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Tropospheric attenuation on Satellite-aircraft propagation: A concise review

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Abstract. The attenuation time together with the Complementary Cumulative Distribution Function of attenuation values play a vital role in the design of communication systems. Passengers on-board during flight can be connected to the internet either via satellite or earth-station depending on the nature of the flight. For long distance flight, this internet connectivity is provided through satellite when the aircraft is flying at the upper troposphere. However, the satellite-aircraft link is subject to attenuation due to the troposphere. A model to characterize the channel has been proposed. In particular, a methodology for the synthesis of attenuation on aircraft-satellite is given by ITU-R P2041 recommendation. However, it has been shown that the impact of tropospheric parameters such as rainfall, cloud, gases etc. On the satellite-aircraft link at different frequencies are insignificant (i.e decreases with height) on the upper troposphere since the aircraft is flying (about 12 km) above the rain height (5 km). The findings will be useful for researchers, scientists and the aviation industries in planning, design and establishing link budget for aircraft-satellite path.

1. Introduction

Services provided by satellite for aeronautical communication are now available for different purposes which ranges from entertainment of passengers to aircraft data transmission (ATM) [1, 2]. For this reason, the characterisation of the aircraft-space link is vital to guarantee all the services proposed. Due to the limitation in weight, space and dimension of in airborne communication systems, the channel characterisation is of importance and several contributors such as ground scattering, atmosphere and the altitude of the aircraft have to be taken into consideration [2, 3]. During flight, the propagation impairments (terms) affect the communication channel with distinctive impact. For this purpose, only accurate analysis based on simulation time series can make provision of precise simulations of the link-budget.

Among the different parameters (impairments) affecting the aircraft-satellite link, the presence of the atmosphere plays a vital role. Meanwhile, for ground-space links, the different layers of the atmosphere induced propagation effects on the communication channel at microwave frequencies bands (3 – 30 GHz) [4, 5]. The two crucial effects are due to the troposphere and the ionospheric layers. For the ionosphere, the ionization due to the sun affects the propagation of signals below a few GHz. The troposphere on the other hand, is a layer where event due to the weather affect propagation of microwave signals at X-band and above [2]. At these frequencies, rain and turbulent air-masses causes fast fluctuations and power absorption. ITU-R has recommended a model mostly for ground-space link and adapting them for aeronautical link [2]. The models are well defined to evaluate the tropospheric propagation taking the variability in both space and time domain into account [2, 6]. The models required some ancillary information which are available in terms of data bases due to long term observations and statistical representation. The two main models recommended by ITU-R are ITU-R P. 1853-1 [7] which is the model that defines the tropospheric total attenuation time series synthesis and the ITU-R P.2041 [8] which predicts the various propagation impairments for planning airborne systems links. This manuscript survey the effect of the tropospheric impairments on satellite-aircraft link at microwave frequency.

2. Propagation Channel

Propagation channel is the environment through which radio signal carry data information transmitted from a transmitter to a receiver in wireless radio communication [9, 10, 11]. The radio propagation channel may be any type of communication between two terminals with at least one in motion. One terminal may be mobile and the other a base-station or both terminals may be vehicles in motion [10, 12]. The radio signal and the information it carries is affected by antenna characteristics, thermal noise and other environmental effects such as fading [9, 10] and physical propagation paths losses caused by terrestrial and atmospheric propagation. Impairments that causes path losses in the atmosphere include, clouds, snow, rainfall etc.[12].

2.1. *Distribution of Tropospheric Margins*

The tropospheric propagation losses for an aircraft-satellite link is limited if the aircraft is flying in the upper troposphere (at its cruise level), at extremely high frequency (EHF) bands. At the upper troposphere of about 11 km above mean sea level (MSL), most of the meteorological impairments are below the aircraft and do not affect the aircraft-satellite path. The largest portion of atmospheric gases is found below the aircraft cruise altitude (lower troposphere) and also with precipitation (rain) and majority of clouds. Although, the impact on the channel of propagation is less significant on the upper troposphere than the lower troposphere, the residual losses have to be assessed [13]. Furthermore, the outage probability during ascent and descent phases needs to be evaluated. To achieve this aim, a specific model for addressing the issue in other to obtain the propagation losses complementary cumulative distribution function (CCDF) for an aircraft at a specific height and geographical position has been given in International Telecommunication Union Radio-communication sector (ITU-R) recommendation P.2041 [8].

2.2. *ITU-R Model for Aeronautical communication*

The ITU-R model for aeronautical communication depend mainly on the models used for the estimation of propagation margin for fixed earth-space links given by ITU-R recommendation P.618-12 given by [14]. The main difference is that aircraft-satellite link account for the height of the aircraft in the computation of the margins according to [13]. The methodology for predicting attenuation due to rain, cloud, gas, scintillation etc. exceeded of time (p%) for aircraft-satellite link is explain extensively in [8]. The use of this methods are sufficient to provide an estimate value for the attenuation undergone by an aircraft-satellite link..

2.3. *Application of ITU-R Rec P.2041 for Aircraft-satellite Link*

The methodology given by [8] have been used by researchers to predict the effects of tropospheric impairments such as rain, cloud, gases etc. on the aircraft-satellite link. The scaling in height of the results of ITU-R recommendation P.2041 [8] is shown in Figure 1 for an equatorial and climate region. The actual difference between these two types of climate is linked to the average height of the 0° isotherm and consequently the height of the rain (5 km). From the Figure, it shows that the losses is significant in the equatorial regions up to a higher height than in temperate regions considering the higher rain altitude in these regions. Also, [13] presented the distribution of tropospheric impairments at 50 GHz and 80 GHz using ITU-R recommendation P.2041 [8] for a path between an aircraft and a satellite at an elevation of 35°for the same region in Figure 1 shown in Table 1.

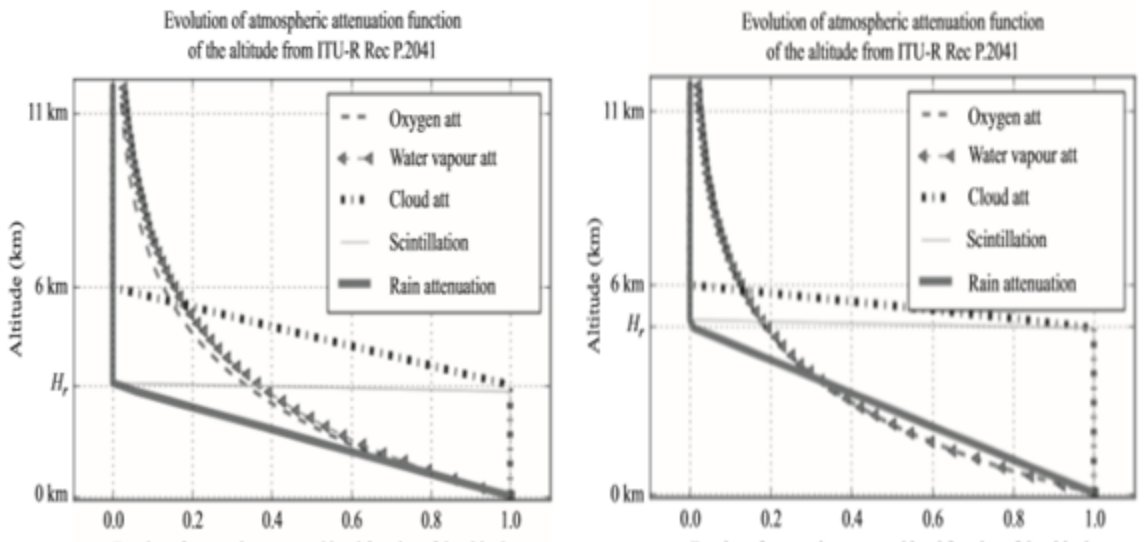

Figure 1: Scaling of atmospheric impairments with altitude for a temperate location [13]

Table 1: Attenuation CCDF for different altitudes at V (50 GHz) and W-band (80 GHz) from ITU-R Recommendation P. 2041 for Toulouse, France and Kourou, (French Guiana) and the elevation of the link is 35^0 [8].

	Temperate location (Toulouse)		Equatorial location (Kourou)	
Altitude (km)	A* (dB) at 50 GHz	A* (dB) at 80 GHz	A* (dB) at 50 GHz	A* (dB) at 80 GHz
0.0	65	90	140	200
1.5	50	70	120	175
3.0	10	19	85	120
6.0	1.5	1	1.5	1

It was observed that the propagation margins decreases with height at a fast rate. In the temperate regions, the propagation margin at a height of 3 km for W-band link is less significant than margins for a fixed receiver at Ka-band. For a height greater than 6 km, there is only a minor residual attenuation due to gases. Thus, it is assumed that the propagation effects are no barrier in the establishment of links at extreme high frequency (EHF) bands between aircraft flying in the upper troposphere (cruise height) and satellites. In order to make available an attenuation margin for a particular flight path, the availability can be estimated by integrating the path of flight in the time interval (t_1, t_2), the outage probability at every location (position) $P_{\psi(t),\phi(t),h(t)}\left(A_{tot} > A^*\right)$ weighted by the time spent at this location using the expression given by [13]:

$$P_{flight}\left(A_{tot} > A^*\right) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} P_{\psi_a(t),\phi_a(t),h(t)}\left(A_{tot} > A^*\right)dt \qquad (1)$$

where $h_a(t)$, $\psi_a(t)$ and $\phi_a(t)$ are the height, longitude and latitude of the aircraft at time t . The determination of the margin holds if and only if the parameters of the satellite or equivalent isotropically radiated power (EIRP) do not experience significant fluctuations during the course of flight. [13] evaluated the outage margin for several flight cases for frequencies link of 40 GHz and 70 GHz as shown in Table 2. The satellite is anticipated to be stationed at a longitude corresponding to the midpoint of the flight path for each flight. It is observed that both Q-band (40 GHz) and W-band (70 GHz) offered availability of 99 % and above for flight paths between tropical regions. However, different trends are noticed: the total availability is lower for shorter flight and this will require a larger margin. For shorter flights, the path of the time spent by the aircraft at a lower height during taking-off and landing phases when the propagation impairments are significant is larger compare to long-haul flights. Links for flights between unfavourable locations such as tropical regions in this light (propagation point of view) will require a larger margin or the availability of the link will be lower than flight links for temperate regions. The authors also showed that, for all the phases of flight, the larger attenuation margin for availability greater than 99 % are mostly required for lower altitude flight phases. However, there is a possibility that the communication system will not operate during take-off and landing phases. At an altitude of 3 km and below when the communication system is switch-off produces similar results which is similar to the case of estimating the availability for a whole flight path but the required margins are very low (10 dB) to make an availability of 99.9 % irrespective of the flight path. This is shown in Table 3

Figure 2: Attenuation CCDF for various flight paths at 40 and 70 GHz considering all the flight phases for all altitudes [8].

Flight phases	Temperate location (Toulouse) A* (dB) at 40 GHz	Equatorial location (Kourou) A* (dB) at 70 GHz
Edinburge-London	>50	>50
Baton Rouge-Houston	32	>50

Munich-New York	25	48
Scattle-Tokyo	38	>50
Pune-Delhi	22	43
Doha-Amsterdam	23	42

Figure 3: Attenuation CCDF for various flight paths at 40 and 70 GHz considering flight phases below 3 km of altitude [8].

Flight phases	Temperate location (Toulouse) A* (dB) at 40 GHz	Equatorial location (Kourou) A* (dB) at 70 GHz
Edinburge-London	23	42
Baton Rouge-Houston	17	30
Munich-New York	5	12
Scattle-Tokyo	8	15
Pune-Delhi	5	9
Doha-Amsterdam	3	8

2.4 Flight Path Channel Model

Time series representation of the sequential evolution of the channel is essential for more analyses of the system. In order to generate time series of propagation impairments for an airborne platform (aircraft)-satellite link, the model to generate the time series propagation for earth-space link with terminal on the ground is illustrated in [7] has been modified to the aeronautical situation with the same approach reported by [15]: the modification done is a change of the models to convert meteorological parameters to attenuation based on the methods proposed by [8] and secondly, the modification is change of the correction parameters to account for the motion of the aircraft (particularly, the rate at which the attenuation changes in most cases can be higher in an aircraft than a fixed terminal). The inputs data are flight routes defined by the height $h_a(t)$, latitude $\phi_a(t)$ and longitude $\psi_a(t)$ as well as link parameters such as satellite position, polarization and frequency. Time series can be constructed from routes using meteorological parameters. The outputs are the time series attenuation indexed by time for the several propagation effects. The correlation parameters adjusted for the generation of time series using [7] has been discuss in literature with different parameters by [2].

[13] evaluated the time series attenuation generated at a frequency of 70 GHz for a flight between Toulouse and London for moderate to heavy rain as shown in Table 3. The effects of the height (altitude) on the propagation impairments was observed. The result showed that gaseous attenuation decreases rapidly with height. Also, attenuation due to rain is insignificant (disappear) when the aircraft is above the altitude (height) of the rain (5 km) and the attenuation due to cloud when the aircraft is above 6 km. They also observed that the fluctuations of the propagation channel are rapid because of the fast displacement of the aircraft with respect to the spatial correlation of the impairments. [2] synthesized the tropospheric total attenuation for time series for satellite-aeronautical link at microwave frequency (from L to Q band). The authors carried out a horizontal validation analysis for fixed position by comparing the total attenuation CCDF of the atmospheric time series with RAPIDS II software for four selected locations (Oslo, Munich, Toulouse and Dakar) with different climate zones. The comparison of the results showed a good agreement between both methods, with a bias of few dBs, which is justified by the different combination of the rain and cloud attenuations between both simulations defined by [7]. Also, they conducted a vertical validation using the same approach as in horizontal validation, but in this case, the receiver has been placed at a mid-air position and not on the ground. They also showed good agreement, with a bias of few dBs taking into account oxygen, rain and water vapour at a height of 3 km. They further carried a validation analysis by comparing the models output at different frequencies (10 GHz, 26 GHz and 50 GHz respectively). The result showed a strong correlation between all the effects. In particular, rain effect is due to the presence of clouds and the scintillation effect during rain is related to the level of attenuation.

Figure 4: Time series generated for moderate rain conditions [8]

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Altitudes (km)	Time (s)	A (dB)
2	200	4
4	400	2
6	500	1
8	700	0.5
10	900	0

3 Findings and Recommendations for Further Studies.

The results from this survey showed that, for aircraft-satellite link, the effect of atmospheric parameters such as rain, cloud etc decreases with height since the aircraft is cruising at an altitude of about 12 km above the height of rain (5 km). This means that, at the upper troposphere the path loss due to oxygen is significant to a large extent while the path loss due to rain, cloud etc on the aircraft-satellite link are insignificant since they are found below the aircraft (i.e lower troposphere). Also, it was observed that propagation effects such as rain, cloud, gases etc. are no barrier in the establishment of links budget at extreme high frequency (EHF) bands aircraft-satellites path. It is recommended that, more research should be carried out to estimate the path loss due to the tropospheric parameters such are rain, cloud, water, vapour, oxygen scintillation on aircraft-earth direction to fully commercialize the technology. In order to plan, design and establish a link budget for aircraft-earth link, an accurate knowledge of the tropospheric impairments is required. Also, the effect of fluctuations on the channel due to the relative movement between the aircraft and earth terminal cause a shift in frequency resulting in fast fading. This fading need to be access.

Conclusion

Satellite has played a significant role in providing in-flight connectivity for passenger’s entertainment onboard in wireless communication owing to its potential advantages at microwave frequency. However, the satellite-aircraft link is unaffected by propagation impairments such as rainfall, cloud, gases etc on the upper troposphere. Although, studies are still on-going but it has been shown that the impact of propagation impairments for an aircraft flying at an altitude of about 12 km for long-haul flight decreases with height. More studies are required to estimate path loss due to propagation impairments for aircraft-earth link when the aircraft is flying at an altitude of about 12 km in other to fully commercialize the technology. Also, there is need to investigate the Doppler effect resulting from the relative movement between the aircraft and earth terminal when the signal of the aircraft is supported by an earth-station.

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