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Development of Polarized UV Raman and Infrared Emission/Absorption Spectroscopy for Rocket Engine Applications

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Motivation for Work

Provide measurements of species concentrations and temperature for hot-fire test articles at Test Stand 115 at NASA MSFC.

Measurements can be useful for comparison to CFD simulations and help to evaluate combustion perform.

Past Achievements using Raman at NASA MSFC

1997 -- Linewise, multispecies, single-pulse images providing qualitative information about the presence of gaseous major species (H_20, H_2, and O_2) in a single-element LOX/GH_2 swirled injector (6.04 MPa chamber pressure) achieved using spontaneous vibrational ultraviolet Raman scattering.

1997 – Development of a single-pulse technique to separate fluorescence signals (e.g. OH, vibrationally-excited O_2, and PAH) from Raman signals.

1998 – Sheridon holographically ruled grating used to improve the stray light rejection of Rayleigh/Mie scattering in spectrometer.

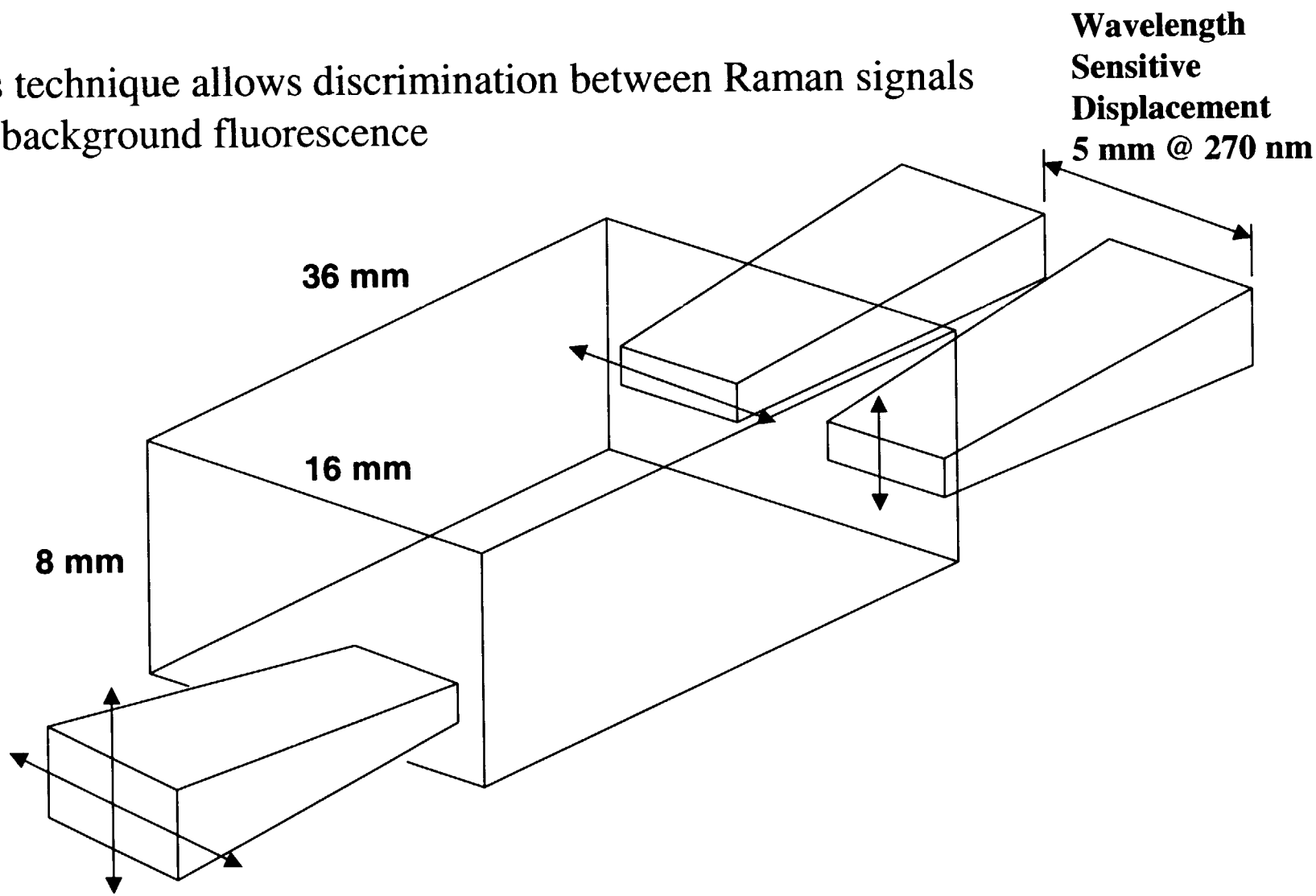
1999 – UV Raman system used to obtain qualitative species data in liquid CH_4/LOX combustion in Modular Combustion Test Article (MCTA).

An ultraviolet Raman system offers advantages over conventional visible Raman systems:

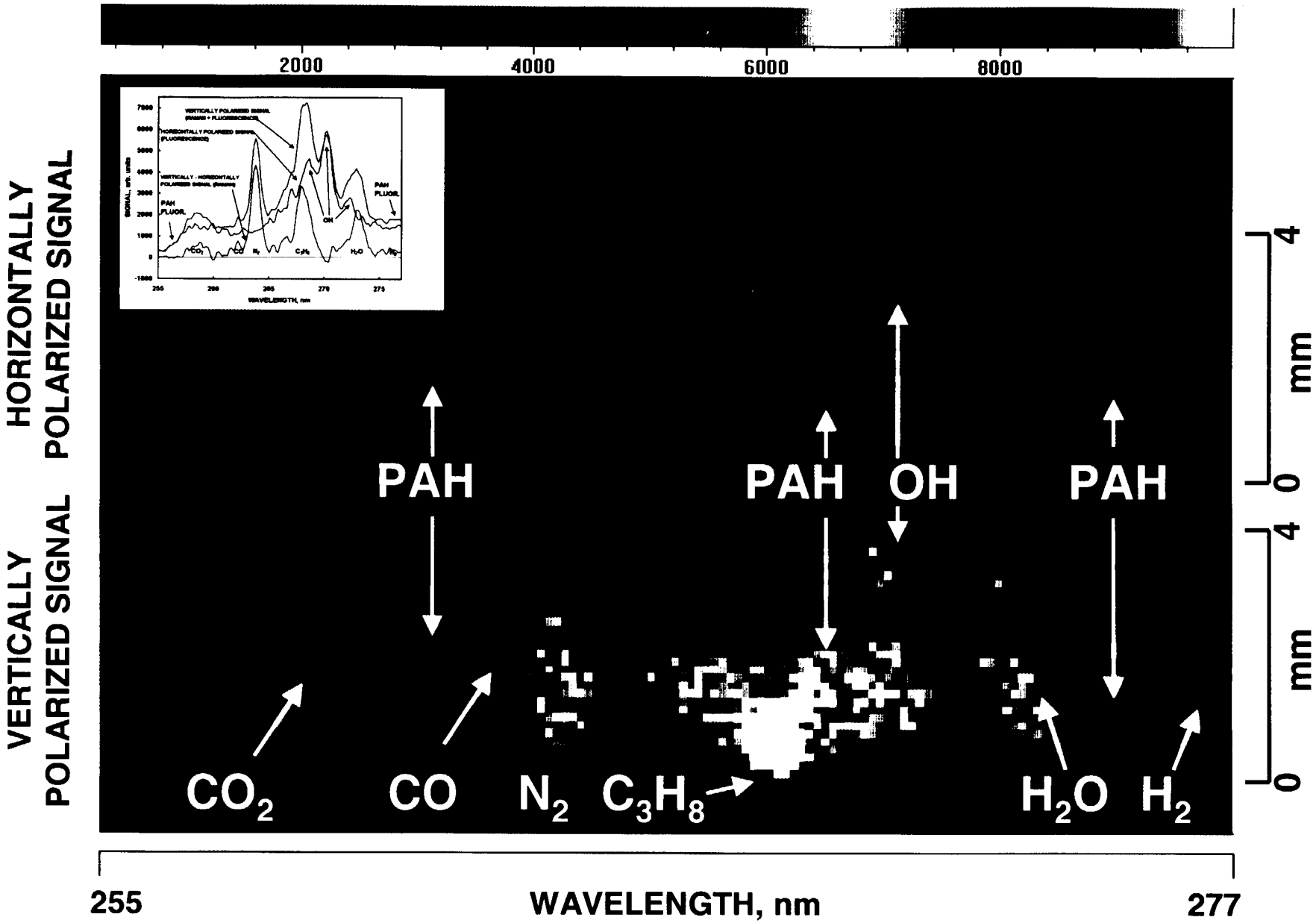
- Raman cross section and UV enhancement, along with increased ICCD QE increase signal strength by a factor of 25.
- No H_2O emission in the range of UV Raman wavelengths, and overall reduction in blackbody radiation compared to visible range.

Calcite rhomb used to separate horizontally and vertically polarized light

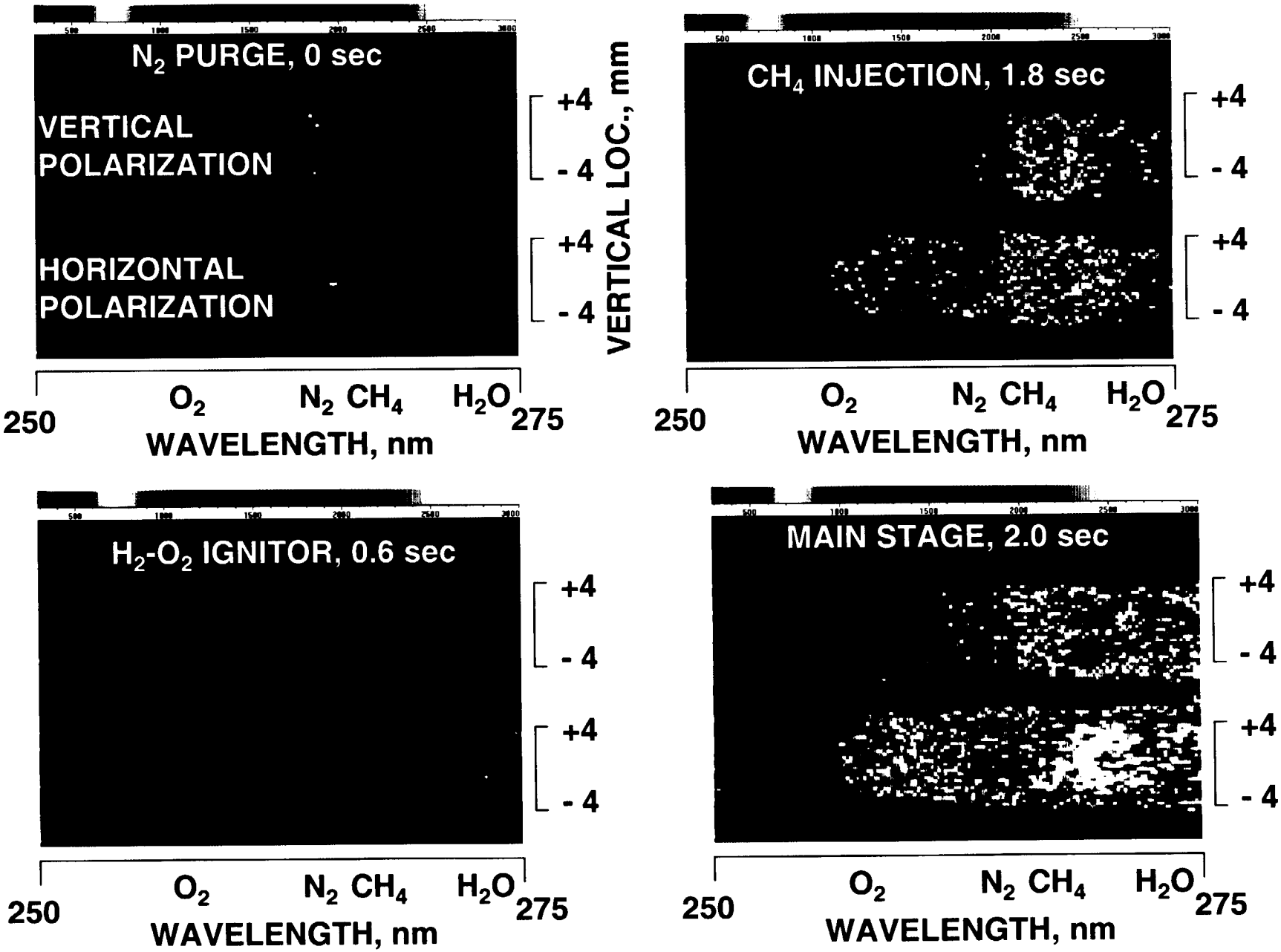
This technique allows discrimination between Raman signals and background fluorescence



Instantaneous Spatially-resolved UV Raman Image Through C_3H_8/air Flame



SELECTED RAMAN IMAGES FROM MCTA CH_4-LOx TEST 25, 9/20/99



Present Work

Quantitative measurements of species concentrations and temperature in plume of Vortex Chamber using two different, independent optical diagnostic techniques:

- Ultraviolet Raman Scattering
- Emission/Absorption Spectroscopy

Improvements to Raman System in 2000-2001

- **Calibration capability added to make quantitative measurements possible**
  - Hencken burner and gas heater provide calibration source
  - Calibration gases added along with computerized flow monitoring system
- **Safer operation environment**
  - Gas monitoring systems added to protect against toxic (fluorine) gas leaks
  - Laser safety goggles, laser barriers, door interlock, etc.
  - Air pressurization system and new HVAC system to be added for better environmental control
- **Control and monitoring software upgraded to LabVIEW**
  - Modernization of instrumentation interfaces
  - Allows real-time calculations and monitoring that in the past were not easily achievable
  - Custom software to suit test or calibration environment
- **Network capability allows remote control of system via a laptop computer**
  - System can be controlled and monitored from anywhere on the test stand
- **Replacement of KrF stepper motor**
  - Existing motor replaced with finer resolution motor and software written to add remote control capability. Elimination of unnecessary re-setting of laser grating.

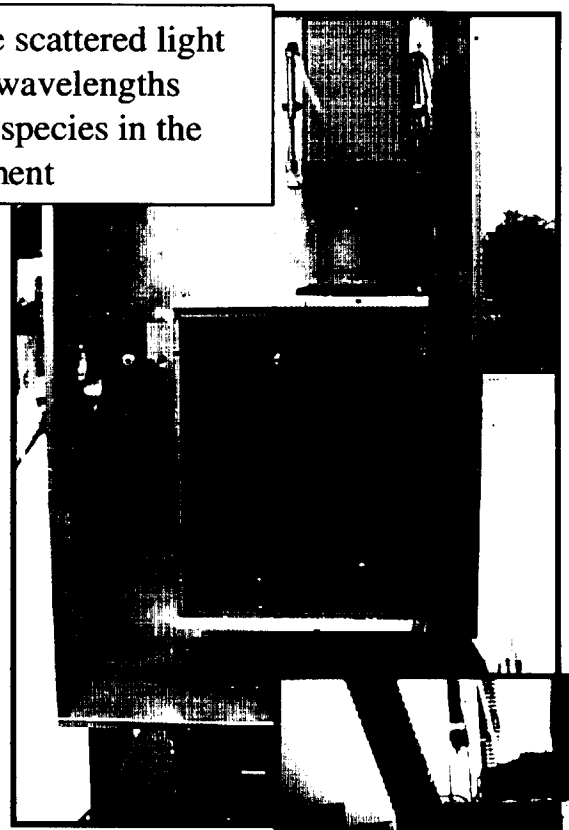
Vortex Chamber Test Article

3rd Gen RBCC Test Article

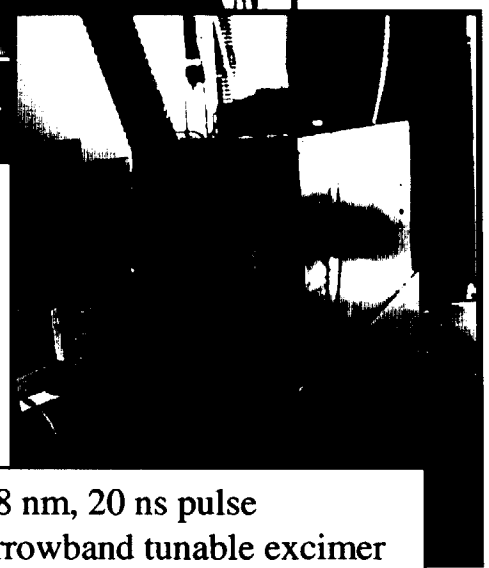
Note:
1st Gen: Space Shuttle
2nd Gen: Upgrades that increase reliability of current propulsion systems and technology
3rd Gen: Combination of air-breathing and rocket cycles, RBCC (Rocket-Based Combined Cycle)
4th Gen: Non-chemical propulsion systems

Raman Scattering Light Detection System

Separates the scattered light into various wavelengths representing species in the gas environment



Laser

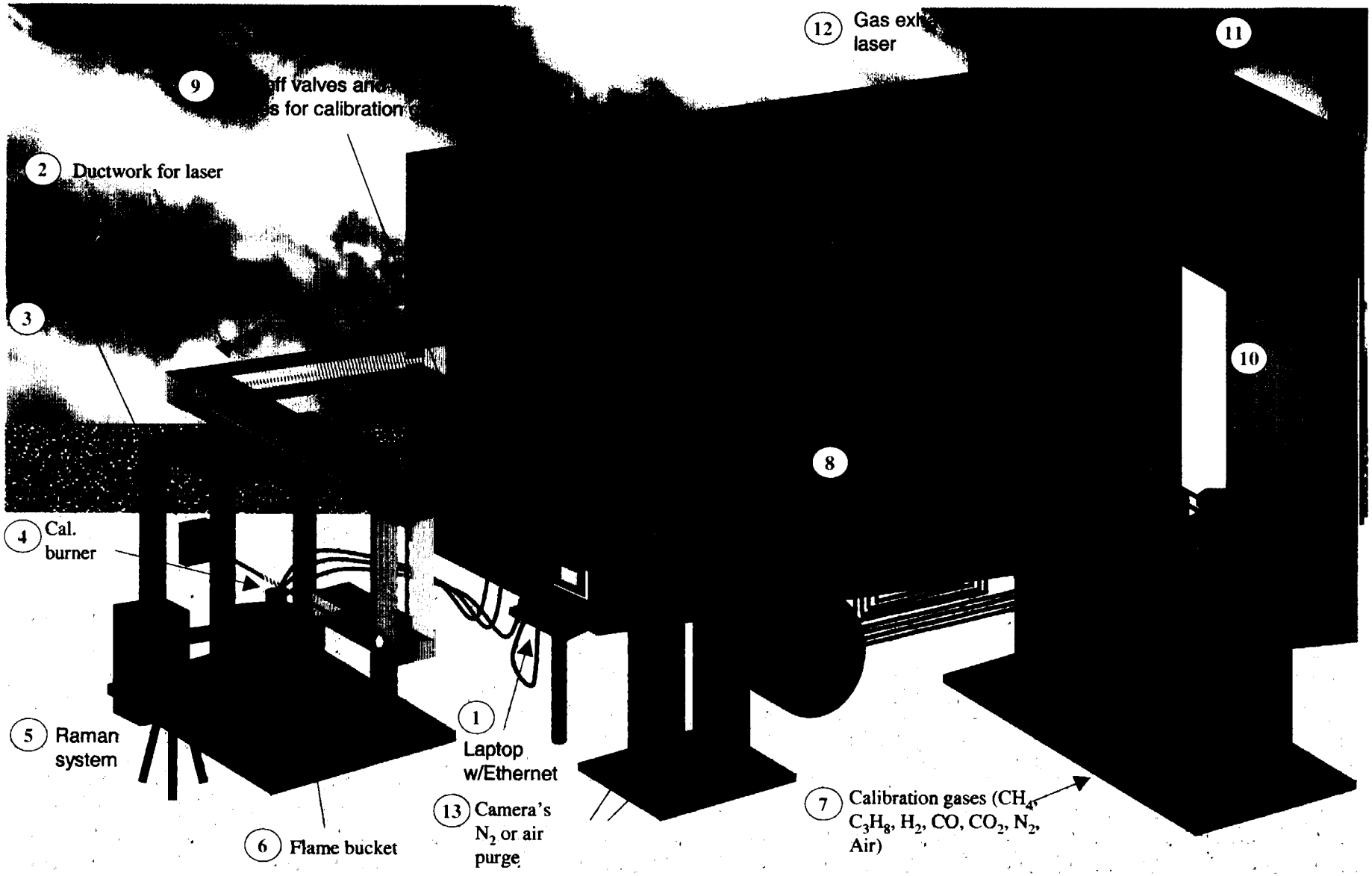


248 nm, 20 ns pulse narrowband tunable excimer

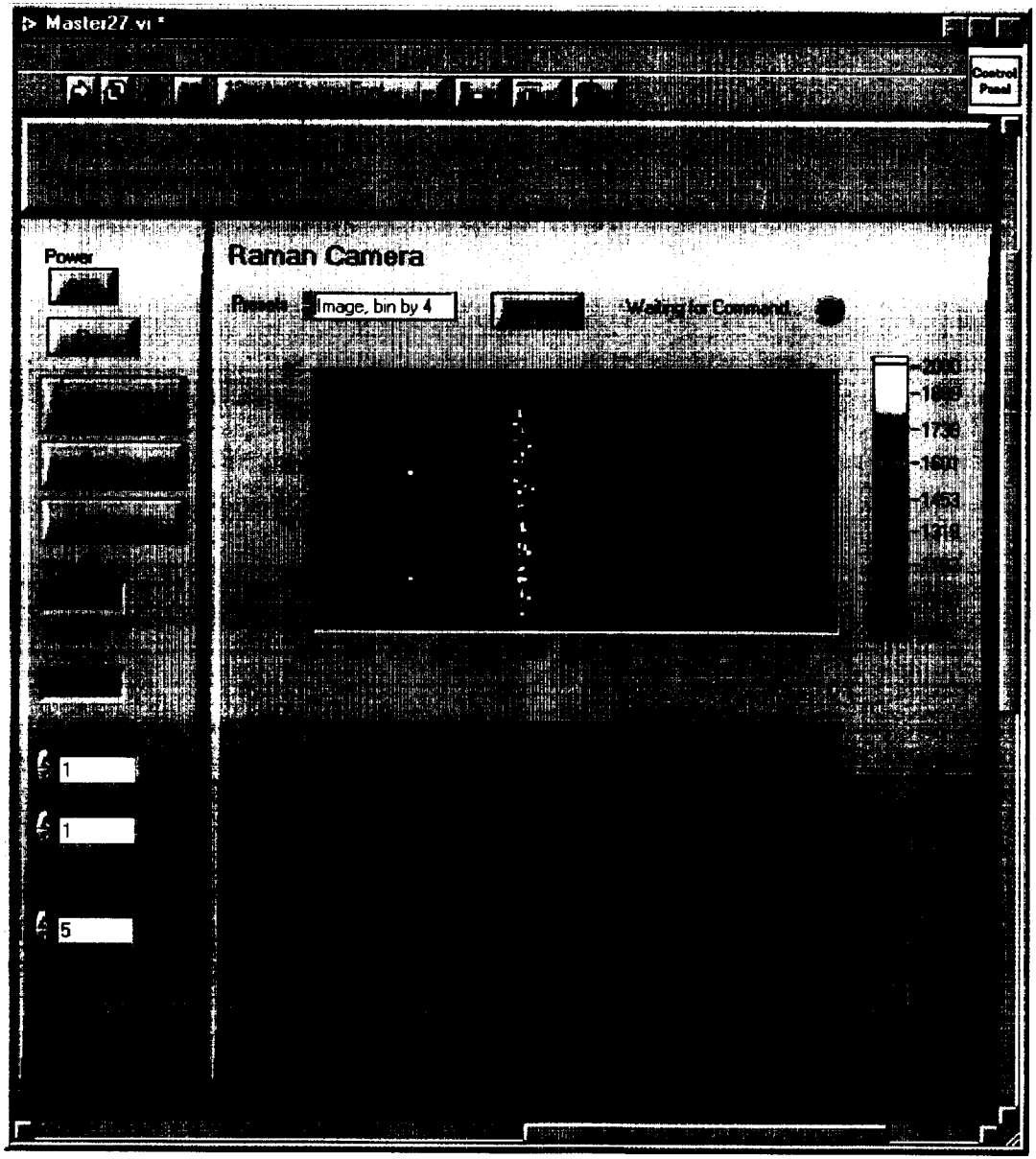
Calibration Burner for Optical Diagnostics

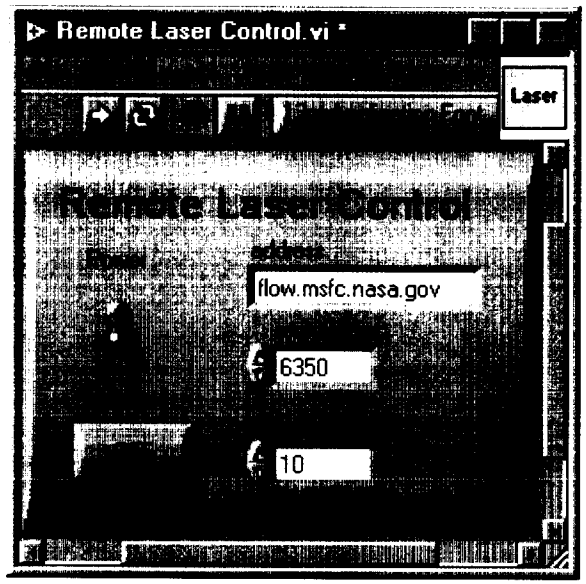
Used to calibrate gas species such as O_2, N_2, CO_2, CO, H_2, H_2O, CH_4, etc.

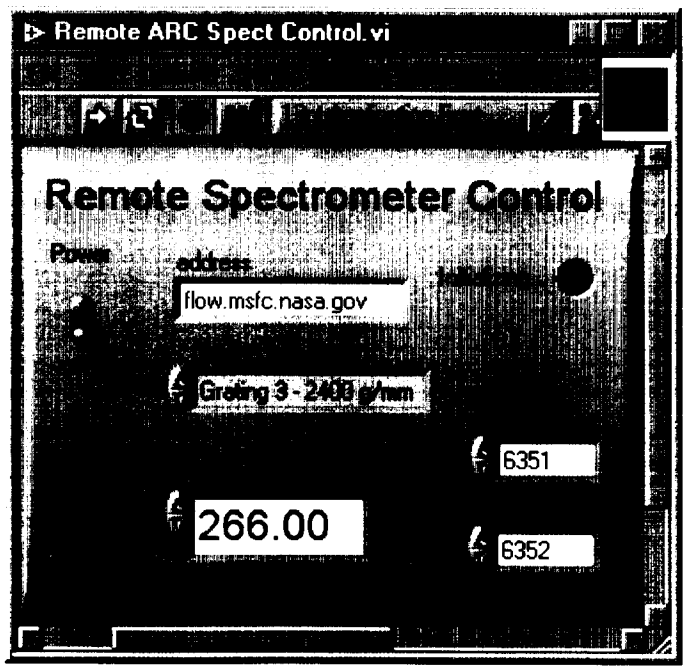
Test Stand 115 Outdoor Configuration



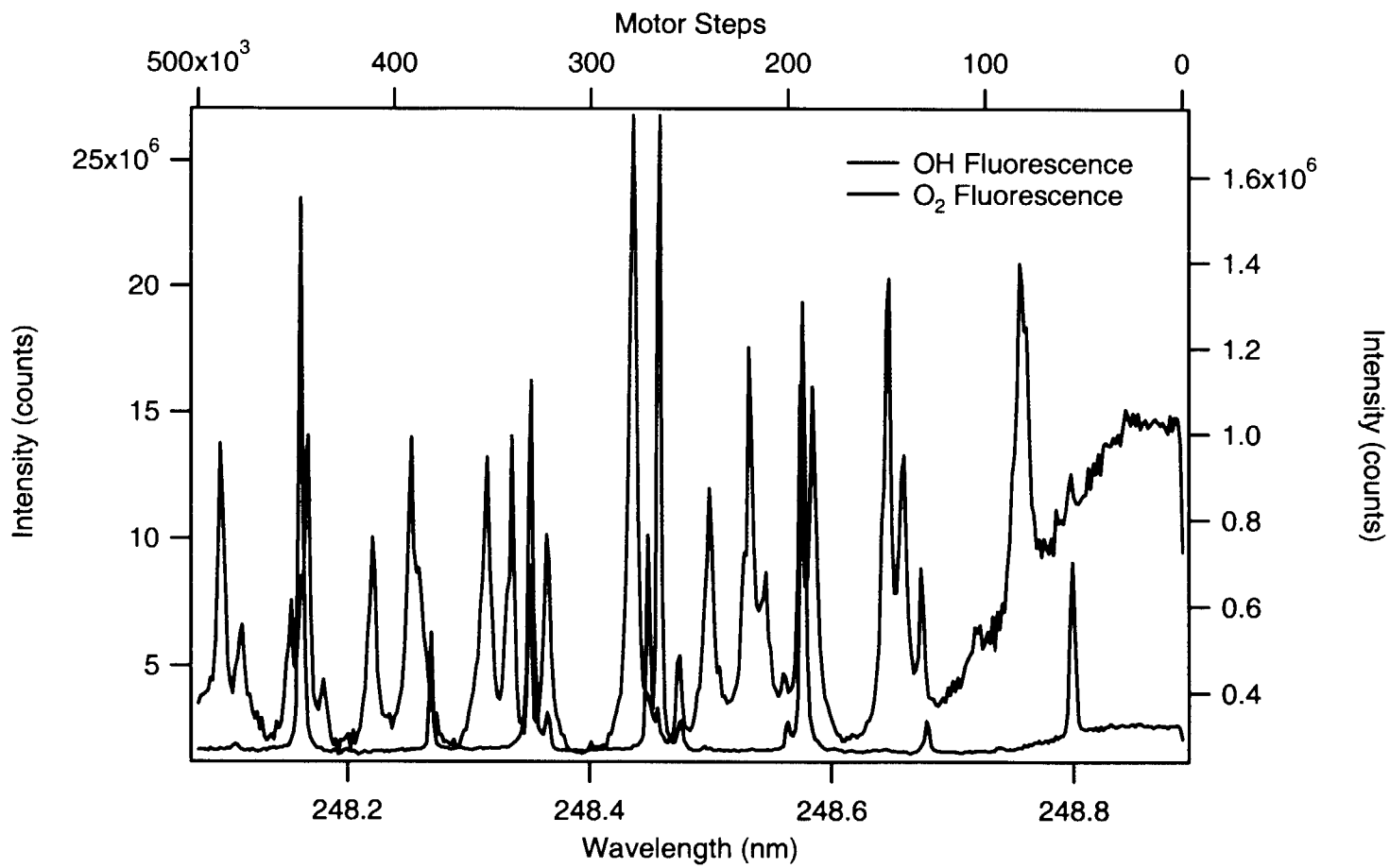
LabVIEW Software





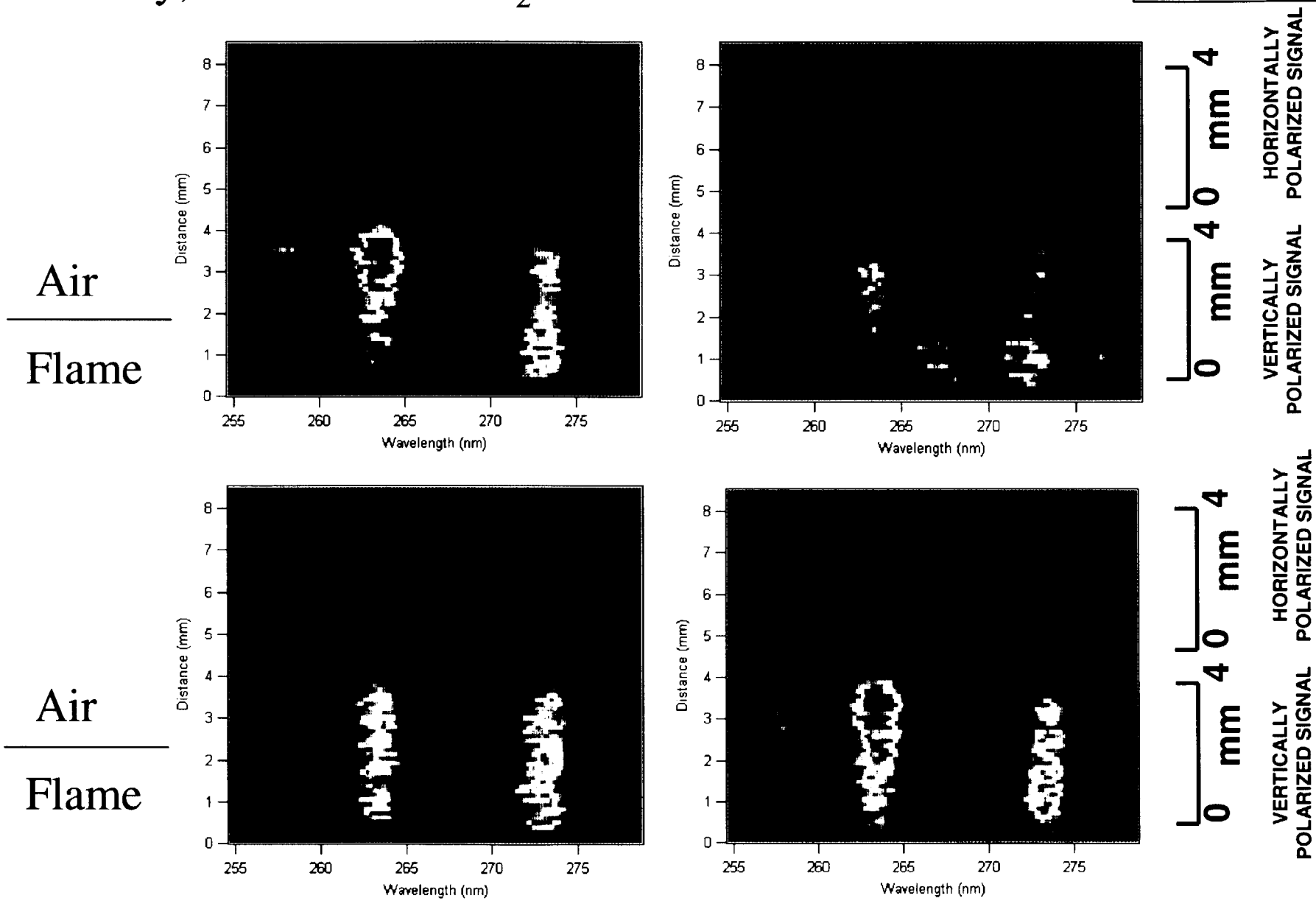


Prior to Raman measurements, narrowband KrF laser must be tuned to a wavelength that minimizes OH and hot O_2 fluorescence



Single-pulse UV Raman images taken on the edge of an unsteady, stoichiometric H_2-air flame in a Hencken burner

Images demonstrate the ability to capture spatial variations of gas species



Temperature Measurements In High Pressure H_2-O_2 Combustion From UV Raman H_2 Vibrational Q-branch Spectra

Highly-resolved spontaneous Raman spectrum for Stokes vibrational Q-branch of H_2 is temperature-dependent.

Best-fit between experimental spectrum and synthetic spectra provides temperature measurement.

Spectral shape depends upon temperature through:

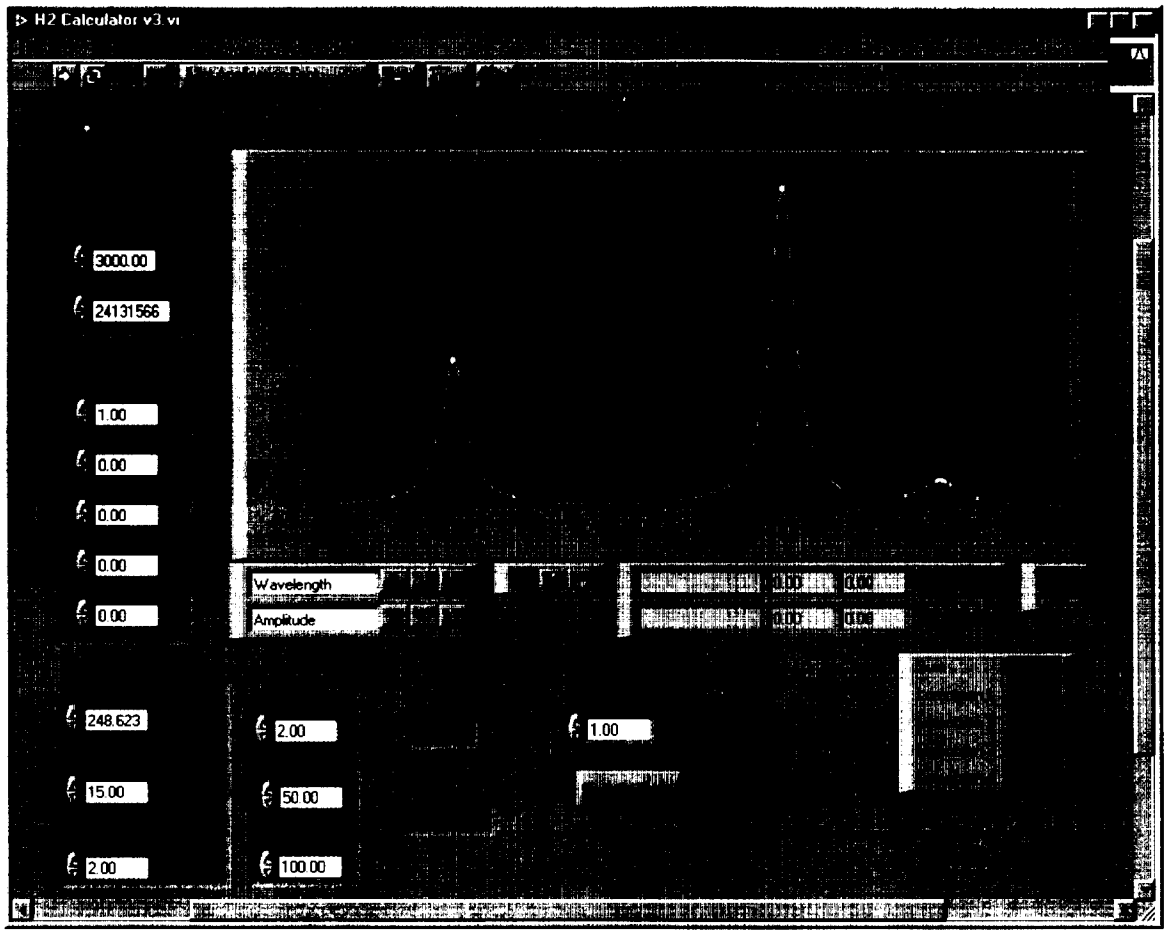
1. Population fractions for ro-vibrational levels
2. Doppler broadened linewidths
3. Collisionally narrowed linewidths
   (Temperature-dependent "optical" diffusion coefficient)
4. Collisionally broadened linewidths
   (Temperature-dependence of line broadening coefficient)
5. Shifting of Raman wavelength peaks
   (Temperature-dependent lineshift parameter)

Spectral shape also depends upon density (through density-dependent Collisional broadening) and collision partner.

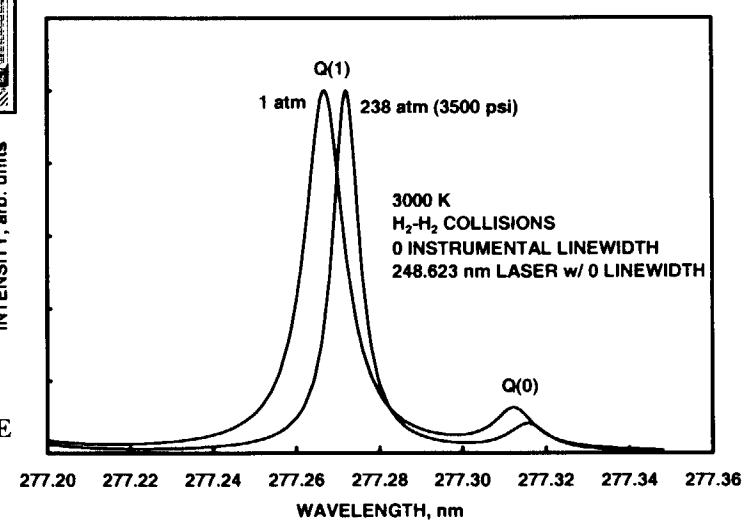
COLLISIONAL LINE BROADENING DATA FROM: Hussong, J., W. Stricker, X. Bruet, P. Joubert, J. Bonamy, D. Robert, X. Michaut, T. Gabard, H. Berger. 2000. "Hydrogen CARS Thermometry in H_2-N_2 Mixtures at High Pressure and Medium Temperature: Influence of Linewidth Models". Applied Physics B, Vol. 70, pp. 447-454.

COLLISIONAL LINE SHIFTING DATA FROM: Sinclair, P. M., J. Ph. Berger, X. Michaut, R. Saint-Loup, R. Chaux, H. Berger, J. Bonamy, and D. Robert. 1996. "Collisional Broadening and Shifting Parameters of the Raman Q-Branch of H_2 Perturbed by N_2 Determined from Speed-Dependent Line Profiles at High Temperatures." Physical Review A, Vol 54, pp. 402-409.

LabVIEW "Virtual Instrument" Models Synthetic Raman Spectra



H_2 Raman lines shift and broaden nonlinearly with temperature, pressure, perturber, and rotational level

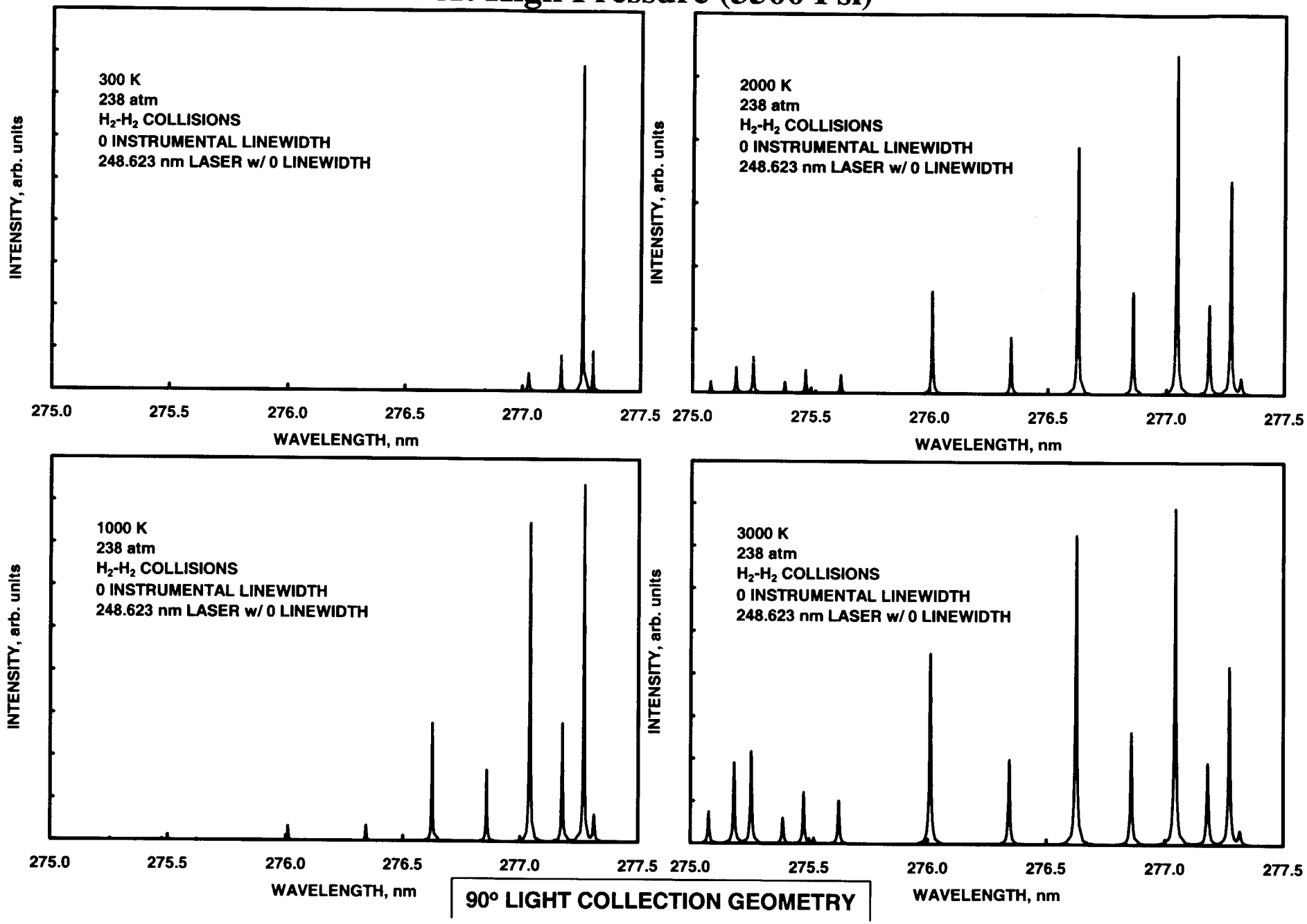


H_2 RO-VIBRATIONAL ENERGY LEVEL DATA FROM: Weber, A. 1973. "High Resolution Raman Studies of Gases." in *The Raman Effect*, edited by A. Anderson, Marcel Dekker: New York.

"OPTICAL" DIFFUSION COEFFICIENT MODELED AS MOLECULAR DIFFUSION COEFFICIENT x 1.13, BASED ON: Rahn, L. A., R. L. Farrow, and G. J. Rosasco. 1991. "Measurement of the Self-Broadening of the H2 Q(0-5) Raman Transitions from 295 to 1000 K." Physical Review A. Vol. 43, pp. 6075-6088.

RO-VIBRATIONAL LEVEL-DEPENDENT CROSS SECTIONS MODELED AS (V+1) (σ), WHERE σ FOR V=0 OBTAINED FROM: Ford, A. L., and J. C. Browne. 1973. "Rayleigh and Raman Cross Sections for the Hydrogen Molecule." Atomic Data. Vol . 5, pp. 305-313.

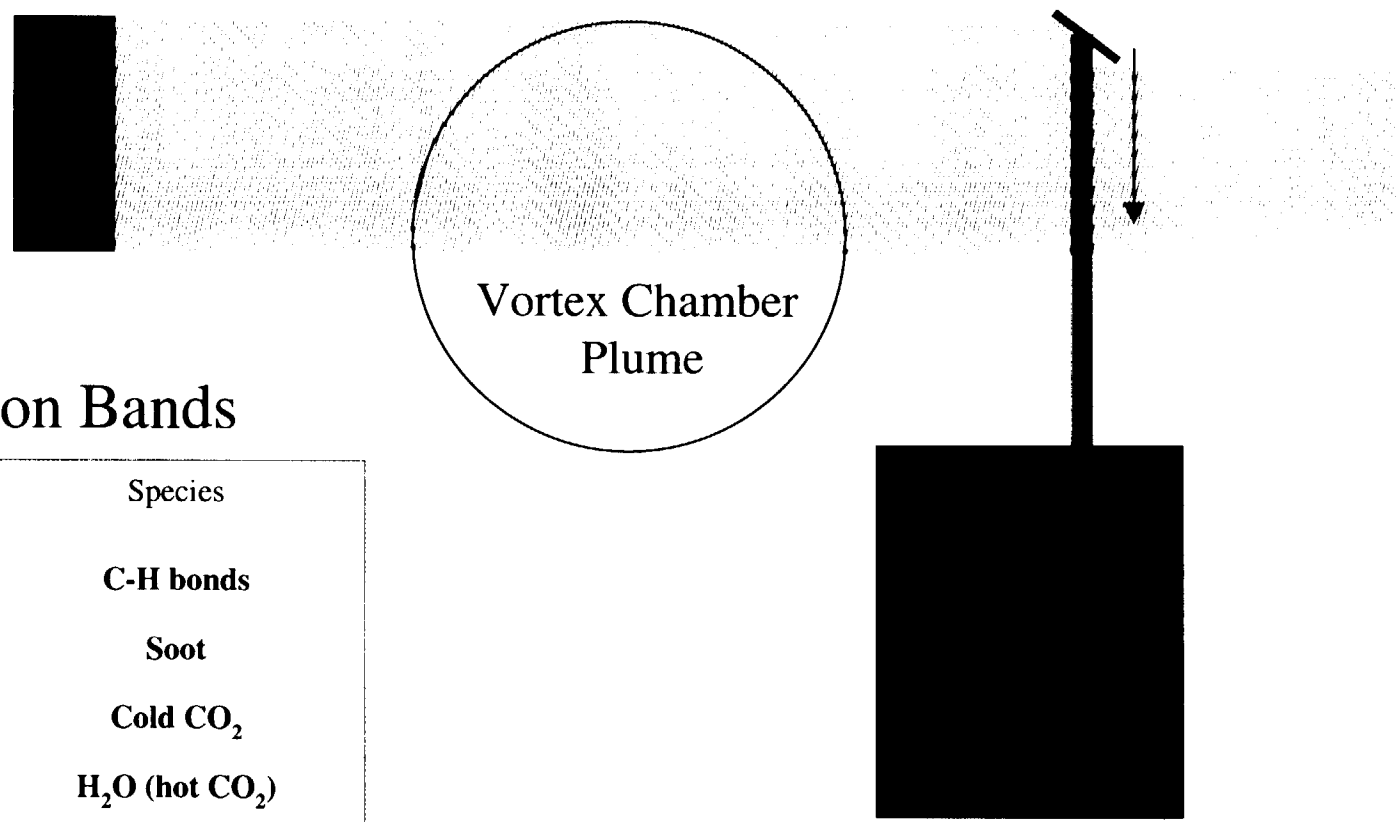
H_2 Spontaneous Raman Stokes Vibrational Q-branch, Synthetic Spectra At High Pressure (3500 Psi)



Infrared Emission/Absorption Spectroscopy

With each line-of-sight chord measurement, an Abel Inversion or "onion peel" method can be used to extract radial profiles

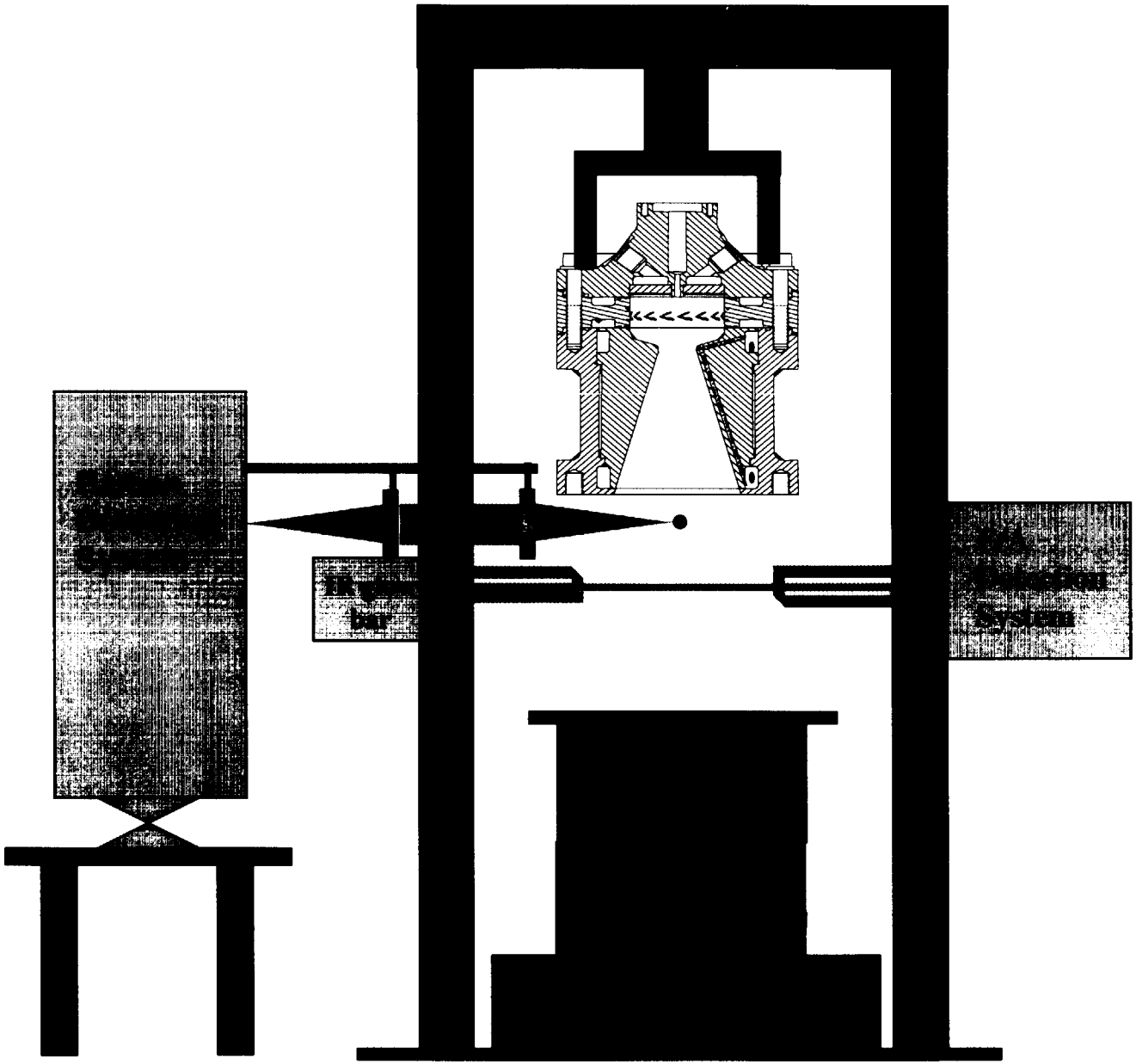
Mirror translates in order to collect consecutive spatial "chords"



Absorption Bands

Wavelength (μm)	Species
3.3	**C-H bonds**
3.8	**Soot**
4.3	**Cold CO_2**
4.45	**H_2O (hot CO_2)**
4.7	**CO**

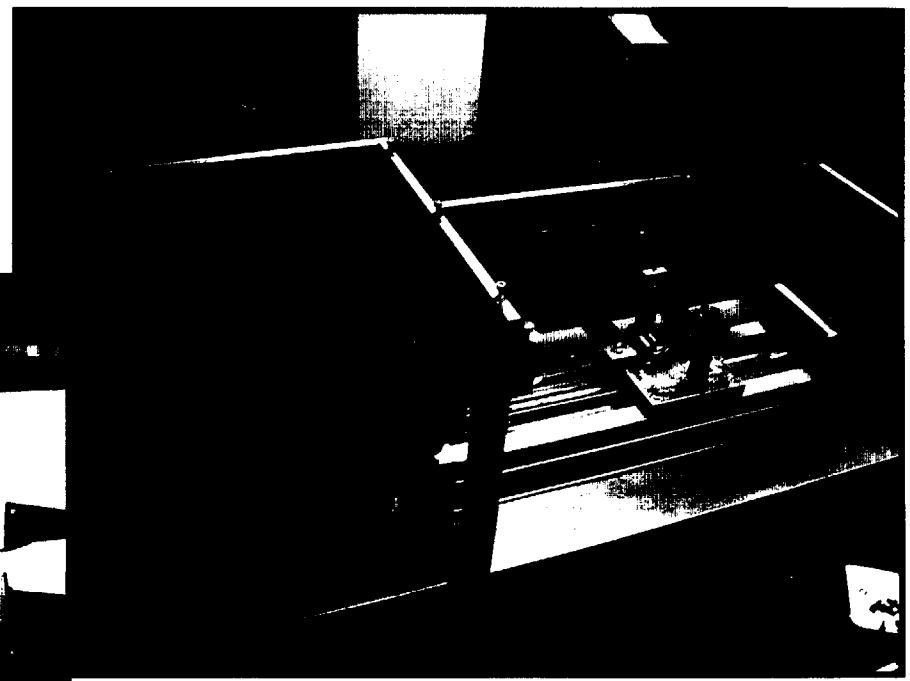
Schematic of Front View of Raman and E/A Setup



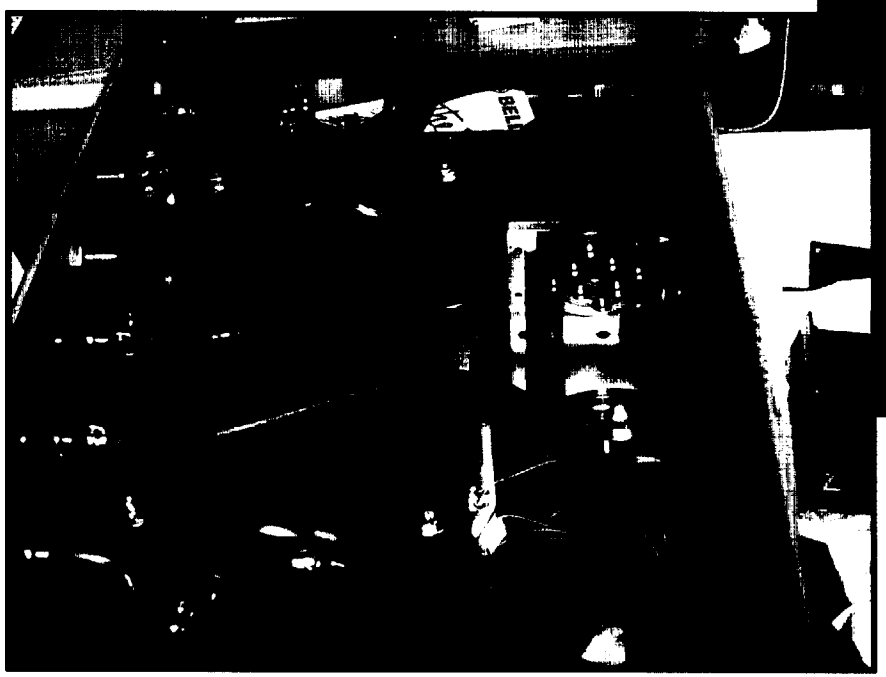
E/A Spectroscopy Test Stand Hardware

Detection System:

Spectrometer with linear array CCD
Mirror mounted on translation stage directs "chords" of light into spectrometer



Glow bar emits IR light



Future Work

- Measure Vortex Chamber Plume in September 2001

- Use optical diagnostics to measure inside optically accessible LOX/LH_2 test article

- Direct temperature measurements using spectrally-resolved Q-branch of Raman H_2 signal

- Improvement of data reduction techniques, Possibly through the use of curve fitting as shown on the right (sample data from Vanderbilt University)