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A Computational Tool for Evaluating THz Imaging Performance in Brownout Conditions at Land Sites throughout the World

Seth L. Marek

A COMPUTATIONAL TOOL FOR EVALUATING THz IMAGING PERFORMANCE IN BROWNOUT CONDITIONS AT LAND SITES THROUGHOUT THE WORLD

THESIS

Seth L. Marek, Captain, USAF

AFIT/GAP/ENP/09-M08

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Seth L. Marek, BS

Captain, USAF

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Captain, USAF

Approved:

Steven T. Fiorino (Chairman)	17 FEB 09 Date
Robb M. Randall (Member)	30 Jan 2009 Date
Paul A. Gehred (Member)	17 Feb 2009 Date
Matthew J. Bohn (Member)	6 Feb 2009 Date

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Abstract

This study quantifies terahertz (THz) or sub-millimeter imaging performance during simulated rotary-wing brownout or whiteout environments based on geographic location and recent/current atmospheric weather conditions. The atmospheric conditions are defined through the Air Force Institute of Technology Center for Directed Energy (AFIT/CDE) Laser Environmental Effects Definition and Reference or LEEDR model. This model enables the creation of vertical profiles of temperature, pressure, water vapor content, optical turbulence, and atmospheric particulates and hydrometeors as they relate to line-by-line layer extinction coefficient magnitude at wavelengths from the UV to the RF. Optical properties and realistic particle size distributions for the brownout and whiteout particulates have been developed for and incorporated into LEEDR for this study. The expected imaging performance is assessed primarily at a wavelength of 454 μm (0.66 THz) in brownout conditions at selected geographically diverse land sites throughout the world. Seasonal and boundary layer variations (summer and winter) and time of day variations for a range of relative humidity percentile conditions are considered to determine optimum employment techniques to exploit or defeat the environmental conditions. Each atmospheric particulate/hydrometeor is evaluated based on its wavelength-dependent forward and off-axis scattering characteristics and absorption effects on the imaging environment. In addition to realistic vertical profiles of molecular and aerosol absorption and scattering, correlated optical turbulence profiles in probabilistic (percentile) format are used. Most evaluated scenarios are brownout environments over ranges up to 50 meters. At sub-millimeter wavelengths and the short ranges studied, preliminary results indicate the main source of image degradation in brownout conditions is water vapor content, even with visibility less than 10 m and strong optical turbulence.

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Seth L. Marek

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I. Introduction

Background

The Department of Defense (DoD) has lost rotary-wing aircraft and personnel due to accidents that occur when re-circulating dust degrades visibility during low altitude hover, landing and take-off. This phenomenon is known as “brownout”. In aviation, a brownout is an in-flight visibility limitation due to dust or sand in the air. In a brownout, the pilots cannot see close proximity objects which offer visual cues necessary to control the aircraft near the ground. Pilots lose their visual cues as blinding, disorienting dust clouds are generated by rotor wash during flight near ground. It is precisely in this condition when the aircraft is most vulnerable to brownout. Significant flight safety risks include aircraft and ground obstacle collisions, and rollover due to sloped and uneven terrain. Similar problems can be encountered with dry snow and water operations (Davis, 2007). According to the US Army Safety Center, spatial disorientation accidents result in the loss of an average of 40 lives per year. The cost of spatial disorientation accidents also include, mission failure, impairment of mission effectiveness, monetary value of aircraft and equipment lost, and fatalities and disabilities.

The annual material cost of spatial disorientation accidents is estimated to be in the billions of dollars (Jennings, 2008). Air Force Special Operations Command (AFSOC) has said that brownout is their number one operational problem. AFSOC has attributed the loss of more than 30 rotary-wing aircraft and 60 service member lives to brownout. In total there have been over 230 cases of aircraft damage and/or injury due to unsuccessful take-offs or landings in a brownout situation. Using frequencies in the terahertz (THz) domain to image through the dust cloud during a brownout environment offers a feasible solution to combating future brownouts.

Rotary-wing brownout is a U.S. Million dollar per year problem for the military in Afghanistan and Iraq (Davis, 2007). It is imperative that our rotary-wing aircraft pilots have the ability to see through the dust cloud and are able to perform their landing and take-off procedures without having to worry about encountering a brownout that could possibly end in accident.

Motivation

In May 1980, the Joint Chiefs of Staff commissioned a Special Operations Review Group to conduct a broad examination of the planning, organization, coordination, direction, and control of the Iranian hostage rescue mission. The mission was titled Operation Eagle Claw, which was developed to rescue the 53 hostages from the U.S. Embassy in Tehran, Iran. The operation was designed as a complex two-night mission. The first stage of the mission involved establishing a small initial staging site inside Iran, the site, named Desert One was to be used as a temporary airstrip for the USAF special ops aircraft. One month prior to the assault on the U.S. Embassy, a USAF

Combat Controller reconnoitered the landing zone at Desert One and planted landing lights to help guide the 8 helicopters and 12 USAF aircraft to the correct spot. Pilots of the various aircraft had reported back that their sensors had picked up radar signals at 3,000 feet but nothing below that. Despite these findings helicopter pilots were instructed to fly below 200 feet to avoid radar. This restriction caused them to run into a dust storm which they could not fly over because of the earlier restriction of 200 feet. Through dust storms and high winds the helicopters made it to the landing zone an hour late. After one of the aircraft lost its primary hydraulic system and was unsafe to use, only five aircraft were serviceable and six were needed, so the mission was aborted. Having already aborted the mission, one of the helicopters moved to reposition and in so doing its rotors kicked up an immense amount of dust making it impossible for the pilot to see his surroundings. What he thought he saw was the landing lights that were laid down the month prior, but in reality it was the lights of an EC-130. The helicopter landed on top of the aircraft, rolled over and in so doing the rotors sliced through the fuel tank, and both aircraft burst into flames (Staff, 1980).

Problem Statement

Much of the defense industry has conducted research on mitigating the brownout problem; many of the solutions have involved one of two approaches

1. Laying something on the ground before a landing to hold back the dust cloud from forming, or
2. Developing different landing maneuvers allowing the helicopters to land faster, both resulting in a smaller and more manageable dust cloud.

Not until the emergence of millimeter and sub-millimeter frequency technology has the ability to image small (< 1m) objects through the cloud become a real possibility. This interest is, in part driven by the ability to form images during day or night; in clear weather or in low-visibility conditions such as haze, fog, clouds, smoke, or sandstorms or even through clothing (Yujiri, 2003). The ability to see in low-visibility conditions that would normally blind visible or infrared sensors can potentially improve or perhaps renovate the way these types of low-visibility conditions are approached. The advantage of sub-millimeter wave radiation is that it can be used in all poor visibility conditions and unlike the radiation signal sent out by the current sensors being used, the sub-millimeter range provides a level of covertness with a much smaller signal. The cloud produced by a rotary-wing aircraft with major downwash can send a cloud of dust and silt hundreds of feet into the air. The aircraft may have been heard but not seen, yet the brownout cloud can be seen for quite some distance. This thesis will focus on using frequencies in the THz domain of the electromagnetic spectrum to provide a solution to see through the dust clouds encountered during a brownout as well as providing an accurate picture/image of the surrounding area during landing and take-off.

Research Approach

Developing a tool for forecasting rotary-wing brownout potential based on geographic location and recent/current atmospheric weather conditions with today's technology is feasible. The bulk of this research will focus on providing a brownout forecast through modeling and simulation, using the Laser Environmental Effects Definition and Reference or LEEDR model. LEEDR enables the creation of profiles of temperature, pressure, water vapor content, optical turbulence, atmospheric particulates and hydrometers as they relate to line-by-line atmospheric layer transmission. While

LEEDR ranges spectrally from the ultraviolet to radio frequencies, this research focuses on the THz domain of the electromagnetic spectrum, specifically the 0.66 THz frequency (wavelength 454 μm). This frequency has been 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. This frequency will also be evaluated against several different atmospheric parameters such as dust cloud concentration, time of day, time of year, rain, and specific geographic location.

Document Structure

Chapter 2 is a literature review of the different types of THz imaging devices that have been or are currently being developed in the industry. It will also give a brief summary of some of the sub-millimeter wave applications relating to this research and the results they have obtained, as well as the background on LEEDR. Chapter 3 will detail the methodology by which this research is to be conducted. Chapter 4 contains all the results obtained through the modeling and simulation, and gives an analysis of the results. Chapter 5 summarizes the results, identifies trends and lists final conclusions about this research. The final chapter will also outline possible future research areas for enhancement of the solution.

II. Literature Review

Chapter Overview

This research sought to link imaging through the cloud generated during brownout conditions via modeling and simulation and relate that to the THz domain of the electromagnetic spectrum. Multiple scientific disciplines were included to make the research possible. This chapter is divided into five main sections. The first describes the LEEDR program, including why it was chosen, and what atmospheric parameters are taken into account to perform its calculations. The second part focuses on the characterization of dust, including methods used in forecasting dust storms, helicopter downwash data, and atmospheric sand and dust aerosols as well as particle size distributions. The third part summarizes information from prior and current research on millimeter and sub-millimeter wave applications as well as dust cloud transmission. Fourth, THz imaging will be investigated, including theory, imaging devices, and suitability for brownout applications. The fifth section briefly gives expert testimony from actual helicopter pilots detailing their desires/needs to help combat brownout.

Laser Environmental Effects Definition and Reference (LEEDR)

LEEDR is a fast-calculating, first principles atmospheric characterization package. It enables the creation of vertical profiles of temperature, pressure, water vapor content, optical turbulence, atmospheric particulates, and hydrometeors as they relate to line-by-line layer extinction coefficient magnitude at wavelengths from the ultraviolet to radio frequencies. The two primary purposes of LEEDR are:

1. To create correlated, physically realizable vertical profiles of meteorological data and environmental effects such as gaseous and particle extinction, optical turbulence, cloud free line of sight; and

2. To allow graphical access to and export of the probabilistic data from the Extreme and Percentile Environmental Reference Tables (ExPERT) database

(Fiorino, et al., 2008). LEEDR obtains its climate data from several climatological databases namely the ExPERT database, the Master Database for Optical Turbulence in support of the Airborne Laser, the Global Aerosol Data Set (GADS), and Air Force Weather Agency (AFWA) numerical weather forecasting data. The ExPERT database has 408 ground sites around the world, providing the following surface data (Figure 1):

- Altimeter (by month and time of day)
- Dewpoint (by month and time of day)
- Absolute, relative and specific humidity (by month and time of day)
- Temperature (by month and time of day)
- Wind speed (by month and time of day)
- Cloud coverage (by month)
- Weather occurrence (by month)
- Yearly min/max (from 1973-2004)
- Diurnal temperature change (by month)

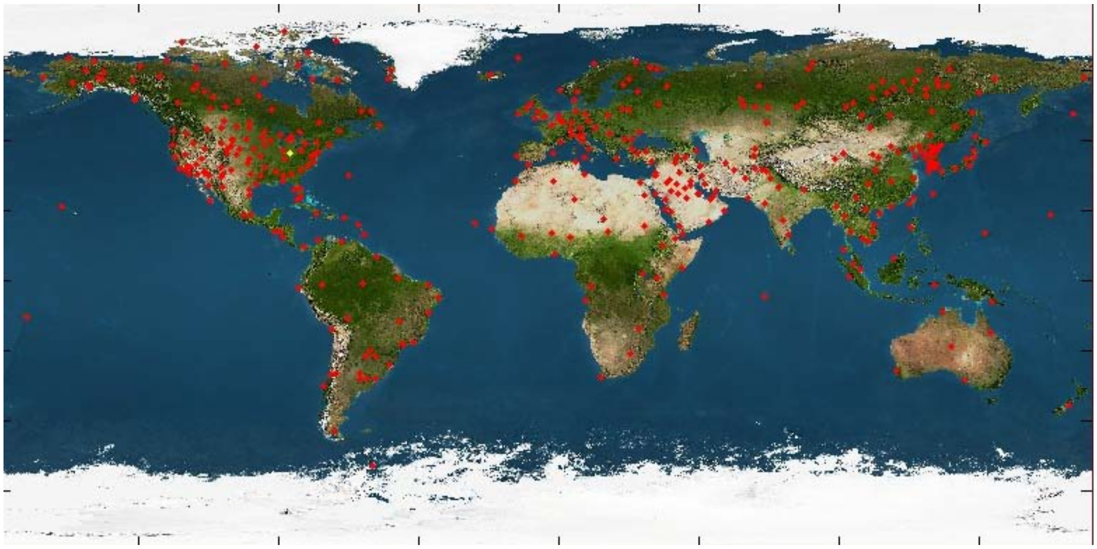

Figure 1. The 408 ExPERT sites represented in LEEDR

In addition to the ExPERT database there is an extensive array of 16 different aerosol profiles and one user defined profile, five liquid water cloud types, and several optical turbulence profiles to choose from. If an ExPERT site is chosen, the aerosol profile for that site is defined using the information from GADS. LEEDR will also support any user defined wavelength from 0.4 µm to 8.6 m, with 24 specific wavelengths associated with laser operation available through lookup tables for minimum runtime.

Dust Characterization

Dust and sand storms comprise one of the more troubling meteorological aspects of Southwest Asia. Worldwide, these storms can adversely affect millions of people, delay critical missions and effectively grind operations to a halt. Greatly reduced visibility in the horizontal, vertical and slant range is the primary hazard affecting operations within dust storms (Bartlett, 2004). Desert dust, generally regarded as small aerosol particles and sediment from desert surfaces, is an ubiquitous feature of the world's deserts (McDonald, et al., 2004). Dust is introduced into the atmosphere through the entrainment process which occurs whenever air from a non-turbulent region is drawn into an adjacent turbulent region; it is a one-way process that adds air mass to the turbulent mixed layer. The entrainment process can occur naturally through wind erosion of soils and sediments or mechanically through human activity such as vehicle movement. The most favorable surfaces for dust production are areas of scarce vegetation, precipitation limited, ample dust and sand sources as well as unstable mixed air providing essential vertical transport. Dust particle size depends on the distance from the dust source. Large particles (100 – 1000 µm) will settle to within a few kilometers of the dust source area. These particles travel mainly by saltation with transport primarily lasting minutes to a few days and occurring only when wind velocities exceed thresholds required for entrainment (McDonald, et al., 2004). Smaller particles (<100 µm) can remain suspended in the atmosphere for many days and can be transported tens to thousands of kilometers from source areas (Pye, 1987).

In March and April of 2006, Midwest Research Institute (MRI) was tasked to characterize the brownout challenge for a total of six airframes (UH-1, CH-46, HH-60, CH-53, V-22, MH-53), with each exhibiting a range of rotor characteristics and disk loadings. Disk loading is defined in this case as the helicopter weight divided by the area swept out by the rotors. Testing was conducted at Yuma Proving Ground (YPG), with the primary measurement parameters being dust cloud concentration and particle size distribution generated by the aircraft during hover and taxi operations (Midwest Research Institute, 2007). YPG has been used as a representative site to test brownout conditions because both YPG and Iraq soils have exhibited very similar particle size and shape characteristics (Figure 2).

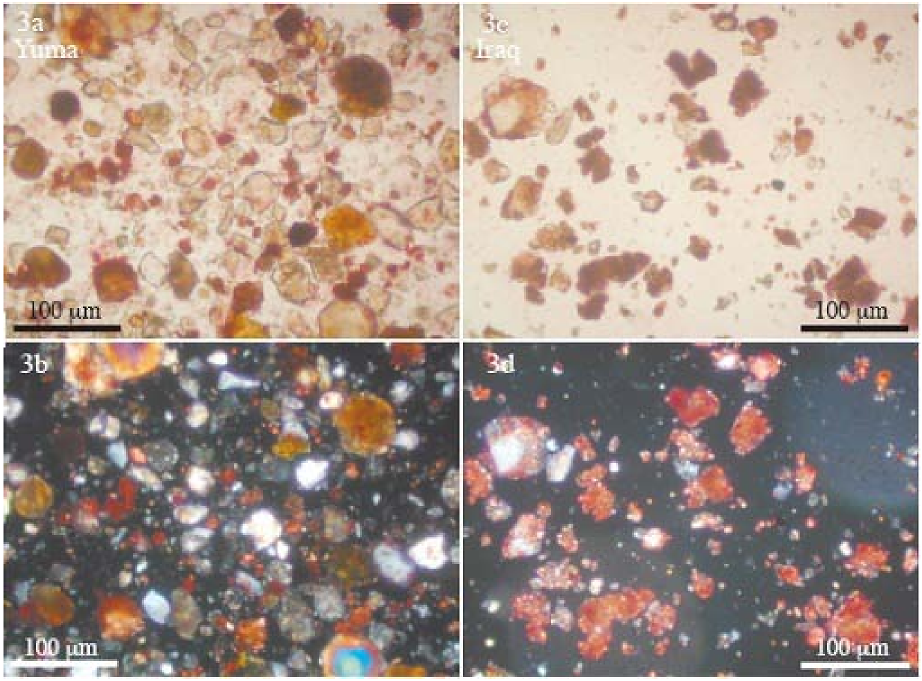

Figure 2. Photomicrographs YPG and Iraq soils. Pictures 3a and 3b are the Yuma soils and pictures 3c and 3d are Iraqi soil samples, courtesy of MRI

The results of the MRI testing showed that the higher dust cloud densities were associated with larger airframes and associated rotor disk loadings. Particle sizes ranged from particles as small as 1µm to particles as large as 800µm (Figure 3). The coarse particle end of the distribution is highly dependent on the size of the aircraft and disk loading which substantiates the fact that stronger downwash air currents are more effective in entraining large particles into the dust cloud. The CH-53, V-22, and MH-53 airframes showed the highest dust cloud intensities.

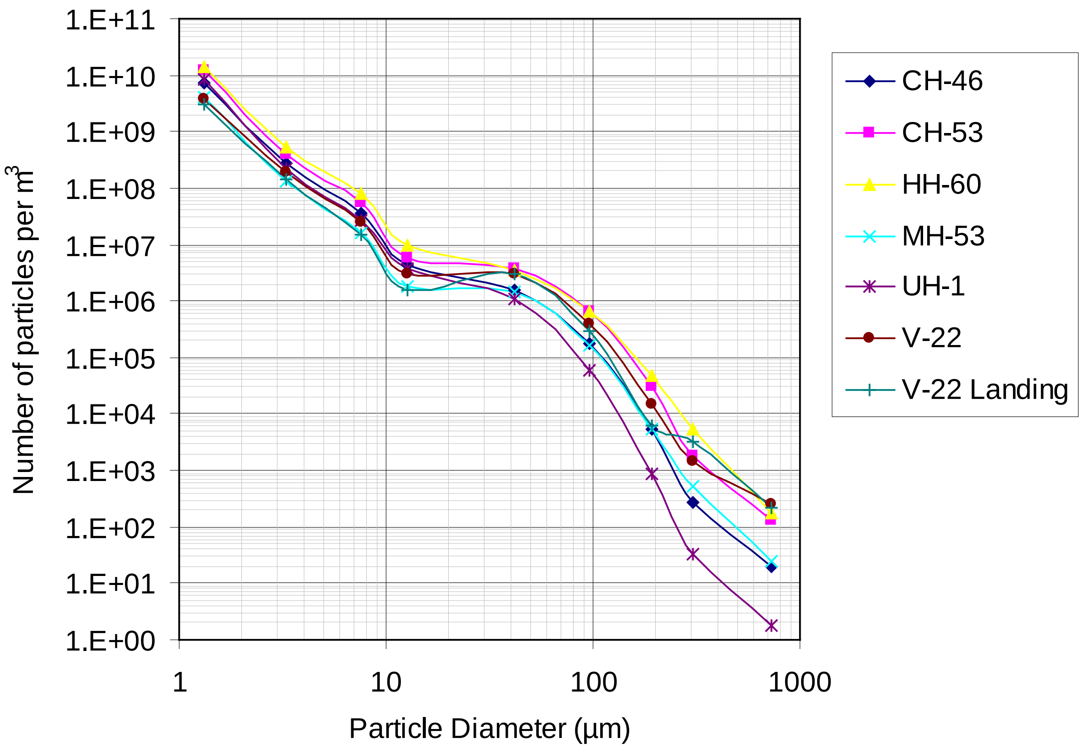

Figure 3. Particle size distribution during hover and taxi operations of 6 airframes during testing at YPG (Midwest Research Institute, 2007).

Dust Storm Forecasting

Dust storms throughout Saharan Africa, the Middle East and Asia are estimated to place more than 200-5000 million metric tons of mineral dust into the earth's atmosphere each year (Barnum, 2003). Dust storms directly effect visibility and impact daily commercial and military operations near desert regions. Dust mobilization normally begins when the surface wind velocity exceeds a threshold wind speed.

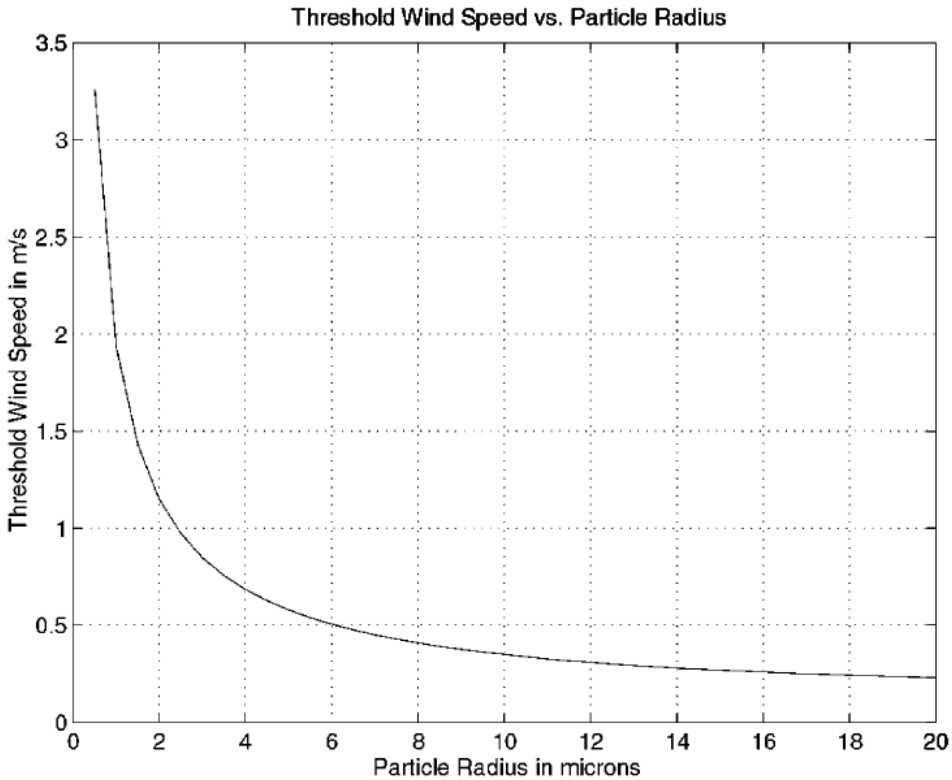

Figure 4. Dust threshold surface wind velocity calculated in CARMA (Barnum, 2003)

At the threshold speed, larger particles which are not embedded in the soil, are blown along the surface in saltation where they collide and set free smaller particles from the soil. Several years ago, the Air Force Weather Agency (AFWA) in a joint project with John Hopkins University's Applied Physics Lab, released a dust specific, synoptic scale model. Together they applied the University of Colorado, Boulder Division's Community Aerosol Research Model from Ames/NASA (CARMA) and combined it with the AFWA Mesoscale Model 5th generation (MM5) model output and called it the Dust Transport Application (DTA) model. CARMA was originally developed to be a scalable aerosol model to study atmospheric processes such as cloud formation, smoke and dust aerosols.

In the model, dust aerosols are lofted into the air by vertical advection and diffusion. The model then calculates the potential temperatures profile, heat flux, Monin-Obukhov length (height at which the Richardson number equals one), and friction velocity. The forecasting model uses a global dust source database which was developed using topography and dust source regions that are identified using satellite data from the Total Ozone Mapping Spectrometer (TOMS). The TOMS measures the amount of ultraviolet absorption by dust aerosols by taking the ratio of 331nm and 360nm measured radiance to the calculated radiance based on a model Rayleigh scattering atmosphere (McPeter, 2008).

The forecast capability of the model was conducted by AFWA over a 66 day evaluation period. They evaluated the Saharan Africa, Southwest Asia, and the Middle East. The goal of the study was to determine how well the model could forecast dust storms and conditions of reduced visibility caused by the dust. The study was unique because it used satellite and ground based observations of dust storms to verify the presence or absence of dust storms and to score the model's effectiveness using standard meteorological statistics. The results of the study showed that the dust model has good skill in forecasting dust conditions over short (12 hr) and medium (36 hr) forecasting periods. In the Saharan Africa the average probability of detection was 67 percent with an average false alarm rate of 15 percent. Southwest Asia forecasts had average probability of detection values of 61 percent with false alarm rates averaging 10 percent. Long range forecasts of 54-60 hours indicated decreasing forecast accuracy of the weather model, while analysis of surface visibility observations showed that a forecasted dust concentration of 2500 μg m^{-3} or greater was sufficient enough to reduce visibilities to less than 2 miles (Barnum, 2003).

Dust Cloud Generated By Helicopter Rotor Downwash

In 1968 the U.S. Army Aviation Materiel Laboratories located at Fort Eustis, Virginia conducted a study which focused on the dust cloud generated by tandem-rotor helicopters (very similar to the MRI test). The study was done as a function of soil type, hover height, and disc loading. Ninety-eight tests were conducted at three different locations and samples were collected at twenty-five locations on the helicopter. The soil locations used in the study were Phillips Drop Zone, YPG; Vehicle Dust Course, YPG; and Lee Drop Zone, Ft. Benning, Georgia. The objectives of the program were to determine dust concentration and dust particle size, once these characteristics were known the next step was to equate those values to pilot visibility. Tests were made at three hover heights of 1, 10 and 75 feet. The 1 and 10 foot altitudes represented an in-ground effect condition, and the 75 foot height represented the height at which the dust cloud begins, because of the risk involved the number of tests made at the 75 foot altitude were much less than the 1 and 10 foot heights (Rodgers, 1968).

The area of smallest dust concentration was found to be beneath the rotor hubs, while the highest dust concentration was near the area of rotor blade overlap, concentration was also high at distances corresponding to about 1/3 to 2/3 the rotor radius. Higher dust cloud concentrations were found at the lower heights (1 to 10 foot), while the highest concentration at the 75 foot height was attributed to the smaller particle size that had been lofted. The difference between this test and the MRI test mentioned in section 2.3 is that there was an attempt to correlate the dust cloud concentration with visibility. At the 1 and 10 foot hover heights, the horizon was completely obscured, but at the 75 foot height the horizon was visible. For some of the tests markers were placed along the flight/hover path, the markers were of high contrast as compared with the background of dust and terrain. They were placed at 50, 75, 100, 125, and 150 feet. The 150 foot marker was occasionally visible, but objects of low contrast could not be seen beyond 10-20 feet. This test along with MRI's work provides valuable information about the dust cloud concentration and particle size distributions encountered during brownout. With these results it makes it possible to test the THz capabilities against actual dust cloud concentration values.

Atmospheric Transmission and Extinction

As a laser or an electromagnetic beam propagates through the atmosphere the overall transmittance through the cloud free atmosphere is controlled primarily by absorption due to various constituent gases (Petty, 2006). Where absorption is strong, the transmittance is small; where the absorption is weak or missing, the transmittance is close to 100 percent (in the absence of scattering).

Table 1. Key atmospheric constituents (Petty, 2006)

Constituent	**Fraction by volume in dry air**	**Significant Absorption bands**	**Remarks**
N_2	78.1%	-	
O_2	20.9%	UV-C, MW near 60 and 118 GHz, weak bands in VIS and IR	
H_2O	0-2%	numerous strong bands throughout IR; also in MW, especially near 183 GHz	highly variable in time and space
Ar and other inert gases	0.936%	-	monoatomic
CO_2	370 ppm	near 2.8, 4.3, and 15µm	concentration as of 2001; increasing 1.6 ppm per year
CH_4	1.7 ppm	near 3.3 and 7.8 µm	increasing due to human activities
N_2O	0.35 ppm	4.5, 7.8, and 17 µm	
CO	0.07 ppm	4.7 µm (weak)	
O_3	$\sim10^{-8}$	UV-B, 9.6 µm	highly variable concentration; high in stratosphere and in polluted air
$CFCl_3CF_2Cl_2$	$\sim10^{-10}$	-	industrial origin

While transmission is directly affected by the key atmospheric constituents in Table 1, the laser beam can also be attenuated through extinction which includes scattering effects. Energy received at a specific point can also be affected by turbulence effects. To characterize the total extinction along a particular propagation path the contributions of scattering and absorption must be considered, as the extinction coefficient (β_e) is the sum of absorption and scattering coefficients in the following manner:

$$\beta_e = \beta_a + \beta_s \quad (1)$$

where β_a is the absorption coefficient and β_s is the scattering coefficient each with units of inverse length. The total atmospheric extinction is linearly proportional to the intensity of radiation and to the concentration of gases causing the extinction along the propagation path. When the atmosphere absorbs energy it results in an irreversible transform of radiation into another form of energy (i.e., heat, chemical, etc…). If the laser beam is not absorbed then the energy lost from beam is being scattered out of its original direction of propagation into other directions. There are two types of atmospheric scattering processes namely Rayleigh and Mie scattering. Rayleigh scattering consists of scattering from atmospheric gases. This happens when the particles that cause the scattering are much smaller in size than the wavelengths of radiation that interacts with the particles. Rayleigh scattering is inversely proportional to the fourth power of wavelength (λ^{-4}), which means that the shorter wavelength of blue light will scatter more than the longer wavelengths of green and red light. This is the reason the sky appears blue. Mie scattering is caused by dust, smoke, water drops, and other particles in the atmosphere. It occurs when the particles are equal to the wavelengths of radiation. Mie scattering is responsible for the white appearance of clouds.

While extinction is extremely important, it is best understood when combined with the concept of transmission. Although transmission was loosely defined above it is better defined by explaining the values that it carries. Transmission is a dimensionless quantity that ranges from 0 to 1, where a value of 0 means complete extinction of the radiation and a value of 1 mean no extinction or perfect transmission.

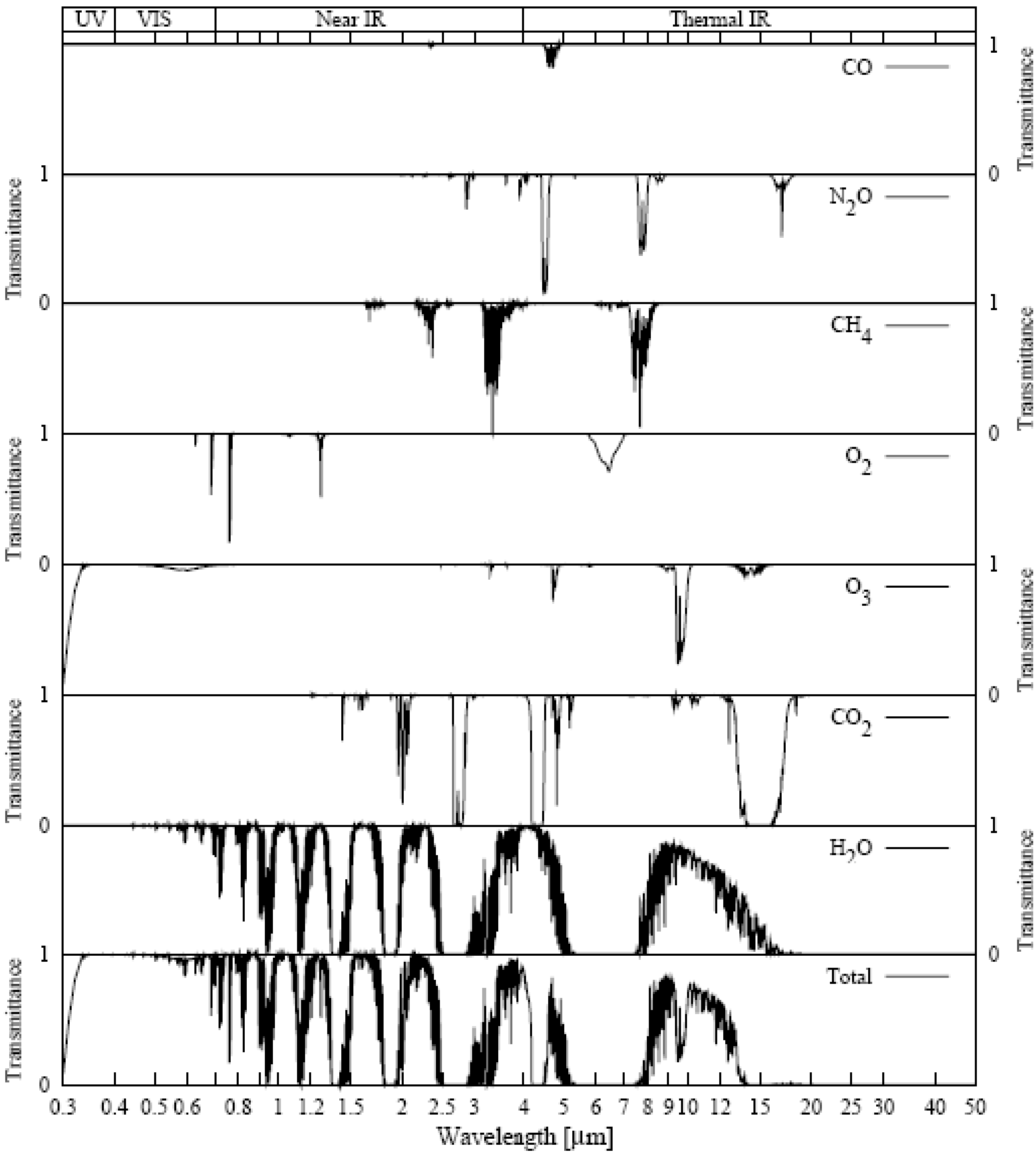

Figure 5. Zenith transmittance of the cloud & aerosol free atmosphere (Petty, 2006)

The relationship between transmittance and extinction is represented by the following equation:

$$t = e^{-\beta_e s} \qquad (2)$$

Where t is the transmittance, β_e is the total extinction and s is the distance or path length over which the radiation is propagating.

The second important factor in transmission is optical turbulence or scintillation. Scintillations are atmospheric optical path disturbances due to fluctuations in the index of refraction of air. In the 1950's, theoretical studies came about attempting to explain the scintillation phenomenon, however, it wasn't until the invention of the laser in the 1960's that experimental studies were conducted which validated the proposed propagation models (Cohen, 2008). These turbulent flows are generated mechanically, thermally, and inertially. In order to characterize a turbulent environment researchers developed a calculated value to better understand the turbulence between two points known as the index of refraction structure constant C_n^2. As one might imagine, the air surrounding a brownout is very turbulent because of the high speeds of the helicopter rotors. As stated earlier, optical turbulence is a key ingredient to the overall transmission, but in the case of brownout, the optical turbulence doesn't play as large a role due to the fact that we are only looking at transmitting distances of the length of the rotors which is about 15m. In such short distances and with the THz wavelength the optical turbulence is not as significant as one might initially think.

Dust Cloud Transmission

When propagating a radiation source through a typical atmosphere the atmospheric constituents can pose big problems to the propagation path. In a brownout there are constituents, and an immense amount of dust that can degrade visibility and possibly cause more attenuation to the radiation. Signal energy is lost from the path through these types of dust clouds primarily by absorption created when the dust particles introduced to a volume of air change the electromagnetic properties of that volume (Wikner, 2006). When the particle size becomes comparable to the particular wavelength that the radiation source is operating at, scattering as mentioned above, also contributes to transmission loss.

Several studies have been performed to better understand the radiation source propagation through a brownout environment. The first study was conducted by the Army Research Laboratory, to quantify the millimeter-wave (MMW) signal propagation loss created by airborne soil particulates typically encountered during brownout. The transmission loss was measured at three frequencies respectively 35, 94, and 217 GHz, with the density and particle size distribution of the dust cloud created to approximate an actual cloud formed by a military helicopter. The dust clouds measured in this test included particle sizes from 10μm up to approximately 0.8mm (Wikner, 2006). It was found that transmission loss at the 94, and 217 GHz frequencies was very low over a 1m path length, it was stated by Wikner that the loss was so low, "that measuring the exact loss using a simple propagation technique became very challenging". The test ultimately provided an upper bound on the mass extinction coefficient of approximately 8×10^{-4} m^2

g^{-1} for the 94 and 217 GHz frequencies, while the 35 GHz loss was too small to measure, thus implying that it was lower than the loss at 94 GHz.

The second test was conducted by the Air Force Research Laboratory via Cold Regions Research and Engineering Laboratory. The request for this test came from AFSOC and the Defense Advanced Research Projects Agency Sandblaster Program. The program has taken two approaches to solve the problem:

1. “See and Remember” approach which uses LADAR to scan the landing zone prior to brownout cloud formation and provide a synthetic image of the landing zone once aircraft has become engulfed in the cloud to safely guide the pilot to the ground.

2. “See Through” approach which is to identify all potential see through technologies and test them in controlled conditions to determine their extinction in dust.

As part of approach #2 AFRL chose four technologies to evaluate:

1. Passive MMW
2. Active MMW
3. Ladar, and
4. Infrared

As one can see from these four options the THz domain of the electromagnetic spectrum was not one of the choices considered by AFRL, which is why this research is so valuable in quantifying the transmission of THz or sub-millimeter frequency/wavelength. Among the several taskings, the Army Corps of Engineers Engineer Research and development Center Cold Regions Research and Engineering Laboratory (ERDC-CRREL) was to evaluate the infrared extinction in dust clouds specifically the 3.0µm to 5.0µm and 7.5µm to 13.0µm (Ryerson, et al., 2007). The test was conducted in a dust tunnel where the dust concentration and particle size distribution was known, which was representative of actual concentrations and size based on research from Rodgers (1968).

The particle size distributions ranged from <75μm to >420μm in diameter, while the maximum particle size measured was approximately 840μm. Details of the test plan are presented by (Cowherd, 2006). The conclusions to the report included that in general, lower mass concentration have lower mass extinction coefficients for all wavebands, it was also noted that for the same mass concentration there was no significant difference in the mass extinction coefficients between Iraq dust and YPG dust.

Millimeter-Wave and Terahertz Technology

In recent years submillimeter-wavelength and terahertz imaging technologies have been maturing rapidly. This technology has showed promise in meeting aviation security requirements through airport screening, however, security gaps still exist. These gaps in security were brought to the forefront with the attacks of September 11, 2001. “Terrorists and others with similar intent can be expected to continue to examine transportation security operations, both overtly and covertly, to find weaknesses that can be exploited” (O'Bryon, 2007). Currently airport security equipment includes x-ray systems for carry-on bags and walk through metal detectors for the passengers. As a result of the 9/11 Commission Report it was recommended that each passenger selected for screening should also be screened for explosives. With THz technology the ability exists to penetrate clothing and other nonmetallic coverings. This use of THz is aimed to find objects such as knives, guns, and explosives by detecting their shapes through concealment as shown in Figure 6 the individual is concealing a knife inside the newspaper.

Figure 6. THz imaging of concealed weapon (Network, 2006)

Imaging through THz relies on contrast between objects of high and low emissivity of radiation. Imaging can be either passive or active. “Passive systems are not designed to generate or emit radiation, but use natural background radiation for the illumination of the detection space. Active-illumination systems generate and emit radiation that is used to illuminate the detection space (O'Bryon, 2007)”.

The atmosphere attenuates THz radiation through absorption by water vapor, oxygen, and other atmospheric molecules. Figure 7 shows the atmospheric attenuation under various conditions from 10GHz to 10,000GHz. The clear condition represents the U.S. Standard Atmosphere, which is typical for mid-latitude states in the spring, the humid represents what is expected (i.e., temperatures, humidity, pressures, etc…) in the same region for the August timeframe. The dust data was based on a dust model (Goldhirsh, 2001) that was validated at 10 GHz and represents the attenuation for a storm with visibility 10m.

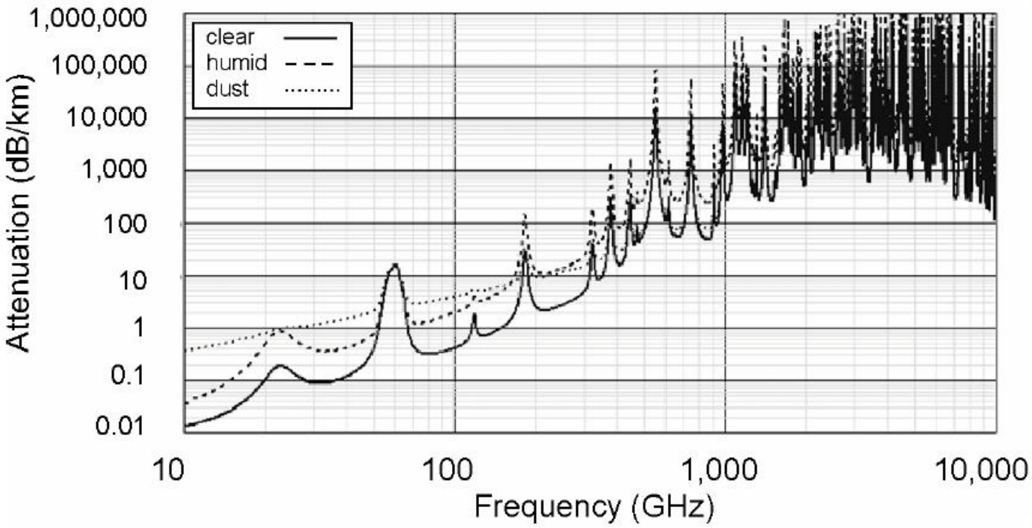

Figure 7. Atmospheric attenuation (O'Bryon, 2007)

Figure 7 shows, that in the submillimeter range, the atmospheric windows are approximately 340, 410, 660, 850 GHZ and above 1 THz. Given that 660 GHz (0.66 THz) is considered an atmospheric window and has been characterized by its low water vapor absorption lines solidifies why this frequency was chosen for this research, along with the fact that in a brownout the path length parameter does not have to be many kilometers but rather only tens of meters, thus providing a level of covertness that one cannot achieve with today's modern radar systems.

Expert Testimony

In a phone interview with U.S. Army Warrant Officer and Apache helicopter pilot Shannon T. Wooten, it was stated that all pilots must attend brownout training. In training pilots are taught to keep the dust cloud behind them which means developing techniques to enable the helicopter to land faster and at certain angles. Currently in the cockpit the pilots have a helmet display, that when encountering brownout it sees through the cloud and identifies thermal signatures of objects that are below them (i.e., tanks, people, etc…), but doesn't give an accurate image of what the terrain might look like. In terms of visibility it was stated that in order to request an approach to any airfield or heliport at Ft. Rucker, the minimum visibility required is ½ mile. It was also stated that "anything less than an ½ mile is truly an experience to fly through". When in a brownout, it would be ideal to at least see beyond the rotor (~ 15m) to ensure no rotor strike takes place. Warrant Officer Wooten stated that as a helicopter pilot, he sees the #1 problem for helicopters to be the Iraqi infrastructure (i.e., wires), with brownout coming in a close second. He has actually experienced more whiteouts, which is the same thing as brownout except snow is present instead of dust, and stated that the techniques are different in that the snow dissipates faster and it is better to descend slower, at rates of 200 – 300 ft/min.

III. Methodology

Overview

This chapter discusses the methodology used to conduct this research. It focuses on the development of a representative dust distribution that is encountered during brownout conditions. It also discusses the development of two new brownout distributions for desert and mid-latitude locations and the soil composition of those locations. Lastly the optical properties will be discussed for the THz region based off a study done on the optical properties of silica.

Brownout Distribution

In order to model and simulate brownout conditions it is critical to understand what types and sizes of particles exist in such an environment. With the results of previous tests performed by Midwest Research Institute and Figure 3, a representative distribution was available to implement into LEEDR. Figure 3 was fitted with a power law to simulate similar techniques used in determining a distribution of rain drop sizes and the rain rates associated with the raindrops, namely the Marshall-Palmer distribution. From an empirical study of the distribution of raindrop sizes scientists Marshall and Palmer concluded that the raindrop distributions could be adequately represented as power law functions.

$$N(D) = N_0 e^{-\Lambda D} \tag{3}$$

Where N(D) is the number of drops per unit volume with diameters between D and D+dD, and $\Lambda(R) = 4.1R^{-0.21}$, N_0 is fixed at 8000 m^{-3} mm^{-1}, and R is the rain rate in mm hr^{-1}. Although the properties that make up rain and dirt are very different, it is the sizes and distribution of both raindrops and dust particles that allow the MRI distribution to be fitted with a power law as in Figure 8.

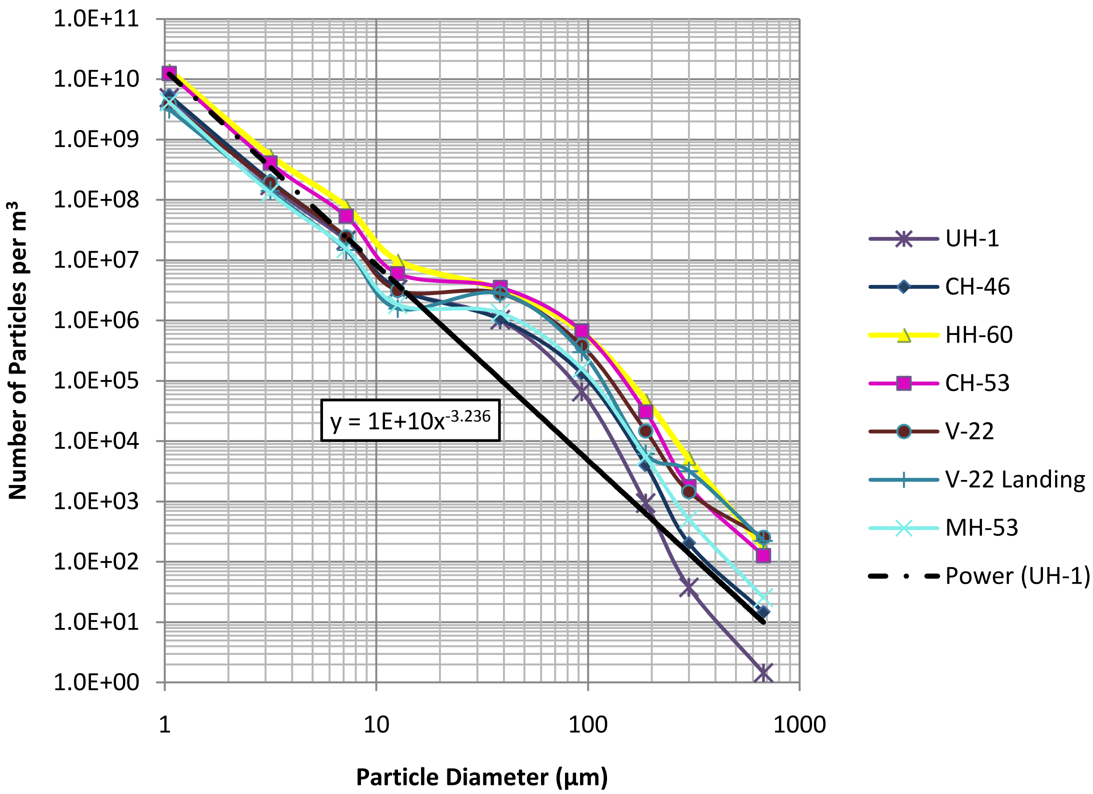

Figure 8. Brownout particle size distribution with a power law fit (dashed line). The equation of the power law was incorporated into LEEDR and is used for the distribution of the brownout aerosol models

Aerosol Model Development

LEEDR allows the user to select from three different aerosol effect models respectively; GADS worldwide aerosol model, a simple profile, and a standard aerosol model which has embedded within it eighteen different aerosols models to choose from. Table 2 is the list of the eighteen aerosol distribution models.

Table 2. 18 Standard aerosol models in LEEDR

OPAC	MODTRAN	Windspeed Driven	Brownout
Continental Average	Rural	Navy Aerosol Model	Desert
Urban Aerosols	Urban	Advanced Navy Aerosol Model	Mid-Latitude
Continental Clean	Maritime		
Desert			
Maritime Polluted			
Maritime Tropical			
Arctic			
Antarctic			
Clear (no aerosols)			

Of the eighteen aerosol models 10 of the profiles are defined through the Optical Properties of Aerosols and Clouds (OPAC) code, 3 MODTRAN aerosol models, and the windspeed-driven aerosol mixtures from the Navy Aerosol Model and Advanced Navy Aerosol Model. The OPAC profiles have within them an aerosol component where each component is meant to be representative for a certain origin. Each OPAC profile has a size distribution, and lognormal distributions are applied for each profile. The aerosol components consist of the following (Hess, et al., 1998):

- Insoluble – consists mostly of soil particles with a certain amount of organic material

- Water-Soluble – consists of various kinds of sulfates, nitrates, and other, and also organic water-soluble substances
- Sea-salt – consists of the various kinds of salt contained in seawater
- Minerals – consists of a mixture of quartz and clay materials
- Soot – used to represent absorbing black carbon

Because LEEDR didn't originally contain a representative brownout distribution both the desert and mid-latitude brownout aerosol models were developed for this research. The difference between the brownout profiles and the OPAC profiles comes from the particle size distributions; the brownout was fitted with the power law that was discussed earlier rather than a lognormal distribution which is typically the case as in OPAC. The difference in distributions is what distinguishes between a user choosing a desert aerosol and a desert brownout aerosol. The particle sizes and distributions of those particles will vary thus giving two different results.

Mid-Latitude Brownout

The aerosol component that was chosen for worldwide mid-latitude sites was water-soluble, although not all mid-latitude sites have water-soluble aerosols that dominate the scattering and absorption effects, it is was chosen for the expectation that the optical properties of the dirt will behave more like the optical properties of water in the presence of increased water vapor. Thus as the relative humidity increases, water vapor condenses out of the atmosphere onto the particulates that have been suspended in the atmosphere. The condensed water will increase the size of the aerosols and changes their composition and their refractive index also called water uptake (Shettle, et al., 1979). The change in the particle size is related to the relative humidity by Shettle and Fenn as:

$$r(a_w) = r_0 \left[1 + \rho \cdot \frac{m_w(a_w)}{m_0} \right]^{1/3} \tag{4}$$

Where

r_o is the dry particle radius,

ρ is the particle density relative to that of water,

$m_w(a_w)$ is the mass of condensed water,

m_o is the dry particle mass, and

a_w is the relative humidity corrected for curvature of the particle surface.

When aerosol size distributions are considered as they are in this research Equation 4 becomes more complicated. Equation 4 considers only one particle, therefore when many particles are considered equation 4 changes to:

$$\log r(a_w) = \pm \left[-\ln(ND\sqrt{2\pi}\log\sigma) \cdot 2(\log\sigma)^2 \right]^{1/2} + \log r_M \tag{5}$$

LEEDR considers aerosols dry if the relative humidity < 50%. For more information on how LEEDR handles atmospheric particulate characteristics see (Fiorino, et al., 2007).

Desert Brownout

The aerosol component chosen for worldwide desert sites was a mineral which consists of quartz and clay minerals. This aerosol was selected because minerals are found in arid desert regions. In the desert sites the mineral aerosol particles are assumed not to enlarge with increasing relative humidity, which allows for a comparison between the mid-latitude aerosols which in theory get larger with increased humidity, although the model used in this research does not capture a size change, but rather a change in the complex index of refraction.

Optical Properties

A significant amount of aerosols are of anthropogenic origin and they can have a significant impact on the radiative balance of scattering and absorption of electromagnetic radiation. Research by scientists such as Shettle and Fenn and Hess et al (OPAC) have documented optical properties for a specific set of aerosol types. Each type of aerosols has different optical properties associated with it. "Optical Properties" mean a material's response to exposure to electromagnetic radiation. Currently optical properties have been established out to 40µm for the aerosols in OPAC, which means, associated with each aerosol type and wavelength there is a complex index of refraction (N) denoted by:

$$N = n_r + n_i \tag{6}$$

Where n_r is the real part and determines the phase speed, scattering, and turbulence characteristics. The imaginary part n_i, is a measure of the absorptive properties of the medium and is sometimes called the absorptive index. As noted earlier many of the optical properties do not extend beyond the 40µm limit, which initially posed a large problem as the bulk of this research focuses on determining the absorption coefficient of the aerosols in wavelengths longer than 40µm specifically 454 µm (0.660THz) and 1360µm (0.220THz). To get somewhat of an accurate shape of the absorption vs. frequency curve for the frequencies of interest, a study of the terahertz time-domain spectroscopy was recently employed to investigate transmission properties of several types of glasses (Naftaly, et al., 2007). Of the materials investigated, Silica, which is the closest material to the dust particles encountered in a brownout, was formed into optical flats between 1mm and 2mm thick and the absorption coefficients and refractive indices of the sample was measured with results shown in Figure 9.

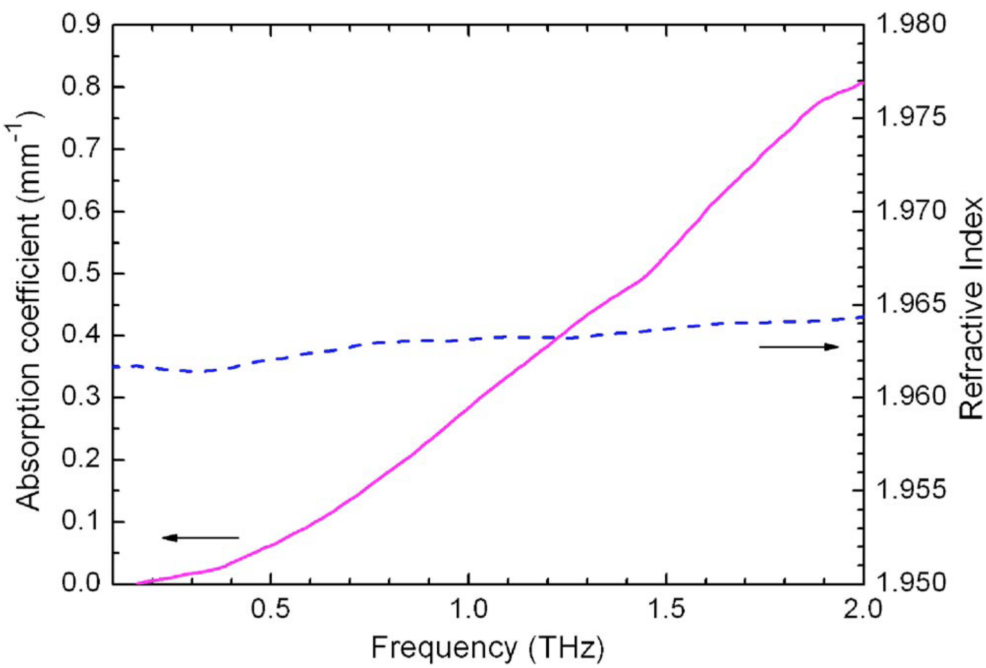

Figure 9. THz absorption coefficient and refractive index of Silica (Naftaly, et al., 2007)

The information in Figure 9 provided a baseline for the absorption coefficients in the THz region for silica. This data was used to back out an assumed absorption coefficient for both the desert and mid-latitude brownout environments through a comparison of ratios. At 2 THz the absorption coefficient for silica was 7.8 cm^{-1} and at 1.5 THz the absorption coefficient was 5.0 cm^{-1}. The widely used absorption coefficients at 40µm (7.50 THz) were extended to 2 THz for both the desert and mid-latitude, thus providing an initial value of the absorption index at that 2 THz for each environment. In order to calculate the absorption coefficient needed at 1.5 THz, 1.0 THz, and 0.5 THz one would begin with the initial value that LEEDR calculated at 2 THz for the desert environment, which in the example below was 6.5 cm^{-1} and by taking the ratio of the silica lines at 2 THz and 1.5 THz then multiply that by the initial 6.5 to obtain 4.16 cm^{-1} this process was performed on all frequencies related to (Naftaly, et al., 2007) to obtain a similar ratio and line shape it was found for desert brownout in the following way which was discussed above.

$$\left(\frac{5.0}{7.8}\right)\times 6.5 = 4.16$$

This means at 1.5 THz in the desert brownout, an absorption coefficient of 4.16 cm^{-1} was needed. Figure 10 is the results of the above calculations from 2 THz to 0.5 THz, the area beyond 0.5 THz was interpolated, but provides little information as the absorption coefficients rapidly approaches zero, which means that at frequencies less than 0.5 THz there is little to no absorption taking place.

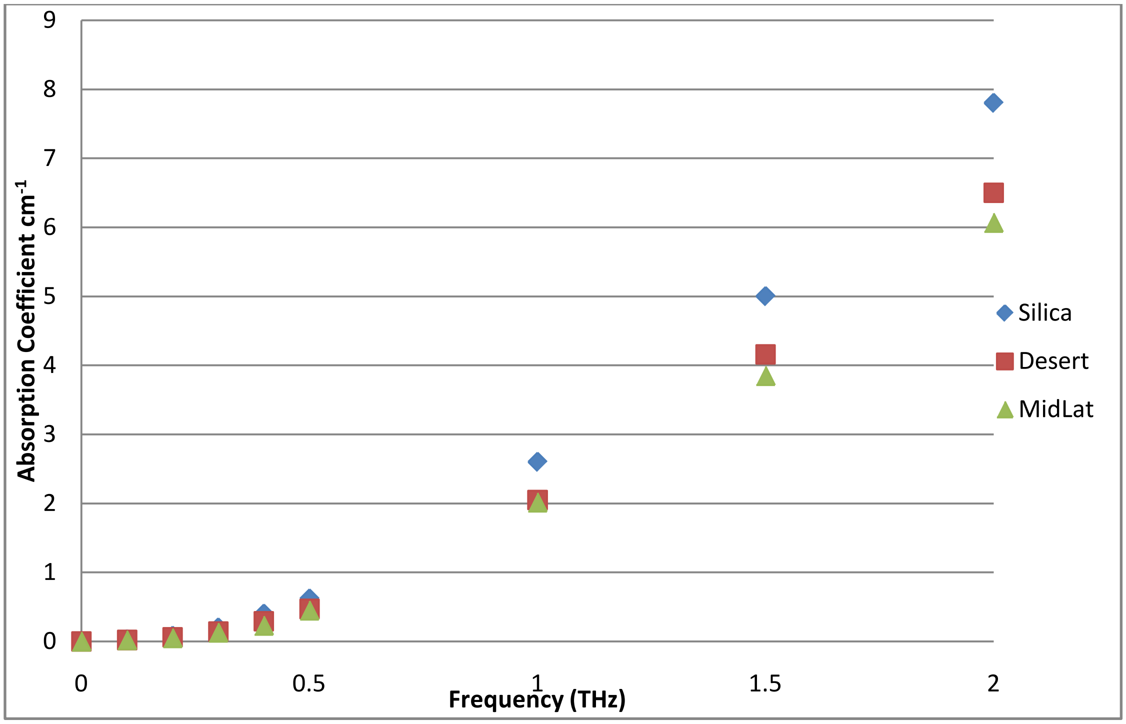

Figure 10. THz absorption coefficient for silica, desert brownout mineral aerosols, and mid-latitude brownout water-soluble aerosols

Once the absorption coefficient values were obtained seen in Figure 10 it was then a matter of changing the absorptive index within the LEEDR code until those coefficients (i.e., 4.16) were obtained. Table 3 lists the complex index of refraction data that is coded into LEEDR and the correct imaginary values that correspond to the values from Figure 10 with regard to the desert and mid-latitude brownout. The real part of the index of refraction was kept constant as to obtain as much real information as possible.

Table 3. Complex Index of Refraction from 40 μm to 3 millimeters. The real part was kept constant while the imaginary part was changed to capture the same ratio and line shape of Silica.

Wavelength (μm)	Brownout Desert		Brownout Mid-Latitude	
	real	imaginary	real	imaginary
40	2.34	-0.7	1.86	-0.5
150	2.34	-0.7	1.86	-0.5
200	2.34	-0.2	1.86	-0.19
300	2.34	-0.08	1.86	-0.08
600	2.34	-0.02	1.86	-0.027
750	2.34	-0.016	1.86	-0.018
1000	2.34	-0.012	1.86	-0.016
1500	2.34	-0.011	1.86	-0.013
3 mm	2.34	-0.002	1.86	-0.002

IV. Analysis and Results

Overview

This chapter provides the analysis and results of the LEEDR output resulting from the previous chapter's methodology, specifically the transmission versus wavelength in brownout conditions over various visibilities. It shows the LEEDR output of each aerosol model that was created for this research with an atmosphere that consist of only aerosols, followed by a plot of the same scenario with the exception that the atmosphere consists of molecular and aerosol effects. Following the plots is a table which makes a comparison of the transmission values for the different scenarios. It also discusses the signal to noise ratio needed to provide accurate THz images of possible landing sites.

Desert Aerosol Model Brownout Results

Figure 11 compares the transmittance versus wavelength of the Baghdad Desert ExPERT site from 150μm to 3000μm. The atmosphere depicted in the figure is not showing molecular effects, but only showing aerosol effects, which means there is no molecular absorption or scattering taking place.

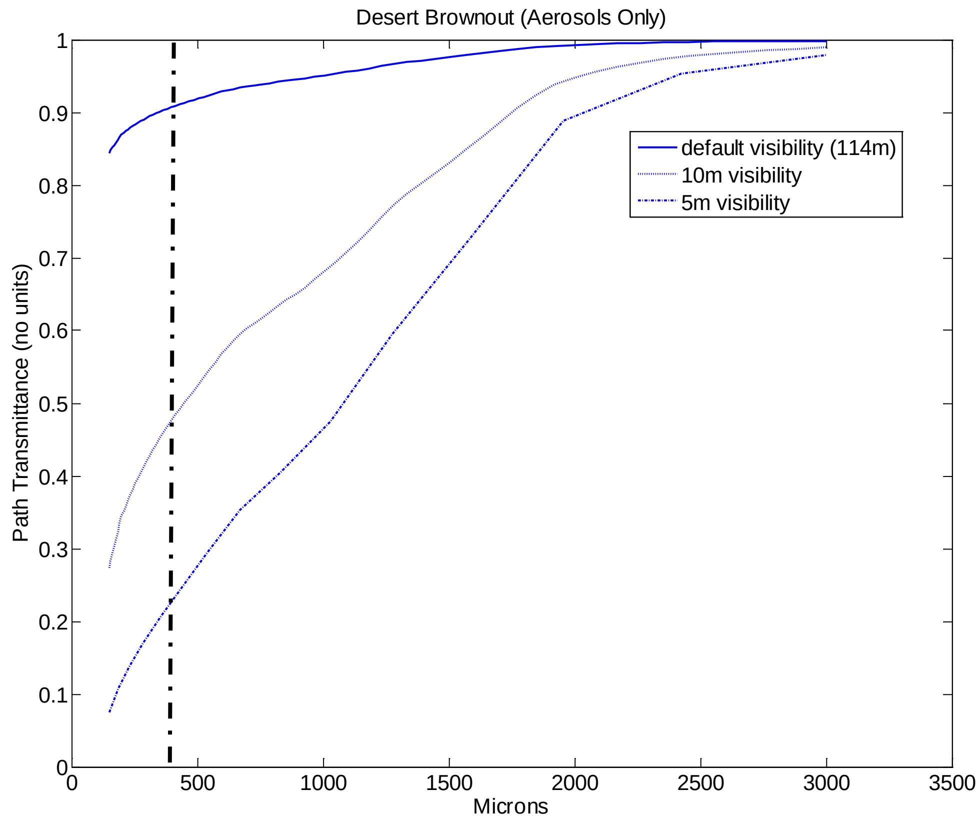

Figure 11. Transmission vs. Wavelength (μm) profile for Baghdad desert brownout conditions, the geometry for this calculation consists of a platform located at 15 meters above the surface, with a 15 meter propagation path length. Only aerosol attenuating effects (absorption and scattering) are being depicted, molecular attenuation effects (absorption and scattering) are not being represented.

In LEEDR as the visibility changes the number of particles depicted in Figure 8 changes by either shifting up or down depending on the visibility decreasing or increasing. This is because the limits of integration do not change in the LEEDR code, taking account for all particle sizes ranging from 0.5 μm to 350 μm in radius. As the number of particles increases there is an increase in the number of larger (> 100 μm) particles that are closer to the wavelength of interest (454 μm), thus those aerosols will absorb and scatter more radiation as compared to the number of smaller particles, which in turn decrease the transmittance. The transmittance values for the wavelengths of 454μm (0.660 THz) and 1360μm (0.220 THz) are shown in Table 4.

Table 4. Transmittance values that correlate to Figure 11 based on the different visibility conditions.

Wavelength (μm)	Visibility (m)	Transmittance (no units)
454	114	0.91
1360	114	0.96
454	10	0.50
1360	10	0.79
454	5	0.24
1360	5	0.59

While aerosols are an important factor to consider when looking at transmittance and extinction, the molecules in the air, namely water vapor 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, where, of all the atmospheric constituents that LEEDR takes into account the water vapor is five orders of magnitude greater than any other constituent. For the sake of this research the maximum path length investigated will be 50 meters with most scenarios having a 15 meter or shorter path length. At these short distances molecular and aerosol absorption proportionally contribute to the total extinction; which means that the proportion of molecular to aerosol absorption would remain the same if a longer or shorter propagation path was chosen. Figure 12 holds the same geometry, path length, and location as does Figure 11 with the exception that the atmosphere now consists of both aerosols and molecules thus allowing both mechanisms to contribute to the extinction.

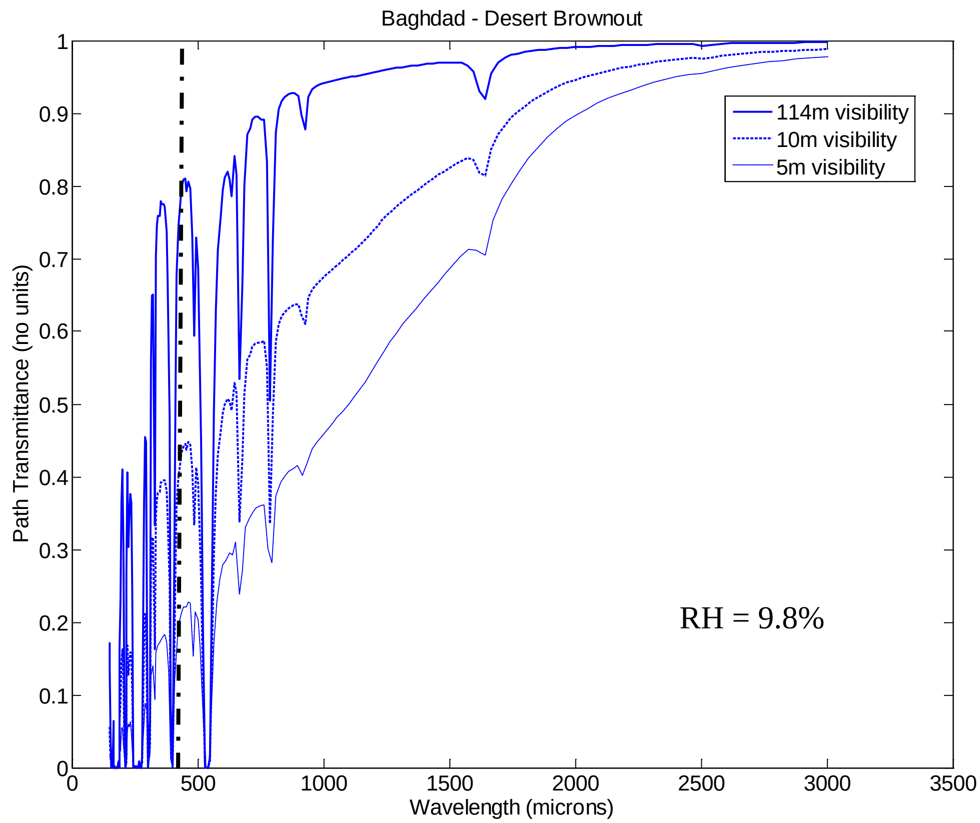

Figure 12. Transmission vs. Wavelength (μm) profile for Baghdad desert brownout conditions, the geometry for this calculation consists of a platform located at 15 meters above the surface, with a 15m propagation path length. It is depicting both molecular and aerosol attenuation effects.

Table 5. Transmittance values which correlate to Figure 12.

Wavelength (μm)	Visibility (m)	Transmittance (no units)
454	114	0.80
1360	114	0.96
454	10	0.43
1360	10	0.79
454	5	0.22
1360	5	0.63

By comparing Figures 11 and 12 and their transmittance values one can see that the 1360 μm line remains the same value, meaning there are no appreciable molecular effects taking place, and that the probability of transmitting through the dust cloud in a worst case scenario is still very high (approximately 78%). Therefore the 1360μm line shows that it is influenced very little by the water vapor as aerosols dominate the extinction effects, but the aerosol effects are not terribly strong against longer wavelengths. In the case of the 454μm line with both molecular and aerosol effects the transmittance drops 12% in the default visibility case and 14% in the 10 meter visibility case. Table 6 shows both the scattering and absorption values calculated at the wavelength of 454μm against the different visibility conditions.

Table 6. Molecular and Aerosol scattering and absorption values calculated in LEEDR over a 15 meter path length at a wavelength of 454μm in a desert brownout atmosphere. The molecular scattering effects are essentially negligible and can be disregarded.

	Molecular Absorption (km^{-1})	Aerosol Absorption (km^{-1})	Molecular Scattering (km^{-1})	Aerosol Scattering (km^{-1})
Default Visibility (114m)	9.39	1.21	2.4×10^{-14}	4.76
10m Visibility	9.4	9.26	2.4×10^{-14}	36.3

From Table 6 one can see that both molecular and aerosol absorption values become the same order of magnitude when the visibility decreases. With this decrease in visibility the number of particles increases across all sizes from 0.5 μm to 350 μm in radius. As the number of particles increases there is an increase in the number of larger (> 100 μm) particles that are closer to the wavelength of interest (454 μm), thus those aerosols will absorb and scatter more radiation as compared to the number of smaller particles. So in general as the visibility decreases, the large particles (i.e., those close to the wavelength of interest) dominate the attenuation as compared to the millions of small particles which in high concentrations actually look more like an absorbing gas to the radiation source rather than a bunch of very small aerosol particles because of the high density.

Mid-Latitude Aerosol Brownout Results

Figure 13 shows the aerosol only atmosphere and the transmittance across wavelengths from 150µm to 3000µm.

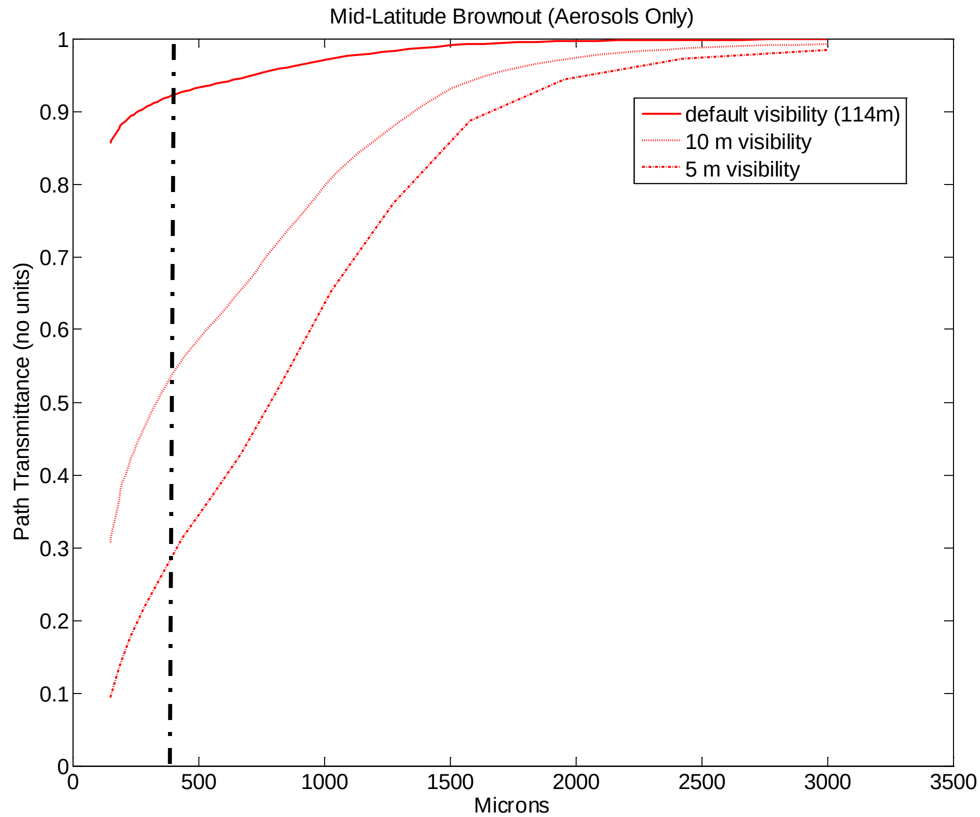

Figure 13. Mid-Latitude brownout aerosol only model transmission across wavelengths from 150µm to 3000µm. The geometry consists of a 15 m propagation path and again molecular effects are not shown, to show the possibility of transmission through different visibilities.

Table 7. Transmittance values that correspond to Figure 13.

Wavelength (µm)	Visibility (m)	Transmittance (no units)
454	114	0.92
1360	114	0.98
454	10	0.57
1360	10	0.89
454	5	0.31
1360	5	0.77

The transmittance values of the mid-latitude brownout in the 114m visibility range are approximately the same in both the desert and mid-latitude aerosol models. When the visibility decreases the transmission through the water-soluble atmosphere is better than when propagating through a desert environment.

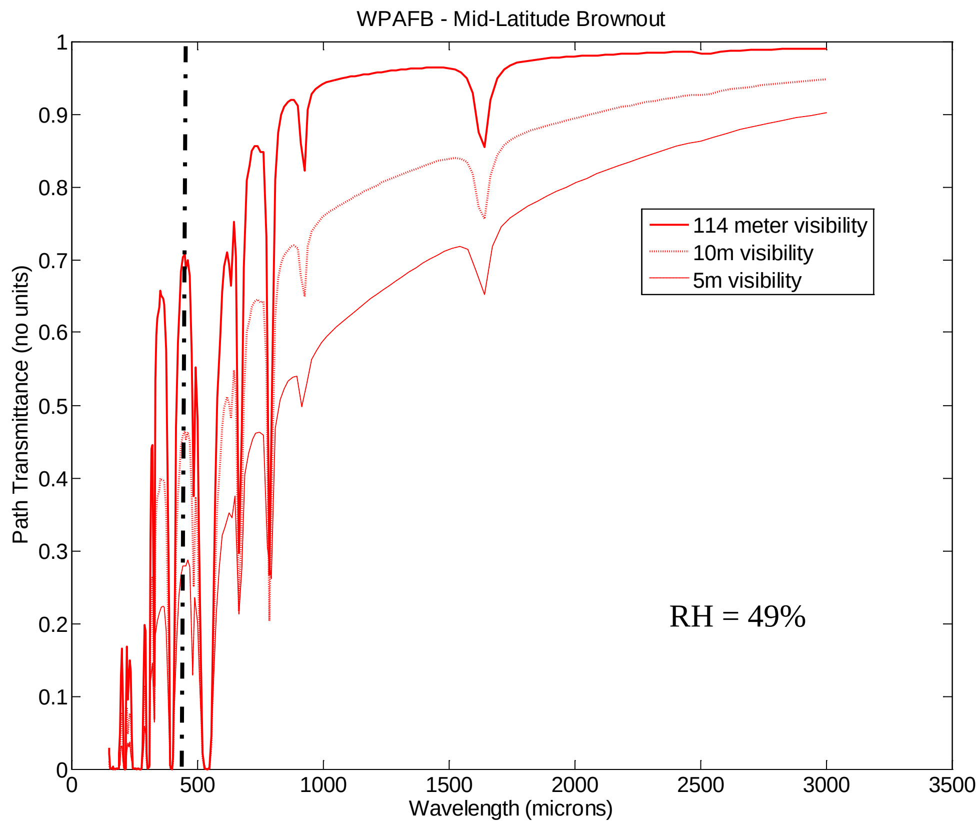

Figure 14. Transmittance versus wavelength across an atmosphere with molecular and aerosol effects. The water vapor absorption lines can be seen to attenuate the radiation significantly across the THz spectrum.

Table 8. Transmission values corresponding to Figure 14.

Wavelength (μm)	Visibility (m)	Transmittance (no units)
454	114	0.68
1360	114	0.96
454	10	0.45
1360	10	0.82
454	5	0.27
1360	5	0.68

Table 9. Molecular and Aerosol scattering and absorption values calculated in LEEDR over a 15 meter path length at a wavelength of 454μm in a mid-latitude brownout atmosphere. The molecular scattering effects are essentially negligible and can be disregarded.

	Molecular Absorption (km^{-1})	Aerosol Absorption (km^{-1})	Molecular Scattering (km^{-1})	Aerosol Scattering (km^{-1})
Default Visibility (114m)	20.05	2.06	2.1×10^{-14}	2.73
10 m Visibility	20.06	14.01	2.1×10^{-14}	18.58

From Table 9 in the 10 meter scenario the molecular absorption provides slightly more attenuation to the radiation than does the aerosol scattering. This also shows at slightly longer visibilities the water vapor in the air causes approximately ten times more attenuation than the aerosols.

Signal to Noise Ratio (SNR)

The impact of variations in atmospheric path transmittance on the signal to noise ratio (SNR) performance of a theoretical THz imaging device is assessed for this research by using the standard radar equation. It will give an estimate to the amount of power required to achieve a desired SNR. For the case of radar frequencies noise energy is computed assuming a matched filter design (Fiorino, et al., 2007).

$$noise = k \cdot T_s \cdot F_n \tag{7}$$

Where k is Boltzmann's constant ($1.38 \times 10^{-23} m^2 kg\, s^{-2} K^{-1}$), 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 radar range equation is applied:

$$signal = \frac{P_{avg} \cdot G^2 \cdot RCS \cdot \lambda^2 \cdot t_{ot} \cdot T}{(4\pi)^3 \cdot R^4} \tag{8}$$

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. SNR is computed as the ratio of these two equations. Equation 7 has units of Joules and in order to get Equation 8 in units of Joules the gain G must be converted from decibels to a power ratio through the following equation:

$$Power\ Ratio = 10^{dB/10} \tag{9}$$

In consultation with THz imaging expert Lt Col. Matthew Bohn, USAF he estimates that a SNR of 10 would be sufficient to provide an accurate image of the ground, thus allowing a pilot to see if the terrain is uneven or another obstruction that could possibly cause the helicopter to crash.

If a SNR of 10 is desired for a wavelength of 1360 µm which has a transmittance value of 0.96, then one can back-out the average power needed to obtain the desired SNR in the following manner:

$$noise = (1.38\times10^{-23})\cdot(288)\cdot(3) \Rightarrow 1.19\times10^{-20}\,J \tag{10}$$

$$Signal = \frac{P_{avg}\cdot(10^{30/10})^2\cdot(1)\cdot(.00136)^2\cdot(10\times10^{-6})\cdot(.96)^2}{(4\pi)^3\cdot(15)^4} \Rightarrow P_{avg}\cdot(1.7\times10^{-13}) \tag{11}$$

$$\frac{Signal}{noise} = 10 \Rightarrow \frac{P_{avg}\cdot(1.7\times10^{-13})}{1.19\times10^{-20}} \Rightarrow P_{avg} = \frac{10\cdot(1.19\times10^{-20})}{1.7\times10^{-13}} = 0.7\,\mu W \tag{12}$$

In general as the transmittance gets closer to 1, (i.e., improves) the amount of power needed to get an acceptable SNR will decrease. Conversely as the transmittance decreases, the amount of power needed will increase. In calculating the power needed to get the appropriate SNR for the case where the transmittance at 1360µm is 0.79 it was found that an average power of 1.03µW would be required.

V. Conclusions and Recommendations

Overview

This chapter summarizes the analysis performed in chapter four and identifies the emerging trends. It also includes some broad conclusion statements regarding this work. Finally, recommendations are made for future research regarding this topic.

Conclusions of Research

A tool has been developed 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.

Significance of Research

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 off of an experimental study by MRI which was able to quantify the particle concentration that exists in rotary-wing brownout conditions.

Recommendations for Future Research

Given the conclusions of this thesis there are a few areas of future research that could provide significant value. These areas of research are listed in order of perceived value. First, obtaining better values for the optical properties of dirt samples through experimentation would prove valuable information for the optical properties at wavelengths past 40 µm. This would allow one to implement new optical properties into LEEDR that would provide more realistic extinction values, it would also validate the results obtained in this thesis, or show that the assumptions made with the silica was incorrect. Dr. Andrew Phelps from the Air Force Coatings Technology Integration Office (AF CTIO) has offered his services which would provide samples of dirt in different forms such has having a sample formed into wafers to be experimentally tested with a THz laser system to find extinction values. His extensive and expert knowledge of the different types of soils worldwide allows one the better understanding of perceived results. Second, using a THz imager that can operate at the frequencies depicted in this thesis one could experimentally setup a scaled brownout environment with a known distribution and particle size and image through the cloud with a THz system. Third, this work could be replicated for a whiteout scenario. Although it might be difficult to quantify the particle size distribution of snow and snowflakes, it would provide a gage of transmission values one might expect to see during a whiteout at land sites around the world.

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Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way, Building 640
WPAFB OH 45433-8865

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AFWA Det 3 2WG
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14. ABSTRACT

This study quantifies terahertz (THz) or sub-millimeter imaging performance during simulated rotary-wing brownout or whiteout environments based on geographic location and recent/current atmospheric weather conditions. The atmospheric conditions are defined through the Air Force Institute of Technology Center for Directed Energy (AFIT/CDE) Laser Environmental Effects Definition and Reference or LEEDR model. This model enables the creation of vertical profiles of temperature, pressure, water vapor content, optical turbulence, and atmospheric particulates and hydrometeors as they relate to line-by-line layer extinction coefficient magnitude at wavelengths from the UV to the RF. Optical properties and realistic particle size distributions for the brownout and whiteout particulates have been developed for and incorporated into LEEDR for this study. The expected imaging performance is assessed primarily at a wavelength of 454 μm (0.66 THz) in brownout conditions at selected geographically diverse land sites throughout the world. Seasonal and boundary layer variations (summer and winter) and time of day variations for a range of relative humidity percentile conditions are considered to determine optimum employment techniques to exploit or defeat the environmental conditions. Each atmospheric particulate/hydrometeor is evaluated based on its wavelength-dependent forward and off-axis scattering characteristics and absorption effects on the imaging environment. In addition to realistic vertical profiles of molecular and aerosol absorption and scattering, correlated optical turbulence profiles in probabilistic (percentile) format are used. Most evaluated scenarios are brownout environments over ranges up to 50 meters. At sub-millimeter wavelengths and the short ranges studied, preliminary results indicate the main source of image degradation in brownout conditions is water vapor content, even with visibility less than 10 m and strong optical turbulence.

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a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Steven T. Fiorino, Lt Col, USAF
U	U	U	UU	62	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565, ext 4506 (steven.fiorino@afit.edu)

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