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# Tropospheric propagation studies carried out by CNES and ONERA for satellite communication systems at Ka and Q/V bands

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## Abstract

This paper presents results from propagation experiments carried out by CNES and ONERA in Toulouse and Le Fauga-Mauzac (France), Kourou (French Guiana), as well as in Shillong and Hassan (India) in collaboration with the India Space Research Organization ISRO. Then, the development of propagation models performed by ONERA and CNES is addressed, focusing on statistical prediction methods of gas attenuation, as well as on channel models allowing the space-time behaviour of the propagation channel to be generated.

**Keywords:** satellite communication, propagation, rain attenuation, channel model

## Acronyms/Abbreviations

CCDF: Complementary Cumulative Distribution Function

ITU-R: International Telecommunications Union, Radiocommunications sector

## 1. Introduction

CNES and ONERA have been collaborating for more than 20 years in the domain of tropospheric propagation for the design of high frequency satellite communication systems. In order to provide attractive access to the Internet, satellite systems have to cope with more bandwidth to deliver high data rates required by the end users. These wide bandwidths are not available in conventional frequency bands such as C-band or Ku-band and operators are migrating to higher frequency bands such as Ka-band (20/30 GHz) and Q/V band (40/50 GHz) for future GEO Very High Throughput Satellite (VHTS) systems. The main limitation of frequencies higher than 20 GHz is their sensitivity to propagation impairments, it is therefore needed to better characterise and model tropospheric propagation.

To achieve this goal, CNES and ONERA have launched a research work programme on the one hand through propagation experiments carried out both in temperate and in tropical and equatorial areas and on the other hand propagation model development in terms of statistical prediction methods and channel models.

The objective of this paper is first of all to present results from propagation experiments carried out by CNES and ONERA in Toulouse (France), Kourou (French Guiana), Shillong and Hassan (India) in collaboration with ISRO.

Then, the development of propagation models performed by ONERA and CNES is addressed, focusing on statistical prediction methods of gas attenuation, as well as on channel models allowing the space-time behaviour of the propagation channel to be represented. Examples of testing activity realized with these propagation models are presented.

## 2. Propagation experiments carried out by CNES and ONERA

### 2.1 Propagation experiments in Southern France

Satellite propagation experiments have been carried out in different places in South of France [1,2]:

- in Toulouse: from April 2011 with the 20.2 GHz beacon of Astra 3B and from May 2015 with the 39.4 GHz beacon of Alphasat (see Fig. 1)°;
- in Le Fauga-Mauzac (26 km away from Toulouse): from December 2013 with the 20.2 GHz beacon of Astra 3B (see Fig. 2)°;
- in Aussaguel (16 km away from Toulouse): between June 2013 and December 2014 with the 20.2 GHz beacon of Astra 3B and from June 2021 with the 19.7 and 39.4 GHz beacons of Alphasat;
- in Salon de Provence (294 km away from Toulouse): from June 2013 to December 2014 with the 20.2 GHz beacon of Astra 3B.

Examples of CCDFs of rain attenuation obtained in Toulouse between 2015 and 2021 are presented in Fig. 1 whereas examples of CCDF of rain attenuation collected in Le Fauga-Mauzac over the period 2014-2017 are given at Fig. 2.

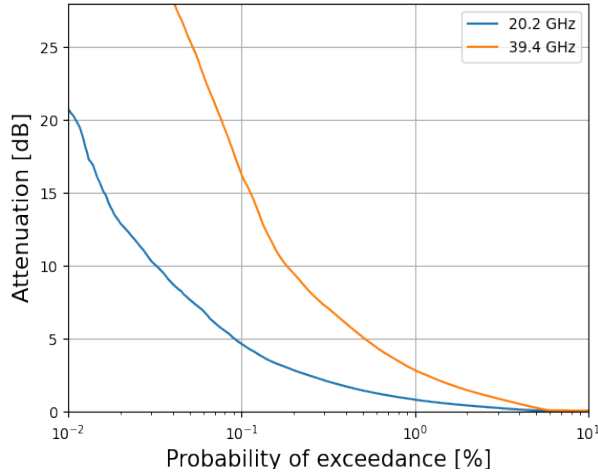


Fig. 1. CCDF of rain attenuation collected in Toulouse between 2015 and 2021

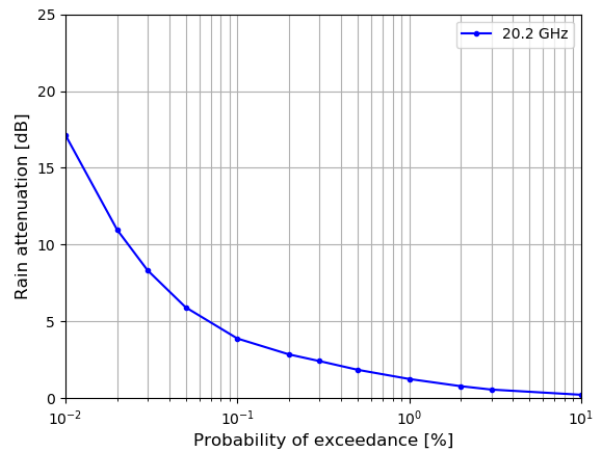


Fig. 2. CCDF of rain attenuation collected in Le Fauga-Mauzac between 2014 and 2017

Even if the reference periods of time are not the same, similar rain attenuations can be observed between these two sites separated by a short distance of 26 km. For instance, 5 dB in Toulouse and 4 dB in Le Fauga-Mauzac are exceeded for 0.1 % of the time. For the same time percentage of 0.1 %, more than 16 dB have been exceeded at 39.4 GHz in Toulouse, which is almost four times more than at 20.2 GHz.

### 2.2 Propagation experiment in French Guiana

A satellite propagation experiments has been carried out in the Guiana Space Centre in Kourou (latitude: 5°N, French Guiana) [3,4] with the 20.2 GHz beacon of Amazonas-3 and along to an elevation angle of 80°. Four years of measurements have been collected in 2017, 2018, 2020 and 2021 (see Fig. 3).

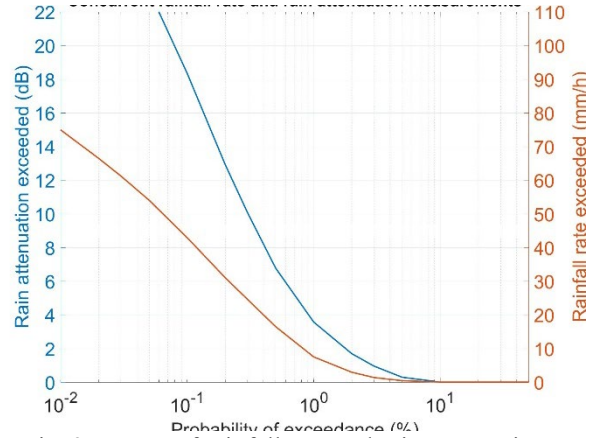


Fig. 3: CCDF of rainfall rate and rain attenuation obtained in Kourou in 2017-2018-2020-2021

Fig. 3 presents the statistics of rainfall rate and rain attenuation obtained in Kourou during years 2017, 2018, 2020 and 2021. As Kourou is an equatorial climate (latitude of 5°N), very intense precipitation occur in this region, with a rainfall rate of 75 mm/h exceeded for 0.01 % and of 42 mm/h exceeded for 0.1 %.

Consequently, very high rain attenuation levels have been recorded and for instance, 18 dB have been exceeded for 0.1 % of the time at 20.2 GHz. This is even more than the rain attenuation measured at 39.4 GHz in Toulouse that exceeds 12 dB for the same period (see Fig. 4). In comparison, still in Fig. 4, the rain attenuation exceeded for 0.1 % of the time in Toulouse at the same frequency of 20.2 GHz is 4 dB "only".

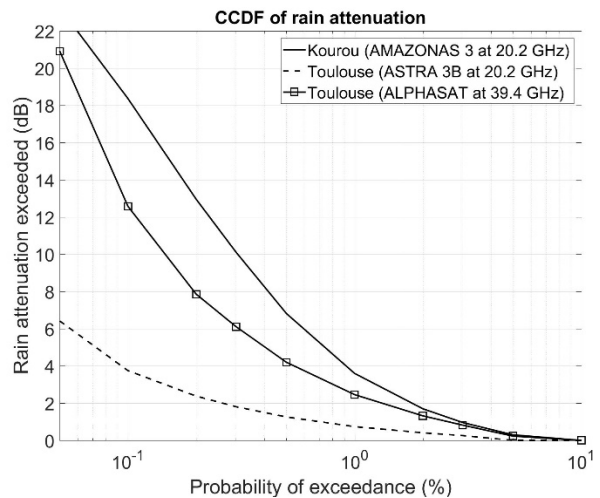


Fig. 4: CCDF of rain attenuation measured in Kourou in 2017-2018-2020-2021 and comparison with those obtained in Toulouse from June 2015 to May 2018

### 2.3 Propagation experiments in India

A collaboration has been set up between ISRO, CNES and ONERA to carry out a propagation campaign in India with the Ka-band beacons of the GSAT-14 satellite [5] at 20.2 GHz and 31.5 GHz. Beacon receivers have been installed in two locations: In Shillong (Northern-Eastern India, North of Kolkata) by ONERA and in Hassan (Southern India, West of Bangalore) by CNES.

Shillong climate is very wet with a total rain amount of 2415 mm with a mean number of 128 rainy days per year, whereas Hassan climate is characterized by 913 mm of total rain amount for 65 rainy days per year. More details about availability and conditions of these experiments are given in [6].

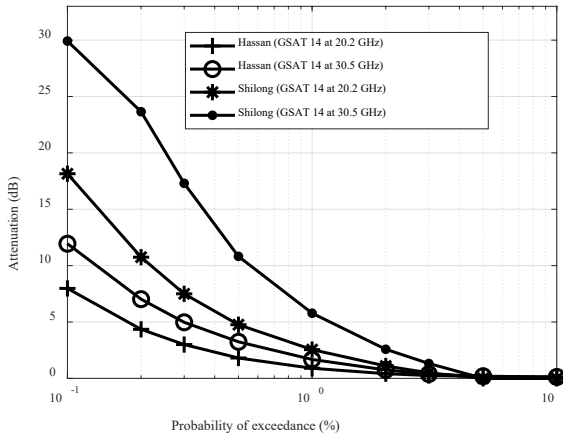


Fig. 5: CCDF of rain attenuation measured in Hassan for the period 2015-2019, and in Shillong for the period 2015-2021.

Fig. 5 shows the statistical distributions obtained from the measurements performed in the two locations. The climate being strongly different between these two areas, the attenuation statistics are quite different with 8 dB and 12 dB exceeded respectively at 20.2 and 30.5 GHz for 0.1% of the time in Hassan and 18 dB and 30 dB exceeded respectively at 20.2 and 30.5 GHz for 0.1% of the time in Shillong.

### 3. Propagation models developed by CNES and ONERA

Propagation experiments are useful to characterise the behaviour of the propagation channel both in terms of first order statistics such as attenuation or scintillation for link budget analysis or in terms of fade dynamics when adaptive techniques are needed to mitigate propagation attenuation. However, propagation data are not available at any frequency or for all climatic conditions. Therefore, propagation models are needed in order to predict the behaviour of the propagation channel at any frequency and anywhere in the World. Statistical prediction methods are commonly used to

estimate link budgets and so system margins whereas dynamic channel models (i.e time series synthesizers) are useful to optimise fade mitigation techniques.

#### 3.1 Statistical prediction methods

As previously mentioned, the design of satellite communication systems implies an estimation of the link budget. Propagation margins are often tackled by the CCDF with respect to a target availability of the systems. International Standards (Recommendations) from ITU-R SG3 provide multiple statistical methods especially for the prediction of:

- Gaseous attenuation (Rec. ITU-R P.676)
- Cloud attenuation (Rec. ITU-R P.840)
- Rain attenuation (Rec. ITU-R P.837 and P.618)
- Reference atmospheres (Rec. ITU-R P.835)
- Variability of propagation phenomena (Rec. ITU-R P.678)

CNES and ONERA are actively contributing to ITU-R and several statistical prediction methods they have developed are now included into ITU-R Recommendations:

- A model to derive the rainfall rate exceeded for a given average annual probability of exceedance and given location provided by the in-force Recommendation ITU-R P.837-7 [7]
- A model to estimate the inter-annual variability of rainfall rate and rain attenuation statistics and the risk associated with propagation margin provided by the in-force ITU-R P.678-3 [8,9]

More recently, CNES has developed new statistical prediction methods of gaseous attenuation and in particular models to estimate the CCDF of oxygen and water vapour attenuation from 1 to 350 GHz [1]. Both have been recently approved by ITU-R SG3 to be the new reference prediction methods provided by Recommendation ITU-R P.676-13. A brief description of these two models is given in the following two sections.

#### 3.1.1 Statistical distribution of oxygen attenuation

The idea was to propose a new model to compute the oxygen equivalent height,  $h_o$  (in km), such that oxygen attenuation exceeded for  $p$  % of the time,  $A_o(f, p)$ , can be easily derived from surface meteorological parameters with the following relationship:

$$A_o(f, p) = \frac{\gamma_o(f, \bar{P}_s, \bar{T}_s, \bar{\rho}_{w_s}) \cdot h_o(f, T_s(p), P_s(p), \rho_{w_s}(p))}{\sin \theta}$$

$f$  is the frequency.  $\gamma_o$  (in dB/km) is the oxygen specific attenuation.  $\bar{P}_s$ ,  $\bar{T}_s$ , and  $\bar{\rho}_{w_s}$  are respectively the mean of surface pressure (in hPa), surface temperature (in K) and surface water vapour density (in g/m<sup>3</sup>) over the period of interest (e.g. annual or monthly mean).  $P_s(p)$ ,  $T_s(p)$ , and  $\rho_{w_s}(p)$  represent respectively the CCDF of surface pressure, surface temperature and surface water vapour density over the same period of interest (e.g. annual or monthly CCDF), i.e. the values of  $P_s$ ,  $T_s$ , and  $\rho_{w_s}$  exceeded for  $p$  % of the time.

In [10], it has been proposed to compute the oxygen equivalent height such that:

$$h_o(f, T_s(p), P_s(p), \rho_{w_s}(p)) = a_o(f) + b_o(f) \cdot T_s(p) + c_o(f) \cdot P_s(p) + d_o(f) \cdot \rho_{w_s}(p)$$

The coefficients  $a_o$ ,  $b_o$ ,  $c_o$ , and  $d_o$  are frequency dependent only and have been optimized using multiple mean annual reference atmospheres [10]. A worldwide example of zenith oxygen attenuation exceeded for 1% of the time at 26.5 GHz is shown in Fig. 5.

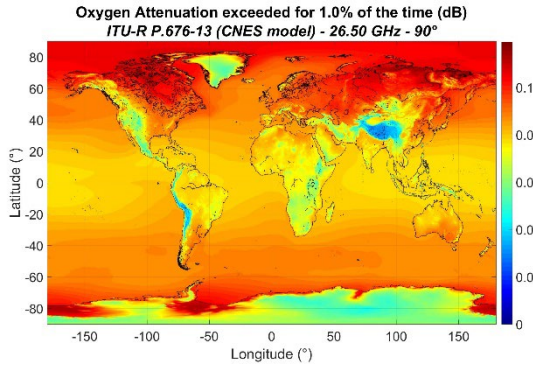


Fig. 5: Zenith oxygen attenuation exceeded for 1% of the time at 26.5 GHz

### 3.1.2 Statistical distribution of water vapour attenuation

The idea was to propose a new model to water vapour absorption coefficient,  $K_V$ , in dB/mm, such that the water vapour attenuation exceeded for  $p$  % of the time,  $A_W(f, p)$ , can be easily derived from the total columnar content of water vapour,  $V$ , in mm, with the following relationship:

$$A_W(f, p) = \frac{K_V(f, \bar{\rho}_{w_s}, \bar{T}_s, \bar{P}_s) \cdot V(p)}{\sin \theta}$$

$f$  is the frequency.  $\bar{P}_s$ ,  $\bar{T}_s$ , and  $\bar{\rho}_{w_s}$  are still respectively the mean of surface pressure (in hPa), surface temperature (in K) and surface water vapour density (in g/m<sup>3</sup>) over the period of interest (e.g. annual or monthly mean).  $V(p)$  represents the CCDF of the total columnar content of water vapour over the same period of interest

(e.g. annual or monthly CCDF), i.e. the values of  $V$  exceeded for  $p$  % of the time.

In [10], it has been proposed to compute the water vapour absorption coefficient such that:

$$K_V(f, \bar{\rho}_{w_s}, \bar{T}_s, \bar{P}_s) = a_V(f) + b_V(f) \cdot \bar{\rho}_{w_s} + c_V(f) \cdot \bar{T}_s + d_V(f) \cdot \bar{P}_s$$

The coefficients  $a_V$ ,  $b_V$ ,  $c_V$ , and  $d_V$  are frequency dependent only and have been optimized using multiple mean annual reference atmospheres [10]. A worldwide example of zenith water vapour attenuation exceeded for 1% of the time at 26.5 GHz is shown in Fig. 6.

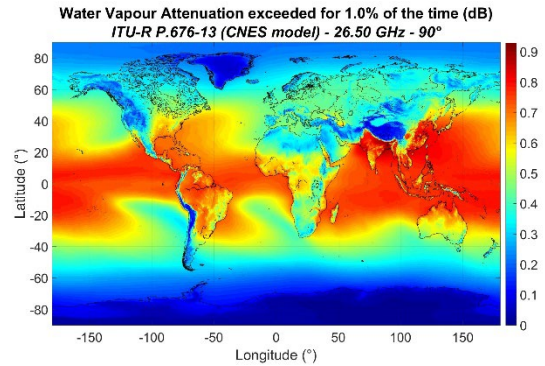


Fig. 6: Zenith water vapour attenuation exceeded for 1% of the time at 26.5 GHz

### 3.2 Channel models

Since the beginning of 2000's, CNES and ONERA have been involved in the development of channel models for example in the synthesis of correlated attenuation fields and time series. They have developed different versions of Recommendation ITU-R P. 1853:

- P.1853-0: time series synthesis of rain attenuation on a single Earth-space link,
- P.1853-1: time series synthesis of total impairments on a single Earth-space link,
- P.1853-2: time series synthesis of total impairments on multiple Earth-space links.

These prediction methods are applicable for frequencies between 4 GHz and 55 GHz and fixed elevation angles (GEO satellite links) between 5° and 90°.

The principle of these channel models is to generate a Gaussian white noise signal, to filter it using specific filters representative of the behaviour of the different components of the tropospheric impairments (rain, cloud, water vapour attenuation as well as tropospheric scintillation) and to normalise them in order to reproduce the local statistical distribution of the considered impairment.

The main limitations of these channel models are that first of all they do not take into account the non-stationarity of the propagation channel and local constraints such as micro-climates or orography and afterwards they cannot be used for non-GEO configurations. Therefore, more recently, CNES and

ONERA have developed a specific channel model able to consider any types of terrestrial orbits and constrained by a meteorological database in order to represent the non-stationarity of the channel. The main principles of this channel model are presented at Fig. 5.

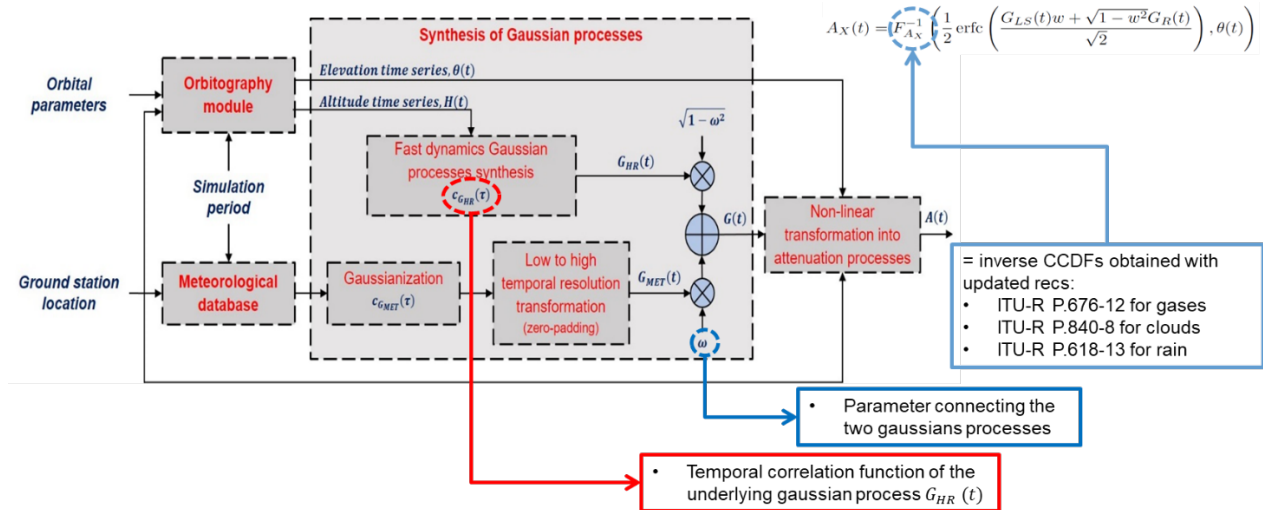


Fig. 5: Channel model relying on the main principles of Rec. ITU-R P.1853 but constrained by the ERA5 ECMWF re-analysis database.

The channel model relies on the one hand on an orbitography module in order to be able to take into account all types of terrestrial orbits and on the ERA5 re-analysis database [11] to take into account orography and local meteorological influence. Then the Gaussian processes are synthesized to produce a signal at the required sampling rate and in a last step, a non-linear transformation is applied in order to convert the Gaussian processes into the single components (rain, cloud and water vapour attenuations, as well as tropospheric scintillation) of the total tropospheric impairment. Examples of generated attenuation time series are given in Fig. 6.

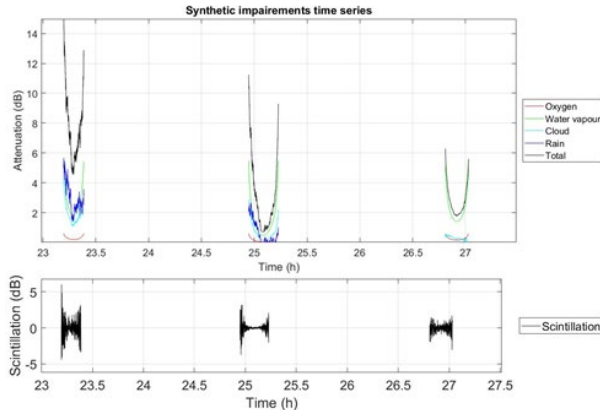


Fig. 6: example of time series generated with the channel model of Fig. 5.

#### 4. Conclusion

With the new projects proposed by the actors of the new space, mega-constellations are built at high frequency bands. For their design and optimization or to carry out sharing studies with existing standard GEO satellite systems, new propagation models are developed by ONERA and CNES, especially to optimise specific Fade Mitigation Techniques required to offer acceptable link availability taking into account non-GEO configurations.

These channel models allow the space-time behaviour of the tropospheric propagation channel to be synthesized at any frequency, for every climatic condition and for varying elevation angles. As input of these channel models, appropriate statistical prediction methods are needed to compute statistics of rain, cloud, gas and total attenuation.

To design and test these channel models, new propagation data are needed, not only in temperate areas as for the majority of the measurements available nowadays, but also in tropical and equatorial regions characterized by high population density. Examples of such models and data at disposal of CNES and ONERA have been described in this paper. The next future could see the development of similar propagation campaign and channel model for higher frequency bands like W-band (uplink at 80 GHz and downlink at 70 GHz).



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