A Global Model for Estimating Atmospheric Phase Scintillation Statistics

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Abstract

Since 2007, the National Aeronautics and Space Administration (NASA) has been collecting atmospheric phase turbulence data from various NASA ground stations throughout the world. The goal of these measurement campaigns has been to generate statistics to characterize the local site turbulence conditions and their impact on widely distributed ground based antenna arrays. This is of critical importance for the situation of uplink arraying, in which a priori knowledge of the fast varying turbulent conditions of water vapor in the troposphere may not be known, and will impact the power combining efficiency of ground based transmitting arrays. Therefore, the design of these type of systems will be dependent on the local climatology of the particular ground station site. Based on the 30+ station years of data collected characterizing atmospheric phase scintillation statistics at various sites, a global model is presented which attempts to predict the average phase statistics of a generic site based on local surface weather data, such as surface pressure, temperature, relative humidity, wind speed, and median wind direction. A model is proposed and based on a standard log power distribution similar to amplitude scintillation models trained on the existing data sets and shows reasonable accuracy against existing data sets.

Introduction

A ground-based communications architecture for deep space based on arrays of widely distributed reflector antennas provides several inherent advantages over single, large monolithic structures. This includes the following: reduced maintenance costs; graceful degradation of performance; relative ease of meeting the surface accuracy requirements for small apertures at higher frequencies (i.e., Ka-band); N^2 improvement in Effective Isotropic Radiated Power (EIRP), where N is the number of elements in the array; and the enabling of novel communications capabilities, such as multibeam operation. Based on these benefits, NASA has already begun outfitting each of its Deep Space Network (DSN) sites with additional 34-m aperture antennas with the goal of providing comparable/improved performance over existing 70-m aperture antennas via implementation of an array-based architecture. However, the optimal performance of widely distributed ground-based antenna arrays will be naturally limited by atmospheric phase scintillation imposed on the propagating signal. This phenomenon is the result of large amounts of inhomogeneous distributions of water vapor exposed to turbulent air flow conditions in Earth's upper atmosphere (troposphere), which directly leads to variations in the effective electrical path length (phase) of a received or transmitted signal. For receive signals, post processing can readily resolve these issues, since the structure of the signal is well known. However, for transmitted signals, this atmospheric phase scintillation must either be measured in real time (to allow for pre-compensation of the individual antenna element transmissions), or, at a minimum, be statistically characterized to effectively estimate link availability degradation due to this effect. This paper attempts to address the latter point through a proposed global model to predict atmospheric phase scintillation statistics.

Since 2007, NASA Glenn Research Center and the Jet Propulsion Laboratory have been collecting atmospheric phase turbulence data from various NASA ground stations throughout the world. The goal of these measurement campaigns has been to generate statistics to characterize the local site turbulence conditions and their impact on widely distributed ground based arrays. Based on the 30+ station years of data collected characterizing atmospheric phase scintillation statistics at various sites, a global model is presented which attempts to predict the average phase statistics of a generic site based on local surface weather data, such as surface pressure, temperature, relative humidity, wind speed, and median wind direction. A model has been developed and based on a standard log power distribution trained on the existing data sets.

In this paper, we will present the results comparing the accuracy of the predictive model with the measurements taken at various NASA sites throughout the world. This includes the following locations:

- Deep Space Network: Goldstone, California
- Space Network: White Sands, New Mexico
- Space Network: Dededo, Guam
- Deep Space Network: Canberra, Australia
- Deep Space Network: Madrid, Spain
- Kennedy Space Center: Merritt Island, Florida

Phase Turbulence Propagation Campaign

Phase turbulence data was collected at each of the 6 sites across varying numbers of years between 2009 and 2015. This data has been tabulated and submitted to the International Telecommunications Union, following the guidelines set forth in the propagation databanks of Table II-11: Slant path standard deviations of differential path length [1]. Table I, below, provides a summary of the relevant parameters for each site where data was collected and was used in the derivation of the proposed phase turbulence model.

Table I. Summary of Experiment Parameters at Each Measurement Site

Parameter	Goldstone, CA (Venus)	White Sands, NM	Dededo, Guam	Goldstone, CA (Apollo)	Canberra, AUST	Madrid, Spain	Cape Canaveral, FL
Latitude	35.248 N	32.542 N	13.591 N	35.340 N	35.2 S	40.24 N	28.51 N
Longitude	116.791 W	106.614 W	144.840 E	243.126 E	148.98 E	355.75 E	279.37 E
Altitude	1038.8 m	1469 m	127.4 m	964 m	690 m	830 m	3 m
Baseline Separation	256 m	208 m	600 m	190 m	250 m	246 m	191 m
Elevation Angle	48.63 deg	51.8 deg	38.1 deg	47.1 deg	48.2 deg	41.3 deg	55.6 deg
Frequency	20.2 GHz	20.2 GHz	20.7 GHz	12.45 GHz	11.95 GHz	11.95 GHz	12.45 GHz

Site Test Interferometers: Description

A description of the site test interferometer hardware developed by GRC and JPL for the measurement of atmospheric phase turbulence has been thoroughly described in [2-4. A comparison of the statistics generated from the two approaches has also been discussed in [4] and indicate that both techniques, though different in approach, provide comparable results. A brief overview of the interferometric hardware developed by GRC and JPL is summarized below.

GRC Site Test Interferometer

The GRC site test interferometer is configured at Goldstone, CA on a 256 m east-west baseline and tracks a 20.199 GHz beacon on the geostationary communication satellite, Anik-F2, at an elevation angle of 48.5 degrees. A full description of the interferometer hardware is provided in [2] and depicted below in Figure 1.

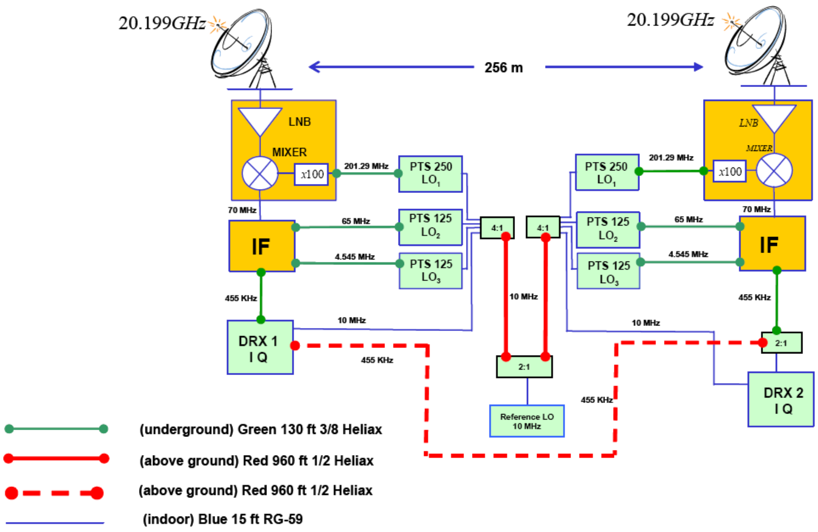


Figure 1 – Block Diagram of Goldstone Site Test Interferometer

Each element of the interferometer consists of a 1.2 m offset-fed parabolic reflector with antenna half-power beamwidth of 0.7 degrees. A 10 MHz GPS-disciplined Rubidium oscillator provides the reference timing for all operations. Thermal control of the Radio Frequency (RF) enclosure box and Intermediate Frequency (IF) enclosure box is maintained at an internal temperature of 49°C, independent of outside weather conditions. The unmodulated beacon signals at 20.199 GHz are received, amplified, and down-converted in two stages: first to 70 MHz in the RF feed box, then to 455 kHz in the IF box. These 455 kHz signals are sent to the indoor facilities for Analog-to-Digital (A/D) conversion (3.64 MHz sampling rate, with 524,288 samples) and further signal processing. From the spectrum, a DSP algorithm locates the carrier peak and determines its frequency domain in-phase (I) and quadrature (Q) components. These values are stored at a sample rate of 1 Hz every 24 hours and written to a text file. Laboratory tests indicate the interferometer system is capable of resolving phase differences down to 1.8 deg rms.

JPL Site Test Interferometer

The JPL STI design is that of an equal-arm white noise interferometer which makes use of a satellite's wideband digital TV broadcast signals. This design uses two (or more) 0.84-m diameter reflector antennas and associated electronics to receive the broadband signals emitted by the Ciel 2 geostationary broadcast satellite at an orbital longitude of 129°W, at an elevation angle of 47° and center frequency of 12.45 GHz. The received signals are mixed with LO signals carried on optical fiber from the central processor rack located within an environmentally-controlled building. The resulting IF signals are brought back to the indoor signal processing rack on separate optical fibers where they are cross-correlated using analog I-Q mixers that output in-phase (I) and quadrature-phase (Q) components of the cross power. The outputs of the IQ mixers are digitized and averaged over each 0.1 s interval; these are the raw observables of the instrument which are recorded in real time to a local disk drive, and periodically downloaded via TCP/IP connections to other computers for further processing and analysis. Measurements from other instruments at the site (or nearby) are also downloaded, such as from water vapor radiometers (WVRs) and meteorology stations.

Phase Turbulence Prediction Model Procedure

The primary driver for phase scintillation on an earth-space link is due to the effect of atmospheric water vapor turbulence in the form of refractive index fluctuations along the signal path. Herein, a physical based model is implemented which first estimates the expected value of the path averaged microwave refractive index structure constant, C_n^2, for a given location based on surface meteorological measurements and standard profiles of temperature, pressure, and water vapor. The path averaged C_n^2 value is then transformed to a site-specific reference phase, which is related to the saturation rms phase (i.e., reference rms phase at the outer scale of turbulence) measured by a site test interferometer on a fixed baseline. A log-polynomial fit of the measured phase statistics data, normalized by the site-specific reference phase, is then performed to derive a global statistical model for the prediction of the rms phase statistics for some percentage of time, p, for a given site. The following steps are utilized in the implementation of this model.

Step 1: Input Parameters

Inputs:

h0:	Altitude of Site (km)	
z:	Height above mean sea level (km)	
d:	Antenna Element Baseline Separation (m)	
θ:	Elevation Angle (deg)	
H:	Turbulence Height (km)	ASSUME = 2 km
beta:	Kolmogorov Turbulence Spectrum	ASSUME = between 5/3 and 2/3
γ:	Elevation Angle Scaling Parameter	ASSUME = 1
L0:	Average Outer Scale of Turbulence (km)	ASSUME = 50 m [derived from 1]
P0:	Standard Sea Level Pressure (mbar)	ASSUME = 1013.25 (1 atm)
T0:	Average Surface Temperature (K)	
RH0:	Average Surface Relative Humidity (%)	

Step 2: Utilize Atmospheric Profile Models [5]

Temperature Profile:

$$T(z) = T0 - 6.5(z - h0) \tag{1}$$

Pressure Profile:

$$P(z) = P0\left(\frac{T0}{T(z)}\right)^{-34.163/6.5} \tag{2}$$

Water Vapor Profile:

$$EF = 1 + 10^{-4}\left(7.2 + P0\left(0.0032 + 5.9 \times 10^{-7}(T0 - 273.15)^2\right)\right) \tag{3}$$

$$es = EF \times 6.1121e^{\left(18.678 - \frac{T0-273.15}{234.5}\right)\frac{T0-273.15}{T0-273.15+257.14}} \tag{4}$$

$$E0 = RH0\frac{es}{100} \tag{5}$$

$$\rho 0 = E0\frac{216.7}{T0} \tag{6}$$

$$\rho(z) = \rho 0 e^{-\frac{z-h0}{2}} \tag{7}$$

Water Vapor Partial Pressure Profile:

$$eps(z) = \rho(z)\frac{T(z)}{216.7} \tag{8}$$

Step 3: Calculate Path Averaged Cn2 (derived from [6])

Specific Humidity Profile:

$$q(z) = 0.622\frac{eps(z)}{P(z)} \tag{9}$$

Specific Temperature Profile:

$$Q(z) = T(z)\left(\frac{1000}{P(z)}\right)^{0.2858} \tag{10}$$

Vertical radiofrequency refractive index gradient, M(z) Profile:

$$\frac{dq}{dz} = 0.622\frac{27.663}{216.7}\frac{\rho(z)}{P(z)} - \frac{q(z)}{2} \qquad (11)$$

$$\frac{d}{dz}\ln(Q(z)) = \left(-6.5\frac{1000}{P(z)}\right)^{0.2858} + \frac{\left(\frac{1.8577\times 34.163}{6.5}\right)\left(\frac{1000}{P(z)}\right)^{0.2858}}{Q(z)} \qquad (12)$$

$$M(z) = 77.6\times 10^{-6}\frac{P(z)}{T(z)}\frac{d}{dz}\ln(Q(z))\times\left(1+\frac{15500q(z)}{T(z)} - \frac{15500}{2T(z)}\frac{\frac{dq}{dz}}{\frac{d}{dz}\ln(Q(z))}\right) \qquad (13)$$

Path Averaged Cn2:

$$\overline{Cn2} = 2.8\times L0^{4/3}\left(\frac{1}{1000}\right)^{2/3}\frac{1}{H-h0}\int_{h0}^{H} M(z)^2 dz \qquad (14)$$

Step 4: Calculate Interferometer Saturation Phase (mm) [7]

$$D(\infty) = 1000\sqrt{0.25\overline{Cn2}\times d^{beta}H\frac{1000}{0.043}\csc(\theta)} \qquad (15)$$

Step 5: Derive Phase Scintillation Statistics Curve

$$\Delta\phi(p) = D(\infty)(a1\log(p)^3 + a2\log(p)^2 + a3\log(p) + a4) \qquad (16)$$

where,

a1 = 0.045	a3 = -5.044
a2 = 0.315	a4 = 9.142

The final coefficients for the derivation of the phase scintillation statistics curve are derived from a best fit of the model to the measured data. Figure 2, below, shows the site-normalized differential path length rms statistics and curve fit to statistics from all sites. A beta value of 0.7 resulted in the best fit to the data, with an average rms error calculated for all sites of 0.056 mm.

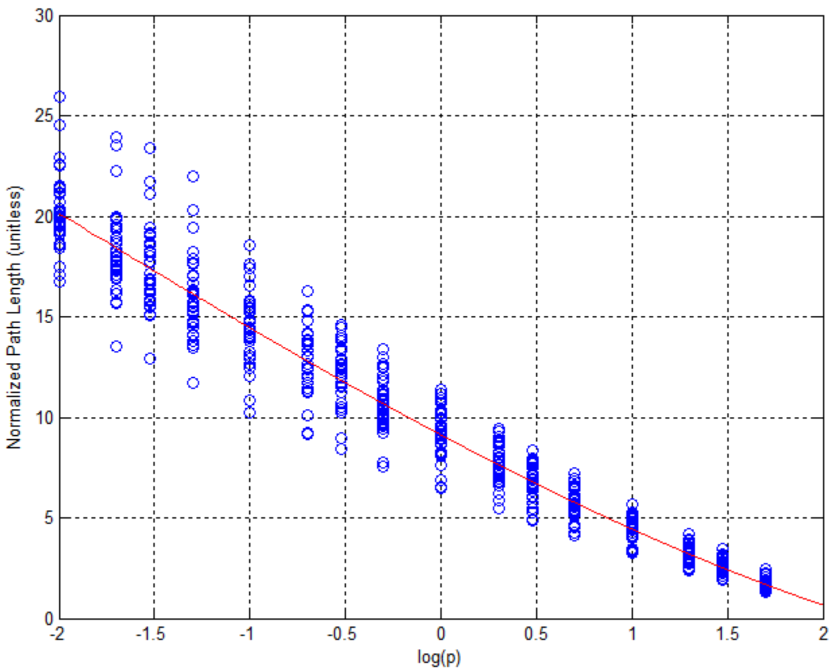


Figure 2. CDF of phase statistics from all sites, normalized by site-specific reference saturation phase (blue circles), with LMS log-polynomial fit to data (red line).

Phase Turbulence Prediction Model vs. Measurements

Preliminary results indicate good agreement with the data collected at these uniquely located sites throughout the world. Figures 3-9 show the results of the predicted differential path length statistics at Goldstone, CA (Venus Site); Goldstone, CA (Apollo Site); White Sands, NM; Guam; Canberra, Australia; Madrid, Spain; and Cape Canaveral, FL, respectively. The assumptions stated in Step 1 for the various input parameters are used, with a fixed beta of 0.7.

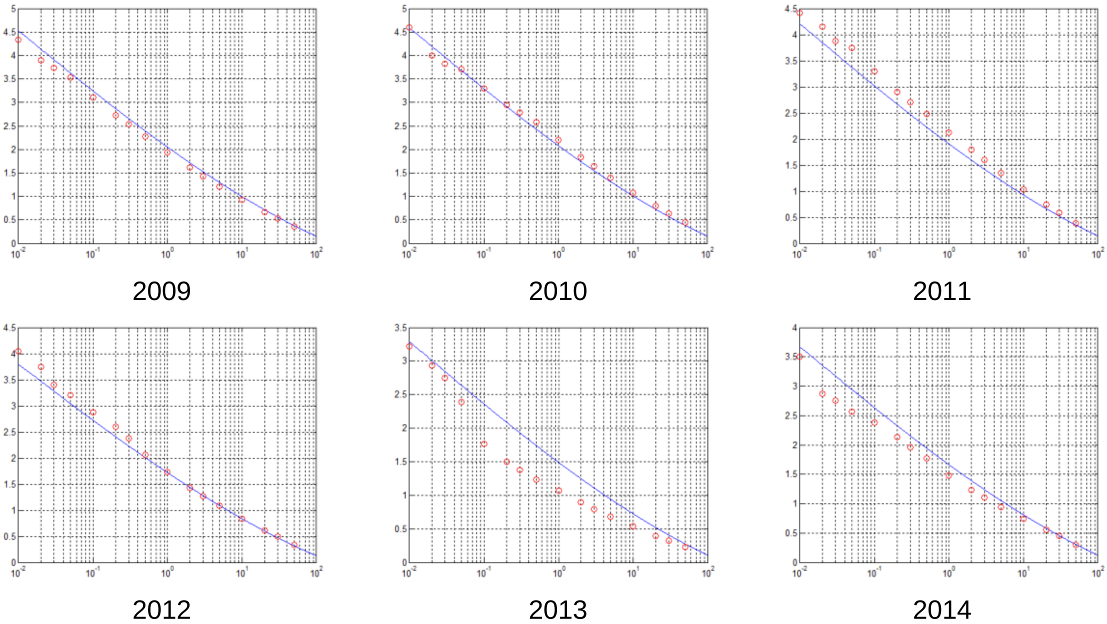


Figure 3. Results of fit for Goldstone, CA (Venus Site) for 2009-2014. Note 2013 and 2014 data are limited as there was a large outage during summer months, which experience the highest turbulence conditions.

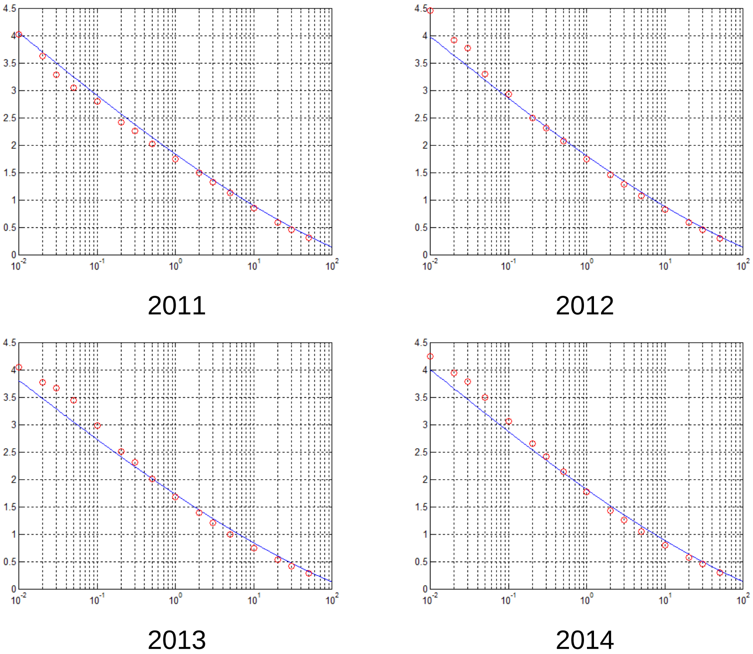


Figure 4. Results of fit for Goldstone, CA (Apollo Site) for 2011-2014.

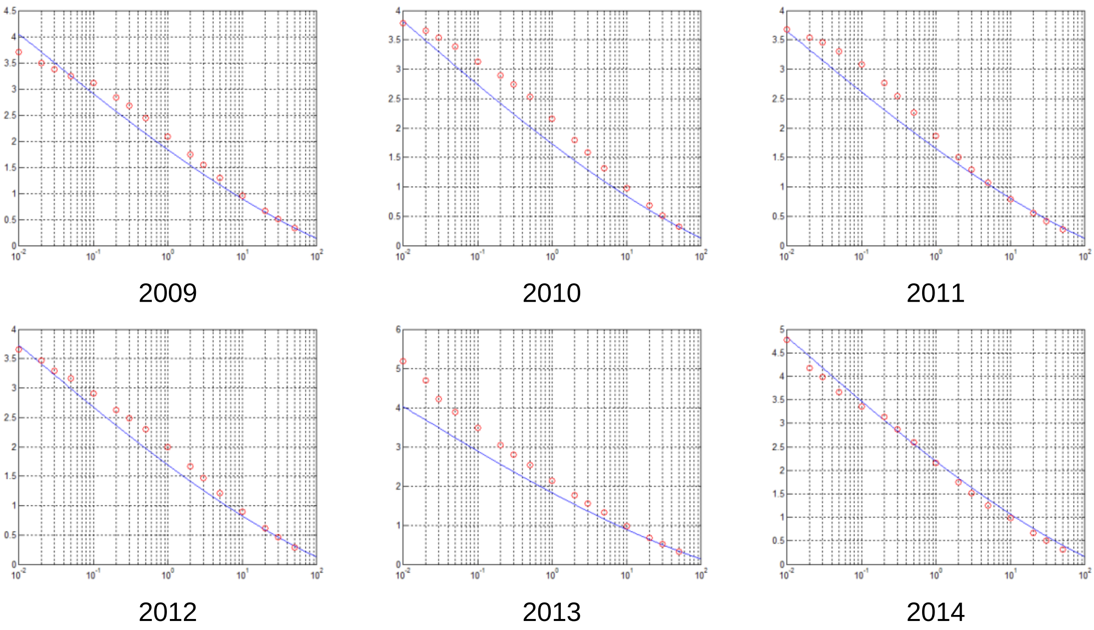


Figure 5. Results of fit for White Sands, NM for 2009-2014.

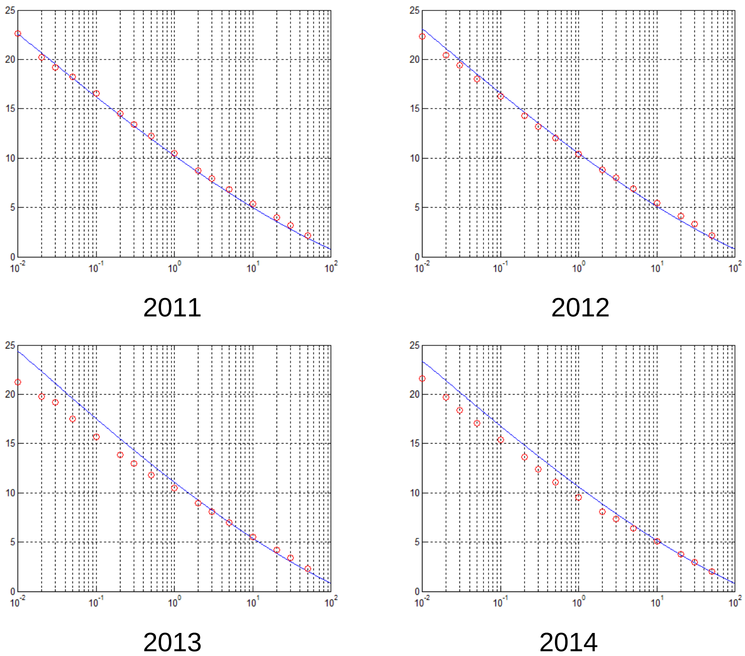
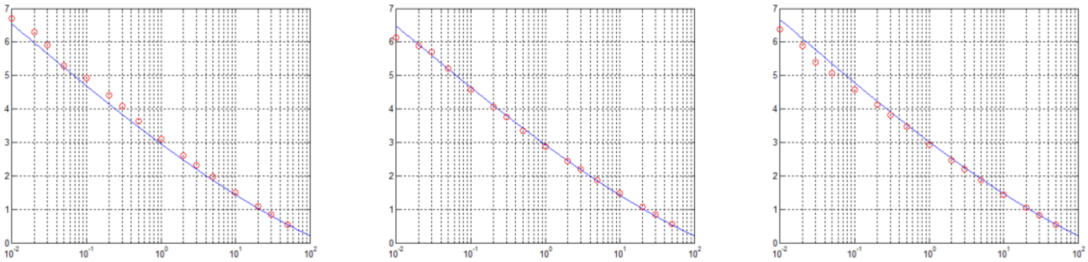
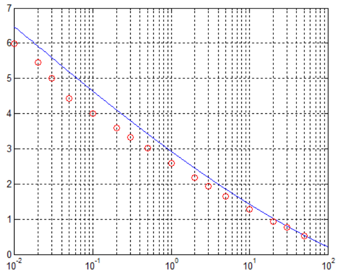


Figure 6. Results of fit for Guam for 2011-2014.



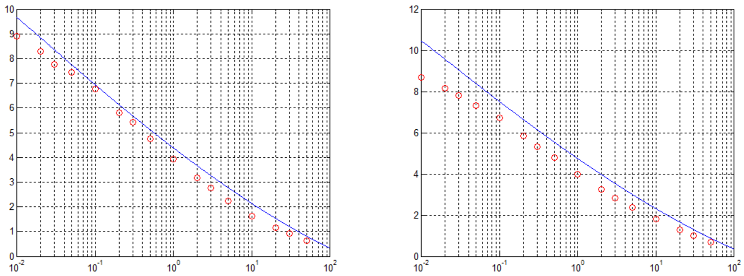
2012 2013 2014

Figure 7. Results of fit for Canberra, Australia for 2012-2014.



2014

Figure 8. Results of fit for Madrid, Spain for 2014.



2014 2015

Figure 9. Results of fit for Cape Canaveral, FL for 2014-2015.

Table II summarizes the rmse performance of the proposed model relative to the data collected. Note that some of the largest errors between the model prediction and data collection is for situations in which the data availability is below about 90%.

Table II. Summary of Model Accuracy per site per year

Site Location	Year	Data Availability	RMSE (mm)
Goldstone (Venus)	2009	97.75	0.1270
	2010	75.9	0.0922
	2011	90.48	0.2132
	2012	90.77	0.1313
	2013	76.0	0.3442
	2014	56.8	0.2316
Goldstone (Apollo)	2011	87.25	0.1077
	2012	93.78	0.1717
	2013	98.26	0.1884
	2014	96.83	0.1656
White Sands	2009	97.4	0.1964
	2010	99.3	0.3099
	2011	98.36	0.2556
	2012	86.74	0.1914
	2013	98.21	0.5312
	2014	80.5	0.1224
Guam	2011	99.8	0.2812
	2012	99.54	0.4069
	2013	95.51	1.4700
	2014	97.0	1.1489
Canberra	2012	92.62	0.1743
	2013	98.57	0.1003
	2014	97.75	0.1664
Madrid	2014	95.98	0.4172
Cape Canaveral	2014	84.0	0.4476
	2015	82.95	0.8959

Conclusions

Herein a global model has been proposed for the prediction of atmospheric-induced phase scintillations statistics. This model is based on physical parameters and is fit to data collected and tabulated within Table II-11 in the ITU SG3 databanks. The model shows reasonable agreement with data, with improvements possible, particularly in the estimation of the Kolmogorov turbulence parameter, beta. This model is expected to be utilized for the effective systems planning of ground-based widely distributed arrays for the determination of losses induced in array power combining for a given site around the world.

References

[1] International Telecommunications Union (ITU) Study Group 3 (SG3) Databanks – Formatted Tables. https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/dtbank-form-tables.aspx

[2] R. Acosta, B. Frantz, J. Nessel, D. Morabito, "Goldstone Site Test Interferometer", 13th Ka and Broadband Communications Conference, Turin, Italy, September 25, 2006.

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[4] D. Morabito, L. D'Addario, R. Acosta, J. Nessel, "An Inter-Comparison of Two Independent Site Test Interferometers Located in Goldstone, California: Initial Study Results", 18th Ka and Broadband Communications Conference, Ottawa, Canada, September 2012.

[5] ITU-R P.835-6, Reference Standard Atmospheres, December 2017.

[6] H. Vasseur, "Prediction of Tropospheric Scintillation on Satellite Links from Radiosonde Data," IEEE Antennas and Propagation, Vol. 47, No. 2, pp.293-301, Feb. 1999.

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