National Aeronautics and Space Administration

SLS-RFM_23-04 Performance Validation of Bi-Phase Filtering for Category A Space-to-Earth Links

Wing Lee and Wai Fong, Ph.D.

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NASA's Goddard Space Flight Center

Flight Microwave & Telecommunication Systems Branch

www.nasa.gov

Background

- During Fall 2022 meeting, ESA presented input paper SLS-RFM_22-10 on bi-phase filtering for Category A Space-to-Earth links so that the spectrum is compliant to the SFCG mask for symbol rates < 300ks/s.

- The recommendation is to apply a 3rd order Butterworth filter before phase modulation of the baseband signal (referred as Option 2).

- The goal of this effort is to verify ESA's spectral and BER results by MATLAB simulation which serve as a means of independent validation required by CCSDS.

SFCG 21-2R4 Guideline for Bi-Phase

RECOMMENDS

1. that space agencies use the most bandwidth efficient modulation schemes practicable for their missions;

2. that, PCM/PM/Bi-phase or PCM/PM/NRZ modulation only be used when a carrier component is technically necessary and for symbol rates below 2 Ms/s.

3. that the emitted spectrum[3,4] for all Space Science Services projects that will utilize space-to-Earth link frequency assignments in the bands 2200–2290 MHz, 8025–8400 MHz and 8450–8500 MHz, adhere to the low rate spectral emission mask of Figure 1 for symbol rates below 2 Ms/s and to the high rate spectral emission mask of Figure 1 for symbol rates equal or above 2 Ms/s;

4. that the emitted spectrum[3] for all Space Science Services projects designed for launch after 2020 that will utilize space-to-Earth link frequency assignments in the 25.5-27.0 GHz band and for channel symbol rates[5] equal or above 10 Ms/s, adhere to the high rate spectral emission mask of Figure 1;

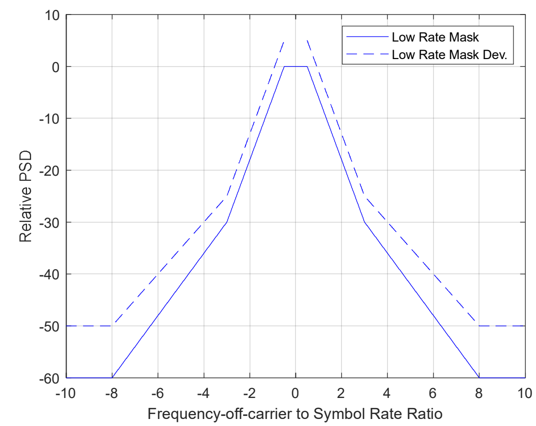
5. that transmissions that include a ranging signal be exempt from the spectrum masks in Fig 1;

6. that PCM/PSK/PM transmissions in accordance with REC SFCG 21-3 be exempt from the spectrum masks in Fig 1.

[3] Measured relative to the peak of the telemetry spectrum and excluding the residual carrier as well as all spurious emissions.
[4] PCM/PM/Bi-phase emissions with symbol rates up to 300 ks/s may deviate from the low rate mask by up to 5 dB in the slope region and up to 10 dB in the plateau region, and in the transition between the two regions.

Interpretation:

1. Relaxation on the low rate mask is allowed for bi-phase with symbol rates up to 300ks/s.



Mathematical Model for Unfiltered and Filtered Bi-Phase Signal with Residual Carrier

- Bi-phase with no filtering:

$$s(t) = e^{jm \underbrace{\sum_k a_k p(t-k/R_s)}_{\text{This term has power = 1}}}$$

where

m – input modulation index

a_k – k^{th} data value (-1 or 1)

p(t) – bi-phase pulse shape

R_s – symbol rate (before bi-phase converter)

- Bi-phase with filtering before PM:

$$s(t) = e^{jm \underbrace{\sum_k a_k (g*p)(t-k/R_s)}_{\text{This term has avg. power < 1 due to filtering}}}$$

or

$$s(t) = e^{j\overbrace{m\sqrt{C}}^{\text{Effective mod index m'}} \underbrace{\frac{1}{\sqrt{C}} \sum_k a_k (g*p)(t-k/R_s)}_{\text{This term has avg. power = 1}}}$$

where

C – avg power of $\sum_k a_k (g * p)(t - k/R_s)$

g(t) – spectral shaping filter

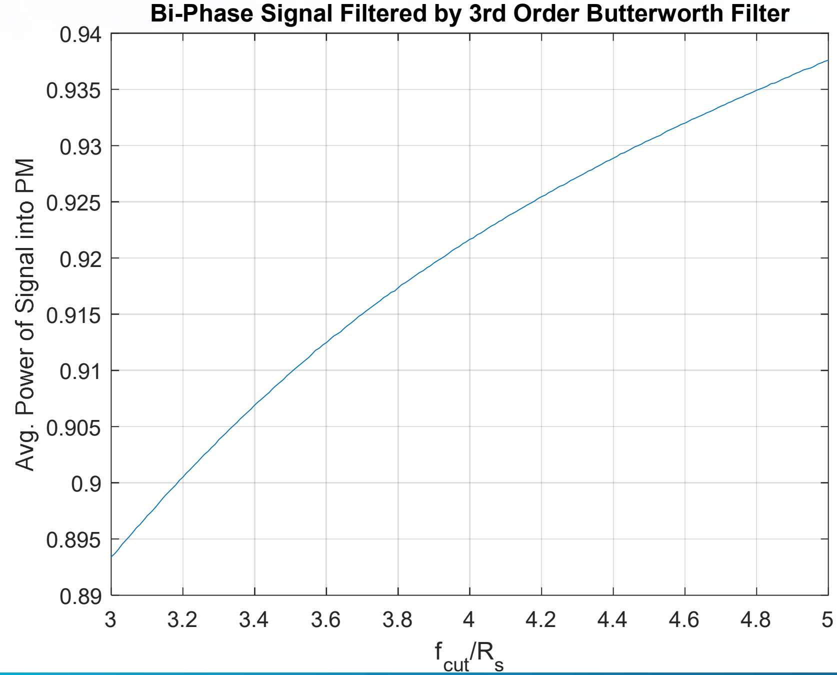
$*$ denotes the convolution operator

ESA has chosen 3rd order Butterworth filter for *g(t)* with a range of cutoff frequencies to satisfy the SFCG spectral mask for different modulation indices.

Effective Modulation Index

- Since average power in the data modulation is reduced by the spectral shaping filter, the constant term C needs to be estimated by simulation so that input mod index, *m*, can be adjusted accordingly to achieve a desired "effective" mod index, *m'*.

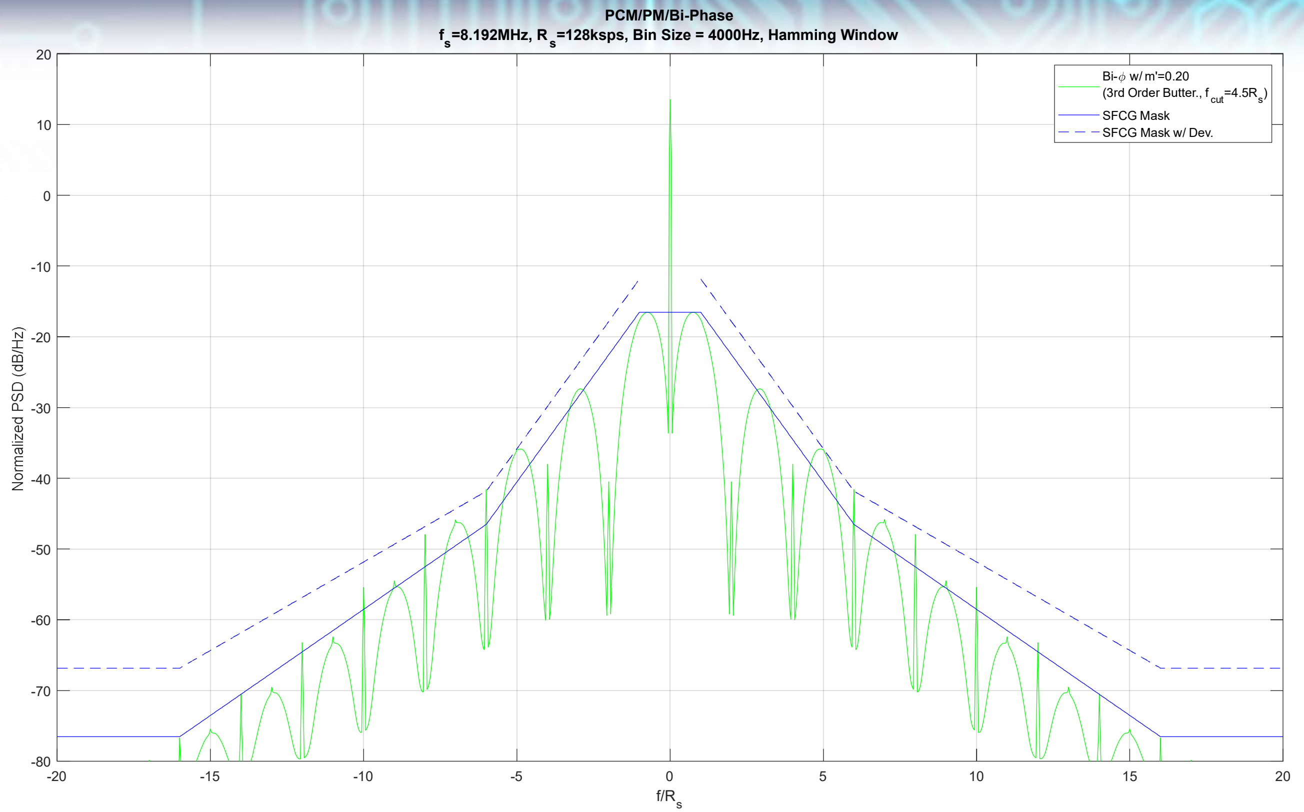
$$m = \frac{m'}{\sqrt{C}}$$



Spectral Analysis

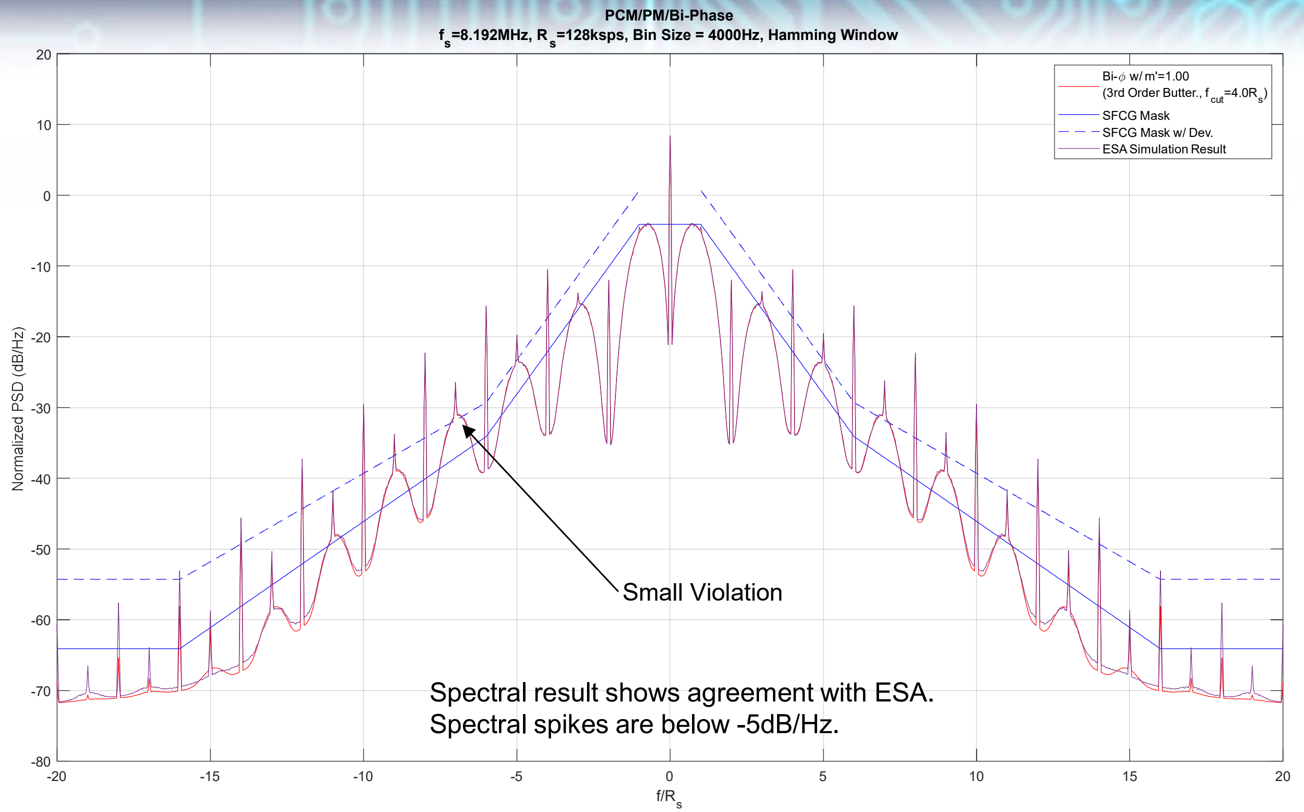
- ESA showed that f_{cut} settings of $4.5R_s$, $4.0R_s$, $3.5R_s$ for m' = 0.2, 1, 1.25 are sufficient to meet SFCG mask.

Effective Mod Index 0.2 rad-pk with f_{cut}=4.5Rs

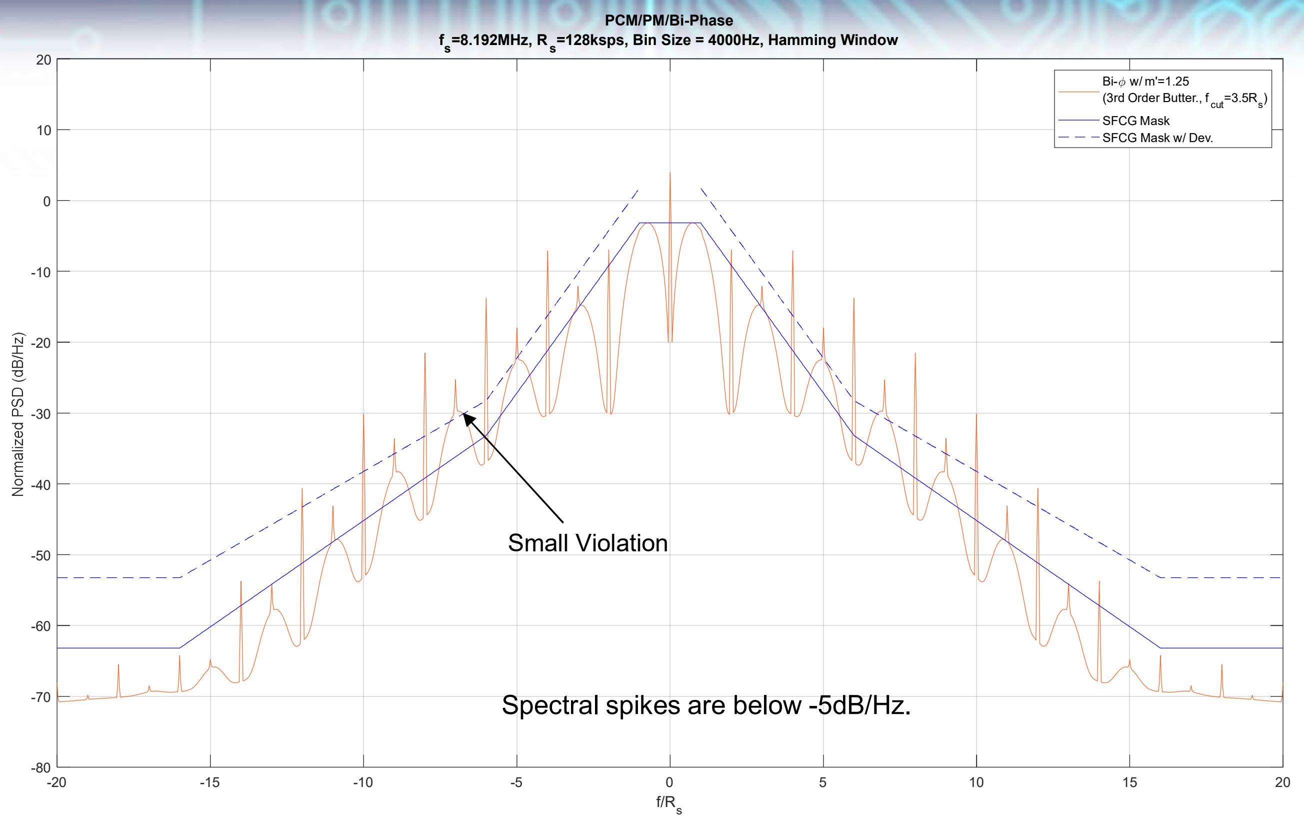


Spectrum meets SFCG mask.
Spectral spikes are below -5dB/Hz
(ESA's requirement for spectral spike is 20dBc below unmodulated carrier)

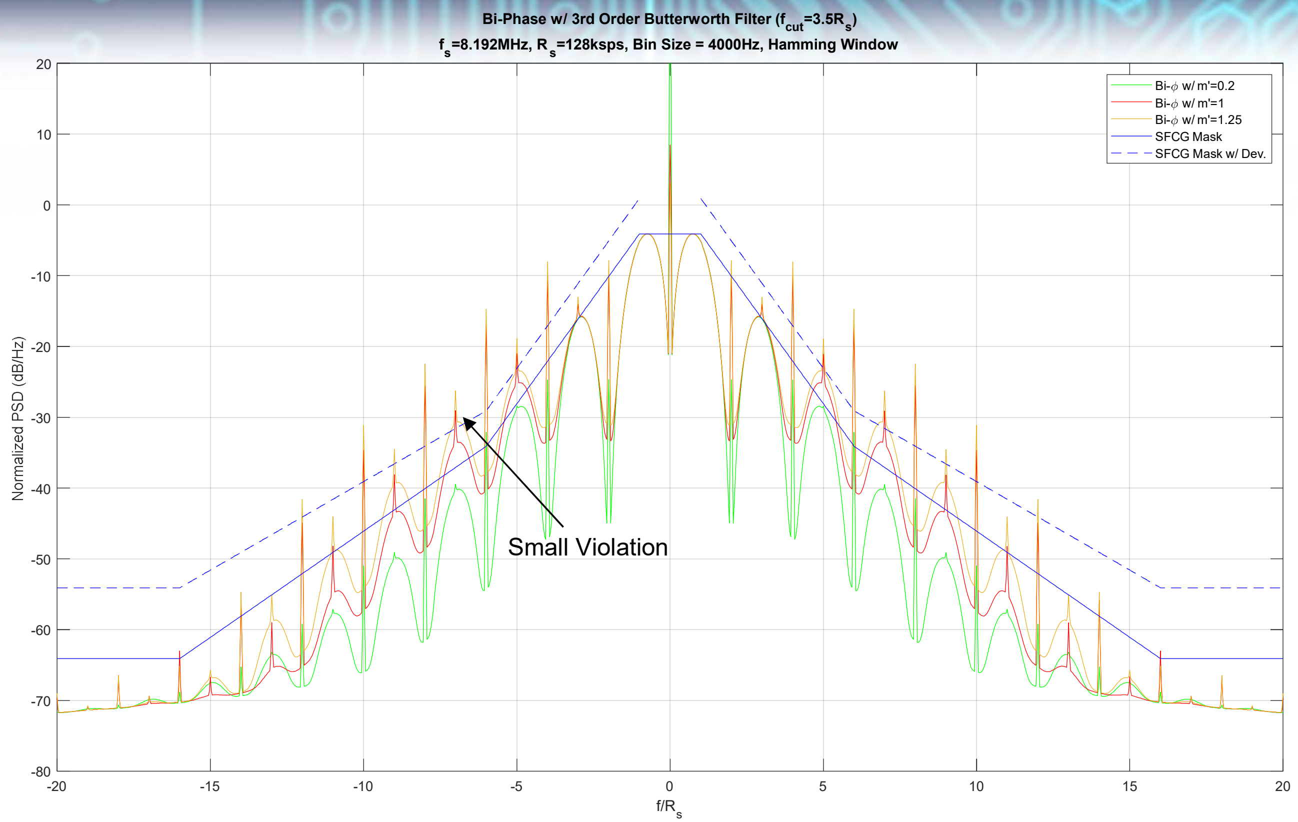
Effective Mod Index = 1.0 rad-pk with f_{cut}=4.0Rs



Effective Mod Index = 1.25 rad-pk with f_{cut}=3.5Rs

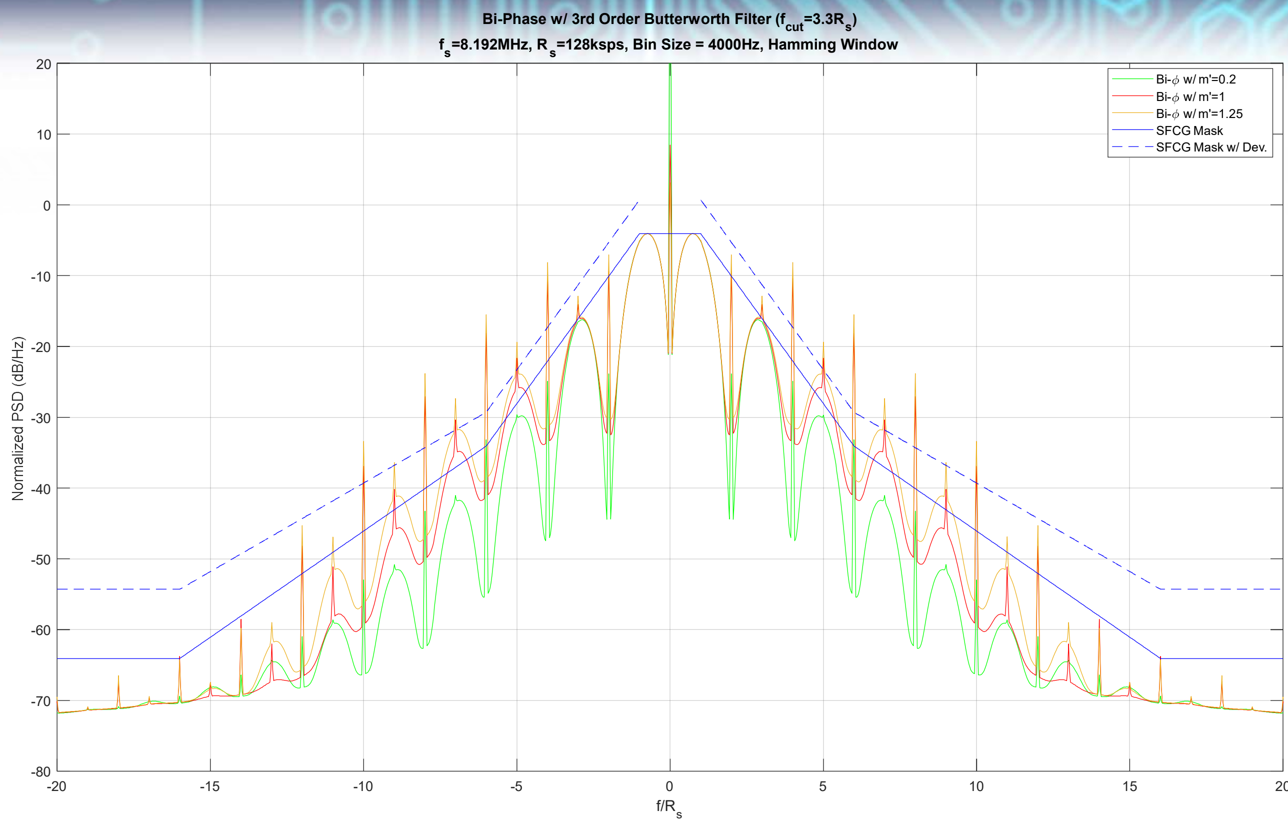


Effective Mod Index = 0.2, 1, 1.25 rad-pk with f_{cut}=3.5Rs



Note: Plots are shifted to the same level for comparison.

Effective Mod Index = 0.2, 1, 1.25 rad-pk with f_{cut}=3.3Rs



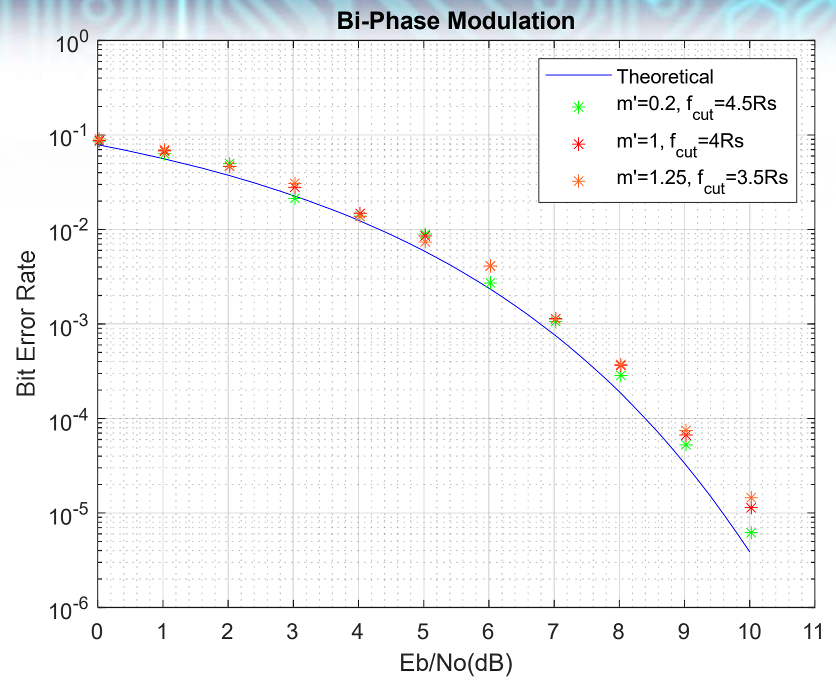
Spectral results show that there is some small potential spectral violations for m' of 1.25 using f_{cut} of 3.5Rs therefore we reduced f_{cut} setting to 3.3Rs.

Note: Plots are shifted to the same level for comparison.

Bit Error Rate Analysis

- Assumptions:
  - Receiver is unaware of the additional filtering and therefore uses the bi-phase pulse as the matched filter.
  - Therefore BER simulation plots are generated based on the expected Eb/No for unfiltered bi-phase signal with power of $\sin^2(m')$.
  - Channel model is AWGN.

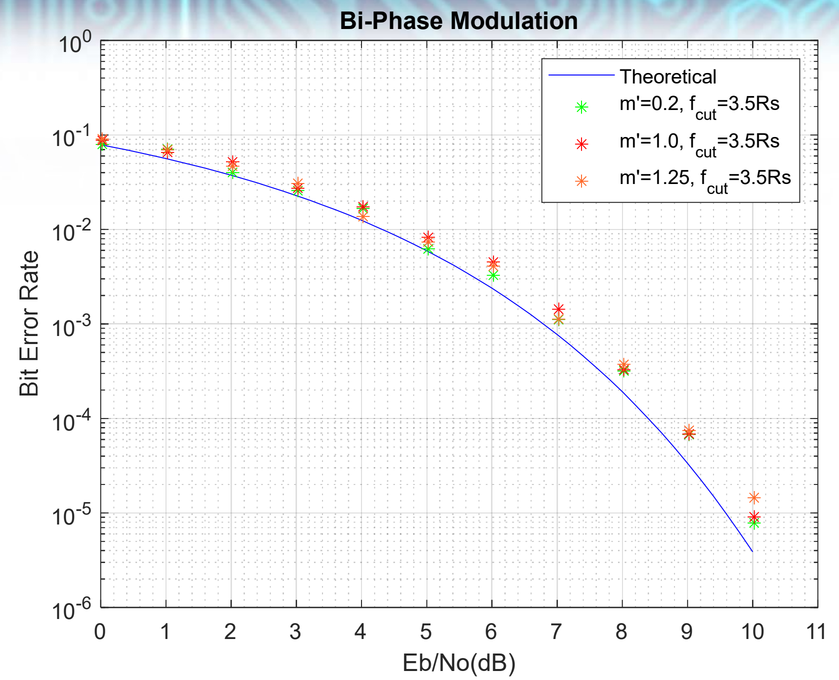
Effective Mod Index 0.2, 1.0, 1.25 rad-pk at f_{cut}=4.5Rs, 4Rs, 3.5Rs



Loss @ 1e-5	ESA's Result	NASA's Result
m'=0.2, f_{cut}=4.5Rs	~ 0.2 dB	~ 0.2 dB
m'=1, f_{cut}=4Rs	~ 0.4 dB	~ 0.5 dB
m'=1.25, f_{cut}=3.5Rs	~ 0.5dB	~ 0.6 dB

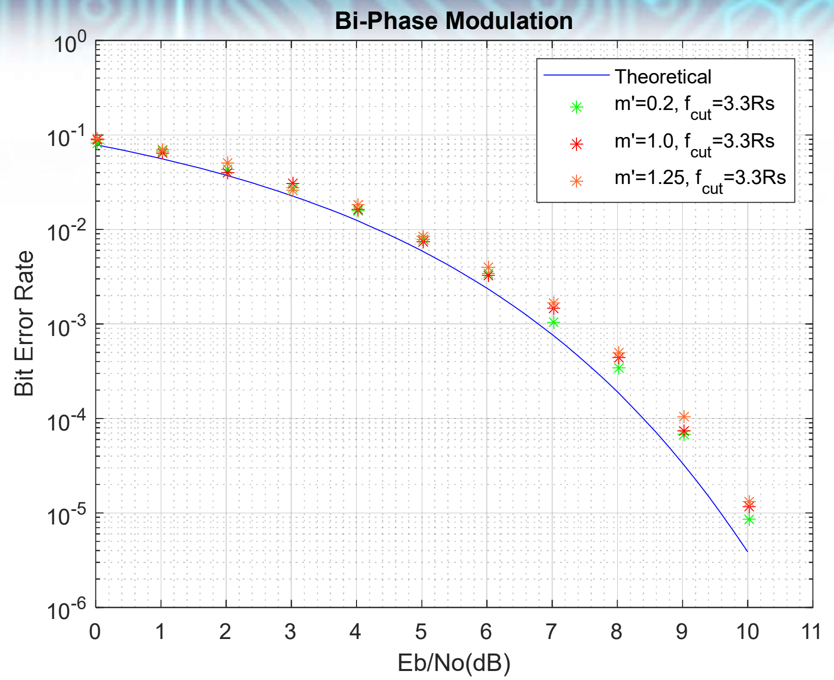
NASA's results are similar to ESA's.

Effective Mod Index 0.2, 1.0, 1.25 rad-pk at f_{cut}=3.5Rs



If smallest filter cutoff frequency, 3.5Rs, is used for all mod indices, implementation loss ranges from about 0.3 to 0.6dB at 1e-5 BER.

Effective Mod Index 0.2, 1.0, 1.25 rad-pk at f_{cut}=3.3Rs



If smallest filter cutoff frequency, 3.3Rs, is used for all mod indices, implementation loss ranges from about 0.3 to 0.6dB at 1e-5 BER.

Some Observations

- NASA spectral requirement is to meet both SFCG and NTIA masks.
  - We are currently trying to understand spectral regulations on the spikes.
    - Section 5.6.2 of Redbook indicated that single frequency unwanted emissions be at least 60dBc below mean transmit power. Spikes shown in spectral plots do not meet this requirement.
    - Per Dennis Lee's initial suggestion, it might be possible to argue that the spikes are a necessary byproduct of PM filtering, and be considered as part of the inherent modulation spectrum.
    - NTIA Annex J regulations, Section J.3.4 January 2021 Edition, Table 5 is shown on right with regards to PCM/PM/Bi-Phase

K-factor specifications for filtered PCM/PM/Bi-Phase from NTIA Annex-J document:

Table 5: K-factors for PCM/PM Bi-Phi with Filtering and without Subcarrier

Modulation Index (m)	Filter Type	Filter Characteristics	K-factor
1.2	Square Root Raised Cosine	2000 tap; roll off factor=1	2x2.0
1.2	Butterworth	3 pole; Bandwidth Symbol Time Product (BTs)=2	2x3.0
1.2	Bessel	3 pole; Bandwidth Symbol Time Product (BTs)=2	2x3.0
π/2	Square Root Raised Cosine	2000 tap; roll off factor=1	2x2.6
π/2	Butterworth	3 pole; Bandwidth Symbol Time Product (BTs)=2	2x4.0
π/2	Bessel	3 pole; Bandwidth Symbol Time Product (BTs)=2	2x4.0

Definition for necessary BW, Bn, is not specified for bi-phase modulated signal. The closest one is for BPSK signal where Bn = 2*Rs*K.

- Table 3.2.2.2-1 in ICSIS document specifies PCM/PM/Bi-Phase-L be used for the X-band return link when ranging is required, for symbol rates (before bi-phase converter) between 64ksps and 1.024Msps.
  - SFCG allows exemption for transmissions with ranging signal, but NTIA doesn't. Necessary BW needs to be increased to account for this.

X-band Return Link (8450-8500 MHz)[6] (~~CSP~~ Lunar Exploration System to Earth)

Symbol Rates[1, 10]	Modulation and Encoding[1, 10]	Ranging	Coding LDPC[4]	Space Data Link Protocol AOS[3], USLP[5]	Space Data link Security
128ksps ≤ symbol rate ≤ 4 Msps[7]	Filtered OQPSK + NRZ-L	No	Code Rates ½, ~~2/3,~~ 4/5, 7/8, uncoded. Depending on the codeword selected, the following codeword size and ASM is to be used:	Depending on the codeword selected, the following AOS Frame size is used:	CCSDS Space Data Link Security Protocol[8]
64 ksps ≤ symbol rate ≤ 4 Msps[7]	Filtered BPSK + NRZ-L	No			
64 ksps < symbol rate ≤ 1.024Msps[7]	PCM/PM/Bi-phase-L (modulation on residual carrier)	Yes[2]	• 4096 octets plus 64 bit ASM (for rate ½) • ~~3072 octets plus 64 bit ASM (for rate ⅔)~~ • 2560 octets plus 64 bit ASM (for rate 4/5) • 1020 octets plus 32 bit ASM (for rate 7/8) • Uncoded size: 2048 octets plus a 32 bit ASM	• 2048 octets (for LDPC rates ½, ~~⅔,~~ 4/5, or uncoded) • 892 octets (for LDPC rate 7/8)	
0.1 ksps[9] ≤ symbol rate ≤ 64 ksps	PCM/PSK/PM + NRZ-L (modulation on subcarrier)	Yes[2]	LDPC Code rate ½ using the following codeword size and ASM: • 256 octets plus 64 bit ASM • Uncoded size: 128 octets plus a 32 bit ASM	• 128 octets (for LDPC rate ½ or uncoded)	

Summary

- In this report, we have successfully verified the spectral and BER performance of the bi-phase filtering recommended by ESA:
  - Spectral performance with effective mod index m' of 1.0 and filter cut-off at f_{cut}=4.0Rs
  - Eb/No degradation at BER of 1e-5 for various combinations of m' and f_{cut} settings

- Our spectral results show that there is some small potential spectral violations for m' of 1.25 using f_{cut} of 3.5Rs therefore we reduced f_{cut} setting to 3.3Rs.

- For NASA missions, necessary BW for NTIA mask needs to be increased to cover the spectral emissions.

- Question: When PN ranging is on, does shaping the bi-phase pulse have any additional impact to chip tracking performance and also how does ranging impact BER of bi-phase detection?

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