NOAA Technical Memorandum ERL WPL-41

COHERENT LIDAR AS A TOOL FOR REMOTE TEMPERATURE SENSING IN THE TROPOSPHERE

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Wave Propagation Laboratory
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Abstract

Doppler broadening of single frequency radiation scattered by air molecules is temperature dependent. Remote air temperatures may be determined if the line width of the scattered radiation can be determined. Heterodyne detection may be used in this application although several drawbacks are inherent. Atmospheric turbulence presents the primary difficulty. It is estimated that a 1 joule pulsed system operating at .488 μm could achieve a 30 dB SNR at a range of 1 km. Many pulses would be required to achieve a temperature resolution of 1°C. Daytime operation seems feasible.

Introduction

Spectral analysis of single frequency radiation scattered by the atmosphere can provide information on wind, temperature, and aerosol to molecular mixing ratios. This report considers a technique for performing the spectral analysis required for measuring temperature using a heterodyne detection scheme.

The idea of extracting atmospheric information from the spectrum of scattered laser radiation is not new. Fiocco et al. have outlined the theory[1] and have demonstrated partially successful measurements using a Fabry-Perot spectrometer[2,3]. In one nighttime experiment they were able to measure temperature and aerosol to molecular mixing ratio at a height of a few hundred meters.

Fiocco has suggested the obvious application of optical heterodyning as an alternative technique of spectral analysis[1]. This technique has been very successfully used at visible wavelengths for measuring the velocity and turbulence of fluids in laboratory and industrial applications[4]. It will be shown that this technique is also applicable to remote sensing in the atmosphere despite atmospheric turbulence effects.

Theory

If a single frequency beam of light is scattered by air containing aerosols the spectrum of the scattered light will contain at least three distinct features as shown in Fig. 1. The returned spectrum consists of a narrow aerosol component added to a very broad molecular component. In addition, there is a gross shift of the returned spectrum relative to the frequency of the transmitted beam. The broad molecular component of the spectrum is due to Doppler broadening of Rayleigh scattered light. The Doppler broadening occurs because all air molecules are in random, Brownian motion. The velocity distribution, and therefore Doppler frequency shift distribution, is a function of temperature.

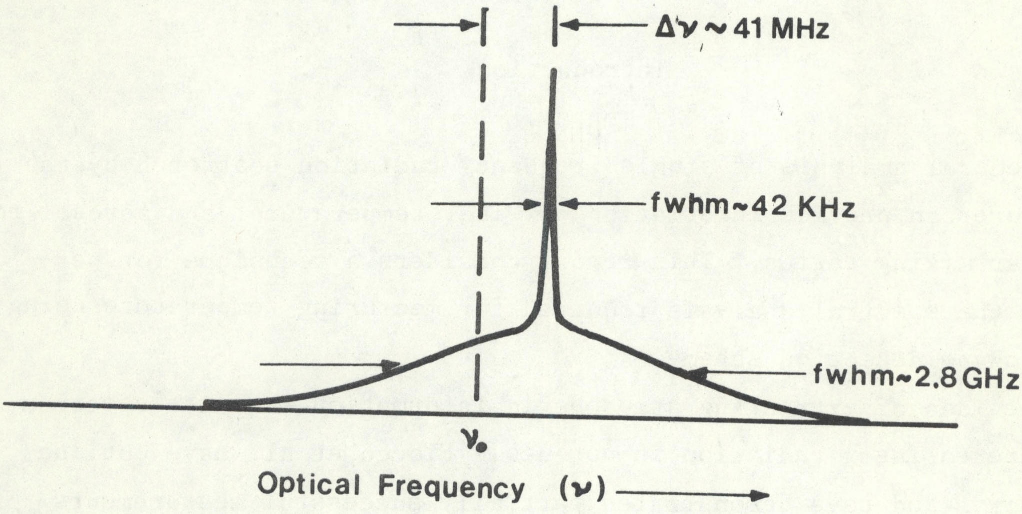

Fig. 1. TYPICAL SPECTRUM OF SCATTERED LIGHT. T=290 K, wind velocity = 10 m/s.

In the visible part of the spectrum, aerosol scattering cross sections are generally greater than Rayleigh scattering cross-sections. For this reason the aerosol component of the returned spectrum will generally be much greater than the Rayleigh component. Here again Browian motion causes a broadening of the scattered spectrum. In the aerosol case, however, the diffusion coefficient for the aerosols is the predominant factor in determining the spectral width of the returned spectrum. This broadening is much less than that due to molecules.

Finally note that wind will cause a gross movement of all scatterers and hence also a Doppler shift. This effect, and the others with representative parameters are shown in Fig. 1.

Since the primary thrust of this proposal is to consider a technique for the measurement of air temperature, not much more will be said about the Doppler shift due to wind or the aerosol component of the returned spectrum. It is important to note however that the spectral width of the aerosol component is many orders of magnitude less than that of the molecular component. In fact, by comparison the aerosol component is a delta function superimposed on the molecular component.

The Doppler broadening due to Rayleigh scattering from molecules is conveniently accounted for theoretically by adding a power spectrum factor to the usual Rayleigh scattering cross section. Using Fiocco's[1] notation this is expressed as,

$$\frac{d^2\Sigma}{d\omega d\Omega} = \frac{d\Sigma}{d\Omega}\,\Phi(|\vec{k}|,\omega)\ .$$

Here $d\Sigma/d\Omega$ is differential scattering cross section per unit volume for the molecules ($m^{-1}\ sr^{-1}$). $\Phi(|\vec{k}|,\omega)$ is the optical frequency power spectrum of the scattered radiation. The optical (angular) frequency is ω, Ω is the solid angle subtended by the receiver at the scattering volume, and $\vec{k}$ is the vector difference between the incident and scattered light wave propagation vectors.

The power spectrum of the scattered light is given by Fiocco to be,

$$\Phi(|\vec{K}|,\Delta\omega) = \left[\frac{m}{2\pi|\vec{K}|^2 k_B T}\right]^{1/2} \exp\left[\frac{-m\Delta\omega^2}{2|\vec{K}|^2 k_B T}\right] .$$

m = mass of scatterers

k_B = Boltzman's constant

T = temperature

$\Delta\omega \equiv \omega - \omega_o$.

This spectrum is clearly Gaussian.

The angular dependence of the scattered light is given by the usual expression for Rayleigh scattering. The result may be expressed in many forms; a convenient one is the following,

$$\frac{d\Sigma}{d\Omega} = \frac{\pi^2 (n^2-1)^2 m}{\rho_m \lambda^4} \sin^2\phi .$$

n = refractive index of the air

m = average molecular mass of air molecules in sample volume

ρ_m = mass density of air

λ = wavelength

ϕ = angle between incident electric field vector and the scattered wave propagation vector.

By simple manipulation the following features of the Doppler broadened spectrum may be determined:

Full-width-at half maximum $\quad \Delta\omega_{fwhm} = 2[k_B\ 2\ \ln 2]^{1/2}\ |\vec{K}| \sqrt{\frac{T}{m}}$

Fractional change in fwhm as a function of fractional temperature change	$\frac{d(\Delta\omega_{fwhm})}{\Delta\omega_{fwhm}} = \frac{1}{2}\frac{dT}{T}$
Fractional change in power spectrum with fractional change in fwhm	$\frac{d\Phi}{\Phi} = \frac{m\ \Delta\omega^2}{\lvert\vec{K}\rvert^2\ k_B\ T}\ \frac{d(\Delta\omega_{fwhm})}{\Delta\omega_{fwhm}}$

It is important to note that the fwhm of the Doppler broadened spectrum depends on factors that are nearly constant except for temperature. The first relationship is shown graphically in Fig. 2. The second and third relationships may be used to estimate the required SNR for a given temperature resolution. This concept is illustrated in Fig. 3.

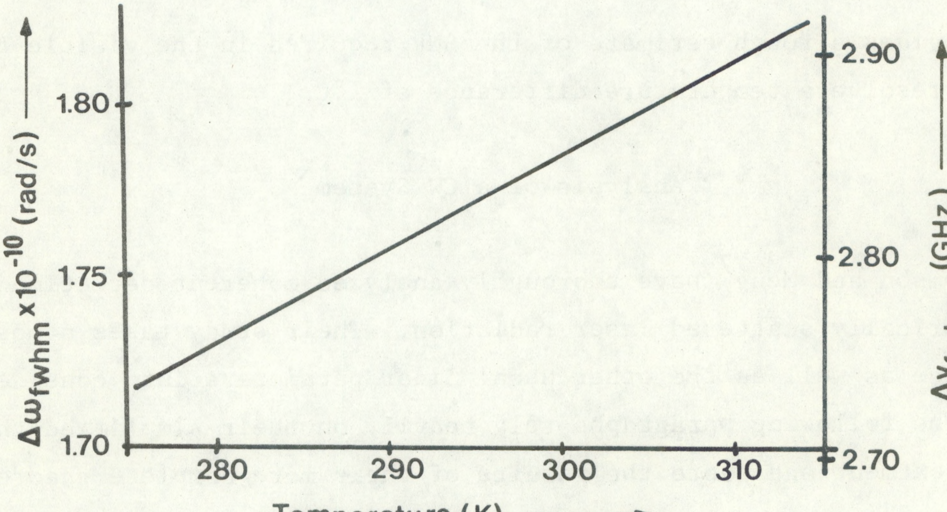

Fig. 2. VARIATION OF FWHM OF DOPPLER BROADENED SPECTRUM WITH TEMPERATURE. $|k|=2.58\times10^{7}$ m^{-1} (λ= .488 μm), $m=4.74\times10^{-26}$ Kg.

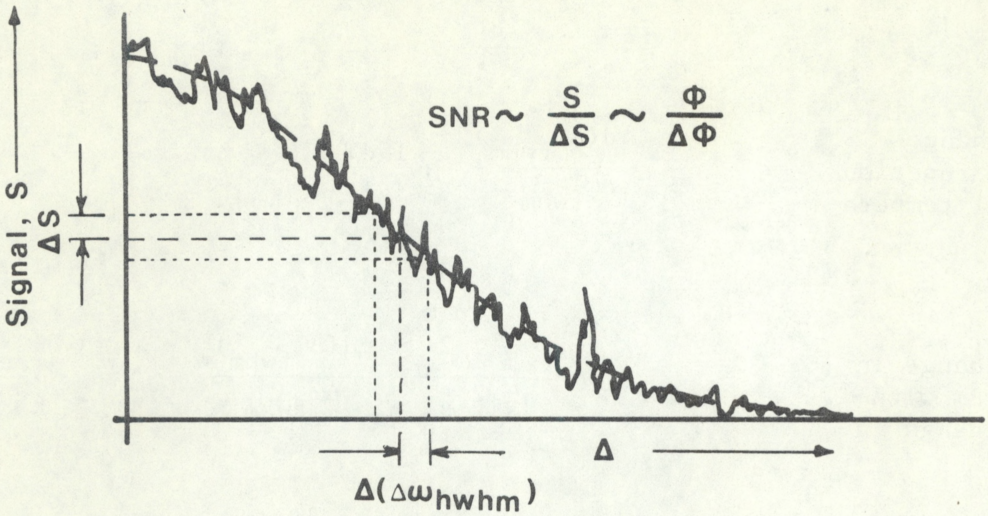

Fig. 3. RECEIVED SIGNAL AS A FUNCTION OF Δω. This graph illustrates the basis for estimating required SNR.

Using dT = 1k, λ = .5 μm, T = 290 K, $\Delta\omega = 2\pi \cdot 1.4 \times 10^{9}$ sec^{-1} and $m = 4.74 \times 10^{-26}$ Kg one obtains,

$$SNR \approx 440$$

this provides a rough estimate of the SNR required in the visible to be able to resolve a temperature difference of 1°C.

Analysis of a CW System

Thomson and Meng[7] have thoroughly analyzed coherent detection of atmospherically scattered laser radiation. Their study takes atmospheric turbulence as well as the other usual lidar parameters into consideration. The following paragraphs rely heavily on their simplified theoretical treatment and quote the results of their more complete theoretical analysis.

The general procedure for calculating the heterodyne SNR is to: (1) calculate the number of photons transmitted, (2) calculate the number of photons scattered and received by the receiver and (3) determine the SNR based on the number of photons received.

In a CW system photons are transmitted continuously. However if a specific measurement time interval, τ, is assumed, the number of photons transmitted for that interval is,

$$N = T_t \frac{P_t \lambda}{hc} \tau$$

where: T_t is the transmission of the transmitter optics and P_t is the single frequency power output of the laser. The number of photons scattered by uniformly distributed scatterers at a point where the transmitted beam diameter is d_t is,

$$\frac{N T_t}{\pi d_t^2/4} \frac{\partial\Sigma}{\partial\Omega} \Delta\Omega \, \Phi(|\vec{K}|,\omega) \, \Delta\omega \, V$$

where: $\partial\Sigma/\partial\Omega$ is the differential volume scattering cross-section, $\Delta\Omega$ is the solid angle subtended by the receiver at the scattering volume, Φ is the optical power spectrum of the scattered radiation, $\Delta\omega$ is the optical bandwidth detected, and V is the scattering volume. If R is the radius of the receiver aperture and L is the path length to the scattering volume,

$$\Delta\Omega = \pi R^2/L^2 \ .$$

Now we may combine these equations to give the number of received photons,

$$N_r = 4 \frac{T_t N R^2}{d_t^2 L^2} \frac{\partial\Sigma}{\partial\Omega} \Phi \, \Delta\omega \, V \, T_r$$

where T_r is the transmission of the receiver optics.

For a coaxial heterodyne system the scattering volume may be approximated by noting that the diffraction limited transmitted beam diameter (d_t) is equal to the diffraction limited receiver field of view diameter (d_r),

$$d_t \cong \frac{\lambda L}{R} = d_r$$

and the length of the scattering volume is roughly dependent on the depth of focus ($\approx 2\, d_r\, L/R$). Combining these gives,

$$V \cong \frac{\pi}{4} \left[\frac{\lambda L}{R}\right]^2 \frac{2\, d_r\, L}{R} = \frac{\pi}{2} \frac{\lambda^3\, L^4}{R^4}$$

$$V \cong \frac{\pi}{4} d_t^2 \frac{2L}{R} \frac{\lambda L}{R} = \frac{\pi}{2} d_t^2 \frac{L^2}{R^2} \lambda \,.$$

So now we can write an expression for the number of photons received as,

$$N_r = 2\pi\, N T_t \frac{\partial \Sigma}{\partial \Omega} \Phi(|\vec{K}|, \omega)\, \Delta\omega\, \lambda\, T_r \,.$$

The theoretical power SNR for heterodyne detection in the limit of large local oscillator power may be written as,

$$SNR = \eta \frac{P_r}{h\nu\Delta f} = \eta N_r$$

where the assumption that $\tau = 1/\Delta f$ has been made.

Now an expression for SNR can be written,

$$SNR = \eta\, 2\pi\, N \frac{\partial \Sigma}{\partial \Omega} \Phi(|K|, \omega)\, \Delta\omega\, \lambda\, T_t\, T_r \,.$$

This result agrees well with Thomas and Meng's result from a more careful analysis taking atmospheric turbulence into account. Quoting their equation I-35 on p. 110 (ref. 7),

$$SNR = SNR^* / \sqrt{1 + (R/r_a)^2} \,.$$

Here SNR* is the maximum obtainable SNR in the absence of turbulence. With appropriate modifications their result for SNR* is,

$$SNR^* = \frac{1}{4} \eta N \frac{\partial\Sigma}{\partial\Omega} \Phi(|\vec{K}|,\omega) \Delta\omega \lambda T_t T_r .$$

The parameter r_a is related to the level of turbulence present. This parameter is related to Fried's[5] parameter r_o as follows,

$$r_a = 0.315 r_o .$$

At this point it is worth noting that the SNR is independent of the range L. This result may seem incorrect at first. However, two effects need to be noted to bring this result into proper perspective. At near ranges the scattering volume increases with range and the additional scatterers make up for the signal that would ordinarily be lost due to increased range. As the range approaches infinity the effective scattering volume becomes large and invariant with changes in focus. That is, scatterers near the focus for far ranges provide an insignificant part of the signal. Rather, the signal is produced by nearer scatterers within the beam.

The range resolution, $\delta L/L$, decreases rapidly as range is increased. Relying again on results from Thomas and Meng[7],

$$\frac{\delta L}{L} = \frac{\lambda L}{r_a^2 \sqrt{1 + (R/r_a)^2}} .$$

Range resolutions of the order of 10% are easily obtainable at range of 1000 m with visible wavelengths. However significant improvements are probably not feasible.

The range resolution may be increased by going to a bistatic transmitter/receiver system at the price of rapid loss of SNR. Thomas and Meng show that an angular separation of transmit and receive beams of 10° result in a 40 dB loss in SNR for a range of 1000 m, even when they are accurately focused on the same scattering volume. Additionally, pointing problems would be severe since the field of view and transmitter beam widths are exceedingly small for heterodyne systems. For these reasons, a bistatic heterodyne system is probably not desirable.

A pulsed coaxial system would offer potentially better range resolution. A 100 nsec pulse length could provide a range resolution of 15 m independent of range. Such a system will probably ultimately be required for remote temperature profiling. More will be said about pulsed systems in the next section.

In order to evaluate the SNR an assumption for the value of r_a must be made. Fried[5] gives an equation for his parameter r_o for propagation of a plane wave over a horizontal path. By using his equation for spherical wavefronts over a vertical path we will overestimate the effect of turbulence. With this in mind Fried's formula will be used.

$$r_o = (1.2 \times 10^{-6}) \lambda_\mu^{6/5} L^{-3/5} C_n^{-6/5} .$$

Here λ_μ is the wavelength in microns. If the wavelength is expressed in meters this becomes,

$$r_o = (0.19)\, \lambda^{6/5} L^{-3/5} C_n^{-6/5}$$

from which,

$$r_a = (0.060)\, \lambda^{6/5} L^{-3/5} C_n^{-6/5} .$$

(Recall that $r_a \equiv 0.314\, r_o$.) A reasonable value for C_n would be $C_n = 5 \times 10^{-8}\, m^{-1/3}$ for daytime conditions.

In the preceeding analysis it has been tacitly assumed that local oscillator shot noise dominates all other noise sources. The second largest contributor to noise would be shot noise induced by the sky background. Let us evaluate the system limitations imposed by this noise source.

The usual expression for shot noise is,

$$\langle i_n^2 \rangle = 2e\, I_{DC}\, \Delta f \ .$$

In our case I_{DC} is the DC component of the output of the detector. This component results from the sum of three sources of optical power which combine at the detector: P_{LO}, local oscillator power; P_S, signal power; and P_B, background power. The shot noise may be expressed as

$$\langle i_n^2 \rangle = 2e \left[\frac{\eta\lambda}{nc} (P_{LO} + P_S + P_B) \right] \Delta f \ .$$

Shot noise due to the local oscillator will dominate so long as $P_{LO} >> P_S$ and P_B. P_S will be a very small quantity so the first of these conditions will always be met in a properly designed system. P_B must be evaluated to determine the limits on P_{LO}.

P_B may be easily evaluated,

$$P_B = N_\lambda^B \,\Delta\Omega\, \pi R^2\, \Delta\lambda$$

where N_λ^B is the sky background spectral radiance, $\Delta\Omega$ is the solid angle field of view of the receiver, $\Delta\lambda$ is the optical bandwidth passed by the optics, and R is the radius of the receiver entrance pupil. Seyrafi[8] gives a typical value for N_λ^B of 5×10^{-3} watts - cm^{-2} - μm^{-1} sr^{-1} (daytime, sun to observer azimuth 90°, λ = .488 μm). Expressed in mks units this becomes $5.0\ \omega - m^{-2} - \mu m^{-1}\ sr^{-1}$. Allowing a 1 mrad angular field of view, to a good approximation $\Delta\Omega$ becomes,

$$\Delta\Omega = \frac{\pi}{4} \times 10^{-6} \text{ sr} \ .$$

Then assuming $\Delta\lambda = 10\ \text{Å} = 10^{-3}\ \mu m$

$$P_B = (1.23 \times 10^{-8}\ \omega - m^{-2}) R^2 \ .$$

In this case then, in order for local oscillator shot noise to dominate the following condition must be met,

$$P_{LO} >> (1.23 \times 10^{-8}\ \omega\ m^{-2})R^2\ .$$

For example for R = .3 m,

$$P_{LO} >> 1.11 \times 10^{-9}\ \omega\ .$$

As a practical consideration it should be noted that this level of irradiance is near the saturation level for many photomultipliers when operated at maximum gain. For example a reasonable choice for a PMT might be a RCA CA3100A which has a rated maximum anode current of 1.0×10^{-3} amp. Its anode radiant sensitivity at .49 μm is about 1.9×10^5 amp/watt. This leads to a saturation power level of 5.3×10^{-9} watt. This calculation indicates that care must be exercised in the selection and operation of the detector selected for final use.

Evaluation of SNR using Specific Parameters

At this point it is helpful to evaluate the SNR for a particular set of parameters:

Let, $P_t = 1\ \omega$ $\quad N = \frac{P_t \lambda}{hc}\tau = (2.45 \times 10^{18}\ sec^{-1})\tau$

$\lambda = .488\ \mu m$

$\eta = 0.22$

$\partial\Sigma/\partial\Omega = 1.62 \times 10^{-6}\ m^{-1}$*

$\Phi(|K|,0) = 5.4 \times 10^{-11}$ sec*

$\Delta\omega = 2\pi \cdot \frac{1}{10} \cdot (2.8 \times 10^9\ sec^{-1})$*

$T_T = T_r = 0.5$

$L = 1000$ m

$R = 0.30$ m

* These parameters apply to the U.S. Standard Atmosphere (ref. 6) for lattitude 45°N during July. Altitude is 2.5 km which is a height above ground of about 1000 m for Boulder, Colorado. Other applicable parameters are: $T = 283$ K, $P = 754.9$ mb, $\rho_m = 0.929$ Kg - m^{-3}. Average particle mass is taken to be 4.74×10^{-26} Kg.

The following may be calculated,

$$SNR^* = (2.53 \times 10^3 \text{ sec}^{-1})\tau$$

$$r_a = (0.924)\, L^{-3/5} = 1.46 \times 10^{-2} \text{ m}$$

$$SNR = (124 \text{ sec}^{-1})\tau$$

$$\frac{\delta L}{L} = 0.11 \,.$$

The requirement on local oscillator power becomes,

$$P_{LO} \gg 1.1 \times 10^{-9} \text{ watt.}$$

Note that these parameters apply to the measurement of a single spectral element of width equal to 1/10 of the FWHM of the Doppler spectrum. Instrumentally the width of the spectral element measured will depend on the bandwidth of the IF amplifier following the optical detector. Many such spectral elements will have to be measured to determine the entire Doppler broadened spectrum. This is illustrated in Figure 4 below.

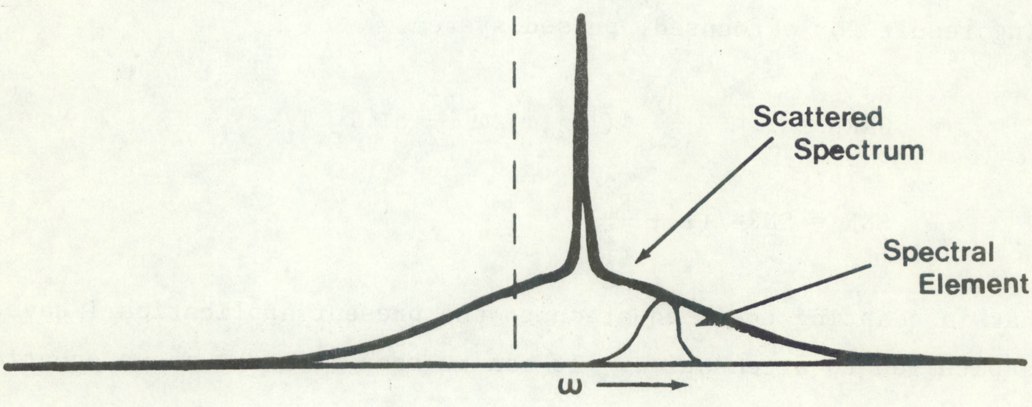

Fig. 4. This graph shows the relationship of a single spectral element to the rest of the scattered spectrum.

Signal to noise ratio and range uncertainty are plotted vs. range in figure 5. Notice that beyond about 1000 meters the range uncertainty becomes very large. At a range of 2500 meters the range uncertainty has grown to 50%.

Previously it was estimated that a SNR of about 440 would be required to measure temperature with an uncertainty of 1°C. For a range of 1000 meters and a mirror of 0.3 m radius this would imply an averaging time of about 4 seconds for each spectral element. To measure the entire spectrum a measurement time of several minutes would be required.

Analysis of a Pulsed System

Most of the foregoing analysis is directly applicable to a focused, pulsed system also. The difference lies in the evaluation of the scattering volume. In this case the scattering volume may be approximated by a cylinder of length $c\tau/2$ where τ is the pulse length. This leads to,

$$SNR = \pi\eta \, N \frac{\partial\Sigma}{\partial\Omega} \, \Phi(|\vec{K}|,\omega)\Delta\omega \, \frac{R^2}{L^2} \frac{c\tau}{2} \, T_r \, T_t$$

in the absence of atmospheric turbulence. Notice that for a pulsed system the SNR depends on both range, L, and mirror diameter, R, as one would expect.

A more careful analysis[9] taking turbulence into account gives the following result for a focused, pulsed system,

$$SNR^* = \frac{\pi}{2} \, \eta \, N \frac{\partial\Sigma}{\partial\Omega} \, \Phi(|K|,\omega)\Delta\omega \, \frac{R^2}{L^2} \, c\tau \, T_r \, T_t$$

$$SNR = SNR^*/(1 + \frac{R^2}{r_a^2}) \; .$$

Note that in adapting their equation to the present application I have ignored path length attenuation. It can be seen from the above equations

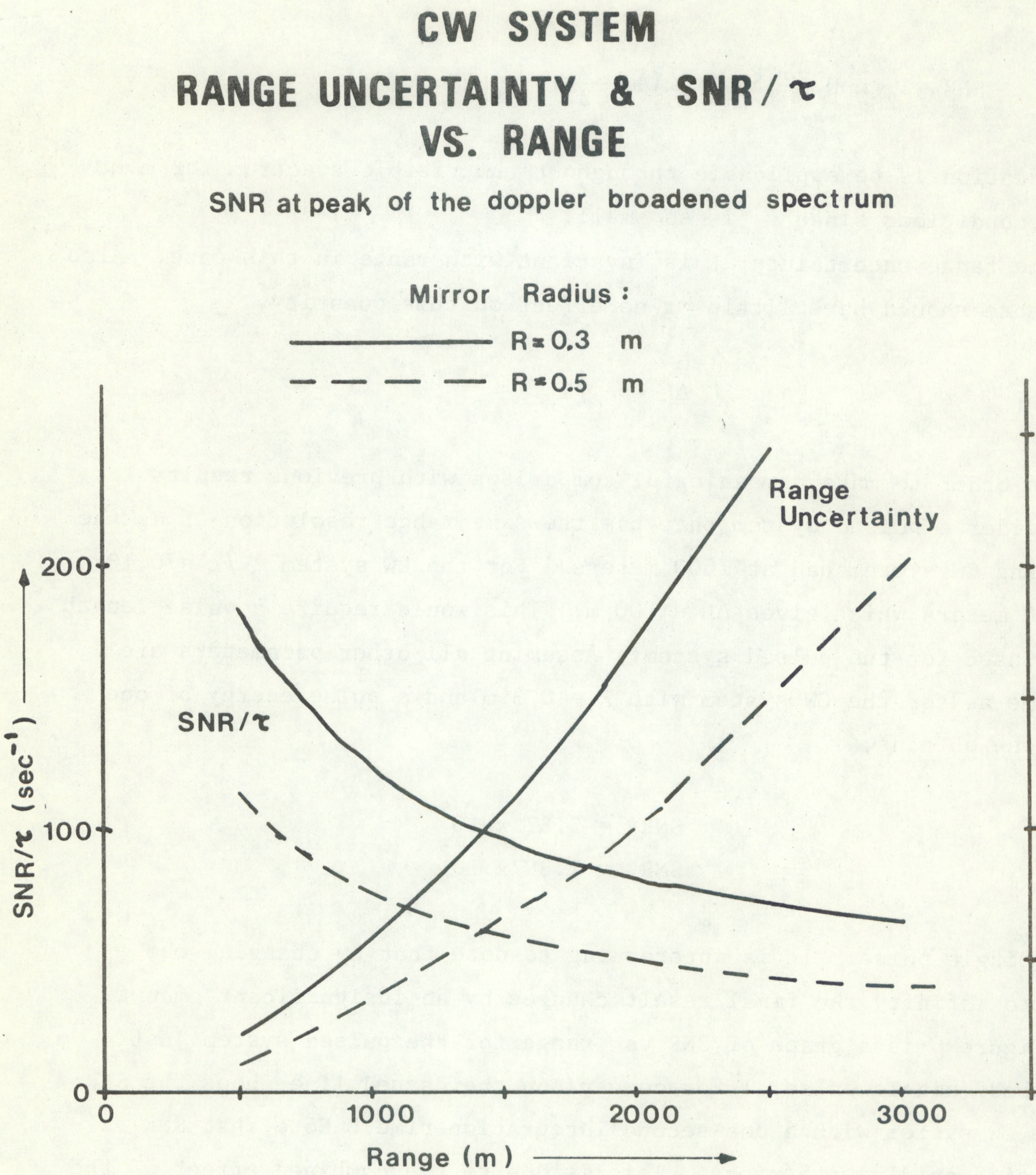

Fig. 5. CW SYSTEM PERFORMANCE. $\lambda=.488$ μm, $\eta=0.22$, $P_t=1$ w., $C_n=5\cdot 10^{-8}$ $m^{-1/3}$, $\Phi(|k|,0)=5.4\cdot 10^{-11}$ sec., $\Delta\omega=0.10$ of FWHM $=1.8\times 10^{9}$ rad/sec.

that in the limit $R \gg r_a$ the SNR becomes independent of mirror diameter. In this case

$$SNR = \frac{\pi}{2} \eta N \frac{\partial \Sigma}{\partial \Omega} \Phi(|K|,\omega)\Delta\omega \frac{r_a^2}{L^2} T_r T_t c\tau .$$

This equation is be applicable throughout the visible spectrum for most seeing conditions since r_a is so small.

The range uncertainty ΔL is invariant with range in this case. Also turbulence should have little or no effect on this quantity,

$$\Delta L = c\tau/2 .$$

In order to make a meaningful comparison with previous results let us consider a pulsed system that has the same range resolution ΔL as the foregoing CW system had at 1000 meters. For the CW system $\Delta L/L = 0.10$ at 1000 meters which gives $\Delta L = 100$ m. This would require a pulse length of 670 nsec for the pulsed system. Assuming all other parameters are the same as for the CW system with $R = 0.3$ m and a pulse energy of one joule one obtains,

$$SNR^* = 5.87 \times 10^5$$
$$SNR = 1.39 \times 10^3$$

for a single pulse. It is interesting to note that by changing the focus to infinity the final result changes by an insignificant amount.

Figure 6 is a graph of SNR vs. range for the pulsed system just described (single pulse). For comparison the dashed line shows the SNR of the CW system with a one second integration time. Note that SNR drops off rapidly with range. This is due to the combined effect of the decreasing r_a with range and the usual L^{-2} factor.

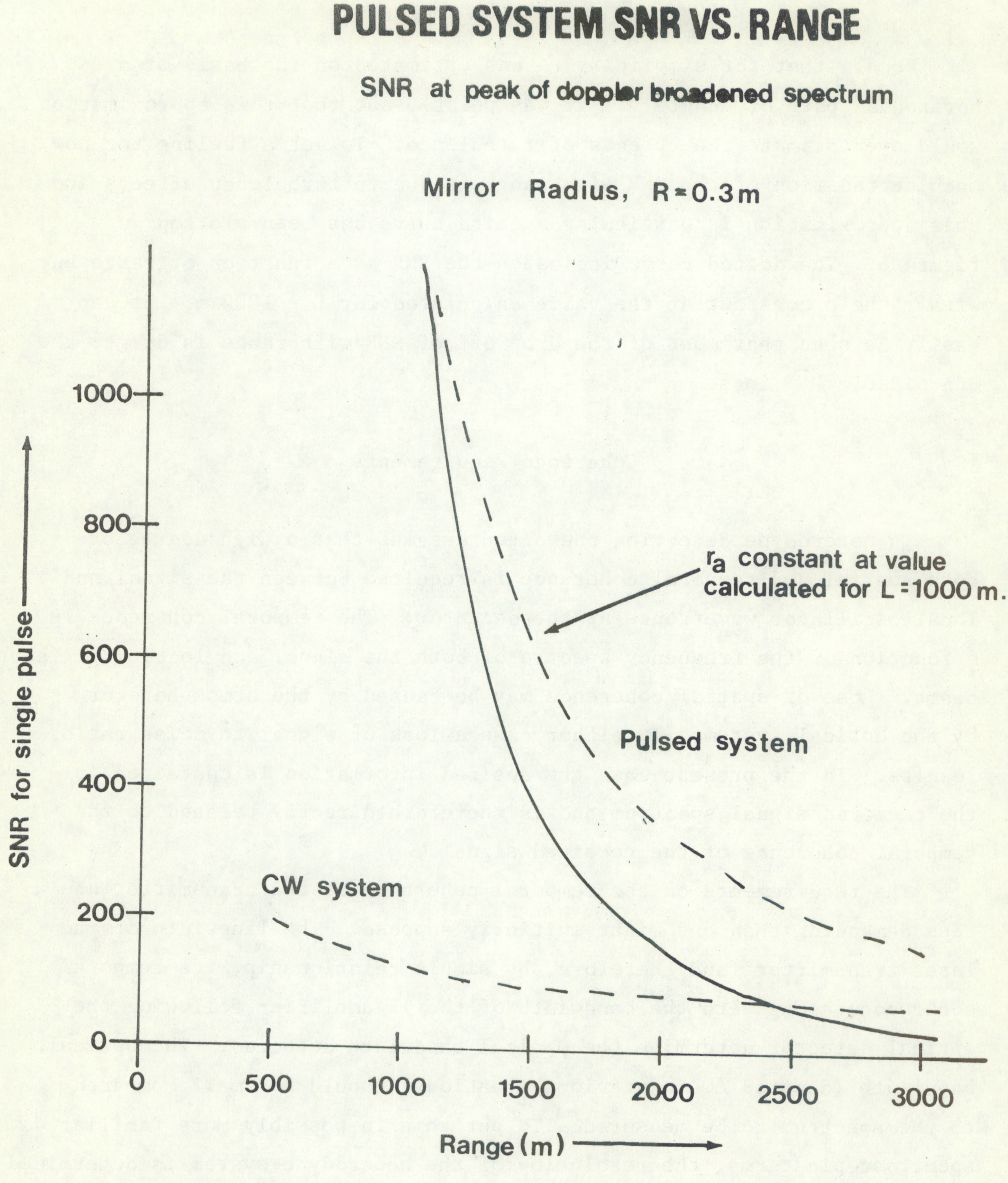

Fig. 6. PULSED SYSTEM PERFORMANCE. $R=0.3$ m, $\eta=0.22$, $J=1$ joule, $C_n=5\times10^{-8}$ $m^{-1/3}$, $\Phi(|k|,0)=5.4\times10^{-11}$ sec, $\Delta\omega=0.10$ of FWHM= 1.8×10^{9} rad/sec.

Recall that for simplicity r_a was estimated on the basis of a horizontal path of length L. It was pointed out that this approximation would overestimate the effects of turbulence. To get a feeling for how much degradation of the SNR with range is due to turbulence effects and this approximation in particular a third curve has been plotted in figure 6. The dotted curve indicates the SNR as a function of range but with r_a held constant at the value calculated for L = 1000 m. It can easily be seen that most of the drop off of SNR with range is due to the unavoidable L^{-2} loss.

Coherence Requirements

In heterodyne detection one often assumes that a high degree of both spatial and temporal coherence is required between the signal and local oscillator wavefronts at the detector. The temporal coherence is a function of the frequency spectra of both the signal and local oscillator beams. Loss of spatial coherence may be caused by the atmosphere or by the optical system. In either case a loss of signal to noise ratio results. In the present case the desired information is contained in the received signal spectrum and is therefore directly related to the temporal coherence of the received signal.

The requirements on the temporal coherence of the transmitter are less demanding than one might initially suppose. The linewidth of the laser transmitter (and therefore, by simple relationship, its temporal coherence) along with the bandwidth of the IF amplifier following the optical detector determine the optical bandwidth detected. The optical bandwidth (denoted $\Delta\omega$ in previous equations) should be small compared to the spectrum to be measured. To put this in possibly more familiar spectroscopic terms, the resolution of the heterodyne system is determined by the convolution of the transmitter line spectrum with the bandpass function of the IF amplifier.

Recalling that the Doppler broadened spectrum we wish to measure is roughly 3 GHz wide, it seems that transmitter linewidths of tens of megahertz may be usable. In this sense, selection of a transmitter is not limited to gas lasers.

Technological Considerations

At this point it is possible to propose only a general system configuration. Many of the system parameters require further study before a choice may be made. In particular some of these parameters are: (1) wavelength, (2) transmitter and receiver antenna size and configuration and (3) type of detector.

In the paragraphs that follow a CW system is described. Although eventually a pulsed system will probably be required to obtain the needed range resolution such a system would be harder to build in practice. Initial development of a CW system would provide needed experience and prove the theoretical grounds for the heterodyne technique in this application.

Consider the system shown in figure 7. Conceptually the system may be broken down into four parts: (1) a transmitter with a closed loop stabilization system, (2) a tuneable local oscillator, (3) the optical antenna system, and (4) the heterodyne signal detector.

The type of laser transmitter used will depend on the wavelength chosen. As an example, however, consider the use of a single line, single mode argon laser. Such lasers are well developed and available from several well known suppliers.

Frequency stabilization is simplified since it is really the difference between the local oscillator frequency and transmitter frequency that needs to be stabilized. This might be accomplished by heterodyning signals from the transmitter and local oscillator and

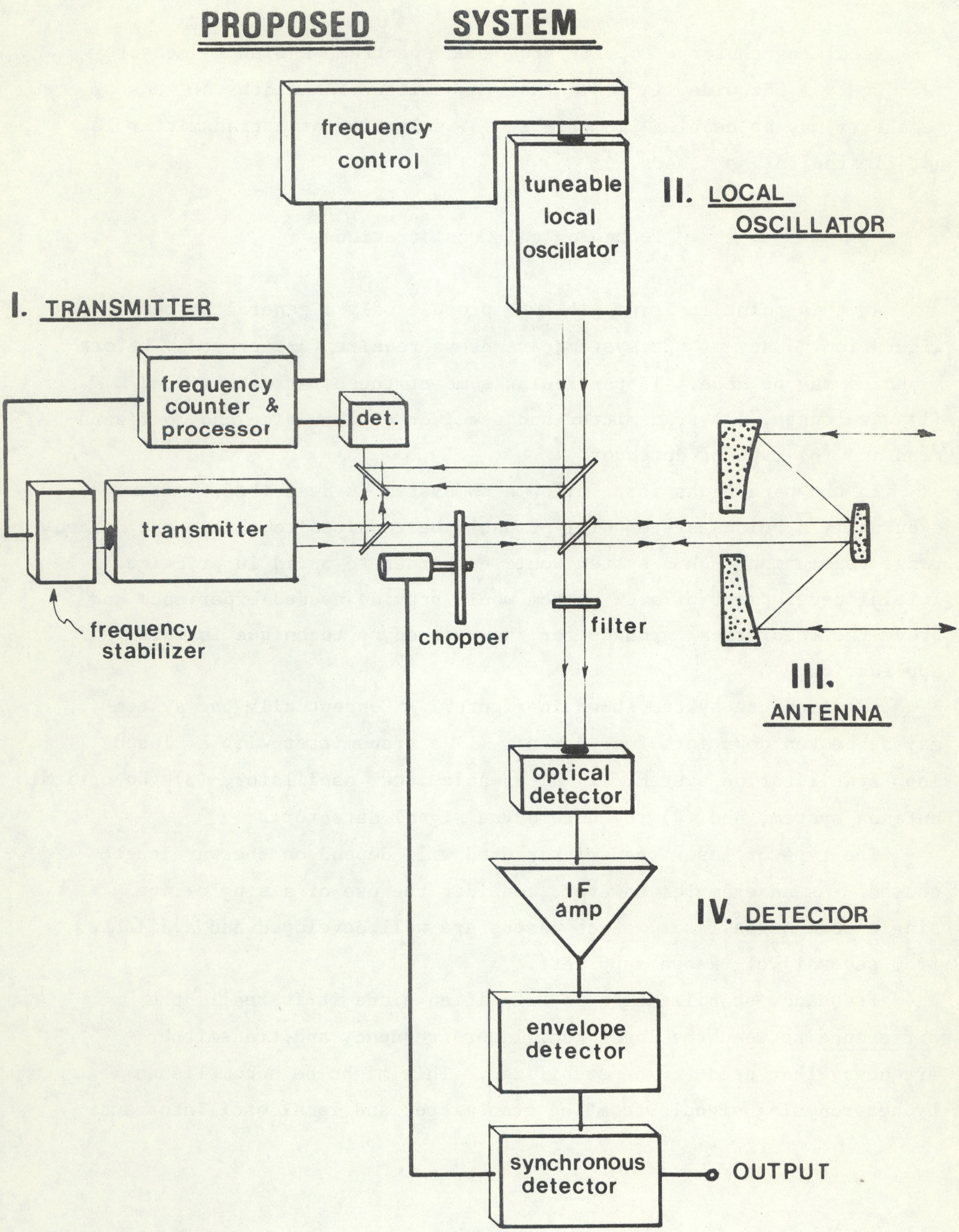

Fig. 7. SCHEMATIC REPRESENTATION OF PROPOSED SYSTEM

then comparing their frequency difference to the desired frequency difference. If the measured frequency difference is different than that desired an error signal would be generated that would modify the transmitter or local oscillator operation and correct the error.

If a visible wavelength is chosen, the local oscillator could be a tuneable dye laser with a sufficiently narrow linewidth. A tuneable dye laser with a linewidth of around 1 MHz has been on the market for several years. In fact several of these lasers are currently in use at JILA on the University of Colorado campus.

The optical antenna system could take on a variety of forms. The simplest form would be that of a Newtonian telescope. Diffraction limited performance of the optical system would be required to maximize SNR. To obtain this goal it would be necessary to test all optical components for wavefront distortion. Such testing could be accomplished by using standard interferometric optical testing techniques.

The heterodyne signal detection subsystem would consist of the following: (1) an optical detector, (2) a bandlimited IF amplifier, (3) an envelope detector, and (3) a synchronous detector. The optical detector used would of course depend on the wavelength selected. Other considerations would be saturation level and frequency response. The frequency response of the optical detector would have to be at least as great as that of the IF amplifier following it. For example, at the argon wavelength (.488 μm) a photomultiplier would be a good choice.

As pointed out previously, the optical bandwidth accepted by the system would depend primarily on the linewidth of the transmitter and the bandpass characteristics of the IF amplifier. A reasonable choice of IF bandwidth would be on the order of a couple hundred megahertz. Many amplifiers are available for this bandwidth requirement and no special problems are anticipated.

The IF amplifier would be followed by an envelope detector to extract the signal power within the bandpass of the IF. At this point all of the noise power with the IF bandpass is also present. To reduce the systems effective electrical bandwidth, the envelope detector would be followed by a synchronous detector that would average the signal over some interval.

The foregoing paragraphs have glibly described an optical and signal processing system that would be difficult to achieve in practice. Since the nature of heterodyne detection is interferometric, correspondingly sophisticated construction techniques would be required. Mechanical vibrations and thermal effects would have to be taken into account. Laser frequency locking is an art in itself. Each of these problems are surmountable but a long development time should be expected.

Conclusion

The theoretical analysis presented in this proposal indicates that within limitations remote temperature measurement in the atmosphere is possible using an optical heterodyne spectrometer. Along with this possibility several drawbacks have also presented themselves.

For a CW system operating at a range of 1000 meters several minutes would be required to obtain a complete scattered spectrum. Range uncertainty increases rapidly beyond about 1000 meters becoming 50% at 2500 meters. Primarily because of the high range uncertainty CW systems should probably be ruled out as a final system choice.

A pulsed system could provide a smaller range uncertainty that would be independent of range. However SNR for such a system would fall off rapidly with range. Loss of SNR with range would probably confine a pulsed system to operation at ranges less than several thousand meters.

It should be noted that the engineering problems associated with a heterodyne system operating at visible wavelengths would be very demanding. All optical components would have to be of high quality. Signal level would be very sensitive to misallignment. Maintaining transmitter and local oscillator stability might be difficult.

Daytime operation seems theoretically possible with this system. In actual practice this may be difficult to achieve. Preliminary experiments should be used to test this possibility.

Judgement of these findings should be made with comparisons to other possible systems. In particular comparison should be made with incoherent systems.

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