SLS-RNG_04-08

AI-04-01: Run simulation of filtered square-wave DOR tones via saturated amplifier and compute spectra[1]

Giovanni Boscagli, Peter Holsters (ESA/ESTEC),

Lorenzo Simone (Alenia Spazio)[2]

1. Introduction

According to the CCSDS recommendation regarding Differential One-way Ranging (DOR) measurements, DOR tones can have frequencies up to 120 MHz in Ka-band. In modern transponders the downlink modulation (telemetry and turn-around ranging) is very often implemented in the digital domain. The addition of the DOR functionality has an impact on the transponder architecture, because digital implementation of such high frequency DOR tone modulation is not feasible. As a consequence the transponder will have to be equipped with an additional fully analogue modulator, at the price of additional mass and power consumption. A reduction of the DOR tone frequency in the range of 1÷2 MHz would allow a fully digital implementation of this function.

For reasons of spectral efficiency, the CCSDS also recommends the use of sine-wave DOR-tones over square-waves. The sine-wave tones are directly phased modulated on the downlink RF carrier, which allows appropriate choices of spanned bandwidth and tone power. When modulating the carrier with the DOR tone, the harmonics of the modulating frequency are also present. If the RF filter of the on-board transmitter does not filter out these harmonics, they can be exploited for DOR measurements.

A wide DOR tone spanned bandwidth and high tone received power are needed for high measurement accuracy. This leads to the fact that using square-wave tones allows to improve the DOR performance due to the fact that the higher order harmonics have more power with respect to the sine-wave case. Indeed for MarsExpress mission, the DOR measurement has been performed using a higher order harmonic (11^{th}, TBC) of the square-wave telemetry sub-carrier at 262 KHz. In addition, square-wave will greatly simplify the digital modulation approach that can be envisaged for low-frequency DOR-tone synthesis.

On the other hand, the use of square-wave DOR tones will lead to a larger spectral occupation because of the higher level of the harmonics. In addition, because of the implementation of the low-frequency DOR tone modulation in digital domain, the spectrum of the modulated carrier will be affected by the analogue RF filtering in the on-board transmitter chain, therefore losing its constant envelope. The non-linear AM-AM and AM-PM behaviour of the high power amplifier (HPA) will therefore lead to an additional spectral re-growth of spurious signals.

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[1] Delta-DOR recommendation - proposal for change (Rec. 2.5.6B) CCSDS Spring Meeting ESA HQ, Paris (France), 3-7 May 2004

[2] The contribution of Alenia Spazio to this paper is based on the analysis performed in the frame of the ESA contract for BepiColombo transponder predevelopment.

Three approaches are hereafter analysed in order to limit the spectral re-growth at the output of the HPA when employing square-wave DOR tones:

1. The *reduction of modulation index* will reduce the level of the spectral lines corresponding to the harmonics with respect to the spectral line of the carrier. In this way the filtering effect on the signal envelope is reduced (because of the lower level of “out-of-band harmonics”) but also less power is available for DOR angular measurement.

2. The *reduction of the square-wave frequency* will compress the spectral distance between the harmonics thus reducing the occupied band (because of the lower level of “out-of-band harmonics”).

3. The *increase of the IBO* will decrease the non-linearity introduced by the HPA. This non-linearity is a source of spectral enlargement.

Assuming square-wave tones, the impact of these three options on the HPA output spectrum will be investigated in the following sections. The AM/AM and AM/PM behaviour of the HPA is based on values provided by Thales and is relevant to a 20W Ka-band TWTA:

IBO [dB]	OBO [dB]	ΔΦ [deg]
-20	-11.48	0
-19	-10.62	-0.28
-18	-9.68	-0.70
-17	-8.77	-1.25
-16	-7.90	-2.08
-15	-7.12	-2.92
-14	-6.29	-4.17
-13	-5.42	-5.28
-12	-4.62	-6.67
-11	-3.92	-8.33
-10	-3.23	-10.21
-9	-2.65	-12.09
-8	-2.08	-14.17
-7	-1.62	-16.67
-6	-1.21	-19.38
-5	-0.86	-22.09
-4	-0.52	-25.00
-3	-0.29	-28.33
-2	-0.12	-31.67
-1	-0.04	-35.42
0	0.00	-39.59

Table 1-1: AM/AM and AM/PM characteristics of 20 W Ka-band TWTA (provided by Thales)

In the annex also simulation results assuming a 35 Watt amplifier are provided. Although the 35 Watt TWTA shows less favourable characteristics, the overall simulate results in terms of spectral occupation remain almost unchanged.

At present the square-wave DOR signal with tone frequency of 1 MHz or less is proposed for the BepiColombo X/X/Ka DST according to the following points:

- It is implemented in the digital domain both for X and Ka-down-link.
- The modulated signal after analogue-to-digital conversion is filtered at the intermediate frequency with a SAW filter having a bandwidth of +/-3.5 MHz approximately around the carrier.
- The transponder output signal is amplified by an external HPA (TWTA).

In the following paragraphs the results of a simulation performing such an approach are reported. The TWTA output plots will be compared with respect to a sinusoidal case considered as reference.

Note that for the BepiColombo X/X/Ka DST we have:

- The digital DOR tone modulation index is in-flight selectable (via dedicated command)
- The frequency (500 KHz or 1 MHz) of the digital DOR tone signal is in flight selectable (TBC) via dedicated command
- The X and Ka DST output power are in-flight selectable (via dedicated command) in a range of 10 dB, this result in a control of the TWTA IBO from 0 to –10 dB.

The Ka-band downlink includes an additional analogue linear phase modulator for higher frequency tones (up to 76 MHz).

2. Simulation set-up

Figure 2-1 shows a top-level block diagram of the transmitter chain in case of DOR digitally implemented.

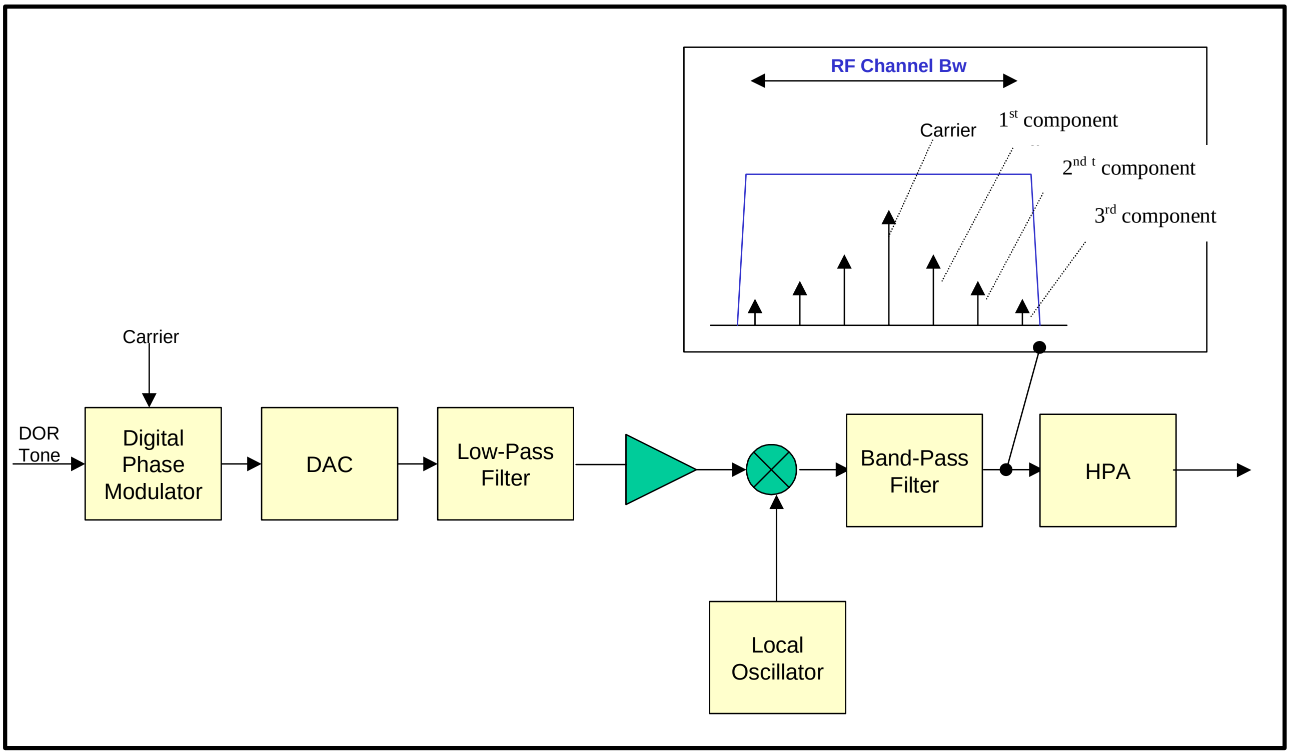


Figure 2-1: All-digital DOR tone modulation & RF channel bandwidth

(Note that in case of square-wave DOR tone the even-order harmonics are not present)

At the band-pass filter output, the harmonics of the modulated signal are filtered out and the RF signal is no longer a constant envelope signal. The high-power amplifier (HPA) at the transmitting chain front-end is usually driven at saturation and, therefore, a spectral re-growth at the transmitter output is expected. (Note that when the phase-modulated signal is not filtered its complex envelope is constant, and the spectral re-growth is not present).

This effect has been analysed as function on the modulation index and the HPA input back-off (IBO) in the following cases:

- Sine-wave DOR at 1 MHz
- Square-wave DOR at 1 MHz
- Quantised sine-wave DOR at 1 MHz
- Sine-wave DOR at 500 kHz
- Square-wave DOR at 500 kHz
- Quantised sine-wave DOR at 500 KHz

The simulation has been carried out using Simulink® and it is based on the set-up reported in the following block diagram.

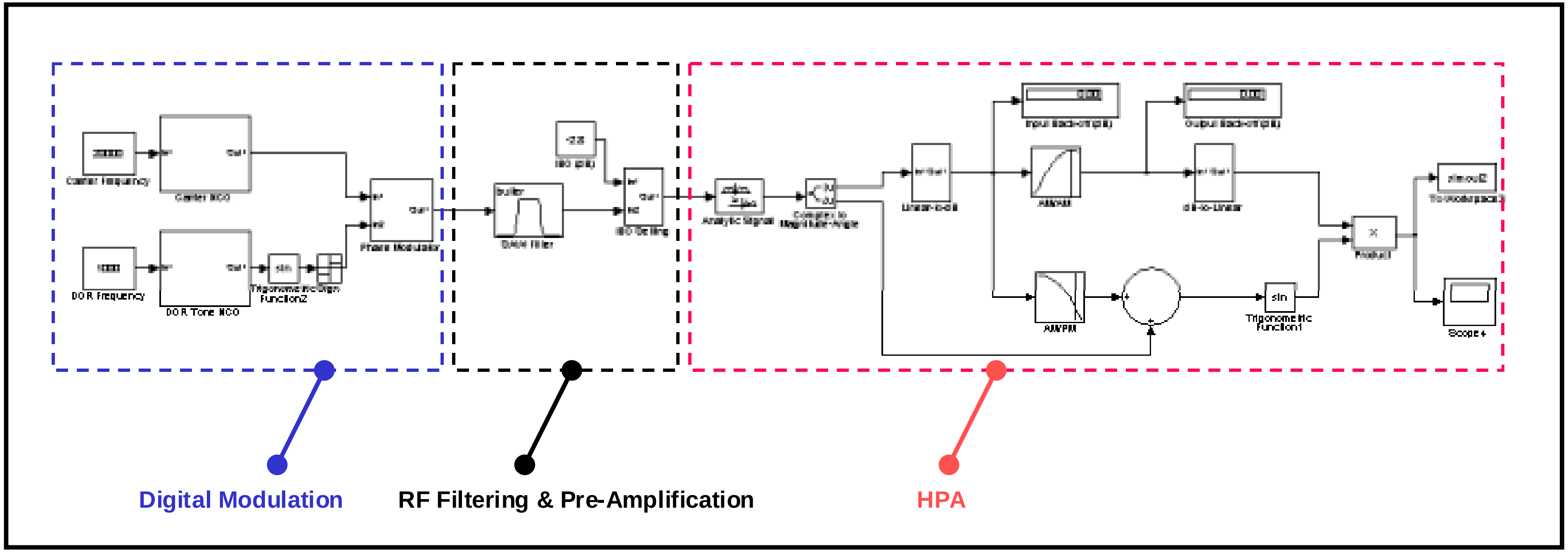


Figure 2-2: Filtered DOR tone via saturated HPA: simulation set-up

The simulation set-up is based on the following main sections:

- **Digital Modulation**. The un-modulated carrier phase is generated by means an NCO with frequency control word equal to ¼ the simulation sampling frequency. A similar NCO is used to generate the DOR tone phase. The DOR tone is obtained by computing the sine of the DOR tone phase at the NCO output; for square-wave tone case, the "sign" is then extracted. The phase modulation is accomplished by adding the DOR tone (either sine-wave or square-wave) to the phase of the un-modulated carrier (see Figure 2-3). Note that in the following, unless specifically indicated, the modulation index is expressed as radiant peak.

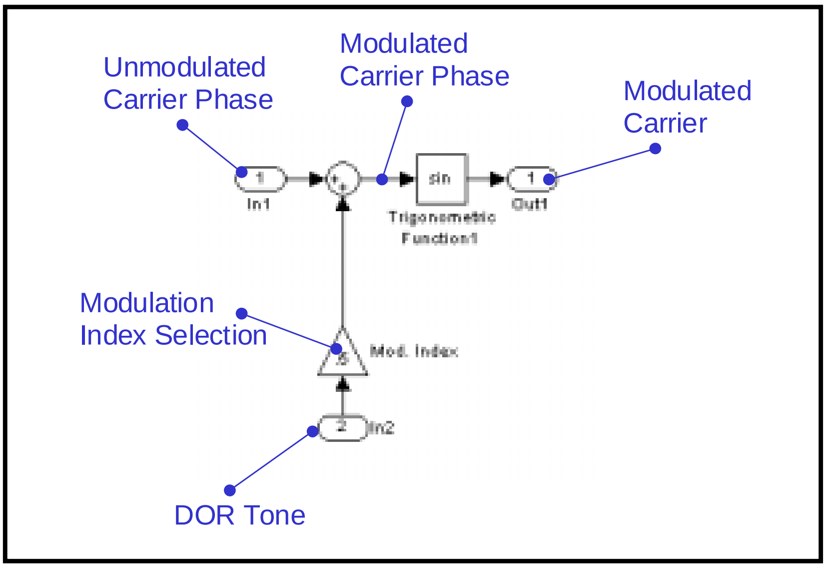


Figure 2-3: Digital phase modulation (simulation set-up)

- **RF Filtering and Pre-amplification**. The RF filtering has been simulated by a 12th-order Butterworth band-pass filter with bandwidth equal to 7 MHz. The "IBO Setting " block allows to select the desired HPA input back-off.

- **HPA**. The influence of the HPA has been simulated by means of the AM/AM and AM/PM curves. First of all, the complex envelope of the filtered real signal is computed using a dedicated block supported by Simulink®. The complex signal is split into its magnitude and angle components. The AM/AM conversion is applied by means a look-up table[3] in order to produce the magnitude of the output signal. The AM/PM conversion is applied by means a look-up table[4] and the resulting phase shift is added to the angle of the input signal to generate the angle of the output signal. Finally, the new magnitude and angle components are combined to provide the output real signal. Simulation displays are used to verify the input and output back-off and to monitor the output signal in the time domain. The spectral analysis is performed in the frequency domain by means a FFT.

In the sections hereafter, the spectra at the input and the output of the HPA are presented for some specific cases; additional plots are reported in Annex A and B. In section 6.2, the results in terms of bandwidth occupation for all simulated cases are summarised in two tables.

3 The look-up table is based on the AM/AM characteristics of Table 1-1.
4 The look-up table is based on the AM/PM characteristics of Table 1-1.

3. The reference case: 1 MHz sine-wave tone

For the analysis reported in this paper we consider as reference case the following:

- 1 MHz sine-wave
- Modulation index = 0.8 (radiant peak).
- 0 dB input back-off (IBO) for the HPA

The figure below gives the spectrum at the input of the HPA (a TWTA), normalised with respect to the carrier. The ratio in dB between the residual carrier and the i-th harmonic is given by the expression:

$$R_i = 20 \cdot \log_{10}\left[\frac{J_i(m_{DOR})}{J_0(m_{DOR})}\right] \qquad \text{for i} = 1, 2, 3 \ \ldots$$

For a modulation index equal to 0.8 rad-pk, this gives about -7.2 dB for the first spectral line, as can be verified from the figure 3-1.

At the output of the non-linear TWTA, we find the spectrum in figure 3-2.

In this reference case, the bandwidth occupied[5] by the DOR-signal is about 6 MHz at –50 dBc. The side-band imbalance that can be noticed is caused by the non-linearity of the TWTA and it reduces when assuming a larger IBO.

As conclusion we can say that using a digital approach with a sinusoidal 1 MHz DOR tone and 7 MHz filtering bandwidth has no impact in terms of band occupation and doesn't suffer from spectral re-growth.

[5] Seepara.6.1 for te definition of occupation bandwidth

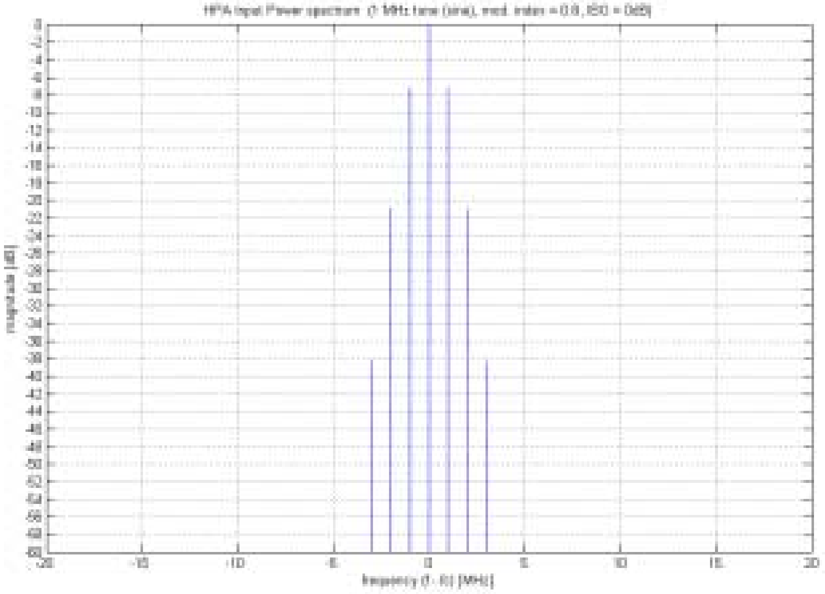


Figure 3-1: HPA Input spectrum: Sine-wave tone at 1 MHz, modulation index 0.8, IBO = 0dB

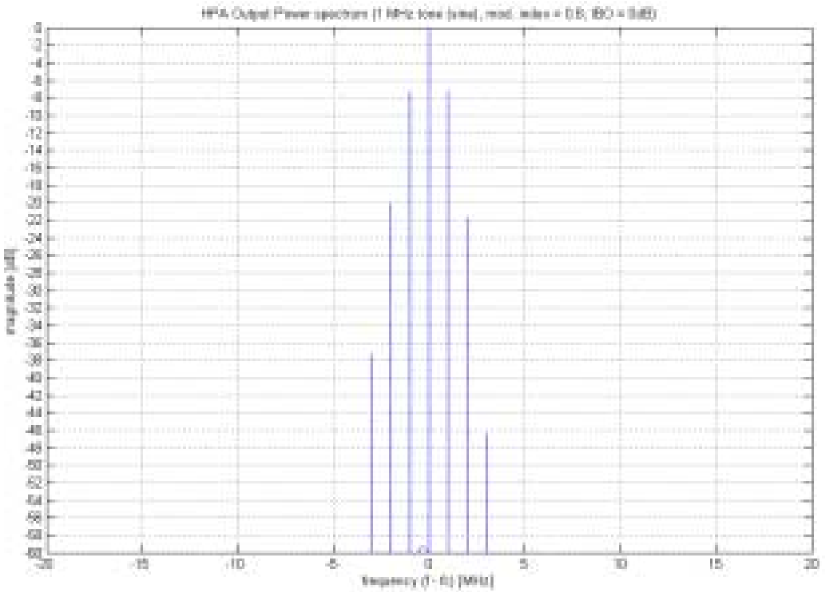


Figure 3-2: HPA Output spectrum: Sine-wave tone at 1 MHz, modulation index 0.8, IBO = 0dB

4. *Square-wave tones*

4.1 Reference conditions

Assuming the same conditions as above in the reference case (i.e. 1 MHz tone, modulation index=0.8 radiant peak, 0 dB IBO) but now with a square-wave tone, the following figures show the spectrum at the input and the output of the TWTA.

At the input, only odd harmonics are present because of the square-wave nature of the DOR-signal. So in theory, only odd harmonics should be present at the output too but the non-linearity of the TWTA causes even harmonics to rise up.

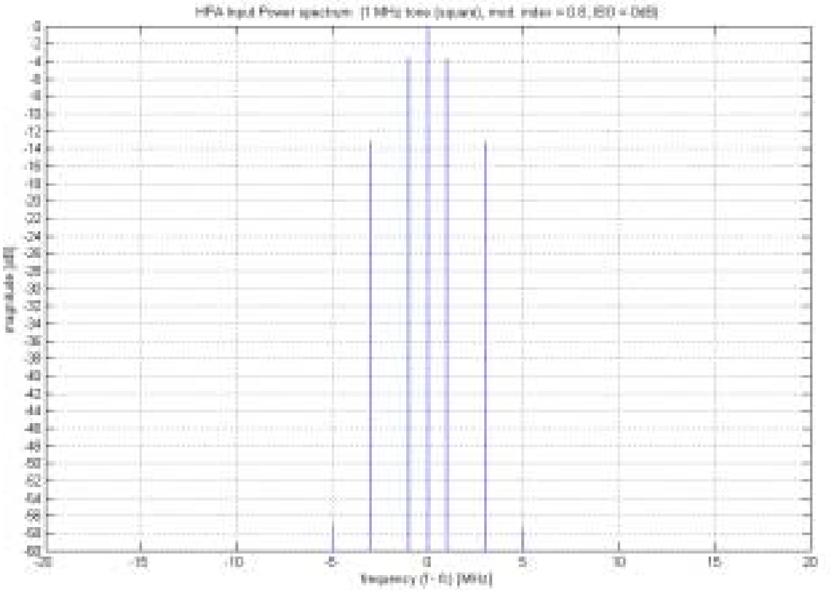


Figure 4-1: HPA Input spectrum: Square-wave tone at 1 MHz, modulation index 0.8, IBO = 0dB

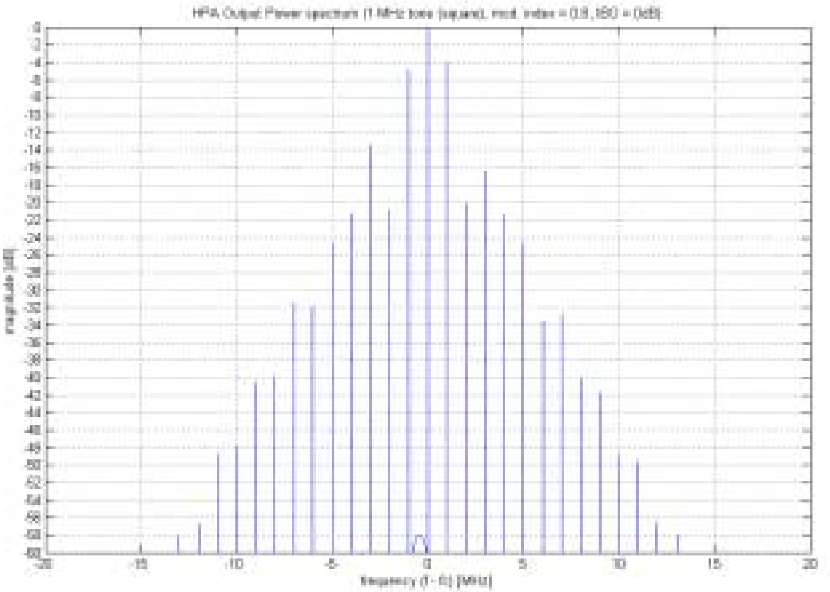


Figure 4-2: HPA Output spectrum: Square-wave tone at 1 MHz, modulation index 0.8, IBO = 0dB

4.2 Reduced modulation index

As reported above, reduction of the modulation index reduces the power in the harmonics. The following figures give the output spectra when assuming a modulation index 0.5 and 0.2 (rad-pk) respectively.

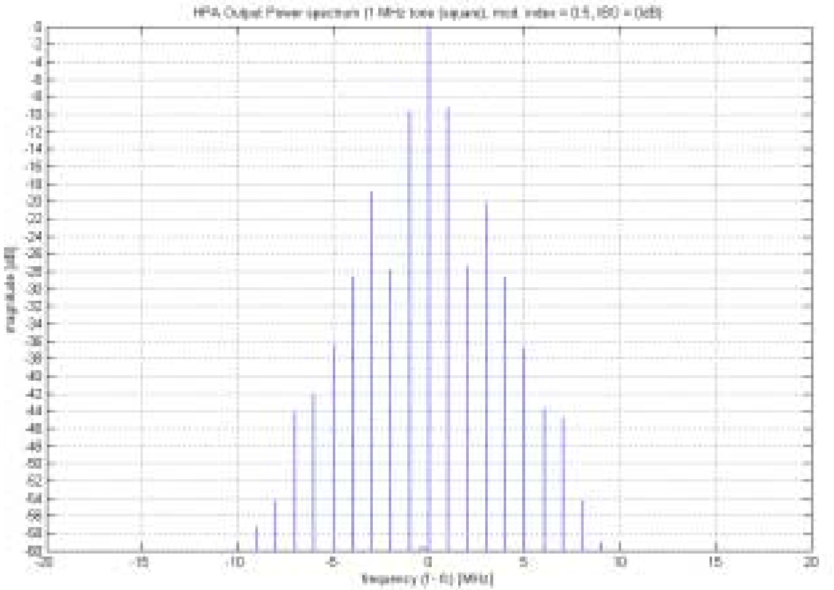


Figure 4-3: HPA Output spectrum: Square-wave tone at 1 MHz, modulation index 0.5, IBO = 0dB

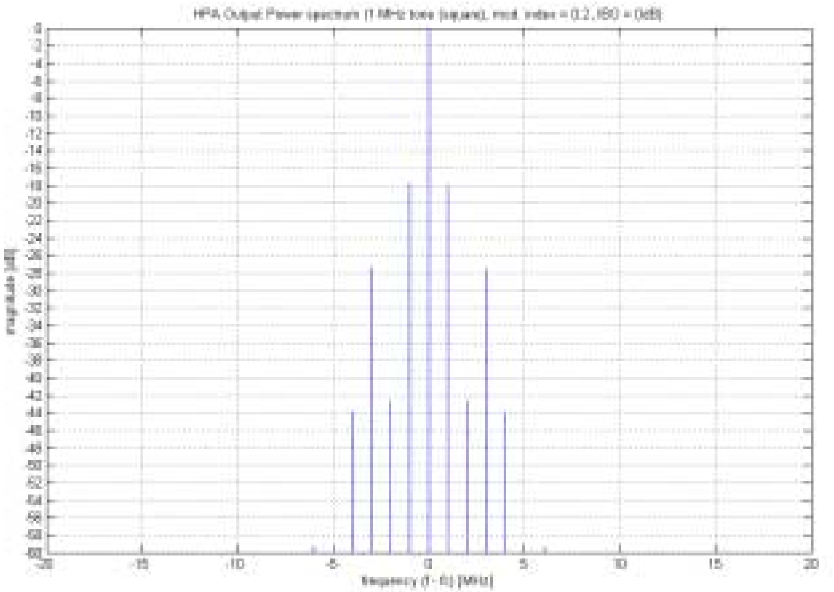


Figure 4-4: HPA Output spectrum: Square-wave tone at 1 MHz, modulation index 0.2, IBO = 0dB

As can be seen from the above figures (figure 4-2, 4-3 and 4-4) we have:

- Lowering the DOR modulation index from 0.8 to 0.5 reduces the -50 dBc bandwidth at the TWTA output from 22 MHz to about 14 MHz.

- Further decrease of the modulation index to 0.2, leads to a further reduction to 8 MHz.

Note that the reduction of the modulation index implies that the level of the first harmonic goes down (approximately –14 dB from 0.8 to 0.2 mod index) with a consequent impact on the DOR signal over noise spectral density at the ground station.

4.3 Reduced frequency

A smaller base frequency for the square-wave DOR tone will compress the occupied spectrum. In the following figures, we assume a 500 kHz, square-wave with IBO = 0 dB and modulation index 0.8 (rad-pk). Compared to the HPA input, the –50 dBc bandwidth at the output is enlarged from 7 to about 17 MHz, some 5 MHz smaller compared to the case where a 1 MHz square-wave tone is used (see figure 4-2).

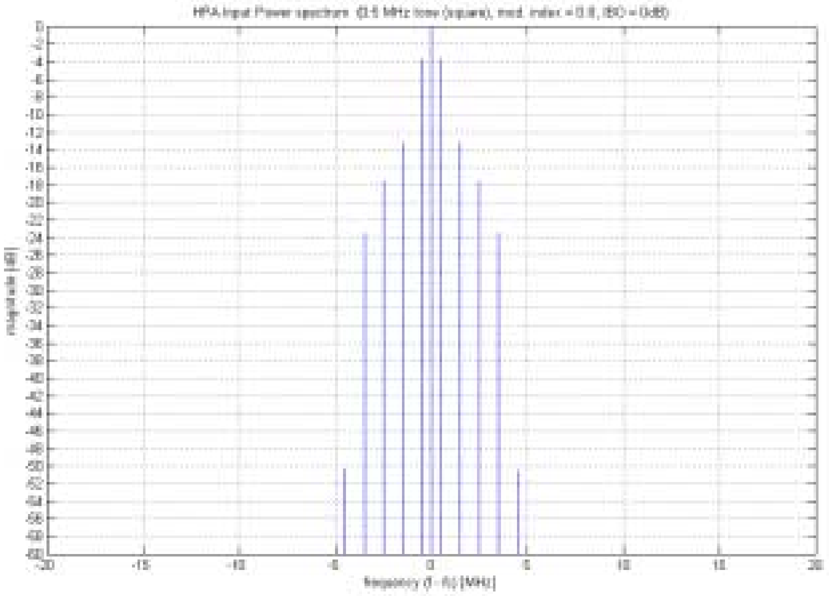


Figure 4-5: HPA Input spectrum: Square-wave tone at 0.5 MHz, modulation index 0.8, IBO = 0dB

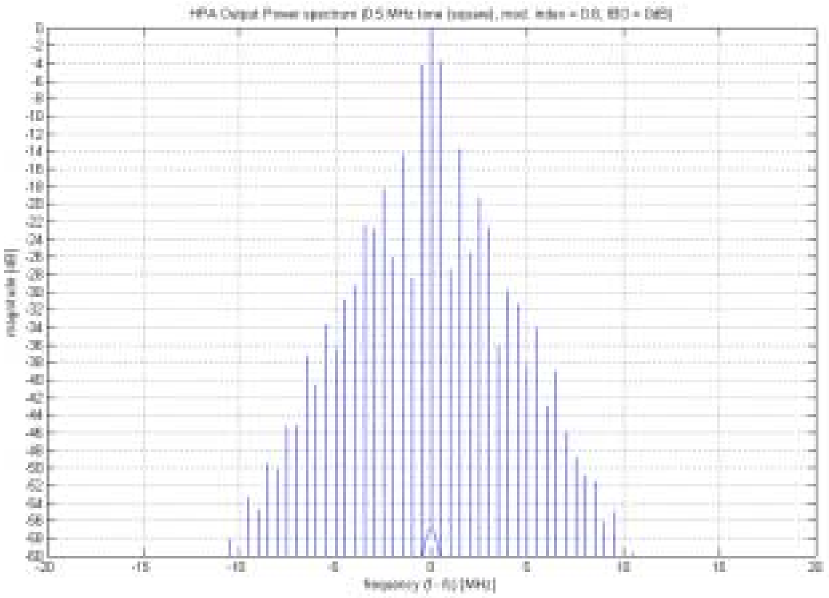


Figure 4-6: HPA Output spectrum: Square-wave tone at 0.5 MHz, modulation index 0.8, IBO = 0dB

4.4 Increased IBO

As a last solution to limit the spectrum of the square-wave DOR signal, we assume a larger IBO for the TWTA in order to reduce the amount of non-linearity introduced. The following figure presents the HPA output spectrum in case of -6 dB IBO. The other parameters remain unchanged, i.e. 1 MHz frequency (square-wave) and 0.8 modulation index. From this figure, a -50 dBc bandwidth of 18 MHz can be derived, some 4 MHz smaller compared to the case where a 0 dB IBO is used (see figure 4-2).

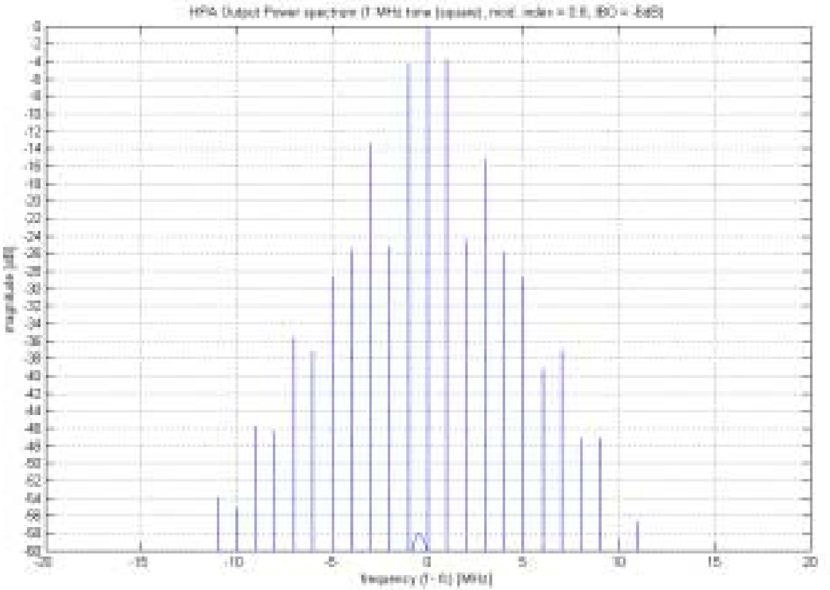


Figure 4-7: HPA Output spectrum: Square-wave tone at 1 MHz, modulation index 0.8, IBO = -6dB

5. *Quantised sine-wave*

In the above simulation the sinusoidal DOR tone[6] is generated at high sampling rate with respect to its frequency; for instance 80 samples per period for 1 MHz tone (see para.3). As a compromise between this nearly perfect sine-wave and the basic square-wave DOR-signal, one could propose a "quantised" waveform. This one is obtained by sampling a sine at low rate, for example at 8 samples per period. This can be easily implemented in the digital domain by storing the sine values in a ROM and read them out at the appropriate DOR frequency. This approach reduces the complexity compared to the "perfect" sine-waveform case, but it is expected to have lower spectral occupation than the square-wave.

In the following figure, the approximation of the sine-waveform is shown by 8 samples/period.

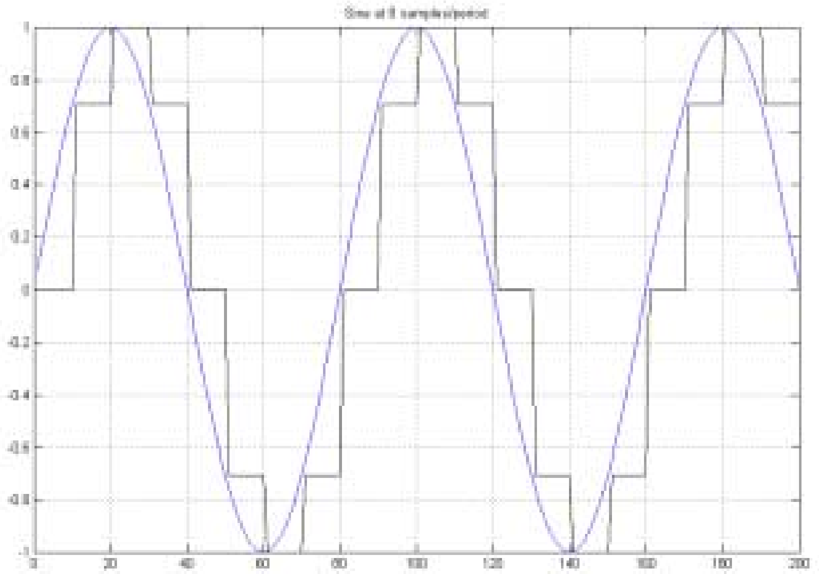


Figure 5-1: Sine-wave sampled at 8 samples/period

The spectra at the input and output of the HPA are shown in the figures below for:

- 1 MHz sine-wave at 8 samples/period
- Modulation index =0.8 rad-pk
- 0 dB IBO

As can be seen, the spectral re-growth compared to the reference case (nearly perfect sine-wave) is almost negligible. At the output, the 4-th harmonic is raised a bit but still stays below -50 dBc. The occupied band is still the same (6 MHz) of the reference case (see figure 3-2).

[6] It is the reference case at 1 MHz described in para.3.

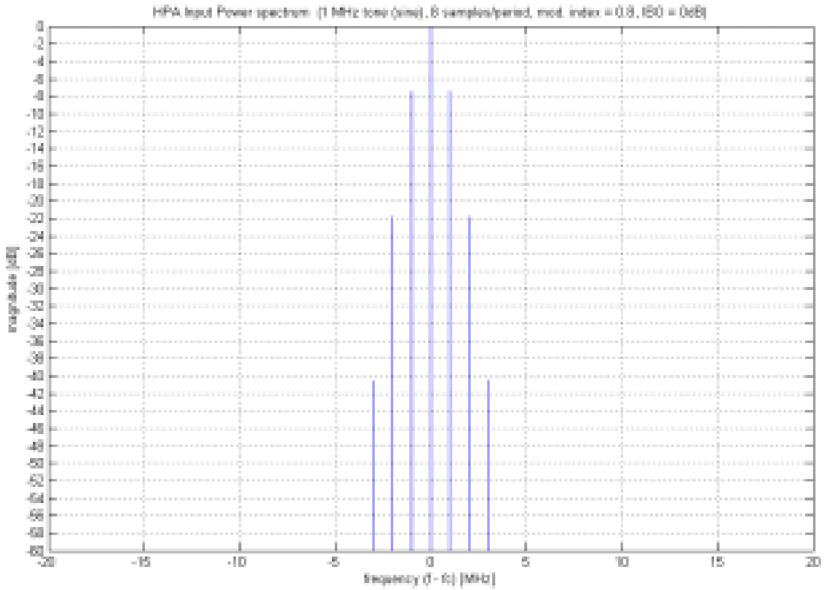


Figure 5-2: HPA Input spectrum: 1 MHz sine-wave tone sampled at 8 samples/second, modulation index 0.8, IBO = 0dB

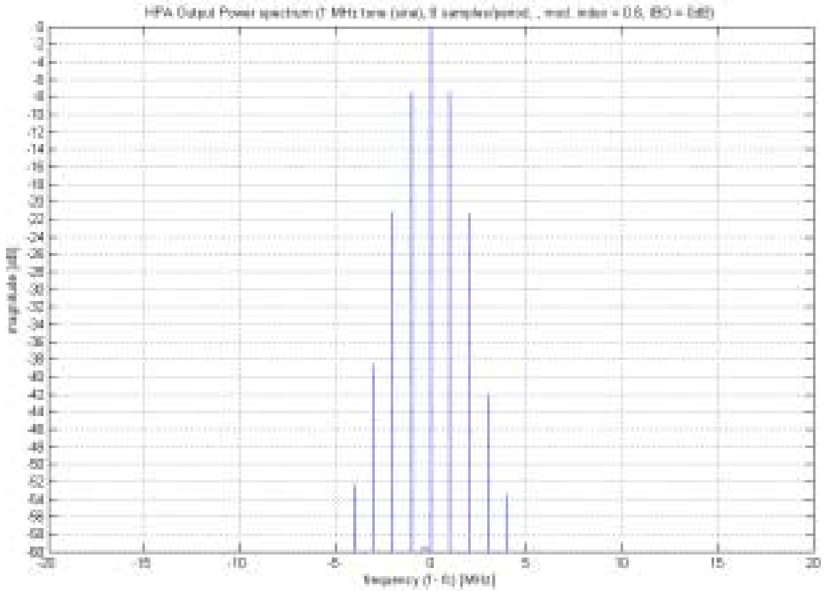


Figure 5-3: HPA Output spectrum: 1 MHz sine-wave tone sampled at 8 samples/second, modulation index 0.8, IBO = 0dB

6. Bandwidth considerations and conclusions

6.1 Definitions

The bandwidth can be defined in several ways. In the analysis performed here, two concepts are retained:

- **99% occupied bandwidth**: According to the ITU, the *occupied bandwidth* is defined as "the width of a frequency band such that, below the lower and above the upper frequency limits, the *mean powers* emitted are each equal to a specified percentage ß/2 of the total *mean power* of a given *emission*. Unless otherwise specified by the Radio-communication Bureau for the appropriate *class of emission*, the value of ß/2 should be taken as 0.5%."

Due to the discreet nature of the DOR spectrum, constituted of the harmonics of the fundamental DOR-tone, another bandwidth measure is also considered in this analysis.

- **-50 dBc bandwidth:** According to the ITU, the *x dB bandwidth* is defined as "*the width of a frequency band such that beyond its lower and upper limits any discrete spectrum component or continuous spectral power density is at least x dB lower than a predetermined 0 dB reference level*." Here, we will assume the -50 dB bandwidth, with 0dB set by the level of the carrier, or -50 dBc, where *dBc* signifies "*decibels relative to the un-modulated*[7] *carrier power of the emission*."

The choice for the -50 dBc bandwidth is based on the assumption that spurious harmonics at a level of 50 dB below the carrier do not cause any serious interference problems and in case of BepiColombo it is compliant to SFCG 23-2 recommendation (see Annex D) for power flux density at the Earth (see Annex C for the relevant analysis).

[7] Sometimes for the bandwidth evaluation of the DOR modulated signal we have considered the residual carrier instead of the un-modulated carrier. Note that this gives a negligible error for the worst case: maximum modulation index equal to 0.8 rad.pk and square wave DOR signal.

6.2 Summary tables of bandwidth analysis

The following two tables give the bandwidth of the DOR-signal according to the above definition in a number of specified cases.
In the first table, a 1 MHz tone is considered. The bandwidths in this table are stated in units of MHz:

1 MHZ DOR tone frequency			99% bandwidth [MHz]		50dBc bandwidth [MHz]		% in ± tone frequency	
Waveform	Mod.index	IBO	Input	Output	Input	Output	Input	Output
Sine	0.8	0	4	4	6	6	98.8	98.7
Square	0.8	0	6	8	6	22	95.1	93.9
	0.5	0	6	6	6	14	97.9	97.6
	0.2	0	2	2	6	8	99.6	99.5
	0.8	-3	6	6	6	18	95.1	94.7
	0.8	-6	6	6	6	18	95.1	95.0
Sine @ 8 samples /period	0.8	0	2	4	6	6	99.0	98.8

Table 6-1: Summary table of bandwidth analysis assuming 1 MHz DOR-tone frequency

The first line corresponds to the reference case, a 1 MHz sine-wave tone with modulation index of 0.8 rad-pk and 0 dB IBO. The columns "input" and "output" refer to the signal bandwidth at the input and output of the TWTA and comparison allows for an estimation of the spectral re-growth caused by the amplifier.

The last two columns of the table give the percentage of the total power that is present in the carrier plus the first components (the two DOR base frequencies on either side of the residual carrier). The 99% reference value is sometimes approached very closely but in most cases the first components are just not enough. This means that also higher order components have to be included to comply with the 99% bandwidth definition. However, these higher order harmonics have usually relatively low power (compared to the basic ones) and are needed just to make up for the few remaining percentages. However, due to the discrete nature of the spectrum, sometimes they are responsible for a rather large increase in bandwidth. As example considering the sine-wave reference case (first line), the power percentage in the band limited by the first components is 98.8%, so a doubling of the band is required to meet the 99% requirement. This leads to an apparently reduction in performances with respect to the quantised sine-wave if thee 99% criterion is applied.
For this reason we prefer to apply the –50dBc bandwidth approach for bandwidth analysis.

In the second table, a DOR-tone frequency of 500 kHz is considered:

0.5 MHZ DOR tone frequency			99% bandwidth [MHz]		50dBc bandwidth [MHz]		% in ± tone frequency	
Waveform	Mod.index	IBO	Input	Output	Input	Output	Input	Output
Sine	0.8	0	2	2	3	3	98.8	98.7
Square	0.8	0	5	6	7	17	93.0	92.8
	0.5	0	3	5	7	11	96.9	96.9
	0.2	0	2	2	7	7	99.5	99.4
	0.8	-3	5	6	7	15	93.0	93.2
	0.8	-6	5	5	7	13	93.0	93.3
Sine @ 8 samples /period	0.8	0	2	2	7	9	98.6	98.5

Table 6-2: Summary table of bandwidth analysis assuming 0.5 MHz DOR-tone frequency

6.3 Bandwidth occupation comparison

In the following paragraphs we want to compare the bandwidth occupation at –50 dBc for the DOR signal (see table 6-1 and 6-2) with the – 50 dBc case for the TLM downlink. The purpose of this exercise is to give an idea of the DOR signal bandwidth occupation if compared with the telemetry signal. Of course we will assume the PCM/PM/Bi-Phase modulation typical of Deep Space mission. Two different criterions are used as underlined in para.6.3.1 and 6.3.2.

6.3.1 Criterion #1 (SFCG Rec. 21-R-2)

Regarding TLM bandwidth occupancy we can consider CCSDS recommendation 222.4.17B, which makes reference to "*SFCG Recommendation 17-2R1 or latest version*". However this recommendation is now indicated as REC 23-1 and is provisional[8], its title is: "*Efficient Spectrum Utilization for Space Research Service, Deep Space (Category B) in the Space-to-Earth Link*". As a consequence in the following we assume as reference the SFCG recommendation 21-R-2 for "*Efficient Spectrum Utilization for Space Science Services on Space-to-Earth Links; Cat. A*".
Since we are referring to BepiColombo mission (Deep Space), for the estimation of – 50 dBc bandwidth, in the following we consider the PCM/PM/Bi-Phase case only.
Note that the SFCG recommendation 21-R-2 (see the plot hereafter attached) doesn't explicitly specify the normalization level of the spectrum, however it is understood to be the peak of the side-band main-lobe.

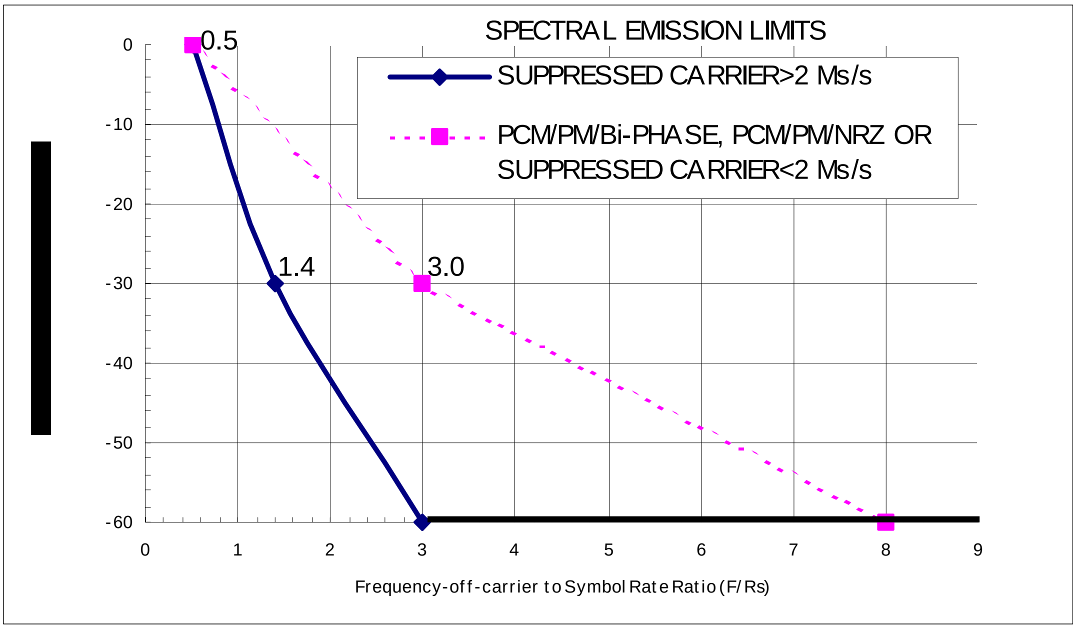


Figure 6-1

[8] At the moment the author was writing this paragraph, this recommendation was under approval (SFCG September 2004). In the next paragraph 6.3.2, we have assumed this recommendation as Criterion #2 for spectral comparison with TLM downlink.

The power spectral density of a PCM/PM/Bi-Phase signal can be represented with the following expression:

- $PSD(f) = P\cos^2(m)$ at the carrier frequency
- $PSD(f) = \frac{P}{2}\sin^2(m)\cdot T_b \operatorname{sinc}^2\left(\frac{\pi}{2} fT_b\right)\sin^2\left(\frac{\pi}{2} fT_b\right)$ modulation side-bands

Where P is the un-modulated carrier power, m is the modulation index and T_b is the bit period.

The factor 2 at the denominator of the modulation side-bands is related to the dual side bandwidth spectral distribution of the modulated signal.

The peak of the side-band main-lobe corresponds to a frequency of about 0.742*Rb (Rb = $1/T_b$ = bit rate) or 0.742*Rs/2 (Rs = symbol rate at modulator input after Bi-Phase coding) and to a normalised level of 0.525/Rb.

So assuming a modulation index of 1.4 radiant peak and a bit rate of 1 Mbit/sec (2Msps at modulator input after Bi-Phase coding) we have a ratio between the maximum of the main lobe and the residual carrier of about:

$$Ratio = \left(\frac{\sin(m)}{\cos(m)}\right)^2 \cdot \frac{0.525}{2} \cdot T_b = \text{-50.5 dBc/Hz}$$

This corresponds to –14.5 dBc assuming a resolution bandwidth of 4 KHz.

So according to the above mask considering the – 35 dBc threshold[9] we have an overall 2-side bandwidth of **14 MHz.** This corresponds to a value of – 50 dBc/4KHz with respect to the residual carrier power.

Assuming this 14 MHz bandwidth as a criterion for comparison with telemetry spectral occupation, we can see (Table 6-1 and 6-2) that with the proper selection of the modulation index, IBO and tone frequency we can achieve almost the same performances also in case of square-wave DOR signal.

6.3.2 *Criterion #2 (SFCG Rec. 23-1)*

In the last SFCG meeting (September 2004) the REC 23-1 has been approved (see Annex E). Considering the mask of Maximum Allowable Bandwidth for a bit rate of 1 Mbit/sec (2 MSPS) we have a –25 dB bandwidth of:

- 7.1 MHz for mission to Mars
- 10.37 MHz for Non-Mars missions.

Assuming these values as criterion for bandwidth comparison we have repeated all the DOR simulations and evaluated the TX bandwidth for the –25 dB value. The results are summarised in Table 6-3. We can conclude that:

- All 500 KHz DOR tone cases can meet the above bandwidth values
- In case of 1 MHz tone the bandwidth occupation is met for non Mars Missions and only slightly out of the spec for Mars Mission case.

[9] The –50 dBc threshold as applied with the DOR is scaled with the –14.5 dB due to the residual carrier modulation.

B25 (-25dB bandwidth)			1MHz tone		0.5 MHz tone	
Waveform	Mod.index	IBO	Input	Output	Input	Output
Sine	0.8	0	4	4	2	2
Square	0.8	0	6	10	7	7
	0.5	0	6	6	5	5
	0.2	0	2	2	1	1
	0.8	-3	6	8	7	7
	0.8	-6	6	6	7	7
Sine @ 8 samples /period	0.8	0	4	4	2	2

Table 6-3: Summary table of -25 dB bandwidth analysis for 1 MHz and 0.5 MHz DOR-tone frequency

6.4 Conclusions

Based on the results presented in the above tables and figures, the simulation results lead to the following considerations:

- Using filtered square-waves leads to a spectral re-growth higher than in the case of filtered sine-wave DOR having a fixed carrier phase modulation index. This is due to the fact that in case of square-wave DOR, the modulated spectrum occupies a larger bandwidth with respect to the sine-wave DOR (compare Figure 3-2 and Figure 4-2) and the impact of the RF filtering (inside the on-board transmitter) is stronger.
- Reducing the DOR modulation index reduces the spectral re-growth, due to the fact that RF filtering has less impact on the signal envelope. In fact, the filtered harmonics will reduce in power when reducing the modulation index (compare Figure 4-2 and Figure 4-3).
- Reducing the DOR frequency reduces the spectral re-growth, due to the fact that smaller tone frequency compresses the occupied spectrum and the RF filtering has less impact on the signal envelope. As an example, compare the spectrum from Figure 4-2 and Figure 4-6.
- Increasing the IBO reduces the spectral re-growth, due to the fact that the HPA has a more linear behaviour. However, the effect of increasing the IBO to decrease the spectral re-growth is less efficient than reducing the modulation index or the DOR tone frequency (see Table 6-1 and Table 6-2).
- By using an approximation of a perfect sinusoidal waveform, obtained by sampling a sine at 8 samples per period (a "quantised" sinusoidal DOR tone), the degradation in terms of spectral re-growth with respect to a sinusoidal tone is negligible (compare Figure 3-2 and Figure 5-3).

The results of the simulation have been compared with a reference TLM spectrum according the following strategy (Criterion #1):

- To avoid interference problems at the ground station we have considered as driving requirement the – 50 dBc threshold, which for BepiColombo mission (embarking HPA's[10]

[10] TWTA both for X and Ka band with RF transmitter power in the range 20÷30 Watt (TBD)

and HGA[11]) guarantees considerable margin with respect to the SFCG recommendations for power flux density at the Earth.

- We have calculated the –50 dBc occupied bandwidth and we have compared this to the reference TLM case of a PCM/PM/Bi-Phase telemetry signal at 1 Mbit/sec based on the mask proposed in SFCG Rec.21-R-2.
- The results show that with the proper selection of the modulation index, IBO and tone frequency we can achieve almost the same performances as the reference TLM spectrum also in case of square-wave DOR signal.

Furthermore we have checked the –25 dB bandwidth versus the TLM requirement from SFCG Rec. 23-1 (Criterion #2):

- We have calculated the –25 dBc occupied bandwidth and we have compared this to the reference TLM case of a PCM/PM/Bi-Phase telemetry signal at 1 Mbit/sec based on the mask proposed in SFCG Rec. 23-1.
- The results show that:
  - All 500 KHz DOR tone cases can meet the above bandwidth values
  - In case of 1 MHz tone the bandwidth occupation is met for non Mars Missions and only slightly out of the spec for Mars Mission case.

As conclusion we propose to amend the recommendation 2.5.6B as in the following:

- The note already proposed to Table 2.5.6-1 during CCSDS Spring 2004 and hereafter repeated should be maintained: *Depending on mission requirement (accuracy versus integration time), lower tone frequencies (< 4 MHz) may be used*.

- Recommends (1) should consider also the possibility of using square-wave or quantised sine-wave provided that the out-of-band TX spurious emissions comply with SFCG Rec.23-2 recommendation regarding the power flux density at the Earth.

[11] High Gain Antenna diameter in the range 1÷1.5 meter (TBD)

ANNEX A: Spectral analysis

This annex lists all the spectra obtained via the simulation of filtered DOR tones via saturated amplifier. The figures come in couples where the first one shows the simulated spectrum at the input and the second one at the output of the amplifier. They are normalised with respect to the carrier. This is done for different DOR tone wave-forms, modulation indices, IBO and tone frequency. Note that some of the figures have already been presented in the main document but are repeated here for completeness.

The amplifier used in the frame of this analysis is a Ka-band TWTA. As a baseline, we consider a 20W output power Ka-band TWTA (characteristics as reported in Table 1-1, provided by Thales) but as a worst case, also simulation results assuming a 35W Ka-band TWTA[12] are provided.

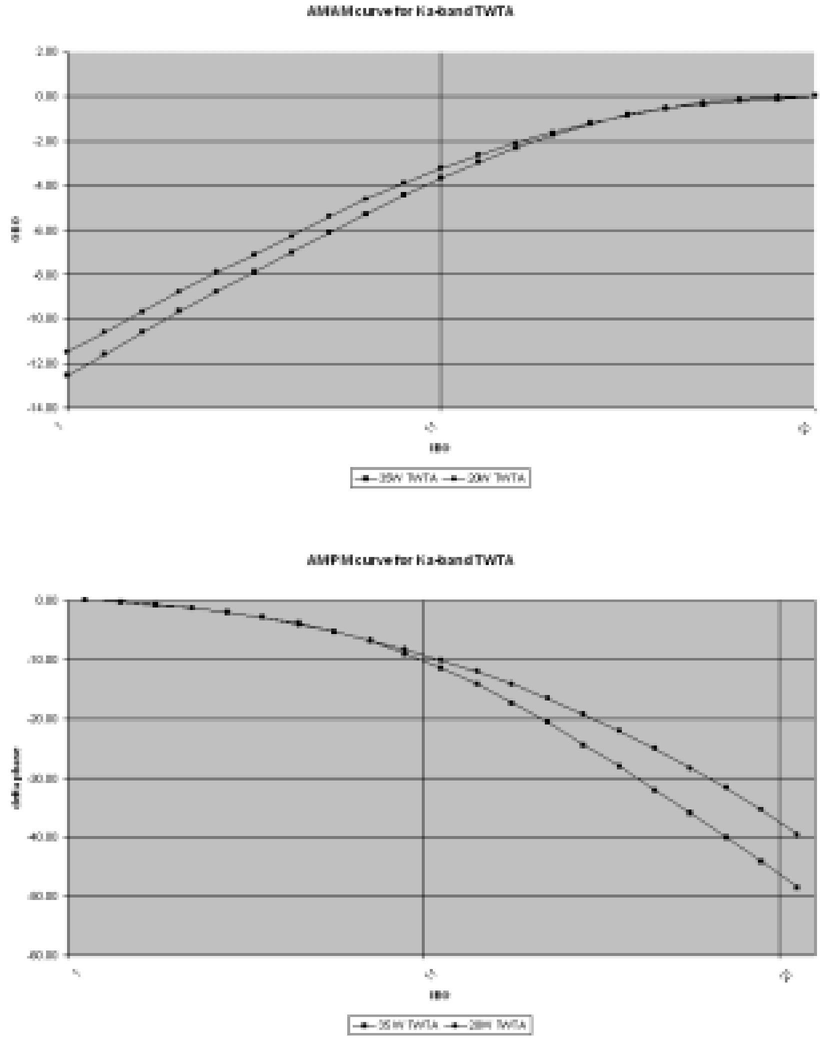
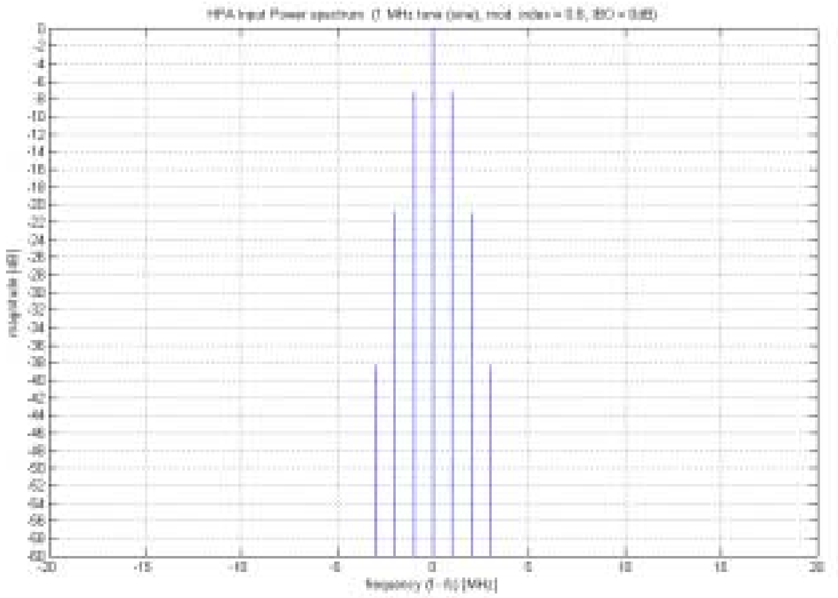


Figure A-1: AM/AM and AM/PM behaviour of simulated Ka-band TWTA

[12] A 35W – 32 GHz TWTA manufactured by Thales Electron Devices (F), S/N FH01, operating point: unknown.

I. *The reference case: 1 MHz sine-wave tone*



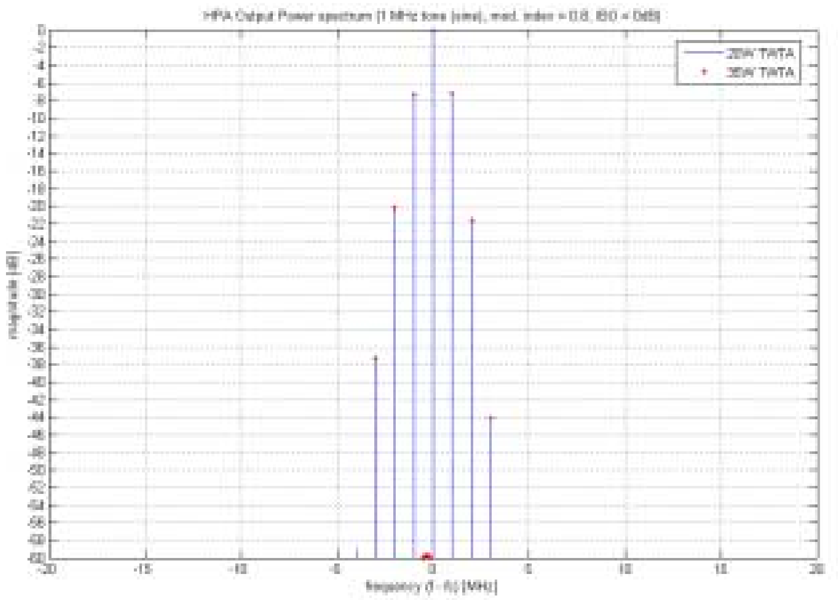


Figure A-2: Sine-wave tone at 1 MHz, modulation index 0.8, IBO = 0dB

II. Square-wave tones

A. Reference conditions

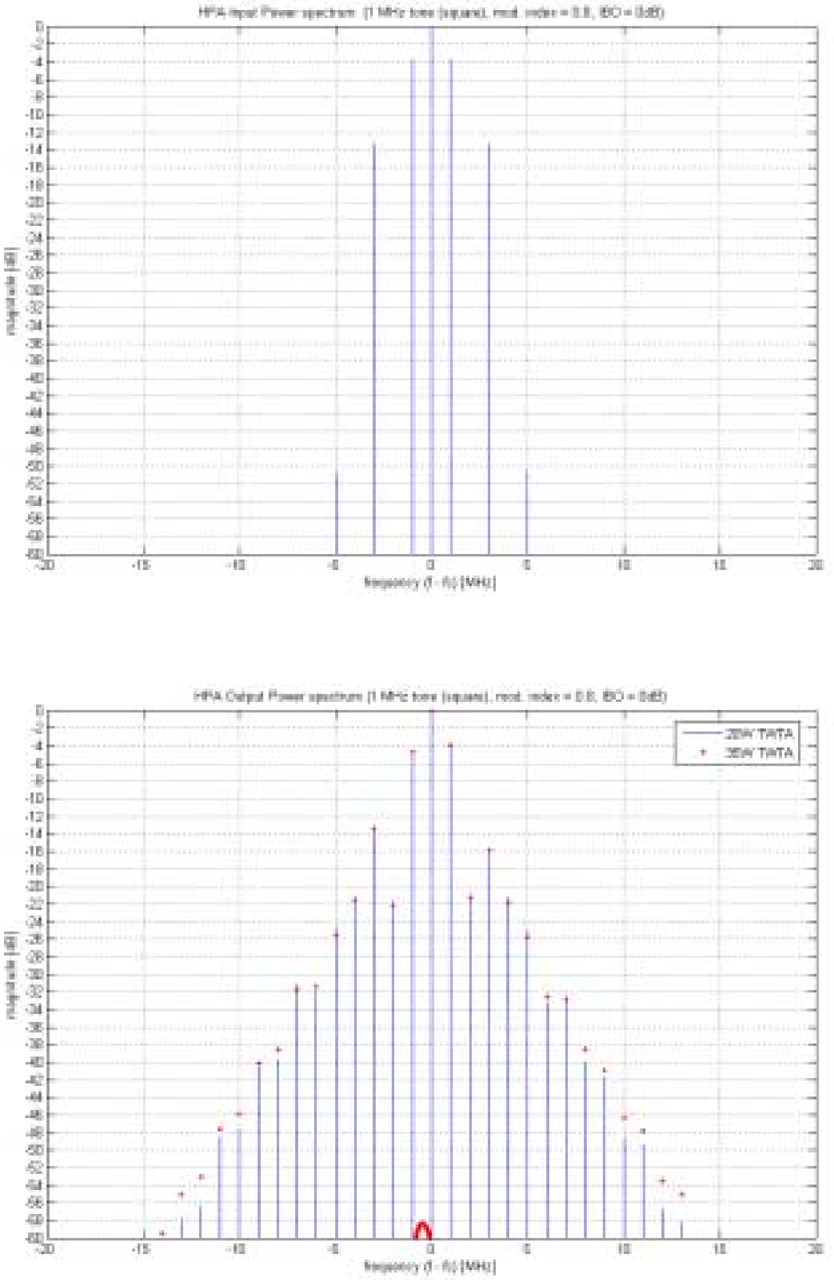
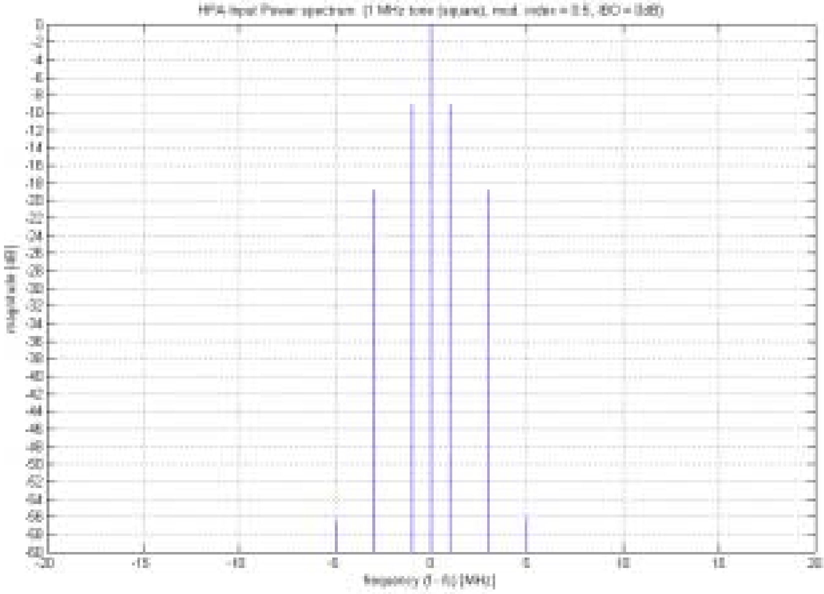


Figure A-3: Square-wave tone at 1 MHz, modulation index 0.8, IBO = 0dB

B. Reduced modulation index



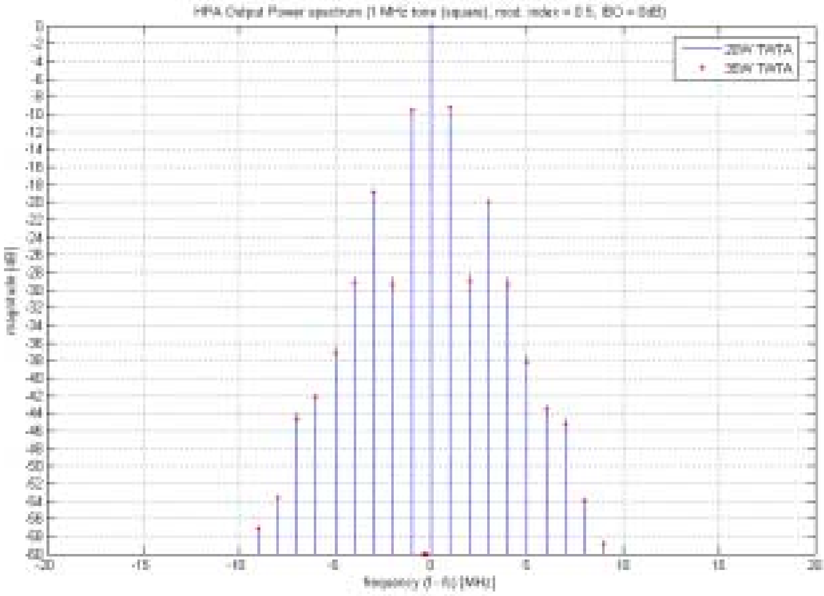
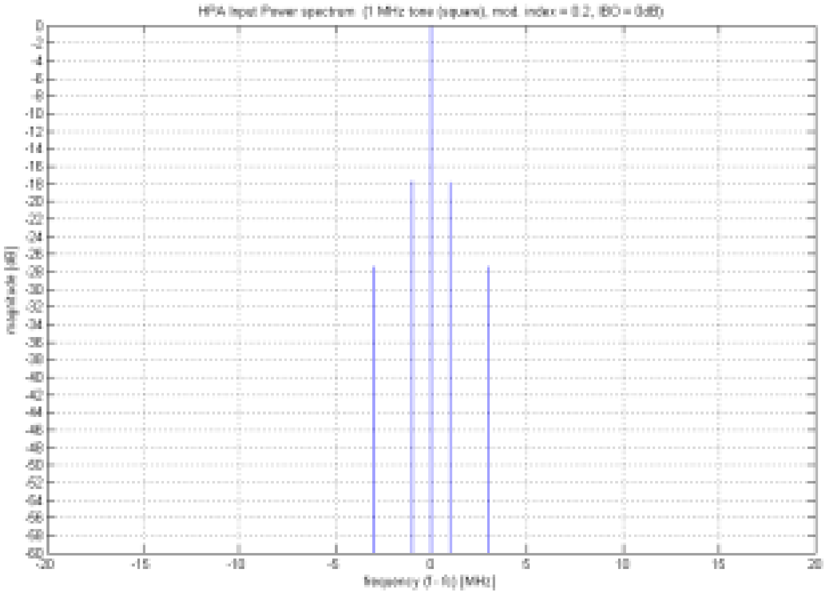


Figure A-4: Square-wave tone at 1 MHz, modulation index 0.5, IBO = 0dB



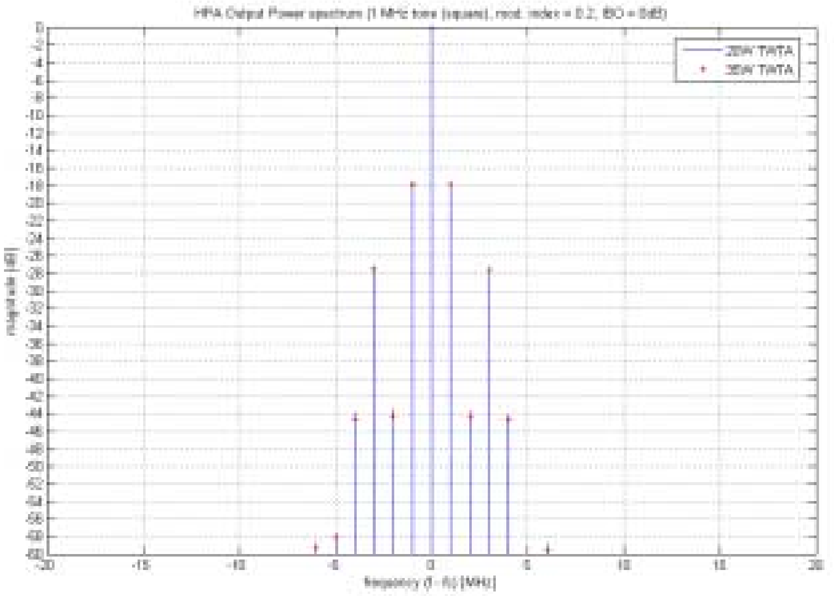


Figure A-5: Square-wave tone at 1 MHz, modulation index 0.2, IBO = 0dB

C. Reduced frequency

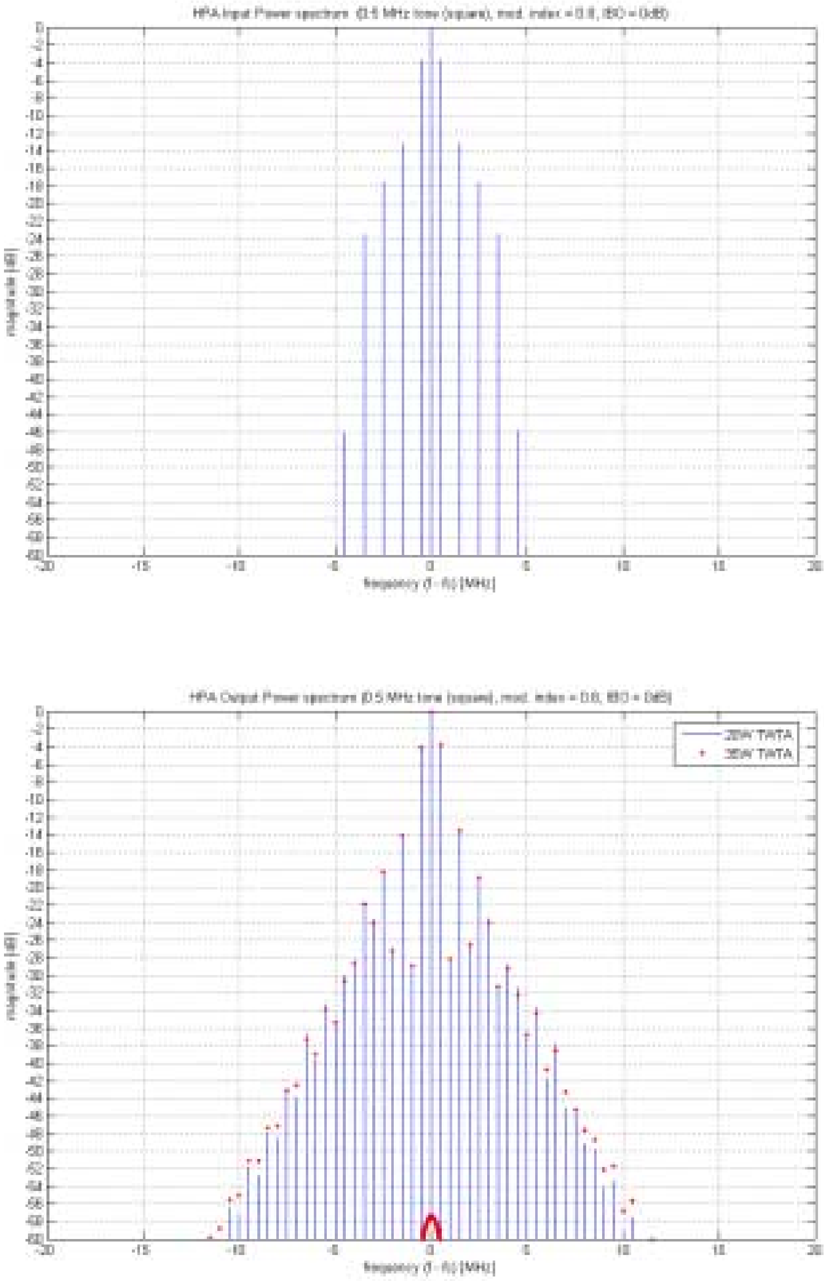


Figure A-6: Square-wave tone at 0.5 MHz, modulation index 0.8, IBO = 0dB

D. Increased IBO

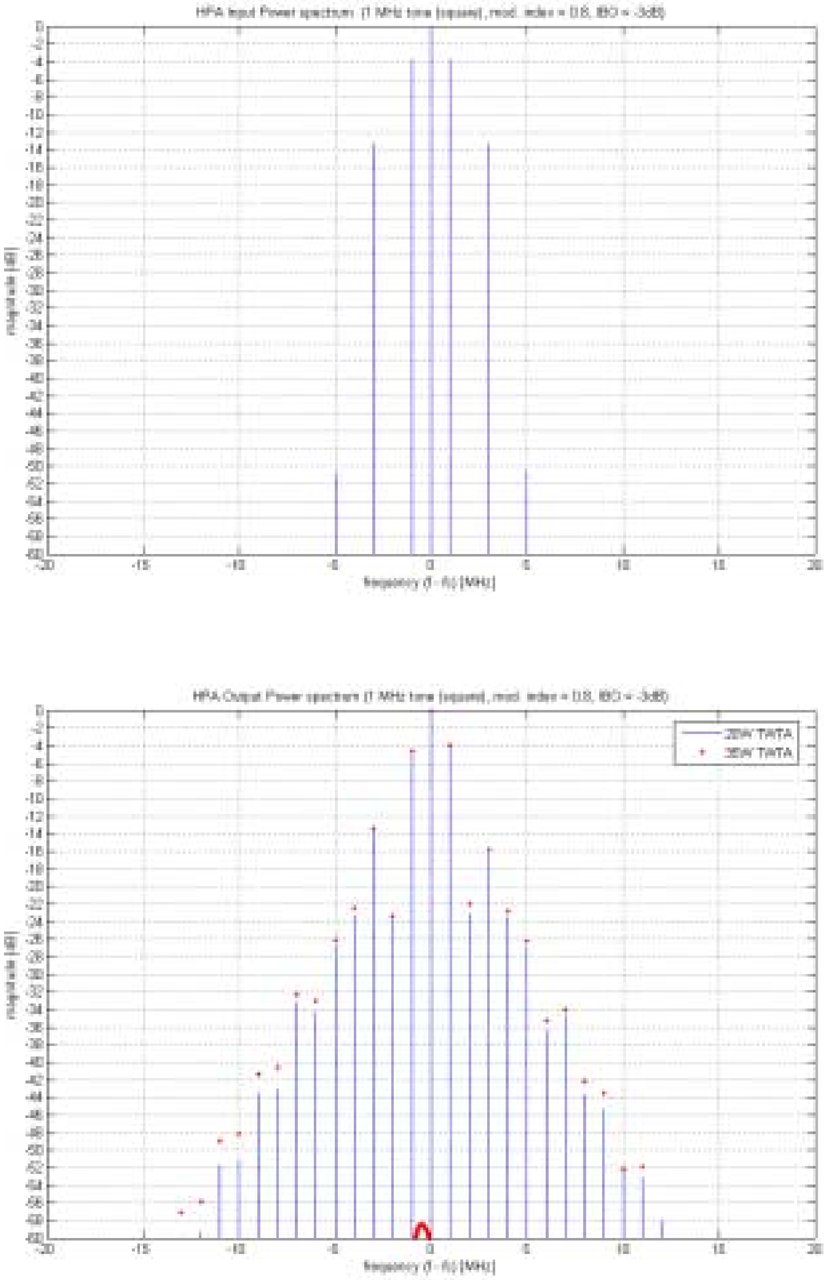
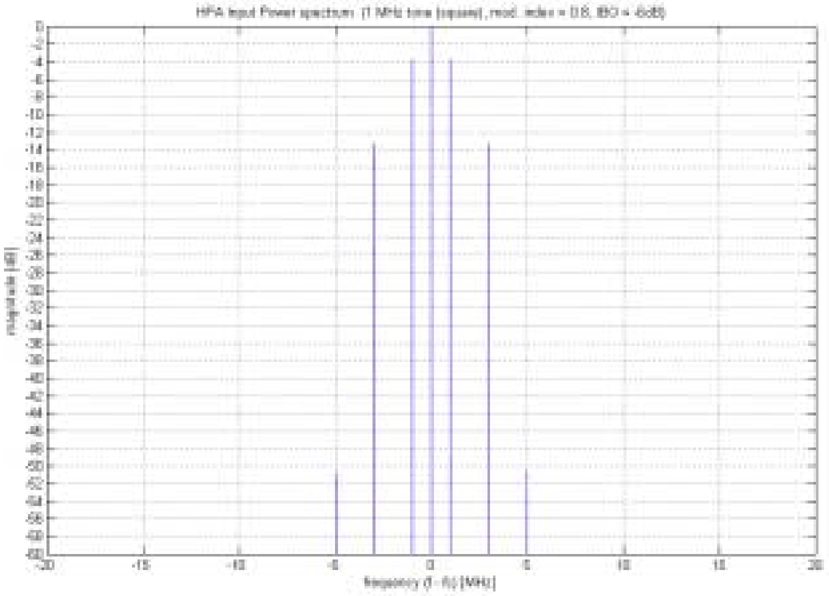


Figure A-7: Square-wave tone at 1 MHz, modulation index 0.8, IBO = -3dB



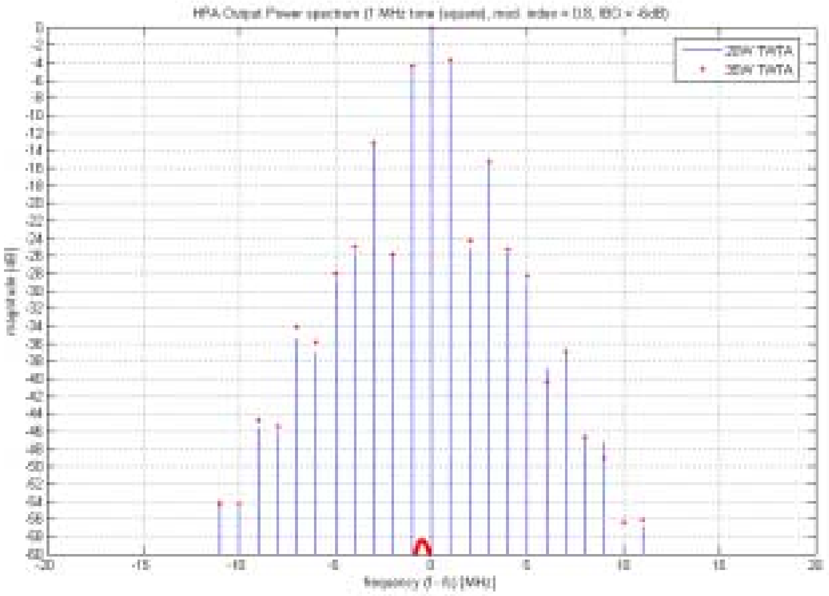


Figure A-8: Square-wave tone at 1 MHz, modulation index 0.8, IBO = -6dB

III. Quantised sine-wave tones

A. 1 MHz frequency

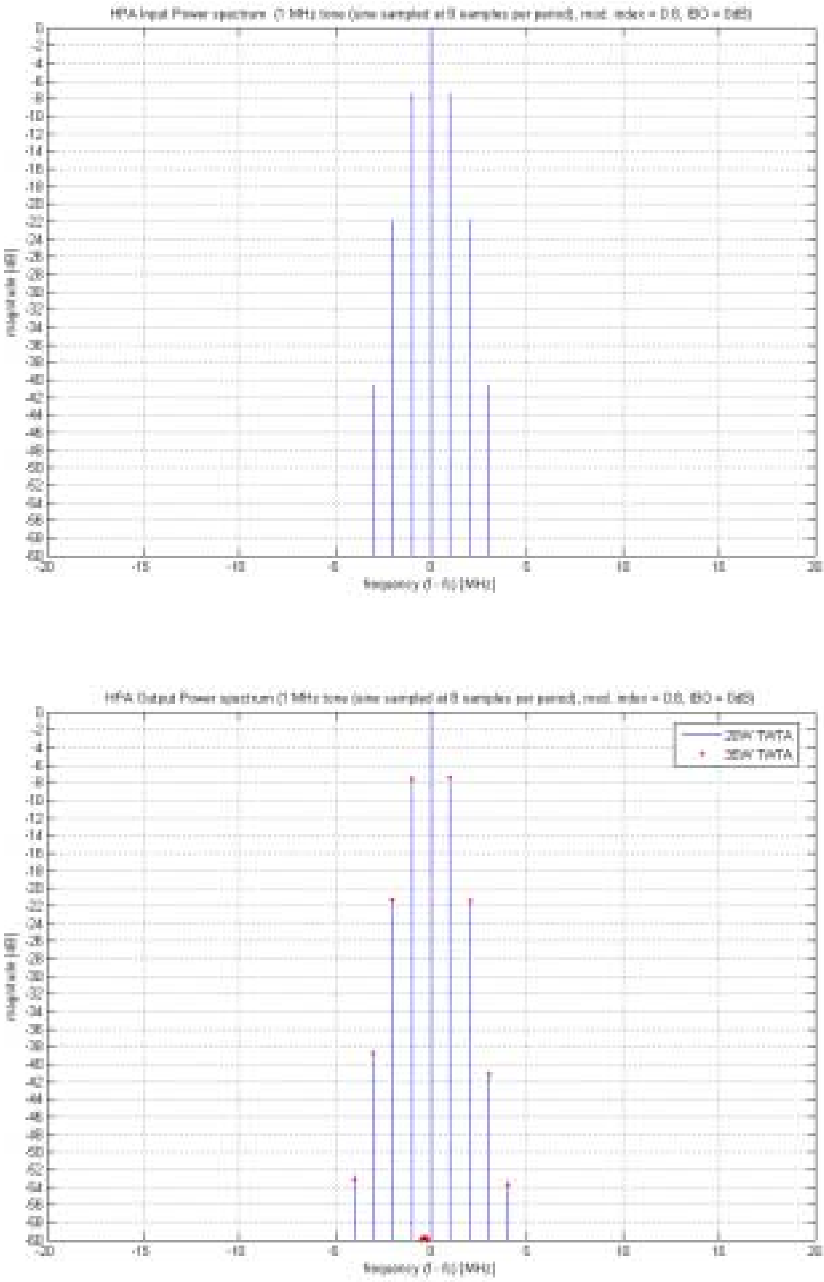
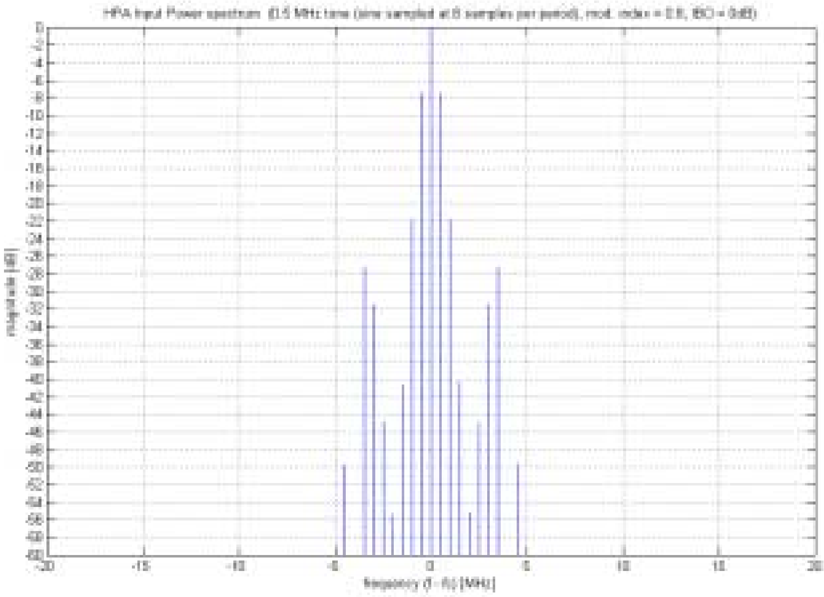


Figure A-9: Quantised sine-wave tone at 1 MHz, modulation index 0.8, IBO = 0dB

B. 0.5 MHz frequency



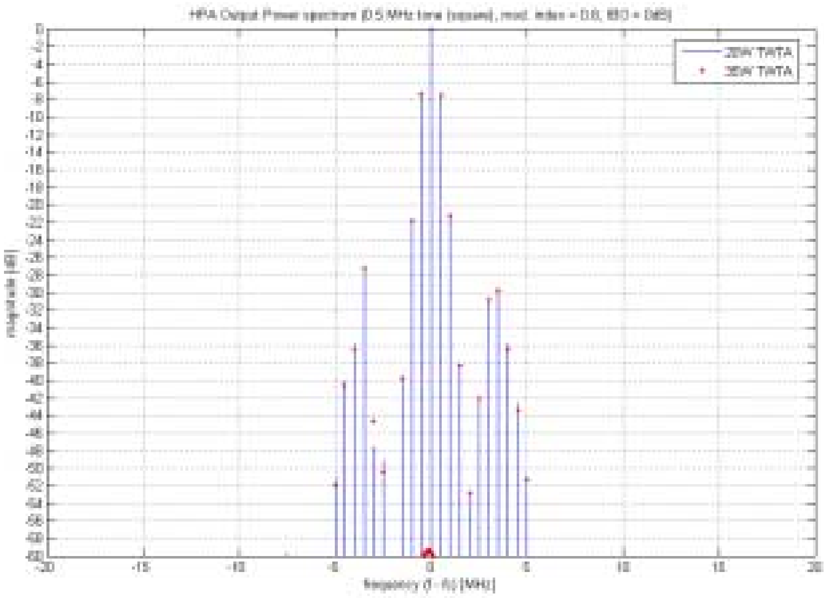
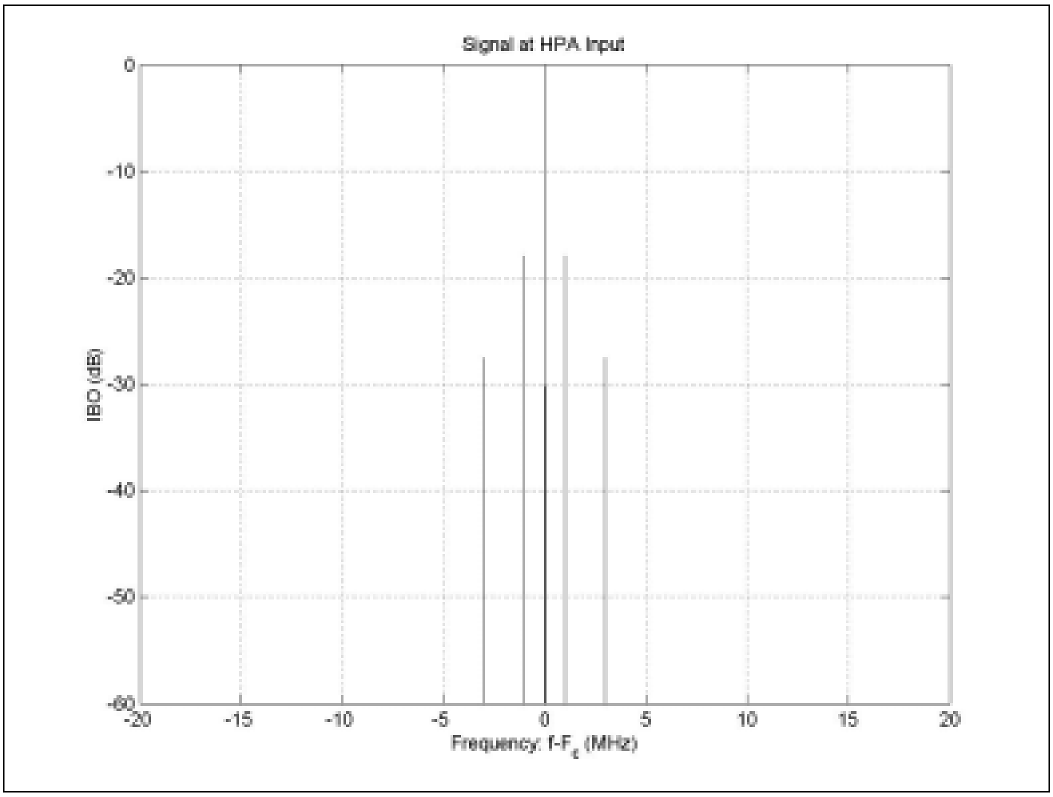


Figure A-10: Quantised sine-wave tone at 0.5 MHz, modulation index 0.8, IBO = 0dB

ANNEX B: Results DOR spectral analysis by Alenia Spazio



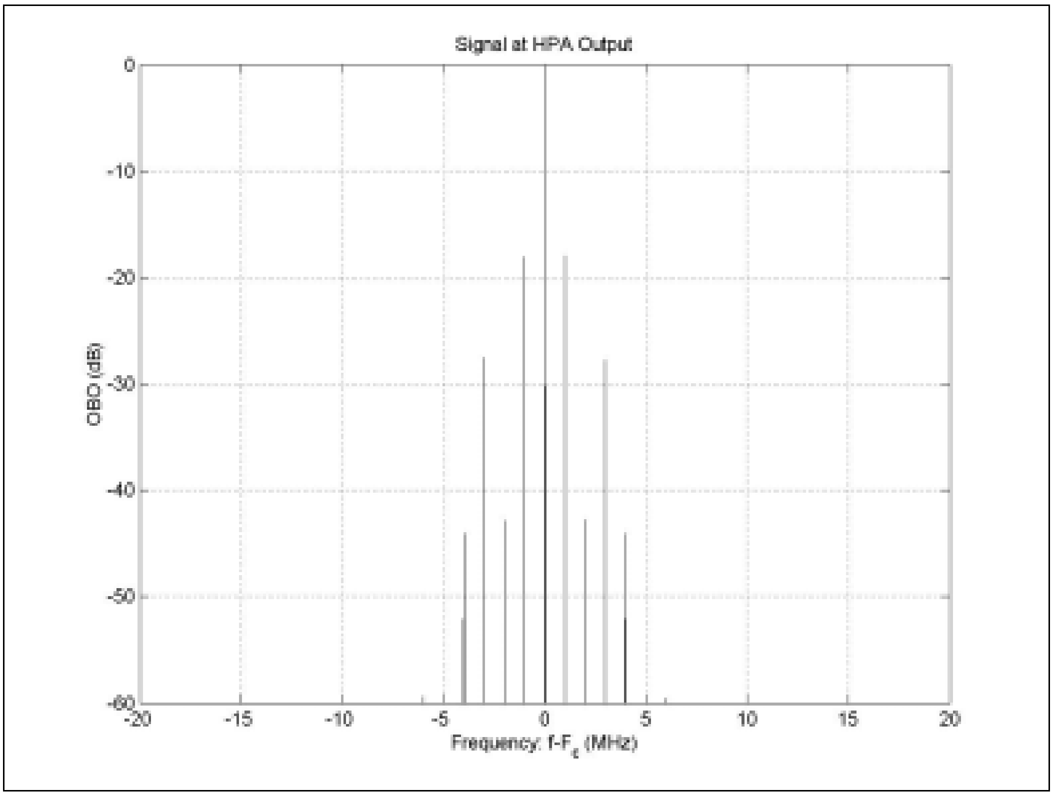
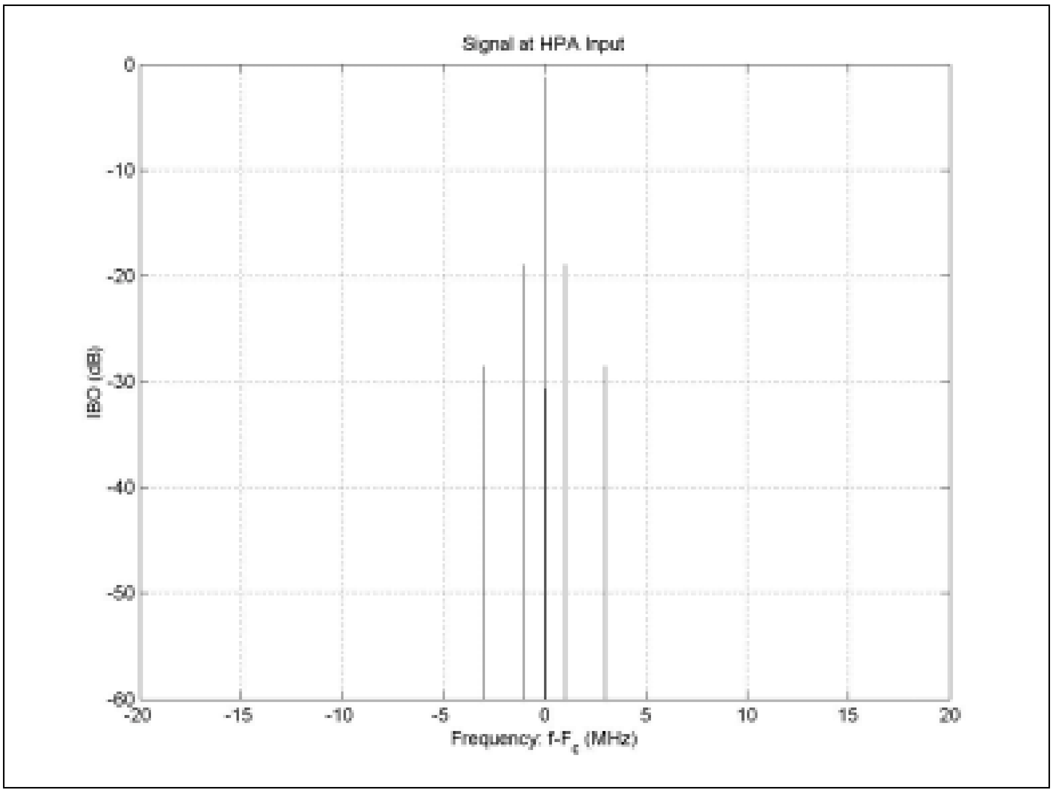


Figure B-1: Square-wave DOR at 1 MHz, modulation index = 0.2 rad-pk, IBO=0 dB



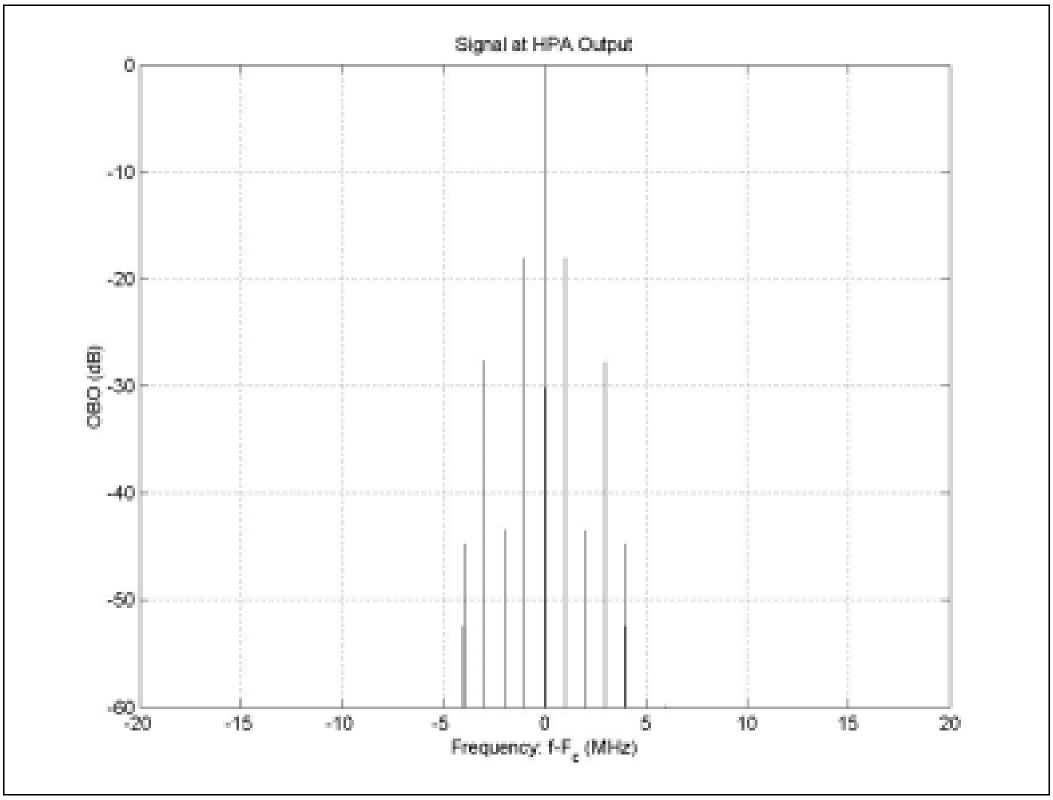
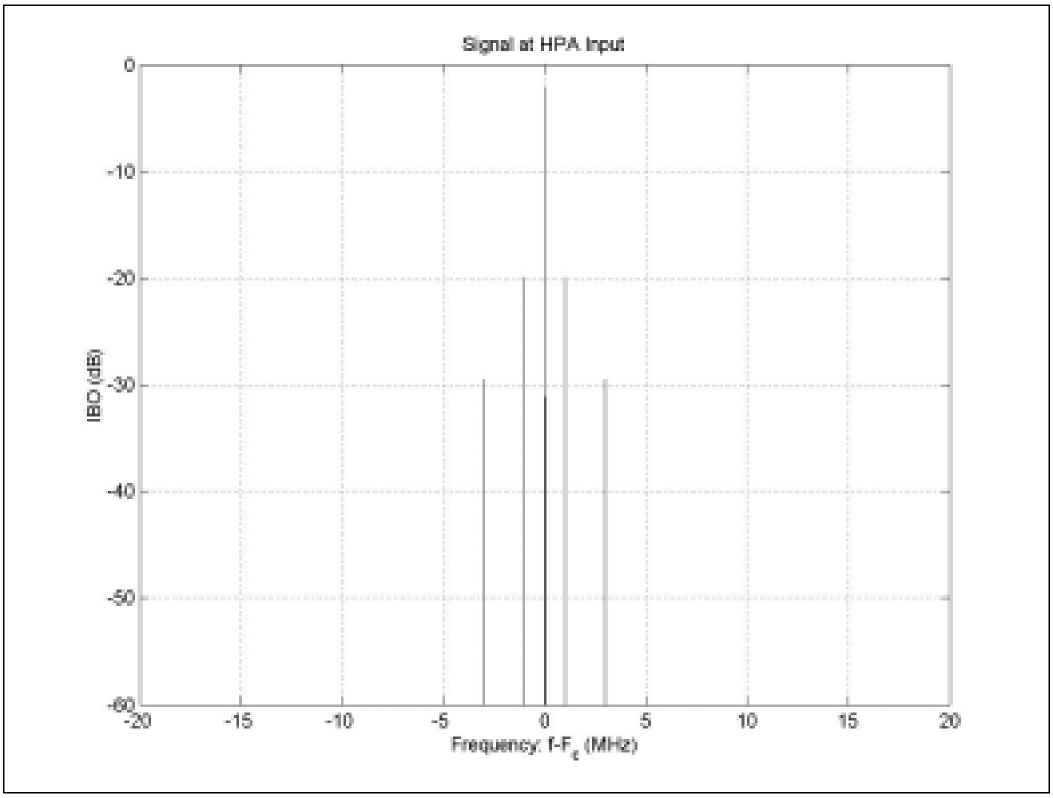


Figure B-2: Square-wave DOR at 1 MHz, modulation index = 0.2 rad-pk, IBO=1 dB



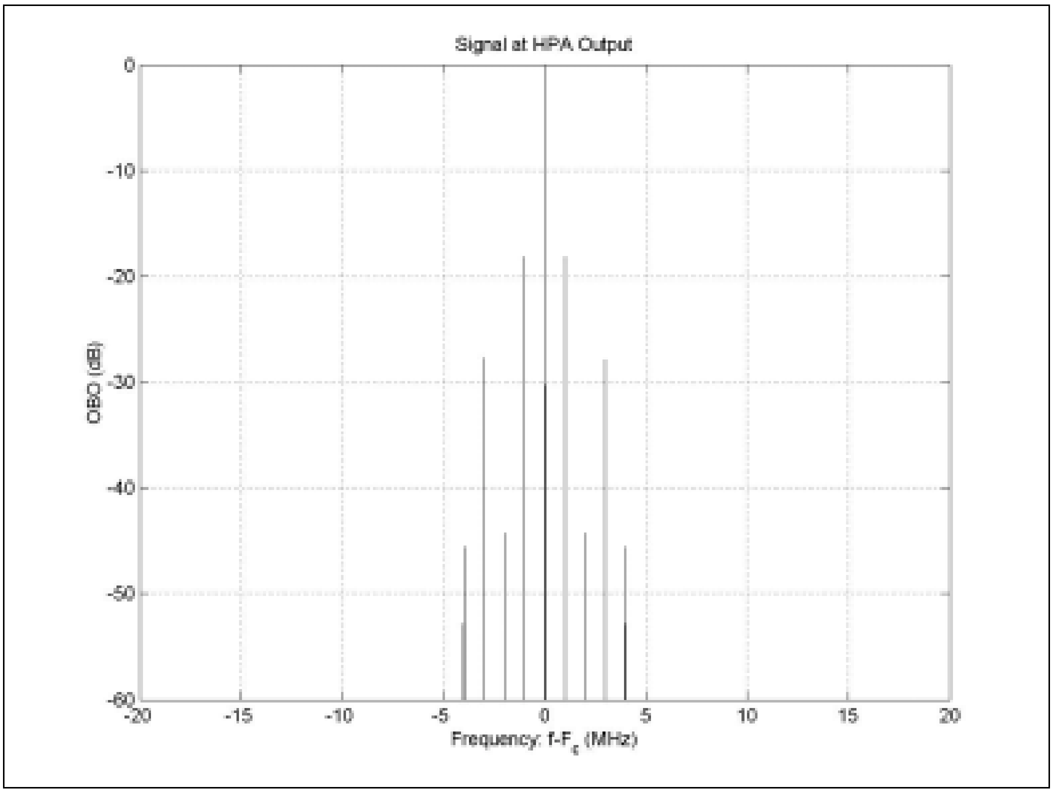
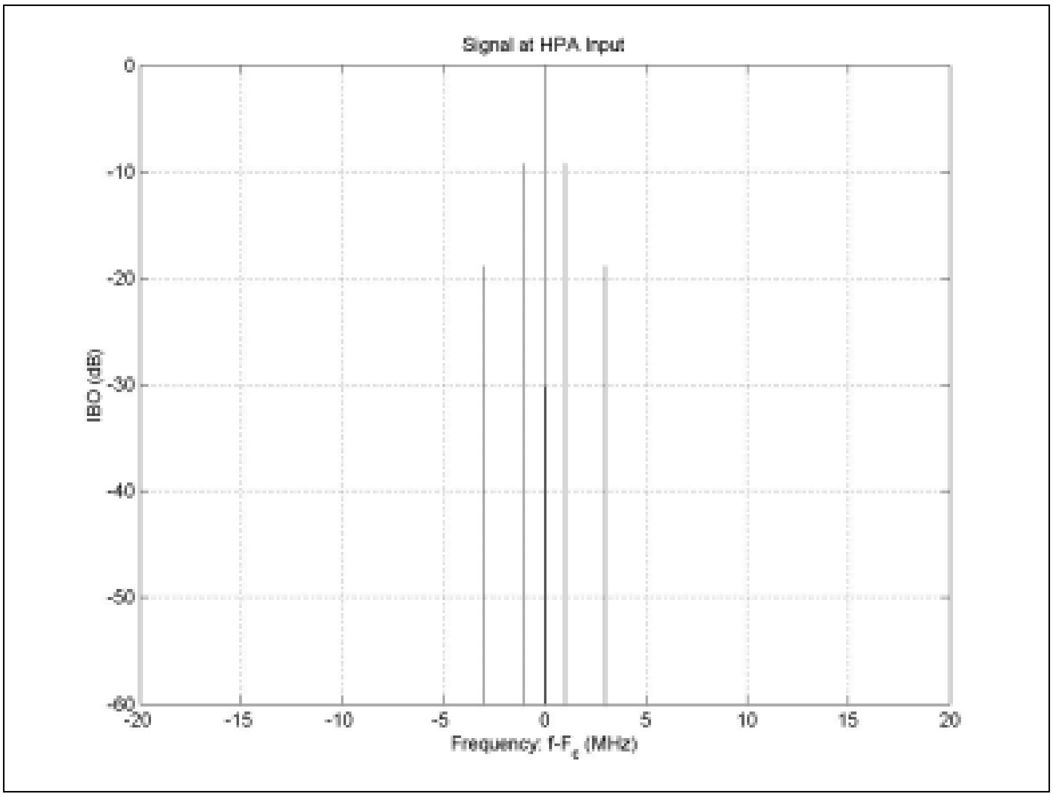


Figure B-3: Square-wave DOR at 1 MHz, modulation index = 0.2 rad-pk, IBO=2 dB



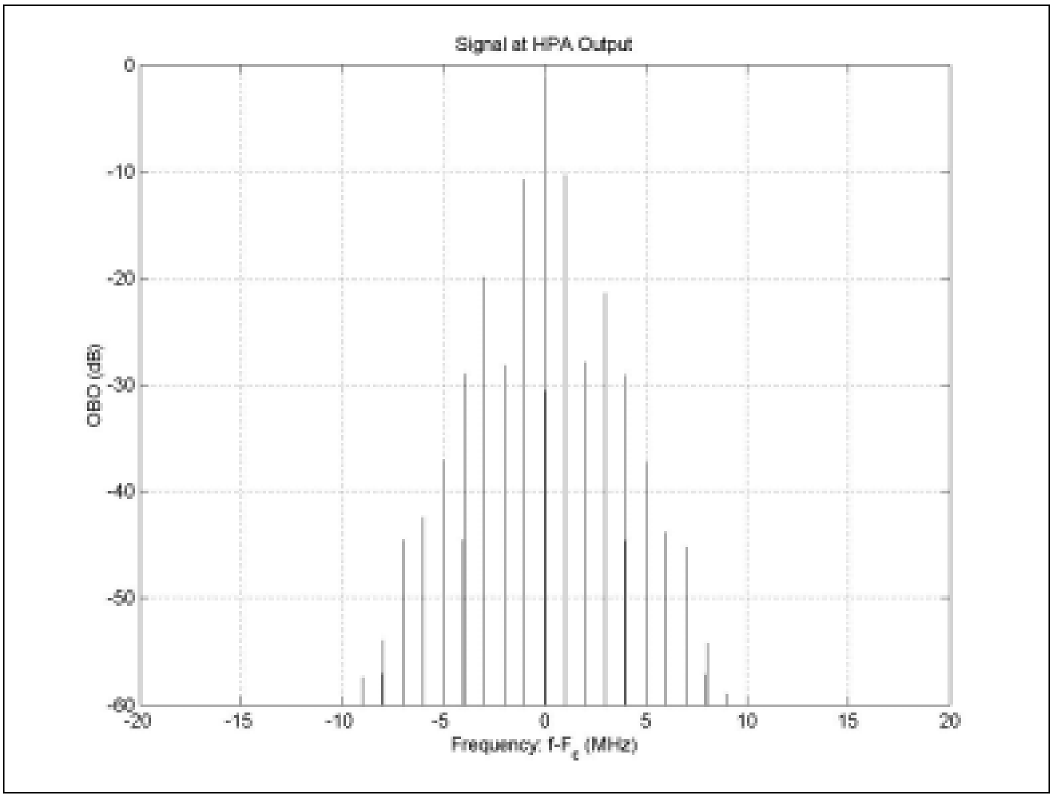


Figure B-4: Square-wave DOR at 1 MHz, modulation index = 0.5 rad-pk, IBO=0 dB

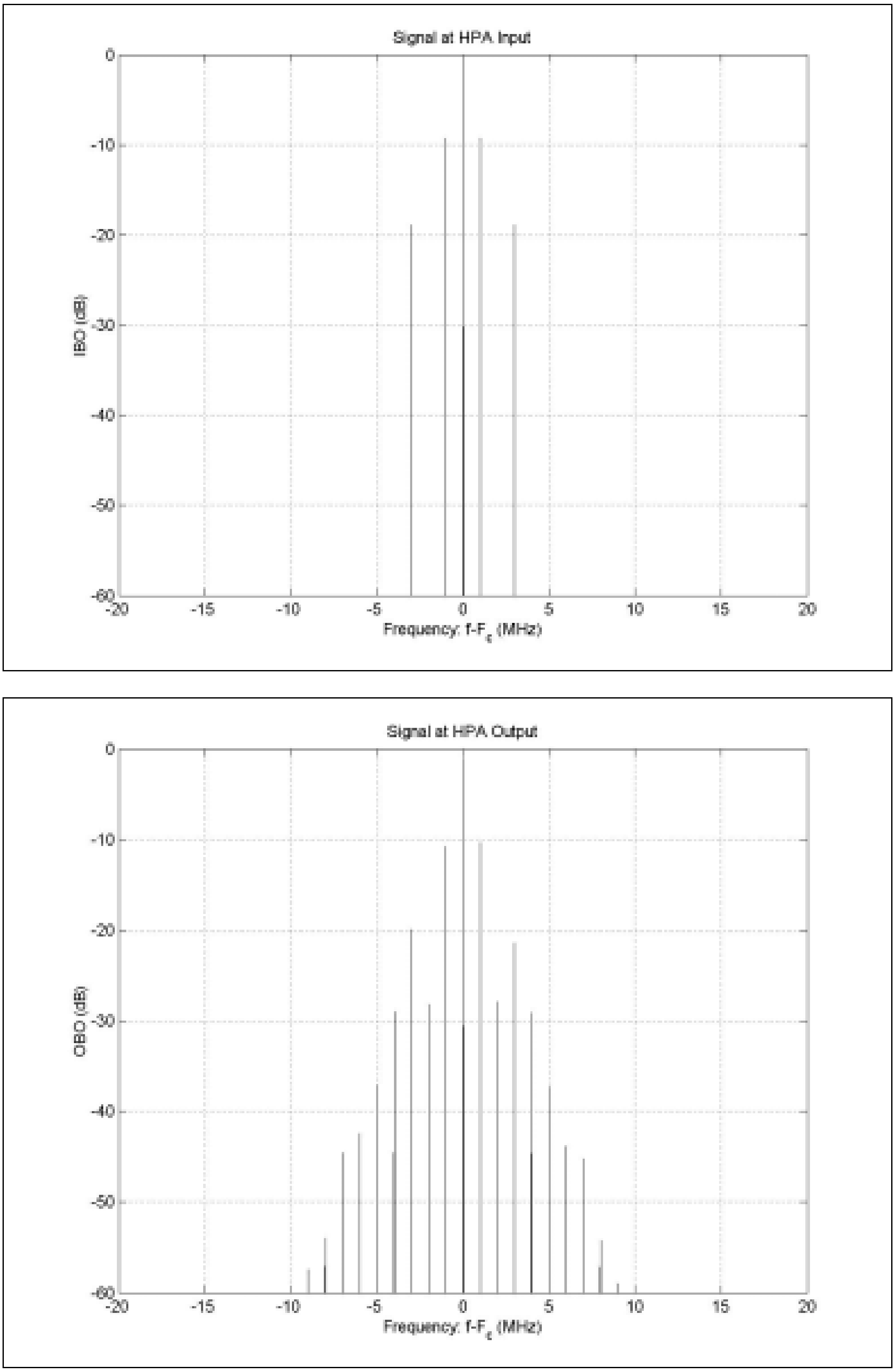
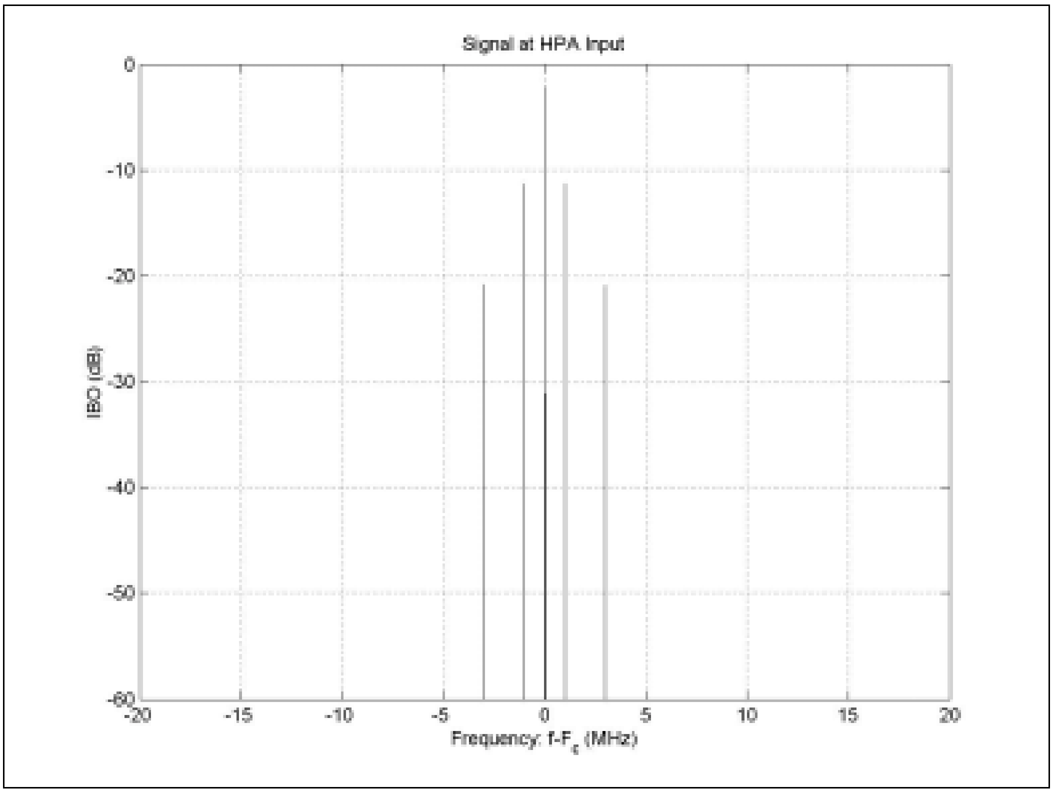


Figure B-5: Square-wave DOR at 1 MHz, modulation index = 0.5 rad-pk, IBO=1 dB



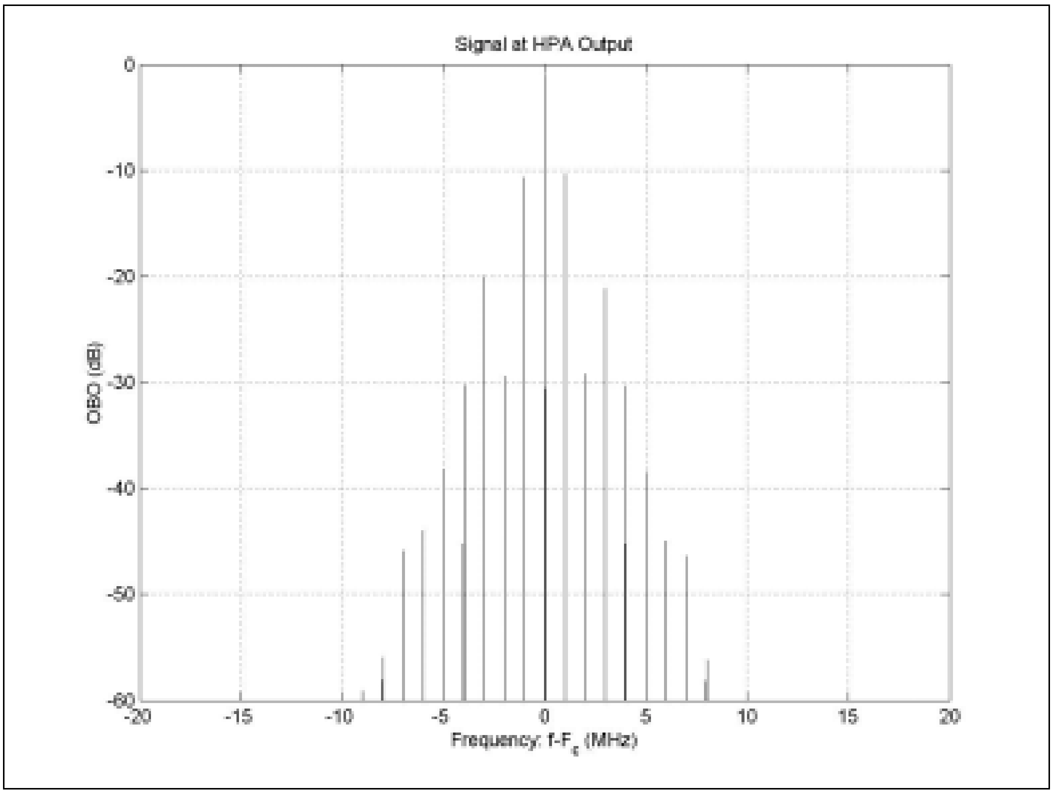
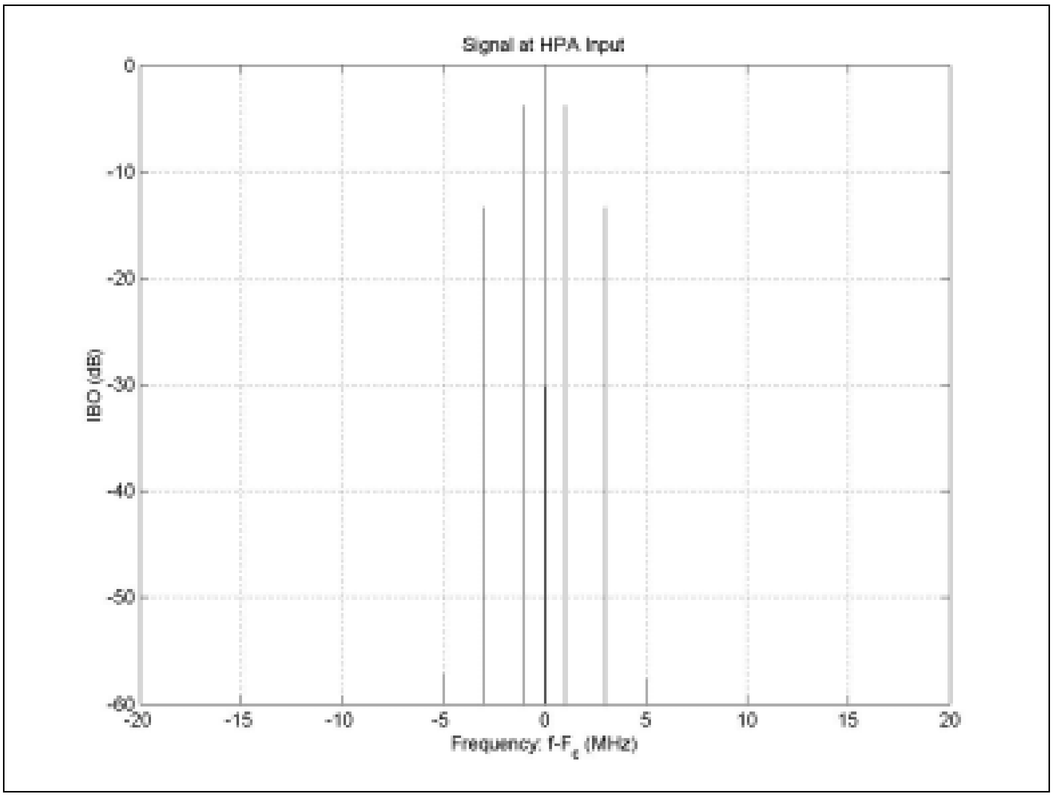


Figure B-6: Square-wave DOR at 1 MHz, modulation index = 0.5 rad-pk, IBO=2 dB



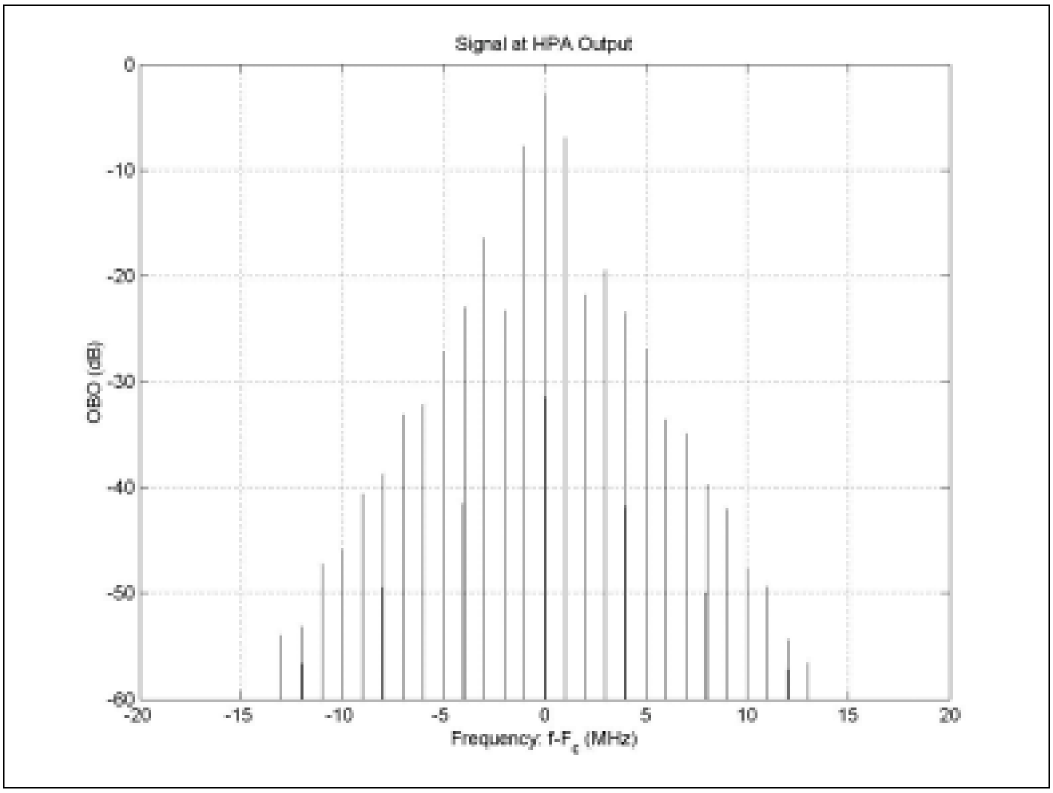


Figure B-7: Square-wave DOR at 1 MHz, modulation index = 0.8 rad-pk, IBO=0 dB

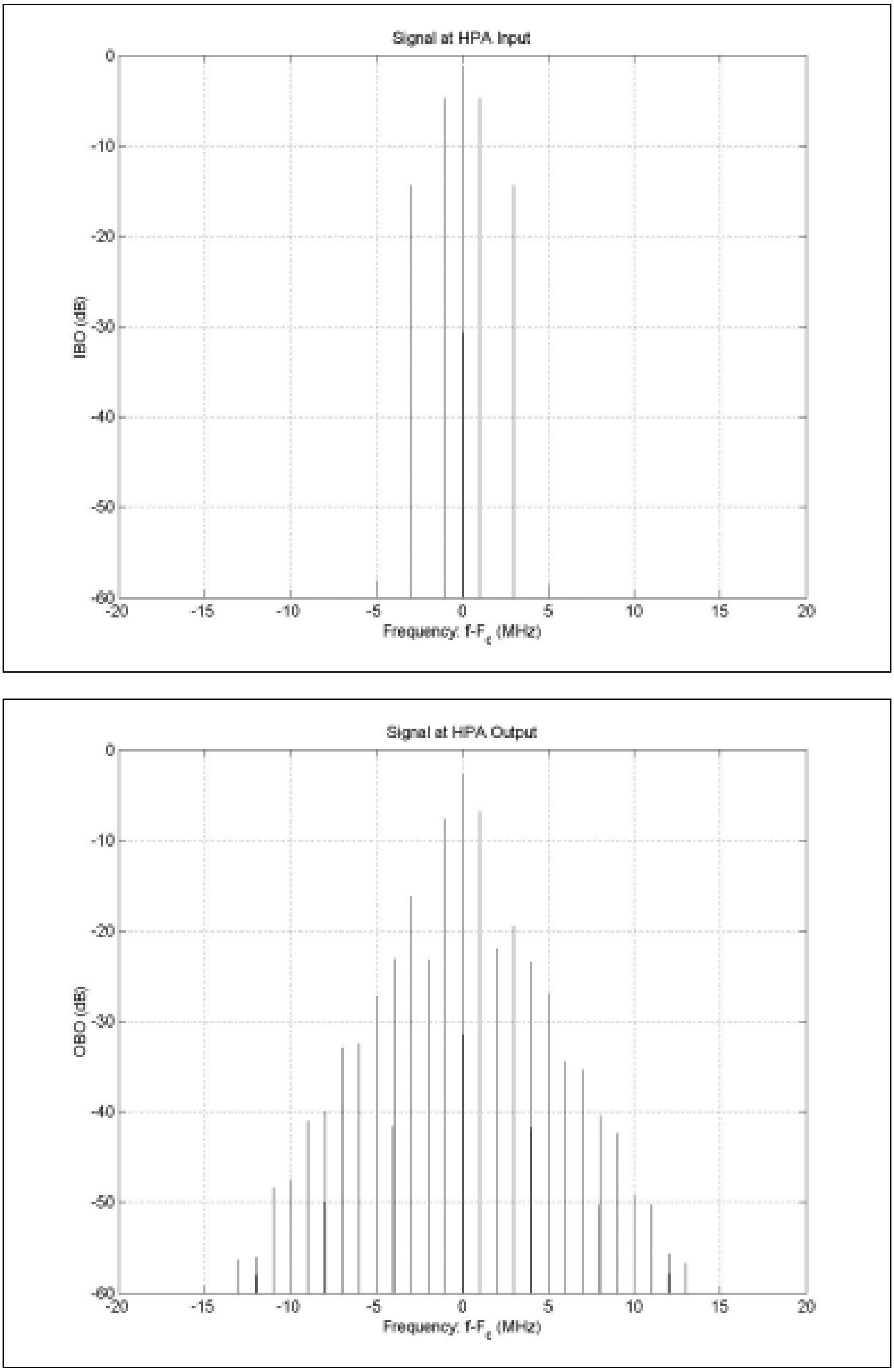
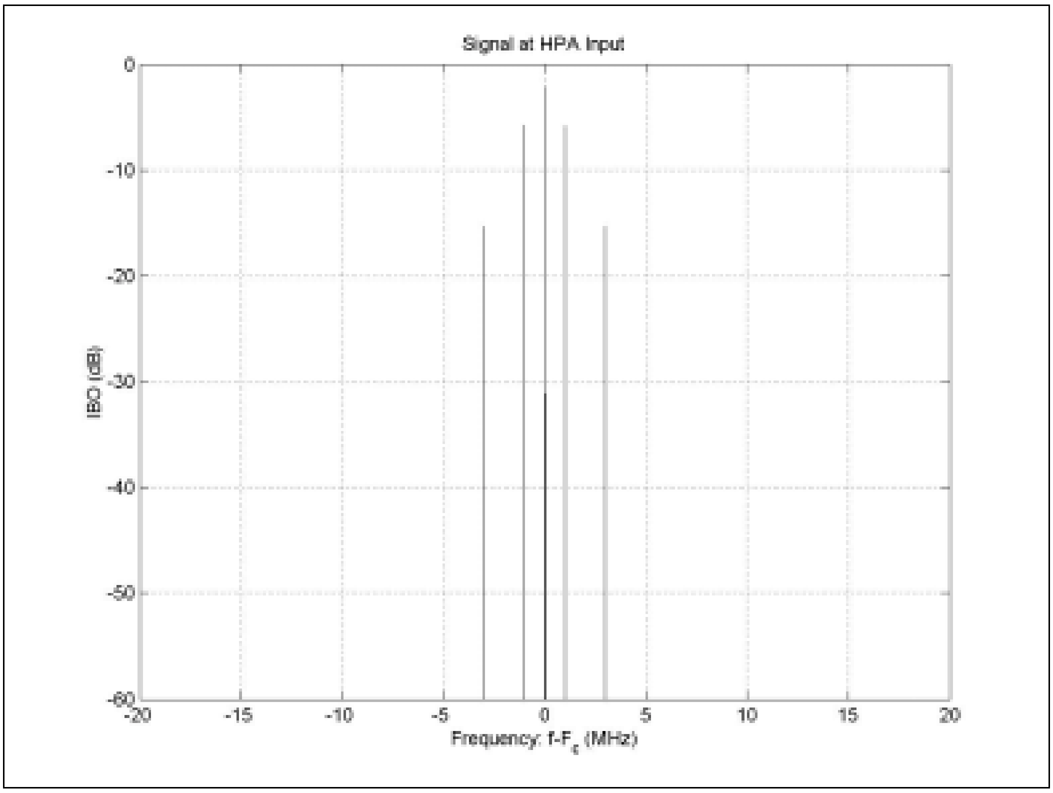


Figure B-8: Square-wave DOR at 1 MHz, modulation index = 0.8 rad-pk, IBO=1 dB



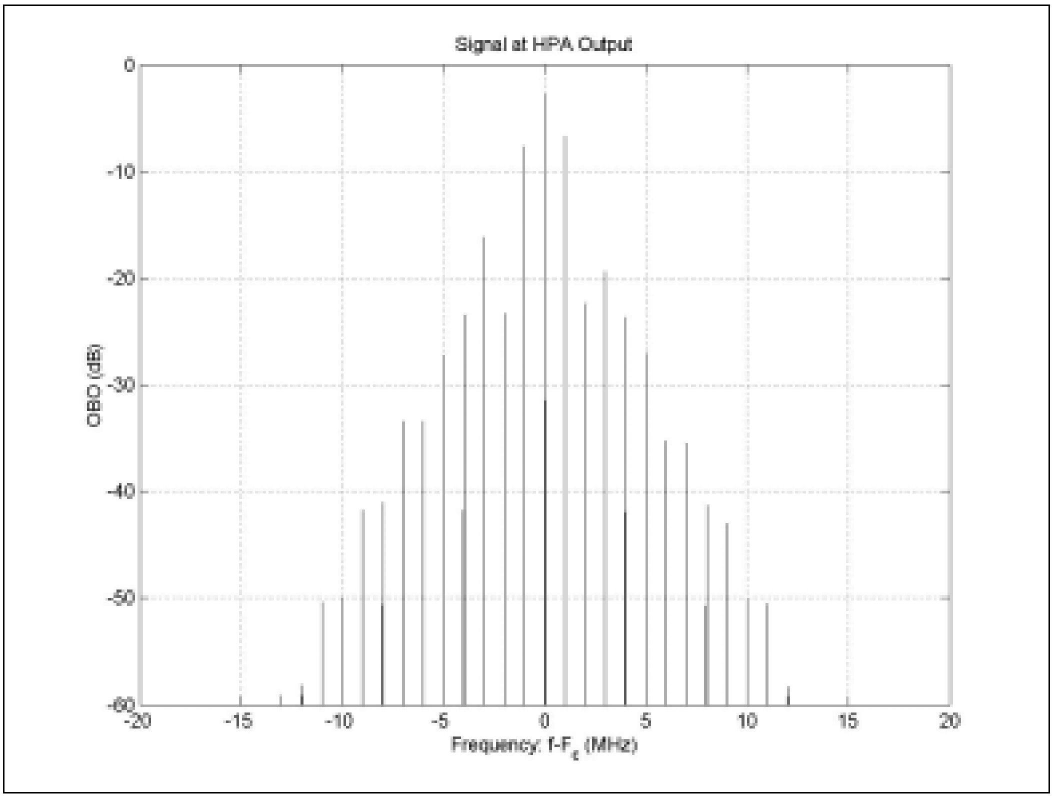
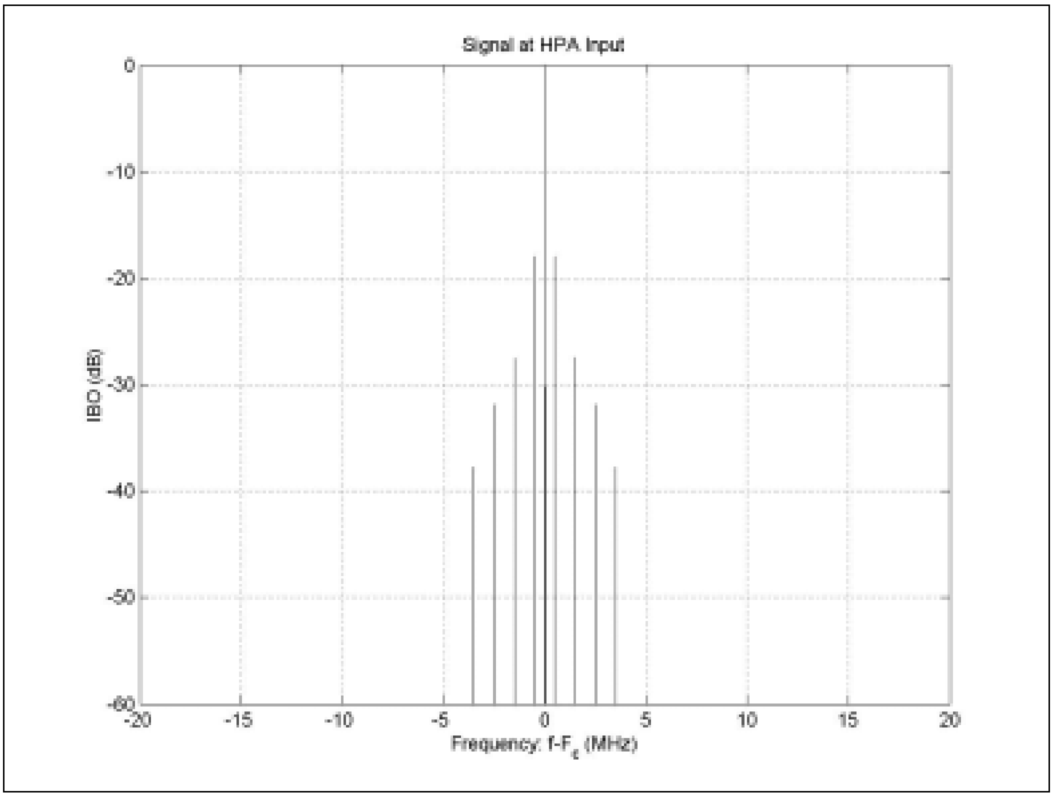


Figure B-9: Square-wave DOR at 1 MHz, modulation index = 0.8 rad-pk, IBO=2 dB



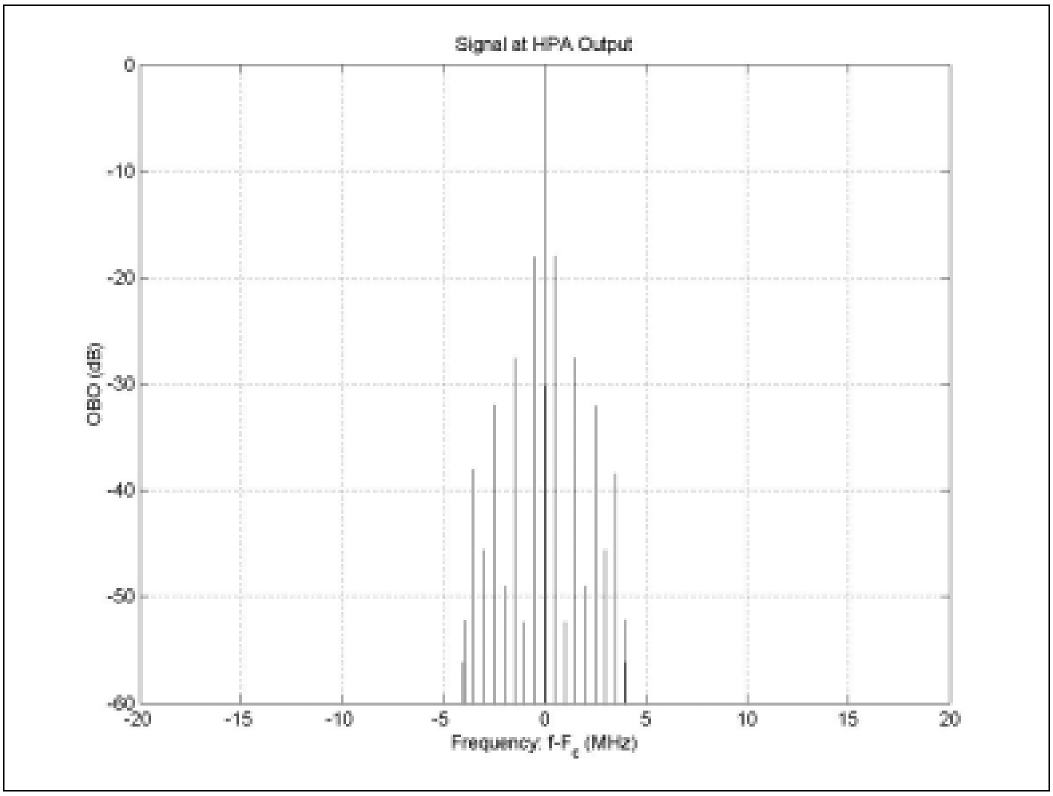


Figure B-10: Square-wave DOR at 500 kHz, modulation index = 0.2 rad-pk, IBO=0 dB

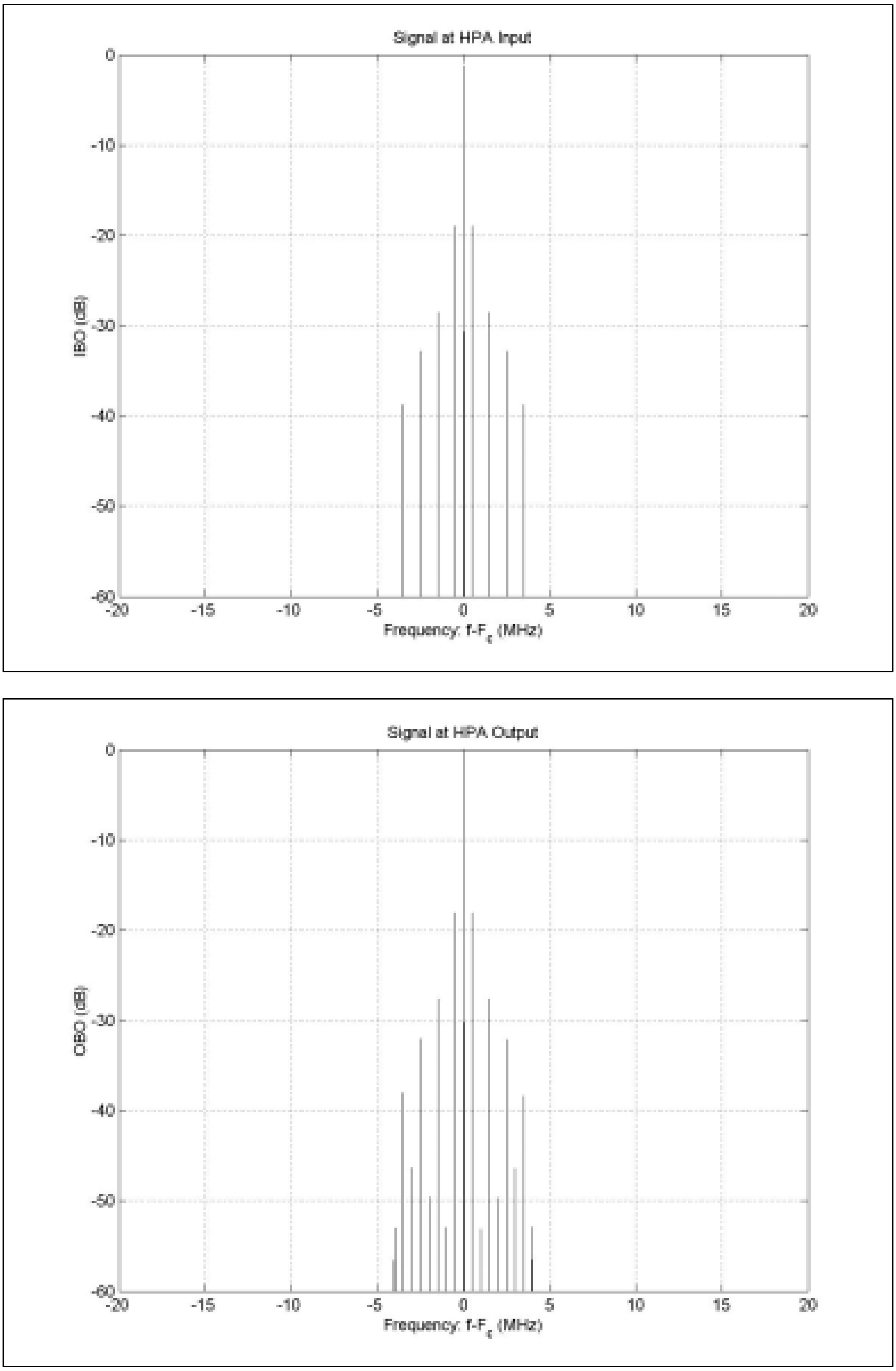


Figure B-11: Square-wave DOR at 500 kHz, modulation index = 0.2 rad-pk, IBO=1 dB

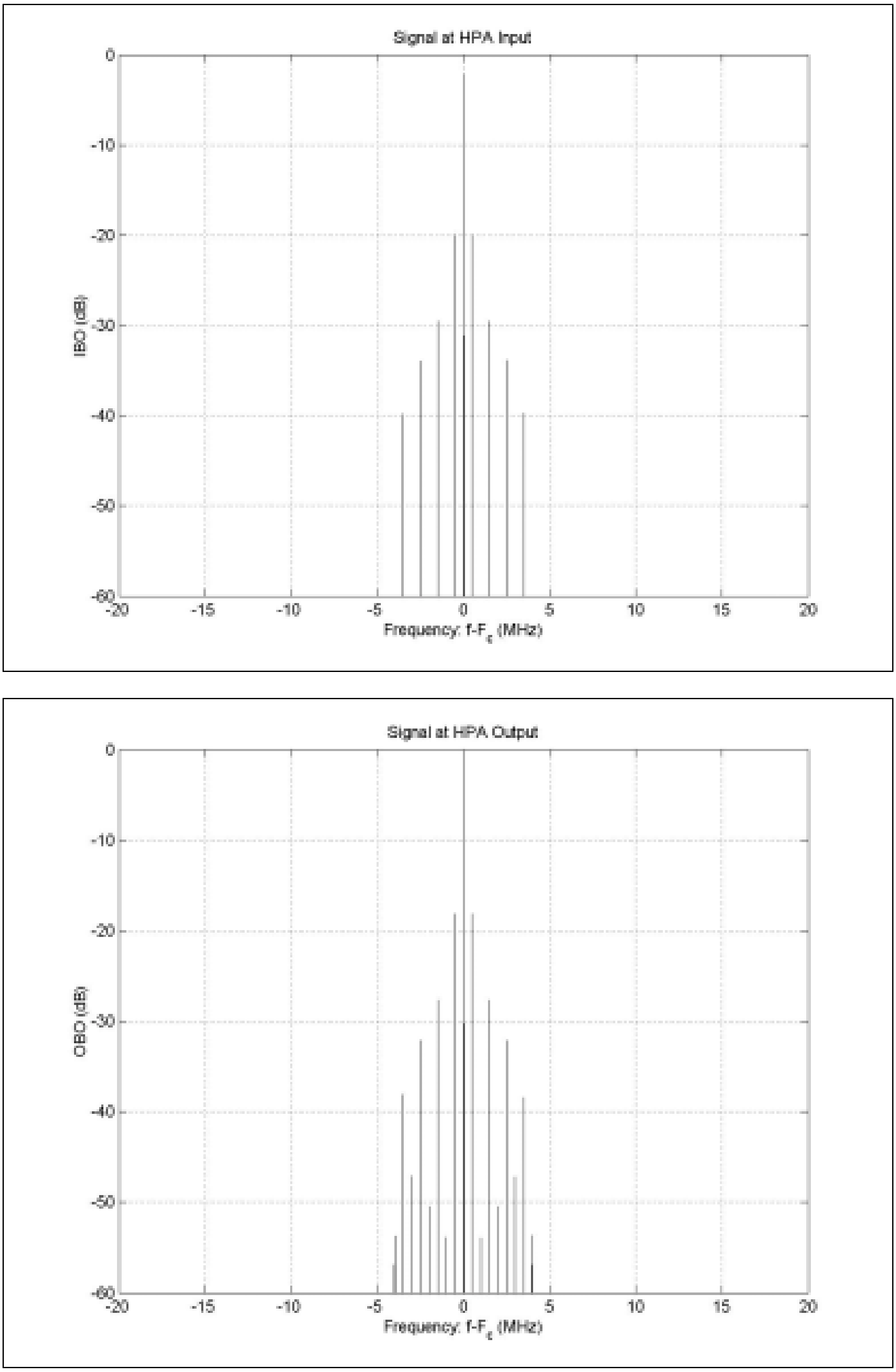
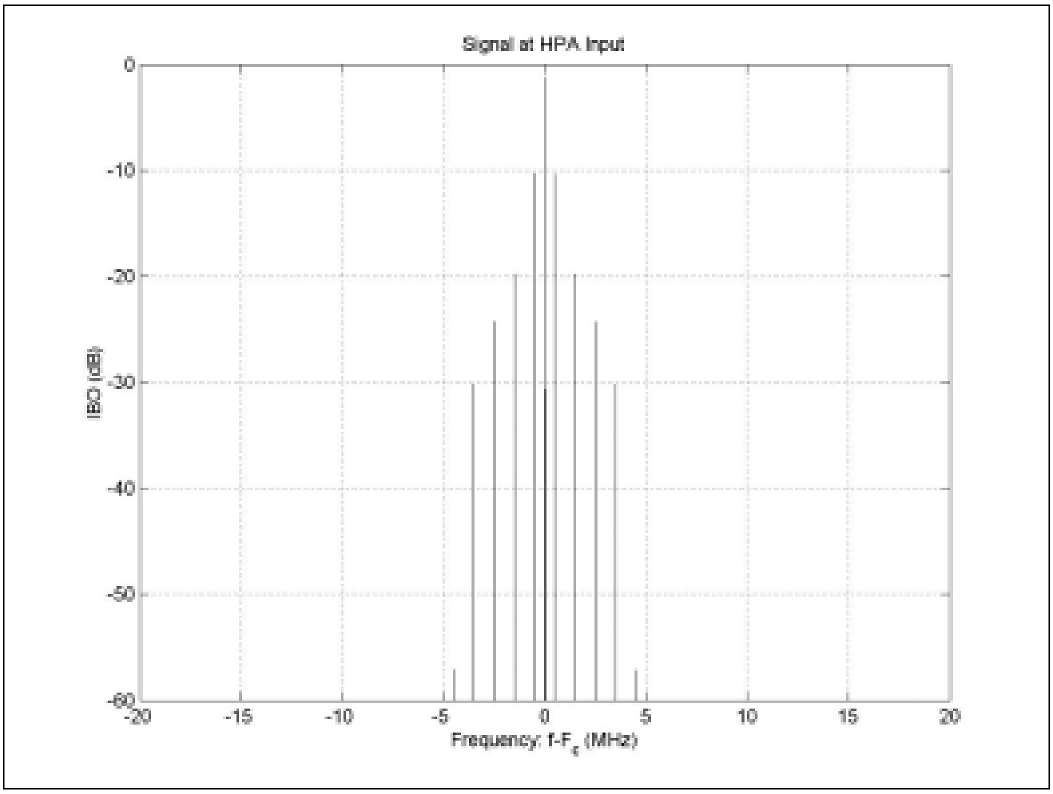


Figure B-12: Square-wave DOR at 500 kHz, modulation index = 0.2 rad-pk, IBO=2 dB



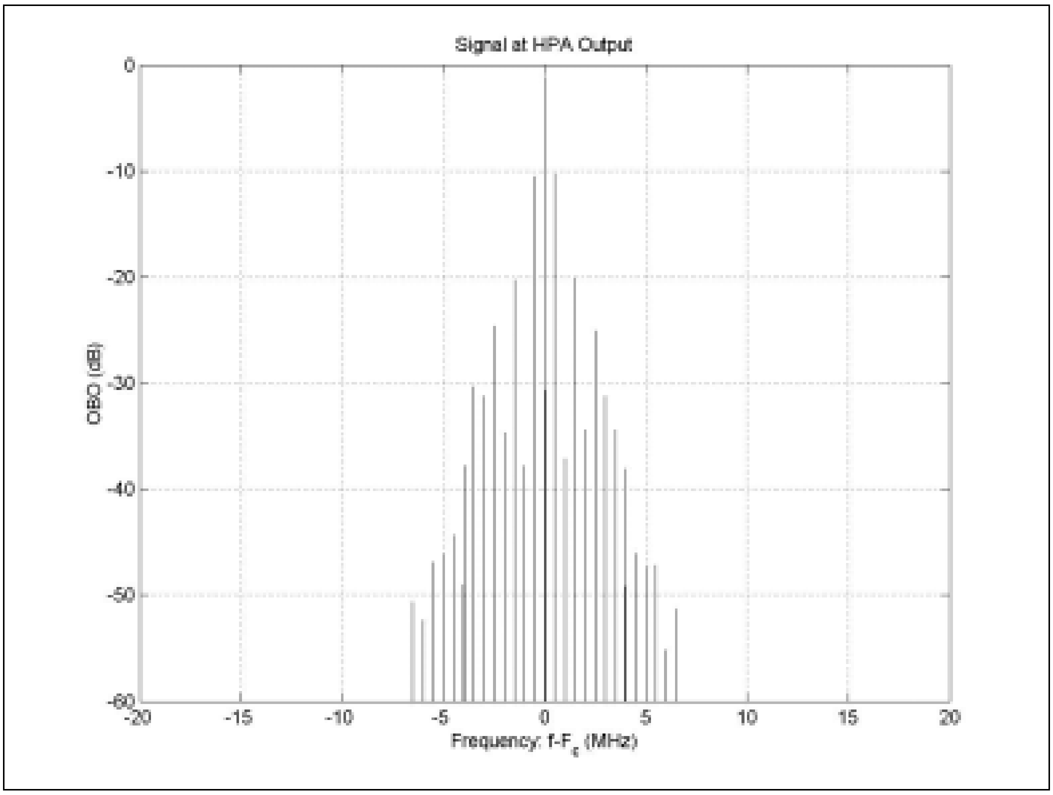
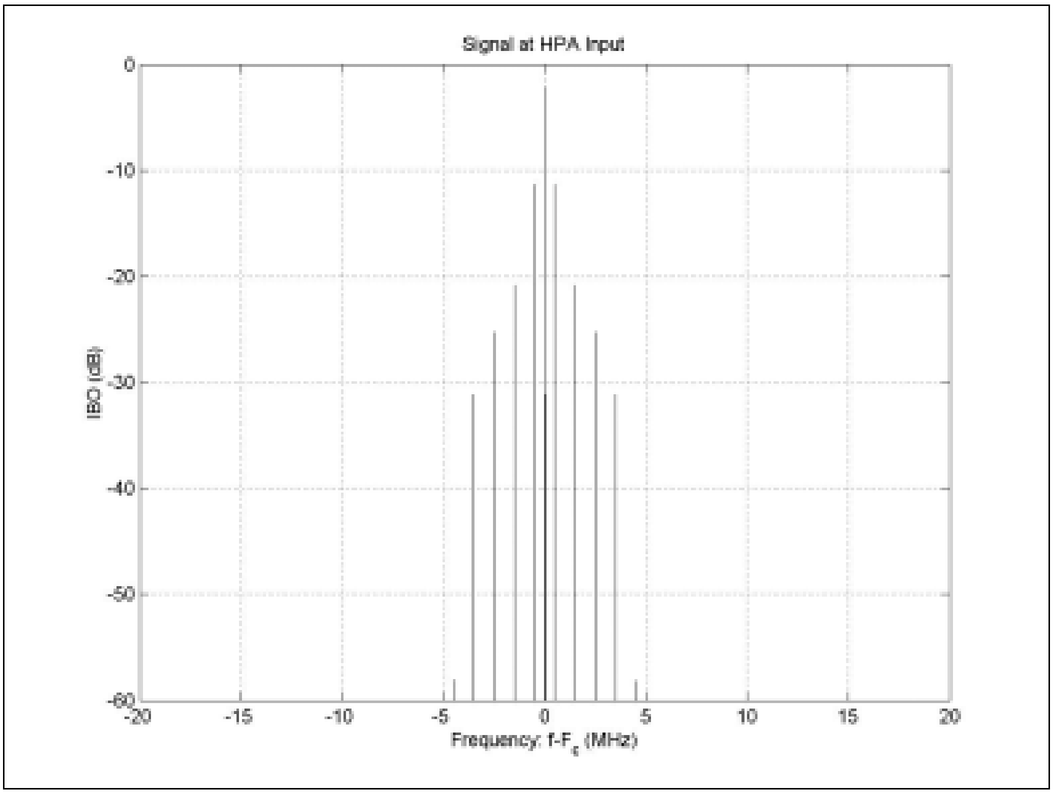


Figure B-13: Square-wave DOR at 500 kHz, modulation index = 0.5 rad-pk, IBO=0 dB



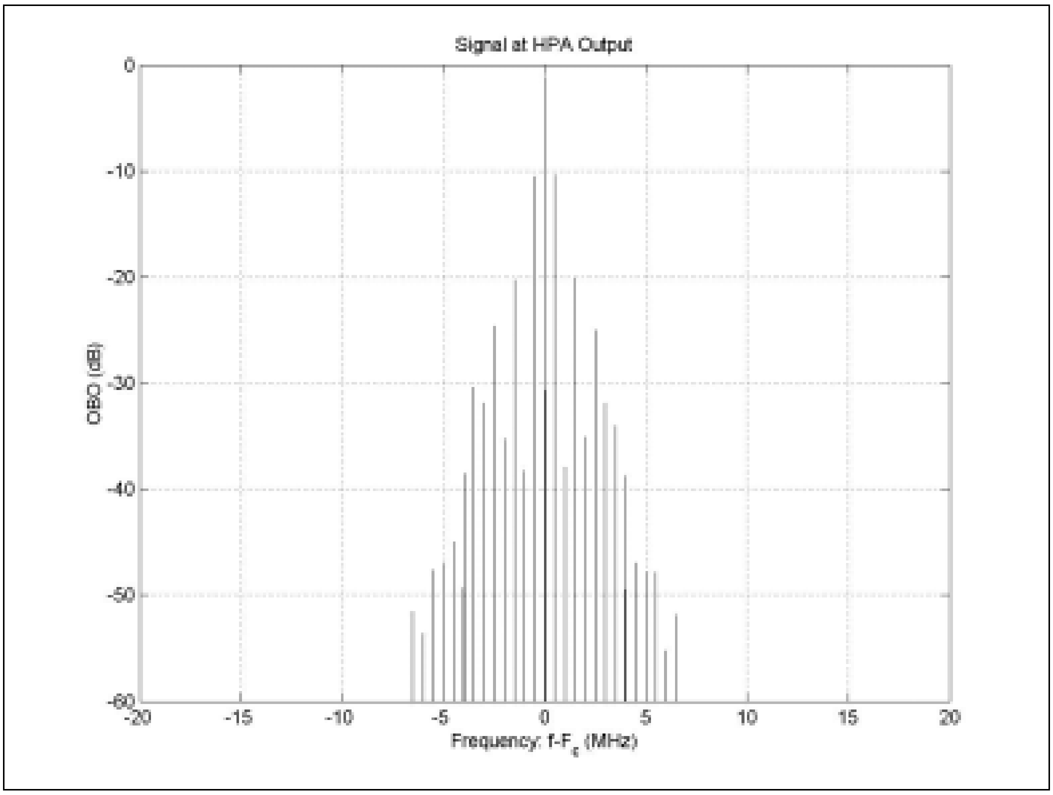
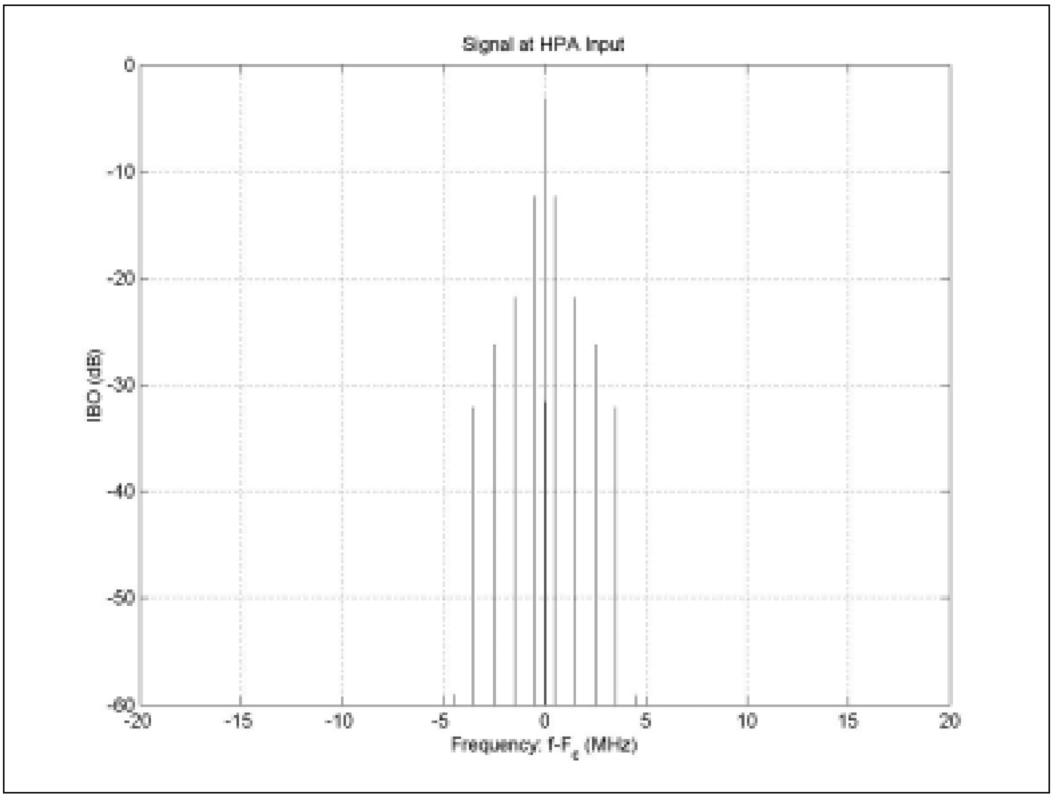


Figure B-14: Square-wave DOR at 500 kHz, modulation index = 0.5 rad-pk, IBO=1 dB



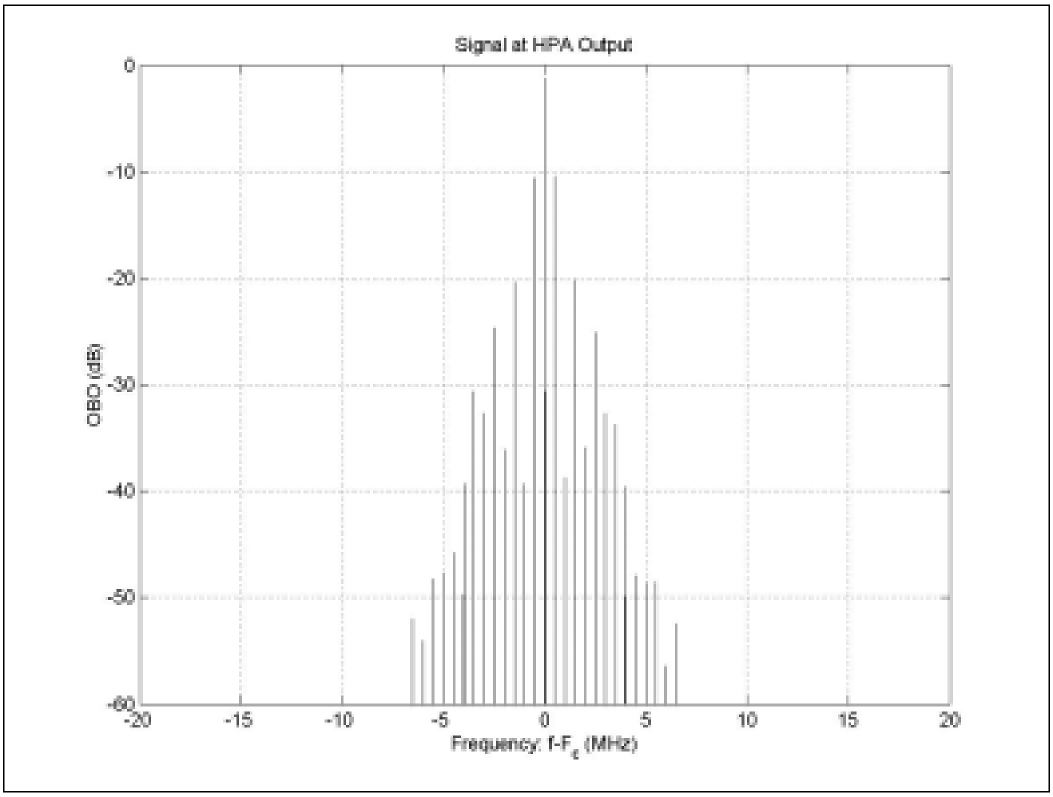


Figure B-15: Square-wave DOR at 500 kHz, modulation index = 0.5 rad-pk, IBO=2 dB

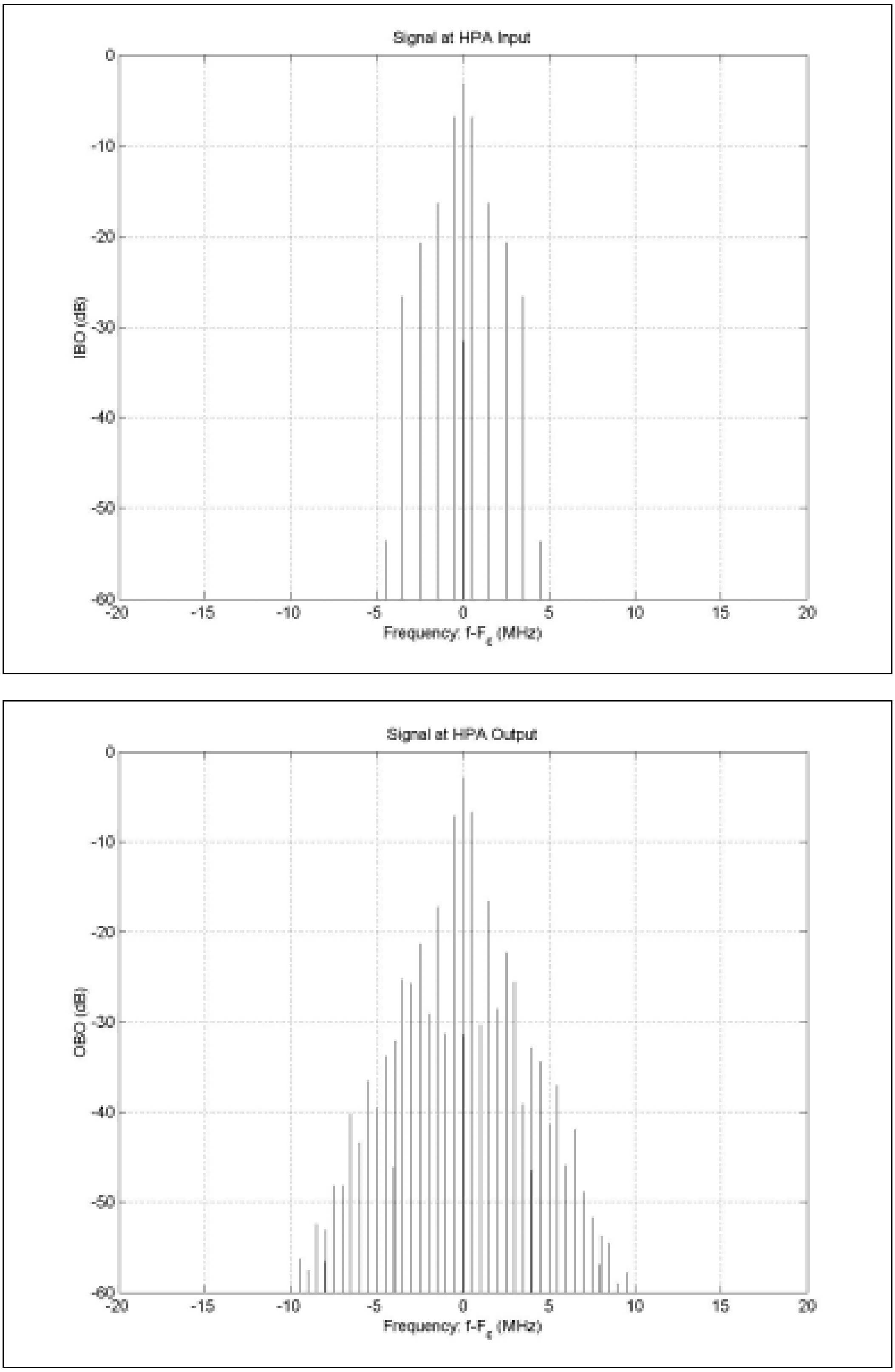
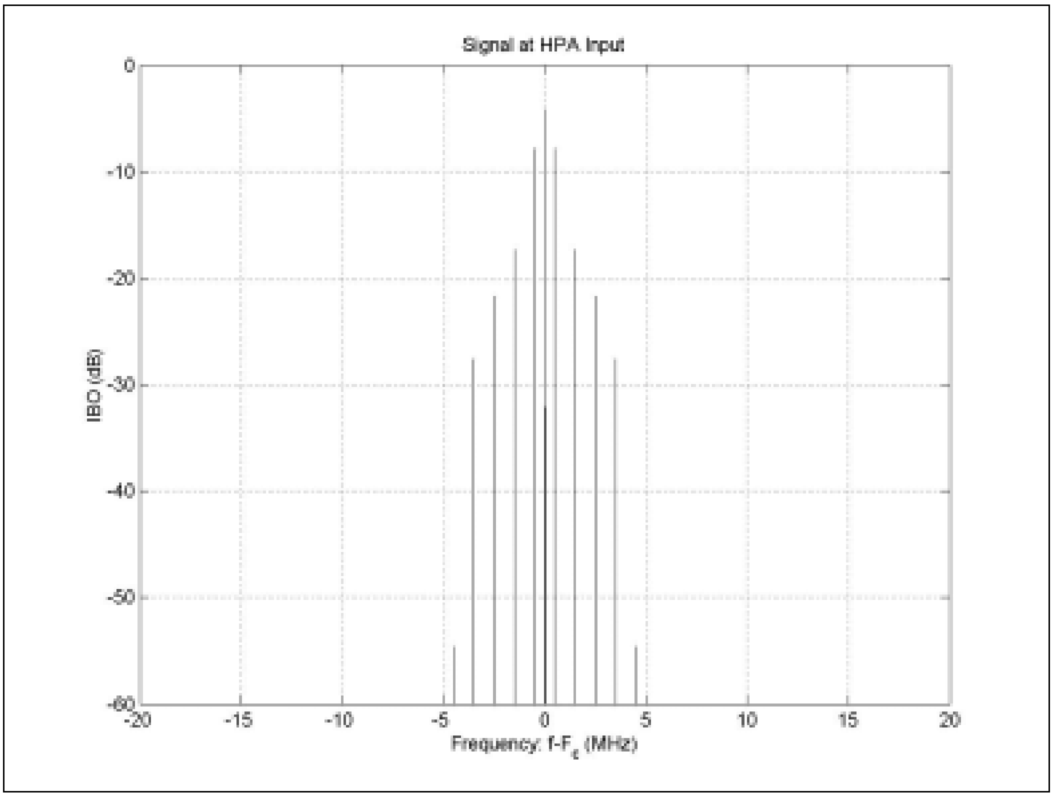


Figure B-16: Square-wave DOR at 500 kHz, modulation index = 0.8 rad-pk, IBO=0 dB



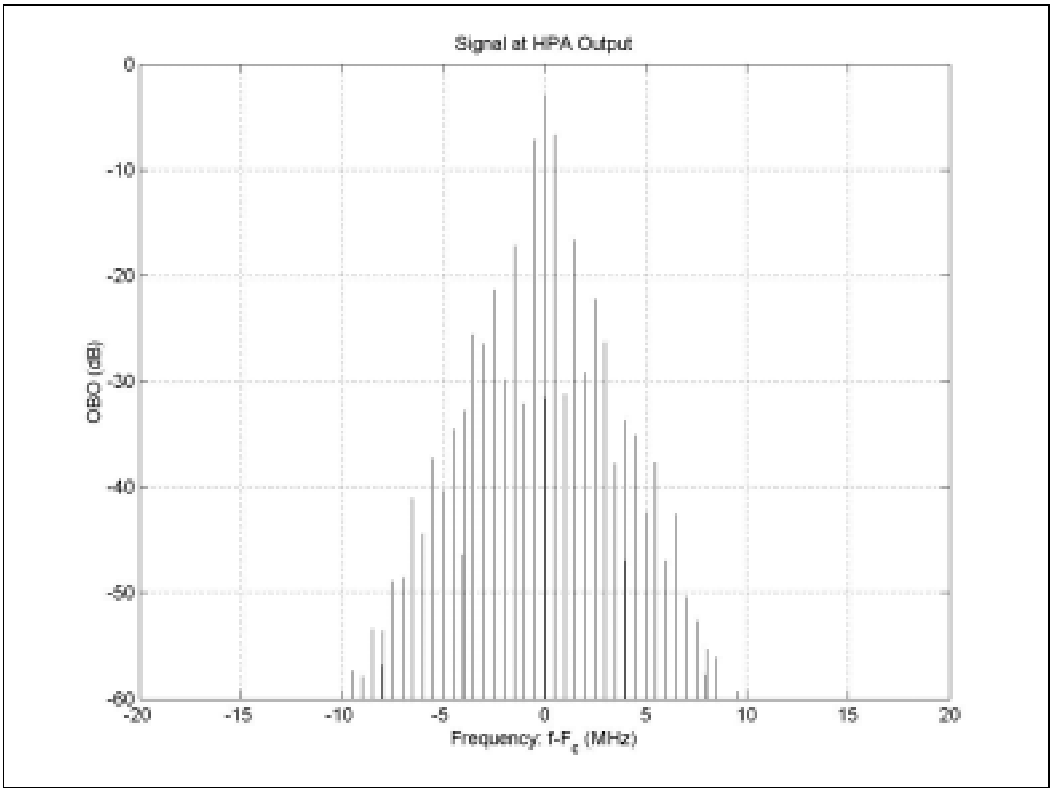
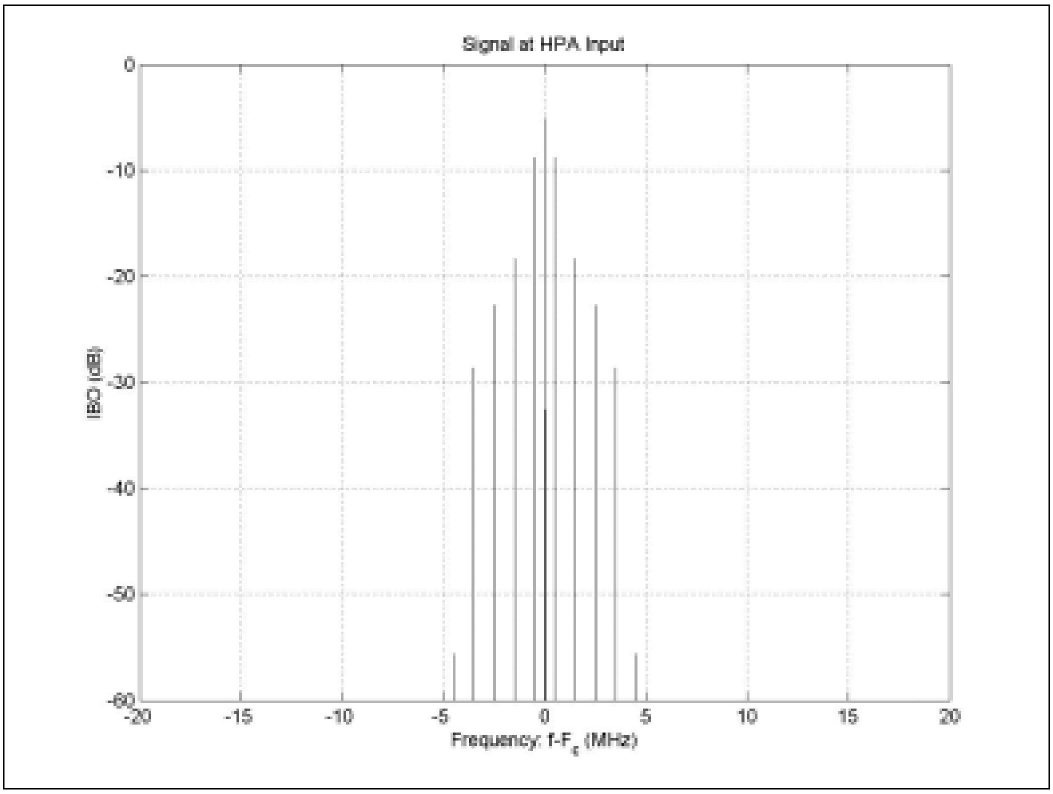


Figure B-17: Square-wave DOR at 500 kHz, modulation index = 0.8 rad-pk, IBO=1 dB



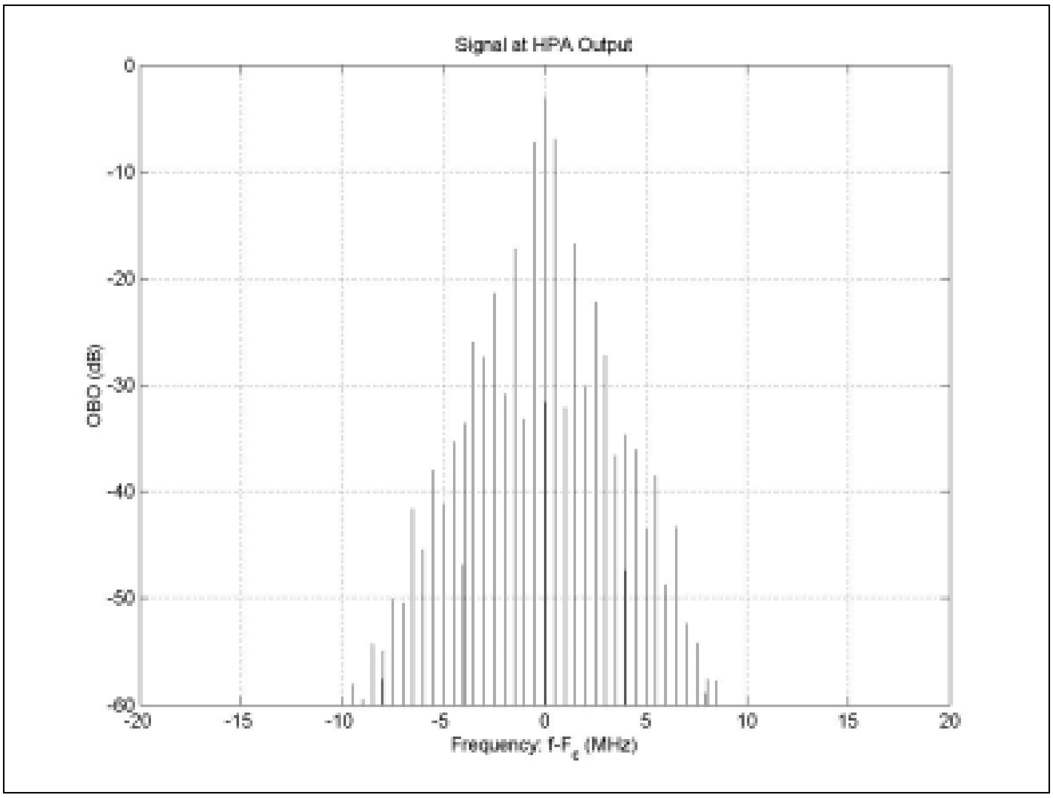


Figure B-18: Square-wave DOR at 500 kHz, modulation index = 0.8 rad-pk, IBO=2 dB

ANNEX C: Spurious Flux Density Evaluation (for BepiColombo Mission)

In order to evaluate the impact of the spectral re-growth at system level, the spurious power flux density at Earth surface has been evaluated as function of the carrier-over-spurious power ratio (C-1) for BepiColombo case. In addition, a similar analysis has been carried out in order to evaluate the spurious flux density at Earth surface versus distance, having fixed *C*/*I*=50 dBc (Figure C-2 and Figure C-3).
Note that, according to SFCG recommendation 23-2 (see Annex D), the maximum power flux density at the Earth surface due to spacecraft spurious emission shall be limited to:

- -211 dBw/m^2 in X-Band
- -204 dBW/m^2 in Ka-Band

This analysis has been performed assuming the following figures, which represent the worst-case values for BepiColombo mission[13]:

- HGA EIRP = 51 dBW in X-band
- HGA EIRP = 61 dBW in Ka-band
- MGA EIRP = 39 dBW in X-band

The following figures show that, assuming the –50 dBc level as a measure for the occupied bandwidth, we can see that we are compliant to the above SFCG recommendation down to 0.1 AU. Note that at 0.5 AU we have almost 20 dB margin.

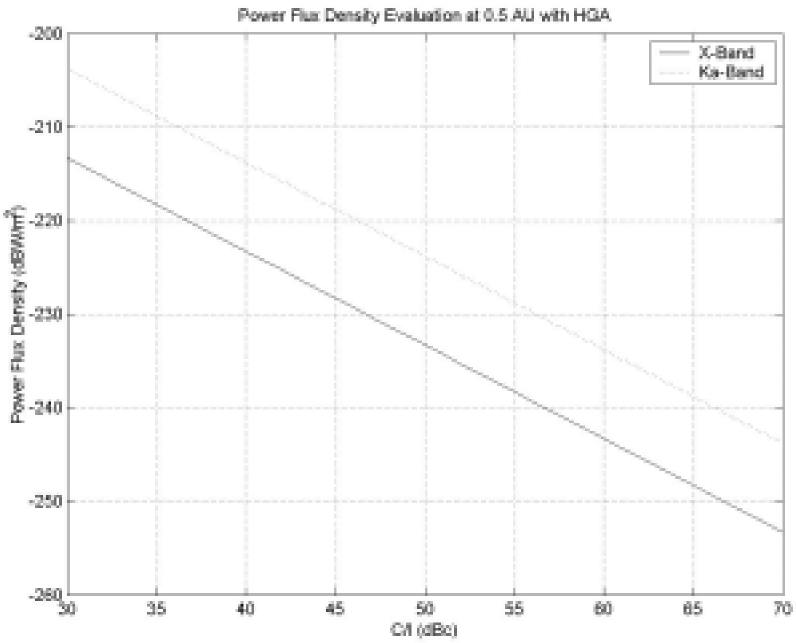


Figure C-1: Power Flux Density vs. C/I (HGA antenna, 0.5 AU)

[13] The BepiColombo TT&C subsystem is under definition, however the final EIRP values should be in the following ranges (depending on the selected High Power Amplifiers and Antenna Gain): HGA EIRP (X-band)=48÷51 dBW, HGA EIRP (Ka-band)=59÷61 dBW, MGA EIRP (X-band)=33÷39 dBW.

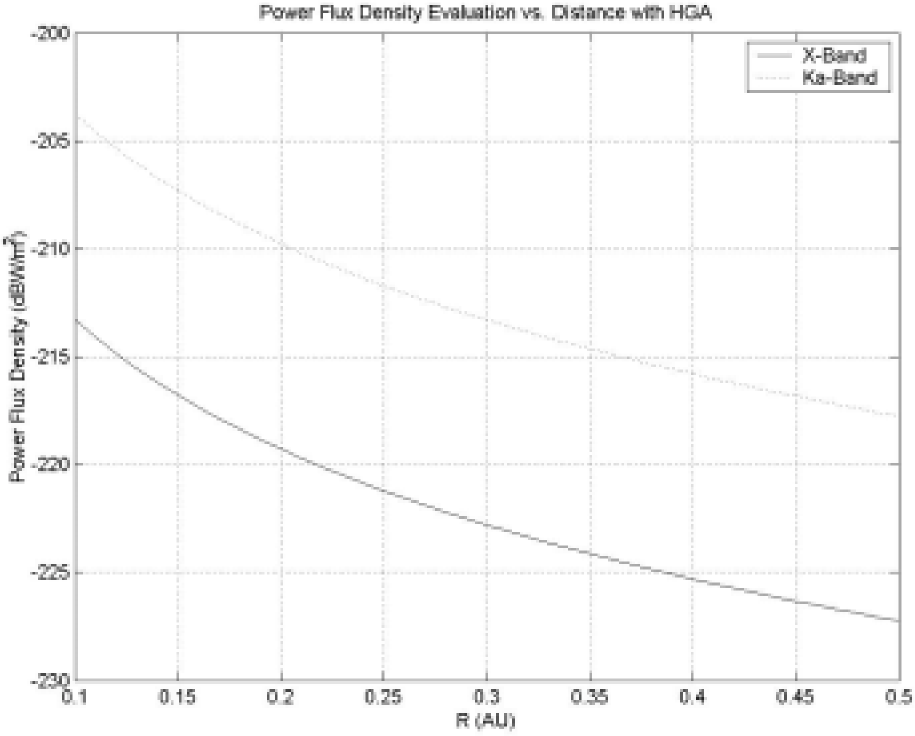


Figure C-2: Power Flux Density vs. Distance (HGA antenna, C/I=50 dBc)

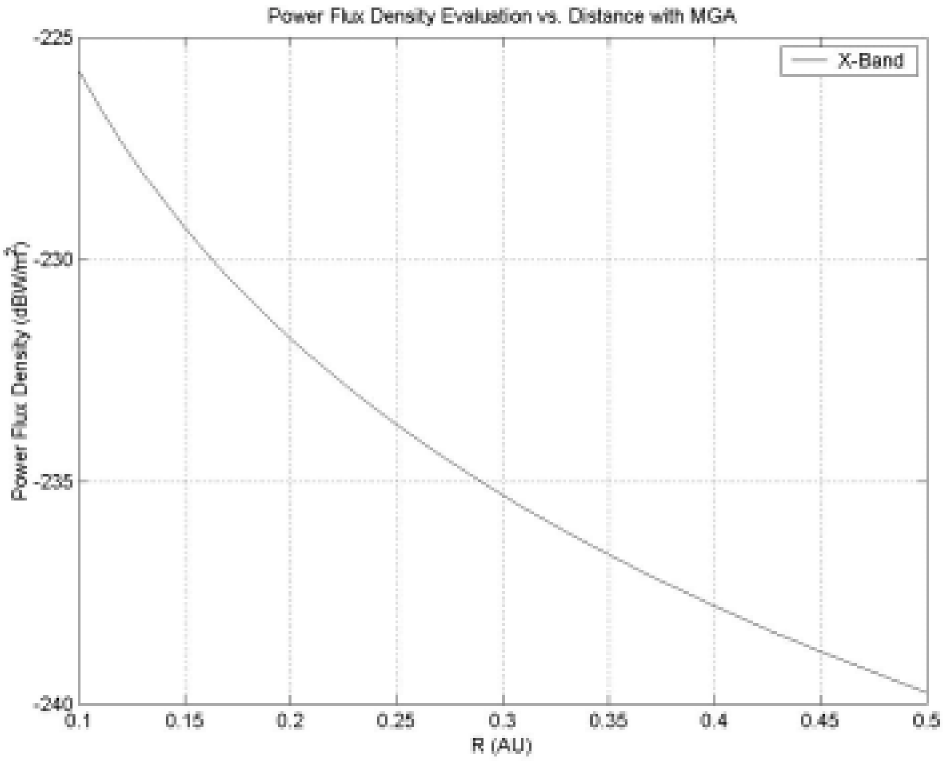


Figure C-3: Power Flux Density vs. Distance (MGA antenna, C/I=50 dBc)

ANNEX D: SFCG Recommendation 23-2 (Approved, Sept 2004)

SPACE FREQUENCY COORDINATION GROUP

SFCG Recommendation 23-2 (provisional text)

ASSIGNMENT OF DIFFERENTIAL ONE-WAY RANGING TONE FREQUENCIES FOR CATEGORY B MISSIONS

The SFCG,

CONSIDERING

a) that differential one-way ranging (DOR) is commonly used by Cat. B missions to enhance navigation accuracy required to satisfy mission objectives;

b) that measurement accuracy requires wide frequency separation between the DOR tones, examples including several missions using 38-40 MHz separation at the 8 GHz band and two missions using 158-240 MHz separation at the 32 GHz Band;

c) that because of the required separation some of the DOR tone frequencies may have to extend outside the Cat. B allocations in the future;

d) that a power flux density (PFD) for reception of DOR tones of –211 dB (W/m^2) in the 8 GHz band and –204 dB (W/m^2) in the 32 GHz band provides a received tone power 30 dB above the noise spectral density for a 34-meter Earth station, which is more than sufficient to guarantee reliable operation and accurate measurement;

e) that at such PFD a DOR tone entering the side-lobe of another antenna will be weaker than the ITU-R recommended interference thresholds[14] of the services operating in the adjacent bands by at least 37 dB;

NOTING

that Radio Astronomy Service (RAS) has a stringent protection requirement that precludes sharing of the 31.3-31.8 GHz band with any other services not mentioned in the Table of Frequency Allocations of the ITU Radio Regulations within this band;

[14] As defined in ITU-R Recommendations RA.769, SA.1029, M.1466, and M.1461.

RECOMMENDS

1. that member agencies assign DOR tone frequencies within the existing Cat. B allocations whenever possible;

2. that member agencies, when it is necessary to assign a DOR tone frequency outside a Cat. B allocation, limit the Power Flux Density of each tone to–211 dB (W/m^2) in the 8 GHz Band and –204 dB (W/m^2) in the 32 GHz Band;

3. that member agencies do not assign DOR tones[15] in the 31.3-31.8 GHz band.

[15] Including intermodulation products when multiple tone pairs are used simultaneously.

ANNEX E: SFCG Recommendation 23-1 (Approved Sept.2004)

SPACE FREQUENCY COORDINATION GROUP

SFCG Recommendation 23-1 (provisional text)

EFFICIENT SPECTRUM UTILIZATION FOR SPACE RESEARCH SERVICE, DEEP SPACE (CATEGORY B), IN THE SPACE-TO-EARTH LINK

The SFCG,

C*onsidering*

a) that spectrum allocated to SRS, deep space, space-to-Earth, is limited to 10 MHz in the 2 GHz-band (2290-2300 MHz), 50 MHz in the 8.4 GHz-band (8400-8450 MHz), and 500 MHz in the 32 GHz-band (31.8-32.3 GHz);

b) that users and data rates in the 8.4 GHz-band continue to increase and congestion in this band is more severe than in the 2 and 32 GHz bands;

c) that the technology and ground support infrastructure for the 32-GHz allocation are available in at least one space agency;

d) that several future missions being planned are considering data rates in the 5-60 Msps range, and that advanced power generating technologies could enable an even higher data rate;

e) that spacecraft in the Mars region are much more vulnerable to mutual interference due to lack of spatial separation, and that a single unrestricted high-rate mission could occupy the entire 50 MHz allocation in the 8.4 GHz band, preventing its use by any other user in the Mars region;

f) that five or six high rate missions could conceivably coexist in the Mars vicinity in the future, making it necessary to limit the maximum allowable bandwidth for each mission to no more than 8 MHz in the 8.4 GHz Band;

Noting

a) that deep space missions designed for destinations other than Mars, should also have restrictions on their maximum allowable bandwidths in the 8.4 GHz band, although at a less severe level, so that costly operational coordination could be minimized every time a mission arrives in the vicinity of other missions in space;

b) that an efficient spectrum usage policy should provide incentives to missions to achieve the most efficient utilization of the spectrum as practical;

c) that several modulations use bandwidths more efficiently than the traditional BPSK and some of the most efficient ones are given in CCSDS Recommendation 2.4.17B;

Further noting

a) that a 20 dB signal to interference ratio is used successfully as a criterion to prevent interference in the selection of frequencies for many deep-space missions, and separating two missions at the point where their power spectral densities (PSDs) are each 25 dB down from their own spectral peaks is generally sufficient to prevent mutual interference;

b) that an interference spectral power flux density (SPFD) of –266 dB(W/Hz/m^2) would, when received by a 70 meter antenna, be 16 dB below the noise floor of the receiving system and would raise the system temperature by 0.1 dB;

c) that it is sometimes necessary for a deep space mission to use a telemetry subcarrier to isolate a residual carrier, which is needed for weak signal acquisition at low date rate, for radio metric measurement, or for a radio science experiment requiring spectral purity;

recommends

1. that, in the 8400-8450 MHz band, the maximum allowable bandwidth of telemetry signals be limited according to Figure 1[16], wherein

   a) the lower curve applies to all missions;
   b) the upper curve applies only to the non-Mars-missions, strictly on condition that they would not interfere with the Mars missions;

2. that, in the 8400-8450 MHz band, the spectral power flux density outside the maximum allowable bandwidth be limited to –266 dB(W/Hz/m^2) on the surface of the Earth;

3. that member agencies use the 32 GHz-band for high rate telemetry with bandwidth requirement higher than those allowed in Figure 1;

4. that except for scientific or technical reasons, subcarrier frequencies above 60 kHz do not exceed 5 times the maximum symbol rate of the mission and do not exceed 300 kHz.

[16] For the purpose of this Recommendation, the Symbol Rate (R_s) is defined in Figure 2.

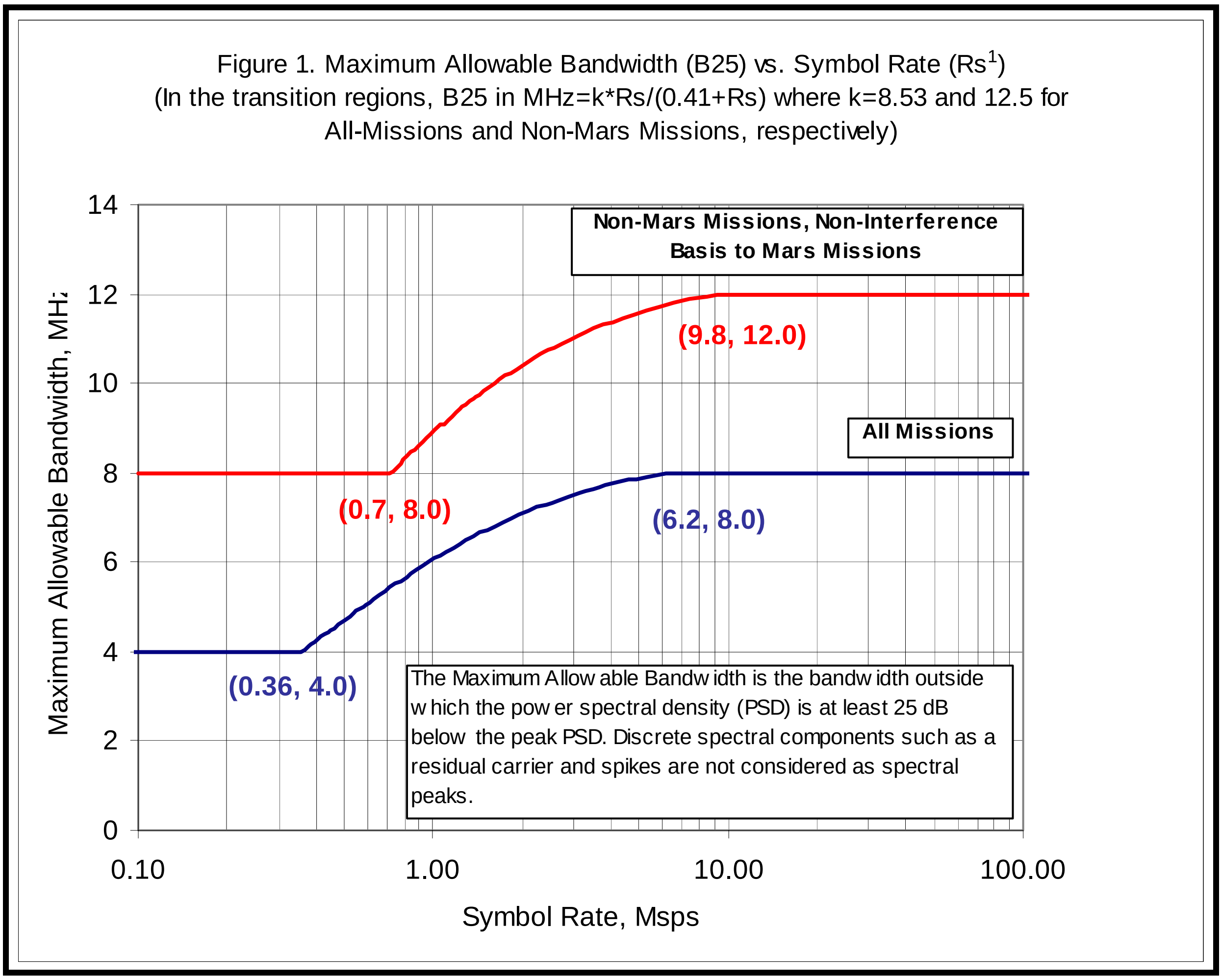


Figure 2. SFCG Symbol Rate Definition