Assessment of Remote Sensing Technologies for Location of Hydrogen and Helium Leaks

NAG10-0290

Phase 2 Final Report

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# TABLE OF CONTENTS

1 EXECUTIVE SUMMARY ........................................................................................................... 2

1.1 PHASE 2 OBJECTIVES ........................................................................................................ 2

1.1.1 Advance Rayleigh Doppler technique from TRL 1 to TRL 2 ........................................ 2

1.1.2 Plan to advance Rayleigh Doppler technique from TRL 2 to TRL 3 ............................ 2

1.1.3 Identify researchers and resources for further advancement ...................................... 2

1.1.4 Extend diffusion model ................................................................................................. 2

1.2 PHASE 2 RESULTS ............................................................................................................. 3

2 ADVANCE RAYLEIGH DOPPLER TECHNIQUE FROM TRL 1 TO TRL 2 ......................... 6

2.1 INTRODUCTION .................................................................................................................. 6

2.2 THEORETICAL MODEL ..................................................................................................... 6

3 PLAN TO ADVANCE RAYLEIGH DOPPLER TECHNIQUE FROM TRL 2 TO TRL 3 ........ 21

3.1 CONCEPTUAL DESIGNS ................................................................................................... 21

3.2 TECHNOLOGY SURVEYS .................................................................................................. 22

3.2.1 Laser Technologies ....................................................................................................... 22

3.2.2 Detector technologies ................................................................................................... 23

3.2.3 Modulator technologies ............................................................................................... 23

3.2.4 Vapor filter technologies ............................................................................................. 24

3.2.5 Frequency discrimination technologies ....................................................................... 24

3.3 CONCEPTUAL DESIGNS ................................................................................................ 24

3.4 PREDICTED SIGNAL-TO-NOISE RATIOS .................................................................. 25

3.5 EXPERIMENT DESIGN ..................................................................................................... 25

3.5.1 Homodyne experiment ............................................................................................... 27

3.5.2 Direct detection experiment ....................................................................................... 27

4 IDENTIFY RESEARCHERS AND RESOURCES FOR FURTHER ADVANCEMENT .......... 30

4.1 LIDAR AND RAYLEIGH SCATTERING ............................................................................. 30

4.1.1 Dr. Richard Seasholtz ................................................................................................... 30

4.1.2 Dr. Richard B. Miles .................................................................................................. 31

4.1.3 Dr. Walter Lempert .................................................................................................... 35

4.1.4 Dr. Dennis K. Killinger .............................................................................................. 36

4.1.5 Dr. David A Krueger .................................................................................................. 37

4.1.6 Dr. Chiao-Yao (Joe) She ......................................................................................... 38

4.2 SONAR ............................................................................................................................... 39

4.2.1 Dr. Stanley E. Dunn ................................................................................................... 39

4.3 RAMAN ............................................................................................................................. 41

4.3.1 NASA JSC .................................................................................................................. 41

4.3.2 NASA GRC (W. A. de Groot) .................................................................................. 41

4.3.3 NASA Stennis ............................................................................................................ 41

4.3.4 NASA MSFC (W. T. Powers) .................................................................................... 41

4.3.5 Dr. Michael D. Hampton ............................................................................................ 41

4.3.6 Myung K. Kim ........................................................................................................... 42

4.4 SCHLIEREN ....................................................................................................................... 44

4.4.1 Dr. Robert E. Peale .................................................................................................. 44

4.4.2 Dr. DeVon W. Griffin ............................................................................................... 45

4.5 FOURIER TRANSFORM INFRARED ............................................................................. 45

4.5.1 Thomas J. Kulp ......................................................................................................... 45

5 EXTEND DIFFUSION MODEL ............................................................................................ 46

5.1 BASIC MODEL .................................................................................................................. 46

5.2 EXTENDED MODEL ........................................................................................................ 49

6 REFERENCE CITATIONS .................................................................................................... 51
1 EXECUTIVE SUMMARY

In Phase 1 of this project, a hierarchy of techniques for H$_2$ and He leak location was developed (see Figure 1). A total of twelve specific remote sensing techniques were evaluated; the results are summarized in Table 1. A basic diffusion model was also developed to predict the concentration and distribution of H$_2$ or He resulting from a leak.

1.1 Phase 2 Objectives

The objectives of Phase 2 of the project consisted of the following four tasks:

1.1.1 Advance Rayleigh Doppler technique from TRL 1 to TRL 2

The first task was to advance the Rayleigh Doppler technique from Technology Readiness Level (TRL) 2 to TRL 3 by developing a theoretical model. The result of this task is an interactive model that provides expected signal-to-noise ratio as a function of key design parameters.

1.1.2 Plan to advance Rayleigh Doppler technique from TRL 2 to TRL 3

The second task was to design and estimate the cost for an experiment intended to advance the Rayleigh Doppler technique from TRL 2 to TRL 3. The result of this task is a design for the experimental apparatus, and a parts list including costs.

1.1.3 Identify researchers and resources for further advancement

The third task was to identify researchers, facilities and other resources that could contribute to the further advancement of this research.

1.1.4 Extend diffusion model

The fourth task was to extend the diffusion model developed in Phase 1 to apply to the following:

1) The case for diffusion into an enclosed volume;
2) Inclusion of the effect of forced convection; and
3) Inclusion of the effect of gravitational convection.

The result of this task is an interactive model of concentration as a function of position, for various leak parameters and environmental conditions.
1.2 Phase 2 Results

A theoretical model has been developed that predicts the signal-to-noise ratio as a function of the key design parameters. This model includes both direct detection and heterodyne detection.

Five approaches to the Rayleigh Doppler have been considered singly and in combination as candidates for a proof-of-principle experiment.

1) Heterodyne
   a) Homodyne
   b) Offset Homodyne
   c) Heterodyne
2) Vapor Absorption Filter
3) Fabry Perot

A survey of the key technologies for the laser, detector, modulator, filter, and frequency discriminator has indicated that two approaches may be currently feasible within the expected budget constraints for Phase 3: homodyne, and a combination of vapor absorption filter and Fabry-Perot. Analyses using the model developed in this phase indicate that both of these techniques are expected to provide signal-to-noise ratios suitable for proof-of-principle experiments.

Designs for these two experiments have been outlined, and the required parts have been listed. Several experts have been identified who may be helpful in pursuing further research, and their curricula vita are included in the report.

The concentration model developed in Phase 1 has been successfully extended to include the effects of gravitational convection and forced convection. This model is an essential tool for relating concentrations to leak rates.
Figure 1: Hierarchy of H₂ & He Location Techniques
Table 1: Technology Evaluation Summary

<table>
<thead>
<tr>
<th>Technique</th>
<th>Distinguishing Characteristic</th>
<th>Measurement</th>
<th>Applicability</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Sonar</td>
<td>Turbulent airflow (ultrasound)</td>
<td>Acoustic intensity (passive)</td>
<td>Demonstrated Low spatial resolution Sensitivity depends on pressure and aperture</td>
<td>4</td>
</tr>
<tr>
<td>Active Sonar</td>
<td>Speed of sound</td>
<td>Phase of acoustic waves (active)</td>
<td>Low spatial resolution Sensitivity limited by clutter</td>
<td>3</td>
</tr>
<tr>
<td>DIAL</td>
<td>Allowable energy levels</td>
<td>Absorption of radiation at characteristic wavelengths (active)</td>
<td>None – absorption lines only in vacuum UV</td>
<td>-</td>
</tr>
<tr>
<td>FTIR</td>
<td>Allowable energy levels</td>
<td>Emission of radiation at characteristic wavelengths (passive)</td>
<td>None – absorption lines only in vacuum UV</td>
<td>-</td>
</tr>
<tr>
<td>Raman - spontaneous</td>
<td>Allowable energy levels</td>
<td>Shift in wavelength of inelastically scattered radiation (active)</td>
<td>$H_2$: Sensitivity of 2% demonstrated $He$: None – monatomic therefore no vibration</td>
<td>6</td>
</tr>
<tr>
<td>Raman – CARS</td>
<td>Allowable energy levels</td>
<td>Shift in wavelength of inelastically scattered radiation (active)</td>
<td>$H_2$: Sensitivity of 10 ppm demonstrated $He$: None – monatomic therefore no vibration</td>
<td>3</td>
</tr>
<tr>
<td>Rayleigh Doppler</td>
<td>Molecular/atomic velocities</td>
<td>Shift in wavelength of elastically scattered radiation (active)</td>
<td>Theoretically applicable for both $H_2$ and $He$</td>
<td>1</td>
</tr>
<tr>
<td>Indirect Thermal</td>
<td>Temperature</td>
<td>Variation in temperature of solids caused by nearby cryogenic gas or expanding gas (passive)</td>
<td>Clutter limited?</td>
<td>3</td>
</tr>
<tr>
<td>Rayleigh Intensity</td>
<td>Molecular/atomic cross-section</td>
<td>Intensity of elastically scattered radiation (active)</td>
<td>Limited by Mie scattering (particulates) Clutter limited?</td>
<td>3</td>
</tr>
<tr>
<td>Schlieren</td>
<td>Index of refraction</td>
<td>Refraction of radiation caused by spatial variations in index of refraction (active)</td>
<td>Sensitivity limited by clutter: $1^\circ \sim 346$ ppm $H_2$ $1^\circ \sim 461$ ppm $He$</td>
<td>4</td>
</tr>
<tr>
<td>Shearography</td>
<td>Index of refraction</td>
<td>Phase (path length) of transmitted radiation (active)</td>
<td>Sensitivity limited by clutter: $1^\circ \sim 346$ ppm $H_2$ $1^\circ \sim 461$ ppm $He$</td>
<td>5</td>
</tr>
</tbody>
</table>
2 ADVANCE RAYLEIGH DOPPLER TECHNIQUE FROM TRL 1 TO TRL 2

2.1 Introduction

When electromagnetic radiation is emitted, scattered, or reflected from an object moving toward or away from an observer, the observed wavelength is shifted in what is known as the Doppler effect. The molecules of a gas will scatter electromagnetic radiation in what is known as Rayleigh scattering. Thus radiation that is Rayleigh scattered from a gas may be shifted in wavelength due to the velocity of the scattering molecules.

Mass \( m \), speed \( v \), and kinetic energy \( E_k \), are related according to the following equation:

\[
E_k = \frac{1}{2}mv^2
\]

The distribution of kinetic energies of the molecules in a gas is independent of the composition of the gas, and depends only (to first order) on the temperature of the gas. But since different gases have different molecular masses, the distribution of speeds will vary with the composition of the gas.

Since the molecules in a gas move in a random distribution of velocities, when light of a single frequency is scattered from a gas the frequency spectrum of the scattered light is broadened in an effect known as Doppler broadening. The degree of broadening will be dependent on the velocities of the molecules, which in turn depends upon the composition of the gas. Thus it is possible to determine the composition of a gas by measuring the Doppler broadening of Rayleigh scattered light\(^1\).

2.2 Theoretical model

The distribution of speeds is given by the Maxwell-Boltzmann distribution:

\[
f(v) = 4\pi \left( \frac{m}{2\pi kT} \right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}}
\]

where \( f(v) \) is the probability density (i.e. \( f(v) \delta v \) is the fraction of molecules with velocity between \( v \) and \( v + \delta v \)), \( m \) is the mass of the molecule, \( k \) is the Stephan-Boltzmann constant, and \( T \) is the absolute temperature. The speed distributions for \( \text{H}_2 \), \( \text{He} \), \( \text{N}_2 \) and \( \text{O}_2 \) at 293 K (room temperature) are shown in Figure 2.
Figure 2: Distribution of speeds for H₂, He, N₂ and O₂ at 293 K
The directions of motion are isotropic; i.e. the velocities are equally distributed in all directions. The observed Doppler shift, however, is a function of the component of the velocity projected along the line of sight to the observer. The line-of-sight distribution is given by:

\[ f(v_x) = 4\pi \left( \frac{m}{2\pi kT} \right)^{\frac{1}{2}} e^{-\frac{mv_x^2}{2kT}} \]

where \( f(v_x) \) is the probability density (i.e. \( f(v_x) \delta v_x \) is the fraction of molecules with velocity between \( v_x \) and \( v_x + \delta v_x \)), \( m \) is the mass of the molecule, \( k \) is the Stephan-Boltzmann constant, and \( T \) is the absolute temperature. The distribution of line-of-sight velocities for \( \text{H}_2 \), \( \text{He} \), \( \text{N}_2 \) and \( \text{O}_2 \) at 293 K (room temperature) are shown in Figure 3.

Figure 3: Distribution of line-of-sight velocities for \( \text{H}_2 \), \( \text{He} \), \( \text{N}_2 \) and \( \text{O}_2 \) at 293 K
We have modified the equation given by Measures to model backscatter from a moving target and to normalize the frequency distribution to the source frequency. The resulting distribution of Doppler shifts for backscattered light is given by:

\[
g'(\Delta\omega') = \frac{1}{2\beta'\pi^{1/2}} \cdot e^{-\frac{(\Delta\omega')^2}{4\beta'^2}}
\]

where \(g'(\Delta\omega')\) is the probability density as a function of the relative frequency shift \(\Delta\omega'\), and \(\beta'\) is defined as:

\[
\beta' \equiv \left(\frac{2kT}{mc^2}\right)^{1/2}
\]

This function is graphed in Figure 4 for \(\text{H}_2, \text{He}, \text{N}_2\) and \(\text{O}_2\):
Figure 4: Probability density as a function of relative frequency shift, for H$_2$, He, N$_2$ and O$_2$ at 293 K
The four largest constituents of standard air are shown in Table 2:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Molar Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>0.78084</td>
</tr>
<tr>
<td>O₂</td>
<td>0.20946</td>
</tr>
<tr>
<td>Ar</td>
<td>0.00934</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.00033</td>
</tr>
</tbody>
</table>

Together, O₂ and N₂ make up a molar fraction of 0.9903 so in the model we have neglected the Ar, CO₂, and other minor constituents. The molar fractions of H₂ or He are inputs to the model, and the molar fractions of N₂ and O₂ in the resulting mixture are given by:

\[
N₂ = 0.78084 \cdot (1 - H₂ - He) \\
O₂ = 0.20946 \cdot (1 - H₂ - He)
\]

where \(N₂, O₂, H₂\) and \(He\) are the molar fractions of the respective gasses.

The molecular densities are given by:

\[
N_{H₂} = N_{air} H₂ \\
N_{He} = N_{air} He \\
N_{N₂} = N_{air} N₂ \\
N_{O₂} = N_{air} O₂
\]

where \(N_{air} = 2.55 \times 10^{19} \text{ cm}^{-3}\) is the molecular density of air at standard temperature and pressure.

The Rayleigh cross-sections at the laser wavelength are given by:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Rayleigh Cross-section [cm² sr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>2.14 x 10⁻²⁸</td>
</tr>
<tr>
<td>O₂</td>
<td>1.80 x 10⁻²⁸</td>
</tr>
<tr>
<td>H₂</td>
<td>0.44 x 10⁻²⁸</td>
</tr>
<tr>
<td>He</td>
<td>0.03 x 10⁻²⁸</td>
</tr>
</tbody>
</table>

The system design parameters are inputs to the model. These include the length of the test chamber \(R\), and the transmitter design parameters:

- wavelength of the laser \(\lambda\)
- power of the laser \(\phi_0\)
- bandwidth of the laser \(B\)

The Rayleigh cross-sections at the laser wavelength are given by:
where \( \sigma \) is the cross-section at wavelength \( \lambda \) and \( \sigma_{694.3} \) is the cross-section at 694.3 nm.

Since the laser wavelength is now defined, the Doppler broadening can be expressed in radians rather than as a normalized frequency shift. As an example, the modeled probability densities for a laser wavelength of 532.225 nm are shown in Figure 5:

**Figure 5:** Probability density as a function of angular frequency shift [radians/s], for a laser wavelength of 532.225 nm, for H\(_2\), He, N\(_2\), and O\(_2\) at 293 K.
The spectral profile of the laser is assumed to be Gaussian, represented by a probability density of:

\[ g_{laser}(\Delta \omega) = \frac{1}{B} e^{-\pi \left(\frac{\Delta \omega}{B}\right)^2} \]

where \( g_{laser}(\Delta \omega) \) is the probability density as a function of the angular frequency shift \( \Delta \omega \), and \( B \) is the bandwidth of the laser (in angular frequency).

The receiver design is described by the following inputs to the model:

- diameter of the collecting lens \( D_r \)
- saturation limit for the detector \( \phi_{sat} \)
- responsivity of the detector \( Resp \)
- noise-equivalent-power for the detector \( NEP \)
- sampling time \( \tau \)

The model assumes that the field-of-view of the receiver encompasses the entire illuminated volume of air. It is up to the user to select a design that does not violate this assumption.

The collected spectral flux from each constituent is given by:

\[ \phi_{\lambda}(\Delta \omega) = \phi_0 N \sigma R \Omega_r g(\Delta \omega) \]

where \( \phi_{\lambda}(\Delta \omega) \) is the collected spectral flux in watt·seconds [W·s], \( \phi_0 \) is the laser flux in watts [W], \( N \) is the molecular density of the constituent in molecules per cubic centimeter [cm\(^{-3}\)], \( \sigma \) is the Rayleigh cross-section in square centimeters per steradian [cm\(^2\)/sr], \( \Omega_r \) is the solid angle subtended by the receiver lens in steradians [sr], \( R \) is the length of the scattering volume in centimeters [cm], and \( g(\Delta \omega) \) is the probability density function in units of seconds [s]. Note that the spectral units used here are in terms of angular frequency, so the spectral flux and the probability densities are per unit angular frequency.

Most of the laser flux will not be scattered by the gas mixture, but will instead continue to propagate until it hits a solid surface, from which it will be reflected. We have assumed that the point where the beam intersects the surface will be in the field-of-view of the receiver. The surface is modeled as a Lambertian (diffuse) reflector with unit reflectance, resulting in a spectral flux of:

\[ \phi_{\lambda w}(\Delta \omega) = \phi_0 \frac{1}{\pi} \Omega_r g_{laser}(\Delta \omega) \]

where \( \phi_{\lambda w}(\Delta \omega) \) is the collected spectral flux in watt·seconds [W·s], \( \phi_0 \) is the laser flux in...
watts [W], \( \Omega \) is the solid angle subtended by the receiver lens in steradians [sr], and \( g_{\text{laser}}(\Delta \omega) \) is the probability density function of the laser in units of seconds [s].

The solid angle subtended by the receiver is given approximately by:

\[
\Omega_r = \frac{\pi D_r^2}{4 R^2}
\]

The total spectral flux is the sum of the fluxes from the constituents and from the wall:

\[
\phi_\lambda(\Delta \omega) = \phi_{\lambda H_2}(\Delta \omega) + \phi_{\lambda He}(\Delta \omega) + \phi_{\lambda N_2}(\Delta \omega) + \phi_{\lambda O_2}(\Delta \omega) + \phi_{\lambda w}(\Delta \omega)
\]

The predicted spectral fluxes are plotted on a logarithmic scale in Figure 6:
Figure 6: Predicted spectral fluxes [W·s] as a function of angular frequency shift [rad/s] for 20% He [molar fraction] at 293 K.
Two detection techniques are included in the model: homodyne and direct detection. For homodyne detection the received flux is mixed with a local oscillator (flux picked off of the transmit beam) to provide amplification. The practical limit for the local oscillator flux is determined by the saturation limit of the detector. We have (arbitrarily) set the local oscillator flux to:

$$\phi_{LO} = 0.9 \cdot \phi_{sat}$$

where $\phi_{sat}$ is the saturation limit of the detector in Watts, and $\phi_{LO}$ is the selected flux for the local oscillator in watts. As may be seen from Figure 6, most of the signal at the high frequencies results from the He in this example. A spectrum analyzer or electronic filters may be used to select the signal from the frequency range of interest, which in this example is 30 – 60 GHz. The flux within this frequency band is given by:

$$\phi_{band} = \int_{\omega_{min}}^{\omega_{max}} \phi_{\lambda}(\omega) d\omega + \int_{\omega_{min}}^{\omega_{max}} \phi_{\lambda}(\omega) d\omega$$

where $\phi_{band}$ is the in-band flux, $\phi_{\lambda}(\omega)$ is the collected spectral flux, and $\omega_{min}$ and $\omega_{max}$ are the limits of the desired band.

The homodyned signal is given by:

$$S = Resp \sqrt{\phi_{band} \phi_{LO}}$$

where $S$ is the signal in amps, and $Resp$ is the responsivity of the detector in amps/watt.

The detector noise is given by:

$$N_{det} = Resp \cdot NEP \sqrt{\frac{1}{\tau}}$$

where $N_{det}$ is the detector noise in amps, $NEP$ is the noise equivalent power of the detector in amps/(Hz)$^{1/2}$ and $\tau$ is the sampling time in seconds.
The shot noise (also called photon noise or quantum noise) is a function of the signal, given by:

\[ \phi = \phi_{LO} + \int_{-\infty}^{\infty} \phi_{\lambda}(\Delta\omega) d\Delta\omega \]

\[ \phi' = \phi \frac{\lambda}{hc} \]

\[ N_{\text{shot}}' = \sqrt{\phi'} \]

\[ N_{\text{shot}} = \text{Resp} \cdot N_{\text{shot}}' \frac{hc}{\lambda} \frac{1}{\sqrt{\tau}} \]

where \( \phi \) is the total flux in watts, \( h \) is Planck's constant, \( c \) is the speed of light, \( \phi' \) is the flux in photons/s, \( N'_{\text{shot}} \) is the shot noise in photons, and \( N_{\text{shot}} \) is the shot noise in amps.

Finally, the signal-to-noise ratio (SNR) for homodyne detection is given by:

\[ \text{SNR} = \frac{S}{\sqrt{N_{\text{det}}^2 + N_{\text{shot}}^2}} \]

In the direct detection approach, we would use a vapor absorption filter to suppress the flux that is reflected from the wall. The absorption line is assumed to have a Gaussian profile, modeled as:

\[ \text{OD}(\Delta\omega) = \text{OD}_{\text{max}} \cdot e^{-\frac{\left(\frac{\Delta\omega}{B_{f}}\right)^2}{2}} \]

where \( \text{OD}(\Delta\omega) \) is the optical depth (exponential absorption coefficient) at a frequency difference of \( \Delta\omega \) from the center of the absorption line in rad/s, and \( B_{f} \) is the bandwidth of the absorption line in rad/s. The transmittance profile is then given by:

\[ t(\Delta\omega) = 10^{\text{OD}(\Delta\omega + \epsilon)} \]

where \( t(\Delta\omega) \) is the transmittance as a function of frequency difference relative to the laser frequency, and \( \epsilon \) is the offset (error) between the center of the spectrum of the laser and the center of the spectrum of the absorption line in rad/s.
When using a vapor absorption filter, all of the fluxes will be attenuated by the transmittance function of the filter:

\[
\phi_\lambda(\Delta \omega) = t(\Delta \omega) \phi_0 N \sigma R \Omega_r g(\Delta \omega)
\]

\[
\phi_{\lambda w}(\Delta \omega) = t(\Delta \omega) \phi_0 \frac{1}{\pi} \Omega_r g_{\text{lasers}}(\Delta \omega)
\]

and the total flux is again given by:

\[
\phi_\lambda(\Delta \omega) = \phi_{\lambda H_2}(\Delta \omega) + \phi_{\lambda He}(\Delta \omega) + \phi_{\lambda N_2}(\Delta \omega) + \phi_{\lambda O_2}(\Delta \omega) + \phi_{\lambda w}(\Delta \omega)
\]

The predicted fluxes are plotted in , using an example absorption line from an iodine vapor absorption cell.
Figure 7: Predicted spectral fluxes [W·s] as a function of angular frequency shift [rad/s] for 20% He [molar fraction] at 293 K, using an iodine absorption line with OD$_{\text{max}}$ = 6, $B_i = 5.6 \cdot 10^6$, and $\varepsilon = 100$ MHz.
For direct detection, the in band flux is simply:

\[ \phi_{\text{band}} = \int_{\omega_{\text{min}}}^{\omega_{\text{max}}} \phi_2(\Delta \omega) d\Delta \omega \]

and the signal is simply:

\[ S = \text{Resp} \cdot \phi_{\text{band}} \]

The detector noise, shot noise and SNR remain the same as for homodyne detection.
3 PLAN TO ADVANCE RAYLEIGH DOPPLER TECHNIQUE FROM TRL 2 TO TRL 3

3.1 Conceptual Designs

We have considered three basic approaches to implementing a Rayleigh Doppler technique. These differ in the techniques used to discriminate between frequencies and the techniques used to detect the signal. The first of these approaches has three variations, resulting in five individual techniques:

1) Heterodyne
   a) Homodyne
   b) Offset Homodyne
   c) Heterodyne
2) Vapor Absorption Filter
3) Fabry Perot

These techniques are not mutually exclusive; they may be used in combination, thus providing a large number of potential conceptual designs to be considered.

The heterodyne approach uses a local oscillator (a laser) to both amplify the signal on the detector and shift the frequency from optical frequencies (which are ~100’s of THz) down to 10’s of GHz. The amplification is proportional to the square root of the local oscillator flux, but the local oscillator flux must be limited to below the saturation limit of the detector.

The heterodyne family of approaches is subdivided into three variations: homodyne, offset homodyne, and heterodyne. In the homodyne variation, the local oscillator is extracted from the transmit beam using a pick-off mirror. The frequencies of the homodyne signal are then equal to the difference between the transmit frequency and the received frequencies. In order to respond to these frequencies, the detector must have a bandwidth of 10’s of GHz.

For offset homodyne, the local oscillator is also picked off from the transmit laser, but the transmitted beam is frequency shifted by an electro-optic modulator (EOM) at a point after the pick-off mirror but before the beam enters the test cell. The offset would in principle be chosen to be close to the frequencies of interest, thus reducing the bandwidth required for the detector, but this variation requires a high-frequency EOM.

For a true heterodyne approach, two separate lasers are used: one for the transmitter, and the other for the local oscillator. This allows the center frequency to be offset without the need for an EOM, but it requires two lasers, both of which must be highly stable in frequency, and one of which must be tunable in frequency.
3.2 Technology Surveys

The feasibility and affordability of any of these techniques depends upon the technologies that are currently available, particularly in regards to lasers, modulators, detectors, filters, and frequency discriminators.

3.2.1 Laser Technologies

The technology map for the laser, summarized in Table 4, shows the trade space in dimensions of wavelength, power, linewidth, cost and weight. The received flux depends upon the transmitted flux and the Rayleigh cross-section. The cross-section in turn depends upon the laser wavelength. So we have defined a merit function as:

\[\text{Merit} = \frac{\phi_0}{\lambda^4}\]

where \(\phi_0\) is the optical power of the laser, and \(\lambda\) is the wavelength of the laser.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Power (mW)</th>
<th>Merit (power/wave^4)</th>
<th>Linewidth (MHz)</th>
<th>Cost ($1000)</th>
<th>Weight (kg)</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>244</td>
<td>100</td>
<td>28.2</td>
<td>&lt; 5</td>
<td>$63,000</td>
<td>93</td>
<td>Innova 90C FreD</td>
</tr>
<tr>
<td>244</td>
<td>125</td>
<td>35.3</td>
<td>&lt; 5</td>
<td>$93,000</td>
<td>93</td>
<td>Innova 300C FreD</td>
</tr>
<tr>
<td>257</td>
<td>1000</td>
<td>229.2</td>
<td>&lt; 5</td>
<td>$304,000</td>
<td>5</td>
<td>Innova Sabre FreD</td>
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<tr>
<td>266</td>
<td>200</td>
<td>39.9</td>
<td></td>
<td>$100,000</td>
<td>59</td>
<td>Azure 266</td>
</tr>
<tr>
<td>266</td>
<td>200</td>
<td>39.9</td>
<td>10</td>
<td></td>
<td></td>
<td>MBD-266</td>
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<tr>
<td>488</td>
<td>20</td>
<td>0.4</td>
<td>&lt; 5</td>
<td>$16,000</td>
<td>2</td>
<td>Sapphire 488</td>
</tr>
<tr>
<td>488</td>
<td>1000</td>
<td>17.6</td>
<td>&lt; 5</td>
<td>$81,000</td>
<td>81</td>
<td>Innova 90C-A3</td>
</tr>
<tr>
<td>514</td>
<td>1400</td>
<td>20.1</td>
<td>&lt; 5</td>
<td>$35,000</td>
<td>81</td>
<td>Innova 90C-A3</td>
</tr>
<tr>
<td>488</td>
<td>1800</td>
<td>31.7</td>
<td>&lt; 5</td>
<td>$81,000</td>
<td>81</td>
<td>Innova 90C-A6</td>
</tr>
<tr>
<td>514</td>
<td>2400</td>
<td>34.4</td>
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<td>81</td>
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<tr>
<td>488</td>
<td>750</td>
<td>13.2</td>
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<td>&gt;$50,000</td>
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<td>81</td>
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<td>1400</td>
<td>24.7</td>
<td>&lt; 5</td>
<td>$81,000</td>
<td>81</td>
<td>Innova 300C-I308</td>
</tr>
<tr>
<td>514</td>
<td>1900</td>
<td>27.2</td>
<td>&lt; 5</td>
<td>$81,000</td>
<td>81</td>
<td>Innova 300C-I308</td>
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<tr>
<td>532</td>
<td>2000</td>
<td>25.0</td>
<td>5</td>
<td>$40,000</td>
<td>43</td>
<td>Verdi Compass-V2</td>
</tr>
<tr>
<td>532</td>
<td>10000</td>
<td>124.8</td>
<td>5</td>
<td>$51,000</td>
<td>51</td>
<td>Verdi Compass-V10</td>
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<tr>
<td>532</td>
<td>15</td>
<td>0.2</td>
<td>&lt; 5</td>
<td>$2,000</td>
<td>2</td>
<td>Compass 214M</td>
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<td>532</td>
<td>20</td>
<td>0.2</td>
<td>&lt; 5</td>
<td>$12,000</td>
<td>2</td>
<td>Compass 315M-20</td>
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<tr>
<td>532</td>
<td>150</td>
<td>1.9</td>
<td>&lt; 5</td>
<td>$23,000</td>
<td>7</td>
<td>Compass 315M-150</td>
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</table>
3.2.2 Detector technologies

The detector technology map is shown in Table 5, and illustrated graphically in Figure 8.

Table 5: Detector technology survey

<table>
<thead>
<tr>
<th>Product</th>
<th>Response (nm)</th>
<th>NEP (W/sqr(Hz))</th>
<th>Dark Current (nA)</th>
<th>Bandwidth</th>
<th>Responsivity</th>
<th>Diameter</th>
<th>Saturation</th>
<th>Price ($)</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV Enhanced PIN Photodiodes</td>
<td>200 - 1050</td>
<td>10^-13 - 10^-14</td>
<td>4 x 10^-4</td>
<td>&lt;33 MHz</td>
<td>&gt;0.10 A/W</td>
<td>2.9 - 10 mm</td>
<td>1.5 - 10 mW</td>
<td>Advanced Photonix</td>
<td></td>
</tr>
<tr>
<td>PIN Photodiode</td>
<td>254</td>
<td>6 x 10^-12</td>
<td>6</td>
<td>22 MHz</td>
<td></td>
<td></td>
<td></td>
<td>Advanced Photonix</td>
<td></td>
</tr>
<tr>
<td>Non-Cooled Avalanche Photodiode</td>
<td>150 - 900</td>
<td>10^-13 - 10^-14</td>
<td>0.2</td>
<td>14 MHz</td>
<td></td>
<td></td>
<td></td>
<td>Advanced Photonix</td>
<td></td>
</tr>
<tr>
<td>Solar Blind Schottky AlGaS</td>
<td>200 - 280</td>
<td>1 - 1000</td>
<td>0.1 - 2 MHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50 - 800 APA Optics</td>
<td></td>
</tr>
<tr>
<td>GaAs Photodiode</td>
<td>175 - 350</td>
<td>10^-14</td>
<td>425 - 650</td>
<td>International Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Gain Detector</td>
<td>185 - 320</td>
<td>10^-12</td>
<td>600</td>
<td>International Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Detector (PMA2120)</td>
<td>240 - 261</td>
<td>10^-13 - 10^-14</td>
<td></td>
<td>Solar Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC UV Photodiode</td>
<td>200 - 350</td>
<td>&lt;0000005</td>
<td>55 - 198</td>
<td>Boston Electronics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC UV Detector</td>
<td>240 - 400</td>
<td>0.01</td>
<td></td>
<td>Laser Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| General Research Detector (D-1)
High-Speed Detector (PX-DT)     | 400 - 1700    | 9 x 10^-11      | 50                | 30 GHz    |              |          |            | 4800 Newport            |
|                               | 400 - 900     | 3 x 10^-10      | 10                | 60 GHz    | 1.7 V/W @ 670 nm | 50 um fiber | 1 mW | 6400 Newport |

Figure 8: Detector technology map
3.2.3 Modulator technologies

No modulators were found that could provide the required frequency shift of 10’s of GHz.

3.2.4 Vapor filter technologies

Only one commercial source was found for vapor absorption filters. Innovative Scientific Solutions Incorporated sells sealed iodine molecular vapor absorption filter cells with prices starting at ~ $2 K. No commercial sources were found for mercury atomic absorption filter cells, but some researchers are open to the idea of providing one to order.

3.2.5 Frequency discrimination technologies

Heterodyne techniques shift the frequencies down to 10’s of GHz, a range for which electronic spectrum analyzers are widely available. For the direct detection technique a tunable vapor filter, tunable laser, or a Fabry-Perot etalon could provide frequency-scanning capability. Frequency tunability for lasers is feasible but expensive. Frequency-tunability for vapor filters is affordable, but very slow and limited in range. Fabry-Perot etalons designed for determining the spectral profiles of lasers are commercially available and affordable.

3.3 Conceptual Designs

The technology maps have provided information that constrains the design options:

The primary driver for laser selection is the cost. The primary trade-off in laser technology is price versus the merit function (based on power and wavelength). Higher powers and shorter wavelengths drive the cost upwards. Only a few of the lasers in Table 4 fit within projected budget constraints for Phase 3. The heterodyne technique is therefore a poor candidate for Phase 3 since it requires two lasers, both of which must be highly stable and one of which must be tunable. The ultraviolet lasers are outside the budget constraints; as are all but the lowest power blue lasers, so green wavelengths seem optimum for Phase 3.

The lack of suitable modulators implies that offset homodyne is not currently feasible.

Detectors are not a cost driver but they are a key performance driver. Two classes of detectors are available: those with high bandwidth but very small sensitive area, and those with moderate bandwidth and relatively large area. The former are appropriate for the heterodyne family of techniques, and the latter for direct detection.

Iodine vapor cells are appropriate for use at green wavelengths, commercially available, and affordable. Such a filter could provide substantial reduction in the background from flux reflected from the wall, so there seems worthwhile to include one in an experiment. The theoretical model (see section 2) shows that the width of the iodine absorption lines
is too narrow to block the unwanted signal from the O2 and N2. The survey of frequency discrimination technologies (see section 3.2.5) shows that a Fabry-Perot etalon would be appropriate for Phase 3.

Thus, based on the technology surveys, the design options for a Phase 3 experiment were narrowed down to two conceptual designs:

1) *Homodyne*, at a *green* wavelength, with a *fast* detector; and, 
2) *Direct detection*, at a *green* wavelength, with a *large-area* detector, an *iodine absorption cell*, and a *Fabry-Perot etalon*.

### 3.4 Predicted Signal-to-Noise Ratios

While the technology surveys constrained the feasible approaches, it was also necessary to determine whether the SNR’s are expected to be sufficient to be used to validate the theoretical model and prove the principle of the Rayleigh Doppler technique. This section present the results of four designs evaluated using the model developed in section 2. Designs 1a and 1b both use homodyne detection while designs 2 and 3 are based on direct detection incorporating vapor absorption filters. Designs 1a and 2 fit within the budget constraints for Phase 3, while designs 1b and 3 illustrate what would be possible in a future phase, employing currently available lasers. These results are summarized in Table 6:
Table 6: Summary of four designs

<table>
<thead>
<tr>
<th></th>
<th>#1a</th>
<th>#1b</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>20% He</td>
<td>20% He</td>
<td>20% He</td>
<td>20% He</td>
</tr>
<tr>
<td>Range</td>
<td>1 m</td>
<td>1 m</td>
<td>1 m</td>
<td>1 m</td>
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<tr>
<td><strong>Laser:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>Compass 315M-150</td>
<td>Verdi V10 315M-150</td>
<td>Compass Azure 266</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>150 mW</td>
<td>10000 mW</td>
<td>150 mW</td>
<td>200 mW</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&lt; 1 MHz</td>
<td>&lt; 1 MHz</td>
<td>&lt; 1 MHz</td>
<td>&lt; MHz</td>
</tr>
<tr>
<td>Wavelength stability</td>
<td>100 MHz</td>
<td>100 MHz</td>
<td>100 MHz</td>
<td>MHz</td>
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<tr>
<td><strong>Receiver:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technique</td>
<td>Homodyne</td>
<td>Homodyne</td>
<td>Iodine Filter + Fabry-Perot</td>
<td>Mercury Filter + Fabry-Perot</td>
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<td>Diameter</td>
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<td>0.3 cm</td>
<td>6 cm</td>
<td>6 cm</td>
</tr>
<tr>
<td>Sampling</td>
<td>1 Hz</td>
<td>1 Hz</td>
<td>1 Hz</td>
<td>1 Hz</td>
</tr>
<tr>
<td>frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Detector:</strong></td>
<td>Newport PXD-7</td>
<td>Newport PXD-7</td>
<td>Photonix SD041-12-22-011</td>
<td>Photonix SD172-13-23-222</td>
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<tr>
<td>NEP</td>
<td>$3.6 \times 10^{-10} \text{ W/(Hz)}^{1/2}$</td>
<td>$3.6 \times 10^{-10} \text{ W/(Hz)}^{1/2}$</td>
<td>$1.7 \times 10^{-14} \text{ W/(Hz)}^{1/2}$</td>
<td>$7.0 \times 10^{-14} \text{ W/(Hz)}^{1/2}$</td>
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<tr>
<td>Responsivity</td>
<td>1.4 A/W</td>
<td>1.4 A/W</td>
<td>0.20 A/W</td>
<td>0.10 A/W</td>
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<td>50 μm dia. fiber</td>
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<td>4700 x 3800 μm</td>
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<tr>
<td>Saturation</td>
<td>1 mW</td>
<td>1 mW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>60 GHz</td>
<td>60 GHz</td>
<td>0.1 GHz</td>
<td>0.017 GHz</td>
</tr>
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<td>Spectral range</td>
<td>400-900 nm</td>
<td>400-900 nm</td>
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<tr>
<td><strong>Signal-to-Noise:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>$1.4 \times 10^{-9} \text{ A}$</td>
<td>$11 \times 10^{-9} \text{ A}$</td>
<td>$4 \times 10^{-14} \text{ A}$</td>
<td>$2 \times 10^{-12} \text{ A}$</td>
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<td>Detector noise</td>
<td>$5 \times 10^{-10} \text{ A}$</td>
<td>$5 \times 10^{-10} \text{ A}$</td>
<td>$3 \times 10^{-16} \text{ A}$</td>
<td>$7 \times 10^{-15} \text{ A}$</td>
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<td>Photon noise</td>
<td>$3 \times 10^{-11} \text{ A}$</td>
<td>$3 \times 10^{-11} \text{ A}$</td>
<td>$0 \text{ A}$</td>
<td>$0 \text{ A}$</td>
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<tr>
<td>SNR</td>
<td>3</td>
<td>20</td>
<td>10</td>
<td>300</td>
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</table>
3.5 Experiment Design

Advancement of the Rayleigh Doppler technique from TRL 2 to TRL 3 requires a proof-of-concept experiment. The objectives of this experiment would be to validate the theoretical model and to demonstrate the principle of operation for this technique. As shown in Table 6, the predicted SNR's are reasonable for both the homodyne and the direct detection approaches. Since the cost of the detectors and iodine vapor cell are a relatively small part of the budget, we recommend experimentation with both approaches.

It is important to note that the minimum detectable concentration for this technique is limited by sensitivity, while all the other techniques for He are limited by clutter. The other techniques all ultimately measure density, which is affected by temperature variations. Therefore we expect that technological improvements in sensitivity will improve the performance achievable with this technique, but will not improve the performance of any other technique applicable to He.

In both experiments the plan is to vary the concentration of He in the test cell and measure the signal. A beam dump may be used initially to minimize the background flux, followed by backgrounds that are representative of the intended operational environment. Other parameters such as the frequency range, FOV, local oscillator flux, etc., may be varied in order to validate the theoretical model.

3.5.1 Homodyne experiment

The small area of the high-bandwidth detector required for the homodyne approach severely limits the field-of-view (FOV) of the receiver. A monostatic configuration must therefore be used to enable this narrow FOV to encompass the volume illuminated by the laser. In a monostatic configuration, the transmitter and receiver use the same aperture. Isolation of the transmitted flux from the receiver is achieved by the use of a quarter wave plate and polarization beamsplitter. This configuration is illustrated in Figure 9 and the required parts are listed in Table 7.
Figure 9: Homodyne experiment
3.5.2 Direct detection experiment

The large-area detectors available for the direct detection approach allow the use of a bistatic configuration, in which the receiver aperture is separate from the transmitter aperture. This allows the use of a relatively large receiver aperture. This configuration is illustrated in Figure 10 and the required parts are listed in Table 7.

![Figure 10: Direct detection experiment](image)

Table 7: Parts list

<table>
<thead>
<tr>
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<tr>
<td>Laser</td>
<td>Coherent</td>
<td>Compass 315M-150</td>
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<td>Beamsplitter</td>
<td>Newport</td>
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<td>Waveplate</td>
<td>Newport</td>
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<td>Oz Optics</td>
<td>HPUCO-35-532-M-0-2.7AS</td>
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<td>Attenuator</td>
<td>Oz Optics</td>
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</tr>
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<td>Combiner</td>
<td>Oz Optics</td>
<td>FUSED-12-532-a/b-50/50-555-3-0.5</td>
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<td>Fiber cables</td>
<td>Oz Optics</td>
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<td>Fabry-Perot</td>
<td>Coherent</td>
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<td>4,566</td>
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<td>KPA052-C</td>
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<td>Iodine cell</td>
<td>ISSI</td>
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<td>3,000</td>
</tr>
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<td>PXD-7</td>
<td>6,372</td>
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<td>Detector, large-area</td>
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<td>SD041-12-22-011</td>
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<td>Amplifier</td>
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<td>&lt;TBD&gt;</td>
<td>&lt;TBD&gt;</td>
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<td>Current meter</td>
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<td>&lt;TBD&gt;</td>
<td>&lt;TBD&gt;</td>
</tr>
<tr>
<td>Low-pass filter</td>
<td>&lt;TBD&gt;</td>
<td>&lt;TBD&gt;</td>
<td>&lt;TBD&gt;</td>
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<td>Mount, laser</td>
<td>Newport</td>
<td>MRP4-1 (6)</td>
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<td>Mount, beamsplitter</td>
<td>New Focus</td>
<td>9481</td>
<td>295</td>
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<tr>
<td>Mount, waveplate</td>
<td>New Focus</td>
<td>9401</td>
<td>150</td>
</tr>
<tr>
<td>Mount, collimator (2)</td>
<td>New Focus</td>
<td>9872-K</td>
<td>398</td>
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<td>Mount, lens</td>
<td>Newport</td>
<td>AC-2</td>
<td>48</td>
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<tr>
<td>Test cell</td>
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<td>&lt;TBD&gt;</td>
<td>&lt;TBD&gt;</td>
</tr>
</tbody>
</table>
4 IDENTIFY RESEARCHERS AND RESOURCES FOR FURTHER ADVANCEMENT

4.1 Lidar and Rayleigh Scattering

4.1.1 Dr. Richard Seasholtz

Glenn Research Center
4.1.2 Dr. Richard B. Miles

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  Princeton University, Princeton, NJ 08544

Research Interests

Research interests include the development of new laser-based capabilities for quantitative imaging of flow fields and combustion phenomena. Other research includes laser-based diagnostics such as pollution monitoring and optical air data systems for high-speed aircraft. This work involves the use of nonlinear optics and precision laser spectroscopy together with the development of new laser sources. Some examples of recent work are:
  - the development of a new capability for writing lines and patterns into air in order to track air motion;
  - imaging of time-evolving supersonic structure by Rayleigh scattering;
  - measurement of high-speed velocity, temperature and density fields by Filtered Rayleigh Scattering;
  - two-photon, laser-induced fluorescence imaging of molecular hydrogen;
  - the capability of writing lines and patterns into water.
  - the possibility of using high power electron beams and lasers as drivers for hypersonic ground test facilities.
  - the use of plasmas for high speed air control and electromagnetic protection.

Curricula Vita

PROFESSIONAL BACKGROUND
1982- Professor, Dept. of Mechanical & Aerospace Engineering, Princeton University
1980-1996 Chairman, Engineering Physics Program, Princeton University
1978-1982 Associate Professor, Dept. of Mechanical & Aerospace Engineering, Princeton Univ.
1972-1978 Assistant Professor, Dept. of Mechanical & Aerospace Engineering, Princeton Univ.
Summer 1972 Research Associate, Department of Electrical Engineering, Stanford University
EDUCATION
1972 Ph.D. Stanford University, Electrical Engineering
1967 M.S. Stanford University, Electrical Engineering
1966 B.S. Stanford University, Electrical Engineering

PROFESSIONAL SOCIETIES
American Institute of Aeronautics and Astronautics, Fellow
Optical Society of America, Fellow
Institute of Electrical and Electronic Engineers, Senior Member
American Physical Society, Member

PROFESSIONAL ACTIVITIES
Member, Board of Directors, Fannie & John Hertz Foundation
Executive Committee, Princeton Univ., Photonics & Opto-Electronics Center
Member, NASA New Millenium Interferometer Project Independent Assessment Team
Chairman, AIAA Aerodynamic Measurement Technology Technical Committee, '92-'94
Chairman, DoE Basic Energy Sciences Combustion Diagnostics Program Review, Oct. '92
Chairman, 1986 Gordon Conference on Vibrational Spectroscopy
Member, Board of Directors, Ice Cap, Inc., Hamilton, New Jersey

(212 Refereed Conference Manuscripts and Journal Articles; 5 U.S. Patents)

Invited Lectures (2000-2001)


July 18, 2000 "RDHWT/MARIAH II Program (An R&D Program for an Advanced M=8-15 Hypersonic Wind Tunnel)," Briefing to DDR&E, Washington, DC.

Aug. 19, 2000 "MARIAH II--Solution, Technology Status, and Future Plans," Briefing to Senator Conrad Burns, Butte, MT.

Sept. 19-22 2000 "La Methode RELIEF de Marquage des Ecoulements et ses Applications dans L'Etude des Phenomenes de Transport et de Melange," Presented at the 7th Congres Francophone de Velocimetric Laser, Marseille, France (Keynote Speaker).

March 8, 2001 "RDHWT/MARIAH II Program," The Ohio State University, Columbus, OH.

April 27, 2001 "Flow Field Diagnostics by Filtered Rayleigh and Raman Scattering," Georgia Tech, Atlanta, Georgia.


Publications in Refereed Journals and Review Articles (2001)


Published Conference Proceedings (2001)


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Degrees

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Ph.D. (Physical Chemistry), University of Utah, 1981

Research Interests

Studies of fundamental spectroscopic phenomena and development of associated optical diagnostics. Laser development and nonlinear optics. Influence of collisional dynamics on spectral lineshapes. Optical propulsion. Recent activities include: Stimulated Raman scattering in oxygen and nitrogen; flow tagging velocimetry measurements in compressible and incompressible flow; spectrally filtered Rayleigh scattering velocimetry; development of pulse-burst Nd:YAG and robust injection-locking of Ti:Sapphire; use of high-power lasers for optical propulsion.

Selected Publications


Principal Research Efforts

- The Radiatively-Driven hypersonic Wind Tunnel
- Flow tagging in air and water for fundamental studies of unsteady and turbulent flow
- Spectrally resolved scattering measurements using atomic and molecular vapor filters
- Development of high-power, pulse-burst laser sources for MHz rate imaging of high-speed phenomena
- Development of high power, single frequency laser sources for quantitative imaging diagnostics

35
4.1.4 Dr. Dennis K. Killinger

Professor, Physics, University of South Florida
Telephone: (813) 974-3995
E-mail: killinge@chuma.cas.usf.edu

Publications


Research Interests

Lidar techniques have proven very versatile in the study of the space and time variation of atmospheric properties such as wind speeds and concentrations of ozone, pollutants, and aerosols. More recently interest has turned to developing techniques to measure air temperatures and densities. The basic difficulty is in separating the effects of aerosols from those of the air molecules. In our experiments shown schematically in the figure, a pulse (10 nsec) of nearly monochromatic light (∼ 0.1 GHz) is sent into the atmosphere, and the spectrum of the scattered light is shown schematically as the heavy line. The light scattered by the aerosols is slightly Doppler-broadened due to the relatively low speeds of the aerosols (few m/sec) characteristic of the wind. The light scattered by the molecules has a much larger Doppler-broadening (∼ 2.7 GHz) due to the relatively high speeds of the molecules (∼ 500 m/sec). This Doppler-broadening is roughly proportional to the square root of the air temperature. The method utilizes three signals. The first two signals (shown in the figure) depend on the molecular scattering only and allows the determination of the air temperature and the air density if the atmosphere is assumed to be in hydrostatic equilibrium. This signal is obtained by using a band-stop vapor filter which will block essentially all of the light scattered by the aerosols. A typical transmission function is shown for an atomic vapor filter. Two slightly different vapor filters are used in channels 1 and 2. The third signal depends on both the molecular scattering and the aerosol scattering and is obtained by measurements without the filter. Subtracting the molecular scattering from the third signal allows determination of the aerosol scattering and thus properties such as aerosol density and shape distribution. In addition to providing a useful tool to atmospheric science in general, these air temperature and density profiles and the characterization of the aerosol properties are important in the analysis of other experiments on the processes of ozone depletion in the atmosphere.
4.1.6 Dr. Chiao-Yao (Joe) She

Professor, Colorado State University

B.S., Taiwan University, 1957
Ph.D., Stanford University, 1964
Fellow, Optical Society of America

(970) 491-6261, joeshe@lamar.colostate.edu

Research Interests

The research interests of Prof. She have been broad and often interdisciplinary. Over the past thirty years, he has been interested in the development of new laser techniques for specific applications on basic as well as applied problems. These included photon-burst fluorescence spectroscopy for single atom detection, coherent Raman spectroscopy for supersonic velocity and temperature measurements, Raman studies of surfaces and thin films. In 1980's, he initiated coherent Rayleigh-Brillouin gain spectroscopy, and pioneered the development of two types of narrowband lidars. Since the existing lidar technique for temperature measurements at the time relies on Rayleigh scattering for measuring air-density profiles from which the atmospheric temperatures are calculated, this approach fails for altitudes below 20 km and above 80 km due, respectively, to the interference of aerosol particles and to the lack of Rayleigh signal. His group remedies these short-comings by inventing new lidar techniques. For altitudes below 20 km, he uses a narrowband laser and a narrowband atomic vapor filter to separate molecular scattering from aerosol scattering so that air temperatures can be measured directly. For altitudes above 80 km, he uses a narrowband tunable laser to induce fluorescence emission of natural Na atoms existed in the mesopause region (between 80 to 110 km, a region too high for airplane and balloon and too low for satellite) for temperature measurements. Both systems are now capable of making atmospheric measurements. The narrowband Rayleigh-Mie lidar recently has provided the first simultaneously measured tropospheric temperature and aerosol extinction coefficient profiles at the popular doubled-YAG laser wavelength (532 nm). The Na temperature lidar based on a narrow-band dye laser system is being reproduced by other research groups. In addition, he has conceived and developed a single frequency coherent source at 589 nm based on sum-frequency generation, along with Na vapor Faraday filter, and acoustooptic frequency shifter permitting Na wind and daytime measurements.

Professor She's technical inventions have led to decade-long observation of the mesopause region in Fort Collins, Colorado which not only confirmed and detailed the predicted bizarre thermal structure with cold summer and warm winter, but also led to unexpected discoveries, linking climate change in this region to the Mt. Pinatubo eruption and solar flux variations, providing the first direct experimental evidence for the fact that different atmospheric layers and planetary space environment are strongly coupled as an integrated climatic system. To gain a basic understanding of this unique thermal structure, measurements of temperatures and winds, as well energy and momentum fluxes should be made from space as well as from the important polar region. For these reasons, Prof. She's lidar group has begun collaborative ground-based measurements in support of the TIMED (Thermosphere, Ionosphere, Mesosphere and Electrodynamic) satellite to be launched by NASA in 2001, and the deployment of a state-of-the-art Sodium lidar in ALOMAR (Arctic Lidar Observatory for Middle Atmospheric Research), Norway based on the Na fluorescence technology developed at Colorado State over the years with NSF support. In the latter case, the unique Faraday filter capable of rejecting sky light background is a must for observation in sunlit Arctic summer.
4.2 Sonar

4.2.1 Dr. Stanley E. Dunn

Professor

Department of Ocean Engineering
Florida Atlantic University
Boca Raton, FL 33431
Boca Raton Campus: (561)297-3437
SeaTech Campus: (954)924-7265
Fax: (561)297-3885
E-mail: dunn@oe.fau.edu

EDUCATION

• Ph.D. - M.E., North Carolina State University, 1970.
• B.S. - M.E., North Carolina State University, 1965.

RELATED EXPERIENCE

• 1988-1990: Acting Dean, College of Engineering, Florida Atlantic University.
• Chairman, NSF Joint US/UK Program in Ocean Engineering - Underwater Vehicles.
• NOAA Committee in AI Technology for Sea Grant Program.
• Editor, 1992 Symposium on Autonomous Underwater Vehicle Technology.
• Reviewer for National Science Foundation (OEID), National Sea Grant Program,
• Transportation Research Board, ABET, UNH UUV Symposium.
• 1992 USNJR Organizer and Coordinator for South Florida (FAU).
• Board of Directors, 3rd International Submarine Races - June 1993.
• National Ocean Resource Technology Development Committee.
• NSF US/Taiwan Workshop on Ocean Resources - 1995.
• DOD Laboratory Infrastructure Capabilities Study, Ships, Submarines, and Watercraft,
• Naval Surface Ship Technology Program, HM&E Integration Workshop- 1996.
• National Research Council Naval Studies Board Panel, Technology for Future Naval
Forces - 1996.
• NSF Russia-US Workshop on Oceans and Oceans/Atmosphere - 1996.
• Engineering Accreditation Commission - 1996-97.

Consulting:

• FHWA, U.S. Navy, USEPA and a variety of other governmental and private parties.

HONORS AND AWARDS

• College Nominations for University Teacher of the Year - 1986.
• Engineer of the Year Award/Palm Beach County FES - 1990.
• Fellow, Florida Engineering Society - 1990.
RECENT PUBLICATIONS
Principal Publications of Last Five Years: 22 publications, of which the following are most recent:


SCIENTIFIC AND PROFESSIONAL SOCIETIES
- American Society of Electrical Engineers (ASEE)
- Acoustical Society of America (ASA)
- Institute of Noise Control Engineering (INCE)
- Society of Naval Architects and Marine Engineers (SNAME)
- American Society of Mechanical Engineers (ASME)
- Institute of Electrical and Electronic Engineers (IEEE)
4.3 Raman

4.3.1 NASA JSC

4.3.2 NASA GRC (W. A. de Groot)

4.3.3 NASA Stennis

4.3.4 NASA MSFC (W. T. Powers)

4.3.5 Dr. Michael D. Hampton

Associate Professor, Department of Chemistry, University of Central Florida

Education:

Ph.D. Analytical Chemistry, Texas Tech University, 1980
B.S. Chemistry, University of Florida, 1975

Research Interests:

Hydrogen storage systems, ion selective electrodes, piezoelectric oscillators as chemical oscillators, materials (inorganic).

Selected Publications:


Contact:
Phone: (407) 823-2136
E-mail: mhampton@ucflvm.cc.ucf.edu
4.3.6 Myung K. Kim

Associate Professor, Department of Physics, University of South Florida

Areas of Expertise
- digital holography; holographic microscopy
- nonlinear optics; coherent optical transient phenomena; photon echo; laser spectroscopy; quantum interference in atomic systems
- applications of photon echo in optical memory and optical processing; associative optical memory; pattern recognition

Education
- Ph.D. in Physics, Jun. 1986, University of California, Berkeley, CA
- B.S. in Physics and Mathematics, May 1979, Cum Laude, University of California, Los Angeles, CA

Employment History
- Associate Professor, Aug. 1995 - present, Dept. of Physics, University of South Florida, Tampa, FL
- Assistant Professor, Aug. 1988 - May, 1995, Dept. of Physics and Astronomy, Wayne State University, Detroit, MI

Refereed Journal Publications
4.4 Schlieren

4.4.1 Dr. Robert E. Peale

Associate Professor of Physics
School of Optics/CREOL
Electrical and Computer Engineering
Advanced Materials Processing and Analysis Center (AMPAC)

404 MAP, (407) 823-5208
rep@physics.ucf.edu
http://www.physics.ucf.edu/~rep

B.S. 1983 (UC Berkeley),
M.S. 1986, Ph.D. 1990 (Cornell)

Dr. Peale's research accomplishments span a wide range of topics. These include defects in semiconductors, spectroscopic and optical instrumentation, rare-earth activated optical materials, and far-infrared semiconductor lasers. Recent interests include semiconductor-device process integration and basic science related to nuclear waste remediation.

Research

Current projects include mode-locking of the p-Ge far-infrared laser, solution growth of calcite single crystals, sputter growth of InAs thin films, and deep ion implantation for device processing.

Selected Publications


4.4.2  Dr. DeVon W. Griffin  
NASA GRC  
Devon.W.Griffin@grc.nasa.gov

4.5  Fourier Transform Infrared  
4.5.1  Thomas J. Kulp  
Sandia National Laborarories, Combustion Research Facility  
Phone: (925) 294-3676  
Email: tjkulp@sandia.gov  
Fax: (925) 294-2595  
Mail Stop: 9056
5 EXTEND DIFFUSION MODEL

5.1 Basic Model

In order to evaluate the various technologies for leak location, it is desirable to have a model (or map) of concentration of H₂ or He as a function of leak rate, distance from the leak, and time since the leak initiated. For the case of a leak into an open area, diffusion follows Fick’s first law, expressed in one dimension as:

\[
J_x = -D \left( \frac{\partial C}{\partial x} \right)
\]

where, \( J_x \) refers to the molar flux in the x-direction in mol m\(^{-2}\) s\(^{-1}\), \( C \) is the molar concentration in mol m\(^{-3}\) and, \( D \) is the diffusion coefficient or diffusivity in m\(^{2}\) s\(^{-1}\). In three dimensions in polar coordinates, this leads to the differential equation:

\[
\frac{\partial C(r,t)}{\partial t} = D \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial C(r,t)}{\partial r} \right)
\]

where \( r \) is the radius from the leak, and \( t \) is the time since initiation of the leak. With appropriate boundary conditions:

\[
\begin{align*}
C(r,t) &= 0 \text{ for } t < 0 \\
C(r,0) &= \delta(r) \\
C(\infty, t) &= 0
\end{align*}
\]

where \( \delta \) is the Kronecker delta function, the solution is:

\[
C(r,t) = \frac{\phi}{4\pi D r} \text{erfc} \left[ \frac{r}{\sqrt{4Dt}} \right]
\]

where \( \phi \) is the leak rate in mol/s, and \( \text{erfc} \) is the complimentary error function:

\[
\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-\xi^2} d\xi
\]

An interactive version of this model has been provided in the form of a MathCAD worksheet.

For the steady state case \( t \to \infty \) and the concentration reduces to:
The diffusion coefficients for gas 1 in gas 2 is given by the Fuller equation:

\[ D_{1,2} = \frac{0.604 \times 10^{-8} \cdot T^{-1.81} \cdot \left[ \frac{M_1 + M_2}{M_1 M_2} \right]^{0.5}}{p \left( \frac{T_{c,1}}{T_{c,2}} \right)^{0.1405} \left( V_{c,1}^{0.4} + V_{c,2}^{0.4} \right)^{2}} \]

where:
- \( M_1, M_2 \): molecular weight of both components in kg/kmol;
- \( T_{c,1}, T_{c,2} \): critical temperature in K;
- \( V_{c,1}, V_{c,2} \): critical volume in m³/kmol (\( V_c = M/(1000d_c) \));
- \( T \): temperature in K;
- \( P \): pressure in bar (1 bar = 0.98692 atm);
- \( D_{1,2} \): diffusion coefficient of gas 1 in gas 2 in m²/s

The critical properties for selected gases are given in Table 8:

<table>
<thead>
<tr>
<th>Gas</th>
<th>( T_c ) [K]</th>
<th>( P_c ) [bar]</th>
<th>( d_c ) [g cm⁻³]</th>
<th>MW [kg kmol⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>132</td>
<td>3.77</td>
<td>0.316</td>
<td>29</td>
</tr>
<tr>
<td>H₂</td>
<td>33.2</td>
<td>1.29</td>
<td>0.031</td>
<td>2.02</td>
</tr>
<tr>
<td>He</td>
<td>5.19</td>
<td>0.23</td>
<td>0.070</td>
<td>4.003</td>
</tr>
<tr>
<td>N₂</td>
<td>126.2</td>
<td>3.39</td>
<td>0.313</td>
<td>28.01</td>
</tr>
<tr>
<td>O₂</td>
<td>154.7</td>
<td>5.04</td>
<td>0.436</td>
<td>32.00</td>
</tr>
</tbody>
</table>

Therefore, at a temperature of 25°C and pressure of 1 atm:

- \( D_{H₂-Air} = 7.78 \times 10^{-5} \) m²/s
- \( D_{He-Air} = 7.73 \times 10^{-5} \) m²/s
A basic diffusion model was developed in Phase 1. Sample results from this model are given in Figure 11, which shows the molar fraction in percent (equivalent to percent concentration by volume) as a function of distance from the leak for an H₂ leak at $10^{-2}$ SCIM after 1 s, 1 min, 1 h, and for steady state. The concentration is linearly proportional to the leak rate, so the form of the curves is the same for all leak rates; changing the leak rate effectively changes only the scale of the y axis. The diffusion coefficient for He is very close to that for H₂, so the graph for He is virtually the same.

![Figure 11: Concentration of H₂ [mol fraction] vs. distance [m] for a leak of $10^{-2}$ SCIM, at 1 s, 1 min, 1 h, and steady state](image)
5.2 Extended Model

In Phase 2, we extended the model to include the effects of gravitational convection and forced convection. Gravitational convection refers to the tendency for lighter gases to rise and heavier gases to sink. Forced convection refers to air currents from wind or ventilation. The steady-state velocity for gravitational convection is given by the Ernst Einstein equation:

\[ V_Z = \frac{F_Z \ast D}{\kappa \ast T} \]

where the net force \( F_Z \) is given by

\[ F_Z = (m_{air} \ast g) - (m_{gas} \ast g) \]

In these equations, \( F_Z \) is the net force acting on the body in the Z direction, \( \kappa \) is the Boltzmann constant \( (1.38 \times 10^{-22} \text{ N m} / \text{°K}) \), \( T \) is temperature in Kelvin, \( g \) is the acceleration due to gravity in \( \text{m/s}^2 \).

Forced convection can result in flow that is laminar or turbulent. The characteristics of turbulent flow are highly dependant on the details of the source of the convection and the dimensions and characteristics of the surroundings, so this model simulates only laminar flow.

Convection breaks the spherical symmetry used to simplify the problem in the basic model. The extended model uses Cartesian coordinates and solves the resulting differential equations numerically rather than analytically. A finite difference approach is used to solve the partial differential equations. This approach divides the volume into a grid in \( x, y, z \) and time.

The generalized three-dimensional equation for diffusion is given by Fick’s second law:

\[ \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} + D \frac{\partial^2 c}{\partial y^2} + D \frac{\partial^2 c}{\partial z^2} \]

The volume is divided into a grid and the step in each direction is given by:

\[ x = i \delta x, \quad y = j \delta y, \quad z = k \delta z, \quad t = l \delta t \]

where \( i, j, k, l \) are positive integers in \( x, y, z \) & \( t \) directions.
Using Taylor's series expansion for the partial differential, one obtains:

\[ C_{i,j,k+1} = C_{i,j,k} + D \frac{\delta t}{(\delta x)^2} \left[ C_{i+1,j,k,l} - 2C_{i,j,k,l} + C_{i-1,j,k,l} \right] \]

\[ + D \frac{\delta t}{(\delta y)^2} \left[ C_{i,j+1,k,l} - 2C_{i,j,k,l} + C_{i,j-1,k,l} \right] \]

\[ + D \frac{\delta t}{(\delta z)^2} \left[ C_{i,j,k+1,l} - 2C_{i,j,k,l} + C_{i,j,k-1,l} \right] \]

The criterion for a stable solution is:

\[ D \left[ \frac{1}{\delta x^2} + \frac{1}{\delta y^2} + \frac{1}{\delta z^2} \right] \delta t \leq 1/2 \]

When forced convection along the x-axis and gravitational convection along the z-axis are added, the differential equation becomes:

\[ \frac{\partial c}{\partial t} = D \nabla^2 c - \nabla (c \cdot v_z) - \nabla (c \cdot v_y) \]

The generalized finite difference kernel is then:

\[ C_{i,j,k+1} = C_{i,j,k} + D \frac{\delta t}{(\delta x)^2} \left[ C_{i+1,j,k,l} - 2C_{i,j,k,l} + C_{i-1,j,k,l} \right] \]

\[ + D \frac{\delta t}{(\delta y)^2} \left[ C_{i,j+1,k,l} - 2C_{i,j,k,l} + C_{i,j-1,k,l} \right] \]

\[ + D \frac{\delta t}{(\delta z)^2} \left[ C_{i,j,k+1,l} - 2C_{i,j,k,l} + C_{i,j,k-1,l} \right] \]

\[ - v_x \frac{\delta t}{\delta z} [ C_{i,j,k+1,l} - C_{i,j,k,l} ] \]

\[ - v_y \frac{\delta t}{\delta x} [ C_{i+1,j,k,l} - C_{i,j,k,l} ] \]

\[ - v_y \frac{\delta t}{\delta y} [ C_{i,j+1,k,l} - C_{i,j-1,k,l} ] \]

\[ - v_z \frac{\delta t}{\delta z} [ C_{i,j,k+1,l} - C_{i,j,k,l} ] \]

where \( v_x \) is the gravitational convection velocity and \( v_x, v_y, v_z \) are the components of the forced convection velocity.
6 REFERENCE CITATIONS

1 Robert Youngquist, private communication.


6 http://chemengineer.about.com/science/chemengineer/library/weekly/aa072197.htm

### 7.1 NASA Technology Readiness Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>Basic principles observed and reported</td>
</tr>
<tr>
<td>Level 2</td>
<td>Technology concept and/or application formulated</td>
</tr>
<tr>
<td>Level 3</td>
<td>Analytical &amp; experimental critical function and/or characteristic proof-of-concept</td>
</tr>
<tr>
<td>Level 4</td>
<td>Component and/or breadboard validation in laboratory environment</td>
</tr>
<tr>
<td>Level 5</td>
<td>Component and/or breadboard validation in relevant environment</td>
</tr>
<tr>
<td>Level 6</td>
<td>System/subsystem model or prototype demonstration in relevant environment</td>
</tr>
<tr>
<td>Level 7</td>
<td>System prototype demonstration in relevant environment</td>
</tr>
<tr>
<td>Level 8</td>
<td>Actual system completed and &quot;Flight Qualified&quot; through test and demonstration</td>
</tr>
<tr>
<td>Level 9</td>
<td>Actual system &quot;Flight Proven&quot; through successful mission operations</td>
</tr>
</tbody>
</table>
7.2 Bibliography

7.2.1 References Included in the Appendix

7.2.2 Additional References