Small Business Technology Transfer (STTR) Program
Proposal Cover Sheet

Knowingly and willfully making any false, fictitious, or fraudulent statements or representations may be a felony under the Federal Criminal False Statement Act (18 USC Sec 1001), punishable by a fine of up to $10,000, up to five years in prison, or both.

Proposal Number: **A09A-001-0291** **Agency:** **Army** DUNS: 115051307
Topic Number: **A09A-T001** CAGE: 3AZB8
Proposal Title: Comprehensive Atmospheric Terahertz Simulator (CATS)

Firm: TeraVision Inc
Mail Address: 5516 E. South Wilshire Dr.
Tucson, AZ 85711-4534

Percentage of Work: 40 %

Research Institution: University of Arizona
Mail Address: The University of Arizona

Tucson, AZ 85721

Percentage of Work: 60 %

Year 1 Cost: 99920 Phase: I Year 1 Duration: 6

Year 2 Cost: Year 2 Duration:

Business Certification:

Are you a small business as defined in paragraph 2.3?	**YES**
Number of employees including all affiliates (average for preceding 12 months):	**9**
Is the INSTITUTION a research institute as defined in paragraph 2.4?	**YES**
University	
Are you a socially or economically disadvantaged business as defined in paragraph 2.5?	**NO**
Are you a woman-owned small business as described in paragraph 2.6?	**NO**
Are you a certified HUBZone small business concern as described in paragraph 2.12?	**NO**
Are you a service-disabled veteran-owned small business as described in paragraph 2.14?	**NO**
Are you a veteran-owned small business as described in paragraph 2.15?	**NO**
Is more than 50 percent of your firm owned or managed by a corporate entity?	**NO**
Are you proposing to use foreign nationals as defined in paragraph 2.18 for work under the proposed effort?	**YES**
Are you proposing research that utilizes human/animal subjects or recombinant DNA as described in paragraph 2.19, paragraph 2.20 and paragraph 2.21?	**NO**
Is primary employment of the principal investigator (identified below) with your firm as required in paragraph 1.3?	**YES**
Is a Historically Black College or University or Minority Institution (HBCU/MI) participating in this effort as a teaming partner or subcontractor?	**NO**
If yes, name of HBCU/MI:	
Has a proposal for essentially equivalent work been submitted to other US government agencies or DoD components?	**NO**
If yes, list the name(s) of the agency or DoD component and Topic Number:	

Project Manager/Principal **Corporate Official (Business)** **Institution Official**

Investigator		**Corporate Official (Business)**		**Institution Official**	
Name:	Dr. Christian d"Aubigny	Name:	Ms. Shari Olsen	Name:	Dr. Robert Kursinski
Title:	VP Engineering	Title:	Treasurer	Title:	Associate Professor
Phone:	(520) 465-1909	Phone:	(520) 275-0870	Phone:	(520) 621-2139
Fax:	(866) 720-4835	Fax:	(866) 720-4835	Fax:	
E-Mail:	cdaubign@teravision-inc.com	E-Mail:	srolsen@teravision-inc.com	E-Mail:	kursinski@atmo.arizona.edu

For any purpose other than to evaluate the proposal, this data except proposal cover sheets shall not be disclosed outside the Government and shall not be duplicated, used or disclosed in whole or in part, provided that if a contract is awarded to this proposer as a result of or in connection with the submission of this data, the Government shall have the right to duplicate, use or disclose the data to the extent provided in the funding agreement. This restriction does not limit the Government's right to use information contained in the data if it is obtained from another source without restriction. The data subject to this restriction is contained on the pages of the proposal listed on the line below.

Proprietary Information (list page numbers):

Signature of Principal Investigator	Date	Corporate Business Official	Date	Institution Official	Date

Technical Abstract (Limit your abstract to 200 words with no classified or proprietary information/data.)

Terahertz (THz) technology has made great strides in the past decade. Potential applications of THz technology to Defense and Security are many, nearly all of them involving standoff detection. At their core is propagation through the atmosphere. As a THz wave travels through the atmosphere it is affected by many complex processes. The effects of the atmosphere on THz waves vary widely with atmospheric conditions and frequency. Often, these effects are more pronounced than the process being investigated. A solid understanding of THz atmospheric transmission is necessary to evaluate the feasibility of a THz solution, and sometime required interpret data from THz systems. Our team brings together sub-millimeter radio-astronomers who concern themselves with atmospheric transmission to plan their instruments and understand their observations; Atmospheric scientists who probe the atmosphere with terahertz waves, and require a precise understanding of the atmosphere's effect on THz waves to derive knowledge about the Earth's atmosphere; and technologists who need to understand atmospheric transmission to design and use THz systems for Defense and Security applications. We propose a comprehensive simulator that includes the effects of pressure, temperature, humidity, hydrometeors, trace gases, pollutants and turbulence to provide an accurate, validated model of the THz atmospheric transmission.

Anticipated Benefits/Potential Commercial Applications of the Research or Development.

A detailed understanding the atmospheric transmission at terahertz frequency is critical for the design, evaluation and use of standoff terahertz systems. The Comprehensive Atmospheric Terahertz Simulator (CATS) proposed here, will take into account pressure, temperature, humidity, hydrometeors, trace gases, pollutants and turbulence to provide accurate, experimentally validated transmission curves over the 0.1-1 THz range. The CATS program will allow program managers and engineers alike to decide whether a proposed THz solution can work, and how well it will work. In some case the results from CATS may be used to analyze the data produced by THz system and help factor out the atmospheric effects and identify the data of interest.

List a maximum of 8 Key Words that describe the Project.

Terahertz Atmospheric Transmission Hydrometeor Aerosols Pollution Turbulence

Signature not required at time of submission (see section 6.1).

Small Business Technology Transfer (STTR) Program
Cost Proposal

Firm:	TeraVision Inc
Address:	5516 E. South Wilshire Dr. Tucson, AZ 85711-4534
Location Where Work Will Be Performed:	933 N. Cherry Ave. Tucson AZ 85721

Proposal #: A09A-001-0291 Title of Proposed Effort: Comprehensive Atmospheric Terahertz Simulator (CATS)

Firm's Taxpayer ID: 33-1016338 CAGE Code: 3AZB8 DUNS: 115051307

Topic Number: A09A-T001

TOTAL DOLLAR AMOUNT FOR THIS PROPOSAL: $99,920.00

DIRECT LABOR:

Category and/or Individual:	Rate/Hour:	Est.Hours:	Phase I:
Dr. Christian d""Aubigny (PI)	38.00	220	8,360.00
Mr. Abram Young (Physicist)	32.50	320	10,400.00
Subtotal Direct Labor (DL):			18,760.00
Fringe Benefits, if not included in Overhead, (rate 0.0000 %) x DL =			0.00
Labor Overhead (rate 98.0500 %) x (DL + Fringe) =			18,394.18
Total Direct Labor (TDL):			37,154.18

DIRECT MATERIAL COSTS:	Phase I:
Gases and cylinder rental for Ozone and Nitrogen Gas used for purging/pressure broadening	300.00
Various supplies for transmission measurements (HDPE, stainless tubing, cables etc.)	500.00
Subtotal Direct Materials Costs (DM):	800.00
Material Overhead (rate 0.0000 %) x DM:	0.00
Total Direct Materials Costs (TDM):	800.00

OTHER DIRECT COSTS:	Phase I:
University of Arizona Subcontract	55,429.00
Subtotal Other Direct Costs (ODC):	55,429.00
Direct Cost Overhead (rate 0.0000 %) x ODC	0.00
Total Other Direct Costs (TODC):	55,429.00

G&A (rate 0.0000 %) x (base: TDL)	0.00
Total Cost:	93,383.18
Fee or Profit (rate 7.0000 %)	6,536.82
TOTAL ESTIMATED COST:	**99,920.00**

Explanatory material relating to the cost proposal (including substantiation/breakout of subcontractor costs):

The budget includes support for 220 hours for the PI ($38/hr) and 320 hours for a Physicist: Mr.Abram Young ($32.50/hr).$300 is budgeted for procuring gases and renting gas cylinders, $500 is budgeted for purchasing supplies necesary to run the THz transmission experiments, lens and window material (HDPE) tubing for the vapor cell, cables etc. $55,429 is budgeted for the University of Arizona subcontractor to support 160 hours of Dr. Kursinski ($57.13 per hour), 160 hours of Dr. Dale Ward ($40.65/hr), 160 hours of Dr. Otarola. ($38.87/hr) and 240 hours of Dr. Kulesa ($27.56/hr). Company fringe and overhead rates are based on a Phase-II pre-award audit by the National Science Foundation in February 2008.

Knowingly and willfully making any false, fictitious, or fraudulent statements or representations may be a felony under the Federal Criminal False Statement Act (18 USC Sec 1001), punishable by a fine of up to $10,000, up to five years in prison, or both.

Firm's official responsible for the cost breakdown:

Sign: ______________________ Date: ______________

Name: Christian d Aubigny Title: VP Engineering

>>Has any executive agency of the United States Government performed any review of your accounts or records in connection with any other government prime contract or subcontract within the past twelve months? No

>>Will you require the use of any government property in the performance of this proposal? No

>>Specify the type of payment desired: Partial payments

Last Updated on: 3/25/2009 4:06:23 AM

Continue

Signature not required at time of submission (see section 6.1).

1. INTRODUCTION

As THz detector technology has become more widely available and THz sources have improved, the number of potential THz applications to Defense and Security has skyrocketed. Potential applications range from the standoff detection of explosives and concealed weapons, to the search for explosives laboratories, and monitoring the exhaust of factories for gases that are characteristic of nuclear material processing. THz spectroscopy could be used to monitor for chemical and bio agents over a battlefield. THz technology also holds promise for high bandwidth, highly directed and secure communications and for compact high-resolution radar. At their core, all these applications involve transmitting a THz signal, propagating it some distance through the atmosphere, and then detecting it.

Central to this paradigm is quantifying the opacity of the intervening atmosphere. Atmospheric attenuation is a strong function of frequency, *often changing by orders of magnitude over the span of only a few GHz,* and is the result of a variety of physical processes. Accurate modeling is therefore critical when designing or judging a THz system. A solid understanding of the dominant physical processes is required to realistically model atmospheric propagation of THz waves. The principal processes are the absorption of radiation by ro-vibrational excitation of gases (e.g. H_2O, O_3, O_2), scattering by particulate solids (e.g. dust, smoke, rain, snow, fog) and air turbulence. We discuss briefly each of these in turn.

2. IDENTIFICATION AND SIGNIFICANCE OF THE OPPORTUNITY

2.1 Clear Air Atmospheric Modeling

Overview

Early efforts in modeling of the THz atmosphere (Zufferey 1972; Liebe et al. 1989) have led to a series of refinements and a variety of excellent physical models of THz transmission in clear air (Liebe 1993; Pardo 2001; Paine 2004; Urban 2005; Buehler 2005) (see figure 1). Although the details of the models vary, they are similar in overall implementation and architecture. First, a structural model of the atmospheric temperature, pressure, and composition is constructed based on the physical conditions along the geometrical path. (Short paths at a near constant altitude may only require a simple one-layer model of the intervening gas, whereas vertical applications with long path lengths require the evaluation of an atmosphere stratified in composition, pressure and density.) A database of ro-vibrational spectral features (e.g. *HITRAN*, Rothman et al. 2004; *Verdandi*, Eriksson et al. 1999) is read and the opacity of each is evaluated computationally, one spectral line at a time. This computation is sensitive to the assumed atmosphere, radiative transfer, and line shape. The total opacity at any given frequency is then the sum of the opacity from all computed molecules.

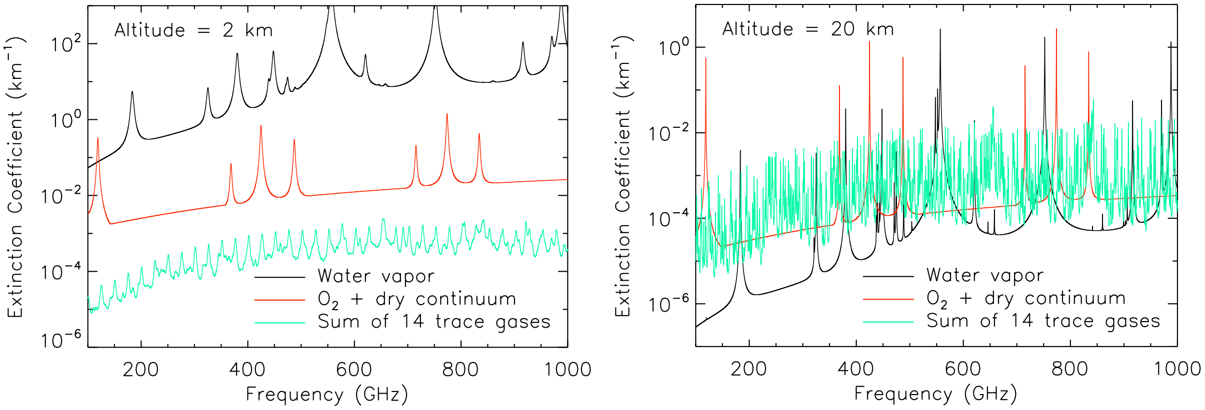


Figure 1: *Computed clear sky extinction coefficients for the LOWTRAN 2 mid-latitude summer atmosphere at 2 and 20 km altitudes. Water vapor and dry air attenuation computed using Liebe 93 model. Trace gas absorption for 14 molecules (O_3, N_2O, CO, SO_2, NO_2, NH_3, HNO_3, HCl, ClO, OCS, H_2CO, $HOCl$, CH_3Cl, and H_2O_2) calculated with a line by line code using HITRAN line parameters. Notice the dominance of water vapor absorption in the lower troposphere.*

In addition to the opacity model obtained from the summation of the contribution of all the spectral lines in a given spectral window of interest, wet and dry pseudo-continua are added. These components include the contribution from the far-wings of strong spectral lines outside the spectral window of interest, and from line-shapes not accurately modeled such that measurable discrepancies arise in the far wings (Clough et al., 1989; Waters, 1976). Several models (c.f. Clough et al., 1989; Kuhn et al., 2002) describe the 'wet' H_2O continuum arising from self-broadening (involving collisions of water molecules) and foreign broadening (involving collisions of water molecules with either nitrogen or oxygen molecules). A study of the water vapor self-broadening continuum is also included in Ma & Tipping (1990). In contrast, the non-resonant 'dry' continuum arises from collision-induced absorption (CIA) due to transient electric dipole moments generated during binary interactions of symmetric molecules with electric quadrupole moments such as N_2 and O_2, and also from the Debye type relaxation absorption of O_2 (Pardo et al., 2001). Generally, the best-fit dry and wet continua scale with the square of the frequency. Comparison of the dry and wet continua between that used by Pardo et al (2001) and that used in the popular radiative transfer codes of Liebe et al., (1989 and 1993) shows measurable discrepancies and is a good candidate for experimental investigation in Phase II.

Validation of Clear Air Models: the example of Submillimeter-Wave Astronomy

A summary of available THz atmospheric models and some of their capabilities is shown in Table 1. A significant motivation for the improvement of long-wave atmospheric models since the 1980's has been the advent of sensitive THz frequency detectors for submillimeter-wave telescopes. Indeed, careful measurement of the atmospheric transmission is vital to the proper interpretation of astronomical data! Particularly valuable at the highest frequencies observed from the ground (0.5-2 THz) are broad band Fourier Transform Spectrometers (FTS) which provide simultaneous measurements of the sky brightness temperature over the entire Terahertz regime (e.g. 100 GHz to >3 THz; Paine et al. 2000; Pardo et al. 2001; Chamberlin et al. 2003).

Model	**Gaseous species**	**Particles**	**Freq Range [THz]**	**Usability & Computational Speed**
Microwave Propagation Model (**MPM**); Liebe et al. 1985-1993	H_2O, O_2	-Liquid water drops -Water ice	0.1-1	Very fast, easy integration
Atmospheric Transmission at Microwaves (**ATM**); Pardo et al., 2001	40 major and minor species	-Liquid water Water ice - Spherical & aspherical particles	0.01-10	Binary availability only, moderate speed
The Atmospheric Radiative Transfer Simulator (**ARTS**);Bühler et al., 2005	40 major and minor species	Hydrometeors, full radiative transfer w/ scattering	0.01-10	Moderate speed, improving integrability
Atmospheric Model (**AM**); Paine, 2004	8 major species	Only gaseous phase included.	0.01-3.5	Fast, easy integration
AER's Line By Line Radiative Transfer Model (**LBLRTM**); Clough et al. (2005)	37 major and minor species	N/A	0.01-100	Moderate speed and ease of integration
Microwave Observation LIne Estimation & Retrieval **(MOLIERE)**; Schneider et al. 2003; Urban et al. 2005	23 major and minor species	N/A	0.01-3	Moderate speed and ease of integration

Table 1: *Comparison of the various atmospheric model codes to be used in the proposed Phase I/II activities. Blue boxes indicate 'best of breed' characteristics, red or yellow indicates a missing or developmental feature as currently implemented. Between them the various models include* H_2O, O_2, O_3, *CO, HDO, ClO,* ^{37}ClO, $^{16}O^{17}O$, $^{16}O^{18}O$, $H_2{}^{17}O$, $H_2{}^{18}O$, $^{16}O^{17}O$, $^{16}O^{18}O$, HO_2, HNO_3, N_2O, *NO,* NO_2, SO_2, CH_4,. NH_3 *and factor the effects of 123 isotopes.*

These measurements have refined clear air atmospheric modeling to the point where measured sky brightness profiles and opacities can be reliably reproduced at a number of diverse astronomical observatories (Mauna Kea, Hawaii, the Atacama desert of northern Chile and the high Antarctic plateau, among others). Figure 2 shows an FTS measurement taken from the summit of Cerro Sairecabur in northern Chile (elevation 5500 meters) from 0.1-3.5 THz with an atmospheric model fit to the measured temperature profile (Paine 2004). The bottom of Figure 1 subsequently shows the derived atmospheric transmission. Similarly, data from a 660 GHz tipping radiometer our group designed and built and which operates at the summit of the Antarctic plateau has been modeled by the AM and MOLIERE atmospheric models. The derived atmospheric water vapor content agrees remarkably well with that *independently* measured by balloon radiosonde and 183 GHz passive microwave soundings by NOAA satellites (Kulesa et al. 2009). These experiments represent some of the strongest validations of clear air THz atmospheric modeling to date, and represent a starting point for the proposed work described in this proposal.

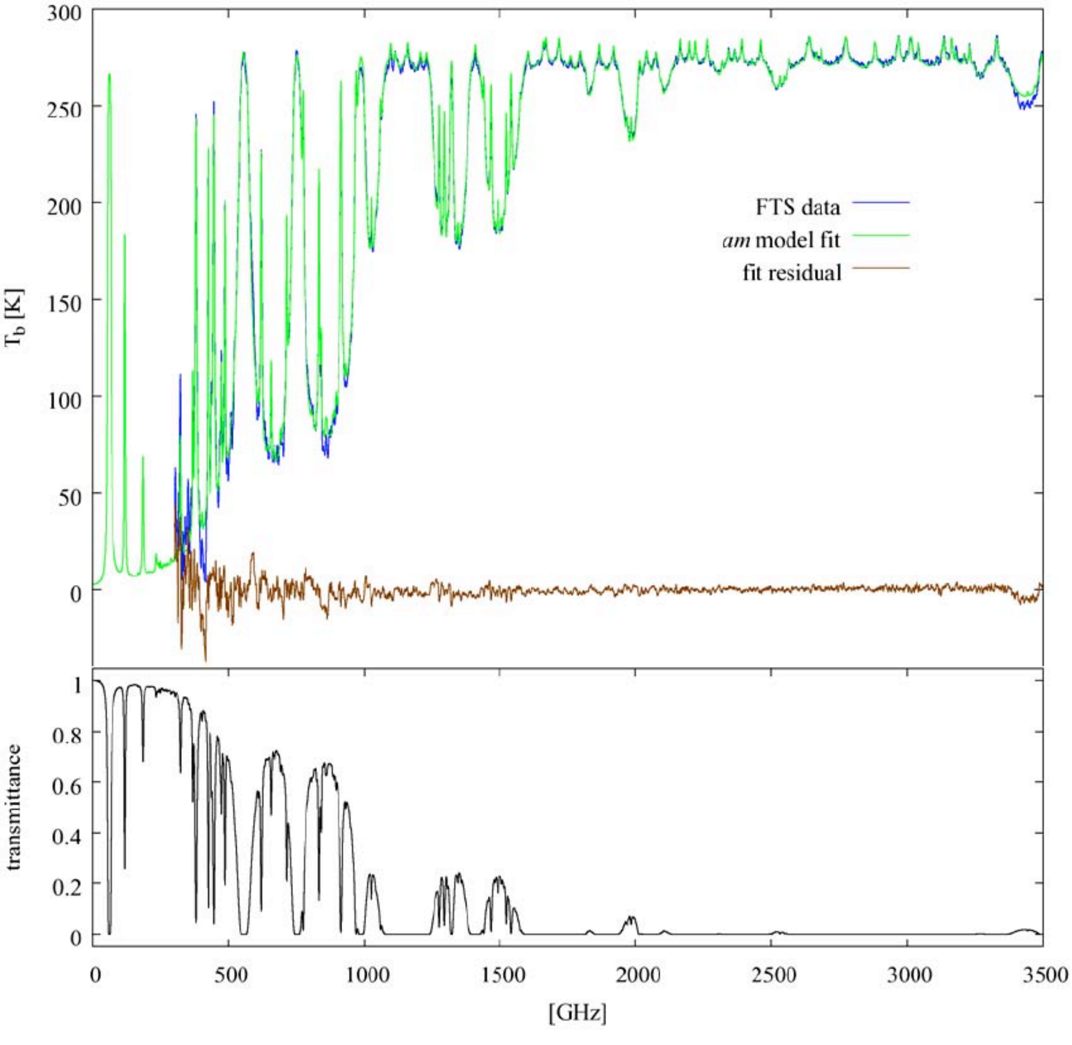


Figure 2: *FTS measurements of the sky brightness from 0.1-3.5 THz from Cerro Sairecabur, Chile are compared with the 'AM' model code (Paine 2004). The small residuals from the model fit lead to high confidence in the derived atmospheric transmission, plotted at the bottom. High transmittance (low sky brightness) at frequencies < 350 GHz results in reduced S/N FTS measurements and increased residual noise.*

Table 1 is a list of existing radiative transfer models suitable for the determination of THz transmission through the atmosphere. The main differences between them is the molecular species considered in their codes, the formulation used for the dry and wet pseudo-continuum, the exact frequency range of application and whether they are to be used in clear/only-gaseous atmosphere or if some model to deal with the absorption of hydrometeors and particles is also incorporated in the codes.

2.2 Hydrometeors and Other Aerosols Modeling

The most complete models already implement methods to deal with the absorption and scattering of electromagnetic radiation in the THz range from hydrometeors (liquid and solid) in the atmosphere. Some models even take into account the complex permittivity of liquid water in solution with sodium chloride (NaCl), as it would be expected for water drops in marine environments.

The most popular model to compute the absorption by liquid water in the atmosphere is that of Liebe et al., 1993, however this model works best for liquid water of temperature higher than 20ºC (Ronne et al., 1997). Better models that account for the complex permittivity of liquid water are available in the literature such as Meitzner & Wentz (2004) for up to 500 GHz, Ellison (2007) for up to 25 THz, and one derived at the Atmospheric Sciences Department (University of Arizona) by Otárola et al. (2006) for electromagnetic signals up to 1.5 THz.

The scattering of electromagnetic radiation by hydrometeors can be treated as Rayleigh scattering by small particles (see for instance van de Hultz, 1957). In such a case the particles are considered spherical and in the absence of additional information they can be considered to have a mono-disperse (same size, shape and mass) distributions.

Alternatively, the scattering can be better represented by the Mie scattering theory. In this case the scattering process involves the calculation of rather complicated Ricatti-Bessel functions. Code is available for this calculation such as that of Mätzler (2002) which consists of a collection of MATLAB© functions that can work together for any scatterer type provided the complex permittivity and size of the scatterers are known. The Mätzler (2002) functions give results on the cross-sections, efficiencies of absorption, scattering, backscattering, the asymmetry parameter, etc. A more complex scattering interaction model that accounts also for polarization and general particle shapes is used in the ATM model (Pardo et. al, 2001) that incorporates the T-Matrix code developed by Mishchenko, M.I., Davis, L., and Lacis, A.A. (2002). This approach can be used to model scattering by airborne particulates and aerosols. A very useful website containing a wide array of electromagnetic scattering programs has been assembled by Thomas Wriedt at the University of Bremen: http://diogenes.iwt.uni-bremen.de/vt/laser/wriedt/index_ns.html

2.3 Effect of Supercooled Suspended Water Drops

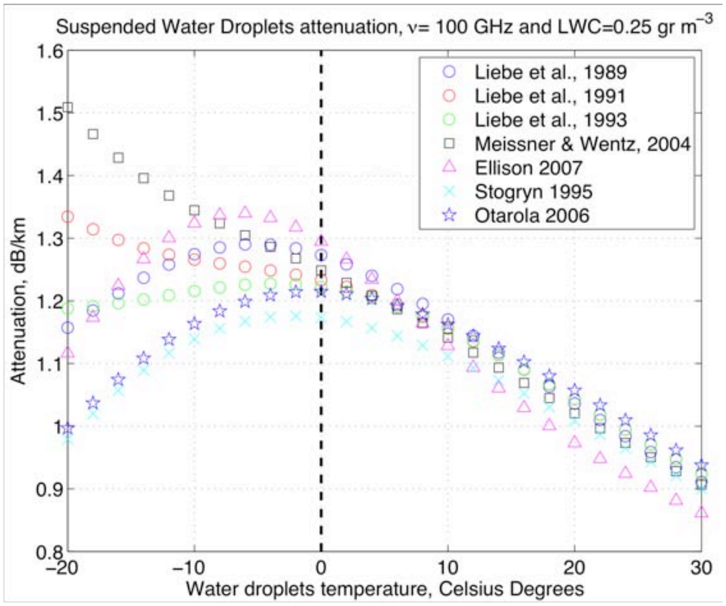


Figure 3: *Attenuation of a 0.1 THz beam (dB/km) as a result of going through a cloud with suspended liquid water drops in a concentration equal to 0.25 gm/*m^3 *as predicted by various models. The models agree with each other for liquid water drop temperature above freezing. Results from these models diverge for temperatures below freezing.*

Existing THz absorption models for liquid water in the atmosphere are generally in good agreement with each other. Research conducted at the University of Arizona found a large discrepancy among these models when predicting the absorption caused by supercooled suspended water drops (see Figure 3). Supercooled liquid water in clouds has much larger radiative impact than ice clouds of the same water content. A layer of supercooled liquid water can develop at the top of clouds at temperatures as low as -30ºC. Possible mechanisms for the formation of a supercooled liquid water in top of clouds involve the imbalance between the condensate supply rate, the bulk ice crystal mass growth rate and updraft speeds within the cloud (Rauber and Tokay, 1991). In 2004, Hogan et al. showed 40% of stratiform clouds contain a supercooled liquid water layer using the Lidar In-space Technology Experiment (LITE).

2.4 Trace Gas Contaminants Modeling

Terahertz spectroscopy can in theory be used detect gas precursors released by a number of illicit activities ranging from nuclear weapons material processing to explosives and methamphetamine fabrication laboratories. In particular, our team has started investigating the THz signatures of Nitrous Oxide (NO), Sulphur Hexafloride, (SF_6), Ammonia (NH_3), and Phosphine (PH_3). The THz spectra of all of these gases are dominated by rotational transitions well understood by quantum mechanical selection rules. The strength of these absorption lines are due to the dipole moments of the molecules, and vary widely among common trace contaminants found in the atmosphere. Line broadening and shifts are also understood under laboratory conditions.

To detect these gases, we must not only understand the effects of a pristine atmosphere on the propagation of the probing terahertz beams but also know the signatures of common pollutants and obscurants. Many obscurants are present and used on the battlefield, including Perchloroethane (C_2Cl_6), White Phosphorus (WP), diesel smoke, and dust. White Phosphorus is particularly interesting, due to its molecular spectra in its crystalline forms of Phosphorous Pentoxide (P_2O_5) and its tendency to form Mie scattering droplets, very effectively disrupting IR signals. We propose to study the effects of these on THz signal propagation through a combination of resonant molecular absorption and or scattering models as appropriate.

The following are the most common atmospheric trace gases found in urban and rural environments (ozone O_3, Sulfur dioxide (SO_2), Nitrogen Oxides (NOx), Carbon Dioxide (CO_2), and methane (CH_4)). The most ubiquitous atmospheric trace gas is Ozone. Often found at 1% concentration, the prolate asymmetric molecule Ozone (O_3) is known to have a large permanent dipole moment giving rise to intense absorption features spaced 200 GHz apart at approximately 0.6 THz, 0.8 THz, and 1.0 THz. Sulfur Dioxide (SO_2) is another prolate asymmetric molecule. Its significance as one of the most common trace gas pollutants comes from its creation in combustion processes. Purely rotational spectral lines are numerous owing to its *b*-type transitions covering a large range of quantum number *J* between 200 GHz and 1 THz.

Several of the models described in table 1 already include (ozone O_3, SO_2, NOx, CO_2, CH_4).

Phase I measurements will include pressure broadening studies to investigate broadening as a function of varying collision gases including water vapor. The variability of broadening parameters for all gases with respect to the collisional gas or scatterer is of specific interest to the resulting model fidelity. Most published studies of the rotational lines of these listed gases are done with self-collisions, rather than collisions with water vapor or other abundant atmospheric constituents. We propose to increase model fidelity through these extensions to these rotational lines between 100 GHz and 1 THz.

2.5 Effect of Atmospheric Turbulence on the Propagation of Electromagnetic Signals

Atmospheric turbulence is responsible for fluctuations in the air index of refraction through the mixing of eddies of different thermodynamic properties. In the mm/sub-mm spectral range, the air index of refraction depends on both air temperature (dry component) and air humidity (wet component). There are several models for the air refractivity in the mm/sub-mm spectral range. A compilation of some known models are included in the work of Rueger (2002). Consequently, the variance in the air index of refraction can be related to the variance induced by turbulence on its dry and wet components (see for instance, Peltier and Wyngaard, 1995).

In the Troposphere, the fluctuations in the air index of refraction (at microwaves) are dominated by turbulence-related fluctuations in the wet (water vapor) component (Otárola, 2008, Chapter 2). Much of the previous work on the effects of atmospheric turbulence were done for higher frequencies, beyond 1 THz, where fluctuations in the air index of refraction are dominated by the dry component. Research conducted at the Department of Atmospheric Sciences (University of Arizona) that uses sampling of the temperature and humidity from instrumented aircrafts at several altitudes (from the surface up to 10 km) has shown that the strength of the wet turbulence can be modeled as function of the square of the mean wet-component of refractivity along a path in the atmosphere (Equation 2.9, Otárola, 2008). That equation provides an important tool for the determination of the strength of the turbulence given by the so-called refractive index structure constant, C_n^2, because it relates, *for the first time*, the level of turbulence (at microwave frequencies) to the mean amount of water vapor.

Scintillation corresponds to the amplitude fluctuations of an electromagnetic signal due to random fluctuations in the index of refraction through the medium in which propagates. The scintillation of electromagnetic signals has been investigated for almost 60 years starting with the work of Obukhov (1949). A great contribution to the theory is due to the work of Tatarskii (1961). A large number of relevant manuscripts dealing with the scintillation theory have been summarized in the works of Wheelon (2001, 2004). Equations can be derived for the determination of the log-amplitude fluctuations of an electromagnetic signal affected by random fluctuations in the medium's index of refraction due to atmospheric turbulence. These equations involve integration of the refractive index structure constant, C_n^2, along the path traversed by the signal, where C_n^2 is estimated from variations in temperature and humidity.

Previous work cited above is in good agreement with measurements as long as the frequency of the electromagnetic signal is away from strong absorptions such as the gaseous resonant bands in the atmosphere. However, when the signal frequency falls within a strong absorption band such as the 183 GHz water band, the signal will also experience absorption. Fluctuations in the absorption coefficient (or equivalently the imaginary part of the index of refraction) due to atmospheric turbulence will also introduce amplitude fluctuations as the electromagnetic signal propagates through the medium. Research on this subject conducted at the University of Arizona led to a new equation (Otárola, 2008, Chapter 4) in order to best represent the overall log-amplitude fluctuation experienced by an electromagnetic signal propagating through an absorbing medium affected by turbulence. Prior to Otárola (2008), little previous work had been done to estimate the effects of turbulent variations in the imaginary component of the index of refraction on the propagation of electromagnetic signals.

2.6 Generation of Atmospheric Turbulence and Distribution of the Power of Refractive Index Fluctuations

The primary source of boundary layer turbulence depends critically on the structure of the wind and the temperature profiles near the surface. As described in Equation 5.14 of Holton (2004), the turbulent kinetic energy changes as a result of mechanical production (produced by wind shear), buoyancy production and loss (driven by convection depending on the temperature lapse rate stability), transport (advection of turbulent eddies into a region via the mean flow) and destruction of turbulence via dissipation (ε).

In the upper troposphere/lower stratosphere, atmospheric turbulence is due primarily to wind shear under conditions where mechanical production is able to overcome the strong stability imposed by increasing temperatures through the lower stratosphere associated with heating due to UV absorption by Ozone. In these regions and above, mechanical production of turbulence can also come from breaking gravity waves that were generated in the lower atmosphere and propagated up into higher levels in the atmosphere.

In three dimensions, vortex stretching and twisting of turbulent eddies cause turbulent energy to flow from large scales down to small scales (Kolmogorov, 1941; 1962). As a result, the distribution of the variance in the fluctuations of the index of refraction of air (that affect the propagation of the signal) as a function of the size of the turbulence eddies are often described by a 3D von Kármán turbulence spectrum where the power in the turbulent fluctuations in the air index of refraction cascades from the outer scale of the turbulence down through the inertial regime to smaller scales where dissipation converts the turbulence to kinetic energy. At scales larger than the outer scale of the turbulence, the von Karman model spectrum is flat and equal to the value at the turbulent outer scale.

Models such as the Kolmogorov or the modified von Kármán models that determine the power of refractive index fluctuations as a function of the scale of the turbulent eddies, assume that turbulence is homogenous and isotropic. There are at least two issues here: First, obstacles, such as complex terrain or in general any structures, natural or manmade, introduce a large degree of heterogeneity that will modify this view of the turbulence resulting in more power generated at the large scales of the spectrum than predicted by the Kolmogorov theory. Second, gravity and atmospheric stability cause turbulence in the vertical dimension to behave differently than that in the horizontal dimensions. Using relatively high vertical resolution soundings of the atmosphere, Otárola (2008, Chapter 3) found that the one-dimensional spectrum of turbulence-generated fluctuations in the air index of refraction, along the vertical axis, departs from the simple, -5/3 power-law behavior of the inertial regime of a von Karman model.

Instead, the 1-D spectrum is typically a sum of two power-law functions, one with a slope of -5/3 at the small scales (large wavenumbers) and one with a slope of -3 at the large scales (small wavenumbers) of the spectrum (see Figure 4). The most probable value of the vertical scale of the transition from one power-law regime to the other was 250 m. Equation 3.2 of Otarola (2008) provides a simple representation of this behavior in the vertical dimension. In cases where heterogeneity generates excess power in the turbulent refractive index fluctuations relative to the von Kármán model, we find the Von Kármán model can still approximate this behavior by introducing an artificially large outer scale of the turbulence.

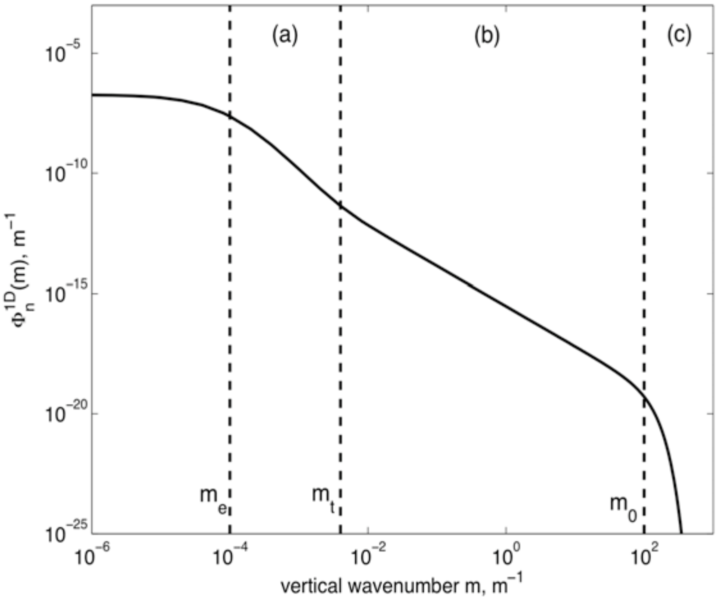


Figure 4: *Model of the one-dimensional power spectral density of air index of refraction perturbations along the vertical axis in the upper-troposphere lower-stratosphere (UTLS) region. The section (a) follows an inertial regime with a power-law function of slope equal to -3 (the spectrum flattens out at large scales), (b) correspond to an inertial regime of slope -5/3 and (c) shows the dissipation region. Sections (a) and (b) have been found from analysis of vertical soundings with vertical resolution of 35 m. The scale for the transition from the inertial regime of slope -3 to the inertial regime of slope -5/3, L_t, has a most probable value of 250 m. In this figure the vertical spatial wavenumber is defined as $m=1/l$, where l is a vertical distance in meters.*

While the intensity of turbulence is often described in terms of a single C_n^2 value, Otarola (2008) showed that at THz frequencies where the atmosphere is absorbing, modeling the effects of turbulence on signal propagation requires three different C_n^2 variables that represent the turbulent variations in the (1) real part of the index of refraction, (2) the imaginary part (associated with absorption) and (3) the cross correlation term between the turbulent real and imaginary fluctuations. The imaginary part becomes increasingly important at more absorbing wavelengths and shorter wavelengths and its impact can be comparable or greater than that of the real part.

2.7 New Experimental Capabilities

The collaboration between TeraVision and the University of Arizona will benefit this STTR through the combination of THz laboratory methods and modeling. The methods developed over two decades of THz radio astronomy are transferred to TeraVision through close collaboration and instrumentation sharing. Available to this effort are a highly unique set of instruments including THz Time Domain Spectroscopy (THz-TDS), Fourier Transform Spectroscopy (FTIR), and high-resolution heterodyne measurements.

The THz-TDS instrument is on loan from Raytheon Missile Systems (see figure 5 Left). Purchased from Picometrix, Inc. it is used regularly for a variety of purposes. For example, the index of refraction (real and imaginary) of the material we use to fabricate refractive optics (HDPE) varies from batch to batch. We routinely measure the index of refraction before machining our lenses. Anti-Reflection groove techniques and coatings are also evaluated before use. The system bandwidth is 0 to 2 THz, emitted and received by a pair of Tx/Rx antennae grown on an LT-GaAs photoconductor. A 150 fsec Coherent, Inc. Vitesse laser is fiber coupled through a dispersion compensator. Instrument resolution is equally limited by the LT-GaAs substrate, gated receiver maximum delay, and laser pulse rise time to less than 10 GHz.

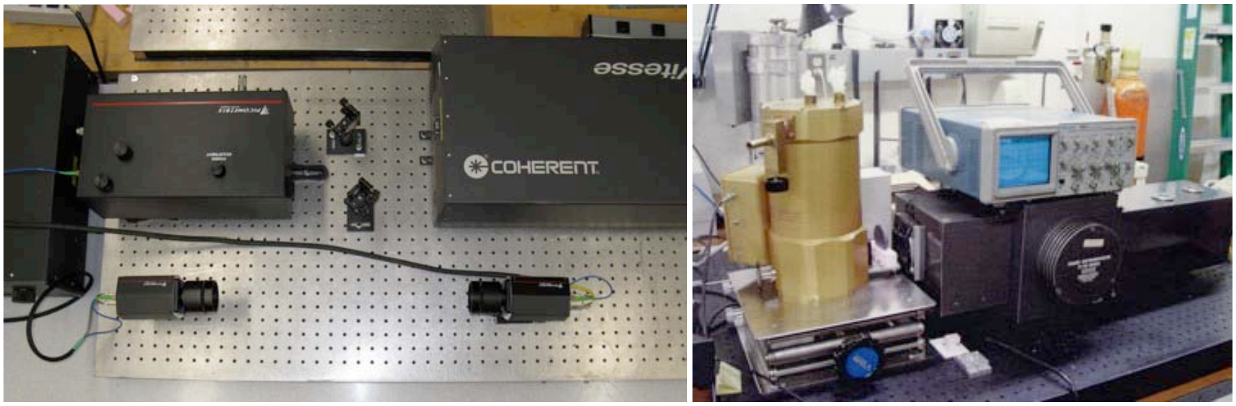


Figure 5: Left *Picometrix THz TDS in our laboratory.* **Right:** *Beckman RIIC FS-720 FTIR in Professor Walker's laboratory.*

Our FTIR system (figure 5 Right) is a 1960 vintage Beckman RIIC FS-270 FTS. The FS-720 is unique in its long wavelength capability (> 1mm) due to its large 4 inch aperture and customizable beam splitter. The original system's Golay receiver has been replaced by a much more sensitive liquid Helium cooled Silicon bolometer from IR Labs, and otherwise optimized for THz operation.

In partnership with Virginia Diodes Inc. we have developed a Scalar Network Analyzer (see figure 6) capable of frequencies between 150 GHz 900 GHz continuous with frequency resolution of less than 10 kHz. The source is a voltage controlled crystal oscillator at 10 MHz providing a reference to a programmable YIG oscillator with three levels of phase lock, providing a stable 10 to 20 GHz signal. Reconfigurable chains of frequency multipliers, each providing doubling or tripling of the input frequency is used to up-convert the synthesized RF signal to up to 900 GHz. The multipliers are high power (10milli W @ 300 GHz, 10 micro W at 1 THz) and stable based on a planar GaAs Schottky diode contact.

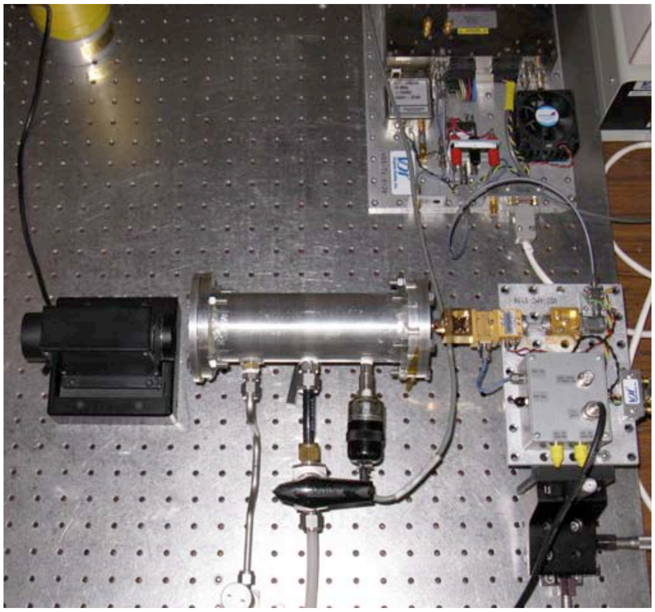


Figure 6: - *Virginia Diodes 6-Band 0.1-1 THz spectrometer and Golay cell detector setup around a vapor cell used to measure the pressure broadening of Ammonia (NH_3) in Prof. Walker's laboratory*

Standard broadband incoherent detection is done either with a Liquid He cooled Si bolometer at 4.2 K, or a room temperature Golay cell. Both are amplified by a lock-in amplifier reference locked to a 20 Hz TTL pulse modulating the CW THz signal by quickly switching on/off the bias supply to a power amplifier in the multiplier chain.

For increased dynamic range, a GaAs sub-harmonic mixer diode driven with a local oscillator of half the transmitter frequency is used as a coherent receiver. The mixed down beat frequency at 15 MHz is sampled by a 250 MS/s digitizer, providing 140 dB of signal range.

These tools are routinely used to prove design of THz components for remote sensing, as well as fundamental work on THz phenomenology. In addition, the recipes for success in tackling problems associated with THz instrumentation are well established among the group members through documentation of previous solutions, and knowledge sharing.

PHASE-1 TECHNICAL OBJECTIVES

Comprehensive Atmospheric Terahertz Simulator – Phase-I Technical Objective Summary

Inputs List: Location; Altitude; Slant Path of interest; Atmospheric pressure; Temperature; Humidity; Hydrometeors (types, concentration); Particulates (type, size, concentrations); Trace Gases Present; Turbulence.

The simulator will run existing codes to build atmospheric models from the unified parameters created by the GUI front end, and run radiation transfer codes that between them take into account every one of the inputs. The simulator uses multiple models to test consistency and optionally uses semi real-time atmospheric data.

For a given scenario, the graphical and tabular products will include: THz transmission, opacity and brightness temperature as a function of frequency, Transmission uncertainty as a function of frequency based on variance from one model to another, estimate of phase error, estimate of amplitude scintillation. Experimental validation of the results will begin in Phase-I.

The first objective for Phase-I is to assemble a state of the art simulator that can accurately model the propagation of terahertz radiation through the atmosphere for a variety of atmospheric conditions. Atmospheric conditions for arbitrary locations, altitudes and slant path/range, with specified atmospheric pressure, temperature and compositional profiles, hydrometeors, particulates and turbulence will be carefully modeled, with the option of specifying additional trace gas components.

The output of the program execution is a plot (and/or table) of transmission (alternatively opacity or brightness temperature) and an estimate of the model uncertainty (based on variation between the different models). Optionally, an estimate of phase error and amplitude scintillation will be provided. This result is achieved by supplementing the publicly available models described in Section 1 and 2 with codes written by members of our team.

We will construct a model-independent 'front end' graphical user interface which will allow a user to completely define a 'scenario' for the propagation of THz radiation, build the corresponding atmospheric model, run a series of independent THz codes, reprocess their output to a uniform format, and plot the results: atmospheric transmission, attenuation, background brightness temperature, amplitude scintillation, and phase variation. Figure 7 illustrates the basic architecture of the simulator. The interface will be designed to require minimal training for users with experience with Optical/Infrared atmospheric transmission industry standard: ONTAR PcModWin. When and where available the simulator will allow the user to access real time or archived weather data and common default values.

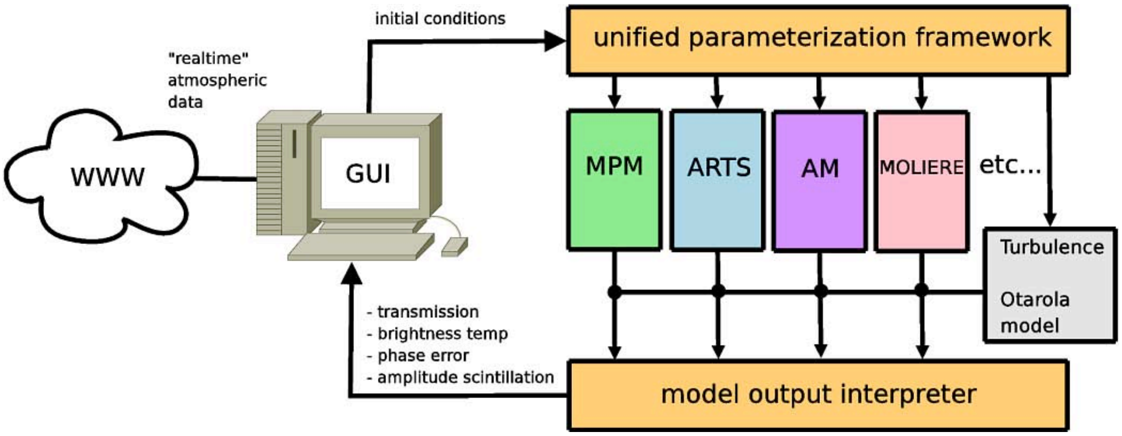


Figure 7: *Block diagram of the Phase I program architecture.*

Although the models described in Table 1 are architecturally similar, the mechanism by which initial conditions are constructed strongly differ from model to model. In order to realize an effective multi-model approach, a unified framework to generate model initialization files is needed and will constitute a significant effort for Phase I.

The parameterization framework will take user input from the GUI to construct initialization files for each of the atmospheric models to be run. Similarly, the output from each model will be re-interpreted into a unified format to be processed by the GUI for display to the user. By writing 'wrapper' code around the models and *not altering the models themselves*, future improvements to any of the individual models by their respective authors can be folded smoothly into the Phase I product.

The realism of any atmospheric model is only as good as the initial (physical) conditions used to generate the model. The graphical user interface will allow alteration of a wide variety of physical parameters, and will provide a handful of 'standard' configurations to start with. However, with Internet access, it will also be possible to load near-realtime weather data for many places on Earth. For example, the nearest radiosonde or mesoscale forecast data can be used to generate accurate vertical pressure, temperature, and humidity profiles. Archival profiles (e.g. “Washington D.C. at 12:00 UTC on August 1st, 2008”) can also be loaded. Available aviation METARs can be processed to estimate optical visibilities and ceilings and the root cause of any restrictions (clouds, haze, mist, fog, dust).

A number of the codes we are planning to bundle in Phase-I are native to Linux. Given enough time and resources, the simulator could be made to run on just about any computer platform. To minimize the software development effort in Phase-I, we propose to develop the simulator to run under Linux. The software can be distributed on a “live” bootable CD-ROM to run on any PC or under any Virtual Machine (VM). In phase III or before if required, we will develop a cross-platform versions of the software that will run across Linux/BSD, MS Windows and Mac OS X.

The second objective of Phase-I of this STTR is to identify areas where the models diverge from reality and plan Phase-II experiments to improve their accuracy. To that effect, we propose to begin Phase I by running a series of common calculations across the six available atmospheric models in Table 1. This approach promotes inter-model comparisons and will demonstrate under what circumstances they collectively agree or disagree. Where the models disagree, we will investigate what the principal point of contention is: whether it is their treatment of collision-induced absorption, the pseudo-continuum of water vapor, the line-by-line radiative transfer (e.g. line shape choice) or some other problem. A multi-model option will be extended to the final Phase I deliverable, since the deviation or uncertainty of a model result is just as important as the result itself. Systematic divergence between models will highlight aspects that we will focus on experimentally in Phase-II.

Comparing the existing models is a valuable endeavor. The true test of our simulator however, will be to compare it against observations. In Phase-I we will use our team’s 0.1-1 THz scalar network analyzer to characterize the atmospheric transmission, over short and medium path lengths (inside a room and between two buildings) under a few, well understood, weather conditions. The results of these measurements will be used to test our models and highlight areas that require further work in Phase-II.

Testing of the University of Arizona’s ATOMMS instrument (see section 6 and 7) will start later this spring and continue in parallel with the Phase-I effort. Terahertz propagation measurements from one building to another will immediately put the new turbulence theory of Otarola to the test.

The treatment of collision-induced absorption (in particular for trace elements) is expected to be one source of error for existing models. Phase-I measurements will include a targeted pressure-broadening study (for example ozone) to investigate broadening as a function of varying collision gases. Should we find that collision-induced absorption is indeed an important source or error in our models, we will perform a comprehensive study of the line broadening in Phase-II.

3. PHASE I - WORK PLAN

In Phase-I of this STTR our team proposes to assemble a state of the art simulator that can accurately model the propagation of THz radiation through the atmosphere for a variety of atmospheric conditions by writing 'wrapper' code around existing models. The models will be compared to each other and to the results of laboratory experiments to identify areas that will be the focus of our Phase-II efforts. The Phase-I effort will track the following task breakdown:

Phase-I Tasks Breakdown

1. **Build the Comprehensive Atmospheric THz Simulator (CATS)**
    a. Install, compile, and run existing models
    b. Design and write input GUI
    c. Design and write unified parameterization framework
    d. Write routines necessary to communicate with and run the different models
    e. Write model result interpreter
    f. Design and write output GUI
    g. Run models to verify that the model results within our simulator are consistent with results obtained when the models are run independently
2. **Investigate areas where the different models used in the simulator disagree with each other**
    a. Run simulator for a variety of standard test cases
    b. Compare the results of the different models to each other
    c. Investigate the physical processes involved where the models disagree
3. **Experimentally Measure THz Atmospheric Transmission**
    a. Over short distances (a few meters) in a controlled environment (laboratory).
    b. Over medium distances (between two buildings) for a few, well understood, weather conditions.
4. **Investigate areas where the models disagree with the THz transmission measurements**.
    a. Run simulator with parameters corresponding to experiments
    b. Compare the results of the models to the measured transmission
    c. Investigate the physical processes that may cause the observed differences
5. **Demonstrate laboratory measurement of foreign broadening (eg. Collision broadening of (O_3) by collisions with (N_2)).**
6. **Prioritize areas that need work to improve the fidelity of existing models**
7. **Devise Phase-II experiments to improve the accuracy of the simulator and validate its results.**
8. **Prepare STTR Phase-I report**

4. PHASE II – POSSIBLE DIRECTIONS AND CAPABILITIES

Phase-II will focus on experimental validation and improvements to our atmospheric models. Our team has numerous resources to achieve this including both common meteorological tools and unique THz instruments to measure atmospheric parameters for inclusion into models.

If warranted by our targeted Phase-I line broadening study, in Phase-II we will perform a comprehensive study of the line broadening for common atmospheric gases. Proposed studies of these gases will start with a low-resolution, broadband measurement by THz-TDS to identify and prioritize lines of interest by a) intensity, b) width, or c) proximity to commonly used atmospheric windows where the atmosphere is not otherwise opaque and where systems would likely operate. Follow-up studies with high-resolution techniques (THz Scalar Network Analyzer) from 1 mTorr to atmospheric pressure would be done to determine pressure broadening and collisional species parameters.

Comparison of the dry and wet continua (which results mainly from the wings of strong out of band spectral lines) used by different models already shows measurable discrepancies and is a good candidate for experimental investigation in Phase II. The slope and power of the dry/wet continua could be adjusted based on a matrix of atmospheric transmission measurements made under well-characterized atmospheric conditions. Alternatively, transmission through a vapor cell, where the temperature, pressure and ratio of nitrogen, oxygen, water vapor can be precisely controlled could be used to constrain the models.

Supercooled liquid water is found in >40% of all stratiform clouds. Yet existing THz absorption models for liquid water in the atmosphere strongly disagree when the temperature of the liquid drops dips below freezing (figure 3). High purity water, sprayed using a low cost ultrasonic mister, into a clean nitrogen atmosphere (to prevent nucleation), can be rapidly cooled below 0°C without freezing. The THz scalar network analyzer can then be used to characterize the complex index of refraction of the supercooled water drops

The University of Arizona's Active Temperature, Ozone and Moisture Microwave Spectrometer: ATOMMS is a new class of active, limb-viewing spectrometer system that works at microwave frequency and in the low Terahertz range. ATOMMS will probe the atmosphere by transmitting radio signals from one aircraft, through the limb of the atmosphere to receivers onboard another aircraft. The instrument is expected to start flying before the beginning of Phase-II of this STTR. This experiment which is independently funded, is expected to validate turbulence models and help evaluate and refine spectroscopic results used to feed THz atmospheric transmission models (see section 7).

Coupled with a fast response hygrometer, the ATOMMS instrument could be used to help improve not only our understanding of how turbulence affects THz propagation through the atmosphere, but also improve our understanding of atmospheric turbulence itself. The response of existing types of hygrometers is too slow to measure the integrated humidity along a line of sight, to capture the distribution function input to turbulence models. We could calibrate a heterodyne spectrometer described in section 2.7 to provide a hygrometer capable of providing integrated water content at tens of kilohertz. The fast hygrometer data can then be input into our turbulence models, where the structure constant C_n^2 can then be compared to simultaneous scintillometer data for model validation.

5. RELATED WORK / SYNERGISTIC ACTIVITIES

Through a Defense University Research Instrumentation Program (DURIP) award from the Air Force Office of Scientific Research the University of Arizona has procured a unique, powerful scalar network analyzer (SNA) capable of performing high resolution ($\leq$ 5 kHz) scans between 0.1 and 1.0THz. The SNA is being used to determine the spectral signature of a variety of hazardous materials to unprecedented accuracy. The resulting spectra will be of great value both in designing detection systems and in understanding the physics of the materials.

The scalar network analyzer (built by Virginia Diodes Inc.) consists of a series of multipliers and detectors each designed for tunerless, instantaneous sweeping across a 40% bandwidth. A plot of source output power versus frequency is provided in Figure 8. The sources are driven by a voltage controlled YIG oscillator, providing a frequency resolution ranging from 1 MHz for the low band to 5 MHz for the high band. At any given frequency the tone purity is ~10 kHz. The source has an electronic modulation capability to allow use with the supplied VDI detectors, as well as customer supplied detectors. At 800 GHz (an interesting regime for some explosives) there is a source and receiver to boost the dynamic range of the standard system. The source covers the band 750-850 GHz with > 0.1 mW of power. The receiver covers 750-850 GHz with conversion loss < 20 dB. The transceiver is driven by voltage-controlled YIG oscillators, providing a frequency resolution of approximately 5 MHz. This frequency resolution is ~10,000x greater than what can be measured using time domain spectroscopy (TDS) systems.

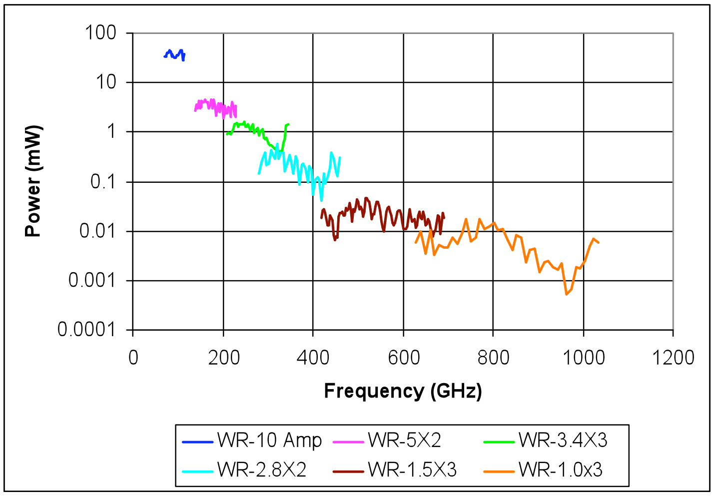


Figure 8: *0.1-1THz scalar natework analyzer output power as a function of frequency. The THz range is covered by six different bands*

The results of this STTR will be of particular importance to TeraVision's activities in both THz Frequency Modulated Continuous Wave imaging and spectroscopy. An ongoing TeraVision project funded through JIEDDO is a dual frequency 350 GHz / 820 GHz imager, now entering a proving stage where field tests will assess operation outside of the laboratory. Verified models will aid investigation into image quality at the standoff range, and perhaps more significantly the phase and amplitude stability of differential absorption spectroscopy.

Intriguing results from TeraVision's work with the imaging detection of the group of nitroamine explosives would also benefit from the analysis of this STTR. Figure 9, shows a 0.8 THz absorption band in the solid state form of

RDX decomposed into multiple peaks from 8.5 to 12 GHz FWHM, separated by 10 to 20 GHz. These are not previously seen in our THz TDS spectra due to the instrumental linewidth, and the peaks being buried in a larger pressure broadened absorption band. Modeling and observing these features in varying atmospheric conditions could prove key to making this 'fingerprint' practical for standoff detection.

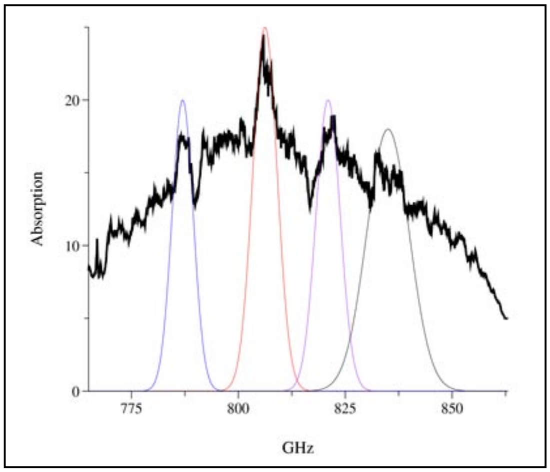


Figure 9: *The 0.8 THz absorption band of RDX at 0.1 GHz resolution. Four peaks are identified in the solid state from 8 to 12 GHz FWHM usually instrument broadened into the main absorption band.*

Dr. Kursinski's research group is leading an effort to develop a next-generation microwave and THz frequency satellite-to-satellite occultation measurement system that we refer to as the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS) with funding previously from NASA and presently from NSF. This new class of active, orbiting, limb-viewing spectrometer measurements is essentially a cross between GPS occultation profiler and Microwave Limb Sounder (MLS). The ATOMMS concept is to probe the atmosphere by transmitting radio signals through the limb of the atmosphere to receivers on the other side. We are currently funded through an NSF MRI grant to build and test an ATOMMS prototype system. The instruments, which consist of transmitters and receivers that operate at frequencies near 13, 22, and 183 GHz, will ultimately be placed on two WB57F aircraft.

Measurements of the transmitted signal phases and amplitudes from one aircraft to the other will be used to determine atmospheric profiles of temperature, pressure, water vapor, ozone, and possibly other trace gases. We have been developing inversion routines that take ATOMMS measurements of transmitted signal amplitude and phase to retrieve profiles of atmospheric temperature, pressure, water vapor, ozone, and possibly other trace gases.

The inversion routine necessarily includes a forward propagation model for the transmission of electromagnetic radiation through the atmosphere, which includes the bending of signals caused by variations in atmospheric refractivity, absorption by gas molecules, scattering and absorption by liquid water and ice hydrometeors (clouds), an estimation of the effects of atmospheric turbulence, and instrumental parameters. The atmospheric bending angle, which is determined from the phase measurements and the forward model, is used to produce profiles of refractivity with altitude. Atmospheric absorption is determined by measuring attenuation via signal amplitudes combined with the forward model. In the final processing step, the refractivity and absorption profiles, together with a spectroscopic database are used to retrieve atmospheric profiles and an estimate of the error in the retrieved parameters.

We will apply this tool (ATOMMS retrieval system) and the knowledge we gained along the way in the development of the transmission model proposed here. In addition, we will begin making short baseline ground observations using the ATOMMS MRI transmitters and receivers to test our expectations for atmospheric absorption and the effects of turbulence on the signals' amplitude and phase beginning in spring 2009. The results of these tests will be used to update the ATOMMS retrieval system and in the development of the STTR transmission model.

The STTR model however will have to be made more general in terms of the propagation geometry. In turn, anything that we learn in the course of putting together the STTR model can be incorporated into the ATOMMS retrieval system. There will certainly be synergy between our current and future ATOMMS work and the development of the STRR transmission model.

6. RELATIONSHIP WITH FUTURE RESEARCH

The ATOMMS remote sensing concept has been developed into what should be an extremely accurate and robust a climate observing system built around the radio occultation technique. ATOMMS is self-calibrating in that its signals are measured immediately before or after each occultation eliminating long-term drift. ATOMMS is a differential extinction system measuring at least two frequencies simultaneously to dramatically reduce or eliminate unwanted effects that are common to both frequencies. This differential approach at cloud penetrating cm to sub-mm wavelengths allows ATOMMS to determine the climate state in both clear and cloudy conditions. We have designed ATOMMS to provide sufficient spectral information to separate extinction associated with clouds from the absorption due to gases such that we estimate ATOMMS' performance in cloudy air will be within a factor of two of that in clear conditions and will yield in the process slant optical depth profiles of clouds.

ATOMMS capabilities are well matched to the objectives of this proposal and easily extended to higher frequencies. In fact, the plans for the flight version of ATOMMS include transmitters and receivers near the very strong 557 GHz water line in order to (1) directly measure temperatures in the mesosphere via the Doppler line width and (2) water isotopes in the middle atmosphere.

Figure 10: *Left: One of the two airborne ATOMMS (Active Temperature, Ozone and Moisture Microwave Spectrometer) transmit and receive modules used as a microwave and Terahertz limb sounder. Right: WB-57F aircraft photograph shows the gymballed nose and in it the present optical imaging instrument that will be replaced by our ATOMMS instrument.*

Key ATOMMS Capabilities

- **Determine gas concentrations:** by actively probing absorption lines such as those that NASA's Microwave Limb Sounder (MLS) measures via emission.
- **Determine particulate extinction:** by sampling at a sufficient number of wavelengths to separate particulate scattering and absorption from gaseous absorption. Future dual polarization can constrin particle shape and orientation.
- **Assess spectroscopic accuracy:** by over sampling the absorption line to determine its shape and center frequency.
- **Measure turbulence:** by measuring phase and amplitude scintillations
- **Measure path length changes:** via the signal phase to determine real part of refractivity
- **Cross compare phase & amplitude variations:** to assess spectroscopy and the potential to use one to estimate turbulence effects and then eliminate those effects on the other.

7.1 Turbulence Measurements: Evaluating the Turbulent Scintillation Theory

While the initial analysis of ATOMMS (Kursinski et al., 2002) did not include the effects of turbulence, we have since come to realize that ATOMMS will be a powerful method for probing and remotely determining atmospheric turbulence and that turbulence will be a dominant error. To quantify and understand the impact of turbulent variations of the index of refraction on the ATOMMS measurements, we used in-situ aircraft measurements of turbulence to develop a simple, parameterization of the wet turbulence based on mean humidity (equation 1). We then used this to estimate the magnitude of turbulence and the resulting scintillations that will result in the ATOMMS amplitude and phase measurements. To isolate and dramatically reduce the scintillations due to turbulent fluctuations in the ***real*** part of the index of refraction, we developed a simple approach that ratios the amplitude of a signal on the absorption line with the amplitude of a signal off the absorption line. This approach removes noise that is common to both signals but leaves most of the absorption that is present on the signal on the absorption line. This approach works quite well, dramatically reducing the scintillations due to the real part of the index of refraction, because of their weak frequency dependence ($f^{7/12}$) (Otarola, 2008).

We have recently been able to estimate the scintillations due to turbulent fluctuations in the ***imaginary*** part of the index of refraction by generalizing existing equations of scintillation theory to work in an absorbing (as opposed to transparent) atmosphere (Otarola, 2008). The magnitude of these amplitude scintillations due to imaginary refractivity variations scales approximately linearly with the optical depth, which is the variable we are interested in to determine constituent densities. The simple ratioing that eliminates scintillations due to real refractivity variations does not eliminate scintillations due to imaginary refractivity variations. The results of Otarola (2008) do indicate that the fractional errors in the optical depth due to imaginary refractivity variations will generally not be too large, typically less than 1% for the aircraft cases we have examined. Furthermore we may be able to estimate the amplitude fluctuations due to the imaginary refractivity variations from the phase fluctuations due to the imaginary refractivity variations. This idea will have to be developed and refined to assess how well it will work in practice.

Our understanding is based on our theoretical understanding of turbulence and equations we have developed that maps the turbulence to amplitude and phase scintillations. To assess the accuracy of our equations, several sets of ATOMMS measurements will be made. The first set of measurements will begin in April or May 2009 across a 1 km baseline on the UA campus using the ATOMMS instrumentation consisting of 8 tones between 18 and 26 GHz and 2 tones in the 183 to 203 GHz band. We are proposing to NSF to add two more 183 GHz channels to the present ATOMMS design in order to measure enough simultaneous information to isolate the (1) absorption, (2) turbulent variations in the real part of refractivity, (3) turbulent variations in the imaginary part of refractivity and (4) spectroscopic errors. Another set of surface tests will be run in the fall after the 2 channel upgrade. This will be followed by 2 sets of aircraft to ground tests and then the full aircraft to aircraft demonstrations. Equipment available through TeraVision and Professor Walker's group could be used to repeat the ground measurements in bands centered around 350 and 810 GHz.

Thanks to their very high Signal to noise ratio and slow occultation speeds, the ATOMMS aircraft-to-aircraft measurements will provide a unique and powerful characterization of atmospheric turbulence. The atmospheric turbulence will be sampled very finely, allowing detailed estimates of the turbulence properties and conditions of the turbulence to be reconstructed from the observations.

7.2 Spectroscopic Evaluation and Refinement

Because the goal of ATOMMS is climate monitoring and research, individual ATOMMS profiles will be averaged to reveal underlying climate behavior. As a result, random errors in individual profiles such as those due to turbulence should dramatically decrease with averaging (assuming weak scintillations). Because we have designed ATOMMS to minimize systematic errors, we anticipate that spectroscopy will likely be the limiting error for climate applications. We discussed spectroscopy issues at length with Dr. Herb Pickett, physicist, remote sensing expert and spectroscopist who recently retired from JPL, and developed a design for ATOMMS that provides the information needed to determine and improve the accuracy of spectroscopy, from the air or alternatively from orbit. The idea is that by sampling the spectrum of a given line at a number of frequencies that is larger than the number of frequencies needed to derive profiles from the measurement, we in some sense oversample the line which allows us to deduce subtle spectroscopic errors in line shape and center frequency and perhaps pressure dependent shifts in line center. In the air, measurements at these frequencies must be done simultaneously because of the rapidly evolving geometry, on the ground however, these measurements can be done sequentially by rapidly shifting the tone frequency to sample different parts of the line spectrum. Any shift in signal amplitude associated with changing frequency will be calibrated in the lab. Spectroscopic uncertainties in line strength can be reduced given independent measurements of the density of the constituent in question, although this error is expected to be smaller than errors in line shape (H. Pickett, pers. comm.). Comparing the measured water vapor density with measurements of the continuum will allow us to refine the knowledge of the wet and dry continua and their dependence on conditions.

7. COMMERCIALIZATION STRATEGY

The great majority of applications of terahertz technology to Defense and Security involve receiving and/or transmitting THz energy from a standoff distance. Different applications are bound to have different path length requirements. An Improvised Explosive Device detector may have to work from a few tens of meters. Spectroscopic systems used to search for explosive or narcotics laboratories based on the THz signatures of their precursors may have to work from hundreds of meters. THz systems that could be used to monitor the exhaust from the smoke stack of a factory or check a battlefield for chemical or biological agents may have to work over a few kilometers. THz radars and high bandwidth communication systems will have to work over hundreds of kilometers or more and in very different environments. As terahertz technology matures, it is becoming clear that the feasibility of a THz solution to a defense or security problem, its design and ultimately its performance will rest upon a detailed understanding of the effects of the atmosphere on propagating THz beams.

In point of fact, the design of TeraVision THz contrast imager based IED detector was based on the fortuitous match of some nitro-amine based explosives THz spectral signature and well known atmospheric windows. Our company's initial foray into modeling the propagation of THz beam in the atmosphere was to evaluate the useful range of our instrument under a variety of atmospheric conditions and the applicability of our THz contrast detection scheme to the detection of explosives with characteristic spectral lines at higher frequencies.

A reliable, validated simulator will help us market our existing products, and steer the design of new instruments for the Defense and Security markets. Government technologists will benefit from the availability of such a simulator when evaluating capabilities of proposed instruments. Other terahertz technology companies could also profit from having ready access to THz atmospheric propagation data. Some THz applications may in fact depend on the availability of a precise accurate atmospheric propagation model to work at all.

8. KEY PERSONNEL (1.5 pages)

Dr. Christian d'Aubigny (TeraVision Inc.) Received BS in Astronomy & Astrophysics and Space Sciences from Florida Institute of Technology, with Highest Honors, MS and PhD in Optical Sciences from the University of Arizona. His graduate and post-graduate work has focused on Laser micro-fabrication technology applied to THz device fabrication, THz imaging optics and THz sources. In his current position as VP of Engineering and New Products Dr. d'Aubigny manages a 10-person interdisciplinary design team that is developing a unique, two-frequency, THz contrast imager for the Department of Defense. He is now leading the same team to add RADAR ranging capability to that instrument. Previously, Christian d'Aubigny lead a 5 person interdisciplinary team that developed a new commercial laser micro-chemical etcher to fabricate THz waveguides based on technology developed at the University of Arizona and MIT.

Prior to his work at TeraVision d'Aubigny lead a program aimed at developing a 3 THz scanning imager for Raytheon Missile Systems. At the University of Arizona he also lead the design and fabrication of optics for a 850 GHz, 32 pixel bolometer array imaging polarimeter and was closely involved in the design of the optics for a 350 GHz 64 pixel heterodyne array. d'Aubigny has extensive laser micro-machining experience. In particular he has used laser micromachining to fabricate a 1 THz orthomode transducer and a variety of other waveguide components (feedhorns, hybrid combiner, bandpass filters, matched loads etc.) at frequencies ranging from 0.8 to 5 THz.

Mr. Abram Young (TeraVision Inc.) obtained BS in Physics and Mathematics from The University of Arizona in 1998. Before working for TeraVision, Inc. in 2007, he worked for 6 years at Raytheon Missile Systems, in particular modeling electromagnetic radiation in turbulent atmospheres and developing THz sources. He has authored papers on Cosmic Ray telescope development and data, and structured electromagnetic devices. Since he joined the company Mr. Young has worked on a couple programs aimed at developing THz TWT amplifiers and on a two frequency THz spectral imager to detect trace amounts of explosive material from range.

Dr. Douglas Miller (TeraVision Inc.) PhD and postdoctoral research involved the computer modeling of the transfer of radiation through the outer layers of supernovae, exploding stars, where the material can travel at relativistic speeds. He later worked on a project to model the light pollution at Astronomical Observatories that involved modeling the transfer of radiation, in particular scattering through the Earth's atmosphere and building a graphical user interface (GUI) so a layperson could setup and run models. Dr. Miller as led the design and development of software systems that controls Adaptive Optics (AO) System, including the Graphical user interface (GUI) that allows the user to operate the AO system, low level software to control motors and communication to the systems that control the telescope.

Professor Walker has over 20 years of experience designing, building, and using state-of-the-art receiver systems for THz astronomy. He has advanced degrees in both astronomy and electrical engineering and has worked in industry (TRW Aerospace and JPL) as well as academia. Dr. Walker is a Professor of Astronomy and an Associate Professor of Optical Sciences and Electrical Engineering at the University of Arizona. As a Millikan Fellow in Physics at Caltech, he worked on the development of many of the world's first submm-wave/THz receiver systems. At the University of Arizona he began the Steward Observatory Radio Astronomy Lab (SORAL), which has become a leader in developing THz receiver systems. SORAL constructed the world's first 810 and 345 GHz heterodyne array receivers. These instruments are multi-institutional efforts, with key components coming from JPL, several universities, and a number of industrial partners. He received the Antarctic Service Medal of the USA for his work on THz receivers at the South Pole. Funded by the NSF, Prof. Walker is leading the effort to design and build the world's largest submillimeter-wave heterodyne array receiver (64 pixels). His team is also employing laser micromachining techniques to the fabrication of integrated THz array receivers.

Dr. Craig Kulesa received a BS in Physics in 1993 from Miami University and a Ph.D. in astronomy from the University of Arizona, where he is currently an Assistant Astronomer. Early in his work in the SORAL group (PI: C. Walker), he helped develop heterodyne arrays for the AST/RO telescope at the South Pole and the HHT telescope on Mt. Graham, Arizona. He is Deputy-PI of the Supercam instrument, an NSF-funded 64-beam heterodyne array receiver at 350 GHz, and the Stratospheric Terahertz Observatory, a NASA-funded long duration balloon experiment that employs linear arrays of heterodyne receivers at 1.4 and 1.9 THz. Both are the world's very first, most powerful instruments of their type. He recently deployed a fully-automated telescope (PreHEAT) with a 660 GHz heterodyne receiver to Dome A, the isolated summit of the Antarctic plateau. Results from this experiment have provided site-testing of the THz transmission above Antarctica and serve as one of the validation points that spurs the efforts of this proposal. His research interests overlap with the proposed research in terms of overall software design and development, atmospheric radiative transfer, and the experimental design and implementation to validate THz frequency propagation models.

Professor Kursinski has over 20 years of experience in atmospheric remote sensing and instrumentation particularly using the radio occultation (RO) technique. He has a Masters degree in electrical engineering from the University of Southern California and a PhD in planetary science from Caltech where his dissertation on the GPS RO technique was nominated for the Klauser prize as the best dissertation at Caltech. He worked at NASA JPL for 20 years before becoming an associate professor in Atmospheric Sciences and in Planetary Sciences at the University of Arizona. He was a member of the Voyager radio science team for Neptune and was awarded the NASA exceptional service award in 1990 as system engineer and manager of the Deep Space Network (DSN) Radio Science System for the Voyager Neptune encounter. Since 1990 he has worked on the GPS RO technique. He co-developed the GPS RO retrieval system used at JPL and developed an error model that established the power of the technique for weather and climate applications. His recent research using GPS has focused on measuring water vapor to study monsoons, El Nino and feedbacks in the climate system. For the past decade he has been pushing RO observations of Earth's and Martian atmospheres to higher frequencies ranging from 22-600 GHz. His group has developed the retrieval theory and associated performance estimates including the effects of clouds and turbulence that indicate this class of observation will play a major role in the global climate observing system. With funding from NSF and NASA, his team, in collaboration with Professor Walker's group, is building a prototype 13 to 203 GHz occultation instrument for a two high altitude aircraft demonstration later this year.

Dr. Dale Ward received a BS in electrical engineering from Case Western University. Before earning his graduate degrees, he worked for five years at Westinghouse in Baltimore, primarily designing and testing RADAR control systems for military aircraft. Dr. Ward received his MS (1995) and PhD (1998) in atmospheric sciences from the University of Arizona. In his PhD thesis, he developed a method to retrieve vertical profiles of pressure and temperature based on measurements of refraction taken by satellite solar occultation platforms. Dr. Ward has years of experience working with and designing inversion algorithms for remote sensing observations. In particular, he developed a simultaneous inversion algorithm for SAGE III satellite solar occultation observations. Dr. Ward is currently a lecturer in the area of weather and climate. His recent research has been focused on the development of inversion algorithms for a proposed multi-satellite active microwave occultation system called ATOMMS (Atmospheric Temperature Ozone and Moisture Microwave Spectrometer). Dr. Ward is lead for the retrieval algorithms in which profiles of temperature, pressure, water vapor, and ozone and estimates of their uncertainty will be derived from observations of the phase and amplitude of transmitted microwave signals.

Dr. Angel C. Otárola obtained a degree in Civil Engineering from Universidad de Santiago de Chile (1989) and a diploma in Computer Sciences from Universidad Católica del Norte, Chile (1992). He was awarded a Master of Science degree (2006) and a Ph.D. (2008) in Atmospheric Sciences from the University of Arizona. Angel's master's thesis concerned modeling the Complex Permittivity of pure liquid water from microwave frequencies up to 1.5 THz. His Ph.D. dissertation was a study of effects of turbulence in an absorbing atmosphere on the propagation of microwave signals for radio occultation studies of the Earth's atmosphere. Both degrees were obtained under the supervision of Dr. E. Robert Kurskinsi. Angel Otarola worked 15 years for the European Southern Observatory (ESO), at facilities in northern Chile, where he contributed to a study of atmospheric transparency and atmospheric turbulence for the determination of the best locale for the deployment of a large collecting area radio interferometer for the study of the universe from the emission of millimeter and sub-millimeter wavelength radiation (the Atacama Large Millimeter Array (ALMA) project). At ESO he also worked as a Test Engineer in the study of structural performance of prototype radio telescopes for their use in the millimeter and sub-millimeter wavelengths bands. Angel also contributed to the design of the long-baseline configuration of the ALMA radio-interferometer for the optimization of the u-v coverage of the array and the overall characteristics of the synthesized detection beam. Dr. Otarola currently holds an Assistant Scientist position with the Thirty Meter Telescope project (a partnership of Canadian Universities for Research in Astronomy, CalTech, and The University of California) where he contributes in studies of atmospheric turbulence and the statistical characterization of water vapor in the atmospheric column. He is collaborating with Dr. Kursinski at the University of Arizona in the development of the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS), an instrument intended for the probing of the Earth's atmosphere by means of the active radio occultation technique.

9. FACILITIES AND EQUIPMENT

TeraVision Inc.

TeraVision rents space in a large 8000 square feet building approximately six miles from the University of Arizona campus. There the company has access to Modern optical, mechanical, electronics, electromagnetic computer design and modeling tools, electronic test equipment, general machine shop services (CNC mills, lathes, welding etc. and a complete suite of vacuum pumps and vacuum testing equipment,

The company maintains close ties to the University of Arizona, and in particular Steward Observatory where the company keeps laboratory space where phase II of this project will be conducted. In its laboratory space at Steward Observatory the company has state of the art solid state THz sources and receivers, matching THz focusing and scanning optics, as well as state of the art Digital Signal Processing (DSP) equipment necessary to analyze receive THz signals. An extensive suite of THz signal processing software has been developed, new functionalities and improved algorithms are constantly being added to the existing code.

University of Arizona.

Prof. Walker's group. In 1992 Professor Walker established a laboratory (the Steward Observatory Radio Astronomy Laboratory,SORAL) for the development of state-of-the-art mm/submm-wave receiver systems. The laboratory contains all the equipment (spectrum analyzers, network analyzer's, vacuum pumps, cryogenic support facilities, etc.) needed for the development of mm/submm instrumentation. His group also has 4He, 3He, and closed-cycle cryostats, a full receiver testbed, THz sources (including a Coherent/DEOS FIR laser), and an antenna test range which allow them characterize a wide range of receiver systems. The lab is equipped with a modified Fourier Transform Spectrometer that can be used to test THz sources, and has access to a THz Time Domain Spectroscopy system that was provided by Raytheon Missile Systems. SORAL has licenses for Hewlett Packard's High Frequency Structure Simulator (HFSS) and Advanced Design System (ADS) software packages, as well as Agilent HFSS and CST Microwave Studio. These programs are used to accurately model and optimize mixers and other crucial receiver components. In addition, the group has licenses for optical design packages such as Zemax, Code V and ASAP.

Using these facilities, SORAL has designed and built a number of receiver systems; including single pixel 230, 490, and 810 GHz receivers and the world's first 345 and 810 GHz heterodyne arrays. In addition, SORAL designed and built the optics, cryogenics, and most of the electronics for a 1.5 THz receiver system (TREND) now in operation on the AST/RO telescope at the South Pole. SORAL has been the primary facility instrument builder for both the 10m

Heinrich Hertz Telescope and AST/RO.

Approximately two years ago the lab procured a high precision numerical mill to machine waveguide and quasi-optical components up to a few THz. In addition the group has a laser micro-machining system that can be used to fabricate waveguide components from 1 to 5 THz. A second laser micromachining system operating in the UV will soon be able to machine waveguide structures from 5 to 30 THz.

Recently, an Air Force Defense University Research Instrumentation Program (DURIP) award has allowed SORAL to purchase a one of a kind, wide band (0.1 THz to 1 THz) high resolution (10 kHz) spectroscopy system. The instrument, manufactured by Virgina Diodes Inc, uses five distinct, solid state heterodyne transmitters to cover the 0.1-1 Thz region. The transmitters can be precisely tuned and swept within their frequency range. A Golay cell is used to make incoherent transmission or reflection measurements. Two of the five transmitters are also matched with solid state heterodyne receivers that can be used to make coherent measurements. Used in its incoherent mode, this instrument will allow us to investigate the THz properties of a variety of construction materials and find the optimal frequency for through the wall imaging. Used in its coherent mode, the instrument will be particularly useful in characterizing materials for the programmable phase grating.

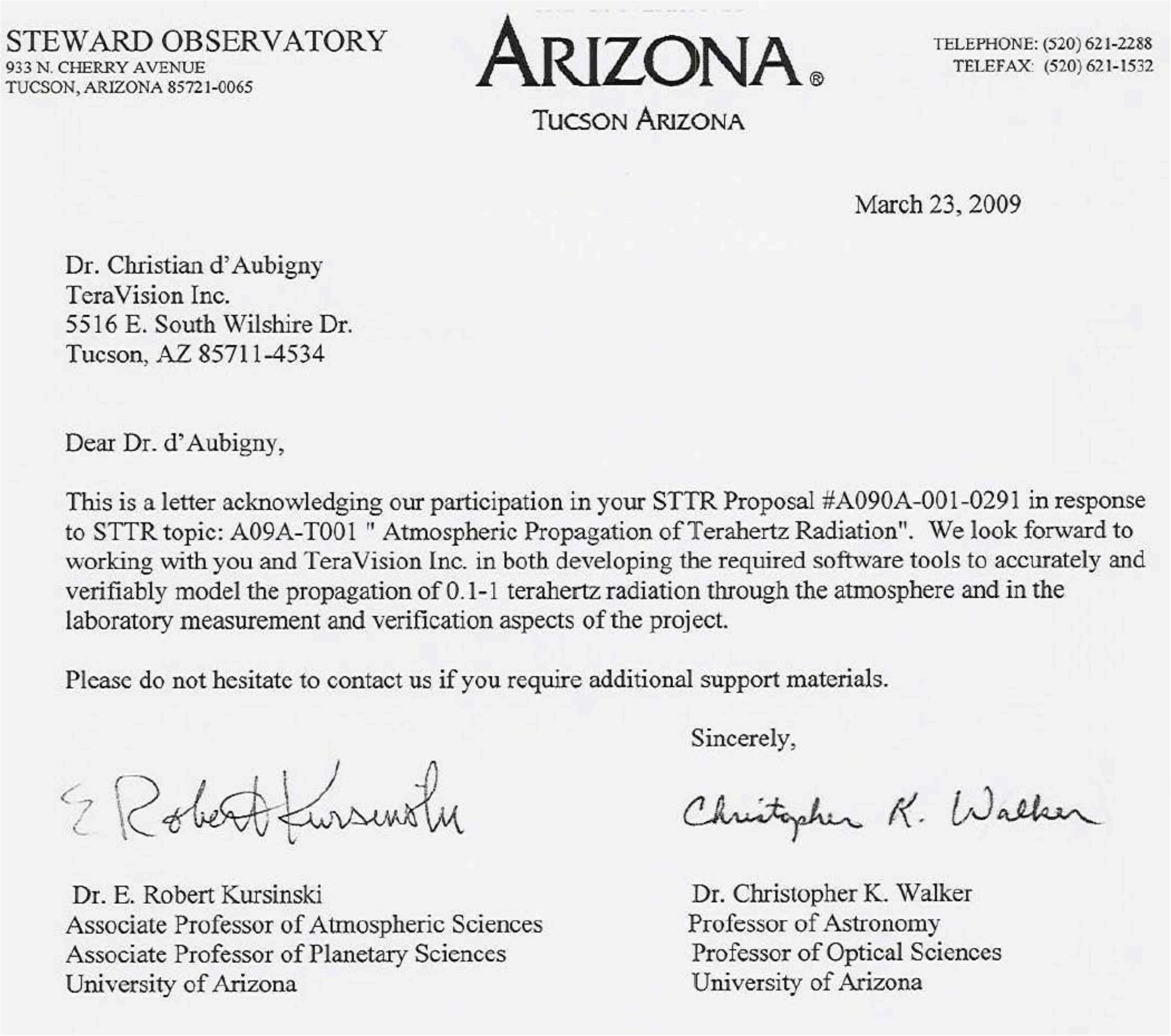
Prof. Kursinski's group. The Kursinski group analysis and data processing facilities reside primarily in the Physics and Atmospheric Sciences (PAS) building at the University of Arizona. They consist of office space, computer workstations and the custom software that resides on them. The software includes models to forward propagate signals through the atmospheres of Earth and Mars, retrieval code that derives profiles of atmospheric properties from observations and error covariance codes that determine the uncertainties in the retrieved profiles. These systems also house databases of GPS ground and RO data such as our gridded GPS RO water vapor results that uses a method we have developed in collaboration with JPL. Other remote sensing data sets at our facility include outgoing longwave radiation (OLR), clouds, sea surface temperature (SST), and rainfall as well as analyses of the atmospheric state from the European Center for Medium Range Weather Forecasts (ECMWF) and the U.S. National Centers for Environmental Prediction (NCEP).

The JPL GPS RO retrieval software system that we are extending to work with the new ATOMMS observations resides in a secure facility shared by the Department of Atmospheric Sciences and Department of Physics at the University of Arizona to comply with United States export control laws and regulations implemented by the Department of Commerce through its Export Administration Regulations (EAR).

The prototype instrument hardware for the ATOMMS demonstration on two high altitude aircraft later this year is being built and tested at Prof. Walker's SORAL facility. The instrument consists of heterodyne transmitters and receivers for two 13 GHz channels, eight channels between 18 and 26 GHz and presently two (to be upgraded to four) 183-203 GHz channels as well as two extremely sensitive 3-axis accelerometers and GPS receivers used to determine the motion of the two aircraft to better than 0.1 mm/sec and the instrument control and data acquisition system. We have developed custom digital signal processing software to evaluate the ATOMMS laboratory test results focused on single channel and differential channel phase and amplitude noise and stability. We also have a phase noise test set provided by Raytheon Missile Systems in Tucson.

10. SUBCONTRACTORS

Professor Kursinski's group will be responsible for providing the atmospheric transmission code covering the frequency range from 0.1 – 1.0 THz. This effort will be divided into four main components: gaseous absorption (clear air transmission), particulate effects (scattering and absorption by clouds, precipitation, and other aerosols such as dust and smoke), turbulence effects (estimation of the amplitude and phase scintillations) and the integration along the user selected path through the atmosphere. The inputs for this code will be the state of the atmosphere along the path from the transmit location to the receive location. Specification of the required parameters, atmospheric state and path, will be ultimately set by the user through a GUI. For cases where the user does not wish to specify the atmospheric state, a representative or default state of the atmosphere will be used. As mentioned, we have access to various transmission codes that account for gaseous and particulate attenuation valid for the 0.1 – 1.0 THz region. We will implement several of these transmission codes, which will allow the user to observe the spread from different models and gain some measure of the uncertainty in the calculations. The turbulence calculations will be unique and derived based on our recent findings concerning the effects of atmospheric turbulence on the propagation of THz radiation (Otarola, 2008). The spectral output from our code will be passed back to the GUI, which will produce the outputs to the user. Professor Walker's group will support the development of the unified parameterization framework and support some of the experimental measurments. A joint letter of support from Prof. Walker and Kursinski is provided below.



STEWARD OBSERVATORY
933 N. CHERRY AVENUE
TUCSON, ARIZONA 85721-0065

ARIZONA®
TUCSON ARIZONA

TELEPHONE: (520) 621-2288
TELEFAX: (520) 621-1532

March 23, 2009

Dr. Christian d'Aubigny
TeraVision Inc.
5516 E. South Wilshire Dr.
Tucson, AZ 85711-4534

Dear Dr. d'Aubigny,

This is a letter acknowledging our participation in your STTR Proposal #A090A-001-0291 in response to STTR topic: A09A-T001 " Atmospheric Propagation of Terahertz Radiation". We look forward to working with you and TeraVision Inc. in both developing the required software tools to accurately and verifiably model the propagation of 0.1-1 terahertz radiation through the atmosphere and in the laboratory measurement and verification aspects of the project.

Please do not hesitate to contact us if you require additional support materials.

Sincerely,

E Robert Kursinski

Christopher K. Walker

Dr. E. Robert Kursinski
Associate Professor of Atmospheric Sciences
Associate Professor of Planetary Sciences
University of Arizona

Dr. Christopher K. Walker
Professor of Astronomy
Professor of Optical Sciences
University of Arizona

11. RELEVANT PRIOR, CURRENT OR PENDING SUPPORT

SOURCE: NSF
TITLE: MRI: Development of the Active Temperature Ozone & Moisture Microwave Spectrometer (ATOMMS) cm & mm-wave occultation instrument
AMOUNT: $1,884K over 3 years
PERIOD: September 1, 2007 to August 31, 2010

SOURCE: NOAA
TITLE: Improving the Impact of GPSRO Data Assimilation in NCEP
AMOUNT: $227K over 2 years
PERIOD: June 2008 – May 2010

12. CONTRACTOR COST PROPOSAL

Dr. Ward will focus on the gaseous absorption and integration along the path. Dr. Otarola (a citizen of Chile, currently working at the University of Arizona on a H1B visa) will focus on particulate extinction and turbulence effects. Dr. Kursinski will focus on integration and testing the transmission code. This effort will require four weeks of full-time equivalent work each from Drs. Kursinski, Otarola, and Ward.

In support of Professor Walker's group participation in the proposed investigation, 6 weeks of salary support for Dr. Craig Kulesa (Assistant Astronomer) are requested to develop software modules for modeling the THz transmission of the atmosphere.

University of Arizona - Army STTR A090A-001-0291 Atmospheric Propagation of THz Radiation

	Phase I
1. Labor/Personnel	
Senior Personnel Subtotal	
Dr. Rob Kursinski (Atmospheric Sciences) - 4 Weeks (160 hrs @ $57.13/hr)	9,141
Dr. Dale Ward (Atmospheric Sciences) - 4 weeks (160 hrs @ $40.65/hr)	6,504
Dr. Angel Otarola (Atmospheric Sciences) - 4 Weeks (160 hrs @ $38.87/hr)	6,219
Dr. Craig Kulesa (Steward Observatory) - 6 weeks (240 hrs @ 27.56/hr)	6,614
Total Salaries	**28,478**
Fringe Benefits 28.9 (F)	**8,230**
Total Labor/Personnel	**36,708**
DIRECT COSTS	**36,708**
MTDC	**36,708**
INDIRECT COSTS (51.0 MTDC)	**18,721**
TOTAL COSTS	**55,429**

13. REFERENCES

Querel, R.R. (2007), IRMA Calibrations And Data Analysis for Telescope Site Selection, Master of Science Thesis, Department of Physics, University of Lethbridge, Lethbridge, Alberta, Canada.

Waters, J.W. (1976), Absorption And Emission By Atmospheric Gases, in Methods Experimental Physics, Orlando, FL: Academic, 1976, vol. 12B, ch. 2.3.

Perrin et al., (2005), Molecular Line Parameters for the "MASTER" (Millimeter Wave Acquisition for Stratosphere/Troposhere Exchange Research) Database, Journal of Atmospheric Chemistry, 51, 161-205.

Rothman et al., (2005), The HITRAN 2004 Molecular Spectroscopic Database, Journal of Quantitative Spectroscopy and Radiative Transfer, 96 (2), 139-204.

Jacquinet-Husson et al., (1999), The 1997 GEISA Spectroscopic Databank, Journal of Quantitative Spectroscopy and Radiative Transfer, 62 (2), 205-254.

Picket et al., (1998), Submillimeter, Millimeter, and Microwave Spectral Lines Catalog, Journal of Quantitative Spectroscopy and Radiative Transfer, 60, 883-890.

Otárola A., (2006a), Spectral Lines in the MM-Wavelength Range: Parameters of Interest, Independent Study Class, Atmospheric Sciences, University of Arizona, Prof. E.R. Kursinski.

Verdes et al., (2005), A Sensitivity Study On Spectroscopic Parameters Accuracies for a mm/sub-mm Limb Sounder Instrument, Journal of Molecular Spectroscopy, 229, 266-275.

Clough, S.A., Kneizys, F.X., and Davies, R.W., Line Shape And The Water Vapor Continuum, Atmos. Res., 23, 229-241.

Kuhn, T., Bauer, A., Godon, M., Bühler, S., and Künzi, K. (2002), Water vapor continuum; absorption measurements at 350 GHz and model calculations, Journal of Quantitative Spectroscopy and Radiative Transfer, 74 (5), 545-562.

Ma, Q., and Tipping, R.H., (1990), Water Vapor Continuum In The Millimeter Spectral Region, J. Chem. Phys., 93, 6127-6139.

Pardo, J.R., Cernicharo, J., and Serabyn, E., (2001), Atmospheric Transmission at Microwaves (ATM): An Improved Model For Millimeter/Submillimiter Applications, IEEE Transactions on Antennas and Propagation, 49 (12), 1683-1694.

Liebe, H.J., (1985), An Updated Model For Millimeter Propagation In Moist Air, Radio Science, 20 (5), 1069-1089.

Liebe, H.J., Manabe, T., and Hufford, G.A., (1989) Millimeter-Wave Attenuation and Delay Rates Due to Fog/Cloud Conditions, IEEE Transactions on Antennas and Propagation, 37 (12), 1617-1623.

Liebe, H.J., Hufford, G.A., and Manabe, T., (1991) A Model For the Complex Permittivity Of Water At Frequencies Below 1 THz, International Journal Of Infrared And Millimeter Waves, 12, 659.

Liebe, H.J., Hufford, G.A., and Cotton, M.G., (1993) Propagation Modeling On Moist Air And Suspended Water/Ice Particles At Frequencies Below 1000 GHz, Presented at the AGARD-CP-542 Meeting, MM-Wave Radiation, Palma de Mallorca, Spain, 3-1, 3-11.

Pardo, J.R., Serabyn, E., and Cernicharo, J. (2001b) Submillimeter Atmospheric Transmission Measurements on Mauna Kea During Extremely Dry El Nino Conditions: Implications For Broadband Opacity Contributions, Journal of Quantitative Spectroscopy and Radiative Transfer, 68, 419-433.

Buehler et al., (2005), ARTS, The Atmospheric Radiative Transfer Simulator, Journal of Quantitative Spectroscopy and Radiative Transfer, 91, 65-93.

Paine, S. (2004), The am Atmospheric Model, SMA Technical Memo #152-Revision 3, August.

Papatsoris, A.D., and Watson, P.A., (1993), Calculation of Absorption And Dispersion Spectra Of Atmospheric Gases At Millimetre-Wavelengths, IEE Proceddings-H, 140 (6), 461-468.

Ronne et al., (1997), Investigation Of The Temperature Dependence Of Dielectric Relaxation In Liquid Water by THz Reflection Spectroscopy And Molecular Dynamics Simulation, J. Chem. Phys. 107 (14), 5319-5331.

Meissner, T., and Wentz, F.J, (2004), The Complex Dielectric Constant of Pure and Sea Water From Microwave Satellite Observations, IEEE Trans. Geosci. Remote Sensing, 42 (9), 1836-1849.

Ellison, W.J. (2007), Permittivity Of Pure Liquid Water, At Standard Atmospheric Pressure, Over The Frequency Range 0-25 THz and The Temperature Range 0-100 °C. Journal Of Physical Chemical Reference Data, 36 (1), 1-17.

Otárola A. et al. (2006b), The Complex Permittivity of Pure Liquid Water From Microwave Frequencies Up To 1.5 THz, Master Thesis, Department of Atmospheric Sciences, University Of Arizona, Prof. E.R. Kursinski.

V. de Hultz, H.C. (1957), Light Scattering by Small Particles, New York: John Wiley and Sons Inc.

Mätzler , C. (2002), Effects Of Rain On Propagation, Absorption and Scattering of Microwave Radiation Based On The Dielectric Model of Liebe. Code available (together with tents of other codes for Mie calculations from: http://diogenes.iwt.uni-bremen.de/vt/laser/wriedt/Mie_Type_Codes/body_mie_type_codes.html)

Mishchenko, M.I., Davis, L., and Lacis, A.A. (2002), Scattering, Absorption, and Emission of Light by Small Particles, Cambridge University Press.

Rueger J. (2002), Refractive Index Formulae for Radio waves, *FIG XXII International Congress*, Washington, D.C. USA.

Peltier, L. J., and J. C. Wyngaard (1995), Structure- function parameters in the convective boundary layer from large eddy simulation, *Journal of the Atmospheric Sciences*, 52 (21), 3641–3660.

Otárola A. et al. (2008), The Effects of Turbulence In An Absorbing Atmosphere On The Propagation of Microwaves Signals Used In An Active Sounding System, Doctoral Dissertation, Atmospheric Sciences Department, University of Arizona, Sup. Dr. E.R. Kursinski.

Obukhov, A. M. (1949), On the influence of weak inhomogeneities in the atmosphere on the propagation of sound and light, *Izv. AN SSSR, Ser. Geogr. I Geofiz*, 2, 155-165.

Tatarski, V. I. (1961), Wave propagation in a turbulent medium, Translated by R. A. Silverman, New York, McGraw-Hill Book Company.

Frehlich, R., and G. R. Ochs (1990), Effects of saturation on the optical scintillometer, *Applied Optics*, 29(4), 548–553.

Rauber, R.M., and Tokay A., An Explanataion For The Existence Of Supercooled Liquid Water At The Top Of Cold Clouds, Journal Of The Atmospheric Sciences, 48 (8), 1005-1023.

Hogan et al., Estimate Of The Global Distribution Of Stratiform Supercooled Liquid Water Clouds Using The LITE Lidar, Geophysical Research Letters, 31, L05105.

Kolmogorov, A. N. (1941), The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers, *Dokl. Akad., Nauk SSSR*, 30(4).

Kolmogorov, A. N. (1962), A refinement of previous hypothesis concerning the local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers, *Journal of Fluid Mechanics*, 13, 82-85.

Wheelon, D. A. (2001), Electromagnetic Scintillation. Cambridge Editorial.

Wheelon, D. A. (2003), Electromagnetic Scintillation, II. Weak Scattering, Cambridge Editorial.

Chamberlin R.A., Martin, R.N., Martin, C.L., Starck A.A., Submillimeter atmospheric FTS at the geographic South Pole, 2003, Proc. SPIE, 4855, 609.

Eriksson, P., Microwave radiometric observations of the middle atmosphere: simulations and inversions. 1999, Technical report No. 355, Chalmers Univ. of Technology, Goteburg, Sweden.

Kulesa et al., Exceptional submillimeter-wave transparency and stability above Dome A, Antarctica, submitted to *Nature*, 2009.

Paine, S., Blundell, R., Papa, D.C., Barrett, J.W., & Radford, S.J.E., A Fourier Transform Spectrometer for Measurement of Atmospheric Transmission at Submillimeter Wavelengths, 2000, *Publications of the Astronomical Society of the Pacific*, 112, 108

Urban, J., P.Baron, N.Lautie, K.Dassas, N.Schneider et al., MOLIERE (v5): A versatile forward- and inversion model for the millimeter and sub-millimeter wavelength range, 2004, *JQSRT*, 83, 3-4, 529.

Zufferey, C.H., A study of rain effects on electromagnetic waves in the 1-600 GHz ranges, *Master's Thesis*, University of Colorado, 1972.

Company Commercialization Report
Summary Page

Firm Name:	**TeraVision Inc**	**Point of Contact:**	**Ms. Shari Olsen**
Mail Address:	**5516 E. South Wilshire Dr.**	**Phone Number:**	**(800) 670-8357 Ext. 102**
	Tucson, AZ 85711-4534	**Fax Number:**	**(866) 720-4835**
Phone:	**(800) 670-8357**	**E-Mail:**	**srolsen@teravision-inc.com**

Commercialization Achievement Index: N/A

This Index is a measure of how commercialization resulting from the proposer's prior phase II SBIR/STTR awards (from 2006 and before) compares with the commercialization resulting from groups of DoD SBIR/STTR projects selected at random from comparable time periods. (Commercialization includes both military and private sector markets.) The index score is a percentile ranking which ranges from 100 (highest) to 0 (lowest). Its statistical meaning is described in detail at http://www.DoDSBIR.net/Submission/CompanyCommercialization/Instructions/DefCAI.asp .

An Index score is only calculated for proposers that have received at least 4 phase II awards in years up to and including 2006.

(END OF SUMMARY)

Company Commercialization Report
Full Report and Company Certification

Commercialization Achievement Index:	**N/A**		
Phase I Awards:	**1**	Number of Employees in **2008**:	**8**
Phase II Awards:	**1**	Current Number of Employees:	**9**
Number of Patents resulting from SBIR/STTR:	**0**		
FIRM's total revenue:	**$500,000-**	Year Founded:	**2002**

Firm's total revenue: **$999,999** Year Founded: **2002**

SBIR/STTR Funding as % of revenue: **22%** IPO resulting from SBIR/STTR: **No**

PHASE II PROJECTS:

Agency: NSF Year of Award: 2008 Topic #: EL Contract #: IIP-0750559

Project Title: Coherent THz Sources and Amplifiers Using Carbon Nanotubes

Sales to:	(a)DoD/Primes: $0	(b)Other Federal Agencies: $0	(c)Export: $0
	(d)Private Sector: $0	(e)Others: $0	(f)3rd Party: $0
Additional Investment from:	(a)DoD: $0	(b)Other Federal Agencies: $0	(c)Private Sector: $0
	(d)Others: $0		

Used in Federal system or acquisition program?: No

Is the technology developed under this project related to manufacturing? No

Has the technololgy developed under this project achieved a cost saving or cost avoidance for the government or end user? NO

Commercialization Track Record Narrative:

TeraVision Inc was created in the wake of 9/11 to bring Terahertz expertise and enabling technologies developed at the University of Arizona and MIT Lincoln Laboratory to the Security and Defense markets. Soon thereafter, TeraVision Inc. licensed laser technology from MIT and entered into a Technology Transfer Agreement with the University of Arizona for THz technology.

TeraVision developed a commercial laser system based on the MIT patent and further U of A work. First commercial sale occurred in late 2007.

In February of 2008 TeraVision was awarded a phase II award from the National Science Foundation to develop 350 GHz Traveling Wave Tube (TWT) oscillators and amplifiers based on carbon nanotube cathodes. The project is on schedule and is drawing considerable interest from DoD contractors (Raytheon, SAIC etc.). Applications range from increasing the standoff range of THz based explosives and precursor materials detectors, increasing the frame rate of THz imagers and increasing the penetration depth when imaging inside objects. Other applications may include communication, and improved detectors that use the low noise THz TWT as a pre-amplifier.

Since the fall of 2006 TeraVision is working on the development and testing of a prototype THz contrast radar imager capable of detecting trace amounts of RDX and other explosives with similar THz signatures from standoff distances for JIEDDO. The effort proposed here will leverage knowledge, software and possibly equipment accumulated during this 2 year ~2 M$ program.

TeraVision has formed strategic partnerships with both Raytheon and SAIC to develop and commercialize both new THz sources and THz imaging systems. Raytheon in particular has provided access to technical personnel, test equipment, in kind help and internal R&D funding. Partnerships with Raytheon and SAIC will become especially crucial in Phase III.

Firm Information Last Updated on: 3/23/2009 1:35:54 AM

Continue