EUROPEAN SPACE AGENCY

Proposed new recommendation for simulation channel model in 26 GHz

Abstract

This paper proposes a new possible recommendation that defines a common channel model for performing numerical simulations and performance assessments of high bit-rate telemetry schemes (i.e., SCCC/SCCC-X, DVB-S2(X), and VCM modcods).

1. Introduction

During CCSDS Spring 2019 Meeting, the C&S WG raised interest in having a common and well defined methodology to be adopted by all members when doing performance comparison of high-bit rate modulation and coding schemes, especially when these are analyzed/simulated by different people.

In light of this, in CCSDS Fall 2020 Meeting, ESA proposed a channel model (SLS-CS_20-13) for performing computer simulations. The channel model includes AWGN, non-linear distortions, and frequency/phase impairments.
However, following feedback by the C&G WG members, the following minor discrepancies were highlighted:

- the channel model does not specify the pulse energy;
- the mathematical notation does not always specify if the computation shall be done in dB or in linear;
- the Doppler profile should be Gaussian, for better representing actual satellites passes (NASA response to AI_20_05).

Therefore, this paper firstly provides a revision of the channel model description that was previously presented in SLS-CS_20-13, followed by a new draft recommendation based on such channel model.

The reminder of this paper is organized as follows: Section 2—6 provides the updated channel model (with revision marks) w.r.t. former ESA input SLS-CS_20-13. Then, Section 7 refers to the proposed new recommendation and draws conclusions.

2. Overview of the channel model

The baseband model of the transmitted signal by the sending end reads

$$x(t) = \sum_k x_k p(t - kT) \ , \quad (1)$$

where x_k are the transmitted channel symbols, $p(t)$ is the shaping pulse, and T the channel symbol duration. The channel symbols and shaping pulse shall be generated as detail implementation of the modulation and coding standard to be simulated, that is, they shall faithfully modulate their physical layer structure including all signalling elements (e.g., preambles, postambles, headers, pilots) and randomizers/scramblers. Additionally, for simulation purposes, channel symbols shall be properly normalized such that $E\{|x_k|^2\} = 1$~~.~~, while the shaping pulse shall have energy $\int |p(t)|^2 dt$ such that the average transmitted signal power, $E\{|x(t)|^2\}$, is equal to one. With such setting, it is easy to show that the energy per symbol E_s is equal to the channel symbol time T.

The linearly modulated signal of Equation (1) is applied to the channel as shown in Figure 2-1 that includes the following elements: a nonlinearity, an RF output filter (mitigating spectral regrowth), frequency/phase impairments $\phi(t)$, and additive white Gaussian noise (AWGN) $w(t)$.

The channel model can be easily set in the following configurations:

- **Linear AWGN**, by removing the nonlinearity and RF filter, i.e., by setting $s(t) = x(t)$, and by removing frequency/phase impairments, as $\phi(t) = 0$. This channel model is particularly useful for assessing modcod performance under ideal conditions;
- **Nonlinear AWGN**, by removing frequency/phase impairments only ($\phi(t) = 0$). This channel model is useful for assessing the performance degradation due to the RF power amplifier, and designing possible pre-distortion techniques;
- **Linear AWGN with frequency/phase impairments**, by removing the nonlinearity and RF filter only. This channel model is particularly useful for assessing the performance of the frequency/phase synchronization chain that typically has algorithms designed for these kind of channels.
- **Nonlinear AWGN with frequency/phase impairments,** by using the full channel cascade, useful for combining all impairments and doing end-to-end performance evaluation.

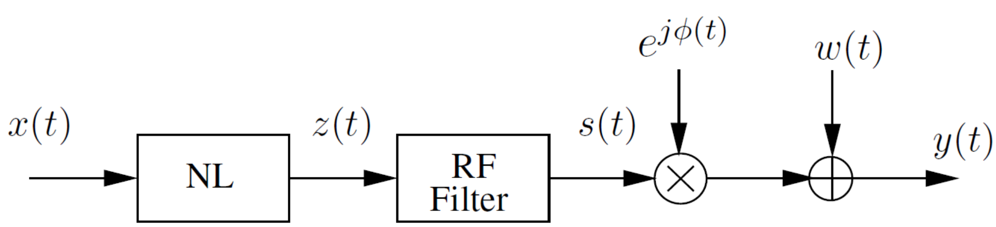

Figure 2-1: Nonlinear channel model block diagram

3. Signal-to-noise ratio and AWGN

The signal-to-noise ratio shall be defined in terms of energy over noise power spectral density at the receiver, as either energy-per-bit, E_b/N_0, or in terms of energy per channel symbol E_s/N_0. The E_b/N_0 is related to the E_s/N_0 by means of the relation

$$\frac{E_b}{N_0} r \cdot m = \frac{E_s}{N_0} \, ,$$

where m and r are the modulation order (number of bits per channel symbol) and the coding rate respectively.

Taking into account the constellation and pulse shaping normalization described in the previous section, in case the channel is used without nonlinearities (i.e., set as linear AWGN with or without frequency/phase impairments) the Gaussian noise in the simulation shall be generated with power spectral density equal to

$$\frac{\cancel{1}T}{\left(\frac{E_s}{N_0}\right)_{\text{target}}}$$

where $\left(\frac{E_s}{N_0}\right)_{\text{target}}$ is the target E_s/N_0 for the simulation (in linear scale).

Instead, if the channel is used with nonlinearities, the Gaussian noise in the simulation shall be generated with power spectral density

$$\frac{T\cancel{1}}{\left(\frac{E_s}{N_0}\cancel{+}\text{OBO}\right)_{\text{target}}}$$

where $\left(\frac{E_s}{N_0}\cancel{+}\text{OBO}\right)_{\text{target}}$ is the target $\frac{E_s}{N_0}\cancel{+}\text{OBO}$ for the simulation, i.e., the product of the target SNR with the OBO (both in linear scale).

4. Nonlinearity

The nonlinearity shall be modelled by means of the input/output relationship

$$z(t) = f_{AM}(|x(t)|)e^{j\angle x(t)+f_{PM}(|x(t)|)} \quad ,$$

where $f_{AM}(|x(t)|)$ and $f_{PM}(|x(t)|)$ are the AM/AM and AM/PM characteristics respectively.

For simulating~~on~~ a TWTA operating in X-Band 8025-8400 GHz and in the 25.5-27 GHz, the specific AM/AM and AM/PM shown in Figure 4-1, and having values as provided in ANNEX A, can be adopted.

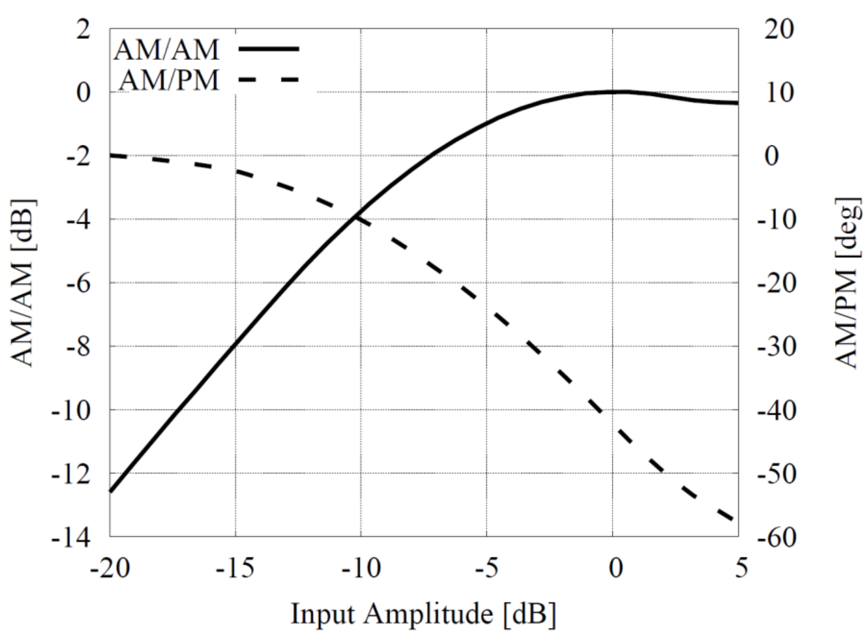

Figure 4-1~~4-1~~: AM/AM and AM/PM nonlinear transfer characteristics for the NL

5. RF filter

The RF filter shall be modelled as 5th order Elliptical filter, having ripple 0.1 dB, and passband and stopband $0.75R_{chs}$ and $0.9375R_{chs}$ respectively, being $R_{chs} = 1/T$ the channel baudrate. Figure 5-1 shows an example of the 5th order Elliptical filter frequency response for $R_{chs} = 100$ MBaud, and thus passband and stopband 75 MHz and 93.75 MHz respectively.

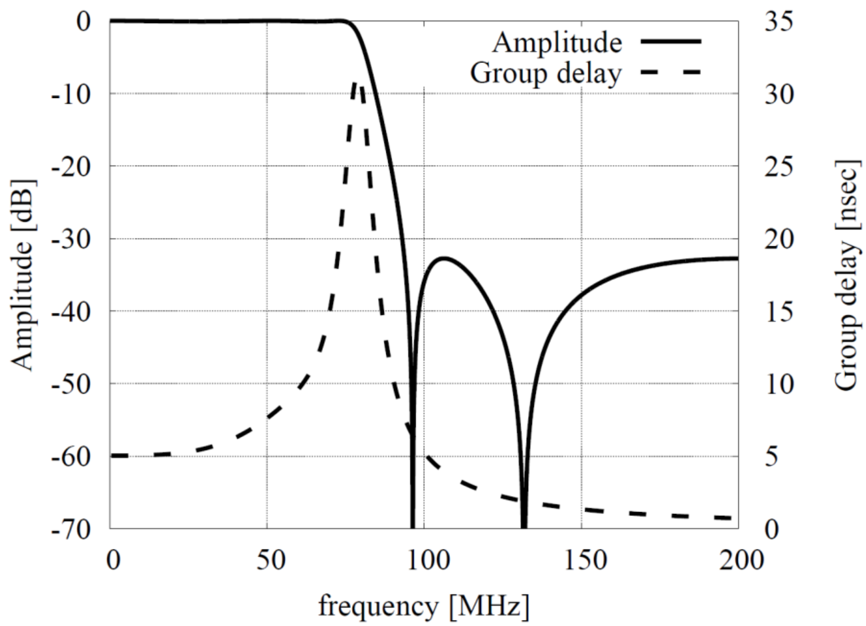

Figure 5-1~~5-1~~: RF filter frequency response in case Rchs=100 MBaud

6. Frequency and phase impairments

The frequency and phase impairment $\phi(t)$ reads

$$\phi(t) = 2\pi \int_0^t f(\tau)d\tau + \theta(t) \ ,$$

with $f(t)$ and $\theta(t)$ the Doppler profile and the phase noise respectively.

For $f(t)$, it is adopted a ~~sinusoidal~~ *Gaussian profile* having expression ~~and derivative as~~

$$f(t) = -\frac{f_0 R_e (R_e + h)\omega_{sat} \sin(\omega_{sat}(t - t_0))}{c\sqrt{R_e^2 + (R_e + h)^2 - 2R_e(R_e + h)\cos(\omega_{sat}(t - t_0))}}$$

where

- f_0 is the carrier frequency;
- R_e is the Earth Radius, to be set as 6378 km;
- h the satellite altitude, that is user defined;
- ω_{sat} is the satellite angular velocity, defined as

$$\omega_{sat} = \sqrt{\frac{\mu}{(R_e + h)^3}}$$

being $\mu = 398601.2$ km^3/sec^2 the Earth's gravitational parameter;

The Doppler profile $f(t)$ is defined over the time interval $[-t_{max}, t_{max}]$ where t_{max} is ~~defined as~~

$$t_{max} = \frac{\arccos\left(\frac{R_e}{R_e + h}\cos\theta\right) - \theta}{\omega_{sat}} \ ,$$

~~where~~being θ ~~is~~ the minimum elevation angle.

Whenever the simulation to be carried out requires a Doppler profile longer than the single pass duration, the user can simulate a continuous $f_c(t)$ Doppler profile obtained as continuation linear shift of $f(t)$ as

$$f_c(t) = \sum_i (-1)^i f(t - 2it_{max}) \, .$$

In this case, it has been observed $f_c(t)$ having an angular point where the two Doppler profile's curves meet for elevation angles greater than 0˚. Figure 6-1 reports the Doppler profile evaluated for a LEO of 1000 km, a carrier frequency of 27.5 GHz, and a minimum elevation angle $\theta = 5°$. In this last, the red rectangle better highlights the angular point above-mentioned. Therefore, it is proposed to adopt a minimum elevation angle of $\theta = 0˚$ (see ANNEX B).

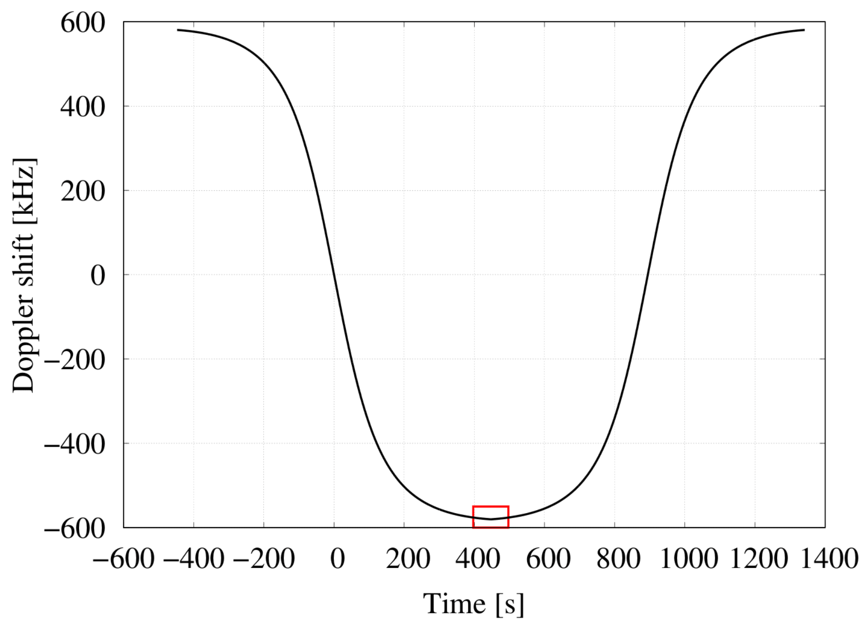

Figure 6-1~~6-1~~: Doppler profile evaluation for LEO of 1000 km, carrier frequency 27.5 GHz and minimum elevation angle 5˚.

Differently, the phase noise $\theta(t)$ is a coloured Gaussian random process. Its power spectral density is defined by the Fourier transform of $E\{\theta(t+\tau)\theta(t)\}$, which is usually known as *phase noise mask*. For the phase noise, the phase noise mask to be adopted is shown in Figure 6-2, that is in line with RFM BlueBook recommendations for Space-to-Earth links in EES at 8 GHz [RD1] and 26 GHz [RD2].

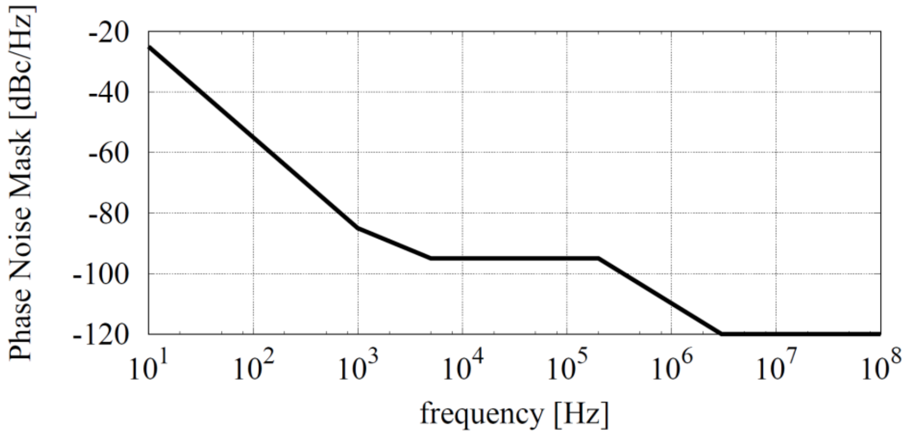

Figure 6-2~~6-2~~: Phase noise mask

7. Conclusions

This paper proposed a channel model that can be adopted in computer simulations . In this way, it would ease the performance assessment and comparison of different high bitrate telemetry schemes coming from different CCSDS members.

As final remark, when adopting the channel model, it is recommended that numerical results documents always specify:

- The setting of the channel model (e.g., linear AWGN, nonlinear, etc.);
- Any changes (if applicable) on the SNR definition (e.g., inclusion of frame overhead), nonlinearity, RF filter, Doppler, and Phase noise w.r.t. those reported here;
- synchronization algorithms adopted (unless ideal synchronization is adopted);
- Addition of other blocks/functions (if applicable), e.g., digital or waveform pre-distortion, timing impairments, etc.

In light of the work done, ANNEX B of this paper contains a draft recommendation for the RFM BlueBook 401 that is provided to CCSDS RFM and C&S WG for discussion and possible review.

8. References

[RD1] CCSDS 401 (2.4.18), Modulation methods at high symbol rate transmissions, Earth Exploration satellites (EES) 8 GHz Band, Space-to-Earth

[RD2] CCSDS 401 (2.4.23), Modulation methods at high symbol rate transmissions, Earth Exploration satellites (EES) 25.5-27.0 GHz, Space-to-Earth

ANNEX A - AM/AM and AM/PM values

$|x(t)|^2$ [dB]	$f_{AM}(|x(t)|)$ [dB]	$f_{PM}(|x(t)|)$ [deg]
-20	-12.6	0
-19.14	-11.7736	-0.2529
-18.28	-10.9635	-0.5954
-17.42	-10.1554	-0.9724
-16.56	-9.37491	-1.4091
-15.7	-8.57182	-1.9118
-14.84	-7.7934	-2.618
-13.98	-7.01234	-3.6336
-13.12	-6.24835	-4.7638
-12.26	-5.50135	-5.9782
-11.4	-4.79981	-7.4928
-10.54	-4.14957	-9.0021
-9.68	-3.52311	-10.848
-8.82	-2.95289	-13.001
-7.96	-2.42572	-15.18
-7.1	-1.93999	-17.617
-6.24	-1.51215	-19.986
-5.38	-1.14152	-22.655
-4.52	-0.80732	-25.424
-3.66	-0.53323	-28.335
-2.8	-0.31722	-31.452
-1.94	-0.16068	-34.652
-1.08	-0.04704	-37.925
-0.22	-0.00824	-41.321
0.64	-0.00379	-44.767
1.5	-0.06	-47.92
2.36	-0.16329	-50.957
3.22	-0.26418	-53.532
4.08	-0.32383	-55.59
4.94	-0.3486	-57.677
5.08	-0.3874	-59.062

ANNEX B – draft recommendation

CCSDS RECOMMENDATIONS FOR RADIO FREQUENCY AND MODULATION SYSTEMS

Earth Stations and Spacecraft

4.1.8 CHANNEL MODEL FOR PERFORMANCE ASSESSMENT OF HIGH CODED SYMBOL RATE TRANSMISISON SCHEMES, EARTH EXPLORATION SATELLITES (EES) 8 GHZ AND 25.5-27.0 GHZ, SPACE-TO-EARTH

The CCSDS,

considering

(a) that efficient use of RF spectrum resources is becoming increasingly important with the increasing congestion of the frequency bands;

(b) that the SFCG has approved a Recommendation suggesting Variable Coding and Modulation (VCM) or Adaptive Coding and Modulation (ACM), where practicable, when operating high data rate EESS space-to-Earth links in the 25.5–27.0 GHz frequency band[1];

(c) that CCSDS 131.0-B-3, CCSDS 131.2-B-1, and CCSDS 131.3-B-1 foresee a number of modulation and coding schemes that can be used in conjunction with VCM or ACM[2] for the Earth Exploration Satellite Service (EESS) 8025-8400 MHz and 25.5–27.0 GHz frequency bands;

(d) that a number of future EESS missions plan to adopt the modulation and coding schemes at point (c);

(e) that CCSDS space agencies need the ability to assess the performance of the modulation and coding schemes at point (c) and exchange results with the following objectives:

- supporting the design of future space missions;
- engaging in cooperative space missions;
- conducting joint space ventures; and
- providing ground station cross support to another agency's spacecraft;

recommends

that CCSDS agencies adopt the channel model in Annex when doing numerical simulations for performance assessment of the modulation and coding schemes at point (c), for the EESS 8025-8400 MHz and 25.5–27.0 GHz frequency bands;

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[1] SFCG recommendation 30-2 or latest version.

[2] See also CCSDS 431.1-B "Variable Coded Modulation Protocol"

ANNEX

CHANNEL MODEL

(Normative)

1. GENERAL

The channel model is a complex-valued baseband model. The transmitted signal by the sending end shall read

$$x(t) = \sum_k x_k p(t - kT) \ , \qquad (1)$$

where x_k are the transmitted channel symbols, $p(t)$ is the shaping pulse, and T the channel symbol duration.

The channel symbols and shaping pulse shall be generated as detail implementation of the modulation and coding standard that is analyzed, that is, they shall faithfully modulate their physical layer structure including all signaling elements (e.g., preambles, postambles, headers, pilots) and randomizers/scramblers.

The channel symbols shall be properly normalized as $E\{|x_k|^2\} = 1$, while the shaping pulse shall have energy $\int |p(t)|^2 dt$ such that the average signal power, $E\{|x(t)|^2\}$, is equal to one.

NOTE – This normalization ensures that the energy per symbol E_s is equal to the channel symbol time T.

The linearly modulated signal of Equation (1) shall be applied to the channel model shown in Figure 1-1. This channel model includes the following elements (later described): a nonlinearity, an RF output filter (mitigating spectral regrowth), frequency/phase impairments $\phi(t)$, and additive white Gaussian noise (AWGN) $w(t)$.

The channel model can be adopted in one of the following settings:

- **Linear AWGN**, by removing the nonlinearity and RF filter, i.e., by setting $s(t) = x(t)$, and by removing frequency/phase impairments, as $\phi(t) = 0$.
- **Nonlinear AWGN**, by removing frequency/phase impairments only ($\phi(t) = 0$).
- **Linear AWGN with frequency/phase impairments**, by removing the nonlinearity and RF filter only.
- **Nonlinear AWGN with frequency/phase impairments,** by using the full channel cascade.

NOTE – Depending on the analysis objectives, the following settings are recommended:

- Linear AWGN model for assessing modulation and coding performance under ideal conditions;
- Nonlinear AWGN for assessing the performance degradation due to the RF power amplifier, and designing possible pre-distortion techniques;

- Linear AWGN with frequency/phase impairments for assessing the performance of the frequency/phase synchronization chain;
- Nonlinear AWGN with frequency/phase impairments for end-to-end performance evaluation.

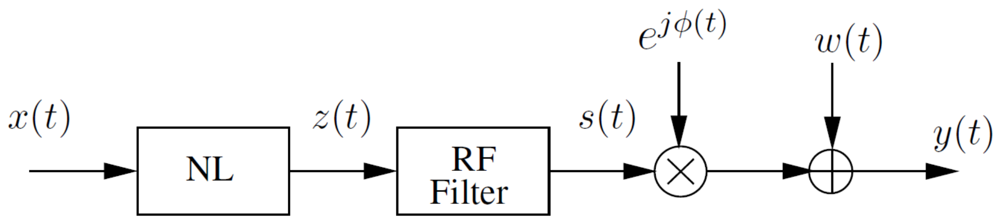

Figure 1-1: Nonlinear channel model block diagram

2. SIGNAL-TO-NOISE RATIO AND AWGN

The signal-to-noise ratio shall be defined in terms of energy over noise power spectral density at the receiver, as either energy-per-bit, E_b/N_0, or in terms of energy per channel symbol E_s/N_0. The E_b/N_0 is related to the E_s/N_0 by means of the relation

$$\frac{E_b}{N_0} r \cdot m = \frac{E_s}{N_0},$$

where m and r are the modulation order (number of bits per channel symbol) and the coding rate respectively.

Considering the constellation and pulse shaping normalization described in the previous section, if the linear AWGN (with or without frequency/phase impairments) is adopted, then, the Gaussian noise shall have power spectral density equal to

$$\frac{T}{\left(\frac{E_s}{N_0}\right)_{\text{target}}}$$

where $\left(\frac{E_s}{N_0}\right)_{\text{target}}$ is the target E_s/N_0 for the analysis (in linear scale).

If the channel is used with nonlinearities, the Gaussian noise shall have power spectral density equal to

$$\frac{T}{\left(\frac{E_s}{N_0}\,\mathrm{OBO}\right)_{\text{target}}}$$

where $\left(\frac{E_s}{N_0}\,\mathrm{OBO}\right)_{\text{target}}$ is the target $\frac{E_s}{N_0}$ and OBO is the adopted output back-off (both in linear scale).

NOTE – The OBO shall be measured after the nonlinearity and before the RF filter, i.e., on the signal $z(t)$ as shown in Figure 1-1.

3. NONLINEARITY

The nonlinearity shall be modelled by means of the input/output relationship

$$z(t) = f_{AM}(|x(t)|)e^{j\angle x(t)+f_{PM}(|x(t)|)} \quad ,$$

where $f_{AM}(|x(t)|)$ and $f_{PM}(|x(t)|)$ are the AM/AM and AM/PM characteristics respectively. These characteristics shall be as shown in Figure3-1, generated as linear interpolation (in dB) of the values in Table 1.

NOTE – These AM/AM and AM/PM characteristics are representative of a TWTA operating in X-Band 8025-8400 GHz and in the 25.5-27 GHz.

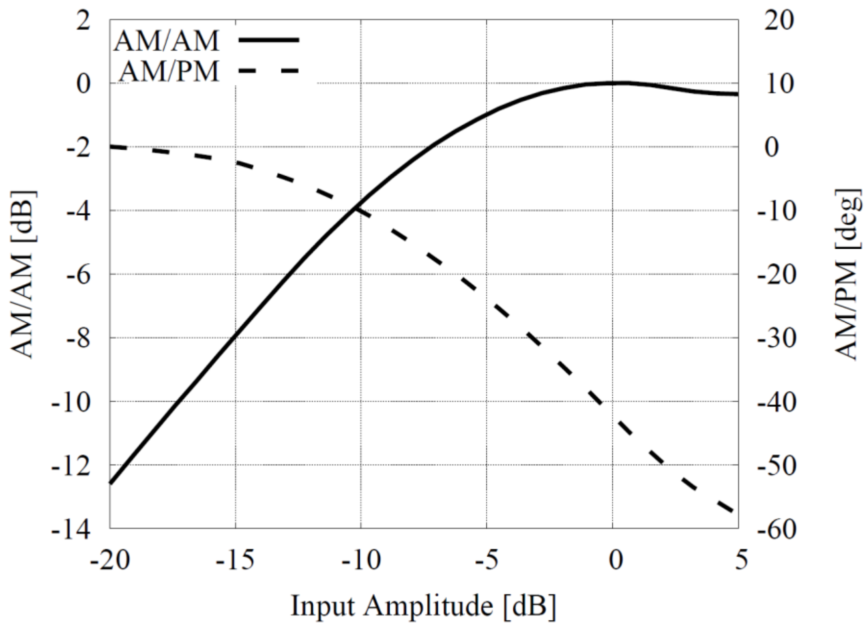

Figure3-1: AM/AM and AM/PM nonlinear transfer characteristics for the NL

Table 1: AM/AM and AM/PM characteristics values

$\lvert x(t)\rvert^2$ [dB]	$f_{AM}(\lvert x(t)\rvert)$ [dB]	$f_{PM}(\lvert x(t)\rvert)$ [deg]
-20	-12.6	0
-19.14	-11.7736	-0.2529
-18.28	-10.9635	-0.5954
-17.42	-10.1554	-0.9724
-16.56	-9.37491	-1.4091
-15.7	-8.57182	-1.9118
-14.84	-7.7934	-2.618
-13.98	-7.01234	-3.6336
-13.12	-6.24835	-4.7638
-12.26	-5.50135	-5.9782
-11.4	-4.79981	-7.4928
-10.54	-4.14957	-9.0021
-9.68	-3.52311	-10.848
-8.82	-2.95289	-13.001
-7.96	-2.42572	-15.18
-7.1	-1.93999	-17.617
-6.24	-1.51215	-19.986
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-4.52	-0.80732	-25.424
-3.66	-0.53323	-28.335
-2.8	-0.31722	-31.452
-1.94	-0.16068	-34.652
-1.08	-0.04704	-37.925
-0.22	-0.00824	-41.321
0.64	-0.00379	-44.767
1.5	-0.06	-47.92
2.36	-0.16329	-50.957
3.22	-0.26418	-53.532
4.08	-0.32383	-55.59
4.94	-0.3486	-57.677
5.08	-0.3874	-59.062

4. RF FILTER

The RF filter shall be modelled as 5th order Elliptical filter, having ripple 0.1 dB, and passband and stopband $0.75R_{chs}$ and $0.9375R_{chs}$ respectively, being $R_{chs} = 1/T$ the channel baudrate. Figure 4-1 shows an example of the 5th order Elliptical filter frequency response for $R_{chs} = 100$ MBaud, and thus passband and stopband 75 MHz and 93.75 MHz respectively.

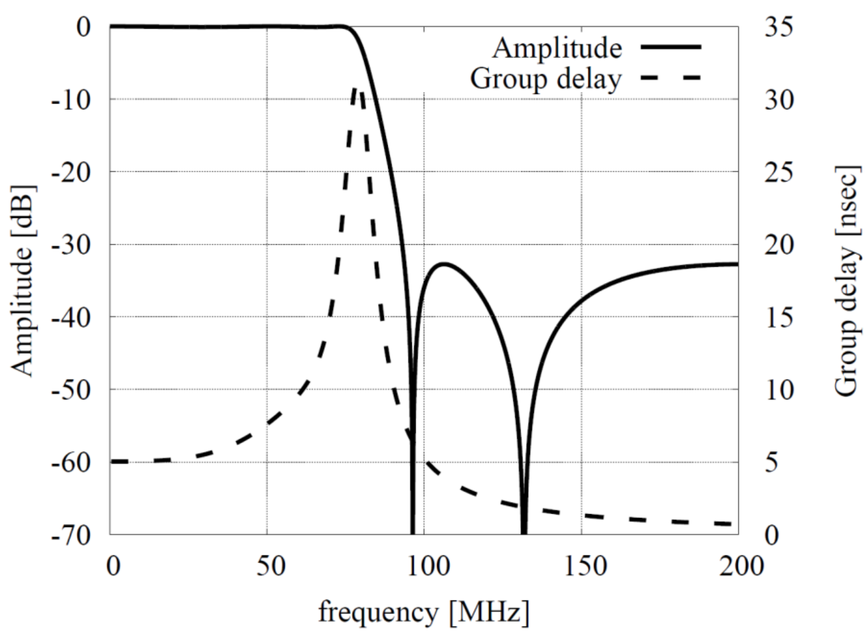

Figure 4-1: RF filter frequency response in case R_{chs}=100 MBaud

5. FREQUENCY AND PHASE IMPAIRMENTS

The frequency and phase impairment $\phi(t)$ shall be implemented as

$$\phi(t) = 2\pi \int_0^t f(\tau)d\tau + \theta(t) \ ,$$

where $f(t)$ and $\theta(t)$ are the Doppler profile and the phase noise respectively.

The Doppler $f(t)$ shall have a *Gaussian profile* with expression equal to

$$f(t) = -\frac{f_0 R_e (R_e + h)\omega_{sat} \sin(\omega_{sat}(t - t_0))}{c\sqrt{R_e^2 + (R_e + h)^2 - 2R_e(R_e + h)\cos(\omega_{sat}(t - t_0))}}$$

where

- f_0 is the carrier frequency;
- R_e is the Earth Radius, to be set as 6378 km;
- h the satellite altitude, that is user defined;
- ω_{sat} is the satellite angular velocity, defined as

$$\omega_{sat} = \sqrt{\frac{\mu}{(R_e + h)^3}}$$

being $\mu = 398601.2$ km^3/sec^2 the Earth's gravitational parameter.

The Doppler profile $f(t)$ is defined over the time interval $[-t_{max}, t_{max}]$, where t_{max} is defined as

$$t_{max} = \frac{\arccos\left(\frac{R_e}{R_e+h}\cos(\theta)\right) - \theta}{\omega_{sat}},$$

being θ the minimum elevation angle.

Whenever the simulation to be carried out requires a Doppler profile longer than the single pass duration, the user shall simulate a continuous Doppler profile obtained as continuation linear shift of $f(t)$ as

$$\sum_i (-1)^i f(t - 2it_{max}) .$$

In this case, the minimum elevation angle shall be set to $\theta = 0^\circ$, to avoid angular points in the continuous function.

NOTE - Figure 5-1 shows the example of a continuous Doppler profile for two passes duration, computed for a satellite at 1000 km altitude, and carrier frequency 27.5 GHz.

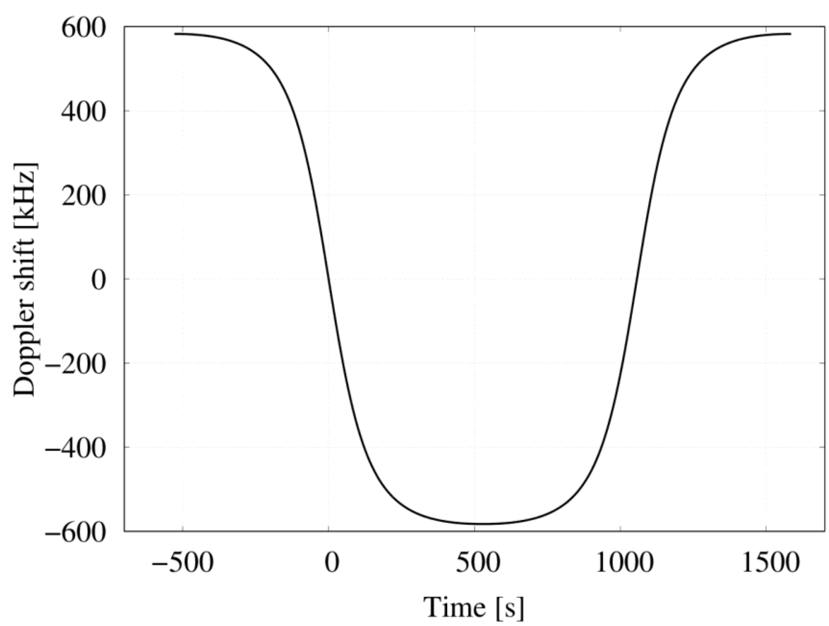

Figure 5-1: Doppler profile for 1000 km altitude, carrier frequency 27.5 GHz, extended for two passes duration

Differently, the phase noise $\theta(t)$ is a colored Gaussian random process. Its power spectral density is defined by the Fourier transform of $E\{\theta(t+\tau)\theta(t)\}$, which is usually known as *phase noise mask*. For the phase noise, the phase noise mask to be adopted is shown in Figure 5-1.

NOTE – The recommended phase noise mask is in line with CCSDS 401 (2.4.18) and CCSDS 401 (2.4.23).

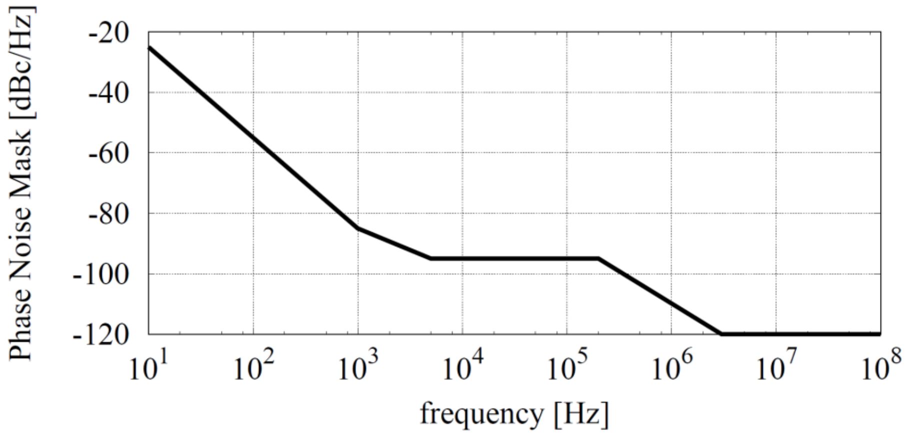

Figure 5-1: Phase noise mask

6. EXCHANGE OF RESULTS AND TAILORING OF THE CHANNEL MODEL

The analysis results, derived by applying the channel model in question, shall always specify the setting of the channel model adopted, as reported in Section 1 of this Annex. Additionally, except where ideal synchronization is adopted, the employed synchronization algorithms shall be reported.

Modifications and adjustments of this channel model can be done, as long as all changes w.r.t. this Annex are explicitly stated.