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9-3-86

ST (2)

(2 copies) I-27780

Dr. 1916-X

UCID- 20846

ASPECTS OF RAMAN SCATTERING AND OTHER
EFFECTS ON LASER PROPAGATION
THROUGH THE ATMOSPHERE

James R. Ipser
Summary of Work for the Period
5/586-6/13/86

August 1986

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

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(Summary of Work for the Period
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UCID--20846
DE86 015152

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I. INTRODUCTION

In this summary I shall first focus on a selected few of the processes thought to be of interest in connection with laser propagation through the atmosphere. I shall review what I have learned about these processes and their possible importance in the present context. I shall then list these and a number of other processes that should be examined further for their possible importance. An Appendix on the SPC subroutine PRAMAN is included.

II. SOME PROCESSES RELEVANT TO ATMOSPHERIC LASER PROPAGATION

A. RAMAN SCATTERING

1. Theoretical Considerations

In Raman scattering an incident photon (e.g. in the laser beam) of energy $h\nu_L$ is absorbed by an interacting particle (e.g. molecule), which then re-emits a photon of lower energy $h\nu_s$ and is left in an excited state. This process is depicted in the associated diagram. The

interacting particle is envisaged as undergoing virtual excitation to an intermediate state via absorption of the incident photon, and as emitting the final photon via relaxation to the final, excited state.

The Raman process can be spontaneous or stimulated. In the spontaneous process, the rate of production of "Stokes" photons of energy $h\nu_s$ is independent of the number of Stokes photons already present in a mode. In the stimulated process that rate is proportional to the number of Stokes photons present. That this is so is evident from the following simple argument.

Consider first the spontaneous process. Here an incident laser photon excites the interacting particle from its ground state and the particle emits a Stokes photon, more or less isotropically. Hence the rate R_{spont} per interacting particle at which this process proceeds should satisfy

$$R_{\text{spont}} = \alpha I_L \quad , \quad (1)$$

where I_L is the incident laser flux and α depends on the energies and the properties of the interacting particle. Consider next the stimulated process. Here an already-present Stokes photon is viewed as inducing a transition from the intermediate state to the final excited state, with the production of a Stokes photon in the same mode as the initial Stokes photon. This implies a rate proportional to the Stokes flux I_s in the mode under consideration. Also, the probability of finding the interacting particle in the intermediate state is proportional to the exciting incident laser flux I_L . Hence the stimulated rate R_{STIM} should satisfy a relation of the form

$$R_{\text{STIM}} = \alpha' I_L I_s \quad , \quad (2)$$

and one thus expects exponential growth for the stimulated process.

To make this a little more quantitative let us focus on simplified rate equations for Raman scattering into a single photon mode at frequency ν_s from an incident source at frequency ν_L (see Yariv 1967).

Thus consider an interacting region of volume V , and let N_L and N_s be the numbers of quanta in the laser and Stokes modes. Using the fact, involving quantum harmonic oscillators, that the probability of absorption of one quantum for a mode containing N quanta is $\propto N$ and the probability of emission is $\propto (N + 1)$, one can write down the approximate rate equations.

$$\begin{aligned} \frac{dN_s}{dt} &= \tilde{\alpha} P_i N_L (N_s + 1) \\ &\quad - \tilde{\alpha} P_f N_s (N_L + 1) \quad , \end{aligned} \quad (3)$$

$$\frac{dN_s}{dt} = -\frac{dN_L}{dt} \quad (4)$$

Here the quantity $\tilde{\alpha}$ depends partly on the properties of the interacting particles, and P_i and P_f are the probabilities of finding an interacting particle in its initial ground state and its final excited state, respectively. On the right hand side of equation (3), the part independent of N_s involves the spontaneous process while the part proportional to N_s involves the stimulated process.

Focus first on spontaneous emission, described by

$$\left(\frac{dN_s}{dt}\right)_{\text{spont}} = \tilde{\alpha} P_i N_L \quad (5)$$

This equation implies that for spontaneous emission into a single Stokes mode,

$$\frac{\Delta(\text{No. of spon. events})}{\Delta(\text{time}) \cdot (\text{Volume}) \cdot (\text{incident flux})} = \frac{\tilde{\alpha} P_i N_L}{V \cdot (N_L c / V)} \quad (6)$$

where c is the speed of light. Now the total number of quantum modes available to the final Stokes photon per degree of polarization, is

$$\frac{d^3 p V}{h^3} = \frac{1}{c^3} \nu_s^2 \Delta \nu d\Omega \quad (7)$$

where $\Delta \nu$ is line width for the transition, p is momentum, and $d\Omega$ is the element of solid angle. Multiplying equation (6) by (7), which amounts to summing over the available final states, and dividing by the number N of interacting particles per unit volume, one obtains the identification

$$\frac{d\sigma}{d\Omega} = \tilde{\alpha} P_i V \frac{\nu_s^2 \Delta \nu}{c^4 N} \quad (8)$$

Here $d\sigma/d\Omega$ is the Raman differential cross-section per interacting particle per degree of polarization. The quantity that is easily measured directly is $N \int (d\sigma/d\Omega) d\Omega$.

Turn now to stimulated emission. In this case

$$\left(\frac{dN_s}{dz}\right)_{\text{STIM}} = \frac{1}{c} \left(\frac{dN_s}{dt}\right)_{\text{STIM}} \approx \frac{\tilde{\alpha}}{c} (P_i - P_f) N_L N_s \quad (9)$$

where Z is distance along the direction of the incident beam. Neglecting depletion of incident photons, one obtains

$$N_s(z) \approx N_s(0) e^{\int g dz} , \quad (10)$$

where the gain factor g satisfies

$$\begin{aligned} g &\approx \frac{\tilde{\alpha}}{c} (P_i - P_f) N_L \\ &\approx \frac{c^3 \Delta N n_l d\sigma}{\nu_s^2 \Delta \nu d\Omega} . \end{aligned} \quad (11)$$

In this equation

$$\Delta N = N \left(1 - e^{-h(\nu_L - \nu_s)/kT} \right) , \quad (12)$$

with k Boltzmann's constant and T temperature, and n_l is the number density of laser photons.

Expression (11) is a good approximation. A more correct expression for the Raman gain factor, obtained by a more careful procedure, is (see, e.g. Wang 1975)

$$g \approx \frac{c^3 \Delta N n_l \nu_L d\sigma}{\nu_s^3 \Delta \nu d\Omega} . \quad (13)$$

2. Raman Gain in the Atmosphere

The results of *Averbakh et al.* (1978) imply that for atmospheric propagation of $\sim 1\mu\text{m}$ laser beams, rotational stimulated Raman scattering (RSTRS) is dominant over vibrational scattering (VSTRS). For the nitrogen molecule and its rotational levels, values of relevant physical quantities are (cf. *Averbakh et al.* 1978)

$$\begin{aligned} \left(\frac{\Delta N}{N} \right)_{\text{max}} &\sim 0.035 \text{ (at } J = 8 \text{ for } T \sim 300\text{K}) , \\ \left(\frac{d\sigma}{d\Omega} \right)_{\text{RSTRS}} &\sim 3.7 \times 10^{-30} (\lambda_s / 0.53\mu\text{m})^{-4} \text{ cm}^2 , \\ \Delta \nu / c &\sim 0.08 \text{ cm}^{-1} / \text{ATM} , \\ \frac{\nu_L}{c} - \frac{\nu_s}{c} &\sim 8(J + 3/2) \text{ cm}^{-1} , \\ &\sim 76 \text{ cm}^{-1} \text{ for } J = 8 . \end{aligned} \quad (14)$$

In these equations, J is the total angular momentum quantum number, λ is wavelength, and ATM stands for an atmosphere of pressure. Substitution into equation (13) yields

$$\frac{g}{I_L} \equiv \frac{g}{h\nu_L n_L c} \approx 3 \times 10^{-6} \lambda^{-1} \mu\text{m}^{-1} \text{ cm/MW} \quad , \quad (15)$$

Where λ is the wavelength of the incident laser radiation in microns, I_L is the incident laser energy flux, and MW = 1 megawatt = 10^{13} erg s⁻¹.

To estimate roughly the total Raman gain factor for the atmosphere, one notes that the gain factor should be roughly constant up to an altitude of ~ 40 km. This is because at lower altitudes the line width is pressure broadened and hence is proportional to the pressure. This cancels out the pressure dependence of the number density N appearing in the numerator of equation (13). Above ~ 40 km, doppler broadening is expected to exceed pressure broadening, and so the gain factor falls exponentially with height. It follows that the total *RSTRS* atmospheric gain factor is

$$g \approx \int_0^{40\text{km}} \frac{g dz}{I_L} \sim 60 \text{ cm}^2/\text{MW} \quad . \quad (16)$$

This predicts a large gain indeed, since g appears as an exponent (cf. Eq. [10]).

3. The Transient Raman Effect

Actually, the validity of the above analysis depends rather crucially on the assumption that the time and spatial dependence of the incident laser beam can be neglected. When this assumption is violated, as is the case for pulsed beams with typical pulse timelength $\lesssim$ the coherence decay timescale $(\Delta\nu)^{-1}$, the gain factor can be modified (decreased) significantly from its steady-state value.

Rather than presenting a rough analysis (available upon request) of the transient case, the case for which the incident beam varies on timescales short compared with the decay time, I shall just quote the final approximate results. In a first approximation for the

transient case, one finds that the steady-state gain factor gz (cf. Eq. [16]) is replaced by the transient gain factor (cf. Wang 1975)

$$G_{TRANS}(z, t) \sim 2 \left[(gz) \frac{c\Delta\nu}{I_L} \int_{-\infty}^{t-z/c} \frac{4\pi}{c} I_L(t') dt' \right]^{1/2} - 2\pi\Delta\nu(t - z/c) \quad , \quad (17)$$

where it is assumed that $I_L = I_L(t - z/c)$. Note that the transient gain is proportional to the square roots of both the length of the medium and the laser energy.

As I shall repeat later, further work is needed before this effect and its importance can be fully understood (at least by me).

B. SELF-FOCUSING OF BEAMS

Suppose that the induced polarization of a particle is of the form

$$p = \alpha E + \gamma E^3 + \dots \quad , \quad (18)$$

where E is the electric field. It follows that if the number density of particles is N , then the polarization P per unit volume is

$$P = Np = N(\alpha + \gamma E^2 + \dots)E \quad . \quad (19)$$

And the dielectric constant ϵ is then

$$\epsilon = 1 + 4\pi N\alpha + 4\pi N\gamma E^2 + \dots = \epsilon_0 + \epsilon_2 E^2 + \dots \quad . \quad (20)$$

Nonlinear contributions (e.g. $\epsilon_2 E^2$) to ϵ can arise in a variety of ways, e.g. from anisotropy in the polarizability of a particle (Yariv 1967).

If ϵ_2 is positive (negative), then the dielectric constant ϵ tends to be larger (smaller) in regions with larger electric-field strengths; and this leads to focusing (blooming) of beams (Akhmanov *et al.* 1972). One can see this from the following simple argument. Consider an electromagnetic beam of diameter D , and let the field strength at beam center be E . If the beam starts out as plane fronted, then after time Δt a ray at the outer edge has

moved forward a distance $\sim \lambda \nu \Delta t$, while a ray at beam center has moved forward only a distance $\sim (\lambda - \delta \lambda) \nu \Delta t$, where $\delta \lambda$ is the decrease in wavelength λ due to the increase in dielectric constant with increasing field strength.

This implies that the wavefront has become concave, with characteristic bending angle

$$\theta \sim \frac{\nu \delta \lambda \Delta t}{D/2} \quad (21)$$

after time Δt . This in turn implies that the beam narrows its diameter by an amount

$$\Delta D \sim \lambda \nu \Delta t \theta \sim \frac{2}{D} \frac{\delta \lambda}{\lambda} (\Delta z)^2 \quad (22)$$

during a time Δt , or over a distance $\Delta z = \lambda \nu \Delta t$. Since

$$\frac{\delta \lambda}{\lambda} \sim \sqrt{\epsilon} \delta \left(\frac{1}{\sqrt{\epsilon}} \right) \sim \frac{1}{2} \frac{\epsilon_2}{\epsilon_0} E^2 \quad (23)$$

(cf. Eq. [20]), the characteristic focusing distance z_f over which $\Delta D \sim D$ is

$$z_f \sim \frac{D}{E} \left(\frac{\epsilon_0}{\epsilon_2} \right)^{1/2} \sim D \left(\frac{c}{8\pi I} \frac{\epsilon_0}{\epsilon_2} \right)^{1/2}, \quad (24)$$

where I is the energy flux.

Can this effect be important for laser propagation through the atmosphere? To investigate this question in a rough approximate way, let us refer the value of ϵ_2 to the value appropriate to molecular hydrogen at atmospheric pressure. That is, let us write

$$\epsilon_2 = 4\pi N \gamma = 4\pi \times 3 \times 10^{19} N_{ATM} \times 10^{-37} \gamma_{(37)}, \quad (25)$$

where

$$N_{ATM} = \frac{N}{3 \times 10^{19} \text{ cm}^{-3}}, \quad \gamma_{(37)} = \frac{\gamma}{10^{-37} \text{ cgs}}. \quad (26)$$

We note that theoretical estimates (Flytzanis 1975) yield γ (37) ≈ 1 for the hydrogen molecule. Substituting equation (25) into (24) and letting

$$I = 10^{13} I_{mw} \text{ erg s}^{-1} \quad (27)$$

we obtain

$$z_f \sim 10^6 D \left[\frac{\epsilon_0}{N_{ATM} \gamma(37) I_{MW}} \right]^{1/2} \quad (28)$$

Let us compare this characteristic length scale for self-focusing with the rotation stimulated Raman-gain length scale z_{RSTRS} . From equation (15)

$$z_{RSTRS} \sim (g/I_L)^{-1} \frac{1}{I_L} \sim 3 \times 10^5 \frac{1}{I_{MW}} \text{ cm} \quad (29)$$

Hence

$$\frac{z_{RSTRS}}{z_f} \sim \frac{1}{3} \frac{1}{D} \left[\frac{N_{ATM} \gamma(37)}{\epsilon_0 I_{MW}} \right]^{1/2} \quad (30)$$

For a given beam power P_{MW} in megawatts,

$$P_{MW} = \frac{\pi}{4} D^2 I_{MW} \quad (31)$$

so that

$$\frac{z_{RSTRS}}{z_f} \sim \frac{1}{3} \left[\frac{N_{ATM} \gamma(37)}{\epsilon_0 P_{MW}} \right]^{1/2} \quad (32)$$

For example, if one envisages a flux of 10^{-1} MW/cm^2 on a beam with spot size $D \sim 30 \text{ cm}$, then

$$\frac{z_{RSTRS}}{z_f} \sim \frac{1}{30} \left[\frac{N_{ATM} \gamma(37)}{\epsilon_0} \right]^{1/2} \quad (33)$$

and self-focusing is probably not important unless $N_{ATM} \gamma(37)$ is large. Can this product be large? We shall pose this question again below.

C. TWO-PHOTON ABSORPTION

Consider a situation in which an interacting particle absorbs 2 incident photons of energies $h\nu_1$ and $h\nu_2$. Roughly, from Fermi's "golden rule" one expects that the rate per particle of such a transition will be of the form

$$\text{Rate}_{2\text{-photon}} \sim \frac{2\pi}{\hbar} \left| \left\langle \frac{H_{INT}^2}{\hbar \Delta \nu} \right\rangle \right|^2 \rho_E \quad (34)$$

Here H_{INT} is the interaction Hamiltonian, $\hbar \Delta \nu$ represents appropriate energy changes involved in the absorption process, and ρ_E represents the number of final states of the interacting particle per unit energy. Further,

$$H_{INT} \sim e E r \quad (35)$$

where e is electric charge, E is electric field, and r is electronic position in the interacting particle. Thus one expects a rate that goes like the fourth power of the incident electric field. Hence if any final states of the interacting particle lie in the accessible energy range, this process could be important.

For the moment I shall just note that a straightforward calculation using time-dependent perturbation theory yields the following expression for the transition rate per unit time per particle:

$$\begin{aligned} \text{Rate}_{2\text{-photon}} = & \frac{8\pi^3}{\hbar} e^4 h\nu_1 h\nu_2 n_1 n_2 \rho_E \\ & \times \left| \sum_{n'} \left\{ \frac{(\mathbf{r}_{fn'} \cdot \hat{\mathbf{e}}_2)(\mathbf{r}_{ni} \cdot \hat{\mathbf{e}}_1)}{\hbar(\nu_1 - \nu_{n'i})} + \frac{(\mathbf{r}_{fn'} \cdot \hat{\mathbf{e}}_1)(\mathbf{r}_{ni} \cdot \hat{\mathbf{e}}_2)}{\hbar(\nu_2 - \nu_{n'i})} \right\} \right|^2 \quad (36) \end{aligned}$$

where n_1 and n_2 are the densities of the incident photons; ν_1 and ν_2 are their frequencies; the subscripts i and f refer to the initial and final states of the particle; n' refers to the intermediate states reached after absorption of one photon; $h\nu_{n'i}$ is the energy difference between intermediate and initial state; $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$ are polarization vectors for the incident photons; and $\mathbf{r}_{fn'}$, for example, represents the matrix element of the electronic position operator between final and intermediate states. Again one sees that for large incident fluxes this process can be important if final states lie in the accessible energy range.

III. FUTURE STUDIES

It would appear that a number of topics merit further study in connection with the assessment of beam propagation through the atmosphere.

A. RAMAN SCATTERING

As mentioned earlier, it is clear that when the incident-beam pulse timescale is short compared with the decay timescale for stimulated Raman emission, the transient Raman effect becomes important. Further work is needed (as far as I am concerned, at least) to assess the precise importance of this effect and to determine how to incorporate it into simulations. In this connection, it appears that the SPC1 and SPC2 codes assume steady-state Raman emission and hence require modification. Further, even in the steady-state regime the above codes appear to use frequency shifts appropriate to vibrational scattering, while it is known that rotational scattering is more important. This also needs to be corrected.

In addition, Raman scattering in clouds, water vapor, etc. should be examined.

B. NONLINEAR SUSCEPTIBILITIES AND FOCUSING

Is it possible that certain envisaged environments will include the presence of particles, in sufficiently large numbers and with sufficiently large nonlinear susceptibilities (cf. Eqs. [25] and [30]), such that focusing becomes important? One must first search the experimental and theoretical literature for the values of the nonlinear susceptibilities of the species that might be relevant. It is useful to note, in this connection, that the calculated values for some atoms and ions are quite large indeed. For example, *Flytzanis* (1975) quotes the following values for $\chi_{(3)}$: 6.8×10^3 for H^- , 2.6×10^3 for K , 6.40×10^2 for Li , 8.4×10^2 for Na , and 10^7 for K^+ .

Naively, one would expect any self-focusing effect to promote beam quality. Actually, this is probably *not* correct: Strong self-focusing would lead to an increase in flux and

hence to a lower threshold for the onset of stimulated Raman emission. In other words it would probably enhance the debilitating effects of Raman emission.

C. NONLINEAR PHOTON PROCESSES

Up to now nonlinear photon processes (e.g. two-photon absorption) have been neglected. An important question is whether the energy-level structures for the relevant species are such that nonlinear photon processes can proceed at a nonnegligible rate. This should be investigated.

D. AEROSOL INTERACTIONS

In general, how does the presence of aerosols affect beam propagation? Topics here would include relative amounts of absorption and scattering (important for thermal blooming), dirty-air breakdown involving plasma formation via heating of aerosols, interactions with soot and other complex structures, importance of clouds, and so on.

An initial step in connection with some of these effects would be to conduct a literature search to determine extinction properties of aerosols in the range $\sim 0.5\text{--}2\text{ }\mu\text{m}$.

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APPENDIX

COMMENTS ON SPC SUBROUTINE PRAMAN

This subroutine calculates the effect of stimulated Raman scattering in the atmosphere.

Some of the variables used are the following:

RSCM	= frequency shift in $\text{cm}^{-1} = \delta\nu/c$, where $\delta\nu$ = frequency shift and c = speed of light;
RLAMBA	incident laser beam wavelength λ_L in microns;
RLAMRS	= scattered wavelength λ_s in microns;
H	= altitude in meters;
GBKPT	= gain breakpoint = value of H above which doppler-broadened line-profile width exceeds pressure-broadened width;
GS	= Raman gain factor g in units cm^{-1} ;
XII	= peak incident laser intensity I_L in watts cm^{-2} ;
DZ	= change in beam pathlength in meters;
Z	= path length in meters.

Other variables will be defined at appropriate stages.

The subroutine sets $\delta\nu/c = 2329 \text{ cm}^{-1}$. This, however, is the frequency shift appropriate to vibrational Raman scattering off N_2 , while it is known *Averbakh et al.* (1978) that rotational scattering dominates at pressures below a few atmospheres thus the appropriate value is $\delta\nu/c = 76 \text{ cm}^{-1}$ (or 92 cm^{-1}), that associated with scattering from the level $J = 8$ (or $J = 10$), which yields the largest Raman gain. Here J is the rotational quantum number.

The Raman gain g is of the form (see above)

$$g \propto \frac{d\sigma}{d\Omega} \frac{N}{\Delta\nu} \frac{I_L}{\lambda_L} \quad (A1)$$

where $d\sigma/d\Omega$ = differential cross section,

N = number density of N_2 molecules, and

$\Delta\nu/c$ = linewidth. At low altitudes, pressure broadening

dominates, which implies that $\Delta\nu/c \propto N$ there.

Hence the dependence on density cancels out at low altitudes, and the subroutine assigns the value

$$g \text{ (or GS)} = 1.15 \times 10^{-5} \times \frac{0.35}{(\lambda_L/1 \text{ micron})} I_L \times 10^{-6} \text{ cm}^{-1}. \quad (A2)$$

This value can be compared with the value obtained by *Averbakh et al.* (1978). Scaling their value from $\lambda_L = 0.53 \mu\text{m}$ to $0.35 \mu\text{m}$, and multiplying by 0.8 to compensate for the fact that they consider a gas of pure N_2 rather than a standard atmosphere, we find that their value of the cross section $d\sigma/d\Omega$ is smaller than that used in PRAMAN by a factor $\approx 3/2$. Since this is the ratio of the cross sections for circularly polarized and plane polarized incident radiation, we conclude that PRAMAN uses a value of the cross section appropriate to circularly polarized incident radiation; and hence that for plane polarized incident radiation the cross section, and also the gain g (or GS), of PRAMAN should be reduced by a factor of $3/2$.

For the doppler broadened profile $\Delta\nu_D/c$ PRAMAN assigns the value

$$\Delta\nu_D/c \approx 0.85 \times 10^{-5} \lambda_L^{-1}. \quad (A3)$$

If we say $\Delta\nu_D/c \approx \alpha v/c \lambda_L$, where $v \approx$ average molecular velocity, and α is a constant, then PRAMAN uses $\alpha v \approx 2.5 \times 10^5 \text{ cm s}^{-1}$. This assumes the value

$$\Delta\nu_p/c \approx 0.08 e^{-9.6 \times 10^{-5} H} \text{ cm}^{-1} \quad (A4)$$

For the pressure broadened profile. Appearing in this equation is the scale height ≈ 10.4 km that PRAMAN assigns to the atmosphere. It would appear that this scale height is somewhat large: it exceeds more commonly used values by about 20 percent.

PRAMAN makes the transition from pressure broadening to doppler broadening simply by finding the value GBKPT of altitude H at which $\Delta\nu_D/c = \Delta\nu_p/c$ and by using $\Delta\nu_D/C$ for the line width above this altitude. A better way to proceed is the following: For doppler broadening use a Voigt profile, obtained by convolving the doppler function with the natural line profile. Then compare this Voigt profile with, or even convolve it with, the pressure broadened profile in order to obtain the correct profile. It is doubtful, however, whether the approximation in PRAMAN introduces errors ≥ 20 percent.

PRAMAN also calculates ZCL, the value of the pathlength Z, at beam center, at which conversion via stimulated emission has occurred. It is assumed that significant beam depletion has occurred once $\int g dz$ reaches the value 30. This value is chosen arbitrarily, but it appears reasonable.

In addition, PRAMAN calculates DEFL, the difference in distances to points of equal phase at beam center and at the edge of the conversion region. This is used subsequently to calculate the defocusing length FLN. The line shift $\delta\nu$ enters essentially in a linear way into these quantities, so it is important to use the correct rotational $\delta\nu$. Recall that the value used in PRAMAN is incorrect by a factor ≈ 30 .

PRAMAN neglects several potentially important effects, e.g. self-focusing, scattering off water vapor, multi-photon processes, interactions among different Raman transitions, Stokes-anti-Stokes coupling, and the transient Raman effect. For example, as discussed earlier, self-focusing will increase the incident intensity and hence the Raman gain, leading to subsequent defocusing. Mixing of waves from different rotational modes can produce lines that seed other modes, yielding complex couplings. If the pulse length is sufficiently short, the transient Raman effect becomes important, thereby reducing the Raman gain. Simple estimates suggest that transient effects will be important for pulse lengths ≤ 1 -2 ns.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.