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Cloud attenuation modelling for satellite network links performance improvement

O. M. Adewusi[2], T.V. Omotosho[1], M. L. Akinyemi[1], S. A. Akinwumi[1], O. O. Ometan[2]

[1]Department of Physics, College of Science and Technology, Covenant University, PMB 1023, Ota, Ogun State, Nigeria.
[2]Department of Physics, Lagos state University, Ojo, Lagos state, Nigeria.

madewusi@gmail.com, omotosho@covenantuniversity.edu.ng, marvel.akinyemi@covenantuniversity.edu.ng,oluwasayo.akinwumi@covenantuniversity.edu.ng, ometanfunmi@gmail.com

Abstract. All local climate zones need to develop relevant climatic models such as cloud attenuation model which can serve as correlative resources to global satellites applications and a means of determining local link margins for satellite networks services in localities. Effects of suspended water droplets (SWD) and suspended ice crystals (SIC) which constitute clouds are major concern in the design and successful operation of satellite communication system at frequencies above 3GHz because the hydrometeors reduces the services availability critically as frequency increases. This work is a review of cloud attenuation modelling, using as a case study typical research work been carried out, to develop cloud attenuation model for tropical Ota (6.7oN, 3.23oE), southwest Nigeria. Cloud attenuation modelling for a station involve obtaining clouds parametric system equation from their numerical representations, taking into consideration the climatic initial and boundary conditions. The numerical representations are collected climatological and radiometric data, derived from well-designed experiments in which cloud parameters measurements are carried out using radiances change measured by satellites and visual observations from the surface station(s) on land and ships in the ocean. The on-going research work begin with the study of performance of eight foundation cloud models at the station, through their detailed evaluation from cloud cover data and radiosonde data analysis, followed by analysis of collected over three years spectrum analyser signal attenuation data. Then modelling analysis of the station spectrum analyser data collected at computed elevation angle 56.18o to Astra 2(E-G) Satellite located at 28.2oE, which involve comparisons of the derived attenuation distribution curves, both of the spectrum analyser data and those of the existing cloud models for the station, with the derived 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 stated and the specific model equation is been worked on.

1. Introduction

The increasing demand for satellite services and consequent increases in bandwidth requirements for current range of telecommunication applications have driven satellite service providers to continually seek wider bandwidth. The consequent increases in transmission frequency are phenomenally accompanied by directly proportional hydrometeors attenuation [1, 2]. The uniqueness of cloud

attenuation among other hydrometeors is that on any given day about half of the Earth is covered by clouds, it is also more persistent and more stable in the atmosphere. Previous research works have established that transmission frequencies above 3 GHz have associated increase in signal propagation impairment in the troposphere due to atmospheric hydrometeors' dielectric relaxation among others, and that the impact of cloud attenuation at Ku band (12/14) GHz, Ka band (20/30) GHz and above have consequently been established as quite significant [3-6]. 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 [7, 8].

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 [9].

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 [10]. 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 [2, 11-14].

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 estimateneeded 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 [15-20].

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 [9].

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 inTable 1 and Figure 1 shows the cloud cover result – 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 figure 1 are used for corroborating the surface visual cloud cover result.
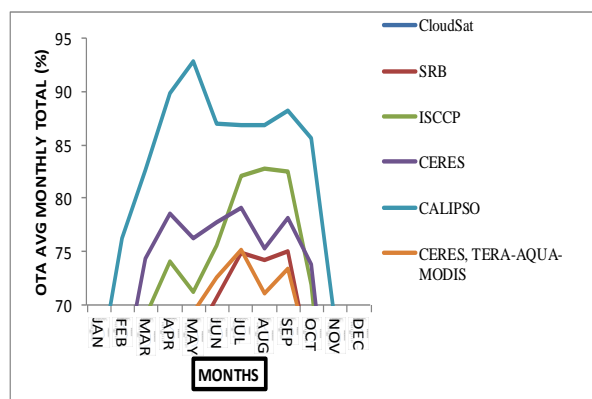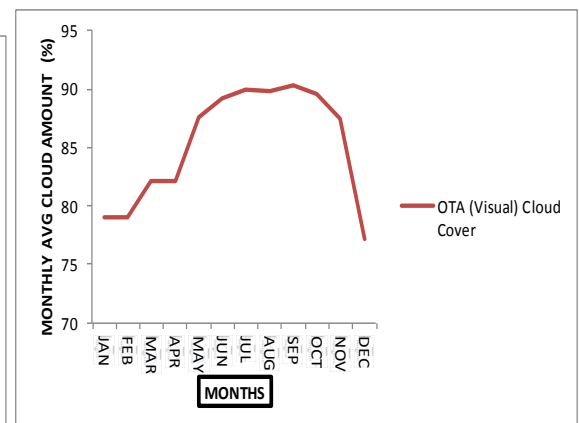

FIGURE 1: SATELLITES CLOUD COVER   FIGURE 2: OTA - CU CLOUD COVER

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 the 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.

Table 1: Typical Monthly Record of Visual data Measurement

DATE	EAST (%) A.M.	P.M.	AVG.	SOUTH (%) A.M.	P.M.	AVG.	WEST (%) A.M.	P.M.	AVG.	NORTH (%) A.M.	P.M.	AVG.	TOTAL	CLOUD TYPES PRESENT — 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 ; 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 ; Ns, Sc	Ns ; Ns, Sc	Ns ; Ns, Sc	Ns, Cu ; Ns, Sc
3-Aug	23.5	24	23.75	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	94.5	Ns ; Ns,	Ns ; Ns,	Ns ; Ns,	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	20.5	21.5	22.5	22.5	22.5	22.5	85.5	St ; Sc	St, Sc ; Sc, St	St, Sc ; Sc, Ns	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, St	Sc ; 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, Ac Cu; Ns	Ns, Ac Cu; Ns	Ns, Ac Cu; N	Ns, Ac Cu; 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	23.25	24	23.5	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	22	23.5	21	22.25	23.5	20.5	88.25	Ns ; St	Ns ; St	Ns ; 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	20.5	20	20.25	82.25	St, ; St	St, ; St	St, ; St	St, ; St
AVG													89.913				

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 geographic, 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 figures 3 and 4.
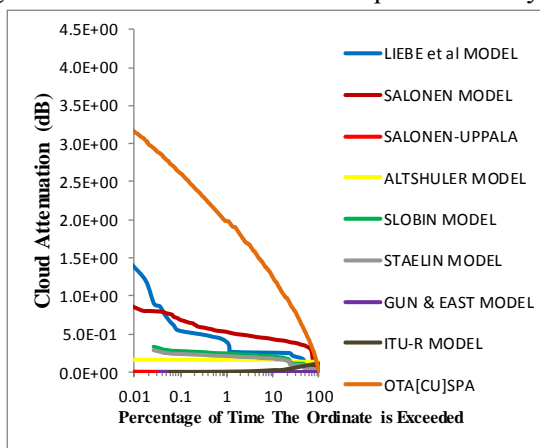
Figure 3 legend: LIEBE et al MODEL; SALONEN MODEL; SALONEN-UPPALA; ALTSHULER MODEL; SLOBIN MODEL; STAELIN MODEL; GUN & EAST MODEL; ITU-R MODEL; OTA[CU]SPA
(Y-axis: Cloud Attenuation (dB); X-axis: Percentage of Time The Ordinate is Exceeded)

FIGURE 3: SPAD AND CLOUD MODELS DISTRIBUTION CURVES AT 12.5 GHz

Figure 4 legend: LIEBE et al MODEL; SALONEN MODEL; SALONEN-UPPALA; ALTSHULER MODEL; SLOBIN MODEL; STAELIN MODEL; GUN & EAST MODEL; ITU-R MODEL; NEW MODEL
(Y-axis: Cloud Attenuation (dB); X-axis: Percentage of Time The Ordinate is Exceeded)
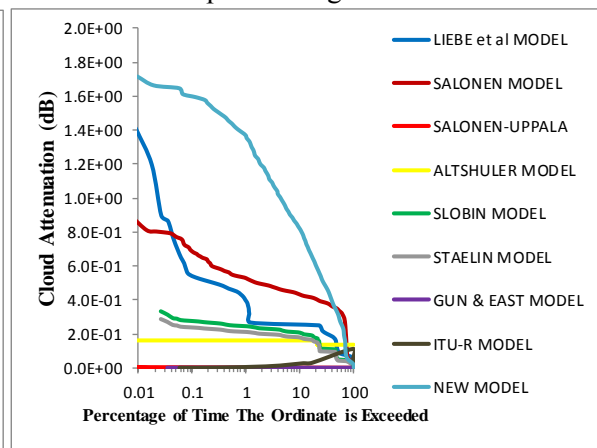
FIGURE 4: CLOUD ATTENNUATION MODELS DISTRIBUTION CURVES AT 12.5 GHz

6. Cloud Attenuation Modelling Result

The SPAD integrated attenuation cumulative distribution curve approximates a straight line of slope -0.31011 and intercepts 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).

$$Ac\ (WL,\ \theta,\ t,\ f) = f(x) = acos(x) + bsin(x) = Acos(x - \alpha) \qquad (1)$$

where $A = (a2 + b2)1/2$ and $\alpha = tan\text{-}1(b/a)$ in the range $0 < \alpha < \pi/2$; 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; 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 ε (f) of water (ITU-R, 2009; Salonen – Uppala, 1991). Considering the relatively gentle slope of the SPAD line, the range of x should be 0 to π rather than 0 to $\pi/2$, and 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 been used in the simulation equation (equation 2) program.

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

Hence equation (2) is a general representation of the cloud attenuation model for the station measured data distribution (SPAD), having shown considerable geometric pattern agreement with the foundation models at various frequencies in Figures 4 – 8. The specific model equation is been worked out.
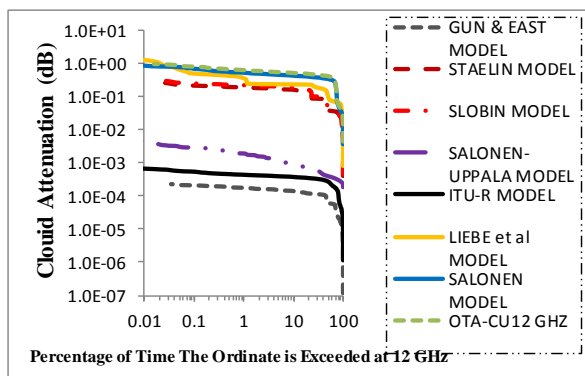

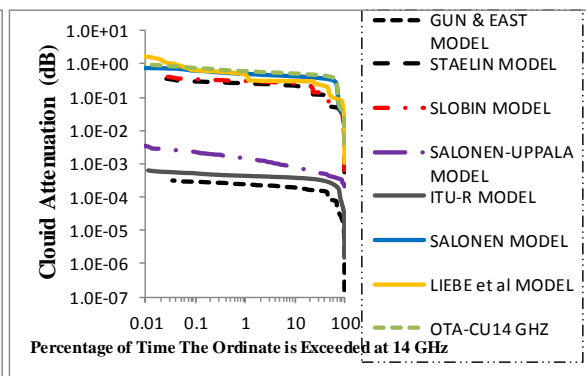**FIGURE 5: OTA-CU CLOUD MODEL AND FOUNDATION MODELS AT 12 GHZ**

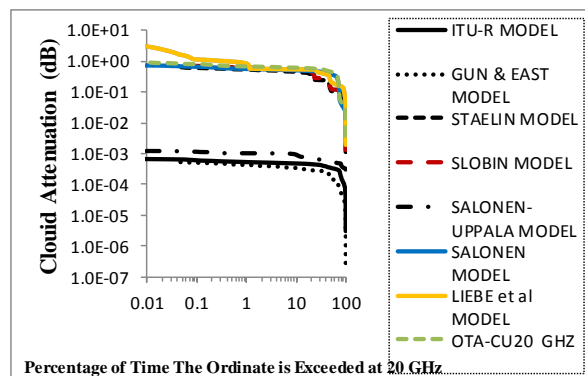

FIGURE 6: OTA-CU CLOUD MODEL AND FOUNDATION MODELS AT 14 GHZ

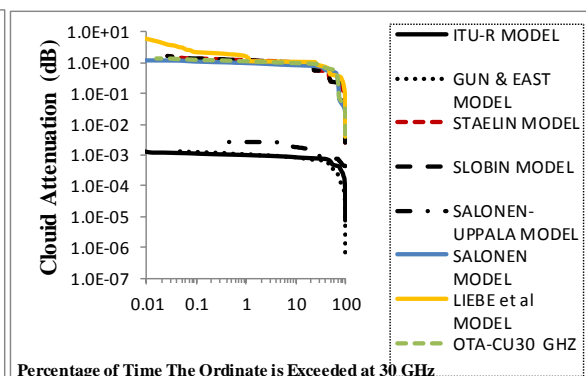**FIGURE 7: OTA-CU CLOUD MODEL AND FOUNDATION MODELS AT 20 GHZ**

FIGURE 8: OTA-CU CLOUD MODEL AND FOUNDATION MODELS AT 30 GHZ

Conclusion

Cloud attenuation modelling begins with a well-designed experimental procedure for effective measurements and data collection scheme of 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 curve from the annual distributions. The integrated cumulative distribution curve is used to develop required model equation using the climatic initial and boundary conditions. This model's chart is compared with those of existing cloud attenuation models as displayed by the figures 4 to 8 for correlation. However, a single global satellite based climatic model is desirable, where modular algorithm would be used to integrate the various climatic zones models.

Acknowledgment

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