Development of Cloud Attenuation Model for Satellite Network Links Performance Improvement

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ABSTRACT

This paper provides a review of cloud attenuation modelling, using as a case study, a typical research effort done to construct a cloud attenuation model for tropical Ota (6.7^{o}N, 3.23^{o}E), southwest Nigeria. Improvement of the satellite services availability in every locality is fundamental. All local climate areas must build useful climatic models, such as the cloud attenuation model, which can be used to determine local link margins for satellite network services in particular locations and serve as correlative resources to applications on global satellites. Effects of suspended water droplets (SWD) and suspended ice crystals (SIC), which make up clouds, are a significant concern in the design and successful operation of satellite communication systems at frequencies above 3GHz, because the hydrometeors significantly reduce the services availability as frequency increases. For the purpose of simulating cloud attenuation at a station, the climatic initial and boundary conditions are taken into account as well as the cloud's numerical representations to derive the cloud's parametric system equation. The numerical representations are based on climatological and radiometric data that have been gathered through well-designed experiments, in which cloud parameters are measured using radiance changes tracked by satellites and visually observed surface stations on land and ships in the ocean. The ongoing research project started with an examination of eight foundational cloud models at the station, through investigation of the radiosonde and cloud cover data. Then, the study of spectrum analyzer's data on signal attenuation that has been gathered over a three-year period is examined. The station data

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from the beacon transmission experiment to and from the Astra satellite at 28.2^{o}E were then analyzed and modelled. This entails comparing the cumulative attenuation distribution curves of the spectrum analyzer data and those of the station's existing cloud models with the cumulative attenuation distribution curves of output data generated by each run session of the station simulation equation program. The general representation of the station cloud attenuation model is given, as well as further modelling development and future work. A single global satellite based climatic model is desirable, where modular algorithm would be used to integrate the various climatic area models.

Keywords: Cloud attenuation model; satellite services; telecommunication applications; climatic model.

1. INTRODUCTION

Since a few decades ago, satellites have become absolutely essential in modern society. Their field of application is expanding constantly. Nowadays, they are widely used in various areas such as navigation, weather forecasting, disaster management and telecommunications. In fact, geostationary telecommunication satellites can offer global coverage, which makes them particularly attractive for bringing broadband Internet in isolated areas where the access to terrestrial networks remains very limited [1,2]. Satellite service providers are constantly looking for broader bandwidth due to the rising demand for satellite services and the ensuing increases in bandwidth needs for the existing spectrum of telecommunication applications. Directly proportionate hydrometeor attenuation is phenomenally accompanied by the resulting increases in transmission frequency [3,4]. Cloud attenuation stands out from other hydrometeors because it is more persistent and stable in the atmosphere, and on any given day, roughly half of the Earth is covered by clouds. A cloud consist of very small mass water droplets, ice crystals, super cool water or some suspended particles present in atmosphere. The formation of clouds is due to saturation of atmospheric air, which is the result of air cooling at dew point [5]. Previous study has demonstrated that transmission frequencies above 3 GHz are associated with a rise in signal propagation impairment in the troposphere due to atmospheric hydrometeors' dielectric relaxation and that the impact of cloud attenuation at Ku band (12/14) GHz, Ka band (20/30) GHz, and above has been established as quite important [6,7,8]. Operating at high frequency bands enables antenna elements size reduction, and moreover it becomes feasible to have multiple antennas not only at base stations, but also on mobile handsets – for producing sufficiently high signal to noise ratio [9,10].

However, satellite climatic models' algorithms need be correlated with accurately developed earth surface local climatic zones' models, as the algorithms requires various experimentally determined input parameters. For example on the Moderate Resolution Imaging Spectrometer (MODIS) which is a 36-bands scanning radiometer flying on the National Aeronautics and Space Administration (NASA)'s Terra and Aqua platforms, differences between model derived and measured clear sky radiances are mitigated with a radiance bias adjustment to avoid height assignment errors [11].

Measureable parameters of an electromagnetic signal are the signal amplitude, frequency, phase, bandwidth and polarization; while the cloud properties affecting radio propagation are the amount of cloud liquid water (SWD) and ice crystals (SIC), cloud top and base heights, and horizontal extent. The ten cloud types have been classified into three based on their normal range of vertical heights of existence in the atmosphere relative to the earth surface, namely – low, middle and high clouds [12]. Attenuation is reduction of the amplitude of a propagating signal with respect to distance travelled along its transmission path and cloud attenuation is due to relaxation losses in the molecules of the SWD. Dielectric relaxation is the inability of the molecules of the dielectric as water to become or remain aligned with the direction of the electromagnetic field applied to it by the signal. Relative to relaxation oscillator circuit, energy loss in the dielectric molecules occur through random interference of generated electromagnetic waves with the interacting signal, since such circuit generate electromagnetic waves by its periodic conduction and non-conduction cycles [13, 14,15].

The provision of broadband internet access through satellites to millions of commercial and individual users globally through small terminals as POS terminals and hand phones has inestimable socio-economic values. Thus improvement of the satellite services availability in every locality is fundamental. This requires studies at each local climate zones to develop relevant models as effective cloud attenuation model, which can be used to reliably estimate needed parameters' values for global satellites applications. Numerous cloud models have been independently developed over the last eight decades based on Rayleigh scattering and Mie absorption theories, using empirical data and assumptions that cloud cover horizontally and vertically are uniform, and that clouds are non-precipitating. Foundation cloud models include Gun and East Model, Staelin Model, Slobin Model, Liebe *et al.* Model, Altshuler and Marr Model, Salonen Model, Salonen and Uppala Model and the ITU-R Model [16, 17, 18, and 19].

2. CLOUD COVER DATA ACQUISITION

This case study station's observatory is at a practical visibility height, having clearance altitude over high rise objects as buildings or trees that may obstruct the view of the clouds. The observation is conducted at fixed regular times daily – 9 A.M. and 3 P.M., considering local times of free or least obscurity or any fixed light interference. A digital camera with correct date and time setting is used to record a short video for each observation view. Each assessment view of the total amount of cloud entails determination of cloud amount in cloud layers between the cloud base and maximum vertical distance visible for each of the four sky quadrants during each of the fixed daily observation times. On the use of instrument to determine the cloud amount surrounding a station, a reliable directly measuring device is not common up to date, however multiple sensors method exist. Available devices for the multiple sensing methods are ceilometer, pyrometer and sky camera. Multiple ceilometers may be used in clustering technique to determine cloud amount, this procedure require more than three ceilometers with sky conditions multiple-ceilometer-algorithm. Similarly, the pyrometers in multiple sensing deployment configurations operate as passive remote sensing infrared thermometer.

In the satellite observations segment of cloud cover determination for a station, radiance changes measured by satellites are interpreted using climatic models' algorithms. For example the MODIS on the National Aeronautics and Space Administration (NASA) earth observing satellites system consisting of Terra and Aqua platforms, provide unique measurements for deriving global and regional cloud properties. Single spectra band approach by earlier satellites programs in estimating global cloud cover variations often under estimate thin or semi-transparent clouds as cirrus. MODIS multispectral observation capacity at high spectra resolution facilitated seasonal and annual changes studies of clouds, particularly the semi-transparent clouds [20].

3. CLOUD COVER DATA ANALYSIS

The cloud cover of a station is a graphical relationship that shows the monthly variation of the percentage of cloud amount on the station's sky dome, thus daily total cloud amount need be accurately estimated by visual method or by an efficient cloud estimating instrument, and the monthly average total is computed through each year. Typical monthly record of the visual cloud data is shown in Table 1. Also, Figs. 1 and 2 shows the station cloud cover results – visual and satellite. At the Ota station, data from SRB, ISCCP, CERES, TERA-AQUA-MODIS, CALIPSO and CLOUDSAT satellites were downloaded and processed. Analyses of each set of satellite data were carried out and their output charts displayed in the Fig. 1 are used for corroborating the surface visual cloud cover result in Fig. 2.

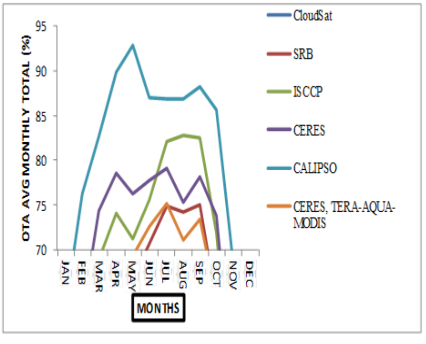

Fig. 1. Station satellites cloud cover

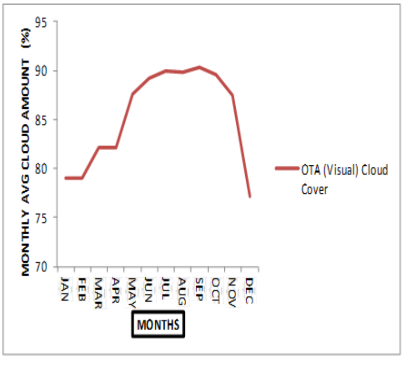

Fig. 2. Station cloud cover

Table 1. Typical monthly record of visual data measurement

	EAST (%)			SOUTH (%)			WEST (%)			NORTH (%)		AVG.	TOTAL	CLOUD TYPES PRESENT			
DATE	**A.M.**	**P.M.**	**AVG.**	**A.M.**	**P.M.**	**AVG.**	**A.M.**	**P.M.**	**AVG.**	**A.M.**	**P.M.**			**E**	**s**	**w**	**N**
1-Aug	24	23.5	23.75	23.5	23.5	23.5	23.5	22.5	23	23.5	23	23.25	93.5	Ns; Sc	Ns; Sc	Ns_s; Sc	Ns; Sc
2-Aug	24	23.5	23.75	23.5	23.5	23.5	23.5	24	23.75	24	24	24	95	Ns_s; Ns, Sc	Ns; Ns, Sc	Ns_s; Ns, Sc	Ns, Cu; Ns, Sc
3-Aug	23.5	24	23.75	23.5	24	23.75	23.5	23.5	23.5	23.5	23.5	23.5	94.5	Ns; Ns,	Ns; Ns,	Ns_sNs,	Ns; Ns,
4-Aug	23	20.5	21.75	22.5	22.5	22.5	22.5	23.5	23	23	22.5	22.75	90	Sc, Ns; Sc	Sc, ; Sc	Sc, ; Sc, Ns	Sc, ; Sc
5-Aug	21	23	22	20	22.5	21.25	20.5	24	22.25	21.5	23.5	22.5	88	St, ; Sc	St, ;Sc	St, Ac ; Sc	St, Ac ; Sc
8-Aug	21	23	22	22	23.5	22.75	22	24	23	22	23	22.5	90.25	Sc; Sc	Sc; Sc	Ns, Sc; Sc	Ns, Sc; Sc
9-Aug	24	22	23	23.5	22.5	23	23	22.5	22.75	24	23	23.5	92.25	Ns, Sc; Sc	Ns, Sc; Sc	Ns, Sc; Sc	Ns, Sc; Sc
10-Aug	20	21	20.5	20.5	20.5	20.5	21.5	22.5	22	22.5	22.5	22.5	85.5	St; Sc	St, Sc; Sc, St	St, Sc ; Sc, N	St, Sc; Cu, St
11-Aug	23.5	23	23.25	22.5	21.5	22	23	22.5	22.75	23	21	22	90	Ns, Cu; Sc	Sc, ; Sc	Sc, ; Sc	Sc, ; Cb
12-Aug	23	21.5	22.25	23	21.5	22.25	22	20.5	21.25	21	20.5	20.75	86.5	Ns, Ac; Cu, S	tSc; Cu, St	Sc; Sc	Ns,Ac,As; Cu
15-Aug	24	24	24	23.5	23.5	23.5	24	23	23.5	23.5	23	23.25	94.25	Ns, AcCu; Ns	Ns, AcCu; Ns	Ns, AcCu	Ns, AcCu; Ns
16-Aug	24	23	23.5	23	22.5	22.75	23.5	22	22.75	24	22	23	92	Ns; St	Ns ; St	Ns ; St	Ns ; St
17-Aug	23.5	23.5	23.5	22	23	22.5	22	23.5	22.75	23	23.5	23.25	92	Ns; Sc	St; ;Sc	St, ; Sc	Sc, ; Sc
18-Aug	22	21.5	21.75	21	22	21.5	21	22.5	21.75	20.5	22	21.25	86.25	As,,Ac ; Sc	As, Ac ; Sc	As, Ac ; Sc	As, Ac ; Sc
19-Aug	23	22.5	22.75	23	23.5	23.25	24	23.5	23.75	24	23.5	23.75	93.5	Sc, ; St, Sc	Sc, ; St, Sc	Sc, ; Ns	Sc, ; Ns
22-Aug	24	20	22	23.5	20.5	22	23.5	21	22.25	23.5	20.5	22	88.25	Ns; St	Ns; St	N_s; St	Ns ; St
23-Aug	23.5	20	21.75	22.5	21	21.75	22.5	21.5	22	23	21	22	87.5	Ns, St	Sc	Sc	Sc
24-Aug	24	21	22.5	23.5	23.5	23.5	23	23	23	22.5	23	22.75	91.75	Ns; Sc	Sc, ; Sc	Sc, ; Sc	Sc, ; Cu
25-Aug	20.5	23.5	22	20.5	23	21.75	20	23.5	21.75	20.5	23	21.75	87.25	As, Ac; Ns, Cu	As, Ac; Ns, Cu	St; Cb	As, Ac; Ns, Cu
26-Aug	22.5	23	22.75	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	93.25	Sc, ; Sc	Sc, ; Sc	Sc, ; Sc	Sc, ; Sc
29-Aug	22	20.5	21.25	22	21	21.5	22.5	21.5	22	23	21.5	22.25	87	St, ; Ac, Cu	St, ; Sc	St, ; Sc	St, ; St, Cu
30-Aug	20	24	22	20.5	20.5	20.5	21	23.5	22.25	21.5	23.5	22.5	87.25	St, ; Ns	St, ; Cb	St, ; Ns	St, ; Ns
31-Aug	20	20.5	20.25	20.5	21	20.75	21	21	21	20	20.5	20.25	82.25	St, ; St	St, ; St	St, ; St	St, ; St
AVG													89.913				

4. RADIOMETRIC DATA ACQUISITION

Radiometric devices commonly deployed on surface stations for measurement of propagation impairment includes Millimetre Wavelength Cloud Radar (MWCR), Microwave Radiometer (MWR), 9103 Spectrum Analyser, Laser Ceilometer and Micropulse Lidar, and Weather Surveillance Radar – 1988 Doppler (WSR – 88D). In a typical observation station, at least one of these listed devices will be required for radiometric data collection and radiosonde data or satellite radiometric data will be needed for corroboration. In this Ota – CU station case study, fifty - three years radiosonde observations data was acquired, filtered and extracted to obtain each cloud layer's values for the required primary parameters – pressure (hPa), temperature (K) and calculated geopotential height (m); and every minute measurement and logged data of signal attenuation for over three years- using spectrum analyser, has been carried out.

5. RADIOMETRIC DATA ANALYSIS

Attenuation distribution and statistics for each of the eight listed cloud models were computed from the processed radiosonde data. The station logged spectrum analyser data (SPAD) were extracted and analysed under two conditions - rainy and non-rainy days, using the climatological device's monthly data for each year. Then all the processed data over three years were integrated and the integrated data cumulative distribution curve obtained. The integrated cloud attenuation cumulative distribution curve has similar curve geometry with those of the 2014, 2015 and 2016 respectively. Each distribution curve is a result of raw data processing using Matlab and electronic spread sheet programming to implement several layers of required station conditions such as climatic and spectra conditions. The resulting cloud attenuation cumulative distribution curves at 12.5 GHz for each of the existing cloud models and that for the spectrum analyser data were compared in Figs. 3 and 4.

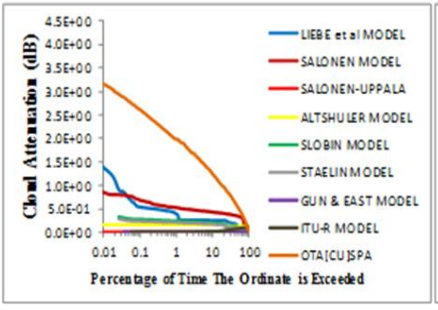

Fig. 3. SPAD and cloud models distribution curves at 12.5 GHz

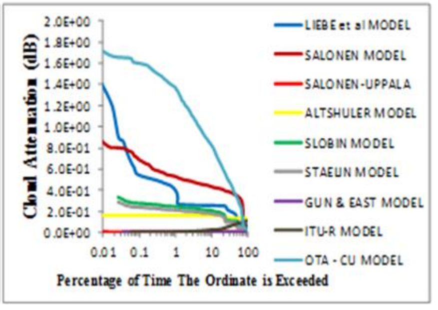

Fig. 4. Cloud attenuation models distribution curves at 12.5 GHz

6. CLOUD ATTENUATION MODELLING RESULT

The SPAD integrated attenuation cumulative distribution curve approximates a straight line of slope - 0.31011 and intercept 3.089 dB, which appear as a resultant constructive interference of some pairs of periodic functions of comparable amplitudes. A possible general mathematical representation of these observations is equation (1).

$$Ac\ (WL, \theta, t, f) = f(x) = a\cos(x) + b\sin(x) = A\cos(x - \alpha) \qquad (1)$$

where A = $(a^2 + b^2)1/2$ and α = tan-1(b/a) in the range 0 < α < π/2; considering the variables of the cloud attenuation (Ac) - cloud liquid water content (W_L) of each cloud layer series (CLS) and their temperature (t), angle of elevation (θ) and frequency (f) of propagating radio signals; while x is considered to be cloud layer specific attenuation coefficient (K_L) defined in the International Telecommunication Union Recommendation (ITU-R) P.840 – 4, corresponding to the frequency function g(f) in the Salonen – Uppala procedure. The definition is based on a mathematical model, using Rayleigh scattering and a double – Debye model for dielectric permitivity Ɛ (f) of water (ITU-R, 2009; Salonen – Uppala, 1991). Considering geometry of the relatively gentle slope of the SPAD line, the range of x should be 0 to π rather than 0 to π/2, hence x = 0.5 K_L. Using the straight line analogue, a = - 0.31011, b = 3.089 dB, as directly measured from the graph; computed A = 3.08915 and α = - 1.560796 are typical values used in the simulation equation (equation 2) program.

$$Ac = AW_L COS\ ((0.5K_L) + \alpha) \qquad 0 \le KL \le \pi \qquad (2)$$

Hence equation (2) is a general representation of the new cloud attenuation model for the station measured data distribution (SPAD). The station cloud attenuation cumulative distribution curves were compared with the cumulative distribution curves of the foundation models at various higher frequencies in Figs. 5 – 8.

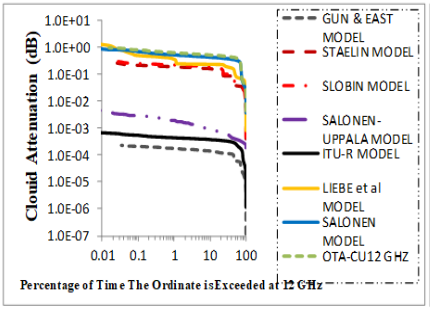

Fig. 5. OTA-CU cloud model and foundation models at 12 GHz

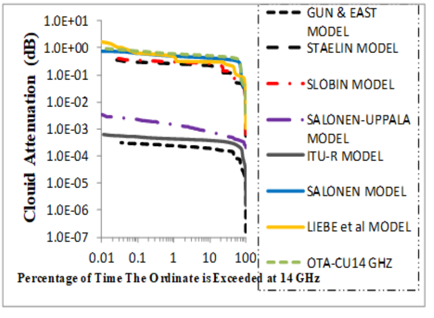

Fig. 6. Ota-CU cloud model and foundation models at 14 GHz

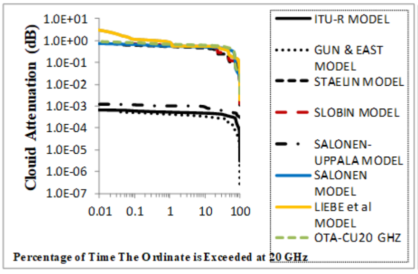

Fig. 7. OTA-CU cloud model and foundation models at 20 GHz

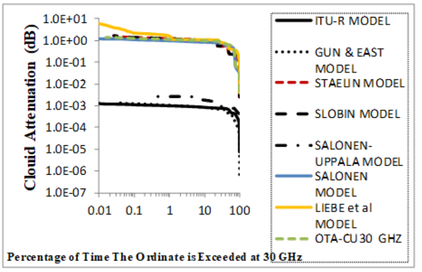

Fig. 8. OTA-CU cloud model and foundation models at 30 GHz

7. DEVELOPMENT AND FUTURE WORK

Typical development works necessary to determine effective local link margin for satellite services in a given locality were further carried out in the Ota (6.7^{o}N, 3.23^{o}E) case study. Adewusi *et al.* [21] derived analytically and present a newly developed cloud attenuation algorithm from the Equation (2) above. The publication described the analytic procedure that resulted in Equation (3):

$$\mathrm{Ac} = \mathrm{Ao}\, W_L \mathrm{COS}\left((0.5K_L) + \mathrm{B}\right), 0 \leq K_L \leq \pi \qquad (3)$$

Where, Ac, Ao and B represents the cloud attenuation (dB) in a given cloud layer(s), the amplitude and phase constant of the propagating (beacon) signal respectfully; W_L and K_L represent liquid water content of the cloud layer(s) and specific attenuation coefficient as defined by the ITU-R. The Equation (3) has been modified to accommodate empirical data. This enable numerical analysis be carried out using set of (W_L, K_L) radiosonde data for the station through a written simulation code (also published in the paper) to determine the values of Ao and B and hence, derived the new tropical cloud attenuation model (NTM) - Equation (4) for the station geographic area:

$$\mathrm{Ac} = 11.5\, W_L\, \mathrm{COS}\left((0.5K_L) + 1.560796\right), 0 \leq K_L \leq \pi \qquad (4)$$

This NTM predicted margin for tropical Ota station agreed with previous research results, particularly the Mandeep and Hassan [22] published result of 2.9 dB maximum cloud attenuation based on data from a similar experimental setup at tropical Penang. It also agreed with, Yuan *et al.* [23] published result that cloud attenuation in the Ka-band can reach up to 4 dB in the tropical region.

Subsequently, the new cloud algorithm and NTM were further established through published climatic data analyses bases [24]. Further still, successful performance evaluation and analysis of the NTM were done, considering wide frequency range between Ku and V bands with respect to primary cloud attenuation models [25].

Future prospect on this work consider a single global satellite based modular climatic model desirable, where modular algorithm would be used to integrate the various climatic zones' models as implied by cloud attenuation publications [26-31].

8. CONCLUSION

This cloud attenuation modelling research begins with a well-designed experimental procedure for effective measurements and data collection scheme for defined climatological and radiometric parameters. Then graphical analysis of the primary data groups directly give some of the required results as the cloud cover of the station; and indirectly produce some other required results as the derived integrated cloud attenuation cumulative distribution curves from the annual distributions. The station integrated cumulative distribution curve is used to develop required model equation using the climatic initial and boundary conditions. The new model's chart is compared with those of primary cloud attenuation models as displayed by the Figs. 3 to 8 where it shown considerable geometric pattern agreement, but consistently practical and unique predicted attenuation values for the tropical station. However, a single global satellite based climatic model is desirable, where modular algorithm would be used to integrate the various climatic area models.

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AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration among all authors. Authors OMA, TVO and MLA did the conception of this study. Authors OMA and TVO did the design of the manuscript. Authors OMA, AOM and OOO did the data Collection and analyses of the manuscript. Author OMA wrote the Manuscript. All authors read and approved the final manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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