Lab Measurements to Support Modeling Terahertz Propagation in Brownout Conditions

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ABSTRACT

Brownout, the loss of visibility caused by dust and debris introduced into the atmosphere by the downwash of a helicopter, currently represents a serious challenge to U.S. military operations in Iraq and Afghanistan, where it has been cited as a factor in the majority of helicopter accidents. Brownout not only reduces visibility, but can create visual illusions for the pilot and difficult conditions for crew beneath the aircraft. Terahertz imaging may provide one solution to this problem. Terahertz frequency radiation readily propagates through the dirt aerosols present in brownout, and therefore can provide an imaging capability to improve effective visibility for pilots, helping prevent the associated accidents. To properly model the success of such systems, it is necessary to determine the optical properties of such obscurants in the terahertz regime. This research attempts to empirically determine, and measure in the laboratory, the full complex index of refraction optical properties of dirt aerosols representative of brownout conditions. These properties are incorporated into the AFIT/CDE Laser Environmental Effects Definition and Reference (LEEDR) software, allowing this program to more accurately assess the propagation of terahertz radiation under brownout conditions than was done in the past with estimated optical properties.

Keywords: atmospheric effects, brownout, optical properties, THz imaging, atmospheric transmission

1. INTRODUCTION

For the purpose of evaluating expected THz imaging system performance, the AFIT Center for Directed Energy (AFIT/CDE) has developed several modeling codes to simulate operating conditions. One of these codes, the Laser Environmental Effects Definition and Reference or LEEDR[1], allows the export of first principles atmospheric characterizations for other simulation codes, military or DoD mission planners, or even non-military scientific research such as climate change impact studies. This paper highlights laboratory measurements to support a newly implemented capability within LEEDR that allows the calculation of transmission through simulated rotary-wing brownout conditions at both desert and mid-latitude land sites throughout the world based on an internal climatological database.

2. BROWNOUT MODEL DESCRIPTION

The purpose of this project is to improve the ability of LEEDR to model the propagation of Terahertz radiation through brownout conditions. The existing model was implemented by S. Marek as part of his Masters work at AFIT[2]. He implemented a particle distribution, number concentrations, and other physical values for brownout situations determined from research done by Midwest Research Institute.

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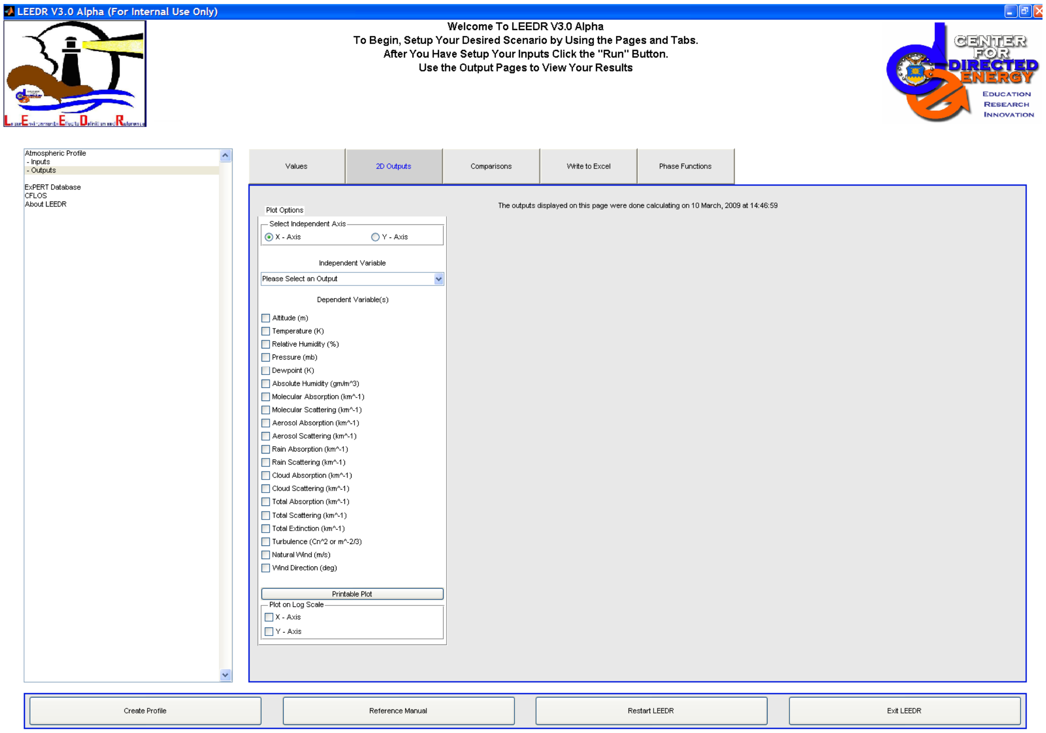
The model used in this research implements the above complex index of refraction values, the particle size distribution, and the desert and mid-latitude brownout aerosols into MATLAB and then creates profiles of altitude vs. absorption as well as transmission vs. wavelength. The model is run by LEEDR, where the climatological inputs are specified by the ExPERT database. The ExPERT database provides climatological profiles of temperature, humidity, and wind speed at different heights in the atmosphere. Looking at Figure 1, the tab panel at the top allows the user see the path result values such as path transmittance, path extinction, and specific attenuation. It also allows for 2D comparisons to print the profiles, write all of the data into a Microsoft Excel spreadsheet, or view the transmission across a range of wavelengths.



LEEDR V3.0 Alpha (For Internal Use Only)

Welcome To LEEDR V3.0 Alpha
To Begin, Setup Your Desired Scenario by Using the Pages and Tabs.
After You Have Setup Your Inputs Click the "Run" Button.
Use the Output Pages to View Your Results

The outputs displayed on this page were done calculating on 10 March, 2009 at 14:46:59

Select Independent Axis: ● X - Axis ○ Y - Axis

Independent Variable: Please Select an Output

Fig. 1: The GUI used in the LEEDR model. The user will be allowed to print and compare various scenarios.

Incorporation of these brownout models into the LEEDR model couples these algorithms with a worldwide THz optical properties characterization capability. Previously, this characterization had not been quantified with an actual distribution of brownout environment particles.

3. COMPARISON PLOTS & SIGNAL TO NOISE RATIO CALCULATIONS

Once the brownout distributions were implemented into the LEEDR model, it was initially assumed that as the visibility decreased from the brownout default of 114 meters that effects of the aerosols would become more attenuating to the THz radiation source than the water vapor molecular effects at a specific geographical location. Figure 2 compares the transmittance versus wavelength of the Baghdad desert ExPERT site across the range of wavelengths from 150 microns to 3 millimeters. The atmosphere depicted in the figure does not show molecular effects, but only shows aerosol effects, which means there is no molecular absorption or scattering taking place[2, 3].

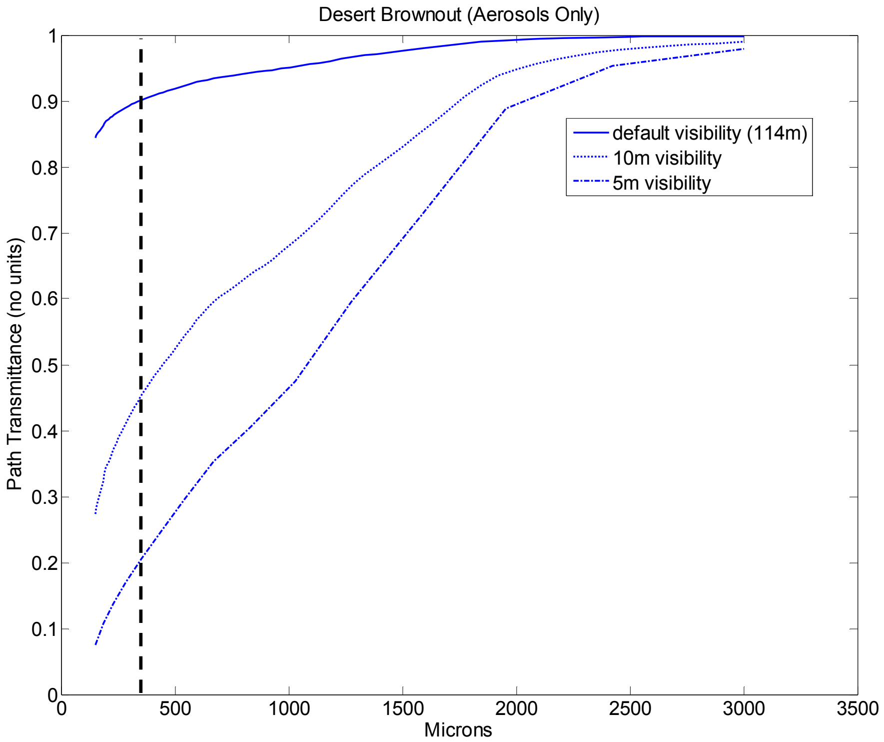


Fig. 2: Transmission vs. Wavelength (microns) profile for ExPERT Baghdad desert brownout conditions. The geometry consists of a platform located at 15 meters above the surface, with a 15 meter propagation path length. Only aerosol attenuating effects (absorption and scattering) are being represented, molecular attenuation effects are not represented. The wavelength of interest of 454 microns or 0.66 THz is depicted by the vertical dashed line.

In LEEDR as the visibility changes the distribution of particles, a power law fit changes by either shifting up or down depending on the visibility decreasing or increasing. This shift takes place because the limits of integration, 0.5 microns to 350 microns, do not change. As the line shifts up due to a decrease in visibility there becomes an increase in the number of particles of all sizes. As the number of particles increases, those particles that are especially close to 454 microns become problematic for the radiation source. It is those aerosol particles that will absorb and scatter more radiation as compared to the large amount of smaller particles, all of this will in turn decrease the transmittance. The decrease in transmittance due to the visibility decreasing can be seen in Figure 2 as well as Table 1 below.

Table 1: Transmittance values that correlate to Figure 2 based on the different visibility conditions.

Wavelength (µm)	Visibility (m)	Transmittance (no units)
454	114	0.91
454	10	0.50
454	5	0.24

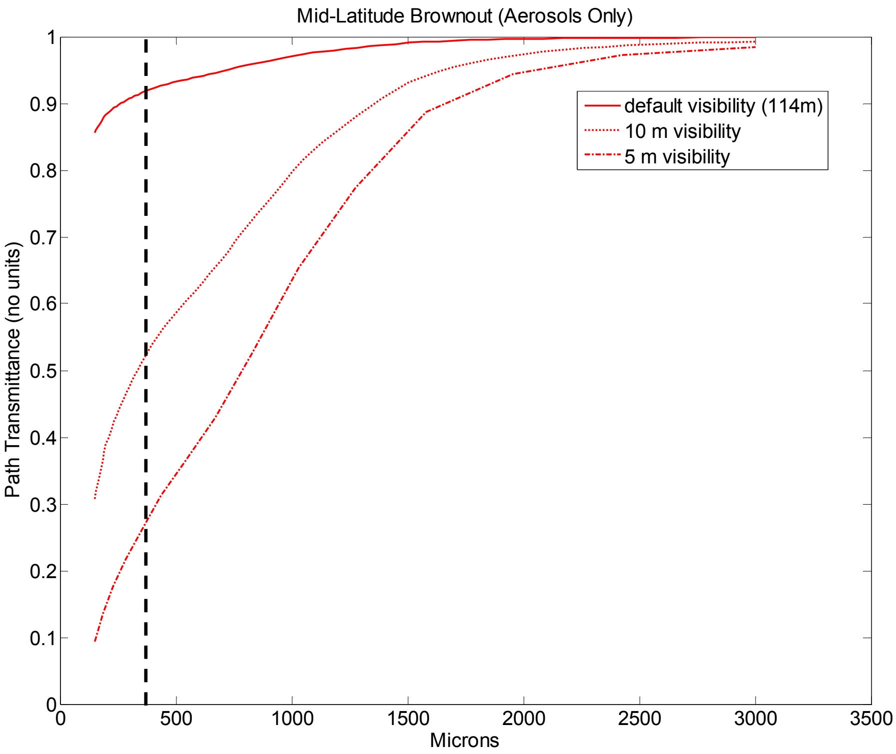


Fig. 3**:** Transmission vs. Wavelength (microns) profile for ExPERT WPAFB mid-latitude brownout conditions. The geometry consists of a platform located at 15 meters above the surface, with a 15 meter propagation path length. Only aerosol attenuating effects (absorption and scattering) are being represented, molecular attenuation effects are not represented. The wavelength of interest of 454 microns or 0.66 THz is depicted by the vertical dashed line.

Table 2: Transmittance values that correlate to Figure 3 based on the different visibility conditions.

Wavelength (μm)	**Visibility (m)**	**Transmittance (no units)**
454	114	0.92
454	10	0.57
454	5	0.31

Figure 3 and Table 2 carry the same information as Figure 2 and Table 1, the only difference is the geographical location and the type of aerosols being implemented into LEEDR.

While aerosols are an important factor to consider when looking at transmittance and extinction, the water vapor molecules in the air can prove to be a serious contributor to the total extinction of the radiation source. This is especially true in the THz region of the electromagnetic spectrum. The specific frequency of 0.66 THz was chosen because while it is characterized by high water vapor absorption, it is in a spectral region of relatively low attenuation compared to other THz frequencies around it. In this part of the spectrum the water vapor absorption is five orders of magnitude greater than any of the other atmospheric gaseous constituents. For the sake of this research the maximum path length investigated was 50 meters with most scenarios having a maximum path length of 15 meters. At 15 meters path length and 10 meter visibility, molecular and aerosol extinction are roughly equal for both desert and mid-latitude brownout conditions. The combined aerosol and molecular effects are illustrated in Figure 4, a comparison of propagation conditions at an ExPERT mid-latitude (WPAFB) and desert (Baghdad) site.

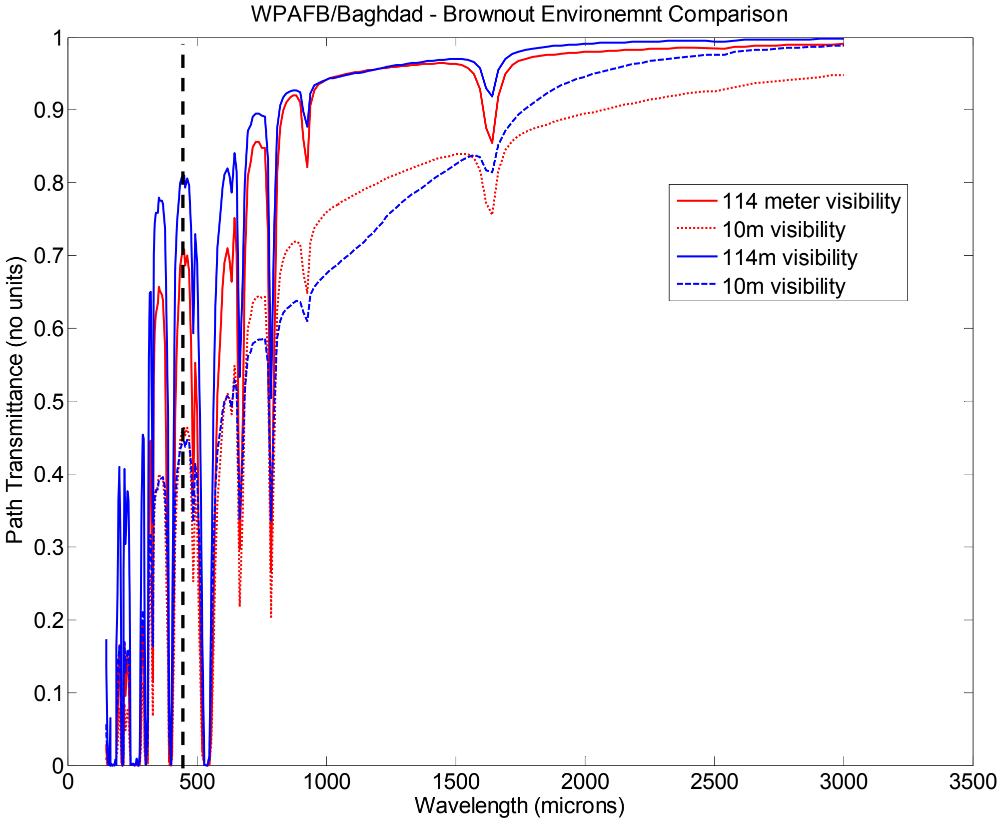


Fig. 4: Comparison of transmission vs. wavelength (microns) profile for ExPERT WPAFB mid-latitude brownout conditions (red) and ExPERT Baghdad desert brownout conditions (blue). The geometry consists of a platform located at 15 meters above the surface, with a 15 meter propagation path length. Aerosol and molecular attenuating effects (absorption and scattering) are being represented. The wavelength of interest of 454 microns or 0.66 THz is depicted by the vertical dashed line. To show the effects of water vapor the percentage of relative humidity at WPAFB is 49% and the Baghdad desert was 9.8%.

Table 3: Transmittance values that correlate to Figure 4 based on the different visibility conditions.

Baghdad (Blue line)		
Wavelength (µm)	**Visibility (m)**	**Transmittance (no units)**
454	114	0.80
454	10	0.43
WPAFB (Red line)		
Wavelength (µm)	**Visibility (m)**	**Transmittance (no units)**
454	114	0.68
454	10	0.45

Figure 4 is a comparison of the two brownout models that were incorporated into LEEDR. This figure depicts the effects that water vapor has on a THz source. In the case of the Baghdad environment there was a relative humidity of approximately 9.8% compared to the WPAFB site which had a value of 49% relative humidity. With the Baghdad aerosols the amount of water vapor in the air does nothing to the particles as they are composed of the minerals which do not uptake the water in the air; therefore, the size distribution of those particles changes little. The WPAFB aerosols are composed of a water-soluble mixture; these particles do uptake the water in the air and in so doing their sizes increase. The more water the particles uptake the more their optical properties begin to look like those of water, thus giving the aerosol mixture a complex index of refraction values very close to that of water. Table 4 is a summary of the results in Figure 4 at 660 GHz.

The impact of variations in atmospheric path transmittance on the signal to noise ratio (SNR) performance of a theoretical THz imaging device is assessed by using the standard radar equations. These equations estimate the amount of power required to achieve a desired SNR.

$$noise = k \cdot T_s \cdot F_n \tag{1}$$

Where k is Boltzmann's constant ($1.38\text{x}10^{-23}$ m^2 kg s^{-2} K^{-1}), T_s is the system noise temperature, assumed to be 288K, and F_n is the noise figure of the receiver, assumed to have a unitless value of 3. The standard Range equation is applied:

$$signal = \frac{P_{avg} \cdot G^2 \cdot RCS \cdot \lambda^2 \cdot t_{ot} \cdot T}{(4\pi)^3 \cdot R^4} \tag{2}$$

Where P_{avg} is the average power in Watts, G is the gain assumed to be 30dB, RCS is the radar cross section of the target, assumed to be 1 m^2, t_{ot} is the time on target, assumed to be 10 microseconds, R is the slant range in meters, and T is the roundtrip atmospheric path transmittance. The SNR is computed as the ratio of these two equations. With LEEDR the value of T is given thus one could easily use this information to back out the amount of power needed to achieve a desired SNR ratio. It is estimated that a SNR of 10 would be sufficient to provide an accurate image of the ground, thus allowing one to see through the brownout cloud and be provided an image of the ground[4].

3. LABORATORY MEAUREMENTS AND INCORPORATION INTO THE MODEL

The implemented optical properties for the brownout particles in LEEDR used published data at 40 micron wavelength and experimentally determined properties for silica presented in [5]. However, [5] provided data at only one frequency, so estimations were made, as detailed in [2]. In order to improve the model, this research seeks to determine the brownout optical properties (or Complex Index of Refraction) experimentally for many wavelengths of interest. The method proposed for doing this was to measure the extinction caused by a thin sample of filtered dirt. It was suggested to put dirt on a piece of tape, which is highly transparent in the THz, and so avoid multiple scattering, wherein radiation is scattered out of its direct path, and then scattered again by another particle back onto the detector, such that it never appears to have been scattered—which would give a falsely low value for the scattering. By knowing the physical properties of the dirt in the sample (i.e. how many grains the beam intersects, the sizes of those grains, and composition of that sand), these physical parameters can be put into LEEDR, which then uses Mie scattering calculations[6] with the existing optical properties as determined by [2] and [3] to calculate the scattering and absorption, and therefore extinction which that sample should cause. Assuming that these values differ, the optical properties are then varied until the calculated and empirical extinctions match. At that point where these values match, the model accurately predicts the extinction caused by brownout-like sand particles, and so the correct optical properties have been determined. A schematic of this method is shown in Figure 5. For this experiment to work, it is necessary to assume that the real portion of the complex index of refraction is correct as already determined, and then alter the imaginary component to adjust the absorption to necessary levels. However, the results of the experiment suggest that this is not the case, and that an additional piece of information will be necessary to fully and accurately determine the complex index of refraction.

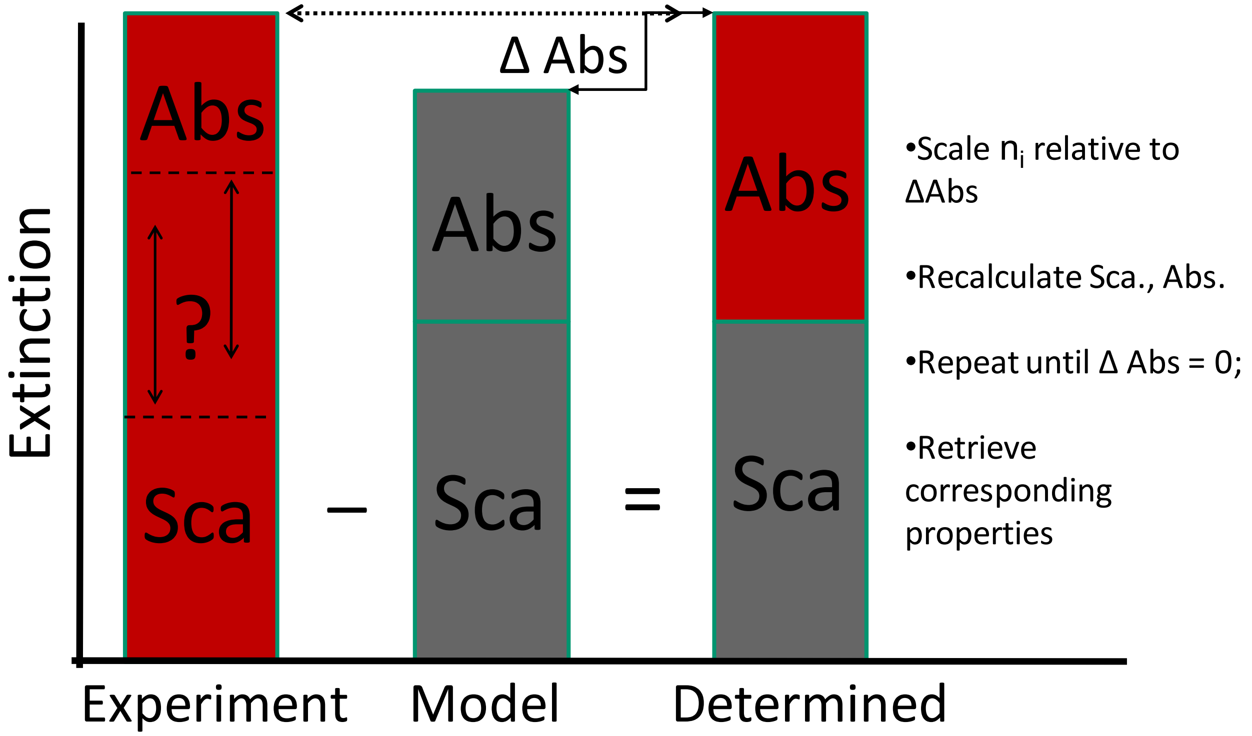
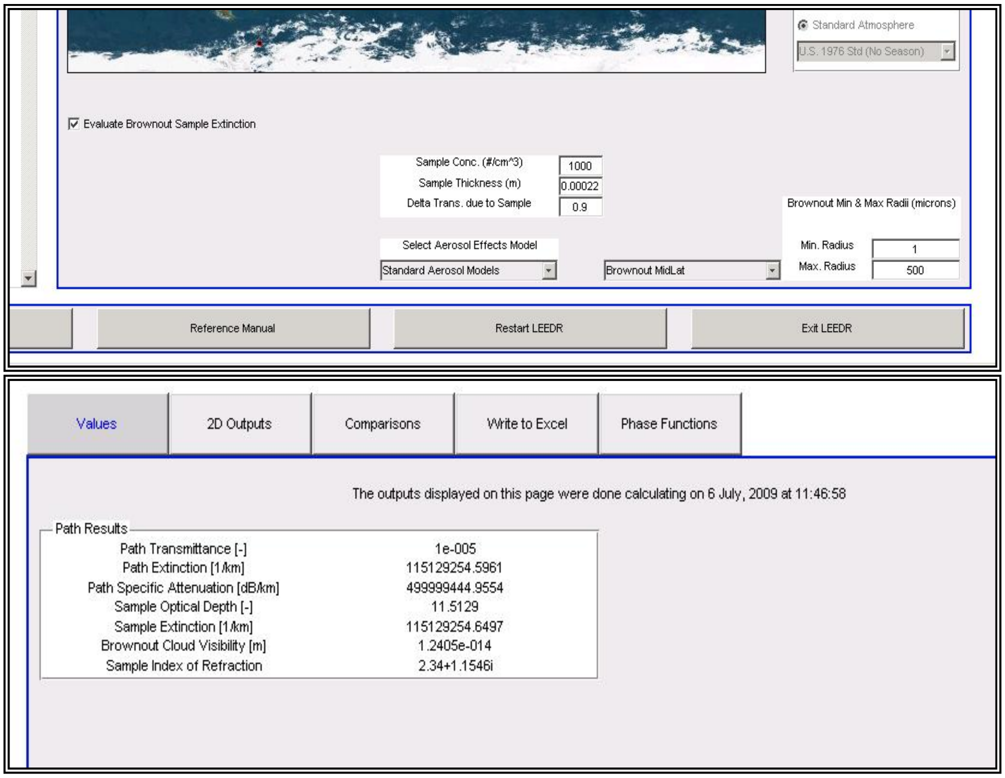


Fig. 5: Schematic of method used to determine optical properties from extinction and calculated scattering.

This research began as a summer internship for the second author. His research plan involved using the terahertz time domain spectroscopy (THz-TDS) system at AFIT. However, this system became mis-aligned and was unusable for the duration of his internship. He did collect some data with the Bruker-80v FTIR spectrometer at AFRL/RXLP with the assistance of Drs. Blackshire and Adam Cooney. Unfortunately this data was not very useful, as only a small portion in the range of ~15-30 micron wavelengths contained a strong enough signal to penetrate the sample. This data overlaps with existing properties in LEEDR, and provided no new information. Finally, samples were taken to the Institute for the Development and Commercialization of Advanced Sensor Technology (IDCAST) in nearby Dayton, where Drs. Doug Petkie and Jason Deibel from Wright State University (WSU) were operating another THz-TDS system. They allowed us to collect data, which included a rough approximation of the beam shape at the target, references through empty air, and a series of collections for holders (clean packing tape) and large samples (240-550 micron diameter) and small samples (177-240 micron diameter) of sand. These data were used for all data processing and results for the remainder of the internship.

Optical properties were determined two different ways using this data. The first method involved creating a special interface within LEEDR to evaluate the experimentally determined extinction against the calculated Mie scattering to determine the absorption component. Example input and output screens of this interface to LEEDR are shown in Figure 6. Specifically the inputs include: particle number concentration, particle size range, sample thickness, and empirical extinction; and the outputs include: complex index of refraction, cloud visibility, and extinction coefficients. In the second method, C. Stoik's MATLAB code[7] was implemented for our data sets. This uses a series of calculations outlined in his dissertation, and also found in [5]. This series of calculations requires a number of assumptions which make these values suspect outside of the 0.1 to 3 THz range. The suspicion placed on these values motivated the design of the broad-spectrum scattering/LEEDR method in the first place. However, the results with the second method provide more reasonable optical properties values in the 0.1 to 3 THz part of the spectrum.



● Standard Atmosphere: U.S. 1976 Std (No Season)

☑ Evaluate Brownout Sample Extinction

Sample Conc. (#/cm^3): 1000
Sample Thickness (m): 0.00022
Delta Trans. due to Sample: 0.9

Brownout Min & Max Radii (microns)
Min. Radius: 1
Max. Radius: 500

Select Aerosol Effects Model: Standard Aerosol Models; Brownout MidLat

Inputs

The outputs displayed on this page were done calculating on 6 July, 2009 at 11:46:58

Path Results

Path Transmittance [-]	1e-005
Path Extinction [1/km]	115129254.5961
Path Specific Attenuation [dB/km]	499999444.9554
Sample Optical Depth [-]	11.5129
Sample Extinction [1/km]	115129254.6497
Brownout Cloud Visibility [m]	1.2405e-014
Sample Index of Refraction	2.34+1.1546i

Outputs

Fig. 6: Screenshots of the LEEDR brownout optical properties inputs/outputs calculator GUI.

Briefly, the first method noted above, the Mie-scattering or LEEDR method, assumes the real index is known from previous research. This real index uses the real index of silica from reference [5]. The results using this method as applied to the data collected with WSU's THz-TDS system are plotted for both desert and midlatitude brownout cases in Figure 7. Clearly, the absorption components seem too low at most of the frequencies sampled. In general when the extinction was relatively high, high values of both the real and imaginary index were deduced. When the measured extinctions were relatively moderate or low, the deduced absorption was found to be near zero. It appears the assumption that the real index is very close to previously published values may be incorrect—thus making this method a univariate solution to a bivariate problem.

The second method, the Stoik method, calculates the complex index of refraction from phase angle differences between the phase of the signal through the sample and the reference phase. As noted above, this method provides reasonable results, as seen in Figure 8, but requires numerous assumptions and is "tuned" for 0.1 to 3 THz. Incorporating these more "reasonable" measured optical properties obtained using the Stoik method into the desert brownout characterization within LEEDR allows a comparison with the across spectrum transmission values obtained with the Marek extrapolated desert brownout optical properties. This comparison is illustrated in Figure 9 for 50 m visibility desert brownout conditions. Note the discernibly improved transmission when using the measured optical properties at frequencies greater than ~600 GHz.

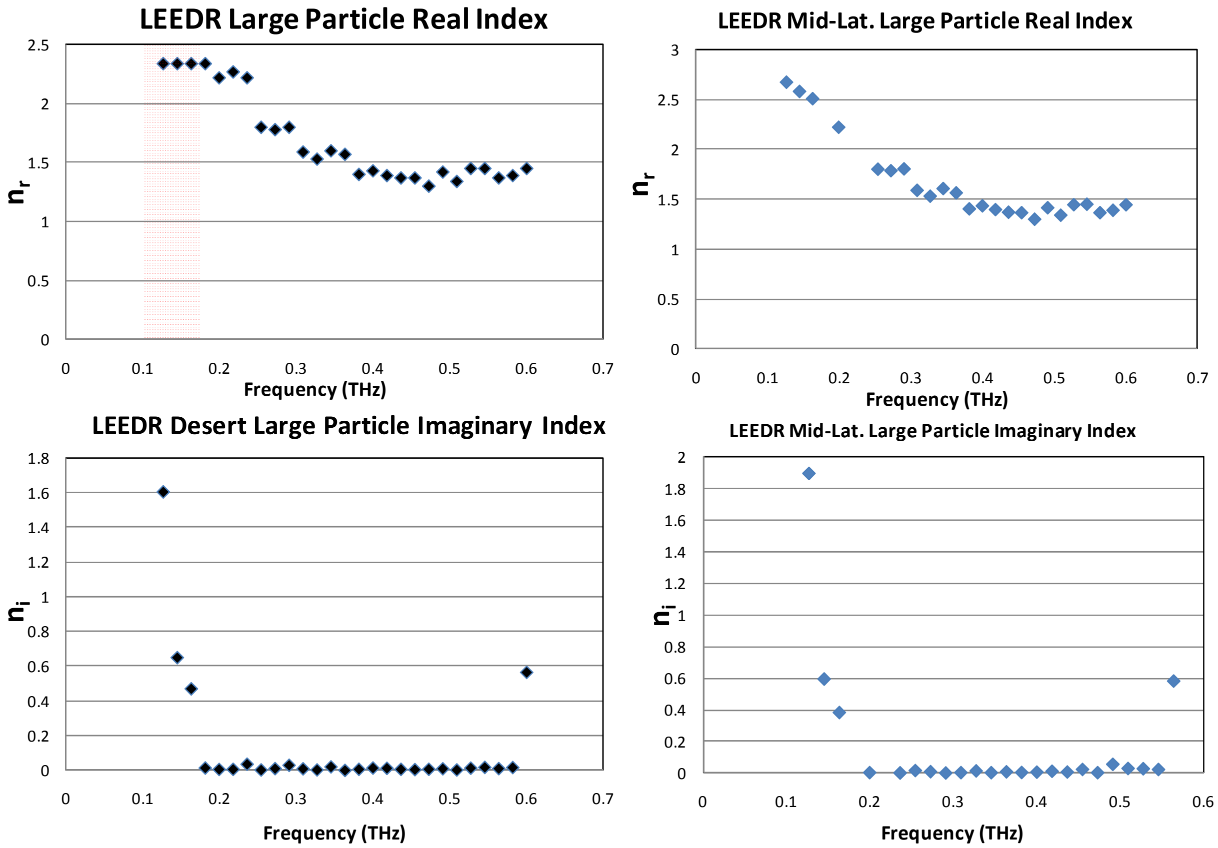
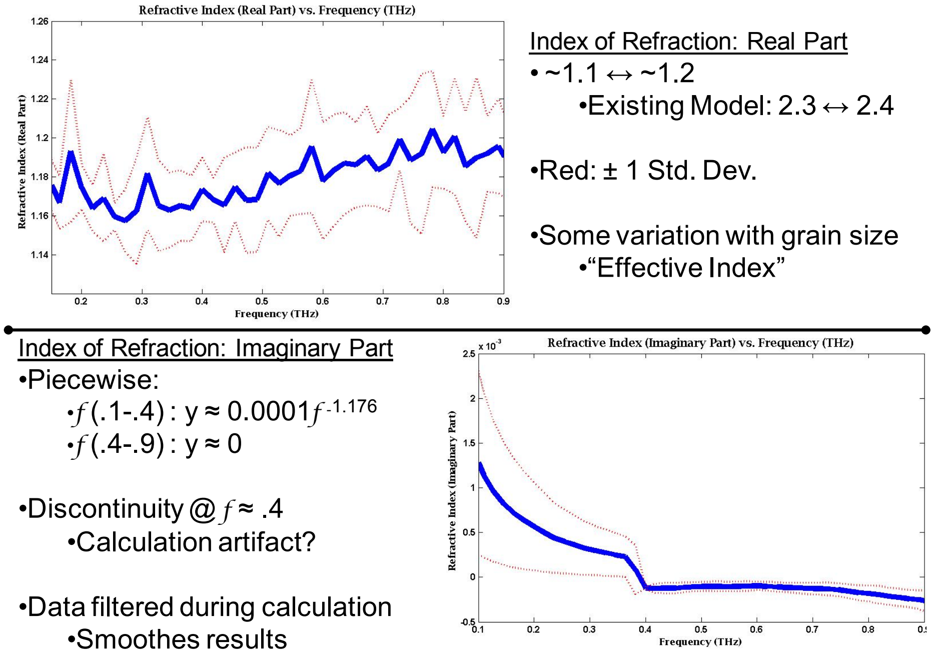


Fig. 7: LEEDR results with measured optical properties and calculated Mie scattering assumed as part of the extinction.



Index of Refraction: Real Part

- ~1.1 ↔ ~1.2
  - Existing Model: 2.3 ↔ 2.4
- Red: ± 1 Std. Dev.
- Some variation with grain size
  - "Effective Index"

Index of Refraction: Imaginary Part

- Piecewise:
  - f(.1-.4) : $y \approx 0.0001 f^{-1.176}$
  - f(.4-.9) : $y \approx 0$
- Discontinuity @ $f \approx .4$
  - Calculation artifact?
- Data filtered during calculation
  - Smoothes results

Fig. 8: LEEDR results with Stoik method optical properties and calculated Mie scattering assumed as part of the extinction.

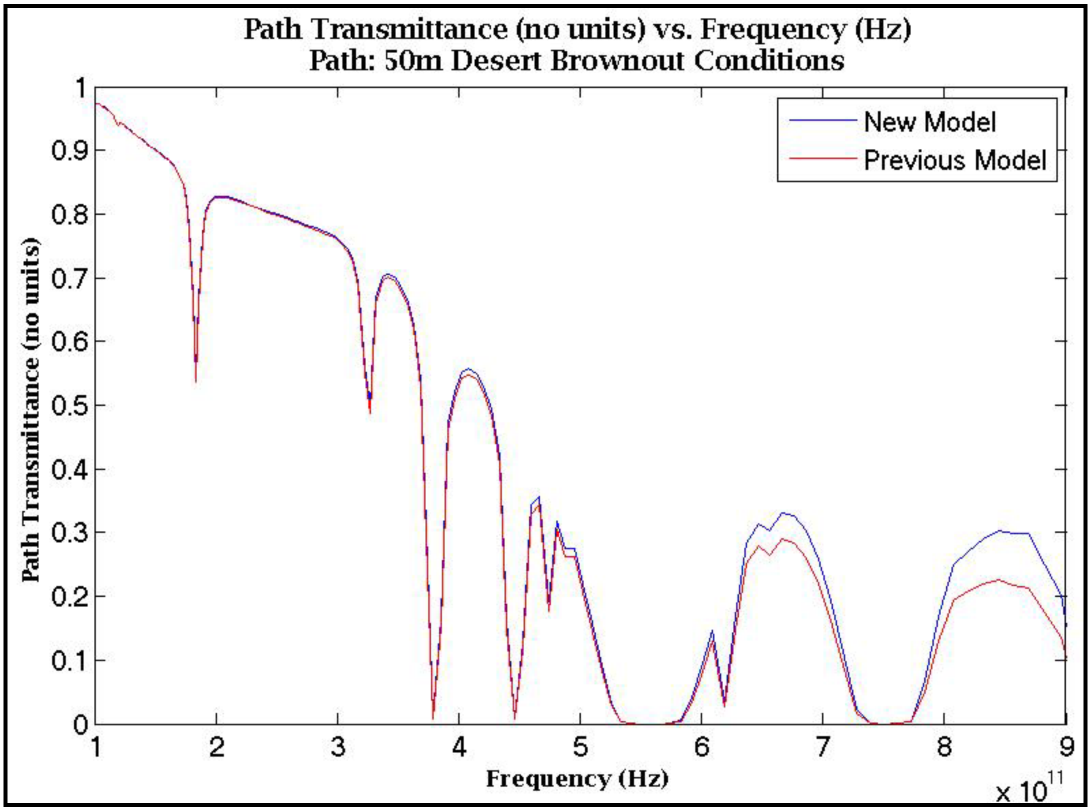


Fig. 9: LEEDR results with Stoik method optical properties and calculated Mie scattering assumed as part of the extinction.

5. SUMMARY

The AFIT CDE has developed a tool to evaluate THz imaging through brownout conditions. The molecular and aerosol absorption and scattering effects have been shown and evaluated in the brownout environment. While the aerosols prove to be the dominating effect at longer wavelengths the ability to transmit through a representative brownout environment can be done at the wavelengths researched. As expected it was shown at different land sites throughout the world, the transmission will be attenuated more or less depending on the specific location's atmospheric conditions. In areas where there is high water vapor content the molecular absorption is the key attenuating factor. In locations where there is a low water vapor content aerosol scattering becomes the key attenuating factor. To image through the brownout cloud in the THz regime, one would need a certain power level to achieve the proper SNR which was assumed herein as 10. This research proves to be of significance by providing approximate values for the optical properties of the THz regime based off of the particle sizes and distribution used, which to this point has not been addressed in current brownout literature. The development of two new aerosol models within LEEDR also adds significance to this research. Both the desert and mid-latitude brownout aerosol models were built based on an experimental study by MRI which was able to quantify the particle concentration that exists in rotary-wing brownout conditions.

To improve the brownout characterizations within LEEDR, laboratory measurements of extinction at THz wavelengths through mono-layers of desert sand were made. These measured values allowed the deduction of optical properties to include both scattering and absorption components. Two different methods were used, the scattering/LEEDR method, and the Stoik method. The basic conclusions obtained from analysis of the two methods are that the assumption that the imaginary (absorption) index can be derived from calculated scattering and measured extinction (scattering/LEEDR method) is not necessarily correct as there is not a unique solution. However, calculating the complex index of refraction from phase angle differences of sample signal and reference phase (Stoik method) provides better solutions. This solution suffers in that it is not a broad-spectrum solution—it is tuned specifically for the THz part of the spectrum.

6. ACKNOWLEDGEMENT

The views expressed in this paper are those of the authors and do not necessarily reflect the official policy or position of the Air Force, the Department of Defense or the U.S. Government.

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