WIDEBAND MATCHED VOLTERRA MODELING OF HIGH-POWER AMPLIFIERS FOR SATELLITE NAVIGATION AND COMMUNICATION PAYLOADS

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Abstract

The increasing demand in the communication and navigation satellite industry for i) greater throughput, ii) flexibility in terms of signal generation, iii) higher efficiency, iv) improved payload re-configurability, has generated the need to develop more accurate simulation/emulation payload models. Inaccurate modelling of payload elements induces a non-negligible risk of over- or under-designed elements as well as an incorrect prediction of the main KPIs derived from emulation/simulation tools. Therefore, assessing the accuracy of currently used models and possibly developing new, more accurate ones turns out to be an essential feature of new-generation system design tools to derive accurate performance metrics, to enable correct dimensioning of all system features, to better specify budget parameters (in particular equipment specifications), and to efficiently support engineers in payload design.

In this respect, High-Power Amplifiers (HPAs) are very sensitive components within the overall payload architecture, because they are non-linear devices that behave differently depending on the

input signal features such as occupied bandwidth, average power, Peak-to-Average Power Ratio (PAPR), etc..

Extensive measurement and characterization activities on such devices performed in Thales-Alenia Space laboratories on GNSS payloads suggested that the standard narrowband/memoryless model of an HPA (i.e., AM/AM and AM/PM characteristics) is not sufficiently representative to derive accurate results concerning (next generation) GNSS signals featuring bandwidth up to 100 MHz or more, especially in terms of the in-band and out-of-band distortions actually introduced by this element. Such inaccuracy, initially considered insignificant, turned out to be not negligible when the payload simulation model is used to define and optimize the specifications as well the on-board Navigation Signal Generation Unit (NSGU) design.

These conclusions led us to carry out an extensive review of the state of art of wideband HPA models, in particular Wiener, Hammerstein and Volterra one, comparing their accuracy, efficiency and easiness of application to real-world devices.

This analysis focuses on the Volterra model, which is usually considered too complicated and hard to be actually tailored to a specific device. In this study, both the issues were tackled: first, how to match the numerous parameters of the nonlinear model to the wideband Device Under Test (DUT) has been considered. Then, a way to reduce the number of significant parameters to be derived from the measurements activity has been defined, in order to guarantee a computationally manageable effort without sacrificing modelling accuracy.

Starting from the lab characterization of a specific DUT operating in the L band, this paper reports a thorough comparison between the performance of a simplified matched Volterra model and the corresponding (memoryless) narrowband equivalent (with measured AM/AM and AM/PM curves). The following metrics were considered to perform the comparison:

- Normalized Mean Square Error (NMSE), both in time and frequency domain, between the simulated HPA output and the result of the measurements after digitization of the corresponding signal at DUT output.

- Power Spectral Density (PSD) deviation, in particular the spectral regrowth, between the simulated signal and the DUT output.

The results obtained exhibit a remarkable agreement between the wideband model and the results measured on the DUT, as well as a remarkable improvement of the performance metrics of the matched Volterra wideband model as compared to those of the standard narrowband algorithm, with a manageable additional complexity.

Introduction

The pursuit of more and more accurate components models, arises from the need to predict the behavior of each payload element, in order to correctly select the pillars requirements of the system design.

In Navigation payload the elements which require greater modeling effort are the HPA amplifiers, in particular SSPAs, as non-linear systems, they are characterized by gain compression and saturation. Traditionally, to characterize these devises the narrowband modelling was selected due to its simplicity, as a result of decoupling memory effects from the nonlinearities However, this kind of approximation cannot model the frequency dependent distortion of the HPAs.

The nonlinearities are very difficult to be modelled, hence several different methods has been proposed, each with its own merits and faults.

In the GNSS domain the increasing demand for flexible P/L in terms of modulation, number of components, power sharing, occupied bandwidth and EIRP has led to the need for a more accurate study of nonlinear component; in particular the increasing bandwidth of the transmitted signal leads

memoryless models no longer being representative of the HPA behavior, moreover having a linear combination of different input components and arbitrary modulations leads to a signal no longer with constant envelope and with a probability density of the instantaneous signal strengths extremely variable and with very high dynamics.
An accurate estimation of the behavior of non-linear devices will lead to a more correct evaluation of the P/L and Signal performances and therefore to a more efficient dimensioning of the P/L requirements and of the various sub-systems.
A correct modelling of the amplification section also makes it possible to carry out an appropriate trade-off on the calibration and equalization systems by identifying the best solution in terms of implementation and computational complexity, since the implementation of a non-linear equalizer involves a series of constraints at the digital section level as:

- increased sampling frequency to cope with the spectral regrowth (e.g. N-th order polynomial nonlinearity produces a N-fold increase of the input signal bandwidth)
- the implementation of a more complex equalizer than linear ones.
- appropriate sizing of the feedback loop in the case of real time equalization

In order to properly address this type of problem, the following wideband amplifier models were studied and analyzed:

- Wiener Model
- Hammerstein Model
- 3 Blocks Model
- Volterra Model

Hammerstein model and Wiener model implement a block oriented approach, have a low complexity, but assume that the non-linear components are separable from the dynamics of the system; in particular there is a non-linear static block without memory (implemented through a polynomial function) in cascade with a linear dynamic one (typically a FIR or IIR filter).
The main advantage of the Volterra model lies in its generality, precisely because of its ability to capture memory-effect and non-linearity, while the main disadvantages are:

- the computational complexity, as the number of coefficients increases exponentially as the order of the model increases
- the need to truncate the order in such a way that the model is computationally manageable
- convergence limitations (e.g in case of strong non-linearities as discontinuities)

In the end, it was decided to implement the Volterra model mainly because of its exhaustive signal representation characteristics (as demonstrated by the results), even though it is a complicated model in terms of implementation, and coefficients evaluation.
As this model is mainly used for P/L performances evaluations (via simulation) and for the dimensioning of some components, the computational effort is not a problem, in this case the accuracy and truthfulness of the obtained results is much more important, as the objective is a definition of the P/L requirements.

The Volterra Model

The Volterra series expansion is general modelling approach for non-linear memory systems based on a Taylor series expansion.
The discrete time domain a representation of the Volterra series expansion expansion is [1]:

$$y[n] = h_0 + \sum_{p=1}^{\infty}\left[\sum_{m_1=-\infty}^{\infty}\sum_{m_2=-\infty}^{\infty}\dots\sum_{m_p=-\infty}^{\infty} h_p[m_1, m_2, \dots, m_p]\left(\prod_{l=1}^{p} x[n-m_l]\right)\right] \tag{1}$$

Where $x[n]$ and $y[n]$ are the system input and the output signals respectively, while the sequences $\{h_k[m_1, m_2, \dots, m_k]\}$ are called the k-th order Volterra kernels.
In particular h_0 is a constant term, $h_1[n]$ is a linear filter, while the other terms $h_k[m_1, m_2, \dots, m_k]$ are higher order convolutions.
If we introduce the following term:

$$h_p[x[n]] = \sum_{m_1=-\infty}^{\infty} \sum_{m_2=-\infty}^{\infty} \dots \sum_{m_p=-\infty}^{\infty} h_p[m_1, m_2, \dots, m_p] \left(\prod_{l=1}^{p} x[n - m_l] \right) \quad (2)$$

The Volterra expansion can be written in the following compact form:

$$y[n] = h_0 + \sum_{p=1}^{\infty} h_p[x[n]] \quad (3)$$

A non-linear system with limited order and limited memory can be represented by a truncated form of the series expansion, substituting the series with a sum of a finite number of terms. Hence, by handling the last compact form of Volterra expansion, we obtain:

$$y[n] = h_0 + \sum_{p=1}^{P} \left[\sum_{m_1=0}^{M-1} \sum_{m_2=0}^{M-1} \dots \sum_{m_p=0}^{M-1} h_p[m_1, m_2, \dots, m_p] \left(\prod_{l=1}^{p} x[n - m_l] \right) \right] \quad (4)$$

Where P represents the order of the truncated Volterra series expansion and $M-1$ the memory dimension.
In this scenario the computational cost of the Volterra model is $O(M^P)$ [1] (the truncated expansion of the output signal is a sum of products).

In communication or navigation systems, the input and the output are in general modulated signals, but even in this case it is possible to derive a suitable formulation of the Volterra series for the signals complex envelope.
Assuming that the amplifier radiofrequency input and output signal are

- $x(t) = Re[\tilde{x}(t)e^{j\omega_0 t}]$
- $y(t) = Re[\tilde{y}(t)e^{j\omega_0 t}]$

Where

- $\omega_0 = 2\pi f_0$ is the pulsation and f_0 is the carrier frequency
- $\tilde{x}(t); \tilde{y}(t)$ are the complex envelope of the modulated input and output signals respectively.

A matched Volterra model for a discrete-time complex baseband signals can be expressed as [2]:

$$\tilde{y}(n) = \sum_{\substack{p=1 \\ p-odd}}^{P} \left[\sum_{m_1=0}^{M-1} \sum_{m_2=m_1}^{M-1} \dots \sum_{m_{\frac{p+1}{2}}=m_{\frac{p-1}{2}}}^{M-1} \dots \sum_{m_{\frac{p+3}{2}}=0}^{M-1} \dots \sum_{m_p=m_{p-1}}^{M-1} \tilde{h}_p(m_1, \dots, m_p) \prod_{i=1}^{(p+1)/2} \tilde{x}(n - m_i) \prod_{j=(p+3)/2}^{p} \tilde{x}^*(n - m_j) \right]. \quad (5)$$

Where:

- the first summation is restricted to odd values of p
- (.)* indicates the complex conjugate operator
- even orders have been removed
- P is the order
- M is the memory

This model obviously has some challenges as it is not easy to extract kernels from the input and output signals, moreover many kernels are needed to obtain an adequate approximation of the complete series. In addition, the truncation of the series may not be sufficient to fully represent the system, as in some cases crucial terms are excluded to approximate the non-linearity effect of the HPA.

Volterra Series kernel Identification

The Matched Volterra series model parameter identification is a process to find the Volterra kernels using the input and the output data samples. In case of an equivalent baseband system, we assume $\tilde{x}(n)$ and $\tilde{y}(n)$ as the complex envelope of the input and output signals, respectively.

It is possible to express the Volterra equations in matrix form and assuming that the process starts from time n and a set of sampling data of length L is obtained, the input matrix and output vector of the system are [4]

$$\boldsymbol{X} = [X(n), X(n+1), \dots, X(n+L-1)]^T \tag{6}$$

$$\boldsymbol{Y} = [\tilde{y}(n), \tilde{y}(n+1), \dots, \tilde{y}(n+L-1)]^T \tag{7}$$

Where:

$$\begin{aligned} X(n) = [&\tilde{x}(n), \dots, \tilde{x}(n-M+1), |\tilde{x}(n)|^2 \tilde{x}(n), \tilde{x}(n)^2 \tilde{x}^*(n-1), \dots, \\ &|\tilde{x}(n)|^{P-1} \tilde{x}(n), \dots, |\tilde{x}(n-M+1)|^{P-1} \tilde{x}(n-M+1)]. \end{aligned} \tag{8}$$

The kernel vector $\boldsymbol{H}$ is defined as

$$\begin{aligned} \boldsymbol{H} = [&\tilde{h}_1(0), \dots, \tilde{h}_1(M-1), \tilde{h}_3(0,0,0), \dots, \tilde{h}_3(M-1, M-1, M-1), \dots, \\ &\tilde{h}_P(0, \dots, 0,0), \tilde{h}_P(0, \dots, 0,1) \dots, \tilde{h}_P(M-1, \dots, M-1, M-1)]. \end{aligned} \tag{9}$$

Finally the Volterra model (Equation (5)), can be written in matrix form as

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{H} \tag{10}$$

It can be used the least square method to solve this pure overdetermined problem. Hence, the estimated kernel vector $\widehat{\boldsymbol{H}}$ is

$$\widehat{\boldsymbol{H}} = (\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}'\boldsymbol{Y} \tag{11}$$

After the training phase, the modelled output signal can be determined through the employment of the previously calculated Volterra kernels:

$$\widehat{\boldsymbol{Y}} = \boldsymbol{X}\widehat{\boldsymbol{H}}. \tag{12}$$

Performance Results

Performance Metrics

Three different performance metrics were used to evaluate the goodness of the model implemented, in particular for navigation signals.
In particular, two of them can be classified as quantitative metrics because we derive the Normalized Mean Square Error (NMSE) parameter both in time and in frequency domain. The third metric is related to the spectrum comparison between the HPA real output signal and the Volterra model output. For the last metric, the Periodogram method is used to compute Power Spectral Densities of real output signal and the modelled one.

The NMSE in time domain [5] is defined as:

$$NMSE_{TD} = 10 \log_{10} \left(\frac{\varepsilon}{\sum_{n=1}^{L} |y_{meas}(n)|^2} \right). \tag{13}$$

Where:

1. ε is the sum square error between the measured $y_{meas}(n)$ and the output model $y_{model}(n)$ signal

$$\varepsilon = \sum_{n=1}^{L} |y_{meas}(n) - y_{model}(n)|^2$$

The frequency domain $NMSE_{FD}$ is the ratio between the error signal power and the estimated output signal over a specified bandwidth. The $NMSE_{FD}$, is expressed in dB, and is given by:

$$NMSE_{FD} = 10\log_{10}\left(\frac{\int_{f=f_{start}}^{f=f_{stop}}|E(f)|^2 df}{\int_{f=f_{start}}^{f=f_{stop}}|Y_{meas}(f)|^2 df}\right). \quad (14)$$

The $Y_{meas}(f)$ represents the Fourier Transform of the sequence $y_{meas}(n)$, while $E(f)$ is defined as the Fourier Transform of the error signal $e(n)$.
The Equation (14) refers to analogue signals instead of numerical for ease of handling. Typically, the frequency domain NMSE metric leads to results similar to that of its time domain counterpart. Though it offers an extra degree of freedom for the integration bandwidth and consequently the inclusion/exclusion of specific frequency components.

The last metric used to evaluate the model is the spectral comparison (evaluated through the Periodogram method), that is a qualitative metric because we evaluate only the matching between the measured signal spectrum and the modelled output signal spectrum.
An important aspect to consider is how the model emulates the real output signal in band and outside the band. The spectral regrowth emulation of the signal model represents surely the most important goal and it can be used to measure the accuracy of the model.

Model validation Setup

Figure 1 shows the HPA modelling validation approach; the aim of this activity is to compare the measured output GNSS signal with that coming from different HPA models (Narrowband and Wideband) considering the same input signal.
Figure 2 shows the measurement setup; in particular, the Keysight AWG M8195A was used for signal generation, while a Keysight M9703B multi-channel digitizer was used for signal recording.
The amplifier that has been characterised is Exodus Advanced Communication AMP-1020 (SSPA with frequency range 800-3000 MHz).

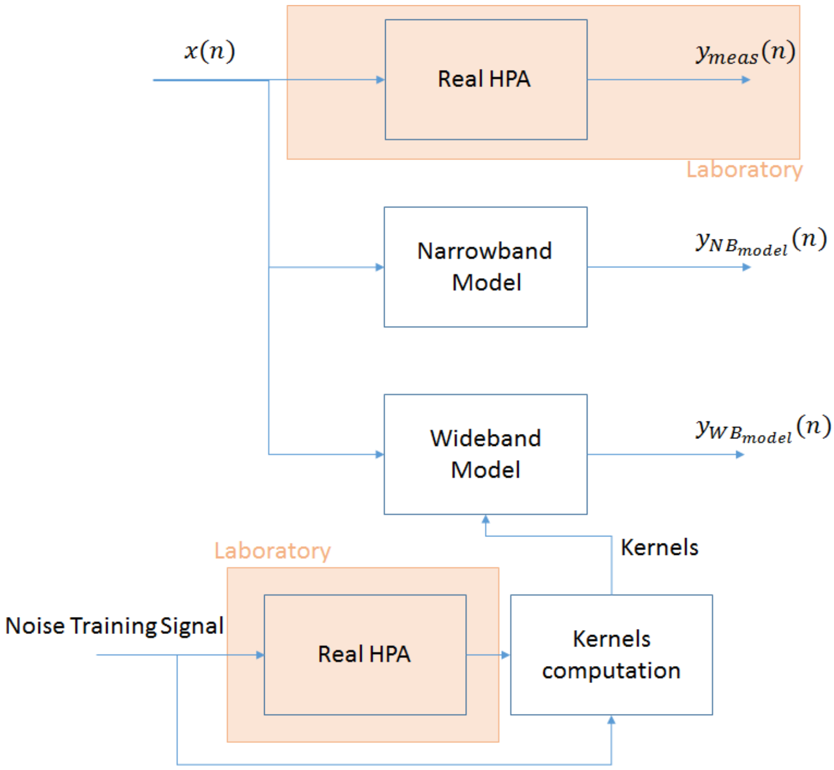


Figure 1 - Model Validation Block diagram

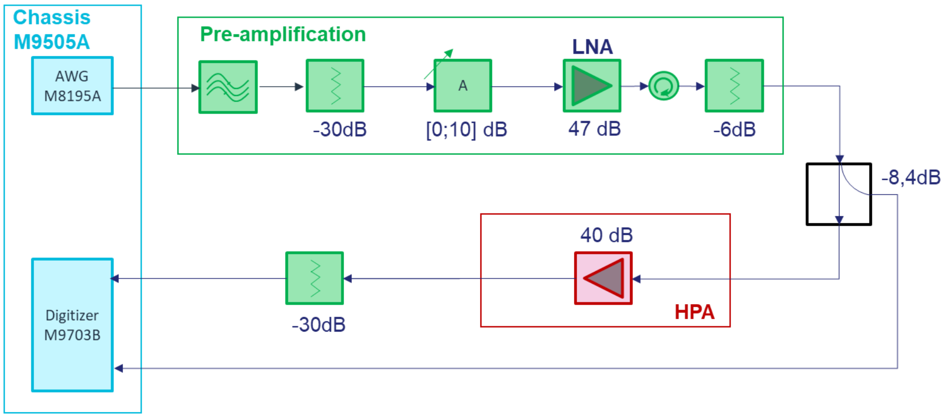


Figure 2 –Measure Setup

In order to create a generic model for the HPA (therefore suitable for different modulations combination) it is necessary to select a specific training input signal, that in our case a filtered AWGN signal with a useful bandwidth equal to that of the modulated signal (25 MHz for E1 and 80 MHz for E5+E6).

Then, Volterra kernels are computed by applying equation (11), where $\boldsymbol{X}$ matrix is computed by using the noisy training signal and $\boldsymbol{Y}$ is the output of the real HPA, when the training signal is applied as input.
The training data is composed by concatenating multiple noisy signals recoded ad different output back-off (OBO).
Finally, considering the pre-computed kernels, it is possible to derive the wideband model output for a generic GNSS input signal.
In order to have a more complete comparison and to evaluate more thoroughly the goodness of the implemented model, the results of the Volterra model were also derived by considering the kernels calculated from the modulated signal of interest (e.g. GNSS signal complex envelope).

Analysis Results

Results have been achieved for GNSS signals both in case of E1 (constant envelope) and E5+E6 (non-constant envelope) signals for two different Output Back-Off (OBO): 1 dB and 3 dB.
The figures are structured in a specific way in accordance to the performance metrics explained above.
For Each Signal and OBO value the following results are provided:

1. a figure showing a comparison in term of power spectral density between:
    - the narrowband model output
    - the Volterra model output with kernel computed on the modulated signal
    - the Volterra model output with kernel computed on filtered AWGN signal (BW equal to the modulated signal one)
    - the measured output data

2. the frequency domain NMSE trend (between measured and modelled signal) varying the integration band

3. NMSE summary table (including the NMSE time domain) for better comprehension.

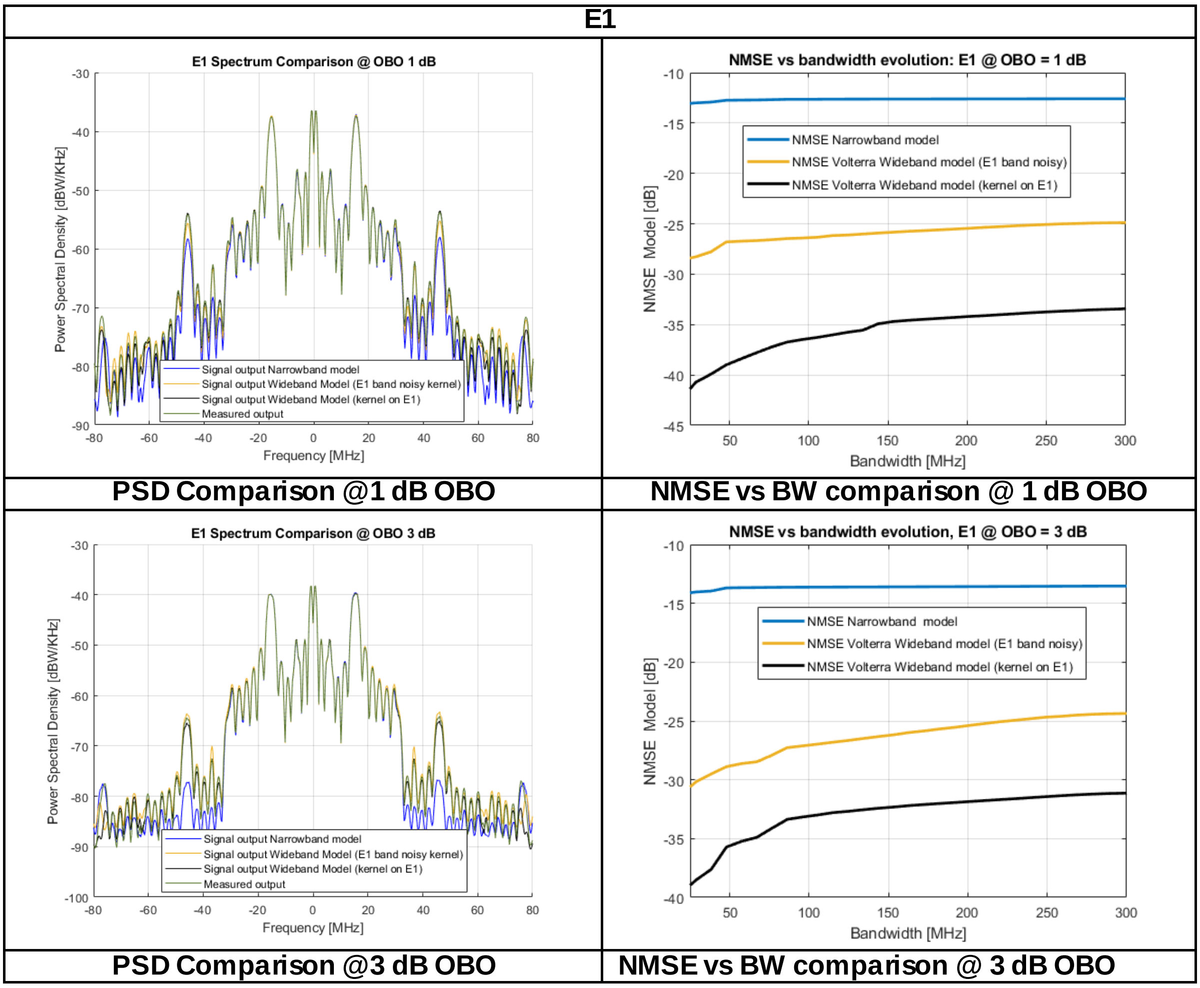
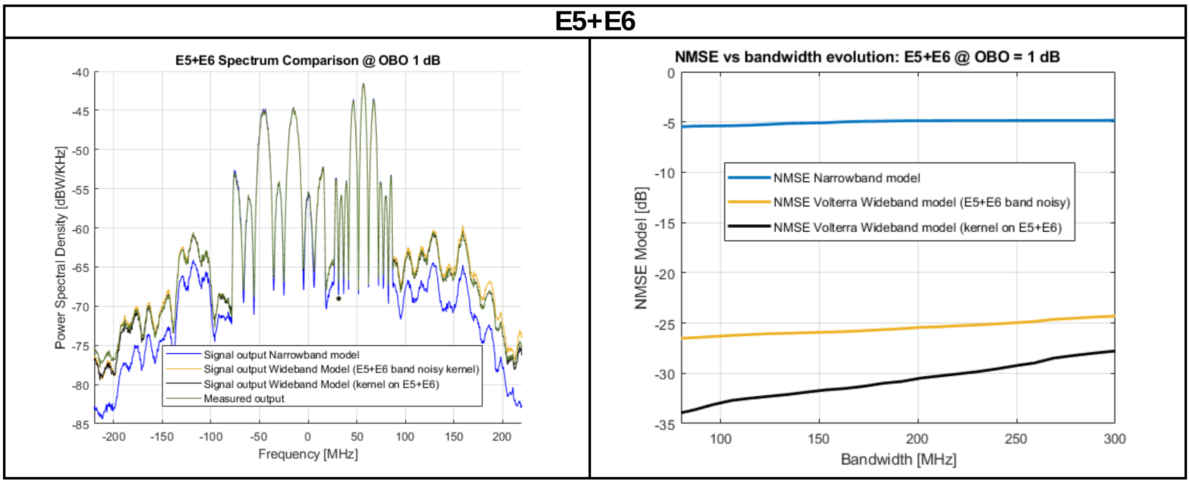


Figure 3 –E1 PSD and NMSE vs BW

NMSE [dB]						
E1	Volterra, E1 kernel		Volterra AWGN filtered Kernel		Narrowband Model	
OBO [dB]	Signal BW	Full Band (t domain)	Signal BW	Full Band (t domain)	Signal BW	Full Band (t domain)
1	-41	-33.5	-28	-25	-13	-12.6
3	-39	-31.5	-30	24.2	-14	-13.6

Table 1 E1 NMSE results



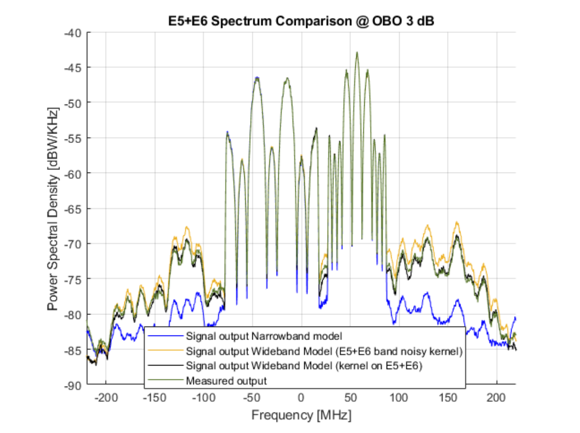
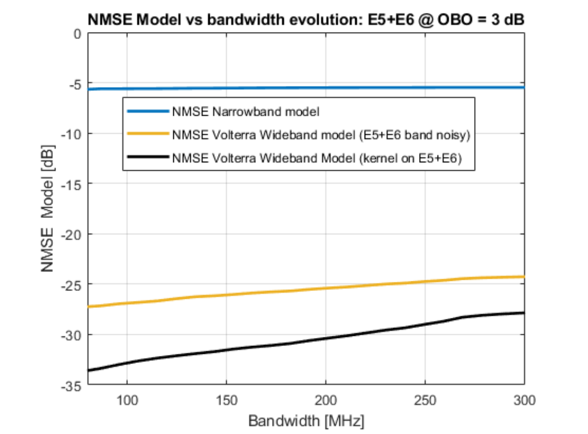
PSD Comparison @1 dB OBO	NMSE vs BW comparison @ 1 dB OBO
	
PSD Comparison @3 dB OBO	NMSE vs BW comparison @ 3 dB OBO

Figure 4 –E5+E6 PSD and NMSE vs BW

NMSE [dB]						
E5+E6	Volterra, E5+E6 kernel		Volterra AWGN filtered Kernel		Narrowband Model	
OBO [dB]	Signal BW	Full Band (t domain)	Signal BW	Full Band (t domain)	Signal BW	Full Band (t domain)
1	-34	-28	-26.5	-24	-5.5	-4.8
3	-33.6	-27.5	-27	-24.3	-5.7	-5.4

Table 2 E5+E6 NMSE results

From the results obtained, it can be seen that the narrowband model is always the worst in all cases analyzed; the model of Volterra with kernels calculated on the same modulated signal obviously has the best performance, but also the results obtained with kernels calculated with AWGN filtered signal are very good as they do not differ much from the previous ones and have an improvement in terms of NMSE compared to the narrowband model of 15-20 dB.
As expected, the narrowband model shows better results for constant envelope signals (E1), whereas it obviously shows worse results in the case of the composite signal E5+E6, which is not only no longer constant envelope but also has a much higher bandwidth.

Observing the Power Spectral Density in the Near Out of Band zone it could be noticed that the Volterra model with signal kernel is the best in following the measured data (0.1 dB error), the Volterra model with filtered AWGN kernel presents a slightly higher maximum error (1 dB), while the narrowband model presents errors up to 10 dB; in particular for E5+E6 signal, the narrowband model could lead to an inaccurate estimation of the amplifier spectral regrowth and then to an incorrect sizing of the downstream filter rejection.
It can be concluded that if it is possible to know a priori the characteristics of the transmitted signal, it is certainly more advantageous to calculate the kernels from the same signal (training data), otherwise it is useful to use kernels calculated from the stimulus signal (e.g. noisy signal with the same bandwidth as the useful signal), obtaining a less accurate but more modulation-independent result.

Conclusions

In this article the problem of selecting a broadband HPA model to meet the needs that have recently emerged in GNSS domain was addressed. In particular, the following requirements have recently arisen:

- modulation flexibility
- power sharing flexibility

- EIRP flexibility
- linear multiplexing and therefore non-constant envelope modulation
- greater and more flexible bandwidth of the HPA input signal

After a large study of literature and after several implementations aiming at evaluating pros and cons of the few available techniques, Volterra model has been selected as wideband model.
The most critical aspect of the Volterra model, as already mentioned, is the kernels computation. In particular, the kernels must be such that the resulting model can be considered as generic as possible. Thus, the model obtained can reproduce the output of the amplifier with different types of input signals in terms of bandwidth, amplitude, modulation, etc.
The kernels computation is performed starting from a suitable constructed training signal. In order to obtain a generic model, white noise on a given frequency band was used as the basic signal.

The Volterra model has been evaluated on a constant envelope signal (E1) and on a non-constant envelope, higher bandwidth signal (E5+E6 linear multiplexing). The obtained results are in line with expectations and show a considerable advantage in the use of the Volterra model over the narrowband model w.r.t the new GNSS challenges. Finally, it can be concluded that the Volterra model with kernels computes using AWGN signals performs very well, obtaining a less accurate but more modulation-independent result w.r.t. Volterra model with kernel computed directly on the desired modulated signal.

At the moment the Kernels identification is done by means of a matrix operations, so possible related problems have to be taken into account; in the future it might be interesting to solve the same problem using an iterative parameter estimation, e.g. the gradient algorithm.
The Volterra model is also valid for TLC signals; however, for the series to converge, it is necessary to consider the characteristics of the signal under examination and the non-linearities introduced by the system on the signal, since the Volterra model presents considerable convergence problems in the presence of strong non-linearities.
In the near future it might be interesting to evaluate the GNSS P/L performances by considering the implementation of a non-linear equalizer based on the Volterra model (or a simplified version), and evaluate the pros and cons compared to a linear equalizer, or a constant envelope generation (CEM) system.

References

[1] P. Jantunen, “Modelling of Nonlinear Power Amplifiers for Wireless Communications”, Helsinki University of Technology Department of Electrical and Communications Engineering, Espoo, Finland (March 5, 2004)

[2] O. P. Nandi, “Behavioral Modeling of Power Amplifier with Memory Effect and Linearization Using Digital Pre Distortion”, University of Gavle, Faculty of Engineering and sustainable development (September 2016)

[3] H. Ku and J. S. Kenney, “Behavioral Modeling of Nonlinear RF Power Amplifiers Considering Memory Effects”, IEEE Transactions on Microwave Theory and Techniques, Vol. 51, No. 12 (December 2003)

[4] D. Su, S. Xie, F. Dai, Y. Liu and Y. Jia, “Theory and Methods of Quantification Design on System-Level Electromagnetic Compatibility”, National Defense Industry Press and Springer (2019)

[5] M. Isaksson, “Radio Frequency Power Amplifiers Behavioral Modeling, Parameter-Reduction, and Digital Predistortion”, Doctoral Thesis in Telecommunications, Stockholm, Sweden (2007)