P4COM: ESA Pointing Error Engineering For Telecommunication Missions

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ABSTRACT

The ESA Pointing Error Engineering Handbook (PEEH) – and with it also the Pointing Error Engineering Tool (PEET) - has been used in several ESA space mission studies and projects in the last years and became a well-known and broadly accepted reference in the European space community.

So far, the application was mainly focused to the field of Earth Observation and Science missions where high-accuracy pointing is generally crucial. However, pointing error engineering for new telecommunication missions has become a more complex and time-consuming task due to the new demands as well: accurately specifying performance and pointing knowledge requirements, identifying and characterising the various error contributors is now critical for the success of these missions. As response, ESA initiated a development study in the Advanced Research in Telecommunications Systems (ARTES) programme.

This paper summarizes the results of the study with a focus on the updates of the PEET software and an assessment of the benefits and challenges of applying the PEEH process to selected telecommunication mission study cases – supported by experts from all European telecommunication mission primes as consultants.

1 INTRODUCTION

In 2011 ESA published the ESA Pointing Error Engineering Handbook (PEEH) [1]. In the following years, the Pointing Error Engineering Tool (PEET) has been prototyped and further developed under ESA contracts jointly with the European space industry to support users in applying the elements in the handbook and in the ECSS control performance standard [2].

The objective of pointing error engineering is to enable the rigorous demonstration of whether the system design meets its application requirements. The scope of pointing error engineering covers the engineering cycle of establishing system pointing error requirements, their systematic analysis throughout the design process, and eventually compliance verification.

In terms of specification, analysis and verification, it is necessary to be aware of the whole pointing error engineering cycle. That is, for specification of pointing error requirements relevant analysis and verification methods need to be identified and vice versa. The objective and scope of the PEEH is to provide a framework with clear mathematical elements, methods and a process with guidelines. This shall enable to establish pointing error engineering in any space mission with appropriate tailoring to a specific design phase.

In practice there are well proven analysis methods to determine the pointing error indices of a spacecraft system. The analysis methods fall into one of the following categories:

- Experimental/measured data
- Numerical simulations
- Compiled error budgets

Experimental and thus measured results are usually not available until later phases of a project, in particular for new or modified spacecraft designs, but also for standard hardware components as e.g. a Star Tracker sensor. Different Star Trackers with the same design have different performance characteristics, e.g. due to the manufacturing process. The Star Tracker as a critical component for S/C performance has the dedicated ECSS standard [9], which gives detailed insights in this respect.

Numerical simulations are the usual choice to analyse the spacecraft design in the feasibility, definition and design phase. However, numerical simulations rely on models with parametric uncertainties. Monte-Carlo simulation campaigns (or equivalent analysis approaches) are thus necessary to analyse the parameter space with a large number of simulations. In practice, several design specific Monte-Carlo simulations (or equivalent analysis approaches) are necessary because different spacecraft design disciplines work with different software tooling. That means such an analysis represents results that are a specific contribution of one part of the system to the overall pointing error. Examples are the analyses of micro-vibrations, the pointing error of the attitude control system and thermo-elastic deformations. The pointing error for the entire spacecraft system is thus a compilation of pointing error contributors derived from pointing error sources which are determined in different analyses or just allocated on system level based on experience. The compilation of pointing error budgets is thus the appropriate choice to evaluate the contribution of the different pointing error sources to a pointing budget that is evaluated w.r.t. the specified pointing error index requirements.

The framework of the PEEH is specifically intended to guide the compilation of pointing error budgets. A key benefit of the PEET software in this respect is its capability to compile the budgets with simplified as well as advanced statistical methods, i.e. probability density estimation, frequency domain characteristics and cross-correlation information of error sources. No commercial tool is available to compile error budgets with such advanced methods on satellite system level. Moreover, “classical” budget assessments via spreadsheet processing do not and cannot implement such methods sufficiently accurate.

Recently, also missions in the telecommunication sector have to increasingly cope with stringent pointing requirements – e.g. for hosted payload concepts or communication via inter-satellite links. However, the application of the PEEH was mainly focused on Earth Observation and Science missions in the past which was one main reason initiating the P4COM study in the ARTES AT programme.

So far, telecommunication missions mainly apply standardized heritage approaches for performance budgeting based on a classification of budget contributions into different frequency classes (bias, short-term, daily and seasonal errors) and more simplified computation rules within and over the different error classes.

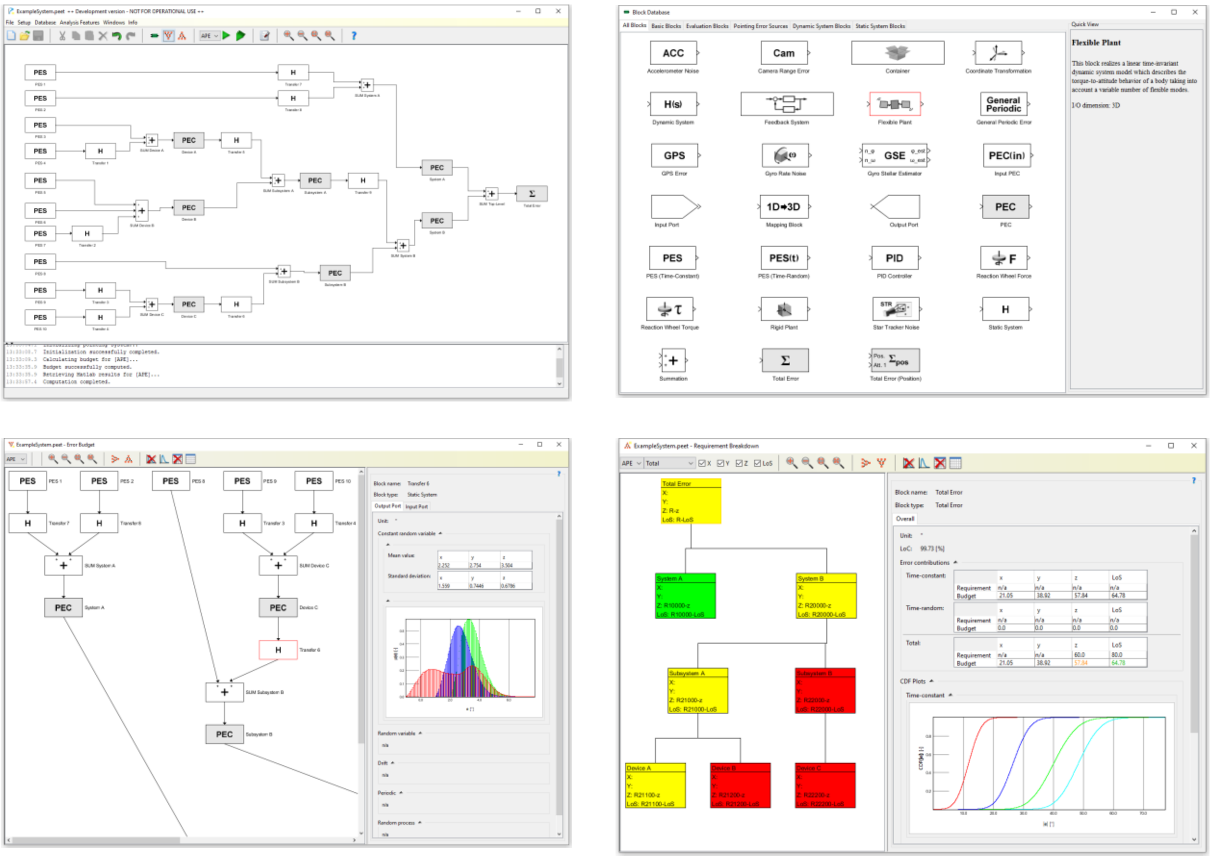
Implementing the PEEH methodology (and realizing its application using PEET) on telecommunication missions requires an initial effort and learning curve as heritage processes for pointing error engineering and budgeting are already in place. However, this is considered as one-time investment. In the long term the benefits of a more efficient design and development process will produce a significant return on invest.

This paper focuses on two main outcomes of the study. The first part of this paper describes the realized extension of the PEET software – both from a general application perspective and with a focus on specific features for telecommunication missions. The second part covers the assessment of the benefits and challenges of applying the PEEH process and PEET to selected telecommunication mission study cases.

2 PEET SOFTWARE EXTENSION

2.1 Baseline

Details on the current PEET software with respect to its implementation background, its evolution and applications are already described in previous publications [3]-[5] or online [6]. Thus, only a brief overview is provided here.



```
13:33:08.7  Initialization successfully completed.
13:33:09.3  Calculating budget for [APE]...
13:33:35.9  Budget successfully computed.
13:33:35.9  Retrieving Matlab results for [APE]...
13:33:57.4  Computation completed.
```

Figure 1. System Editor (top-left), Block Database (top-right), Budget Tree View (bottom-left) and Breakdown Tree View (bottom-right) of PEET

PEET runs inside the MATLAB environment and provides a graphical user interface whose main elements are shown in Figure 1. The Block Database contains building blocks to populate and set up a tree-like budget route in the System Editor from pointing error sources (PES) to pointing error contributors (PEC) on different levels where requirements are specified. All PES model and requirement parameters are in line with the classification and definitions in the PEEH. The budget evaluation follows the methodology and rules described therein using a semi-analytical approach (i.e. combining sample-based and frequency-domain methods).

Budget results are presented in dedicated tree views. The Budget Tree provides auxiliary statistical information on the error signal for each block (and separately for each PEEH error signal class), namely its mean value, standard deviation and the probability density function (PDF) evaluated for the PEEH pointing error index (absolute performance error, mean performance error, etc.) associated to the requirement. The Breakdown Tree shows the requirement breakdown structure composed of all PEC blocks. It provides the budget values computed from the cumulative distribution function (CDF) of the absolute value of the error signals which is evaluated with respect to the level of confidence given by the requirement. If requirement values are specified as well, the compliance with the requirement is highlighted using a color-scheme. Budget results can be exported to spreadsheets in ‘classical’ tabular format.

2.2 Identification of Needs

The identification of features to be considered in the tool update was mainly based on results of a survey conducted among the existing PEET user community after study kick-off. The aim was to account for actual user needs and thus to ensure the development of an industrial reliable tool in terms of stability, user-friendliness, modelling and reporting functionalities.

Further - as the application of the PEEH and PEET was new in this sector – the tool was complemented with focus on the feedback received from the European telecommunication primes, especially with respect to specific analysis features.

The assessment of the received inputs led to about 30 additional or extended mandatory software requirements (and about the same number of goal requirements with different priorities which in the end could almost entirely be met).

The following sections highlight some of the main updates – both from a general application perspective and for specific analyses for telecommunication missions requested by the consultants.

2.3 Updates for General Application

“User-friendliness”

A significant fraction of requests and feedback from the user survey was less related to a lack of models or the computational background (such as complementing the set of statistical distributions available by a (temporal) truncated Gaussian distribution and a Beta distribution with scaling and offset parameters), but to ‘comfort features’ which simplify the work with the tool and the management and processing of results.

As a consequence, an online-help was introduced which provides context-sensitive help directly from menus and block dialogs. The error messaging system was completely revised to crosscheck all user inputs and to clearly identify incompatible parameters during the initialization. To decrease the computation time for trade-offs and quick-assessments, a ‘fast-mode’ was implemented which allows skipping the computation of auxiliary results or reducing the sample size used to represent statistical data.

Typical image formats are now supported in addition to MATLAB figure files and plots can be automatically generated and saved when computing a budget. Similarly, the configuration options for spreadsheet export have been extended, such that the contained information can be individually adapted. Generated spreadsheets further make use of a unique cell referencing to simplify linking to (and updating) results from external documents.

In addition, helper functions have been (re-)introduced that allow for instance a basic estimation of power spectral densities from time-series data or the generation of time-series data based on the error contributions present at a PEC block.

Script-based execution

One intended use case of PEET is its integration into a “toolchain” with other MATLAB analyses and simulations and to import/export results between different tools. In the current release version of PEET, it was already possible to define MATLAB variables for all kind of block parameters to allow external control and a basic functionality was provided to initialize and execute PEET scenarios using MATLAB commands in the workspace or in scripts. In the scope of the current study, this functionality was transferred from a “backdoor” application for expert users to an option accessible to every user – by providing a detailed documentation and by entirely revising existing interface functions (including many additional support functions) to access and manipulate scenario data without requiring the graphical user interface of PEET.

User-Defined Post-Processing

In the context of PEET, “post-processing” must be understood as any additional analysis operation applied to nominal budget results at any error contribution block (PEC / Total Error), i.e. to the sample vectors of (time-constant, time-random and total) error contributions in PEC coordinates (x, y, z and/or line-of-sight).

Such operation could be, for instance, a conversion of data to another coordinate representation or applying a specific function or complete algorithm to the axes data input (somewhat similar to the ‘MATLAB Function’ blocks in Simulink).

The generic interface implemented for that purpose requires the creation of a MATLAB function m-file which contains the user-defined algorithm. This function supports only a single output argument. However, being realized as cell array, a configurable number of outputs can effectively be realized which can be accessed from the MATLAB workspace after the scenario is evaluated.

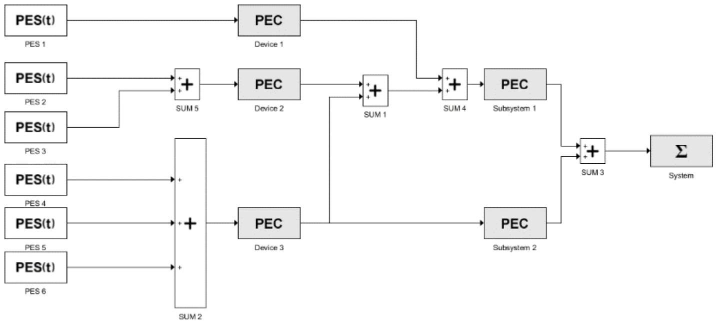
Results can further be automatically displayed in the graphical user interface and/or included in Excel reports in tabular format or as plot (using reserved field names in the function output structure).

This feature is considered as one enabler for analysis of any kind of performance figure which go beyond the scope of the PEEH. It further augments the point of PEET effectively being a general performance assessment tool which is not restricted to pointing applications.

Driver identification

Being able to identify the driving contribution to a (sub-)system level budget provides crucial information for the pointing error engineering process, especially when little margin is present or a requirement is even violated. The identification of such contribution as such is straightforward, but it is more difficult to keep track of the information in larger, complex budgets – in particular when the error sources or subsystem contributions are represented by different physical units which first undergo several transfer analysis steps before being summed up on a common level.

To support this task, analysis options have been introduced in the tool that provide the contribution of each single error source to each PEC block and the contribution of each lower-level PEC to each higher-level PEC in the budget hierarchy. The contribution is provided as percentage computed from the ratio of the budget values obtained with each single error source (or lower-level PEC) alone to the budget values with all sources present – individually for time-constant, time-random and total error contributions and all axes. The overview is presented in tabular form in generated spreadsheets (see Figure 2) and in the graphical user interface using the information panel of each block. It has to be noted that due the statistical nature of the sources (e.g. due to correlation, different signs, etc.), the overall percentage of all contributors to one PEC do usually not add up to 100%, but the relative magnitude of the percentage values allows a qualitative comparison in any case.



PES	Domain	Component	Device 1				Device 2				Device 3				Subsystem 1				Subsystem 2				System			
			x	y	z	LOS	x	y	z	LOS	x	y	z	LOS	x	y	z	LOS	x	y	z	LOS	x	y	z	LOS
PES 1	overall	Time-Constant	100	100	100	100									22.22	16	30	22.52					14.29	11.11	20.69	15.6
		Time-Random	100	100	100	100									68.16	64.13	61.82	62.9					42.61	40.03	39.49	39.72
		Total	100	100	100	100									51.27	27.66	39.34	32.37					32.44	18.7	26.51	21.93
PES 2	overall	Time-Constant					100	20	20	20					22.22	8	5	6.984					14.29	5.556	3.448	4.837
		Time-Random					100	65.76	24.09	45.3					12.43	17.54	8.446	13.86					7.77	10.95	5.395	8.749
		Total					100	29.47	21.92	27.57					17.74	10.9	6.36	9.293					11.23	7.371	4.286	6.296
PES 3	overall	Time-Constant					0	80	80	80					0	32	20	27.94					0	22.22	13.79	19.35
		Time-Random					0	65.77	96.34	90.65					0	17.54	33.77	27.72					0	10.95	21.58	17.51
		Total					0	78.63	87.7	80.9					0	29.09	25.44	27.27					0	19.67	17.14	18.48
PES 4	overall	Time-Constant									0	54.55	22.22	44.5	0	24	10	19.75	0	54.55	22.22	44.5	0	33.33	13.79	27.36
		Time-Random									31.53	44.31	44.42	44.36	22.74	32.06	30.92	31.44	31.53	44.31	44.42	44.36	28.43	40.02	39.51	39.71
		Total									24.95	51.05	30.94	44.45	16.24	25.96	16.16	22.49	24.95	51.05	30.94	44.45	20.55	35.11	21.78	30.47
PES 5	overall	Time-Constant									40	36.36	66.67	50.74	22.22	16	30	22.52	40	36.36	66.67	50.74	28.57	22.22	41.38	31.2
		Time-Random									94.43	88.7	88.67	88.72	68.1	64.18	61.72	62.89	94.43	88.7	88.67	88.72	85.14	80.11	78.86	79.42
		Total									78.72	54.46	75.21	63.91	51.22	27.7	39.27	32.33	78.72	54.46	75.21	63.91	64.82	37.46	52.92	43.8
PES 6	overall	Time-Constant									60	9.091	11.11	9.95	33.33	4	5	4.417	60	9.091	11.11	9.95	42.86	5.556	6.897	6.118
		Time-Random									8.616	12.13	12.14	11.52	6.213	8.773	8.448	8.168	8.616	12.13	12.14	11.52	7.768	10.95	10.79	10.32
		Total									28.8	10.72	12.19	10.83	18.74	5.451	6.362	5.477	28.8	10.72	12.19	10.83	23.72	7.373	8.575	7.422

Figure 2. Example scenario structure (top) and contribution analysis results (bottom)

Frequency-Domain Models and Analysis

PEET implements all frequency domain metrics for time-windowed pointing errors defined in the PEEH which allow an accurate determination of error index contributions for sources which are modelled in the frequency domain (e.g. as power spectral densities (PSD)).

As meanwhile further publications exist on the topic ([7],[8]) and relative performance errors (RPE) have relevance also for telecommunication missions, an assessment of a further RPE decomposition was carried out. Decomposition refers to breaking down the RPE error into unambiguous metrics as started in [8] and extended in the PEEH update performed during P4COM.

This concluded in the definition of additional metrics - e.g. Windowed Performance Drift (WPD) describing the linear 'smear' within a time-window or Windowed Performance Residual (WPR) describing the zero-mean jitter contribution (see Figure 3).

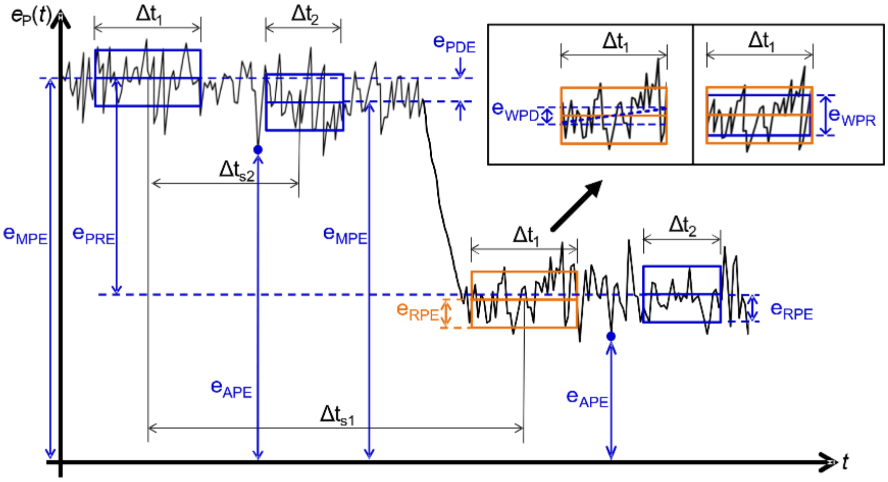


Figure 3. Instantaneous time pointing error indices with RPE decomposition

All metrics currently present in PEEH are defined on 'power-level' which makes them directly applicable to PSDs. As these metrics do not account for phase information required for a more detailed processing of periodic signals as well, equivalent metrics on signal level have been derived and implemented. This enables a description and evaluation of selected 'transient' signals, e.g. exponentially decay or exponentially decaying sinusoids as illustrated in Figure 4.
All findings mentioned above are also proposed to be included in the next update of the PEEH.

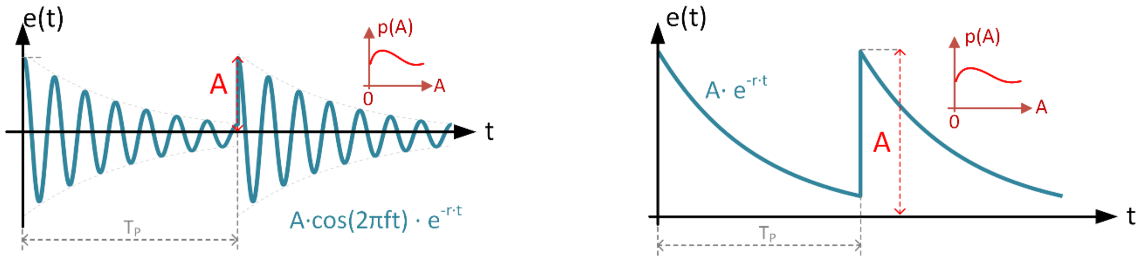


Figure 4. Exemplary periodically occurring 'transient' signals with (ensemble-)distributed amplitude A

2.4 Specific Features for Telecommunication Mission Budgets

Beam Pointing Error (BPE) Analysis

This analysis is applicable to telecommunication missions where a BPE with respect to a given reference latitude/longitude on Earth is of interest. The model behind assumes a geostationary orbit and a reference coordinate frame where the x/y/z axes correspond to roll/pitch/yaw respectively.
Under these assumptions, first the coupling coefficients of the yaw movement to North/South (K_{NS}) and East/West (K_{EW}) directions (see Figure 5) are determined:

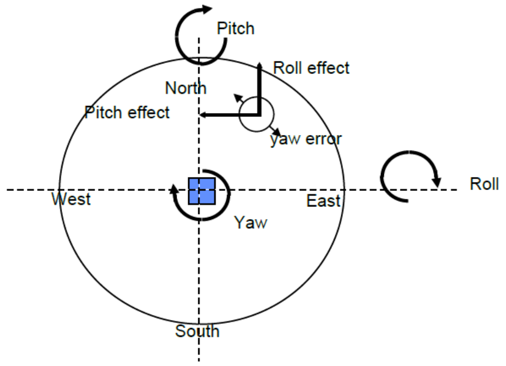


Figure 5. Yaw coupling effect

$$K_{NS} = \sqrt{\frac{\left(\cos(l)\sin(L_C - L_S)\right)^2}{\left(\frac{R_0}{R_E}\right)^2 + 2\left(1 - \cos(l)\cos(L_C - L_S)\right)\left(1 + \left(\frac{R_0}{R_E}\right)\right)}} \tag{1}$$

$$K_{EW} = \sqrt{\frac{\sin^2(l)}{\left(\frac{R_0}{R_E}\right)^2 + 2\left(1 - \cos(l)\cos(L_C - L_S)\right)\left(1 + \left(\frac{R_0}{R_E}\right)\right)}} \tag{2}$$

where L_c and l are the longitude and latitude of the reference pointing direction sub-point on Earth, L_s is the satellite longitude, R_e is the equatorial radius of the Earth and R_0 is the distance from the satellite to the sub-satellite point (i.e. 35786 km for a geostationary orbit).

The NS/EW error angles e_{NS} and e_{EW} are computed from the “nominal” x/y/z error angles e_x, e_y and e_z using these coefficients:

$$e_{NS} = \sqrt{e_x^2 + \left(K_{NS} \cdot e_z\right)^2} \tag{3}$$

$$e_{EW} = \sqrt{e_y^2 + \left(K_{EW} \cdot e_z\right)^2} \tag{4}$$

The half-cone beam pointing error e_{BPE} is then computed using the NS/EW angles:

$$e_{BPE} = \sqrt{e_{NS}^2 + e_{EW}^2} \tag{5}$$

The PDFs $p(\mathbf{e}_{NS})$, $p(\mathbf{e}_{EW})$ and $p(\mathbf{e}_{BPE})$ of these angles are obtained by evaluating above expressions for each realization of the error angles and computing the respective histograms. The CDF of the BPE is integrated numerically and evaluated w.r.t. to the level of the confidence associated to the defined requirement.

Single-Spot Coverage Analysis

This analysis is applicable to telecommunication missions where a single-spot antenna pointing performance for a given coverage area is of interest. The coverage area is defined as a set of azimuth/elevation angles as seen from the satellite, i.e. defined with respect to the selectable line-of-sight axis. It can be provided as contour defined by vertex points (see Figure 6) or by providing explicit points inside the coverage area which shall be analysed.

In the first case, an [Nx2] matrix of N vertices defined contour of interest and a number M of grid points (per direction) can be configured which defines a linearly spaced grid of additional evaluation points inside this contour. In the second case, the [Nx2] matrix directly defines the grid points to be considered.

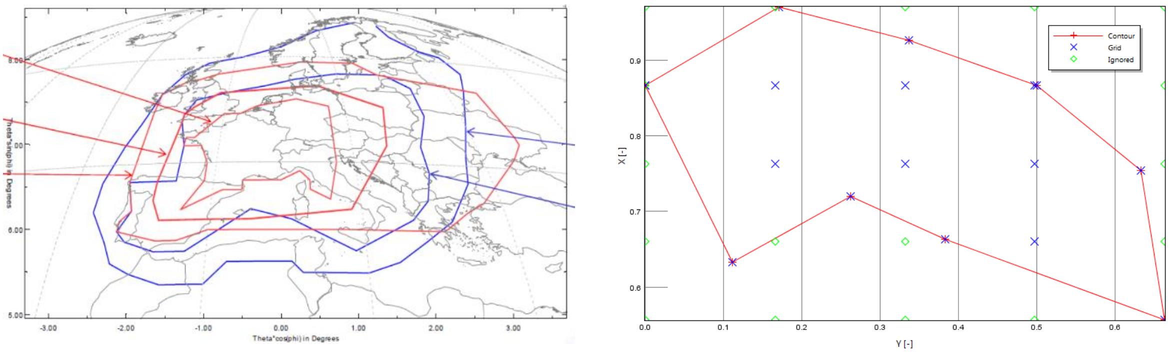


Figure 6. Exemplary coverage area (left) and grid realization in PEET (right)

The analysis returns budget values in terms of azimuth/elevation and half-cone errors for each individual grid point and for an overall spot performance using the accumulated data from all grid point (as schematically illustrated in Figure 7).

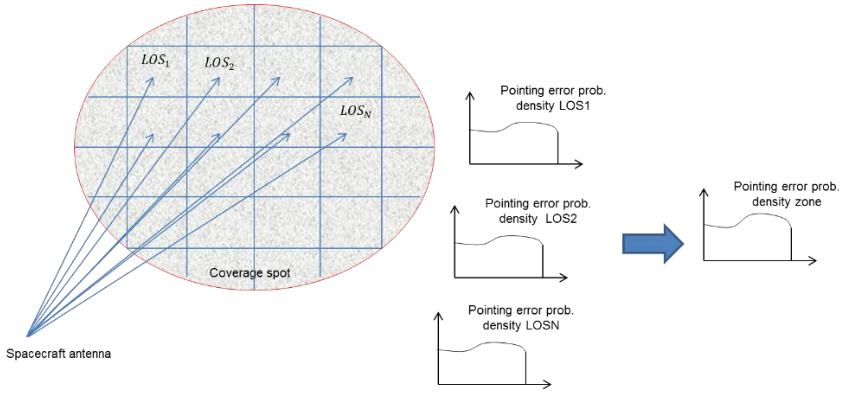


Figure 7. Overall spot performance from individual grid points

First, (for each individual grid point) azimuth φ_{grid} and elevation θ_{grid} are expressed as components of a unit vector $\mathbf{u}_{\mathrm{grid}}$ in the body reference frame (assuming the line-of-sight direction along z) by standard conversion from spherical to Cartesian coordinates:

$$\begin{aligned} u_{x,\mathrm{grid}} &= \cos\left(\theta_{\mathrm{grid}}\right)\cdot\cos\left(\varphi_{\mathrm{grid}}\right) \\ u_{y,\mathrm{grid}} &= \cos\left(\theta_{\mathrm{grid}}\right)\cdot\sin\left(\varphi_{\mathrm{grid}}\right) \\ u_{z,\mathrm{grid}} &= \sin\left(\theta_{\mathrm{grid}}\right) \end{aligned} \tag{6}$$

Then (each realization of) the attitude error angle vector from the nominal x/y/z budget in the reference frame is used to set up a direction cosine matrix $\mathbf{T}(e_x,e_y,e_z)$ to compute the erroneous direction vector $\mathbf{u}_{\mathrm{e}} = \mathbf{T}\cdot\,\mathbf{u}_{\mathrm{grid}}$. The vector $\mathbf{u}_{\mathrm{e}}$ is then converted back to spherical representation:

$$\begin{aligned} \varphi_{\mathrm{e}} &= \tan^{-1}\left(u_{y,\mathrm{e}}, u_{x,e}\right) \\ \theta_{\mathrm{e}} &= \tan^{-1}\left(u_{z,\mathrm{e}}, \sqrt{u_{x,e}^2 + u_{y,e}^2}\right) \end{aligned} \tag{7}$$

The final analysis result is the PDF p (and CDF) of the absolute value of the difference between grid point azimuth/elevation and the disturbed azimuth/elevation for each realization (i.e. a sample vector respectively).

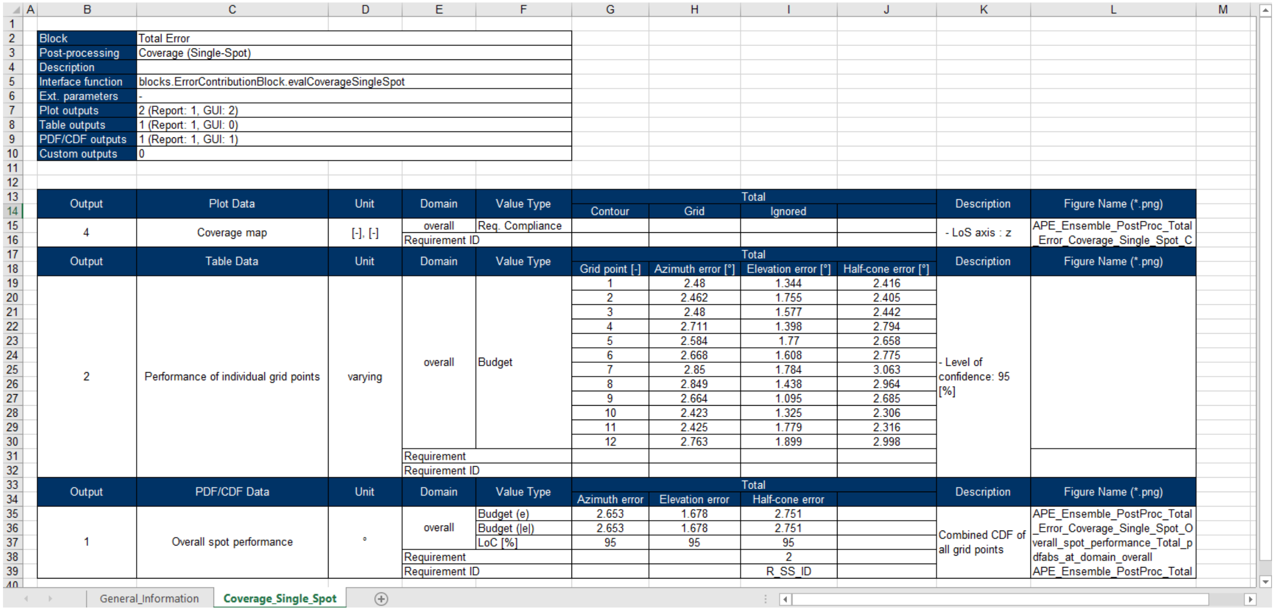
$$\begin{aligned} &p\left(\left|\boldsymbol{\varphi}_{\mathrm{e}} - \varphi_{\mathrm{grid}}\right|\right) \\ &p\left(\left|\boldsymbol{\theta}_{\mathrm{e}} - \theta_{\mathrm{grid}}\right|\right) \end{aligned} \tag{8}$$

Similarly for each grid point, the half-cone errors are computed using the dot-product between the grid point unit direction vector $\mathbf{u}_{\mathrm{grid}}$ and the unit direction vector $\mathbf{u}_{\mathrm{e}}$ with the attitude error vector applied, i.e.

$$e_{half-cone} = \cos^{-1}\left(\mathbf{u}_{\mathrm{e}}^{\mathrm{T}}\,\mathbf{u}_{grid}\right) \tag{9}$$

Above operations are executed for each realization of the x/y/z attitude angle vector which leads to sample vectors of attitude errors in terms of azimuth, elevation and half-cone errors for each grid point. The overall spot performance is represented by appending the half-cone error vectors (azimuth and elevation vectors respectively) errors of each spot into a single, large error sample vector. Then, the PDF, CDF and budget value for a given level of confidence is computed numerically from this sample vector.

Analysis results (plots and values) are displayed on a extra tab in the graphical user interface and can be exported to spreadsheet format including hyperlinks to generated plots (see Figure 8).



Block	Total Error
Post-processing	Coverage (Single-Spot)
Description	
Interface function	blocks.ErrorContributionBlock.evalCoverageSingleSpot
Ext. parameters	-
Plot outputs	2 (Report: 1, GUI: 2)
Table outputs	1 (Report: 1, GUI: 0)
PDF/CDF outputs	1 (Report: 1, GUI: 1)
Custom outputs	0

Output	Plot Data	Unit	Domain	Value Type	Total				Description	Figure Name (*.png)
					Contour	Grid	Ignored			
4	Coverage map	[-], [-]	overall	Req. Compliance					- LoS axis : z	APE_Ensemble_PostProc_Total_Error_Coverage_Single_Spot_C
			Requirement ID							

Output	Table Data	Unit	Domain	Value Type	Total				Description	Figure Name (*.png)
					Grid point [-]	Azimuth error [°]	Elevation error [°]	Half-cone error [°]		
2	Performance of individual grid points	varying	overall	Budget	1	2.48	1.344	2.416	- Level of confidence: 95 [%]	
					2	2.462	1.755	2.405		
					3	2.48	1.577	2.442		
					4	2.711	1.398	2.794		
					5	2.584	1.77	2.658		
					6	2.668	1.608	2.775		
					7	2.85	1.784	3.063		
					8	2.849	1.438	2.964		
					9	2.664	1.095	2.685		
					10	2.423	1.325	2.306		
					11	2.425	1.779	2.316		
					12	2.763	1.899	2.998		
			Requirement							
			Requirement ID							

Output	PDF/CDF Data	Unit	Domain	Value Type	Total				Description	Figure Name (*.png)
					Azimuth error	Elevation error	Half-cone error			
1	Overall spot performance	°	overall	Budget (e)	2.653	1.678	2.751		Combined CDF of all grid points	APE_Ensemble_PostProc_Total_Error_Coverage_Single_Spot_Overall_spot_performance_Total_pdfabs_at_domain_overall
				Budget (|e|)	2.653	1.678	2.751			
				LoC [%]	95	95	95			
			Requirement				2			
			Requirement ID				R_SS_ID			APE_Ensemble_PostProc_Total

Figure 8. Single-spot coverage analysis – exemplary result spreadsheet

Multi-Spot Coverage Analysis

This analysis is applicable to telecommunication missions where a multi-spot antenna pointing performance is of interest. The orientation of each spot in the antenna array is defined as azimuth/elevation pair as seen from the satellite, i.e. defined with respect to the selected line-of-sight axis. As for the single-spot analysis previously described, the main parameter input is an [Nx2] matrix defining the orientation of each of the N spots in terms of azimuth and elevation.

In addition, the analysis takes into account thermo-elastic deformation of the antenna array in a simplified worst-case sense. This requires the maximum daily amplitude as input parameter which is defined for the spot with the largest nominal radial distance from a (selectable) reference spot. Two evaluation options exist for that purpose:

- the maximum daily thermo-elastic amplitude is directly applied to “farthest” spot from the reference spot, i.e. such that their angular distance increases in elevation by the specified maximum daily amplitude value. For all other spots, the thermo-elastic amplitude value is scaled with the ratio of each spots’ radial distance from the reference spot and the radial distance of the farthest spot;
- dimensionless scale factors in the range [-1,1] are explicitly provided as [N x 1] vector and each entry in the vector is used to scale the maximum daily amplitude value. The result is then applied individually to each of the N spots such that their radial distance from the reference spot is increased or decreased accordingly.

The procedure to determine the azimuth, elevation and half-cone errors for each spot is similar to the one described for the single-spot case described in the previous paragraph (with each ‘spot’ in this model equivalent to a ‘grid point’ of the single spot case). The only difference is that not only the x/y/z attitude error input, but also the thermo-elastic errors affect the de-pointed unit direction vector

$\mathbf{u}_e$ for each spot. Thus, first the elevation errors due to the thermo-elastic deformation are applied to the nominal spot direction unit vectors before further applying the rotation due to the x/y/z error angles.

In summary, the analysis provides the following results in the graphical user interface (or in tabular form as spreadsheet similar the single-spot case):

- the reference spot performance in terms of elevation, azimuth and half-cone error (CDF plot and budget values)
- the worst-case spot performance (defined as the spot with the maximum half-cone error) in terms of elevation, azimuth, thermo-elastic error and half-cone error in tabular form.
- an overview plot with the budget values of all spots (in terms of azimuth, elevation and half-cone error) and the thermo-elastic contribution individually.
- an azimuth-elevation map visualizing the nominal spot locations

Weighted Evaluation

During the operational phase of a telecommunication mission, the satellite is usually controlled in different modes (e.g. nominal and station keeping modes). While usually specific pointing requirements apply to each mode individually, also performance requirements over the entire lifetime of the satellite exist.

Assuming that each mode can be represented by a specific requirement set in a PEET scenario (by enabling/disabling error sources relevant for the different modes), a weight w_i can be assigned to each of the i modes according the fraction of time spent in it over lifetime or the time frame of interest.

The ‘cumulated’ overall performance error $e_{weighted}$ can then be approximated by applying these weights to the individual error contributions e_i of each requirement (i.e mode) for a given common level of confidence $LoC_{weighted}$ of the lifetime requirement according to Eq. 10.

$$LoC_{weighted}\big/100 = \int_0^{e_{weighted}} p\left(\frac{\sum\left|e_i \cdot w_i\right|}{\sum w_i}\right) de \qquad (10)$$

3 TELECOMMUNICATION MISSION STUDY CASES

The aim is to establish a standardized pointing error engineering approach for European space missions. The application of the PEEH and PEET software was mainly focused on Earth Observation and Science missions in the past pursuing this aim. However, telecommunication spacecraft have to increasingly cope with stringent and specific pointing requirements, e.g. for hosted payload concepts or communication via inter-satellite links. In this respect the classical or established pointing error engineering approach give room for improvement in terms of physical and numerical accuracy. Improving accuracy and achieving standardization was the main motivation for initiating the P4COM study in the ARTES AT programme.

In this respect four study cases have been identified in P4COM as pilot for detailed assessment in a standardized manner with an approach of improved accuracy. The four study cases were selected such that all Primes in Europe are represented and different type of telecom missions are covered as solid basis for initiating standardization. The selected study cases are SmallGEO (OHB System), E3000 Broadcast Mission (Airbus), SPACEBUS NEO (Thales Alenia Space) and EDRS Global (Airbus). This selection of study cases reflects missions with high interest to ESA and the European space industry in terms of pointing requirements, pointing challenges and pointing error engineering process. The definition, setup and analysis of these study cases was carried out in close iterative co-engineering between the core study team and telecommunication Primes in Europe acting as consultants. An enabler in this respect was the experience gained over several years by the P4COM core study team in the MetOp-SG project where both the ESA PEEH and PEET v1.0 have been made applicable and used for the first time in a complex project in phase B/C/D in a rigorous manner.

In the study case and thus as direct input by the consultants the PEET features in section 2.4 are derived from the needs of telecommunication missions. In addition, the following needs for an evolution of the PEEH have been derived (this evolution will be covered by a dedicated publication and is not scope of this paper):

- Align mathematical elements and methods defined in PEEH with the ones implemented in the PEET software. Mathematical elements and methods in PEEH are a subset of the ones implemented in PEET.
- Pointing Error Source models for transients.
- Application guidelines for Monte Carlo simulations.
- RPE diversification and clarification with additional metrics for analytical computations.
- Formulation of signal-level metrics to enable the computation of accurate distributions in PEET with respect to general periodic signals used to model transients.
- Various minor updates: Objective and Scope of PEEH with guidelines for using PEEH approach, Ensemble Domains, Guidelines for PES identification (e.g. test results, MC simulation, etc.), typos and corrections.

In the study case assessment, the heritage pointing budgets have been modelled in the updated PEET software with equivalent model structure, but with more accurate frequency domain and probabilistic models offered by the software. In this way comparability for benchmarking the PEET model with respect to the heritage model was assured. The SmallGEO model structure is shown in Figure 9 as an example. All study cases are modelled with approximately the same granularity.

The conclusions drawn and lessons learned by the telecom Primes in the study cases are summarized hereafter. In general, it can be stated that the heritage pointing error engineering approach used for the study cases is sufficiently accurate for high level budgets with tendency to be conservative as seen exemplary in Table 1 for the E3000 study case. In the table the reference budgets computed with the heritage approach are compared with the budgets computed by PEET in line with the PEEH approach. The beam pointing error (BPE) is computed directly by PEET in line with the absolute performance error (APE), relative performance error (RPE) over the daily time-window and RPE over the lifetime time-window. The values in the table show that the RPE budgets are less conservative for the PEET budgets. This is given due to the fact that PEET provides accurate frequency domain models as mentioned in section 2.4 and precise metrics for the RPE. This supports the request by the telecom Primes to have accurate frequency domain models and the necessity to compute time-windowed error requirements like the RPE.

The heritage pointing error engineering approaches used by all Primes are very specific as certain assumptions are taken that result in specific summation rules. This leads to representative pointing budgets, but not necessarily physical and mathematical accurate pointing models and thus budgets. This fact is visualized in Figure 10 where the APE probability density function (PDF) and cumulative distribution function (CDF) are shown as they are computed by the PEET software on pointing level per axis and line of sight (LOS). It can be seen that the distributions are strongly not Gaussian for the x- and z-axis. This means that the central limit theorem as necessary condition for the simplified approach in [2] is not given.

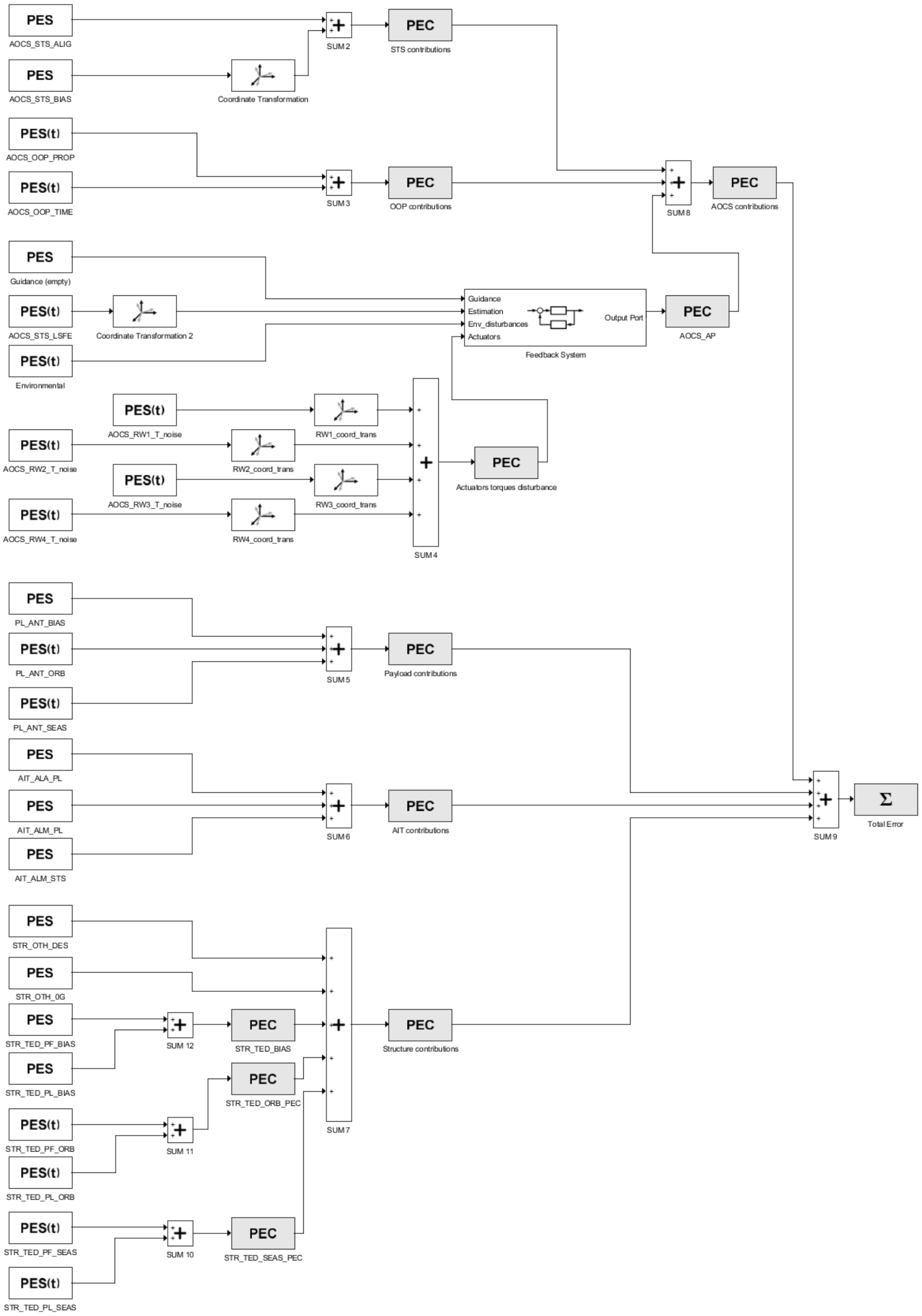


Figure 9. SmallGEO PEET model structure

The north-south (NS) and east-west (EW) beam pointing errors in Figure 11 are also not Gaussian. However, the half-cone BPE is nearly Gaussian. Another exemplary APE is given in Figure 12 for the multi-spot performance of the SPACEBUS NEO.

It can be seen that the multi-spot performance has a considerably different PDF than the BPE performance of the E3000. This is mainly due to the fact that in the multi-spot performance there are no negative values. Hence depending on the final performance criteria very different PDF are to be evaluated to guarantee a performance with a certain level of confidence. This supports the request by the telecommunication mission Primes to have accurate PDF characterization available for the final performance criteria: BPE, pointing error indices (APE, RPE, MPE…), multi-spot performance, and others.

Table 1: E3000 reference budget versus PEET budget, normalized to reference budget values.

Requirement		**Reference budgets in [°]**	**PEET budgets in [°]**
BPE APE	x	1.00	1.13
	y	1.00	0.94
	z	1.00	0.83
	BPE	1.00	1.17
BPE RPE(dt=daily)	x	1.00	0.83
	y	1.00	0.67
	z	1.00	0.65
	BPE	1.00	0.75
BPE RPE(dt=lifetime)	x	1.00	0.86
	y	1.00	0.57
	z	1.00	0.80
	BPE	1.00	0.77

The practical consequence of having different specific approaches is that unnecessary overhead is introduced in the projects in terms of achieving a common understanding and coherent systems engineering with traceable data flow.

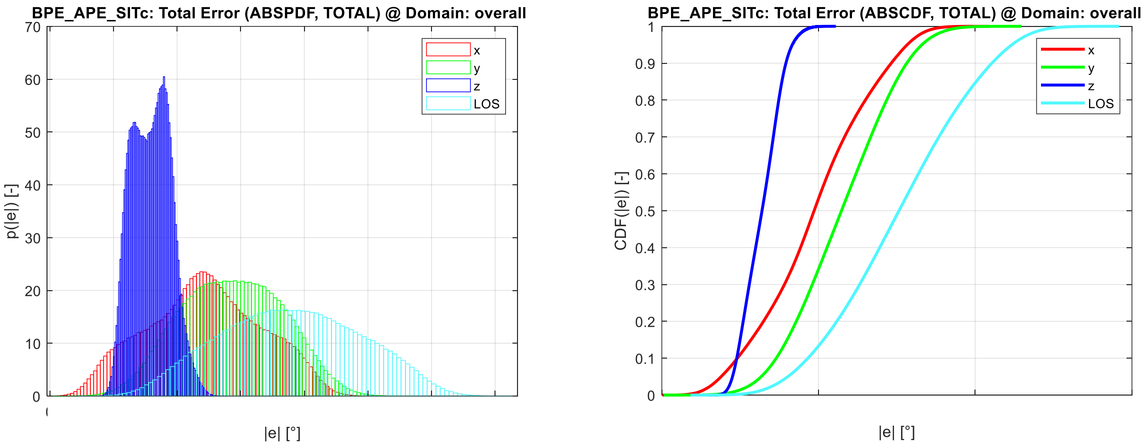


Figure 10. E3000 pointing APE PDF (left) and CDF (right) by PEET

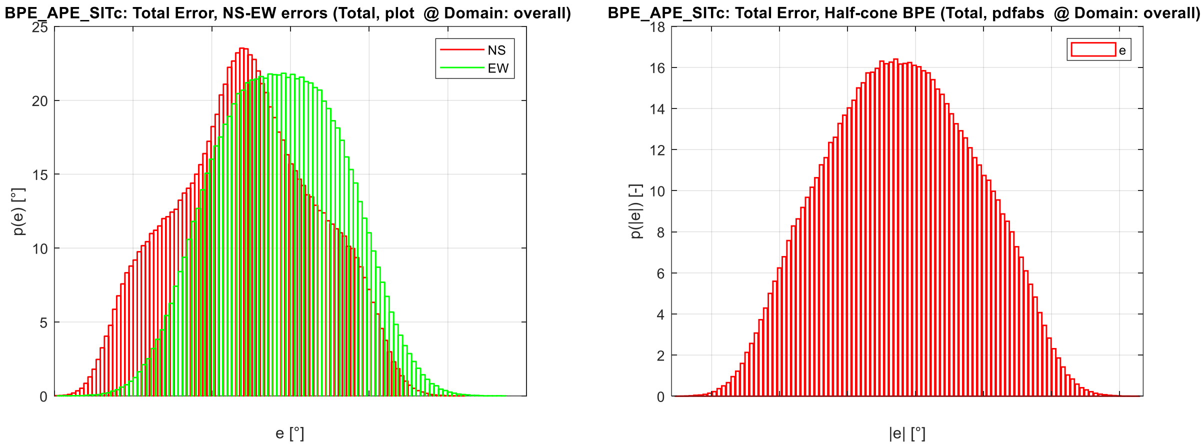


Figure 11. E3000 PDF for NS/EW errors(left) and half-cone BPE (right) by PEET

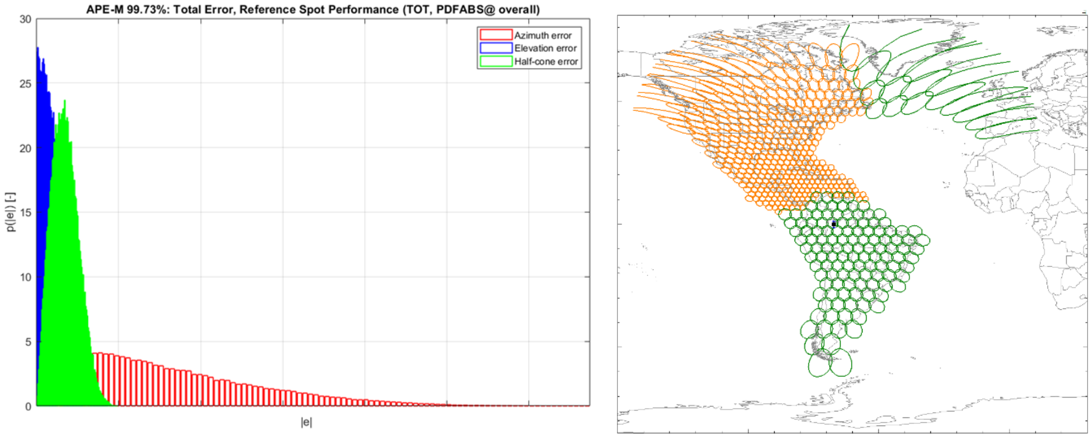


Figure 12. SPACEBUS NEO multi-spot performance by PEET (left) with geo-illustration (right)

In terms of PEET the following conclusions are drawn by the telecom Primes after assessing their study cases with the updated PEEH approach and PEET software:

- PEET enables fast and accurate computations without going into the details of the actual summation. It is sufficient to understand well the PES models and requirements specification. The computation is then done by PEET. The contribution to time-windowed errors is determined by PEET automatically. This reduces the budgeting effort, ensures consistency and improves accuracy. This is not given for the heritage approaches.
- Using a PEET based approach requires some initial learning curve and modelling effort. In specific the software offers more detailed PES models. However, one does not have to use them if the necessary data is not available. Then PEET also offers approximate PES models.
- The overall performance errors in the study case are not Gaussian distributed. The possibility of determining accurately the PDF of the overall performance error thus increases physical as well as mathematical model and thus budget accuracy.
- The conservatism in the budgets was reduced by using PEET for the SmallGEO, E3000, SPACEBUS NEO and EDRS Global study cases by 10-50 %. This is confirmed by in-flight data validation in case of E3000, SPACEBUS NEO and EDRS Global and by test data validation in case of SmallGEO.
- The post-processing in PEET enables to analyse several performance quantities linked to pointing performance. In this way PEET can be used also for these quantities, e.g. direct assessment of BPE, multi-spot performance and any other user defined quantity.
- All telecommunication mission Primes envisage to use PEET for future missions.

4 SUMMARY AND CONCLUSION

Within P4COM study, PEET and the PEEH could be updated to account for identified main needs of the user community. The PEET software in specific has been streamlined to cover requested ‘comfort features’ and to improve interfaces from and to the tool. In this respect, reporting functionalities have been extended for more flexible spreadsheet export and figure generation. Script-based execution and scenario data access have been improved for a smoother integration into toolchains and a generic interface has been created to integrate user-defined analyses. Coverage analyses algorithms - based on inputs from experts from all European telecommunication mission primes - were implemented to support the specific needs for applications in this sector.

Four representative study cases for both “typical” and “high-accuracy” telecommunication missions were investigated in the study. First, scenarios were defined and documented following the error source classification/categorization and requirement formulation of the PEEH. In a second step, PEET scenarios were set up to compute the pointing budgets making use of the new features and analyses – all in close co-engineering with the telecommunication mission consultants. A comparison to heritage budgets revealed reasonable differences to the PEET results - which can be traced back to the more detailed modelling and more accurate summation of contributors based on PDF information – showing that applying the PEEH process is indeed able to remove a certain degree of conservatism compared to heritage approaches by enabling an increased physical and mathematical accuracy.

From the consultants’ perspective, implementing the PEEH process and realizing it with a model-based approach via PEET is considered to have an added value also for future telecommunication mission projects – as it provides potential to improve and simplify the pointing error engineering process (e.g. focus on PES modelling, no assumptions on summation rules and central limit theorem, simplified exchange/tracking of modelling information and results).

The release of the new PEET version (V1.1) is intended for summer 2021 and the tool remains free of charge for industry and institutions within ESA member states. Proposed updates for the evolution of the PEEH, - especially with respect to an extension of the frequency domain metrics which resulted as a side product – are intended to be published in separate papers in the near future.

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6 DISCLAIMER

Note that the view expressed in this paper can in no way be taken to reflect the official opinion of the European Space Agency.

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