SP-L/PM filtering for meeting SFCG mask

Andrea Modenini

CCSDS Spring meeting 2023

Introduction

- In Spring 2022 meeting, ESA submitted paper **SLS-RFM_22-01** regarding **filtering options of SP-L/PM for meeting the SFCG mask** for Cat. A space-to-Earth links.

- During Fall meeting 2022:
  - ESA provided additional simulations (**SLS-RFM_22-10**) and proposed to have a new recommendation for 401.0-B proposing a **Butterworth 3rd Order,** $\boldsymbol{f_{cut} = 4 - 4.5R_s}$ (R_s is the symbol rate);
  - Before going for Agency review, CCSDS RFM WG noticed that results were done only for modulation index $m = 1.0$ rad/peak, and it was not clear the nonlinear effects of filtering before PM;
  - Thus, **the WG agreed to have an AI to perform additional simulations by varying the modulation index** for checking that the proposed Butterworth is still suitable.

- This presentation provides the additional results for different modulation indexes.

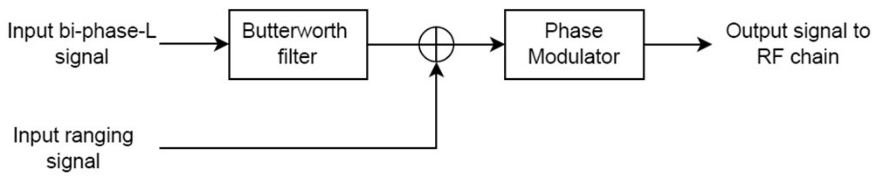
Introduction

- **ESA considered $m = 0.2 - 1.25$ rad/peak**, that are the maximum allowable by ESA standards,
- These modulation indexes provide a full range of suppression levels and avoids special and unpractical cases as $m = 0$ and $m = \pi/2$ rad/peak.

m	$Carrier\ Supp.\,[\mathrm{dB}]$	$Data\ Supp.\,[\mathrm{dB}]$
0.2	-0.17	-14
1.25	-10	-0.45

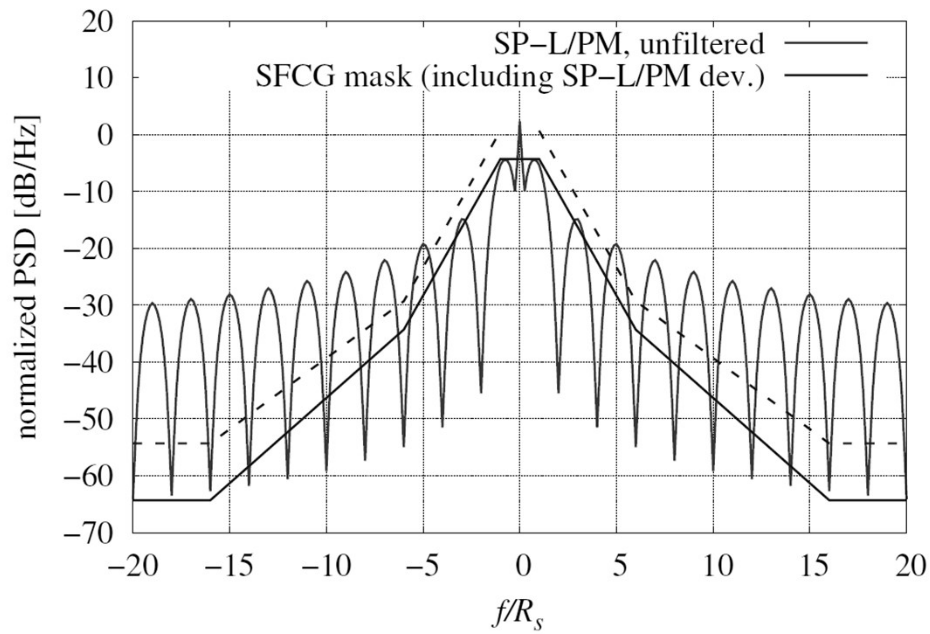
Channel model

- The channel model is AWGN + NL with transmitter 'Option 2' as reported in SLS-RFM_22-02
- filtering is done before PM, that results in a simple digital implementation and the signal is constant envelope (see SLS-RFM_22_10).



- The mask to be met is the SFCG mask in REC 21-2R4,

- SP-L/PM, w/o filtering, does not meet it.



Channel model

- For BER analysis, **a sub-optimal receiver is considered**, that is not aware of the Butterworth filtering.

- Namely, it assumes that the received signal is

$$r(t) = e^{jmx(t)} + w(t)$$

  where

$$x(t) = \sum_{k} a_k p(t - kT),$$

  and $p(\mathrm{t}) = \mathrm{rect}\left(\frac{2\mathrm{t}-\mathrm{T}/2}{\mathrm{T}}\right) - \mathrm{rect}\left(\frac{2\mathrm{t}+\mathrm{T}/2}{\mathrm{T}}\right)$, and $a_k \in \{+1, -1\}$.

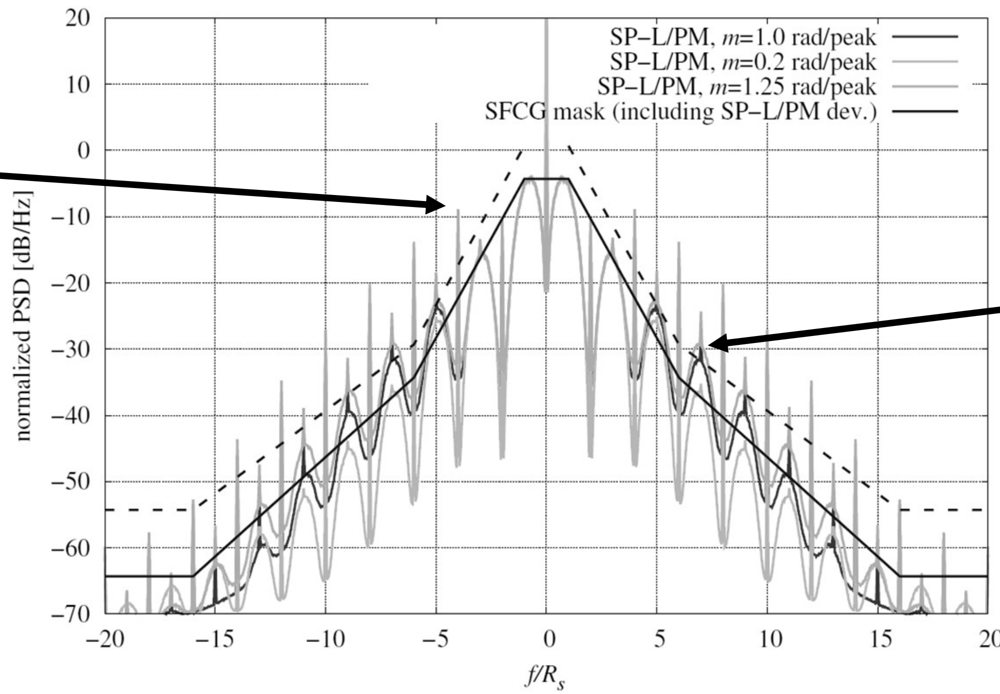
- Thus, the receiver simply takes the imaginary part and applies a filter matched to $p(t)$ without mitigating the distortions caused by the filtering.

Numerical results

Settings:

- Butterworth 3rd order, $f_{cut} = 4$:
- $m = 0.2, 1.0, 1.25$ rad/peak.

Highest spike was found < -20 dBc (compliant to ESA req)



Effect is almost linear but:

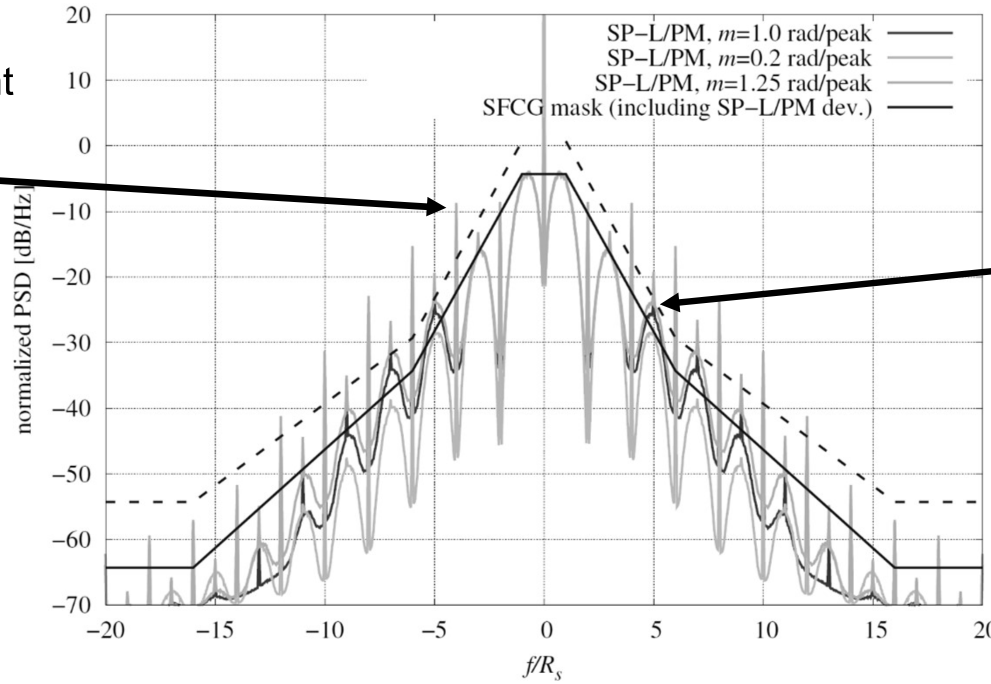
- at high modulation index causes a small NC
- At low modulation index is slightly over-filtered

NOTE: for sake of comparison, PSD spectra were shifted to the same reference level.

Numerical results

- For solving the NC, we checked the following setting:
  - Butterworth 3rd order, $f_{cut} = 3.5R_s$;
  - $m = 0.2, 1.0, 1.25$ rad/peak.

Spikes are still compliant to the ESA -20 dBc requirement



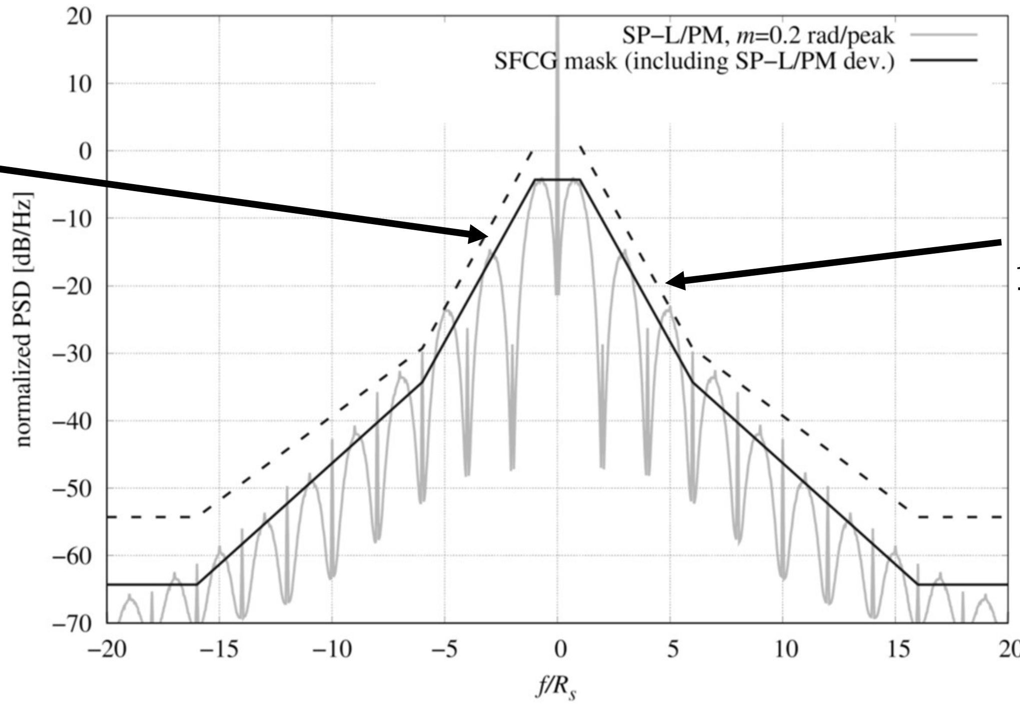
$f_{cut} = 3.5R_s$ is:

- perfect match for the highest modulation index;
- An over-filtering for lower indexes.

Numerical results

- Similarly, for low modulation index, the cut can be relaxed:
  - Butterworth 3rd order, $f_{cut} = 4.5R_s$;
  - $m = 0.2$ rad/peak.

Spikes are still compliant to the -20 dBc with high margin

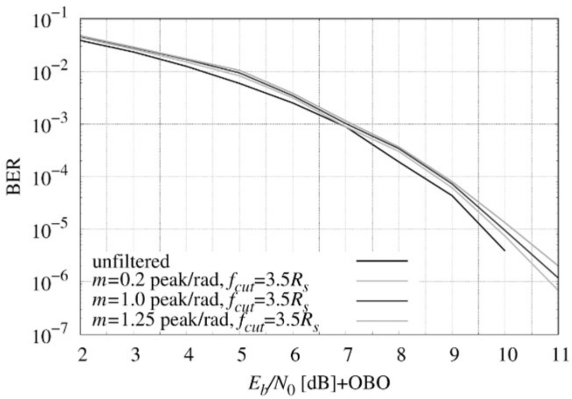


$f_{cut} = 4.5R_s$ is perfect match for the lowest modulation index

Numerical results

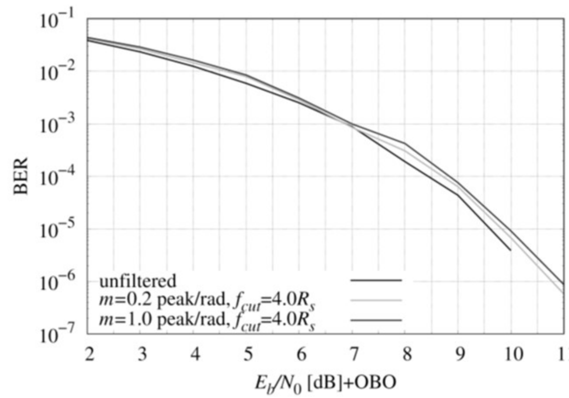
- For all cases that the mask is met, we computed the BER.
- Being the signal constant envelope the non-linearity has not effect: channel is equivalent to AWGN.

$f_{cut} = 3.5R_s$



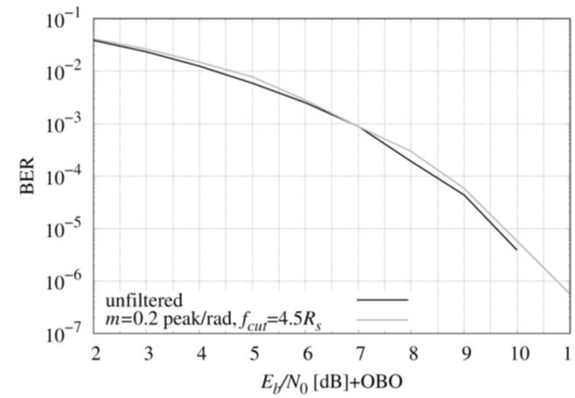
loss @ $10^{-5} \sim 0.3 - 0.5$ dB

$f_{cut} = 4.0R_s$



loss @ $10^{-5} \sim 0.2 - 0.4$ dB

$f_{cut} = 4.5R_s$

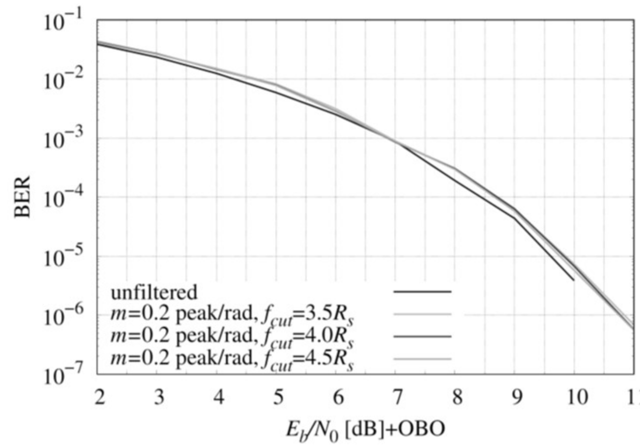


loss @ $10^{-5} \sim 0.2$ dB

NOTE: results are slightly better than previous paper since, for doing a fair modulation index comparison, the m value is adjusted based on the RMS of the signal at the input of the PM (aka, results are reported as effective modulation index).

Numerical results

- By plotting BER results for same modulation index, it was observed that BER is almost constant (~0.1 dB difference) w.r.t. the frequency cut. See example for $m = 0.2$ peak/rad



- In particular, after deep analysis, it was found that the loss is only due to the power loss due to the filtering, unbalancing the total power between carrier/spikes and data. Hence, as seen previously, use of **equalization does not help much**.
- Additionally, low modulation indexes perform slightly better than high modulation indexes. It is believed that this is due to the lower spikes in the spectra.

Conclusions

- For the considered modulation indexes, $m = 0.2 - 1.25$, **the Butterworth filter 3rd order allows to meet the SFCG mask while keeping spikes below -20 dBc**.

- It was shown that:
    - for $m = 0.2$, best is the loosest filtering, $f_{cut} = 4.5R_s$, for not having additional losses;
    - for $m = 1.25$, it is mandatory a strict cut as $f_{cut} = 3.5R_s$, for meeting the mask.

- Two possible strategies for the recommendation:
    1) Recommend a Butterworth 3rd order with $f_{cut} = 3.5 - 4.5R_s$ where the user has to choose the lowest value for modulation indexes as high as 1.25 rad/peak, and the highest value for lower modulation indexes;
    2) Otherwise, to recommend the strictest cut, $f_{cut} = 3.5R_s$ for all cases up to 1.25 rad/peak, but at the price of a small/negligible penalty (~0.1 dB).

- Taking into account that simulations cannot be a catch-all of actual implementations, **ESA preference is to leave some leverage to manufacturers** and go for 1).
- In this way, manufacturers can trade-off the frequency cut taking into account implementation effects for which simulations could be not representative.

Conclusions (cont'd)

- Finally, it was observed by Wing/NASA that the relaxed SFCG mask is applicable only for 300 ksps. Meeting the mask for larger symbol rates would require stricter filtering, that could be not convenient for Category A missions (that can usually resort to suppressed carrier modulations)

- In light of the above, See ANNEX with updated white paper and comments to be solved during the Spring 2023 meeting