

EFFECTS OF IONOSPHERIC SCINTILLATION ON COMMUNICATION SYSTEMS: GPS AND SATELLITE

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The increasing use of satellite communication and GPS operating at 3 GHz and above can be affected by scintillation. Therefore, the knowledge of scintillation, as well as its effects on communication systems (satellite and GPS) is important in the planning and designing of communication systems links. In the past, most of the scintillation prediction models were based on data collected from temperate climates. These models do not perform well in equatorial and tropical climates due to uniform temperature, high humidity and abundant rainfall. Due to the unavailability of the required experimental setup as a result of huge capital cost involved, the measured scintillation fade and enhancement data were extracted from the reported works in JCSAT3 beacon, Indonesia. The results of predicted and measured scintillation intensity (fade and enhancement) were compared by using a few scintillation models. The results of the statistical analysis show that the Otung model is most suitable for scintillation fade and enhancement predictions with the least %RMS errors.

KEY WORDS: ionospheric scintillation, GPS, satellite, scintillation models, equatorial climates, tropical climates

1. INTRODUCTION

Satellite communication is gaining more attention nowadays due to its rapid deployments, larger bandwidths, and the capability of providing ubiquitous communications [1]. The global positioning system (GPS) is currently the only fully functional global navigation satellite system (GNSS) [2].

Atmosphere affects wireless communication significantly, the prominent layers of atmosphere are troposphere, stratosphere and ionosphere. Among all these, most of the

effect on the communication signal is by the ionosphere [3]. The ionosphere is the ionized component of the Earth's upper atmosphere [4] and is defined as the region between 60 km and 1.000 km above the earth's surface, is produced by ionizing radiation [5].

Atmosphere becomes an important medium for the GPS signal communication path, but ionospheric effects (such as scintillation) degrades the signal as a result of fading effect and presence of much electrons contents [6].

Radio waves propagating through ionosphere experience different attenuation mechanisms such as absorption, reflection, refraction, scattering, polarization and fading/scintillation [7,8].

Scintillation refers to rapid fluctuation in amplitude, phase and apparent direction of arrival of received EM wave [9]. It is fast fading process that depends on meteorological information, such as long term mean temperature and humidity at ground level and also system parameters (frequency, elevation angle and antenna diameter) [10].

Ionospheric scintillation is a rapid change in the phase and/or amplitude of a radio signal as it passes through small-scale plasma density irregularities in the ionosphere. It reduces the accuracy of GPS receiver pseudo-range and carrier phase measurements but also can result in a complete loss of lock on a satellite [11]. It results in random fades and enhancements of the received signals amplitude about a mean level. It is one of the main sources of degradation that poses risk especially to low margin satellite communication system operating at frequencies above 10 GHz. Tropical climate have mainly uniform temperature, high humidity and abundant rainfall [12].

GPS satellites, which are located at semi-synchronous altitude, are susceptible to ionospheric scintillation. Therefore the study of scintillation parameters (fades and enhancement) inside the ionosphere for tropical climate using various scintillation models which were mainly developed in equatorial climate [13] such as the Karasawa model [14], ITU-R model [15], OTUNG model [16], Van De Kamp model [17] among others.

2. OVERVIEW OF EXISTING SCINTILLATION MODELS

Most of the statistical scintillation models are time-dependent and provide ionospheric information as a function of height, location, time and ground meteorological measurements such as temperature, relative humidity among other. Some of the models are:

2.1 ITU-R Model

The ITU-R P.618-12 [15] has proposed a model with frequencies between 7-14 GHz and elevation angle at 5° . The seasonal variation may be predicted by using seasonal average surface temperature and seasonal average surface relative humidity. The

required input parameters needed in the model are signal frequency f (GHz), antenna diameter D (m), path elevation angle θ (degrees), average temperature ($^{\circ}\text{C}$), and average relative humidity. The long-term scintillation variance is a function of relative humidity (%) and temperature t and expressed as:

$$\sigma_{pre} = \sigma_{ref} f^{7/12} \frac{g(x)}{\sin \theta^{1.2}}, \quad (1a)$$

$$\sigma_{ref} = 3.6 \times 10^{-3} + 10^{-4} \times N_{wet} \text{ dB}, \quad (1b)$$

$$g(x) = \sqrt{3.86(x^2 + 1)^{0.914} \sin \left[\frac{11}{6} \tan^{-1} \frac{1}{x} \right] - 7.08x^{0.833}}, \quad (1c)$$

$$a(p) = -0.061(\log_{10} p)^3 + 0.072(\log_{10} p)^2 - 1.71 \log_{10} p + 3.0. \quad (2)$$

Cumulative distribution of scintillation fades is given as:

$$X(p_-) = a(p) \cdot \sigma_{pre} \text{ dB}. \quad (3)$$

The scintillation enhancement formula is not available in ITU-R model.

2.2 The Karasawa Model

The Karasawa model was developed based on experimental data collected from Yamaguchi, Japan (long. 131.5° E, lat. 34.2° N, alt. 19m, 6.5°), over a 1-year period using the INTELSAT-V IOR (60, E) satellite with a horizontally polarized beacon receiver. The satellite has a Cassegrain antenna with an elevation angle of 6.50° , a diameter of 7.6 m, and a data sampling interval of 1 s. In addition, the Karasawa model used a frequency range of 7–14 GHz, which is similar to the ITU-R model while the elevation angle was between 4° and 30° [14].

The predicted scintillation intensity, time percentage factor fades and enhancement are given as:

$$\sigma_{pre} = \frac{0.0228(0.15 + 5.2 \times 10^{-3} N_{wet}) f^{0.45} \sqrt{g(x)}}{\sin^{1.3} \theta} \text{ dB}, \quad (4)$$

$$g(x) = 1.0 - 1.4 \left(\frac{R}{\sqrt{\lambda l}} \right), \text{ for } 0 \leq \left(\frac{R}{\sqrt{\lambda l}} \right) \leq 0.5, \quad (5a)$$

$$= 0.5 - 0.4 \left(\frac{R}{\sqrt{\lambda l}} \right), \text{ for } 0.5 < \left(\frac{R}{\sqrt{\lambda l}} \right) \leq 1.0, \quad (5b)$$

$$= 0.1, \text{ for } \left(\frac{R}{\sqrt{\lambda l}} \right) > 1.0, \quad (5c)$$

$$N_{wet} = \frac{22790H \exp\left(\frac{19.7t}{t+273}\right)}{(t+273)^2}, \quad (6)$$

$$a(p) = -0.061(\log p)^3 + 0.072(\log p)^2 - 1.71(\log p) + 3, \quad (7)$$

$$0.01\% < p \leq 50.0\%,$$

$$P = (100 - p),$$

$$e(p) = -0.0597(\log p)^3 - 0.0835(\log p)^2 - 1.258(\log p) + 2.672, \quad (8)$$

$$50\% < p \leq 99.99\%.$$

Cumulative distribution of scintillation fades and enhancement are given respectively:

$$X(p_-) = a(p) \times \sigma_{pre}, \quad (9)$$

$$X(p_+) = e(p) \times \sigma_{pre}, \quad (10)$$

Only region with low elevation angles were considered in the model, without giving consideration to region with high elevation.

2.3 The Otung Model

The Otung model [18] is based on the scintillation measurements obtained at Sparsholt, U.K. The data were collected over a one-year period using the Olympus satellite 19.77 GHz beacon. Otung model took care of scintillation variables such as intensity, fade and enhancement [18]. The scintillation data were collected using a 1.2 m diameter beacon with a 10 Hz sampling rate. The Otung model is valid for 20/30 GHz frequency range and elevation angles higher than 10° [19]. The model is

similar to the ITU-R model, except for the elevation dependence term being $\sin \frac{11}{12}$ compared to $\sin \theta^{1.2}$ for scintillation fade and enhancement.

$$\sigma_{pre} = \sigma_{ref} f^{7/12} \frac{g(x)}{\sin \theta^{0.917}}. \quad (11)$$

Hence, the scintillation fading and enhancement are given, respectively:

$$a(p) = 3.6 \exp \left(-\frac{0.00095}{p} - [0.4 + 0.002p] \ln p \right), \quad (12)$$

$$e(p) = 3.17 \exp(-0.00095p - [0.272 - 0.004] \ln p). \quad (13)$$

Cumulative distribution of scintillation fades and enhancement are given, respectively:

$$X(p_-) = a(p) \times \sigma_{pre}, \quad (14)$$

$$X(p_+) = e(p) \times \sigma_{pre}, \quad (15)$$

The model is complex and was based on collected data from temperate (low-latitude) regions. So, the weakness of the model is that it could not perform accurately for tropical and equatorial climates.

2.4 The Van De Kamp Model

The Van De Kamp model [17] usually called Kamp model was developed based on experimental data from Helsinki (Finland) over a period of one year at frequency of 19.8 and 29.7 GHz, elevation angle of 12.7° and antenna diameter of 1.8 m. The model is an extension of Karasawa model which include both surface layer and cloud scintillation

$$\sigma_{pre} = \frac{\sigma_{ref} f^{0.45} g(x)}{(\sin \theta)^{1.5}}, \quad (16)$$

$$\sigma_{ref} = 0.98 \times 10^{-4} (N_{wet} + Q), \quad (17a)$$

$$Q = -39.2 + 56W_h. \quad (17b)$$

The scintillation Fade and Enhancement are given, respectively:

$$X(p_-) = a(p) * \sigma_{pre} + e(p) * \sigma_{pre}^2, \quad (18)$$

$$X(p_+) = a(p) * \sigma_{pre} - e(p) * \sigma_{pre}^2, \quad (19)$$

$$a(p) = -0.0515 * (\log p)^3 + 0.206 * (\log p)^2 - 1.81 * (\log p) + 2.81, \quad (20)$$

$$0.01\% < p < 20\%.$$

$$e(p) = -0.172 * (\log p)^2 - 0.454 * (\log p) + 0.274, \quad (21)$$

$$0.01\% < p < 20\%,$$

where W_h is the long term average water content for heavy cloud, $W_h > 0.7 \text{ kg/m}^2$.

3. ANALYSIS OF EXPERIMENTAL DATA

The secondary data [20] collected from a JCSAT3 beacon installed at Bandung, Indonesia from 1999 to 2000 were used for scintillation amplitude (fade and enhancement) of link at 0.01 to 10 percentage of time using the graph provided. The measured one-year cumulative distribution (CDF) of scintillation fade and enhancement from 1999 to 2000 are shown in Figs. 1 and 2 [20].

The scintillation models reviewed in Section 2 were used to predict the scintillation fade and enhancement at 12.247 GHz. The site propagation characteristics are shown in Table 1.

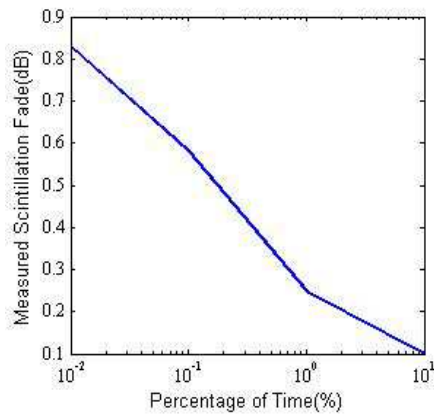


FIG. 1: Measured scintillation fade at 12.247 GHz

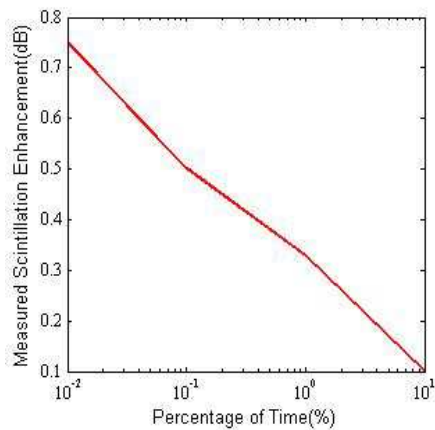


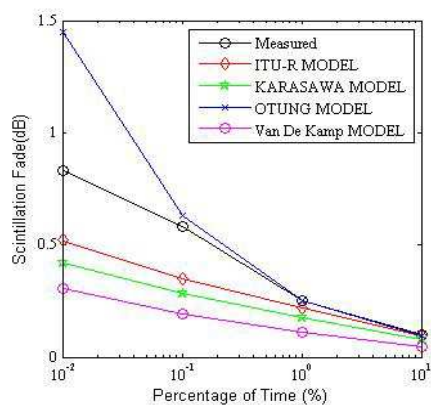
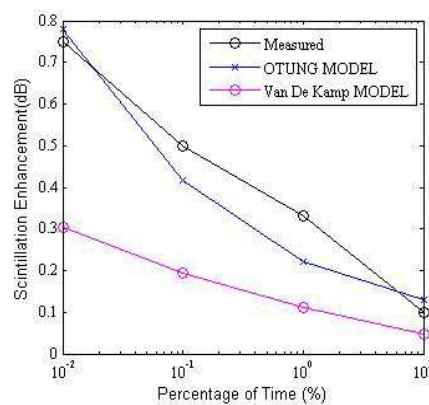
FIG. 2: Measured scintillation enhancement at 12.247 GHz

TABLE 1: Site propagation characteristics [20]

Longitude	107.6° E
Latitude	6.9° S
Altitude	700 m
Elevation angle	64.7°
Frequency	12.247 GHz

4. RESULTS AND DISCUSSIONS

The results of the analysis performed in Section 3 are presented in this section. The comparison of measured and predicted scintillation fade and enhancement at 12.247 GHz are shown in Figs. 3–6, respectively.

**FIG. 3:** Comparison of scintillation fade CDF**FIG. 4:** Comparison of scintillation enhancement CDF

As shown in Figs. 3 and 4, the Otung model predicts the highest scintillation fade and enhancement while Van De Kamp model predicts the lowest scintillation fade and enhancement at 12.247 GHz. Also, the Otung model overestimated the scintillation fade at 0.01% to 1% percentages of time and enhancement at 0.01% percentage of time because of the low frequency. The ITU-R model and Otung model accurately predict scintillation fade at higher percentage of time especially the measured scintillation fade and enhancement at the range of 1% to 10% at 12.247 GHz. The Otung model accurately predicts scintillation enhancement at 0.01% to 10% percentage of time at 12.247 GHz.

All models did not predict measured scintillation fade and enhancement at 12.247 GHz accurately as shown in Figs. 5 and 6.

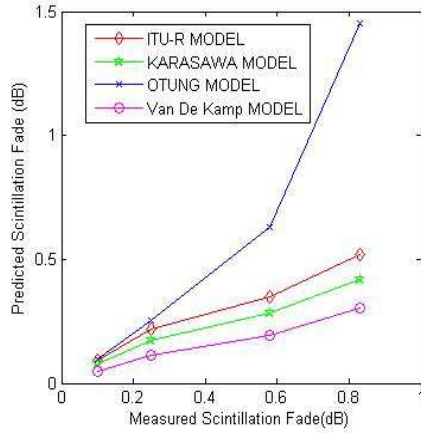


FIG. 5: Comparison of measured and predicted scintillation fade CDF

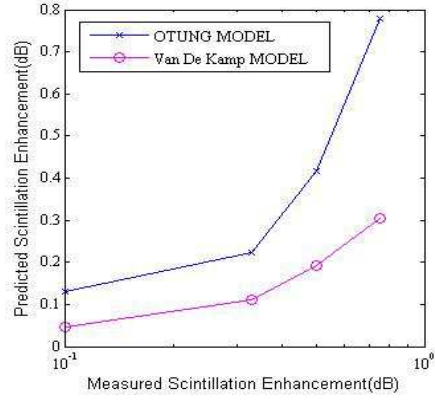


FIG. 6: Comparison of measured and predicted scintillation enhancement CDF

4.1 Models Validation

The performance of each of the prediction models is tested against the measured scintillation fade and enhancement using the Rec. ITU-R P. 311-13 [21] as presented in Tables 2 and 3. The procedure to calculate the mean error, standard deviation and % RMS is given below:

Step 1: Calculate the ratios, S_i , between predicted scintillation fade and enhancement, A_p (dB), and measured scintillation fade and enhancement, A_m (dB), for each

Percentage of time:

$$S_i = \frac{A_{p,i}}{A_{m,i}}. \quad (22)$$

Step 2: Calculate the test variable, V_i , for each percentage of time:

$$V_i = \ln S_i \left(\frac{A_{m,i}}{10} \right)^{0.2} \quad \text{for } A_{m,i} < 10 \text{ dB}, \quad (23a)$$

$$V_i = \ln S_i \quad \text{for } A_{m,i} > 10 \text{ dB}. \quad (23b)$$

Step 3: Calculate the mean error, μ_v :

$$\mu_v = \frac{1}{N} \sum_{i=1}^N V_i. \quad (24)$$

Step 4: Calculate the standard deviation, σ_v :

$$\sigma_v = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_i^2 - (\mu_v)^2)}. \quad (25)$$

Step 5: Calculate the root mean square (R.M.S) value, ρ_v :

$$\rho_v = \sqrt{(\mu_v^2 + \sigma_v^2)}. \quad (26)$$

According to the evaluation procedures adopted by Recommendation ITU-R P. 311-15 [21], the model with lowest standard deviation, σ_v and a lowest R.M.S value, ρ_v for the test variable is the best prediction model. Tables 2 and 3 show the mean value, standard deviation and R.M.S. value of the scintillation model for percentages from 0.01% to 10%. It can be seen in Figs. 7 and 8 that for all models, error varies inconsistently with percentage of time except the Otung model in prediction of scintillation fade which decreases with increase in percentage of time. The Otung model has the most error but more at 1% of time and the Van De Kamp model has the least error, especially at 10% of time this is because the Van De Kamp model considered other meteorological factor (water content for heavy cloud) compared to other prediction models.

TABLE 2: Comparison of percentage errors and R.M.S for predicted scintillation fade

Model	Percentage of Time (%)				Mean error μ_v	Std Dev(σ_v)	%RMS
	0.01	0.1	1.0	10			
ITU-R	-0.9654	-1.0746	-0.8803	-0.9828	-0.9758	0.0690	0.9782
Karasawa	-1.1788	-1.2881	-1.0937	-1.1962	-1.1892	0.0690	1.1912
Otung	0.0607	-0.4878	-0.7275	-0.9607	-0.5288	0.3792	0.6507
Van De Kamp	-1.4998	-1.6632	-1.5421	-1.7146	-1.6049	0.0872	1.6073

TABLE 3: Comparison of percentage errors and R.M.S for predicted scintillation enhancement

Model	Percentage of Time (%)				Mean error μ_v	Std Dev(σ_v)	%RMS
	0.01	0.1	1.0	10			
Otung	0.4802	-0.7830	-1.0768	-0.6644	-0.7511	0.2168	0.7817
Van De Kamp	-1.4238	-1.5535	-1.7719	-1.6904	-1.6099	0.1328	1.6154

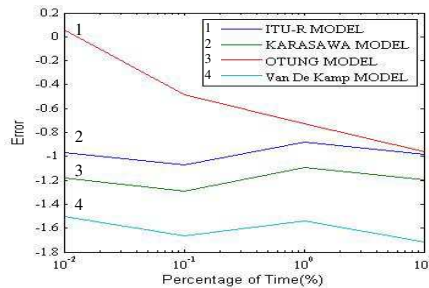


FIG. 7: Errors of predicted scintillation fade CDF

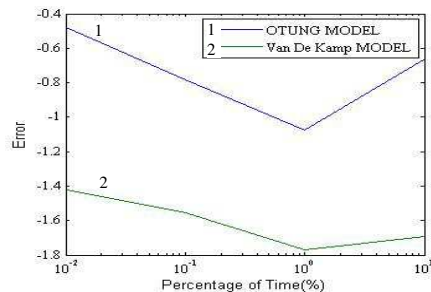


FIG. 8: Errors of predicted scintillation enhancement CDF

As illustrated in Table 2, the Otung model has the least R.M.S value (0.6507%) and Van De Kamp model has the highest R.M.S value (1.6073%) for scintillation fade. Table 3 shows that Otung model has the least R.M.S value (0.7817%) and the Van De Kamp model has the highest R.M.S value (1.6154%) for scintillation enhancement. These results show that the Van De Kamp model is the least suitable model of all the models for predicting scintillation fade and enhancement in the investigated equatorial and tropical climate.

5. CONCLUSIONS

The scintillation enhancement is not available in the ITU-R model. The range of the Karasawa model for scintillation enhancement is outside the scope of study, i.e., $50\% < p \leq 99.99\%$. Scintillation can degrade the quality of signal reception in satellite communication and GPS receivers also suffer from losing lock on most of the satellite. Otung Model has the lowest % R.M.S values of 0.6507 and 0.7817, hence, the Otung model seems to be the most suitable as compared to other prediction models for scintillation fade and enhancement. The results presented in this study have demonstrated the usefulness in planning and designing of reliable satellite and GPS communication links in equatorial and tropical climates.

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