

Nd:YAG LASER-BASED DUAL-LINE DETECTION RAYLEIGH SCATTERING AND CURRENT
EFFORTS ON UV, FILTERED RAYLEIGH SCATTERING

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Extended Abstract

Ongoing research at Polytechnic University in Rayleigh scattering diagnostics both for variable density low speed flow applications and for supersonic flow measurements will be described. During the past several years the focus has been on the development and use of a Nd:YAG-based Rayleigh scattering system with improved signal-to-noise characteristics and with applicability to complex, confined flows. This activity aimed to serve other research projects in the Aerodynamics Laboratory which required the non-contact, accurate, time-frozen measurement of gas density, pressure and temperature (each separately), in a fairly wide dynamic range of each parameter. Recently, with the acquisition of a new seed-injected Nd:YAG laser, effort has also been directed to the development of a high-speed velocity probe based on a spectrally-resolved Rayleigh scattering technique.

Dual-Line Detection Rayleigh Scattering:

The present Nd:YAG-based dual-line detection Rayleigh (DLDR) system is similar to the one developed several years ago at NASA Lewis Research Center which uses a copper vapor laser¹. In this technique, the second and fourth harmonic lines of the YAG laser are used simultaneously to determine the number density of the interrogated gas. The use of two lines through the same transmitting and collecting optics allows the determination and removal of the background (laser glare due to surfaces near the probe) from the Rayleigh signal which improves the applicability of Rayleigh scattering to confined flows.

Central to the system is a Nd:YAG laser with second (532 nm) and fourth (266 nm) harmonic generating crystals. After the second harmonic generator (SHG), the

residual 1064 nm energy is removed using a harmonic separator. The remaining green (532 nm) line is then passed through a half-wave plate so that its wave vector is 45 deg. to the horizontal. Next the green beam goes through the FHG where approximately 12% of the initial green energy is converted to 266 nm frequency. The beam containing both the green and UV lines is then focused into a narrow-waist probe volume through an achromat specially designed for the two frequencies. The waist of the probe is approximately 200 μm . The Rayleigh light scattered at both frequencies is collected normal to the beam and in the horizontal plane which is at ± 45 deg. to the each wave vector of the incident beam (after the FHG the green and the uv wave vectors are normal to each other). This is the optimum collection angle with the given set of optical components. The collimated signal is then color separated using a dichroic beam splitter and signal at each frequency is filtered (to eliminate any cross-contamination) and fed to two photomultiplier tubes (PMT). To eliminate the effect of laser shot-to-shot energy variations, scattered green and uv light near the probe is also collected by two photodiodes (PD) and the signal for each line is normalized by the respective laser energy. The output from the PMTs are fed to a boxcar averager and the PD signals are fed to a sample-and-hold unit all to be digitized by a 12-bit A/D converter and stored in a personal computer. The timing for the boxcar averager, sample and hold units and the A/D board are all provided by the TTL output synchronized with the laser's Q-switch pulse.

Extensive tests were performed to qualify the new DLDR system. Calibration tests were undertaken both using a heated air jet and a vacuum cell. These calibrations were repeated several times starting, initially, with no background contamination and gradually increasing the background intensity to study the effect of background on calibration and to determine the background coefficient ratio, $\beta = C'_g/C'_{uv}$. Here, C'_g and C'_{uv} are the green and uv surface scattering coefficients, respectively. The surface scattered background was obtained using plane aluminum plates. The value of β was found to be 2.15 ± 0.11 indicating that green scattering is twice as efficient as that for uv. The calibrations using heated air jet (temperatures between 292 and 775 K) and a vacuum cell (pressures from about 1100 torr down to about 130 torr) showed that the calibration coefficients, C_g and C_{uv} can be determined with an uncertainty of about 3%. Of course, this level of confidence does require considerable effort to "fine tune" the DLDR system and the calibration setup.

Next vacuum pressures are measured using the DLDR system (in the range 8 and 80 torr) to test the effective dynamic range of the system and to assess its capability to measure time-frozen vacuum pressures. These measurements were then compared to the estimated uncertainties due to shot noise (determines the measurement precision level) and

errors in the determination of the calibration constants (indicates the measurement accuracy). At each pressure 1000 individual realizations (laser shots) were obtained and the mean value as well as the standard deviation were plotted on the same graph. The mean values were quite close to the pressure gage measured values. - The standard deviations were only slightly larger than the estimated shot noise uncertainties.

The comparison of pressure measured by the green line only, the uv line only and the DLDR technique reveal that in the presence of high levels of background, the best and the worst results are obtained by the DLDR and the green line only systems, respectively. The uv line only pressure results are indeed quite close to those obtained by the DLDR. This is due to the fact that the uv Rayleigh scattering cross-section is 16 times larger than that for the green while the surface scattering is only half that of green. The combined effect is that the uv signal-to-background ratio is over 30 times larger than that of green. Therefore, using uv line only is already a major improvement over using the green line alone. Through further tests it was determined that the DLDR technique works robustly up to a level where the background-to-signal level on the green line is approximately 3. At this degree of background contamination, the uv background-to-signal levels will be approximately 0.1. This is still a significant improvement in measurement accuracy over the uv- only measurements.

Further tests were performed in a heated air jet facility with a co-flow. The jet facility is confined in a cylindrical enclosure to protect it from particulate contamination, which adds considerable surface-scattered laser glare. Temperature results obtained by the DLDR system closely match those measured by a constant current anemometry giving further credence to the new DLDR technique.

Spectrally-Resolved UV Rayleigh Scattering:

The goal of this effort is to develop a Rayleigh velocity probe for high speed velocity diagnostics which is based on the shorter wavelengths of a line-narrowed Nd:YAG laser, including the 266 nm fourth harmonic line and which utilizes a gas absorption filter (similar to iodine vapor used in conjunction with the 532 nm line) to block out the unshifted laser line reflected from surfaces surrounding the test section. High speed ground testing carried out in supersonic wind tunnels have various restrictions and present a number of difficulties. One of the more formidable restrictions is the optical access and a major difficulty is associated with surface scattering of laser line from test section walls and windows. The use of shorter incident wavelengths, especially in the uv range, significantly improves the Rayleigh signal-to-surface scattered background ratio due to the increased Rayleigh scattering cross-section and diminished surface scattering at

shorter wavelengths, as discussed earlier. However, surface scattering can still affect the quality of the Doppler-shifted Rayleigh signal under certain optical configurations. The present research aims to minimize this problem by trying to identify a suitable gas which has fine absorption structures around 266 nm wavelength.

The activity on the development of a molecular absorption filter for the FH of the Nd:YAG laser has been concentrated around the testing of benzene and its derivatives. Benzene and its derivatives are the group of organic molecules that have strong absorption bands in the general region which overlaps the tunable range of the FH of the injection-seeded laser (around 266 nm). The first absorption band of benzene is centered at 255 nm. It is followed by more than 30 bands shifted towards shorter further towards lower wavelengths. The gas absorption spectrum of benzene looks similar to that of iodine in the visible spectrum with some fine structures. The substitution on the benzene ring by auxochromic groups or hyboges reduces the symmetry of the new molecule. This change results in a red-shift of the spectral bands as well as an increase in the absorption intensities. Therefore, most of the benzene substitutes are potential strong absorbers around 266.1 nm. On the down side, the red-shift and increased intensity of the spectral bands can in some cases result in the reduction of the fine structures.

In order to be applicable to Rayleigh scattering, the absorption lines of the molecular filter has to have sharp spectral structures in the laser's tuning range. This can be a single isolated spectral line or a sharp "head" of an absorption band. The ultraviolet absorption spectra of gas phase benzene derivatives are available in the literature. However, the spectral resolution of available data is too poor to be useful for Rayleigh scattering applications. Therefore, we are currently studying the absorption spectrum of several compounds in the 266 nm range using the tunable YAG laser.

Reference:

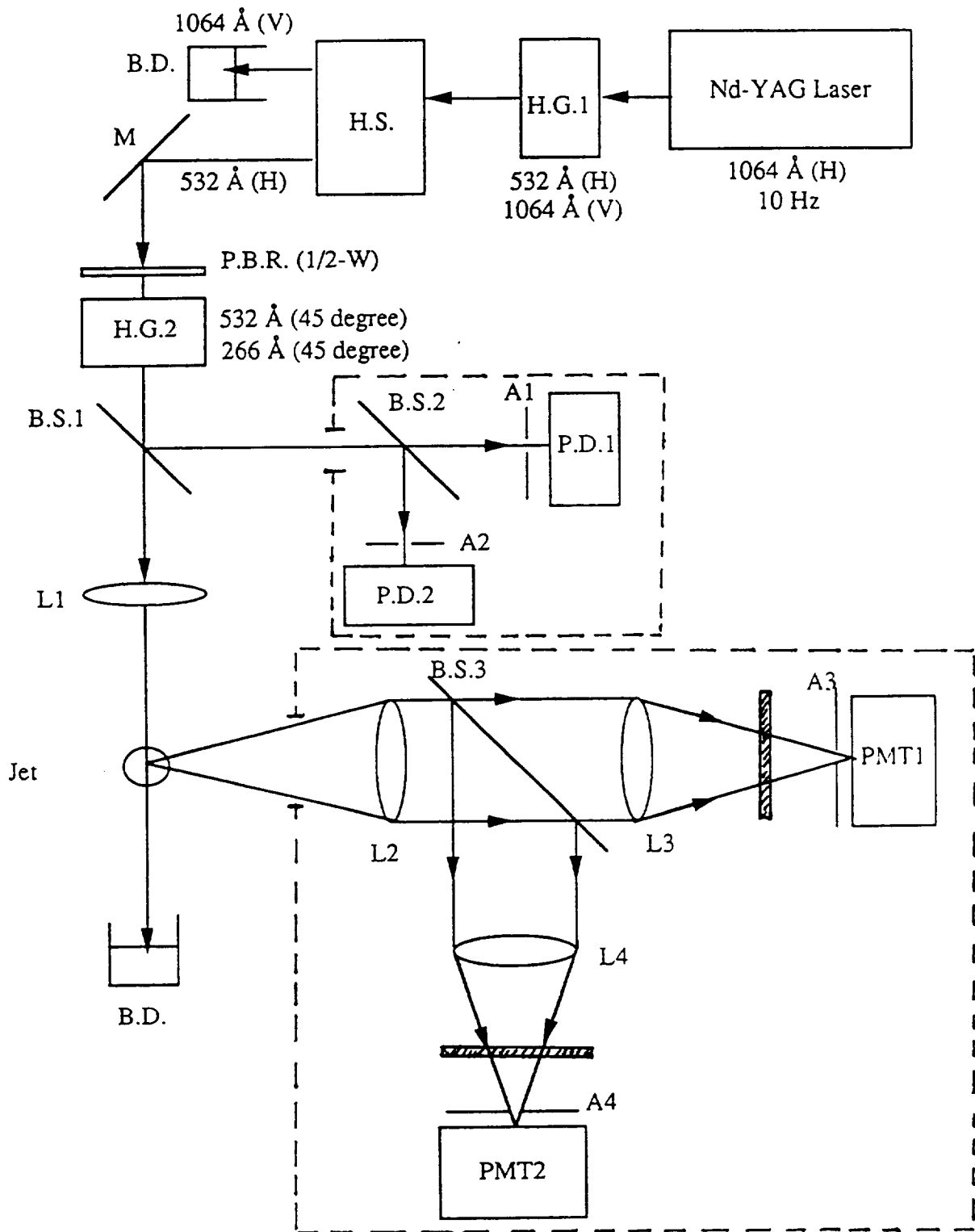
M.V. Otugen, K.D. Annen and R.G. Seasholtz, "Gas Temperature Measurements Using a Dual-Line Detection Rayleigh Scattering Technique", AIAA Journal, Vol. 31, No. 11, November 1993, pp. 2098-2104.

PRESENTATION OUTLINE

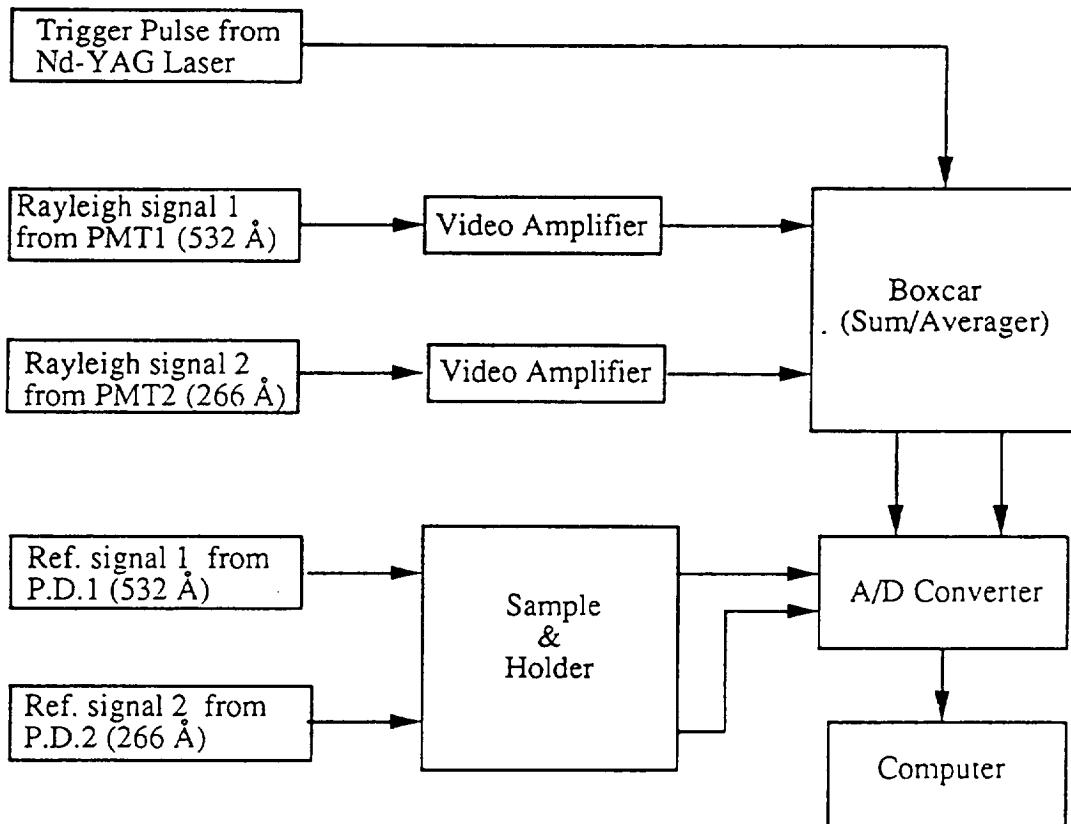
- o Nd:YAG laser-based DLDR System
- o Measurements using the new DLDR system
- o UV filter characterization efforts for Rayleigh scattering

DUAL-LINE DETECTION RAYLEIGH SCATTERING SYSTEM

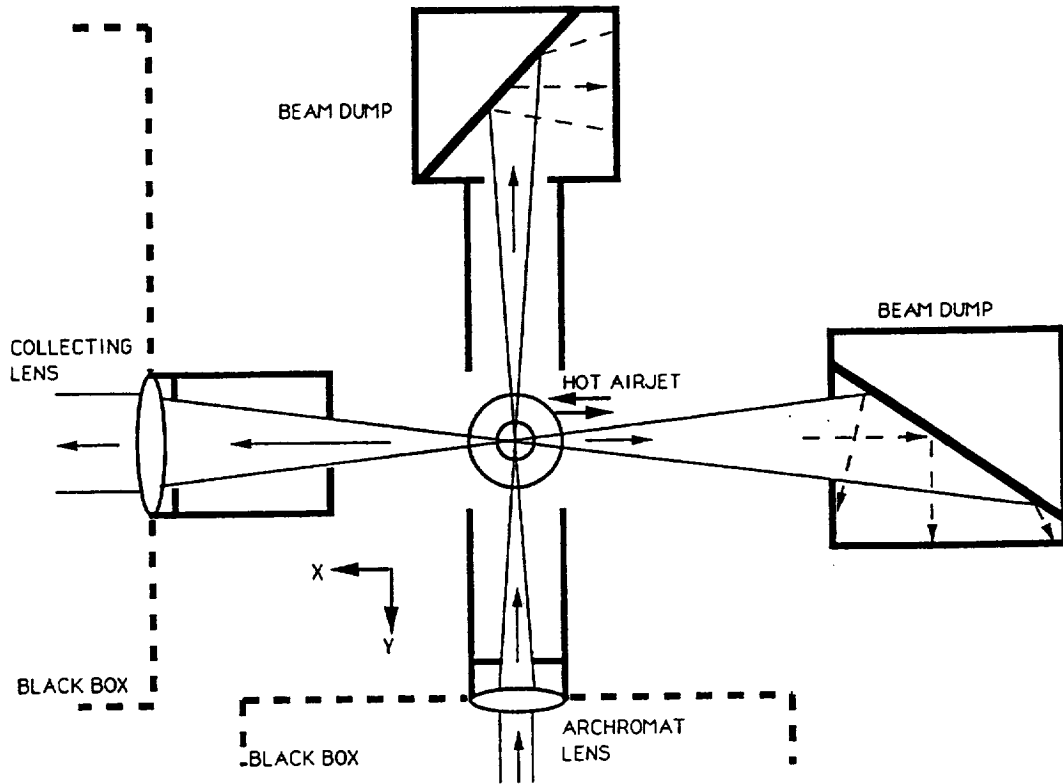
- o For time-frozen, local measurements of temperature and pressure
- o Uses 532 nm and 266 nm lines of the Nd:YAG laser
- o The two lines are focused at the probe volume using a special achromat
- o A single set of collecting optics used
- o Rayleigh scattered light is collected at $\pm 45^\circ$ angle to polarization dir.
- o Green and UV signal analyzed separately



Optical arrangement for Rayleigh scattering measurement



Schematic diagram of the Rayleigh signal acquisition



DLDR EQUATIONS FOR PRESSURE

$$\frac{E_{T,g}}{E_{L,g}} = \left(\frac{C_g \sigma_g}{kT} \right) P + \beta C_g C'$$

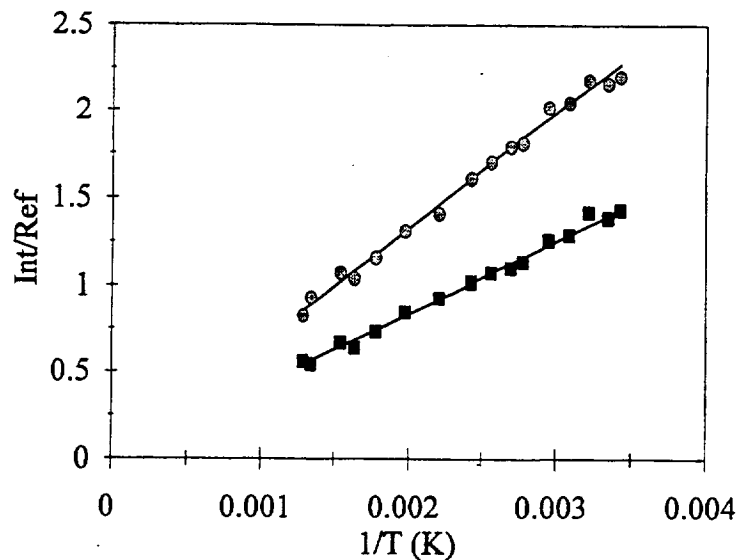
$$\frac{E_{T,wv}}{E_{L,wv}} = \left(\frac{C_{wv} \sigma_{wv}}{kT} \right) P + C_{wv} C'$$

$$P = \frac{\frac{E_{T,g}}{E_{L,g}} \frac{1}{C_g} - \frac{E_{T,wv}}{E_{L,wv}} \frac{\beta}{C_{wv}}}{\frac{\sigma_g - \sigma_{wv} \beta}{kT}}$$

$$C' = \frac{\frac{E_{T,wv}}{E_{L,wv}} \frac{\sigma_g}{C_{wv}} - \frac{E_{T,g}}{E_{L,g}} \frac{\sigma_{wv}}{C_g}}{\beta \sigma_g - \sigma_{wv}}$$

DLDR Cal 1 (Jet Apparatus)

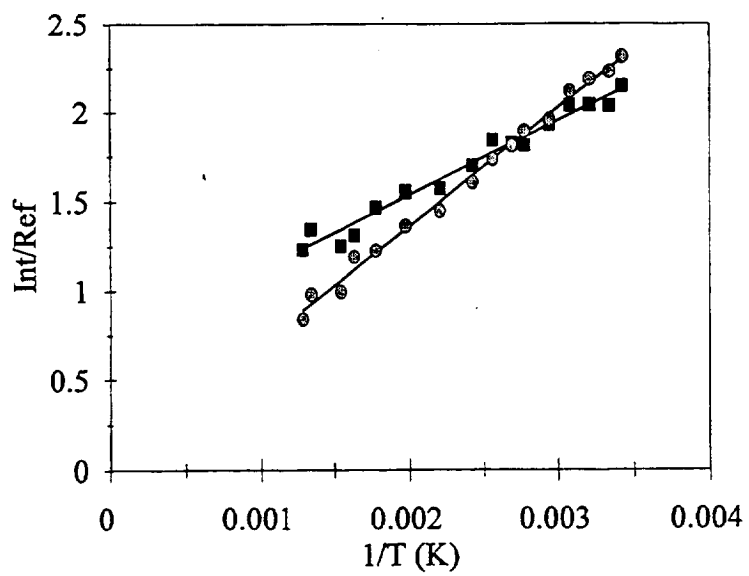
std (g)=3% ; std (uv)=4.2%



■ Green line ○ UV line

DLDR Cal 2 (Jet Apparatus)

std (g)=5.2 ; std (uv)=4.1



■ Green line ○ UV line

Cal. 1 parameters:

$$C_g = 1.367 \times 10^6$$

$$C_{uv} = 1.336 \times 10^5$$

$$C'_g = \text{----}$$

$$C'_{uv} = \text{----}$$

$$C'_g/C'_{uv} = \beta = ?$$

Cal. 2 parameters:

$$C_g = 1.390 \times 10^6$$

$$C_{uv} = 1.351 \times 10^5$$

$$C'_g = 5.120 \times 10^{-7}$$

$$C'_{uv} = 2.415 \times 10^{-7}$$

$$C'_g/C'_{uv} = \beta = 2.12$$

AIR JET CALIBRATION SUMMARY

(Average of six calibrations at the same
optical/electronic settings)

Calibration constants:

$$C_g = 1.365 \times 10^6 \quad (\pm 0.047 \times 10^6)$$

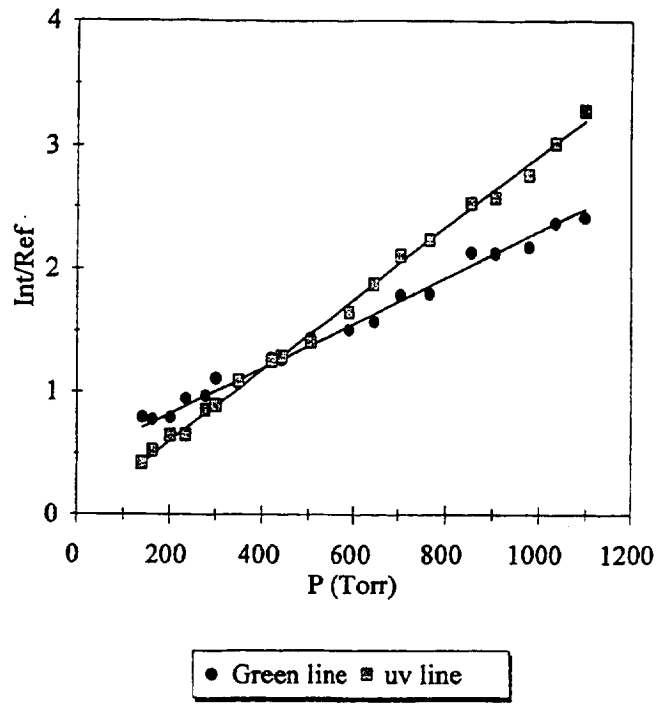
$$C_{uv} = 1.354 \times 10^5 \quad (\pm 0.040 \times 10^5)$$

Background scattering ratio:

$$C'_g/C'_{uv} = 2.15 (\pm 0.11)$$

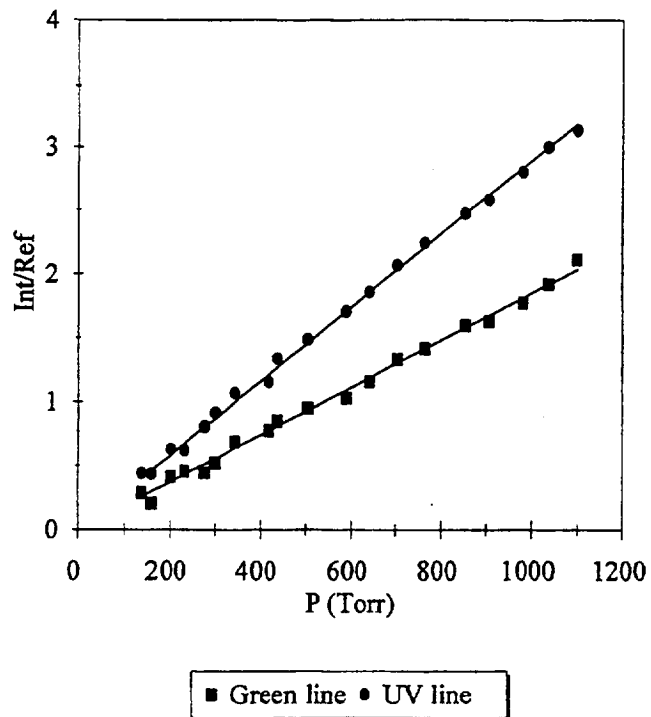
DLDR Cal 2 (Vacuum Chamber)

std (g) = ; std (uv) =



DLDR Cal 1 (Vacuum Chamber)

std (g)=4% ; std (uv)=3.4%



Cal. 1 parameters:

$$C_g = 1.401 \times 10^6$$

$$C_{uv} = 1.372 \times 10^5$$

$$C'_g = \text{----}$$

$$C'_{uv} = \text{----}$$

$$C'_g/C'_{uv} = \beta = ?$$

Cal. 2 parameters:

$$C_g = 1.379 \times 10^6$$

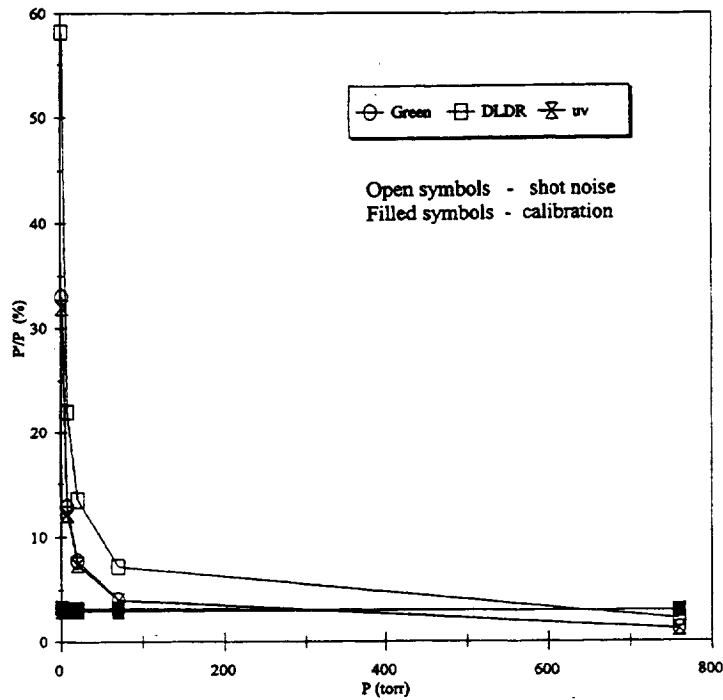
$$C_{uv} = 1.385 \times 10^5$$

$$C'_g = 3.297 \times 10^{-7}$$

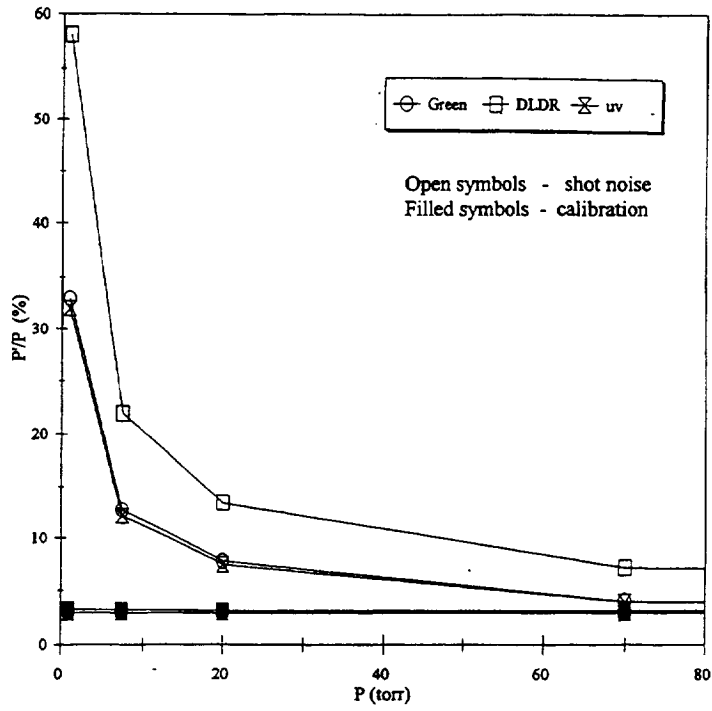
$$C'_{uv} = 1.585 \times 10^{-7}$$

$$C'_g/C'_{uv} = \beta = 2.08$$

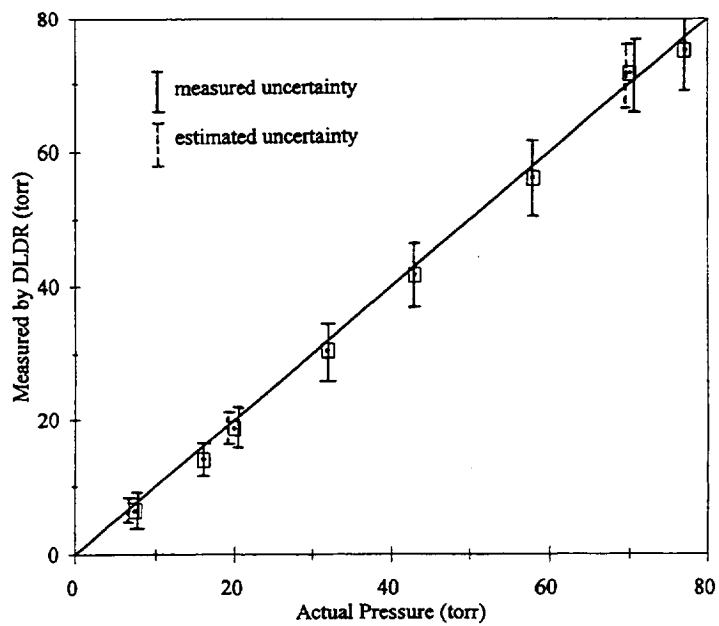
**Calculated uncertainty levels
(shot noise and calibration accuracy)**



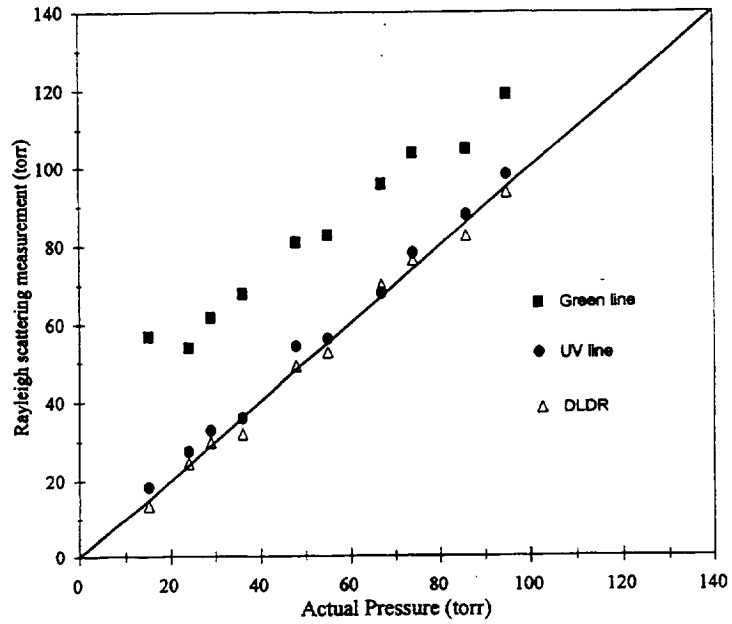
Calculated uncertainty levels
(shot noise and calibration accuracy)



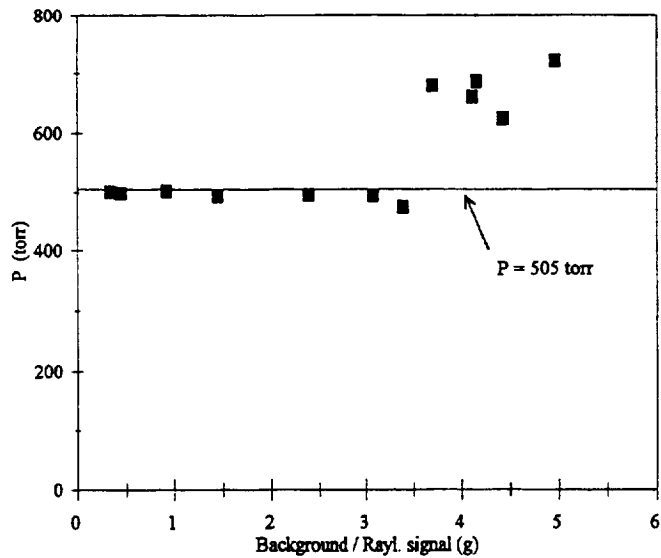
Pressure measurements in vacuum
($T = 298$ K, No background)

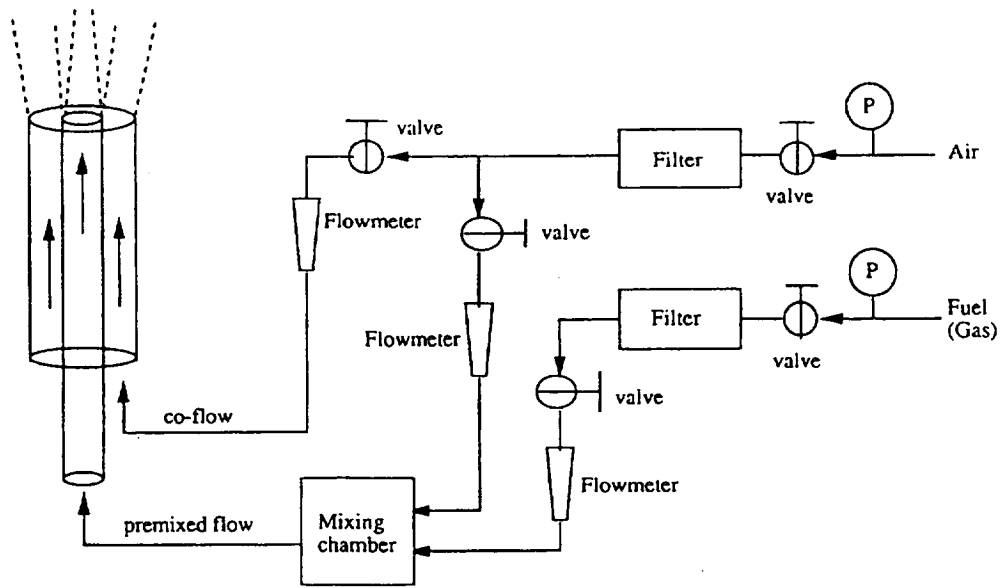


Pressure Measurement with Background (T = 301 K)

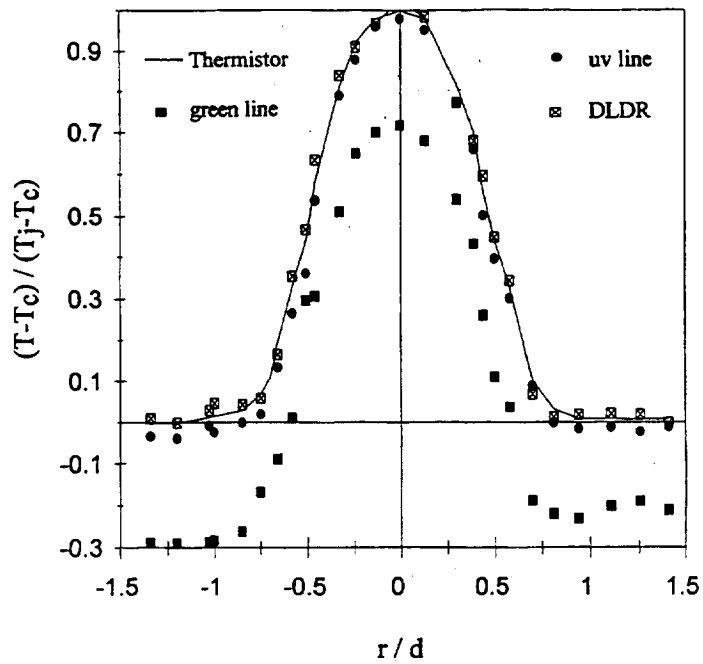


DLDR Pressure measurement (T=298 K ; P=505 torr ; N=1000)

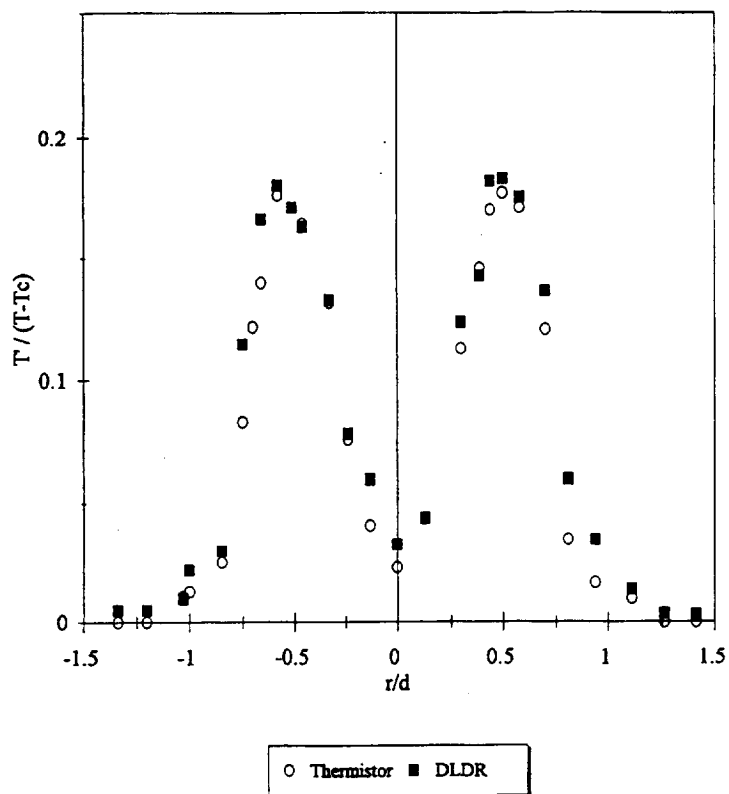




Mean temperature profile in jet
($x/d = 5$)



**Turbulent temperature profile in jet
($x/d = 5$)**



UV FILTER

OBJECTIVE: Develop a molecular absorption filter for 266nm, similar to I_2 for 532 nm

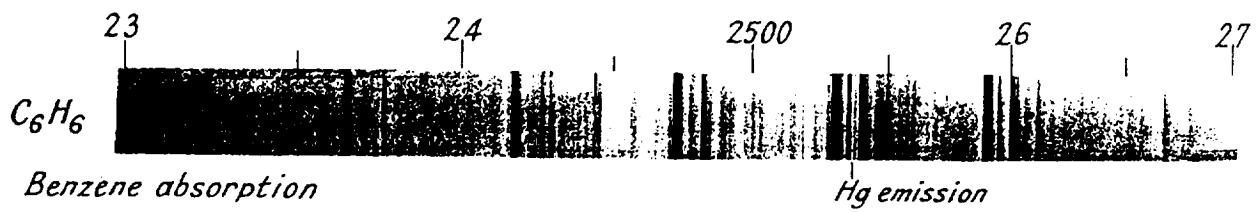
Laser tuning range:

$$k = 37578 - 37580 \text{ cm}^{-1}$$

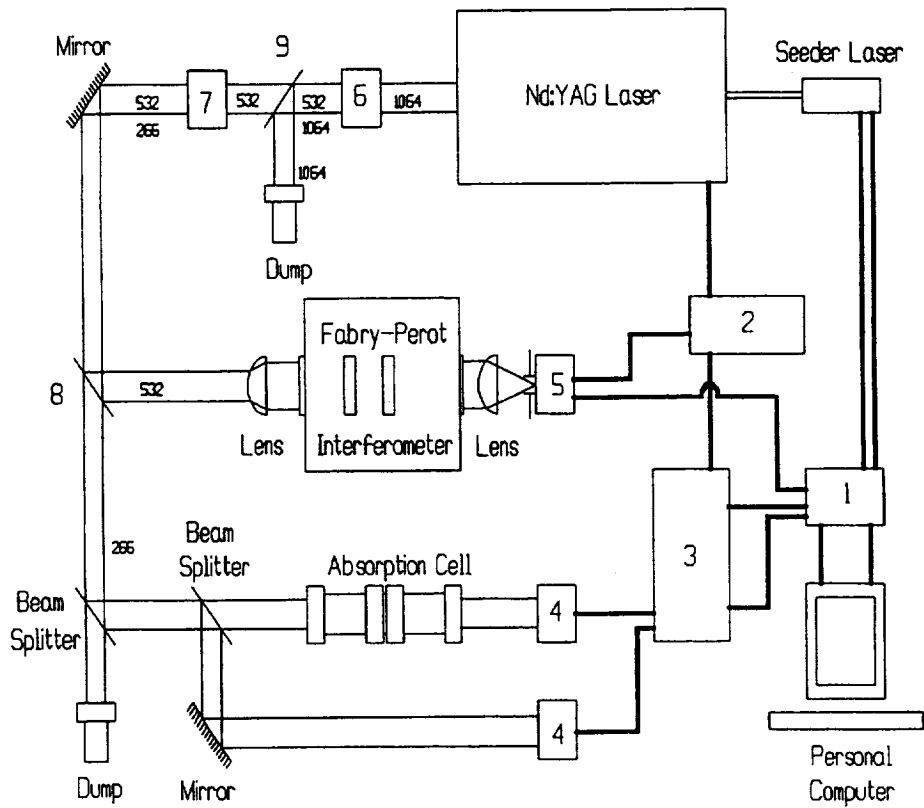
$$\lambda = 266.099 - 266.113 \text{ nm}$$

Investigate the following spectral characteristics:

- (a) Isolated spectral line
- (b) Spectral band structure
- (c) Head of a spectral band



UV Filter Material Testing

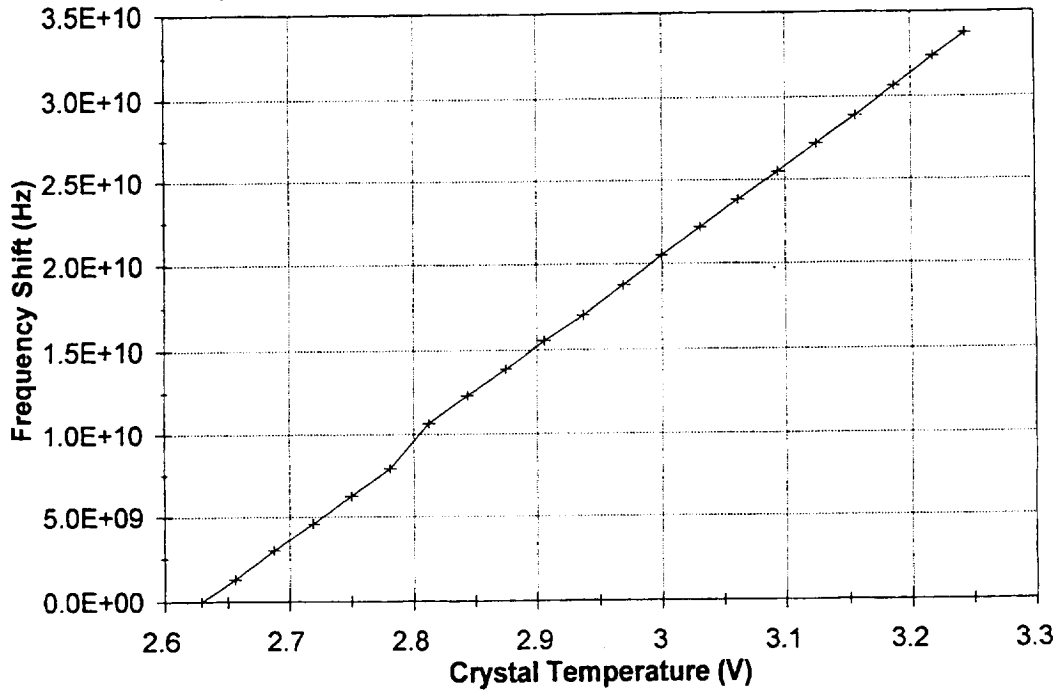


1	Digital/Analog Converter Board
2	Timing Module
3	Boxcar Averager
4	Photomultiplier Tube
5	CCD Camera
6	Second Harmonic Generator
7	Fourth Harmonic Generator
8	Harmonic Separator (532/266 nm)
9	Harmonic Separator (532/1064 nm)

April 3, 1995

Frequency Shift

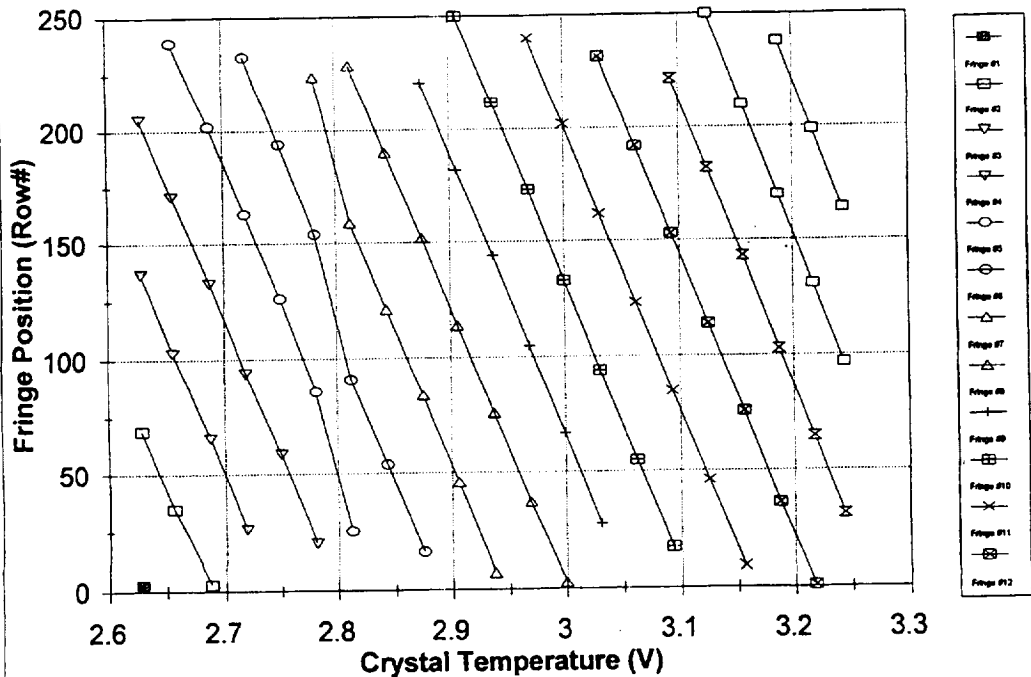
Crystal Temp. @ 0 pin9 Voltage= 2.937V



March 31, 1995

Fringe Position

Crystal Temp. @ 0 pin9 Voltage= 2.937V



CONCLUSIONS

- o Nd:YAG based DLDR system provides improved temp./pressure measurements
- o The system may be limited to the condition: green background-to-signal > 3
- o This can be improved using TH along with FH of Nd:YAG
- o Slightly increased shot noise uncertainty with DLDR

- o Efforts continue to identify a viable candidate for uv (266 nm) filter