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Augmenting the SCaN Link Budget Tool With Validated Atmospheric Propagation

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Abstract

In any Earth-Space or Space-Earth communications link, atmospheric effects cause significant signal attenuation. In order to develop a communications system that is cost effective while meeting appropriate performance requirements, it is important to accurately predict these effects for the given link parameters. This project aimed to develop a MATLAB® (The MathWorks, Inc.) program that could augment the existing Space Communications and Navigation (SCaN) Link Budget Tool with accurate predictions of atmospheric attenuation of both optical and radio-frequency signals according to the SCaN Optical Link Assessment Model Version 5 and the International Telecommunications Union, Radiocommunications Sector (ITU-R) atmospheric propagation loss model, respectively. When compared to data collected from the Advance Communications Technology Satellite (ACTS), the radio-frequency model predicted attenuation to within 1.3 dB of loss for 95 percent of measurements. Ultimately, this tool will be integrated into the SCaN Center for Engineering, Networks, Integration, and Communications (SCENIC) user interface in order to support analysis of existing SCaN systems and planning capabilities for future NASA missions.

Nomenclature

N_{wet}	wet term of radio refractivity
C_n^2	optical refractivity structure parameter
A_T	total radio atmospheric attenuation
A_G	radio attenuation due to gaseous absorption
A_R	radio attenuation due to rain
A_C	radio attenuation due to clouds
A_S	radio scintillation fade depth
L_{red}	total columnar water content reduced to 0 °C

1.0 Introduction

In any Earth-Space or Space-Earth communications link, atmospheric effects cause significant signal attenuation. This loss in power can drive up the bit error rate and ultimately reduce link availability. To offset this degradation, communications systems are constructed with more powerful (and therefore more expensive) equipment that usually accounts for a large uncertainty in loss sources such as atmospheric attenuation. By creating more accurate estimation tools, this uncertainty can be reduced in order to either increase link performance or reduce power costs, or both. The Space Communications and Navigation (SCaN) program relies on such estimations for system analysis and mission planning.

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This project aimed to develop a MATLAB® program that could augment the existing SCaN Link Budget Tool with accurate predictions of atmospheric attenuation of both optical and radio-frequency (RF) signals. The optical attenuation tool was designed according to the SCaN Optical Link Assessment Model Version 5. The RF attenuation tool was designed according to the International Telecommunications Union Radiocommunications Sector (ITU-R) atmospheric propagation loss model.

The SCaN Link Budget Tool, with the atmospheric attenuation add-on, will be integrated into the SCaN Center for Engineering, Networks, Integration, and Communications (SCENIC) user interface (UI). In this context, it will be used for both analysis of existing SCaN communications systems and planning of future NASA missions.

2.0 Background

2.1 Link Budget Analysis

Every system has a maximum allowable bit error rate in order for the transfer of data to be considered successful. In order to determine if a system will meet that requirement, a link budget is created. The link budget tabulates all of the various gains and losses, such as transmit power, receiver antenna gain, and path loss, combined with the necessary signal-to-noise ratio for the required bit error rate in order to determine the overall link margin. The link margin is a single value in decibels that described how well a system will be able to meet its requirements. For example, as shown in *Digital Communications* Figure 4.10, a link with a margin of 6 dB might have 95 percent availability while the same link with a margin of 10 dB might have 99 percent availability (Ref. 1).

One of the losses that must be accounted for is atmospheric attenuation. Because the link budget typically represents a worst-case analysis, any inaccuracy in estimation is counted as a larger loss factor. Therefore, an inaccurate or imprecise model for atmospheric attenuation will lead to a smaller link margin which must be balanced by other gains (such as boosting transmit power) or by cutting other losses (e.g., by increasing pointing accuracy). These balances ultimately make the system costlier, wherein a more accurate model will lead to a lower overall cost.

2.2 Radio Wave Attenuation

Multiple atmospheric effects can attenuate a radio signal, including gaseous absorption, beam divergence due to the change in refractivity through the atmosphere, and atmospheric depolarization (Ref. 2). However, above about 10° in elevation attenuation is driven primarily by gaseous absorption, rain, clouds, and tropospheric scintillation. Attenuation mechanisms are similar on both the uplink and downlink.

2.2.1 Gaseous Absorption

Gaseous absorption in the RF spectrum is largely the result of the oxygen and water vapor spectral lines. As shown in Figure 1, these spectral lines create absorption peaks, e.g., around 22 GHz for water vapor and around 60 and 120 GHz for oxygen. The magnitude of absorption is also relative to temperature, pressure, and water vapor density as described in ITU-R Recommendation P.676 (Ref. 3).

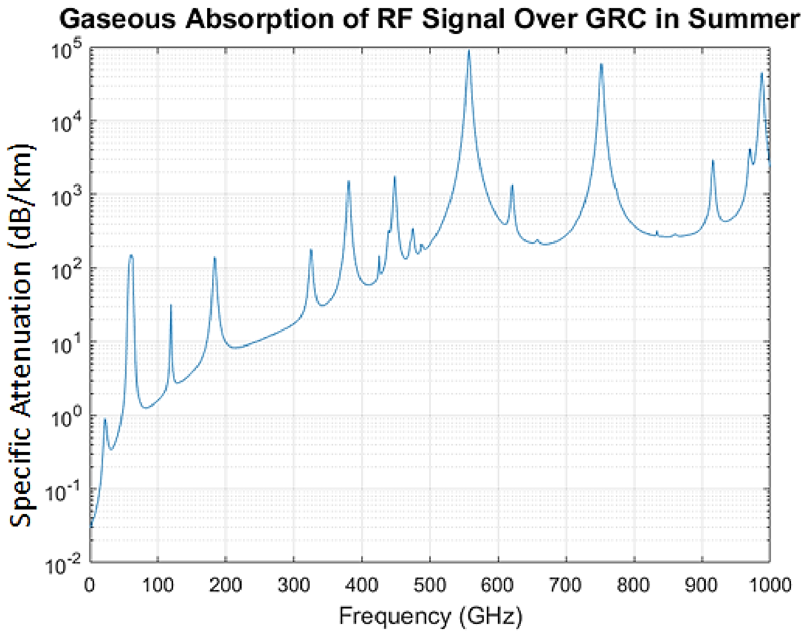


Figure 1.—Example of gaseous attenuation for typical atmospheric conditions over GRC in the summer.

2.2.2 Rain Attenuation

Rain attenuation is one of largest factors in atmospheric attenuation. In many systems with a relatively low availability requirement (e.g., for availability <= 95 percent), for the percentage of time that there is significant rain along the signal path it is assumed that the link will be down, such that for the remaining time the rain attenuation is zero. In higher-availability systems, the system gains must be large enough to account for the large potential loss from rain attenuation. The level of rain attenuation is a function of the path length below the local rain height, local rain height, and signal frequency as descried in ITU-R Recommendations P.618 and P.837-839 (Refs. 2, 4, 5, and 6).

2.2.3 Cloud Attenuation

Attenuation through clouds can be modeled by Rayleigh scattering. The specific attenuation due to clouds or fog depends on the frequency, the temperature, and the liquid water density of the cloud. However, total attenuation along a slant path can be approximated by estimating the total columnar content of liquid water reduced to a temperature of 0 °C, L_{red}, and multiplying by the specific attenuation in a cloud at 0 °C times the cosecant of the angle of elevation as described in ITU-R Recommendation P.840 (Ref. 7).

2.2.4 Scintillation Fade

As a radio signal travels through troposphere, the structure of the refractive index varies. These changes in refractivity bend the wave front in different directions, manifesting as a momentary pointing loss. This scintillation can be accounted for as a single fade depth that corresponds to a worst-case scenario of amplitude scintillation. Scintillation fade is positively correlated with both frequency and path length and negatively correlated with beamwidth. ITU-R recommends estimating fade depth directly from the wet term of the refractivity, Cn, for angles of elevation above 5° (Ref. 2).

2.3 Optical Beam Attenuation

Attenuation of optical signals can be divided into three main categories: optical absorption, scattering effects, and turbulence degradation. Unlike RF propagation, optical attenuation is different for uplinks and downlinks. This is because of the different portion of the beam that experiences turbulence resulting in either de facto beam spreading or in momentary pointing loss.

2.3.1 Optical Absorption and Scattering

While many different types of particles in the atmospheric contribute to optical absorption, the primary sources are gaseous oxygen, water vapor, and carbon dioxide (Ref. 8). These contribute to high-transmittance windows where most in-atmosphere optical communication is performed. The magnitude of absorption is dependent on the density of these molecules and therefore is correlated with other atmospheric conditions such as temperature and humidity.

Optical scattering is dependent on the difference between the signal wavelength and the characteristic radius of the scattering particle (Ref. 9). Particles smaller than the wavelength, such as typical air molecules, cause Rayleigh scattering. Particles whose characteristic radius is approximately equal to the signal wavelength, including most haze/fog, cause Mie scattering. Meanwhile particles significantly large than the wavelength; including most rain, snow, and hail; cause geometrical scattering according to diffraction theory.

Because the characteristic size of fog particles is closest to the wavelengths of most optical signals, optical attenuation is predominantly driven by fog (Ref. 9). Meanwhile, because absorption in the region of most interest to SCaN (i.e., the near-infrared region, particularly around 1550 nm) is controlled by water vapor spectral lines, absorption is also predominantly driven by the presence of fog. Therefore, the SCaN Link Assessment Model Version 5 recommends estimating the total specific attenuation due to absorption and scattering directly from atmospheric visibility (Ref. 10).

2.3.2 Turbulence Degradation

On an optical downlink, turbulence degradation behaves much like in RF communications as described in Section 2.2.4; local variations in the refractivity, described the optical refractivity structure parameter, C_n^2, cause the beam to scintillate around the target ultimately creating a momentary pointing loss effect. However, in an optical uplink, turbulence results in a form of beam spreading in addition to that of normal diffraction. The net result is a drastic increase in overall path loss for a beam attenuated near the start of its path compared to a beam attenuated near the end of its path.

3.0 Methodology

3.1 Radio Frequency Attenuation Tool

The RF tool was developed according to the model described in the ITU-R recommendations listed above in Section 2.2. The tool accepts as inputs the signal frequency, ground station position (latitude, longitude, altitude), angle of elevation, percent chance of exceedance, and antenna diameter. The percent chance of exceedance represents the availability requirement of the system; systems with a 99 percent availability requirement will use a 1 percent chance of exceedance, meaning that the predicted attenuation value will be exceeded 1 percent of the time for those conditions.

The driving factor in estimating RF attenuation is the summing of attenuation from four sources as shown in Equation (1), where A_G is the attenuation due to gaseous absorption, A_R is the attenuation due to rain, A_C is the attenuation due to clouds, and A_S is the scintillation fade depth, all in dB of loss (Ref. 2). Each value is a function of *p* representing the percent of time that the attenuation value is exceeded.

$$A_T(p) = -\left(A_G(p) + \sqrt{\left(A_R(p) + A_C(p)\right)^2 + A_S(p)} \right) \quad (1)$$

The calculations of each of the attenuation sources is done according to their respective ITU-R recommendations; Gaseous attenuation is estimated according to the high-accuracy model in Annex 1 of Recommendation P.676-11 using the latitude-region (low-latitude, mid-latitude, high-latitude), seasonal (summer, winter) reference atmospheres described in Recommendation P.835-5 (Refs. 3 and 11). The rain attenuation estimate uses the annual mean 0 °C isotherm height interpolated for a given location to determine the approximate rain height according to Recommendation P.839-4, the interpolated rainfall characteristics provided by Recommendation P.837-7, and the empirical attenuation relationship provided in Recommendation P.838-3 (Refs. 6, 4, and 5). Cloud attenuation is estimated using ITU-R's monthly statistics for interpolating total columnar water content, L_{red}, and slant-path estimation method described in Recommendation P.840-6 (Ref. 7). Scintillation fade depth is estimated according to section 2.4.1 of Recommendation P.618-12 using the wet term of the refractivity interpolated from annual averages as described in Recommendation P.453-12 (Refs. 2 and 12).

There are two functional modes of the RF tool. The first is a generalized format designed for maximum readability and overall efficiency. The other is an elevation-optimized version designed for computational speed in cases where the ground station parameters are fixed while the angle of elevation changes, such as when a satellite passes over a ground station.

3.2 Optical Attenuation Tool

The goal for the SCaN Link Budget Analysis Tool in version 5 was to reduce estimates of absorption, scattering, and turbulence to a single meteorological parameter (Ref. 13). For absorption and scattering, this tool estimates attenuation directly from the atmospheric visibility for a given wavelength. The tool estimates turbulence degradation from the optical coherence length, ρ_0. In this iteration, the tool uses a rough, worst-case distribution model of visibilities based on 8 arbitrary ground stations around the world for which at least 40 years of NOAA data was available. The resulting distribution function for visibility uses daily-average data for Beijing, China, for percent chances of exceedance of less than 90 percent and for Cleveland, Ohio, for percent chances of exceedance above 90 percent. The current tool estimates ρ_0 using a probability distribution created by Alliss and Felton for a New Mexico ground station (Ref. 14). If the given time of day is between 9:00 a.m. and 3:00 p.m., the tool uses the daytime distribution; for a time between 9:00 p.m. and 3:00 a.m., the nighttime distribution. For all other times, the tool uses an average of the two distribution estimates.

3.3 Verification and Validation Testing

A large body of data exists for radio communication, including verification examples released by ITU-R in order to check that implementations are produced correctly, and long-term studies of attenuation statistics, such as those taken by the Advanced Communication Technology Satellite (ACTS). Contrastingly, significantly less data exists for optical communication. Therefore, most verification and validation testing of the atmospheric attenuation tool thus far was performed on the radio model. However, both programs were developed with strong documentation packages.

3.3.1 Documentation Package

Both the RF and optical programs are provided with the associated reference materials (e.g., the ITU-R recommendations). Each script and function includes a header with a unified format that thoroughly describes inputs and outputs, along with supplemental information such as related files, references, and date created and edited. The code also includes descriptive comments to ensure readability for future developers. Workflows were created that show the relationships between method calls, the potential functional paths for purposes of unit testing, and the logical relationships between parameters and other code segments.

3.3.2 ITU-R Verification Examples

ITU-R has released verification examples for many of the recommendations related to radio propagation, including all of those used for this attenuation model (Ref. 15). However, the verification examples for the gaseous absorption model are not for the high-accuracy method used for this tool (instead they are for the faster, less accurate method described in Recommendation P.676-11 Annex 2) (Ref. 3). Therefore, the estimation for gaseous absorption could only be verified by a visual comparison between a plot of specific attenuation generated using this tool, like appears above in Figure 1, with the similar plot appearing in Recommendation P.676-11 figure 1. The other three attenuation sources were verified using the examples to ensure that the tool matches the ITU-R model.

3.3.3 ACTS Validation Data

The RF attenuation tool was tested against ACTS data collected from 1994 to 1998. The data was provided in the form of a probability distribution function (PDF) and a reverse cumulative distribution function (CDF) for attenuation values with 0.1 dB bins ranging from 0 dB of loss to 40 dB of loss. An example data file is provided in the Appendix. The CDF was used as the input to the attenuation tool for percent chance of exceedance, while the PDF was used to weight the errors between the estimated and measured attenuation value.

4.0 Results

4.1 Radio Frequency Results

As demonstrated in Figure 2(a), for low-percent-exceedance systems (i.e., systems with a high availability requirement) rain attenuation dominates attenuation from other sources, particularly at high angles of elevation, though at low angles of elevation (as shown in Figure 2(d)) attenuation from other sources becomes more significant. Contrastingly, for high-percent-exceedance systems (i.e., systems with a low availability requirement) rain attenuation quickly drops off; following the ITU-R model, rain attenuation is assumed to be zero for percent chances of exceedance greater than 5 percent (Ref. 2). This is because systems that only need to close the link 95 percent of the time or less can afford to go down when there is significant rainfall. Additionally, the low availability system (Figure 2(c) and (f)) estimates a significantly lower total attenuation value than its high-availability counterpart. This confirms that low-availability systems require significantly less power and therefore will be much cheaper than identical systems with a high availability requirement, thus demonstrating an important tradeoff between cost and system performance.

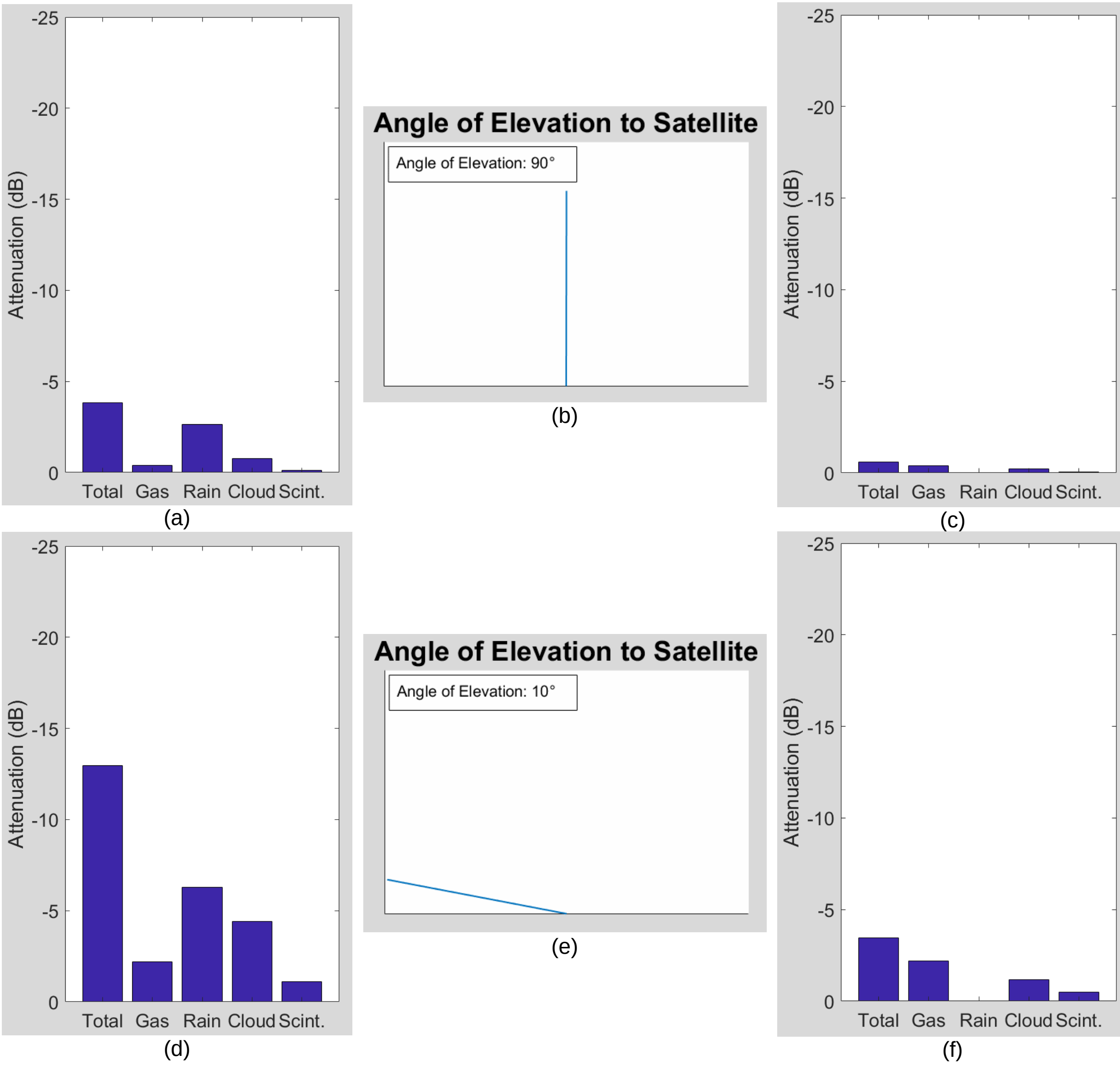


Figure 2.—Top: Estimated attenuation at Ka-band (26.5 GHz) for GRC in July. (a) Attenuation exceeded 1 percent of the time at zenith. (b) Visual representation of pointing angle at zenith. (c) Attenuation exceeded 10 percent of the time at zenith. (d) Attenuation exceeded 1 percent of the time at 10° elevation. (e) Visual representation of pointing angle at 10° elevation. (f) Attenuation exceeded 10 percent of the time at 10° elevation.

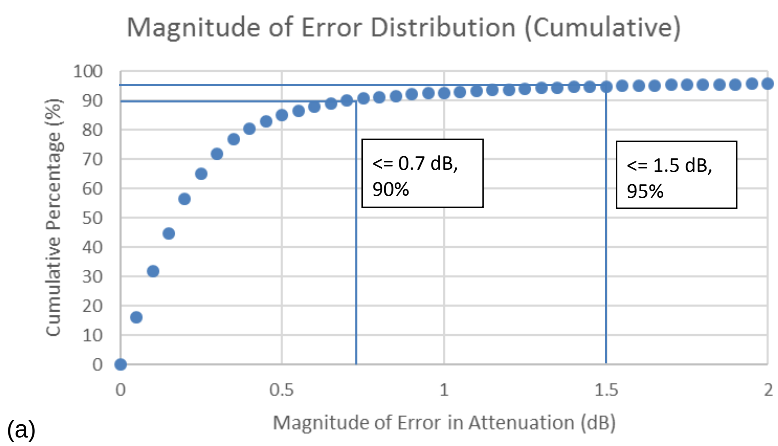
4.2 Optical Results

Because the optical tool has not been well tested, its results are not provided here. However, initial testing of the optical uplink estimate (new to the SCaN Optical Link Budget Analysis Tool in Version 5) shows that the tool estimates more attenuation at zenith than at the horizon. This is the opposite of the expected result (that the beam travelling through the least amount of atmosphere would be attenuated the least). This issue will be corrected before the tool is released.

4.3 Validation Test Results

The average magnitude of error between the RF tool and the ACTS data was 0.27 dB. As shown in Figure 3(a), the RF tool estimated attenuation values to within 0.7 dB of the measured ACTS data for 90 percent of collected data points and to within 1.5 dB for 95 percent. The remaining 5 percent however, contain errors as high as 80 dB and highlight potential issues with the ITU-R model. For example, when current local meteorological data is not available (and for all uses of this attenuation tool) the model uses monthly statistics for cloud density and seasonal, wide-latitude-region statistics for other characteristic such as temperature and pressure, rather than using daily or even time-of-day statistics. Additionally, the model begins to break down at low angles of elevation (the lowest angle of elevation tested with ACTS was 8.1°). Other sources of error could include issues with ACTS data collection.

An important characteristic of model accuracy for link budget purposes is the distribution of under- vs. overestimation. If the total attenuation of a signal is underestimated, the overall link performance will be reduced. However, if the total attenuation is overestimated, signal power is being wasted, and therefore the system cost is being driven unnecessarily high. As shown in Figure 3(b), the average error between this tool and the ACTS data was –0.05 dB, suggesting that the tool tended to underestimate slightly more than it overestimated. However, the full width at half max of the distribution peak was 0.5 dB.



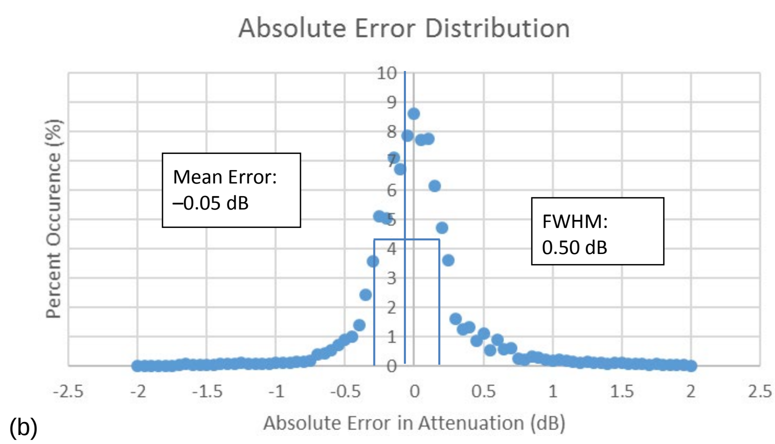


Figure 3.—(a) Cumulative distribution of error magnitude between RF tool and ACTS data. (b) Distribution of absolute error between RF tool and ACTS data.

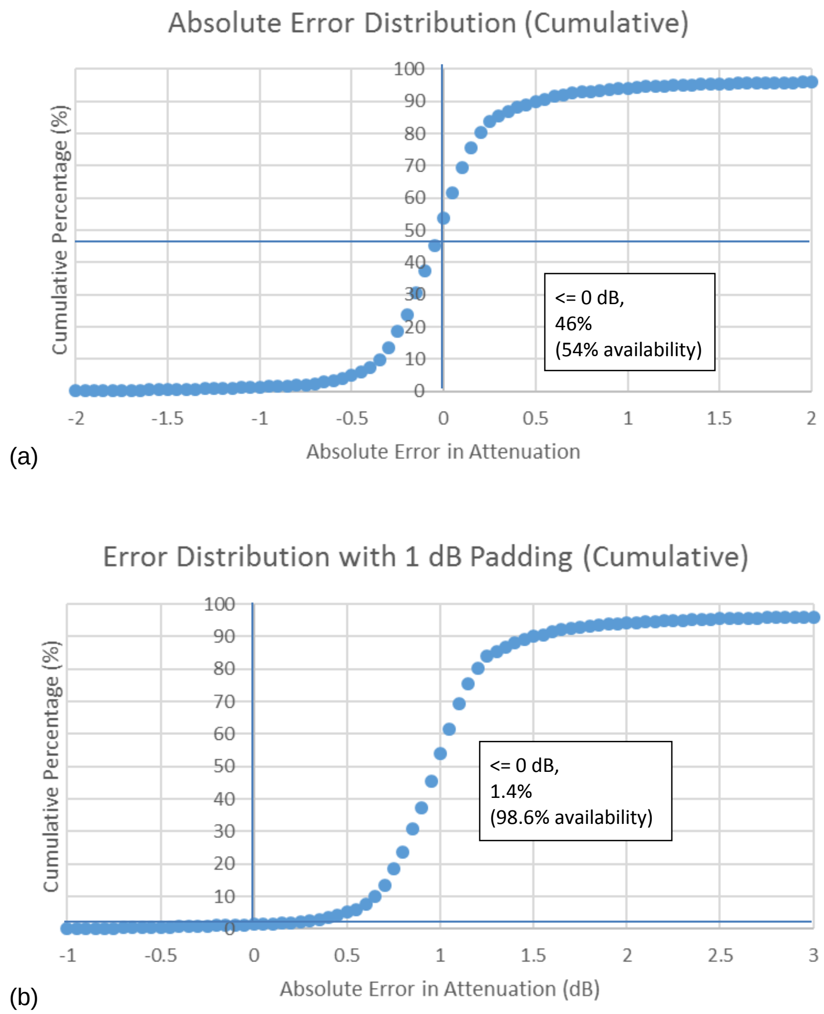


Figure 4.—(a) Cumulative distribution of absolute error between RF tool and ACTS data. (b) Cumulative distribution of absolute error between RF tool with 1 dB of error padding and ACTS data.

As shown in Figure 4(a), if the tool were to be used as is, it would underestimate attenuation 54 percent of the time, leading to a system availability of 46 percent. In order to increase this availability, additional error padding can be added on top of the predicted value. For example, as shown in Figure 4(b), an error pad of 1 dB would raise the availability from 46 to 98.6 percent.

5.0 Conclusions

Ultimately, the RF tool has been verified with the ITU-R model. It has been shown to accurately predict the attenuation values seen in the ACTS data mostly within 0.7 dB. In the future, the model will continue to be tested against validation data, including the results of the ongoing SCaN Propagation Studies, to define its level accuracy and limits of operation. Prior to integration with the SCENIC UI, the optical tool will be corrected and validated with data collected from the Lunar Laser Communication Demonstration (LLCD) mission.

One possible improvement to increase model accuracy would be to compile the information contained in the NOAA database for ground stations around the world to create a global probabilistic reference model for relevant meteorological characteristics to both RF and optical propagation.

Once the RF and optical tools are validated with well-defined limits of operation, they will be integrated into the SCENIC UI for SCaN system analysis and mission planning.

Appendix—ACTS Validation File Example

Figure 5 shows a portion of the ACTS validation data for the Oklahoma ground station in June operating at 20.2 GHz. In row 1, the first entry is the mean attenuation value, the second value is the standard deviation, and the third value is the total number of valid data points taken. In every row that follows, the first column is the attenuation value, the second column is the number of data points that fell in that attenuation bin, and the third column is the reverse cumulative distribution function for that bin.

1	0.8508	1.2625	11049930
2			
3	0.0000	0.0216	100.0000
4	0.1000	0.1337	99.9784
5	0.2000	1.9010	99.8448
6	0.3000	4.1685	97.9438
7	0.4000	6.4071	93.7752
8	0.5000	12.7395	87.3681
9	0.6000	17.2221	74.6286
10	0.7000	16.3703	57.4065
11	0.8000	16.1010	41.0362
12	0.9000	11.5725	24.9352
13	1.0000	5.9903	13.3626
14	1.1000	2.7494	7.3723
15	1.2000	1.0154	4.6229
16	1.3000	0.6607	3.6075
17	1.4000	0.3422	2.9469
18	1.5000	0.2727	2.6047
19	1.6000	0.2280	2.3320
20	1.7000	0.1451	2.1040
21	1.8000	0.1442	1.9589
22	1.9000	0.0958	1.8147
23	2.0000	0.0928	1.7189
24	2.1000	0.0799	1.6261
25	2.2000	0.0766	1.5462
26	2.3000	0.0614	1.4696
27	2.4000	0.0501	1.4082
28	2.5000	0.0521	1.3581
29	2.6000	0.0525	1.3060
30	2.7000	0.0574	1.2536
31	2.8000	0.0473	1.1962
32	2.9000	0.0393	1.1489
33	3.0000	0.0415	1.1096

Figure 5.—Example ACTS validation data file.

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