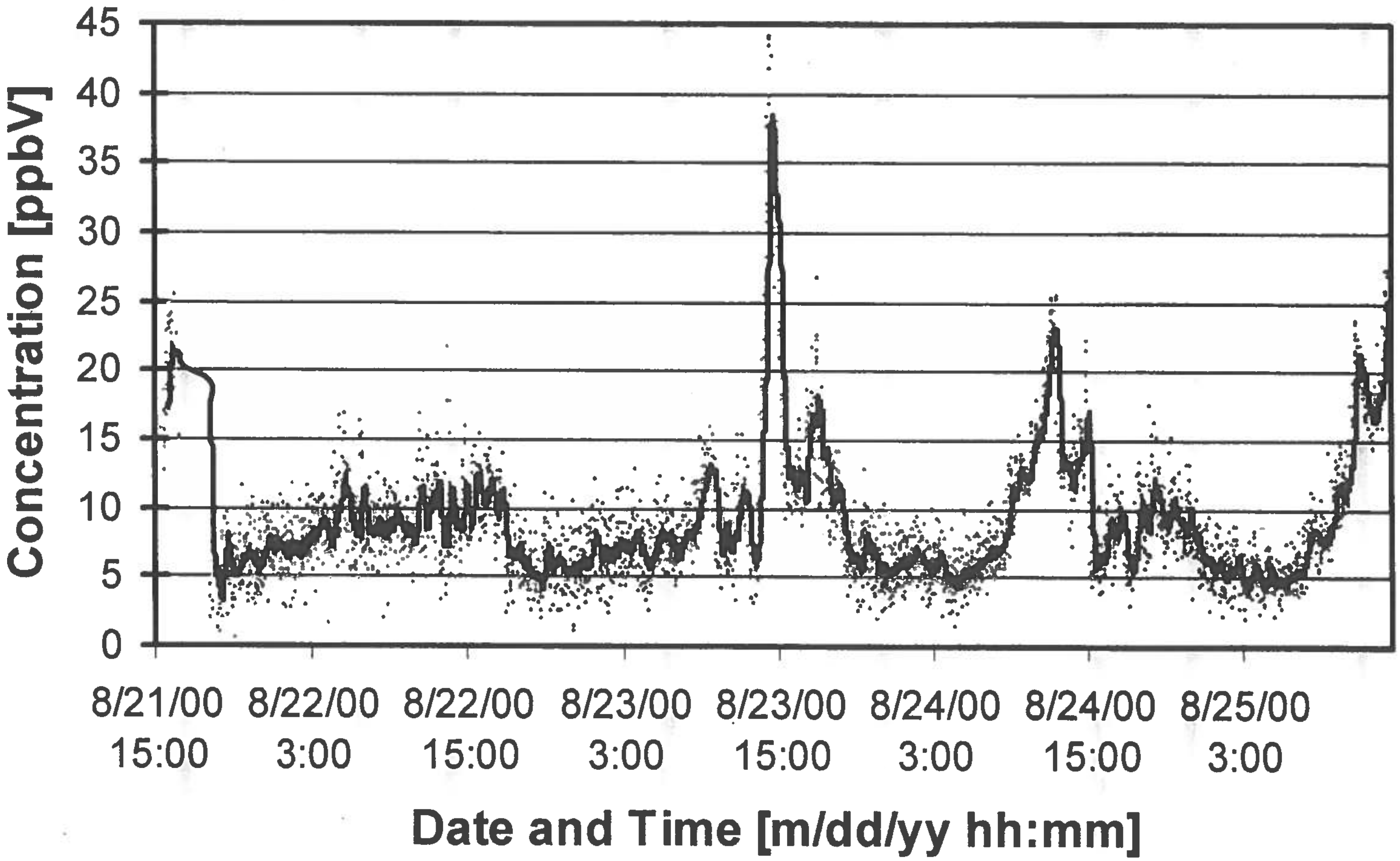
Diode Laser Based H_2CO Sensor



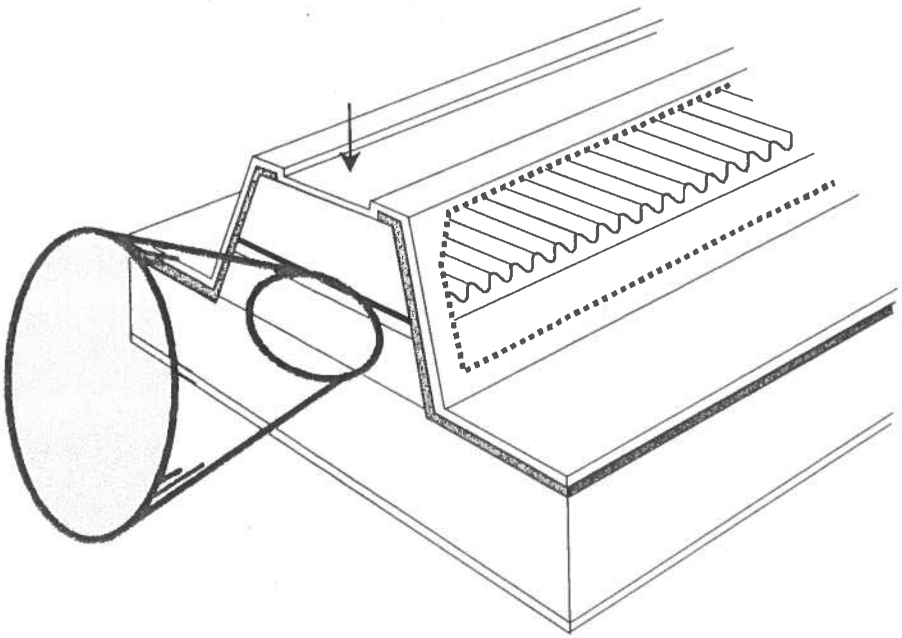
H_2CO Detection in Ambient Air at 3.53 μm

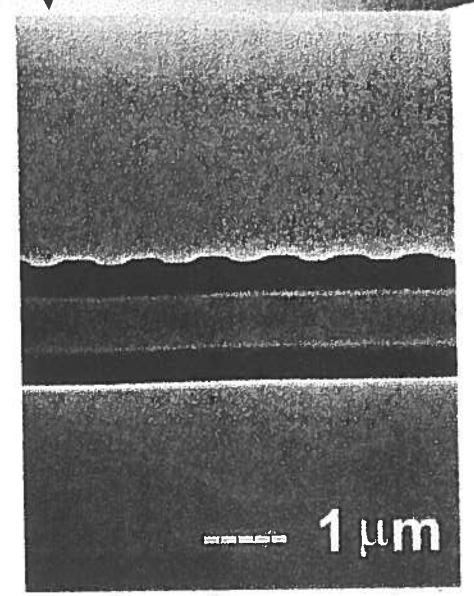


Five Days of Continuous HCHO Data



QC - distributed feedback laser





grating selects single-mode, tunable by temperature

$$\lambda_{em} = 2\ n(T)\ \Lambda_{grat}$$

Key Characteristics of Quantum Cascade Lasers

- Laser wavelengths cover entire range from 3.4 to 19μm determined by layer thickness of same material
- Intrinsically high power lasers (determined by number of stages)
  - CW: 0.2W @ 80 °K, ~100 mW single frequency
  - Pulsed: 0.5W peak at room temperature, ~15 mW avg. @ 300 °K
- High Spectral purity (kHz- cw to 330MHz- pulsed)
- Wavelength tuning by current or temperature scanning
- High reliability: low failure rate, long lifetime, robust operation and extremely reproducible emission wavelengths

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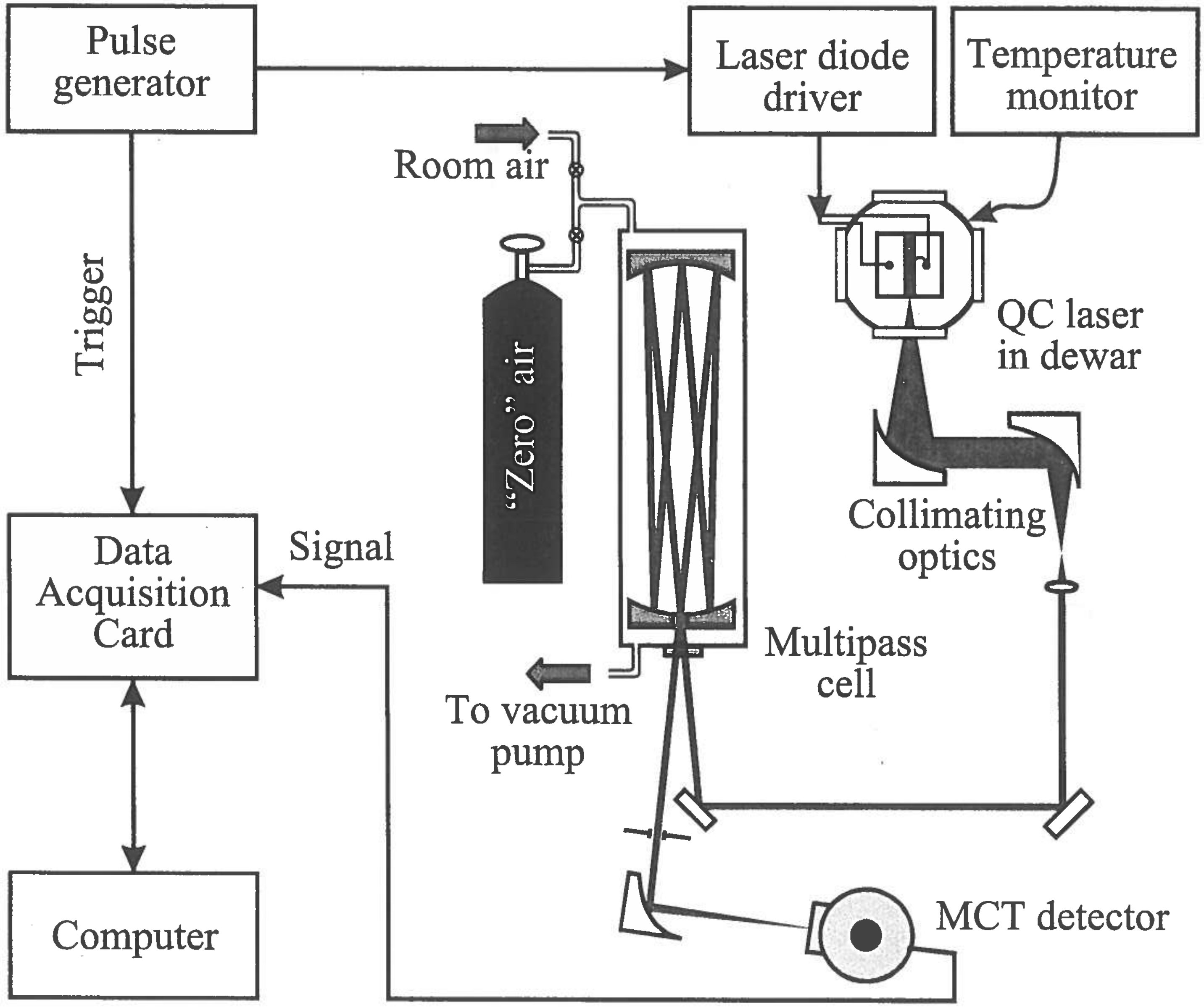
Trace Gas Detection with a Multipass Cell



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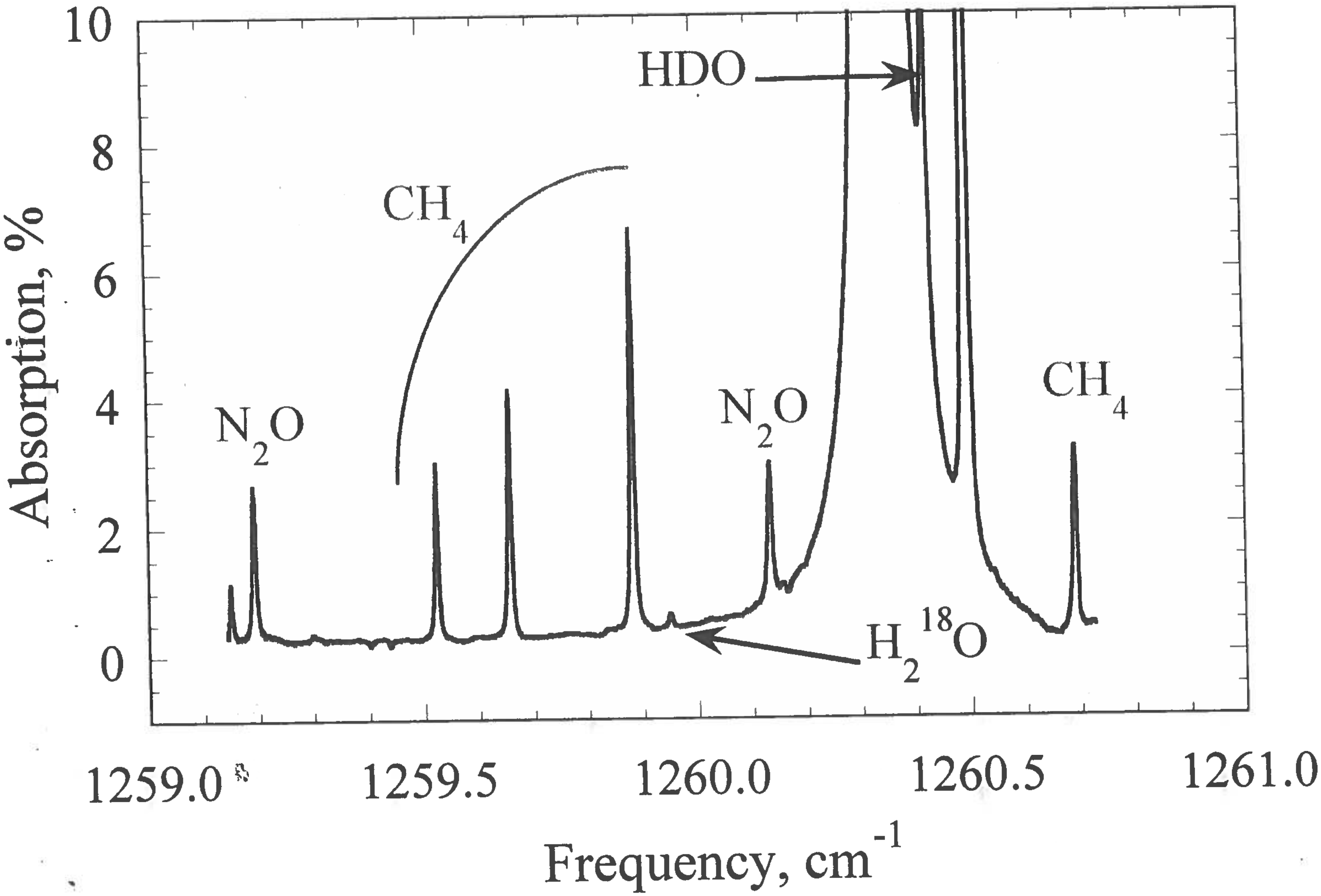
Absorption Spectrum of Room Air



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Pulsed Operation of a QC-DFB Laser

ADVANTAGES	DISADVANTAGES
♦ Laser can be operated at near-room temperature	♦ Broader linewidth (~400 MHz)
♦ Easy temperature handling	♦ Less average power
♦ No consumables (liquid N_2)	♦ More sophisticated electronics for driving QC laser and data acquisition
♦ Compact	

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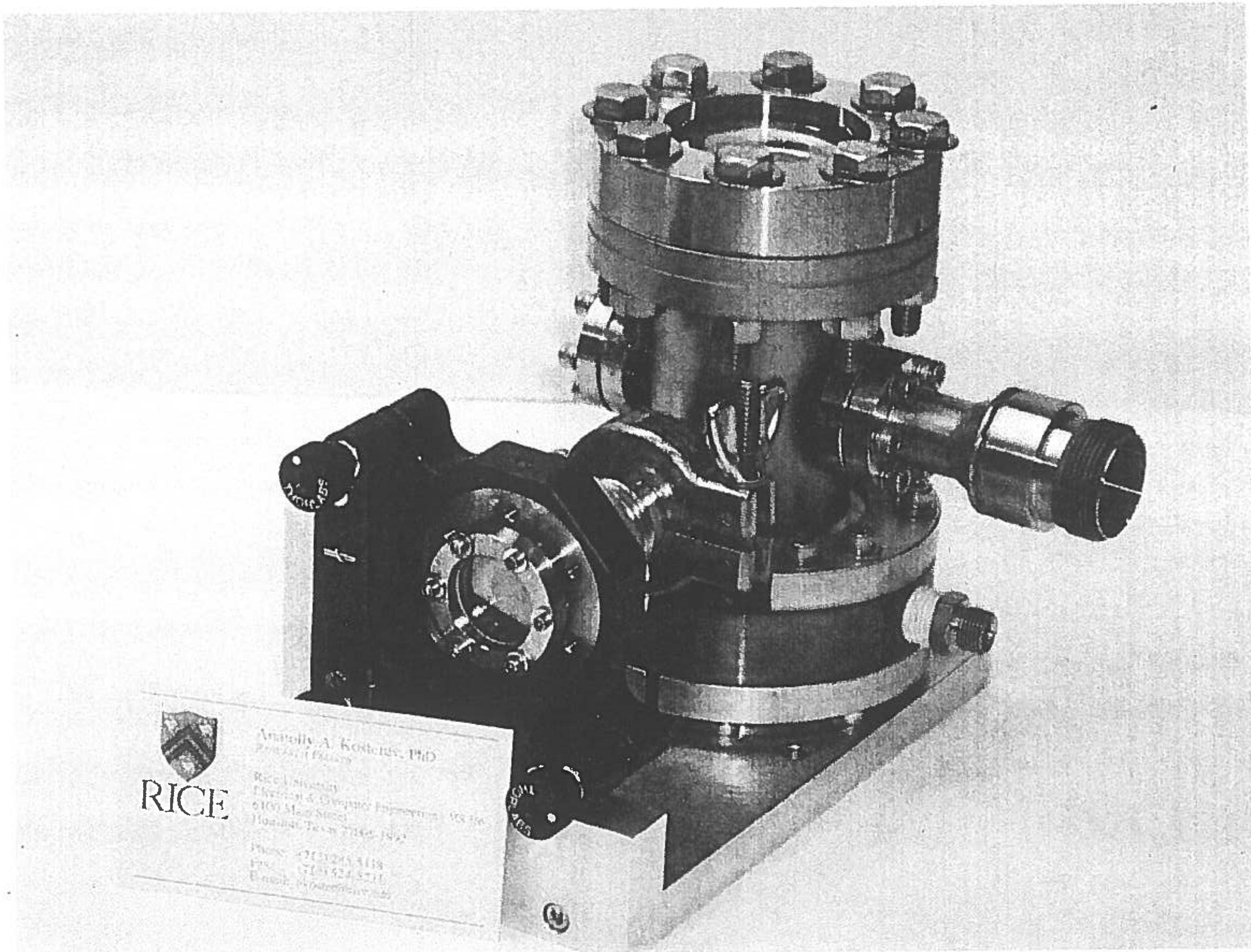
Compact Pulsed Quantum Cascade Laser



Summary

- Diode and Quantum Cascade Laser Based Trace Gas Sensors
  - Compact, tunable, robust (alignment insensitive),fieldable
  - High sensitivity ($<2 \cdot 10^{-4}$ to 10^{-5}) and selectivity (10–300 MHz)
  - Fast data acquisition and analysis
  - Detected trace gases: NH_3, CH_4, H_2CO, NO_2, N_2O, HCl, CO_2, CO, NO, H_2O, SO_2, isotopic species of $^{12,13}C$, $^{16,17,18}O$, $^{35,37}Cl$
- Applications in Trace Gas Detection
  - Environmental monitoring: H_2CO, CO, CH_4 (NASA, NCAR, NOAA, EPA)
  - Industrial process control and chemical analysis
  - Medical diagnostics (NO, CO, CO_2)
- Future Directions
  - Fiber lasers and amplifiers
  - Longer mid-IR wavelengths with orientation patterned GaAs and QC lasers, detection of complex molecules
  - Cavity enhanced spectroscopy

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