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Optical Communication Link Atmospheric Attenuation Model

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Optical Communication Link Atmospheric Attenuation Model

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Summary

The Space Communications and Navigation (SCaN) Strategic Center for Networking, Integration, and Communications (SCENIC) user interface (UI), which provides web-accessible space mission simulation and communication system analysis capabilities by using verified and validated analysis algorithms, can execute analyses, including, but not limited to, line-of-sight, orbit propagation, and dynamic link budget calculations between sets of missions and/or assets. SCENIC's purpose is to provide NASA civil servants and contractors with a user-friendly tool, integrated with model data, that can simulate and analyze a range of space mission architectures without the need for repeated and redundant modeling. Given the abundance and further future development of free-space optical (FSO) communication channels within a modern space infrastructure, the availability of a reliable optical link analysis capability is crucial for SCENIC users. The efforts outlined in this paper aim to provide a model for atmospheric attenuation of FSO communication links, both due to absorption and scattering as well as turbulence, to increase the accuracy of SCENIC's optical link assessment capabilities. A previous model existed for optical absorption and scattering within the SCaN Optical Link Budget Tool, but it was not location specific for Earth ground-based nodes nor was the model optimized for runtime. The new model utilizes years of National Oceanic and Atmospheric Administration (NOAA) visibility data from ground station locations around the world. Visibility, along with the wavelength of the optical signal, are input parameters used to calculate the optical specific attenuation, which is a parameter in the calculation of the slant path attenuation. A final FSO atmospheric attenuation value comprises the absorption and scattering attenuation as well as the turbulence attenuation. A runtime efficient algorithm for the model was then developed and programmed in MATLAB® (MathWorks®). Due to the simple model and vectorization possible in MATLAB®, the algorithm has an average runtime of less than one-fourth of the runtime of the previous implementation.

Nomenclature

CDF	cumulative distribution function
FSO	free-space optical
NOAA	National Oceanic and Atmospheric Administration
PDF	probability distribution function
RF	radio frequency
SCaN	Space Communications and Navigation
SCENIC	Strategic Center for Networking, Integration, and Communications
UI	user interface

[*]Summer intern in Lewis' Educational and Research Collaborative Internship Project (LeRCIP), undergraduate at Tulane University.

Symbols

a	side of a spherical triangle
d	distance
e	Euler's constant
H	characteristic height
q	specific atmospheric attenuation visibility coefficient
R	equatorial radius of Earth
V	atmospheric visibility
γ	atmospheric attenuation
γ_0	specific atmospheric attenuation
θ	angle of elevation above horizontal
Λ	longitude
λ	wavelength
τ_{abs}	total absorption
φ	latitude

1.0 Introduction

NASA's Space Communications and Navigation (SCaN) program works to develop space communication channels and infrastructure to support all NASA missions. SCaN operates the vital Near Earth Network, Space Network, and Deep Space Network communication satellites and ground stations located around the world. These antennas provide communications service to space infrastructure from low Earth orbit to interstellar space. Due to the distance and variable medium characteristics associated with space communications, careful, complex analysis of proposed missions is crucial to success. Proprietary mission architecture design and simulation software exists; however, these tools require licenses to operate and are separate from the databases pertaining to the SCaN assets or the missions that they support. Therefore, SCaN is developing the SCaN Strategic Center for Networking, Integration, and Communications (SCENIC) to provide a simple web-based user interface (UI) to integrate analysis tools with relevant data to support communication analysis. This software will provide NASA civil servants and contractors with a tool that allows for quick, accurate mission simulation and analysis, eliminating the development of redundant models whose applications do not span the gamut of diverse mission architectures.

SCENIC provides orbital propagation, line-of-sight analysis, link budget analysis, dilution of precision analysis, and many more analysis capabilities. Critical to the accuracy of any communication analysis is the ability to accurately predict the link budgets of communication channels. Free-space optical (FSO) communication is becoming more prevalent in modern space communication infrastructure due to its many benefits, such as the lack of bandwidth constraints, high potential data rates, and so on. However, FSO links are more likely to suffer from atmospheric conditions than radio frequency (RF) links. Therefore, SCENIC requires a model for describing signal losses associated with atmospheric conditions in order to provide accurate optical link budget analyses. The efforts described in this paper were directed toward designing and implementing an accurate atmospheric attenuation model for FSO communications. The model was developed in accordance with the SCaN Link Assessment Tool Version 5 Optical Link Calculation. A previous model existed, but it lacked location-dependent accuracy due to an insufficient database of reference locations and had a prohibitively slow runtime. The new model was implemented in MATLAB® and will soon be integrated into SCENIC's optical link capabilities.

2.0 Background

2.1 Free-Space Optical (FSO) Communication

FSO communication is an alternative to RF communication, achieved by transmitting smaller optical wavelengths of light (700 to 10,000 nm) instead of longer radio wavelengths (Ref. 1). The shorter wavelengths, and thus higher frequencies, allow for higher data transmission rates than RF communication. An optical signal frequency of 10^{12} to 10^{16} could produce a data bandwidth of 2,000 THz, a factor of 10^5 larger than that possible with an RF signal (Ref. 1). Optical beams, due to the properties of lasers, also come with a significantly smaller divergence width, with a typical value ranging from 0.01 to 0.1 mrad (Ref. 1). The narrow beam width both increases the difficulty of intercepting a signal, thus providing better security, and eliminates the need for spectrum licenses (Ref. 1), at the expense of pointing the signal.

The tradeoff made when opting for an FSO link versus an RF link is the variable and often large attenuation of FSO signals due to atmospheric conditions. The specific attenuation of an FSO signal can reach values near 350 dB/km in heavy fog (Ref. 2). This is in stark contrast to how atmospheric conditions affect an RF signal.

2.2 Optical Atmospheric Attenuation

FSO beams suffer from signal loss while traversing an atmospheric channel due to gasses and various small particles. These atmospheric attenuators include aerosols, dust, smoke, rain, snow, fog, haze, and more (Ref. 3). These particles can cause one of two phenomena involved in atmospheric attenuation: absorption and scattering. Atmospheric attenuation of optical beams can be modeled mathematically by using both variables associated with atmospheric conditions and with transmitted and received power differences.

2.2.1 Absorption

Absorption occurs when the energy of the photons of the transmitted beam are converted to thermal energy upon interaction with atmospheric particles (Ref. 1). Because absorption depends on the wavelength of the transmitted beam, there exist ranges of wavelengths that are more resistant to the effects of absorption than others are. A wavelength of 1,550 nm is commonly used for FSO communication, an effect of its resistance to atmospheric absorption. The sensitivity of differences in wavelength and resulting attenuations is illustrated in Figure 1. Wavelength ranges resulting in high transmittances, and thus low attenuations, are referred to as “transmission windows” (Ref. 1).

2.2.2 Scattering

Scattering of a light source refers to the redirection of light waves due to contact with suspended particles. There are three types of scattering: Rayleigh, Mie, and geometrical (Ref. 1). The difference between the three lies in their ability to explain scattering due to differing ratios of particle size to wavelength (Ref. 1). While the amount of atmospheric absorption of an optical signal is wavelength dependent, the degree of scattering of a signal does not vary as much, given a specified optical wavelength. However, Rayleigh scattering is present if the radius of the scattering particles is smaller than the wavelength of the beam, Mie scattering occurs with a slightly larger radius to wavelength ratio, and geometric scattering occurs with an even larger radius to wavelength ration, often in the presence of conditions such as rain, snow, and thick fog (Ref. 1). The combination of scattering and absorption contribute to the overall atmospheric attenuation value of an optical beam.

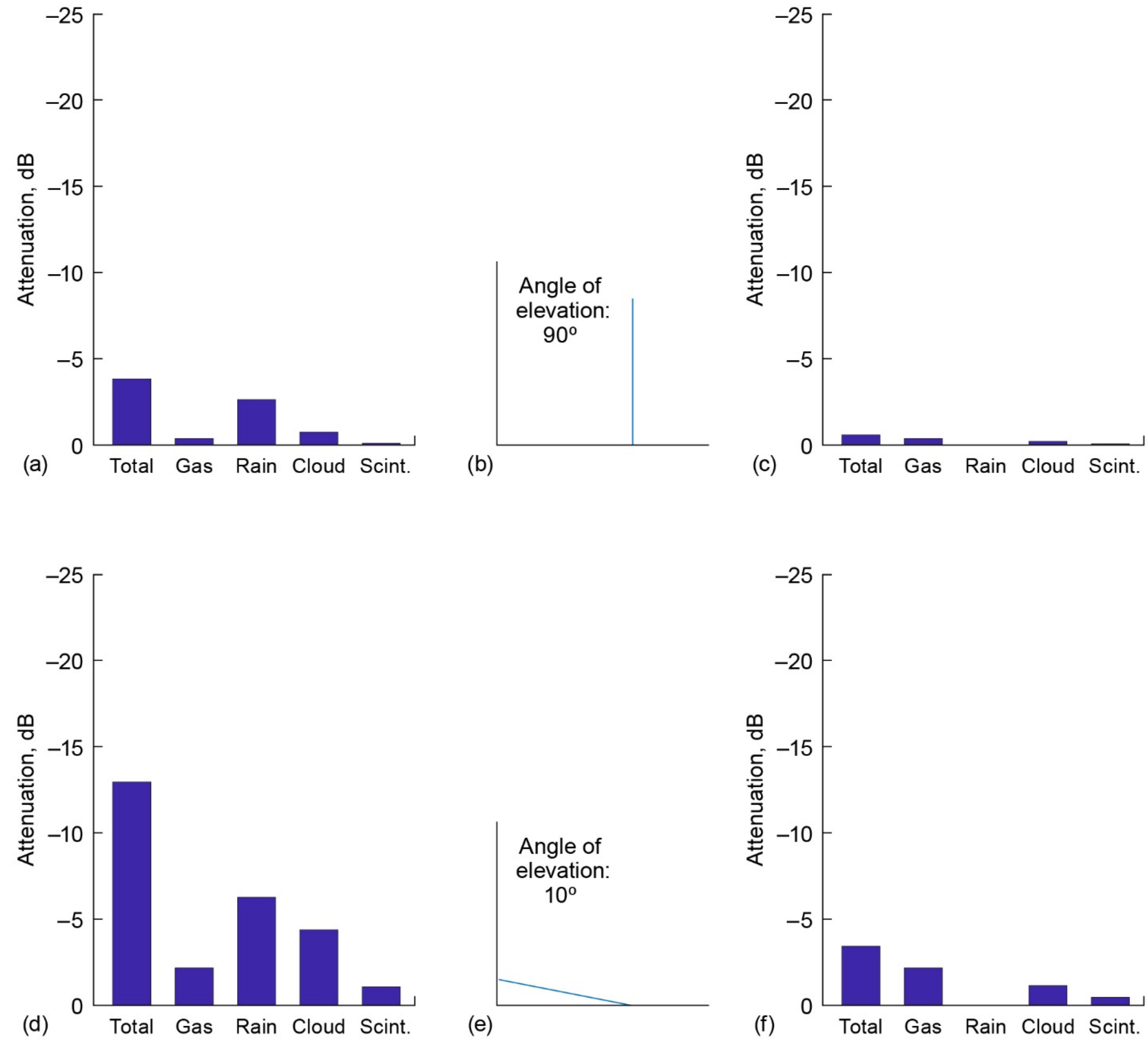

Figure 1.—Optical beam wavelengths in visible and near infrared portions of electromagnetic spectrum and their associated transmittances through atmosphere (Ref. 3). (a) Attenuation exceeded 1 percent of time at zenith. (b) Pointing angle at zenith. (c) Attenuation exceeded 10 percent of time at zenith. (d) Attenuation exceeded 1 percent of time at 10° elevation. (e) Pointing angle at 10° elevation. (f) Attenuation exceeded 10 percent of time at 10° elevation.

2.3 Previous Model

A previous model for optical atmospheric attenuation was developed and implemented in SCENIC. The model used a similar mathematical approach, as specific attenuation was derived using the Kruse model with wavelength and visibility as the independent variables, identical to the new model. However, the algorithm calculated the distance the beam passed through and the prevailing attenuation due to 922 separate layers of the atmosphere. An inefficient for loop was used to accomplish the calculations needed to piece together the effects of each separate atmospheric layer on the beam. The resulting average runtime for the entire routine was 0.55 s. Because this routine will be used as a small fraction of the computation involved in mission analysis, decreasing the average runtime is crucial. In addition, the previously developed model was not location accurate due to a lacking database of ground-based visibility.

3.0 Methodology

3.1 Mathematical Model

In order to mathematically model the atmospheric attenuation of an optical signal, characteristics of the atmospheric conditions, specifically the presence of particles that may cause absorption or scattering, must be present. However, because atmospheric weather conditions are more stochastic than many physical phenomena, it would be easy for such a model to be bogged down in complexity, something that is to be avoided when software runtime is under consideration. A useful weather parameter that does well in encompassing atmospheric conditions is visibility. Visibility is the distance traveled at which the intensity of a parallel luminous beam drops 2 percent of the transmitted intensity (Ref. 3). An increase in the presence of atmospheric particles decreases the visibility measured, and thus visibility correlates directly with attenuation. Even more useful is the prescription, shown in Equations (1) and (2), transforming atmospheric visibility, V, and wavelength of the beam, λ, into specific attenuation, γ_0, or the attenuation along a path normal to the surface of Earth.

$$\gamma_0(\lambda) = 10\log_{10}(e)\frac{3.912}{V}\left(\frac{\lambda}{0.55}\right)^{-q(V)}, \quad [V] = \text{km}, \quad [\lambda] = \mu\text{m} \tag{1}$$

$$q(V) = \begin{cases} 1.6, & V > 50 \text{ km} \\ 1.3, & 6 \text{ km} < V < 50 \text{ km} \\ 0.585V^{1/3}, & V < 6 \text{ km} \end{cases} \tag{2}$$

where e is Euler's constant and q is the specific atmospheric attenuation visibility coefficient.

Equations (1) and (2) are commonly used as a model of attenuation due to Mie scattering, however, because Mie scattering is the most general of the three types of scattering, and absorption of optical signals is negligible when operating in a transmission window, this equation is used as a calculation of overall specific attenuation (Refs. 1 and 3). Equations (1) and (2) are useful in that of the two independent variables, wavelength will be provided by user input and visibility is a commonly collected weather statistic. Further, a simple slant path correction can be made when dealing with transmissions not normal to the surface of Earth.

$$\gamma(H) = \gamma_0 \exp(-1) \tag{3}$$

$$\tau_{\text{abs}}(\theta) = \gamma_0 \int_0^{\infty} \exp\left(-\frac{l\sin(\theta)}{H}\right) dl = -\gamma_0 H \csc(\theta) \tag{4}$$

where θ is the angle of elevation above horizontal and γ is atmospheric attenuation.

Equation (3) determines the characteristic height, H, the height at which the specific attenuation is equal to the specific attenuation divided by e, which is approximately 2.72 (Ref. 4). This characteristic height is then used in Equation (4), resulting is the slant path total absorption value, τ_{abs} (Ref. 4). The characteristic height used in the model is 12 km. The units of the final value are in decibels, apparent in the intermediate step of Equation (4), as the kilometers included in the units of the specific attenuation are eliminated by the integral.

The mathematical model of atmospheric attenuation described allows for the calculation of a final attenuation value due to absorption and scattering with only three input variables: atmospheric visibility, wavelength of the propagated optical beam, and angle of elevation above horizontal of the beam. Given the complexity of the causes of optical atmospheric attenuation, this model provides a critical simplicity for the SCENIC software.

3.2 Database

The mathematical model developed for the purpose of the optical attenuation tool requires certain input parameters that will be inherently included in the analyses due to the specifics of the communication link. These parameters include elevation angle, date and time, location of the ground station, wavelength, direction of communication link, and percent chance of exceedance. However, the model also includes a visibility parameter, which must be extracted from an existing database. Such a database must include substantial amounts of visibility data from around the world for every part of the year. The database developed for this project includes daily average visibility values from 206 ground station locations around the world, which are plotted in Figure 2. Because of a lack of consistency in differing datasets, the amount of visibility data included for each location differs, but is generally a 10- to 20-yr duration of data. The National Oceanic and Atmospheric Administration’s (NOAA’s) publicly available weather statistic database provided the visibility data (Ref. 5).

37.6213 -122.3790

STN---	WBAN	YEARMODA	TEMP		DEWP		SLP		STP		VISIB		WDSP		MXSPD
724940	23234	19800101	53.0	24	51.0	24	1022.4	24	1021.6	24	4.6	24	4.1	23	9.9
724940	23234	19800102	46.7	24	45.3	24	1022.0	24	1021.2	24	1.9	24	3.9	24	12.8
724940	23234	19800103	46.7	24	44.1	24	1019.6	24	1019.0	24	1.5	24	4.2	24	8.9
724940	23234	19800104	49.7	22	43.9	22	1017.6	22	1016.8	22	4.5	22	4.1	22	8.9
724940	23234	19800105	50.6	24	45.2	24	1017.0	24	1016.2	24	4.0	24	4.5	24	9.9
724940	23234	19800106	52.4	24	44.4	24	1018.4	24	1017.7	24	9.9	24	3.7	24	7.0
724940	23234	19800107	51.6	24	45.3	24	1015.2	24	1014.5	24	8.5	24	3.1	24	7.0
724940	23234	19800108	52.3	23	46.4	23	1014.8	23	1014.1	23	6.0	23	4.6	23	8.9
724940	23234	19800109	52.5	23	49.8	23	1007.2	23	1006.5	23	1.9	23	4.5	23	7.0
724940	23234	19800110	50.6	24	41.8	24	1008.6	24	1007.9	24	16.9	24	8.6	24	15.9
724940	23234	19800111	51.8	24	46.5	24	1007.7	24	1006.9	24	8.0	24	6.3	24	10.9
724940	23234	19800112	61.8	22	57.2	22	1011.2	22	1010.5	22	7.2	22	14.2	22	19.8
724940	23234	19800113	61.2	24	57.2	24	1012.8	24	1012.1	24	8.8	24	15.6	24	31.9
724940	23234	19800114	59.0	23	53.7	23	1011.9	23	1011.2	23	10.6	23	11.9	23	25.1
724940	23234	19800115	52.3	22	47.9	22	1018.0	22	1017.2	22	10.8	22	7.0	22	14.0
724940	23234	19800116	55.6	23	51.7	23	1018.2	23	1017.6	23	10.1	23	6.9	23	15.9
724940	23234	19800117	54.5	21	49.8	21	1017.8	21	1017.1	21	12.7	21	7.2	21	16.9
724940	23234	19800118	49.9	24	37.1	24	1015.5	24	1014.8	24	24.9	24	10.4	24	19.8
724940	23234	19800119	46.9	24	25.8	24	1018.4	24	1017.7	24	30.2	24	10.0	24	24.9
724940	23234	19800120	47.2	24	35.5	24	1024.2	24	1023.4	24	19.2	23	4.5	24	10.9
724940	23234	19800121	48.3	24	40.4	24	1023.1	23	1022.4	23	11.0	24	3.7	23	10.1

Figure 2.—Raw weather data from San Francisco International Airport, including daily visibility data.

Once the appropriate data had been gathered, a script was modified to condense each location's data into a cell array with 13 cells, 12 of which contain the visibility data from each year of the month, and one of which contains the latitude and longitude of the ground station. Each month's cell contains a 360 by 3 matrix, with visibility values in kilometers from 0 to 90 in. increments of 0.25 in. in the first column, each visibility range's probability of occurrence in the second column, and the cumulative probability in the third column. Therefore, a probability distribution function (PDF) and cumulative distribution function (CDF) are available for each month and each location included in the data.

Figure 3 shows how the data are structured before processing by the script discussed previously. A graph of the subsequent visibility CDF can be seen in Figure 4. The process of extracting the visibility data from the raw NOAA data was carried out for each of the 206 locations before the data was condensed into one file containing a 13 by 206 matrix of visibility data and latitude and longitude pairs for each location.

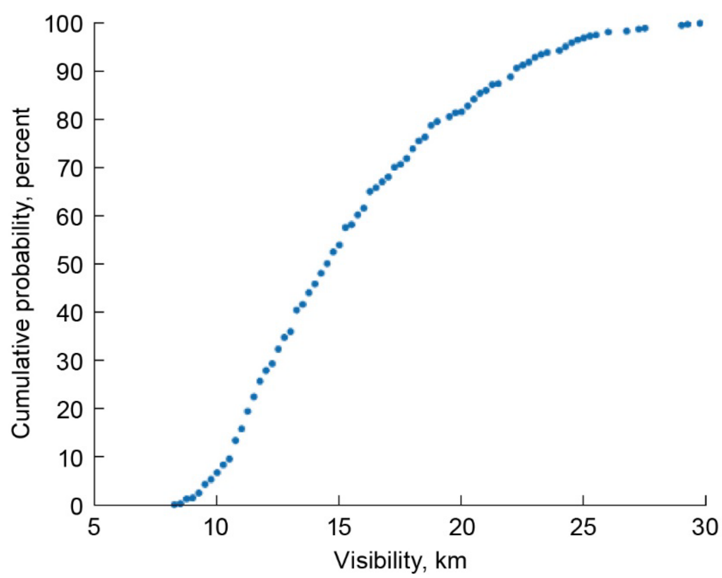

Figure 3.—Graph of cumulative distribution function obtained from San Francisco International Airport visibility data.

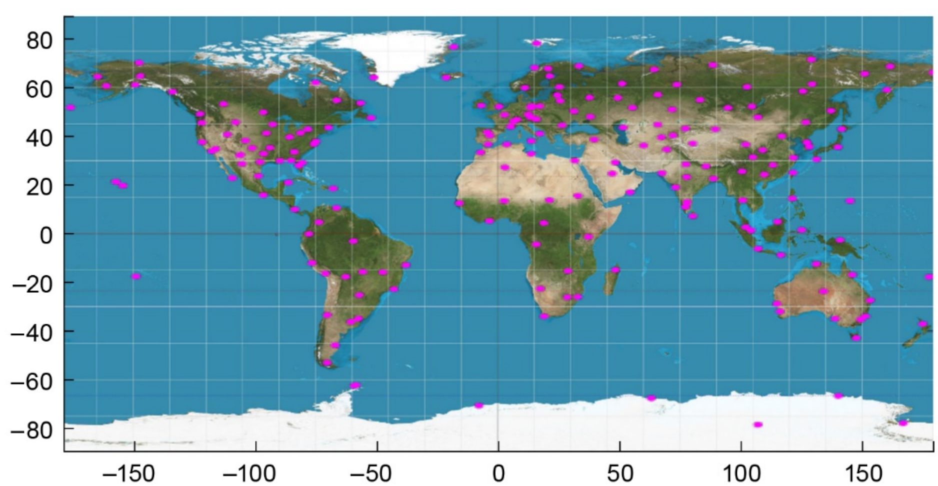

Figure 4.—World map showing 206 ground station locations included in database.

3.3 Algorithm

Using the mathematical attenuation model and the visibility database, an algorithm was implemented in MATLAB®. The routine takes user inputs in the form of angle of elevation above the horizon, percent chance of exceedance, date and time, direction of the link (either initial beam radius or receiver aperture diameter, depending on the direction), wavelength, and location of the ground station. The month is extracted from the date and time input, upon which the subroutine that determines the visibility is called. This subroutine begins by determining the closest location included in the database to the user's input location using the haversine formula (Ref. 6).

$$a = \sin^2\left(\frac{\Lambda\varphi}{2}\right) + \cos(\varphi_1) * \cos(\varphi_2) * \sin^2\left(\frac{\Lambda\lambda}{2}\right) \tag{5}$$

$$d = \mathrm{R} * 2 * \mathrm{atan2}\left(\sqrt{a}, \sqrt{1-a}\right) \tag{6}$$

where a is the side of a spherical triangle, R is the equatorial radius of Earth, and λ is latitude.

Equations (5) and (6) comprise the haversine formula, which calculates the distance in kilometers between two sets of latitude and longitude pairs. Based on the location deemed nearest the input location by the formula, that location's visibility PDF and CDF matrix is pulled from the database. The visibility value having the first cumulative probability greater than or equal to the input percent chance exceedance is chosen as the visibility value to be used throughout the rest of the algorithm. Once the visibility has been extracted from the database, it becomes an input parameter for another subroutine that uses Equations (1) and (2) to produce a specific attenuation value. Finally, the specific attenuation becomes an input parameter for a subroutine that converts the specific attenuation to a final attenuation value due to absorption and scattering by using Equations (3) and (4).

4.0 Results

The developed optical attenuation model was extensively tested by a unit test routine. The routine makes use of a grid of points described by their latitude and longitude containing 20,480 points. Each point was included as a ground station location for a single test; therefore, 20,480 runs of the model were carried out. Several large groups of runs had differing link directions, angles of elevation, percent chances of exceedance, and wavelengths. The exhaustive test produced a matching nearest ground station location from the database and a reasonable value for the optical attenuation for each test case. Relatively small differences in input ground station location can yield dramatically different attenuation values, due to the diversity of atmospheric visibility around the world, meaning that the results are highly sensitive to the input parameters of the ground station location.

Figure 5 and Figure 6 show the sensitivity of the results, depending on the ground station location input. A slight difference in latitude and longitude yields data from separate locations with dramatically different visibility data. When each location is evaluated with a 98-percent chance of exceedance, a 47° angle of elevation, and a wavelength of 1,550 nm, San Francisco, California, produces an attenuation value of –3.0834 dB while Pueblo, Colorado, produces an attenuation value of –1.4570 dB. The lower attenuation value for Pueblo, Colorado, is expected given the higher visibility value.

The tests performed were also analyzed for expected changes in the output attenuation, given adjustments of input arguments. Figure 7 depicts the relationship between elevation angle above horizontal of the optical beam and the prevailing attenuation. The inputs used for the analysis shown in

Figure 7 included a 98-percent chance of exceedance and a 1,550 nm wavelength. Elevation angles from 5° to 90°, in 1° increments, were then input into the model and the prevailing attenuation values were graphed as a function of the elevation angle. The relationship shown is what is expected, as a lower elevation angle results in the beam propagating through the atmosphere for a longer duration, meaning that the beam experiences more attenuation.

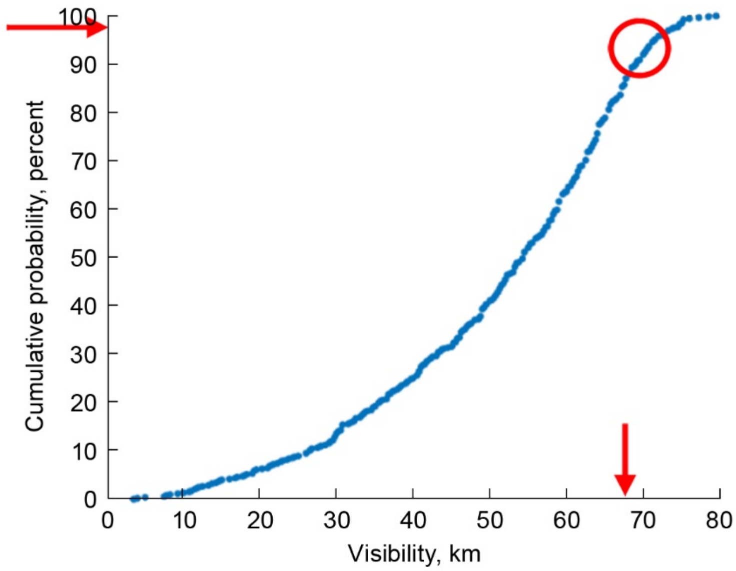

Figure 5.—Visibility cumulative distribution function graph of Pueblo, Colorado, resulting from input latitude and longitude of 38° and –108°, respectively.

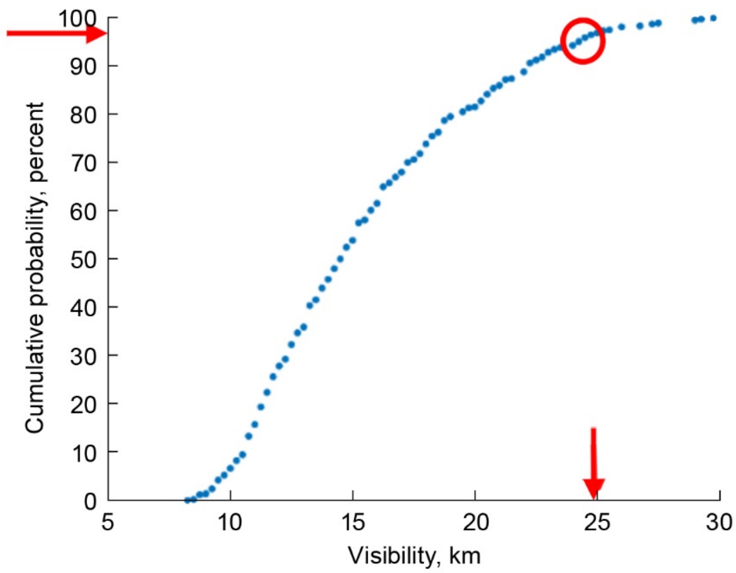

Figure 6.—Visibility cumulative distribution function graph of San Francisco, California, resulting from input latitude and longitude of 40° and –119°, respectively.

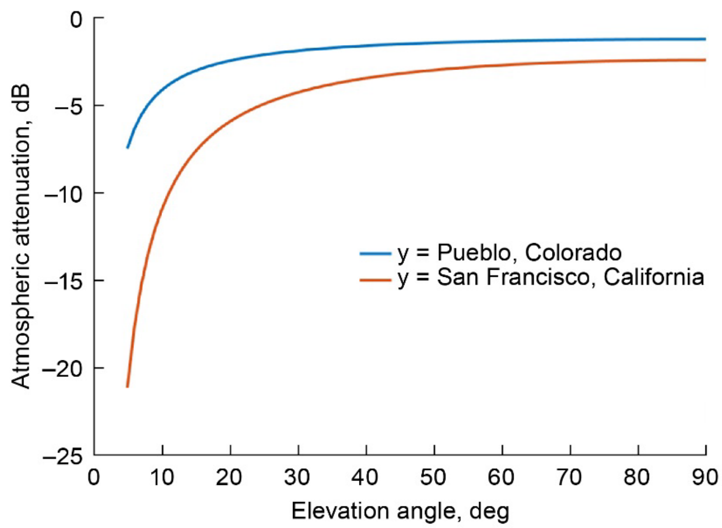

Figure 7.—Graph of atmospheric attenuation as a function of elevation angle for Pueblo, Colorado, and San Francisco, California, with a percent chance of exceedance of 98 percent.

While the previous model's inefficiencies resulted in an average runtime of 0.55 s, the improvements made to the algorithm yield an average total runtime of 0.10 s. The decrease in runtime represents 81.7 percent of the previous runtime. The gains made in efficiency make the routine a viable add-on for the optical link budget capabilities of SCENIC.

5.0 Conclusions

The optical atmospheric attenuation model, designed in accordance with the Space Communications and Navigation (SCaN) Link Assessment Tool, performs as expected, given differing input arguments such as elevation angle, wavelength, percent chance of exceedance, and so on. The runtime efficiency bests the previously developed model and is fast enough to make it a viable add-on for optical link budget analysis capabilities. While there are certain limitations with the data, which for the most part have to do with transmissometer measurement ceilings, the data collected is the best available and lacks outliers or inconsistencies.

There is currently no attenuation data available for validation purposes, however, the output attenuation values obtained through extensive testing all lie within reasonable bounds. In the future, more ground station locations and their visibility data may be added to the database to further increase location accuracy. Software releases in Version 3 of the SCaN Strategic Center for Networking, Integration, and Communications (SCENIC) in fiscal year 2019 are planned to include capabilities that utilize this optical atmospheric attenuation model.

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