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EUROPEAN SPACE AGENCY
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SP-L/PM for Space-to-Earth (Category A) applications: ~~guidelines for its filtering~~draft recommendation for including filtering for compliance to SFCG mask

Abstract

This paper provides a methodology for filtering the SP-L/PM waveform, when used for Space-to-Earth links, Category A (Near Earth), with the objective of meeting the spectral mask required by SFCG (while limiting losses).
The rationale behind is to define a guideline for transmitter manufacturers, to be eventually published as a CCSDS standard (e.g., in a RFM Green Book).

The paper was presented the first time at CCSDS Spring meeting 2022. This version of the paper, for Fall 2022, is the updated version with track changes, for implementing the AI of simulating also a nonlinearity.

1. Introduction

Telemetry systems, using residual carrier modulations, shall resort to NRZ-L when a subcarrier is employed, or to bi-phase-L (known also as SP-L) when there is a direct phase modulation (PM) of the carrier.

The SP-L/PM waveform with symbol rate R_s can be expressed as

$$s(t) = e^{jmx(t)} \tag{1}$$

where m is the modulation index, and $x(t)$ is the SP-L signal, reading

$$x(t) = \sum_k a_k p(t - kT) \tag{2}$$

being $T = 1/R_s$ the symbol time, and $p(t)$ a bi-phase shaping pulse.

Its spectrum is composed by a residual carrier having a power fraction equal to $10\log(\cos^2 m)$ dBc w.r.t. the unmodulated carrier, and a modulated part with power fraction equal to $10\log(\sin^2 m)$ dBc. An example is reported in Figure 1, showing the normalized power spectral density (PSD) for an SP-L/PM with modulation index $m = 1.0$ rad/peak.

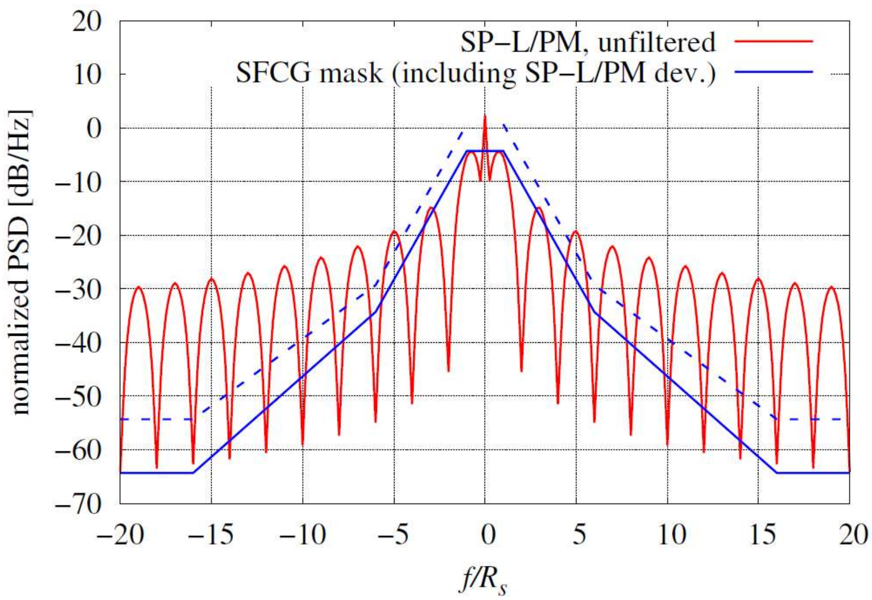

Figure 1: SP-L/PM normalized PSD, $m = 1.0$ *rad/peak, compared with SFCG mask (including the maximum allowed deviation).*

On the other hand, when the SP-L/PM is adopted for Category A Space-to-Earth links, based on SFCG recommendations [RD2], it has also to meet the spectral mask shown in Figure 1 (solid blue line), with a maximum deviation no higher of 5 dB in the slope region, and 10 dB in the plateau region (blue dashed line). As the reader can notice, the standard spectrum of SP-L/PM does not meet such mask. Hence, transmitters shall include a filtering but neither CCSDS nor SFCG provide guidelines how this filtering should be implemented while limiting losses.

In this respect, ESA analyzed this problem by means of numerical simulations. This paper reports the main numerical results and conclusions, for starting the discussion about the possible definition of a CCSDS guideline/standard.

2. Summary of the adopted approach

This section provides a summary of the analyses performed by ESA for defining the kind of filtering to be adopted.

Taking into account that filtering shall not affect the possible presence of a ranging signal (that is usually phase modulated together with the telemetry signal), based on existing transmitter architectures, two possible options were envisaged.

The **first option**, depicted in Figure 2a, foresees that a filter is placed right after the PM modulation of equation (1), for decreasing the magnitude of the spectral side lobes. However, the disadvantage of this option is that the transmitter shall include a dedicated PM for the ranging signal (noted as $r(t)$ in the figure), and complex base-band multiplication, thus increasing the complexity of the digital design.

The **second option** (Figure 2b) is instead to filter the SP-L before the PM. Although this approach is simpler than first option, as shown later, it introduces spectral spikes that should be kept as low as possible. ESA uses as reference ECSS standards, that foresee those spectral spikes in the SP-L/PM signal to be lower than -20 dBc (w.r.t. unmodulated carrier).

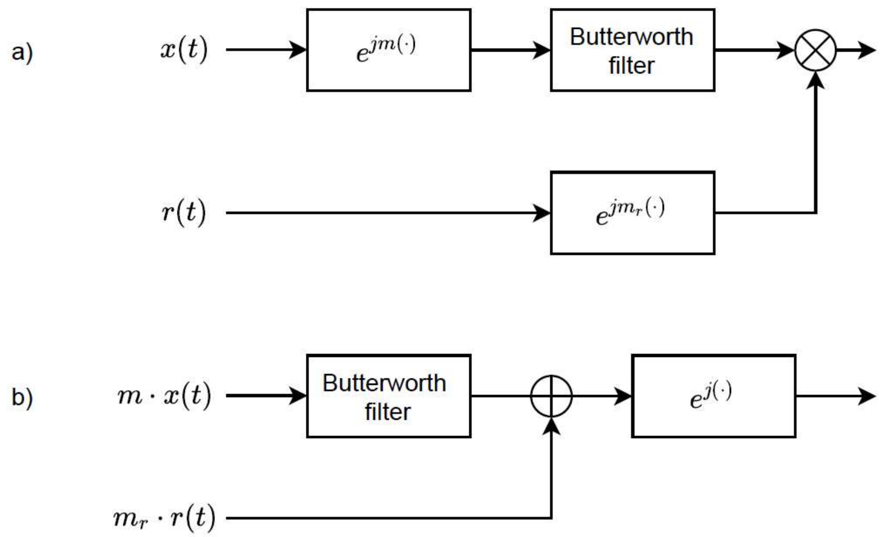

Figure 2: block diagram of the two possible SP-L/PM filtering that can be considered at transmitter, for not affecting the ranging signal.

For both options, an extensive simulation campaign was carried out by choosing different filter design, with the objective to meet the following requirements:

- SP-L/PM to not deviate from SFCG mask more than the limits foreseen by SFCG recommendation [RD2];
- Spectral spikes due to filtering to be lower than -20 dBc (relevant for the second option only);
- SP-L/PM filtered shall have bit error rate over the AWGN channel with loss not higher than 0.8 dB w.r.t. SP-L/PM unfiltered.

As main result, it was found that a **Butterworth filter of the 3rd order**, **with frequency cut $\boldsymbol{f_{cut}} = \mathbf{4.0 - 4.5}\boldsymbol{R_s}$** is a viable solution, and this could be recommended for a possible CCSDS guideline. A summary of the results is provided in the next section.

3. Summary of the numerical results

A Butterworth filter was placed in the transmitting chain as shown in Figure 2, and its frequency cut was gradually increased until it does meet the mask. In this way, we ensured that BER losses (w.r.t. unfiltered case) are minimized.

Figure 3 shows the normalized PSD for SP-L/PM with filtering after PM (first option, as by Figure 2a) by using f_{cut} varying between $3R_s$ to $5R_s$ with step of $0.5R_s$. It was found that $f_{cut} = 4.5R_s$ was the first value meeting the mask, providing the spectrum shown in Figure 4.

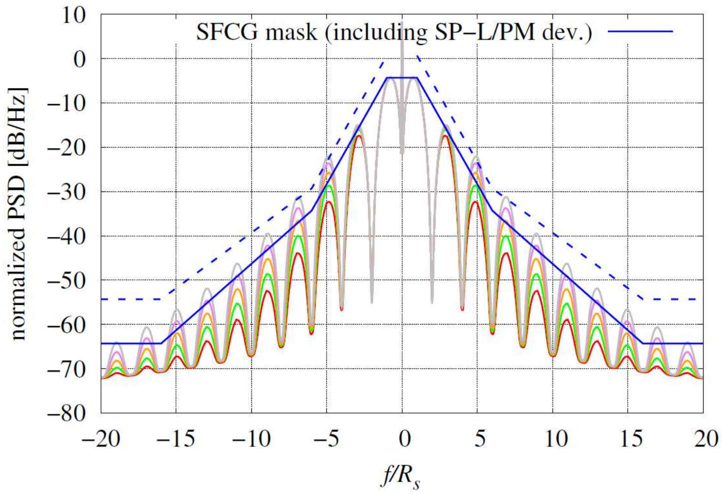

Figure 3: spectra of SP-L/PM m=1.0 rad/peak, for option 1 (filtering after PM), for different values of the frequency cut. The frequency cut 4.5Rs (violet solid line) is the first to meet the mask.

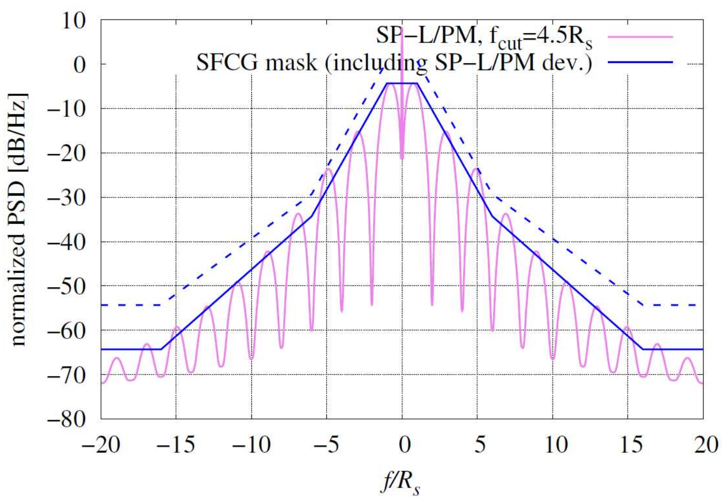

Figure 4: spectrum of SP-L/PM m=1.0 rad/peak, for option 1 (filtering after PM), for fcut=4.5Rs.

Similarly, it was found that $f_{cut} = 4.0R_s$ was the first value meeting the mask when filtering is implemented before the PM (second option, as by Figure 2b). The resulting spectrum is reported in Figure 5.

It can be noticed that the main difference w.r.t. filtering after PM, it is the presence of spikes, that are due to the fact that the SP-L has not anymore a sharp transitions (two square waves) but rather a non-negligible rising/fall time w.r.t. the symbol time.

Nevertheless, the spectrum is compliant to the mask, and the spectral spikes were found lower than -20 dBc. Namely, the PSD figures were plotted for a normalized resolution bandwidth of -15 dB. Hence, the requirement is met if spikes in the figure are below -5 dB/Hz. It can be seen that this holds with very good margins (>10 dB).

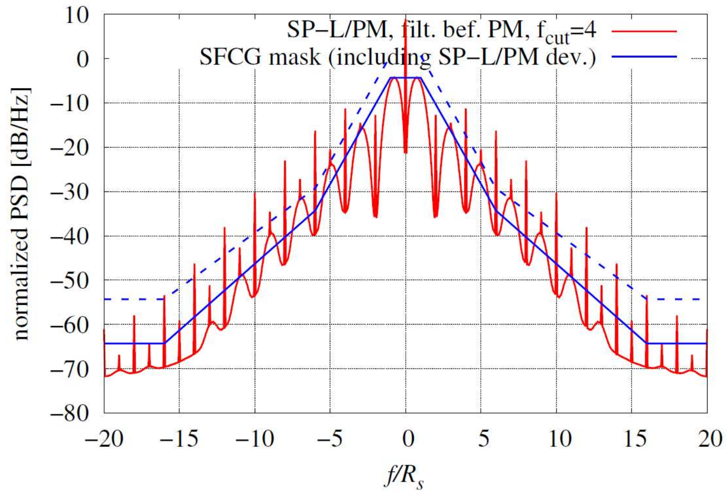

Figure 5: spectrum of SP-L/PM m=1.0 rad/peak, for option 2 (filtering before PM), for fcut=4Rs.

For the two cases we then computed the bit error rate (BER) over the AWGN channel, with a receiver that is not aware of the filtering (i.e., it uses a filter matched to unfiltered SP-L). Figure 6 shows the BER as function of the E_b/N_0 for the two options with the selected f_{cut}. For comparison also the BER for unfiltered SP-L/PM (i.e., ideal BPSK BER curve) is shown. It can be seen that in both cases the loss is about 0.5 dB for BER=1e-5. Hence, we can conclude that the proposed Butterworth filter is able to meet all requirements.

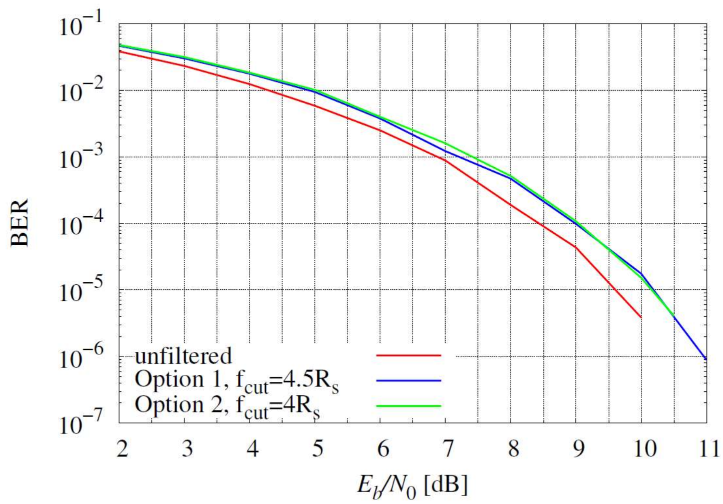

Figure 6: BER curve for the two options (1- filtering after PM, 2-before PM)

4. **Complexity and other filtering**

A 3rd order Butterworth filter can be easily implemented digitally by means of an ARMA filter with 5 poles and 5 zeros. This for instance can be generated in Matlab by using the `fdatools`.

It is finally pointed out that the same methodology was adopted for other filters: Elliptical, one pole, Bessel, Chebyshev, etc., including also Butterworth of other orders. However, the Butterworth of 3rd order was found as the best choice, since it provides a slope similar to the SFCG mask, while keeping the order low.

Figure 7 shows, as example, the spectra when using a One Pole filter, a Bessel of the 4rd order, and the Butterworth of the 3rd order. It can be seen that while the main lobes overlap, the One Pole filter clearly has a rejection not sufficient, while the Bessel requires higher orders as previously mentioned.

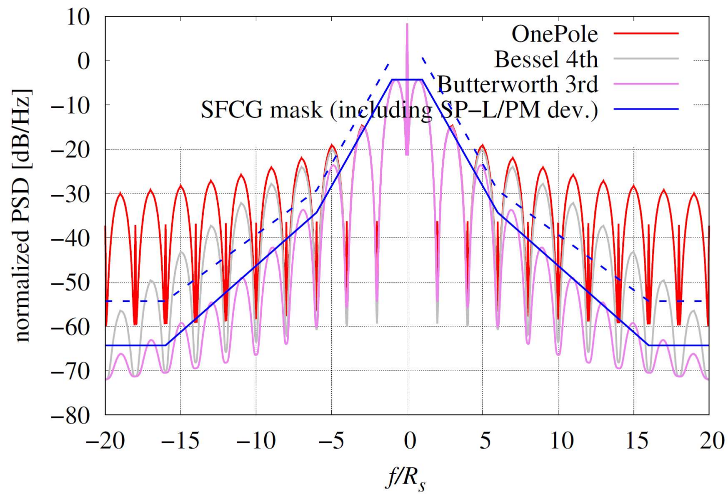

Figure 7: spectrum of SP-L/PM m=1.0 rad/peak for option 12 (filtering after PM), for different kind of filters.

5. Filtering after PM when in presence of nonlinearity

During CCSDS Spring meeting 2022, it was pointed out that in case the TT&C subsystems uses a high-power amplifier, the output signal of option 1 (SP-L/PM with filtering after PM), being non-constant envelope, could be affected by nonlinear distortions and spectral regrowth. Differently, for option 2, the amplifier would cause no impairments.

Thus, for a fair comparison, the analysis was repeated for Option 1 considering the nonlinear scenario in Figure 8, where the nonlinearity is modelled as a TWTA characteristic like the one in the SCCC Green Book [RD3].

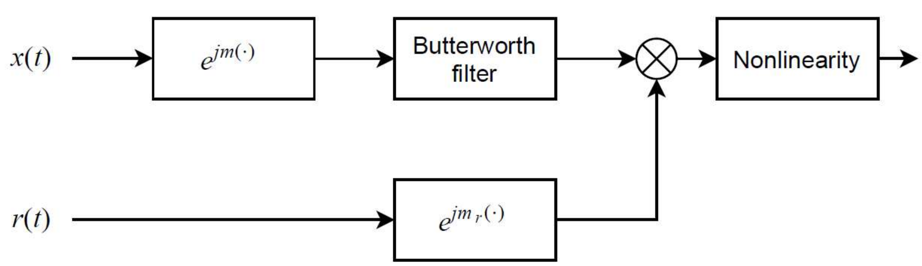

Figure 8: block diagram of the possible SP-L/PM filtering that can be considered at transmitter after PM, for not affecting the ranging signal, and taking into account a nonlinearity.

As first observation, during the simulation campaign, it was found that the spectral re-growth requires performing a joint optimization of the OBO and the Butterworth filter frequency cut, while meeting spectral and BER requirements.
By performing a coarse optimization, it was found that is more convenient to have a stricter Butterworth filter (f_{cut}~$3.0R_s$) while keeping the amplifier close to saturation (OBO < 1 dB). On the other hand, it was found that the nonlinearity re-introduces the spectral spikes as in Option 2.

Figure 9 shows the spectrum and BER for the case of Butterworth 3rd order, with $f_{cut} = 3.0R_s$, with OBO=0.96 dB. For comparison, the BER curves reports also the Option 1 and Option 2 curves, as function of the $\frac{E_b}{N_0} + \text{OBO}$. It can be seen that the spectrum meets the SFCG mask, and spikes are below 20 dBc. On the other hand, the BER loss increases by about 0.5 dB, hence for a total loss of 1.0 dB versus the linear case.

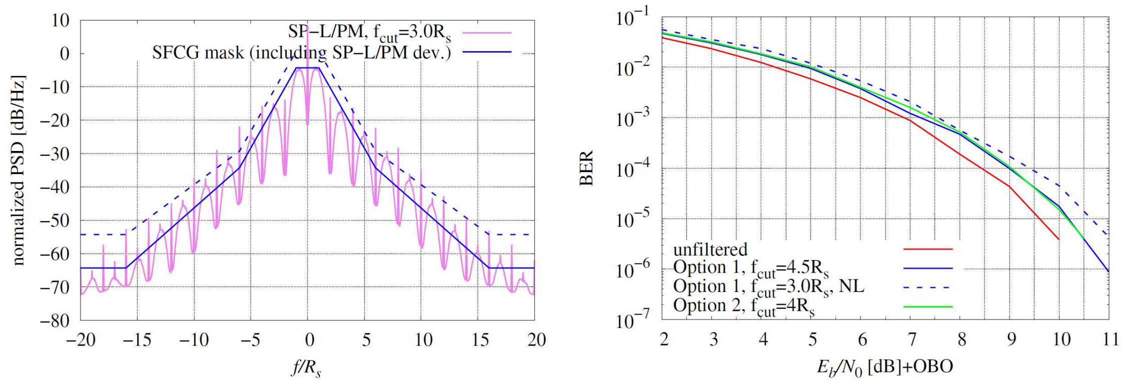

Figure 9: spectrum and BER for option 1 (filtering after PM), in presence of nonlinearity, when $f_{cut} = 3.0R_s$

In light of these results, it can be concluded that in presence of high-power amplifier is easier to simply use a Butterworth filter before PM, while keeping the implementation simple and independent of the amplifier design.

Thus, for a potential update of the related Blue REC, it recommend Option 2 (see Annex).

~~5.~~6. Conclusions

In this paper it was shown that SP-L/PM, as defined in the standards, is not able to meet the SFCG spectral mask.
~~Based on the results here presented, CCSDS RFM working group is invited to consider the possibility of doing a guideline and/or recommendation.~~

Based on the results here presented, CCSDS RFM working is invited to review the proposed changes to REC 401 (2.4.7) in Annex.

~~6.~~7. References

[RD1] CCSDS 401 (2.4.7), Choice of PCM waveforms in residual carrier telemetry systems.
[RD2] SFCG 21-2R4, Efficient spectrum utilization for space research service (Category A) and Earth Exploration-Satellite service on Space-to-Earth links.
[RD3] CCSDS 130.11-G, SCCC – Summary of definition and performance

ANNEX – proposed changes to the recommendation

2.4.7 CHOICE OF PCM WAVEFORMS IN RESIDUAL CARRIER TELEMETRY SYSTEMS

The CCSDS,

considering

a) that NRZ waveforms rely entirely on data transitions for coded symbol clock recovery, and this recovery becomes problematical unless an adequate transition density can be guaranteed;

b) that due to the presence of the mid-bit transitions, bi-phase-L waveforms provide better properties for bridging extended periods of identical coded symbols after initial acquisition;

b)c) that the SFCG has approved a Recommendation[1] specifying a spectrum mask for Category-A Space-to-Earth links operating in certain bands[2].

c)d) that convolutionally encoded data have sufficient data transitions to ensure coded symbol clock recovery in accordance with the CCSDS recommended standards;

d)e) that with coherent PSK subcarrier modulation, it is possible by adequate hardware implementation to bridge extended periods of identical coded symbols even when NRZ waveforms are used;

e)f) that NRZ waveforms without a subcarrier have a non-zero spectral density at the RF carrier;

f)g) that coherent PSK subcarrier modulated by NRZ data and using an integer subcarrier frequency to coded symbol rate ratio, as well as bi-phase-L waveforms, have zero spectral density at the RF carrier;

g)h) that the ambiguity which is peculiar to NRZ-L and bi-phase-L waveforms can be removed by adequate steps;

h)i) that use of NRZ-M and NRZ-S waveforms results in errors occurring in pairs;

i)j) that it is desirable to prevent unnecessary decoder node switching by frame synchronization prior to convolutional decoding (particularly true for concatenated convolutional Reed-Solomon coding);

j)k) that to promote standardization, it is undesirable to increase the number of options unnecessarily, and that for any proposed scheme, those already implemented by space agencies should be considered first;

recommends

(1) that for modulation schemes which use a subcarrier, the subcarrier to coded symbol rate ratio should be an integer;

(2) that in cases where a subcarrier is employed, NRZ-L should be used;

(3) that for direct modulation schemes having a residual carrier, only bi-phase-L waveforms should be used.;

(3)(4) that, to comply with the SFCG Recommendation[1], direct modulation schemes at previous point uses a bi-phase-L waveform filtered with a Butterworth filter of 3rd order, with frequency cut equal to 4 – 4.5 times the coded symbol rate.

(4)(5) that ambiguity resolution should be provided.

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[1] See SFCG recommendation 21-2R4 or latest version.

[2] Category A bands are: 2200-2290 MHz, 8450-8500 MHz, and 25-27.0 GHz.