GNC 2011
8th International ESA Conference on Guidance, Navigation & Control Systems
Karlovy Vary, Czech Republic 5 - 10 June 2011
esa
European Space Agency

ESA POINTING ERROR ENGINEERING HANDBOOK

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ABSTRACT

The ESA Pointing Error Engineering Handbook is intended to be published as an applicable document for ESA projects providing a step-by-step engineering process with clauses, guidelines, recommendations, and examples, for the specific case of satellite pointing errors. The process ranges from the unambiguous formulation of pointing error requirements, to systematic pointing error analysis, and eventually to the compilation of pointing error budgets. The handbook not only puts the different mathematical elements of the ECSS Control Performance Standard E-ST-60-10C in an engineering context, but it also complements the standard by introducing further developments in the field of pointing performance analysis. In this paper the scope and main elements of the ESA PEE Handbook are introduced as well as its application framework.

I. INTRODUCTION

The ECSS Control Performance Standard *E-ST-60-10C* [1], published in November 2008, provides solid and exact mathematical elements to build up a performance error budget. However, the necessity of an additional document was highlighted during the Public Review of the Control Performance Standard and foreseen in its Note 3:

"For their own specific purpose, each entity (ESA, national agencies, primes) can further elaborate internal documents, deriving appropriate guidelines and summation rules based on the top level clauses gathered in this *ECSS-E-ST-60-10C* standard."

In regard of this Note the ESA Engineering Standardisation Board requested in September 2008 to draft and finalize a document providing ESA projects with a clear pointing error engineering methodology. The methodology shall be the basis for a step-by-step process with guidelines, recommendations and examples consistent with and complementing the ECSS standard [1].

The answer to this request is the ESA Pointing Error Engineering (PEE) Handbook [2] that will be published in 2011 as ESA applicable document with the reference *ESSB-HB-E-003*. The handbook is based on the ECSS standard [1], summarized Lessons Learned of projects in the Control Systems Division of ESA/ESTEC and research results obtained in the NPI research cooperation on "*Precision Pointing Control Design"*, as stated in the acknowledgments of this paper.

The ESA PEE Handbook [2] will be published as an ESA internal document (and not an ECSS document) that can be used by ESA projects as applicable document consistent with and complementing the ECSS standard [1]. Once the handbook is published, the ECSS standard together with the ESA PEE Handbook will replace the ESA Pointing Error Handbook [3], which was published in 1993.

In order to introduce the ESA PEE Handbook the following questions will be answered in this paper:

- What is the context and objective?
- What is the scope?
- What are the major elements?

The first question will be addressed in this section and in section II by introducing the ECSS document structure and the application framework of the ESA PEE Handbook. Before addressing the second question in section IV essential nomenclature and definitions used in the handbook will be introduced. In section V the handbook underlying methodology and new elements in the ESA PEE Handbook will be introduced.

II. APPLICATION FRAMEWORK

The ECSS E-60 standards and handbooks in Fig. 1 cover control engineering specific topics. The ECSS Control Performance Standard *E-ST-60-10C* [1] provides normative clauses with clear mathematical elements for control performance analysis in general. It is complemented by the ECSS handbook *E-HB-60-10A* [3], which provides a detailed background on the mathematical elements in the standard and introduces general control performance guidelines. The ESA PEE Handbook [2], however, embeds the elements of the ECSS standard in a step-by-step engineering process for the specific case of satellite pointing errors. The process starts with the unambiguous formulation of pointing error requirements and leads step-by-step to the evaluation of the system pointing error. It provides guidelines for:

- characterizing pointing error sources,
- analysing pointing error source contribution to the ECSS pointing error indices,
- compiling system pointing error budgets.

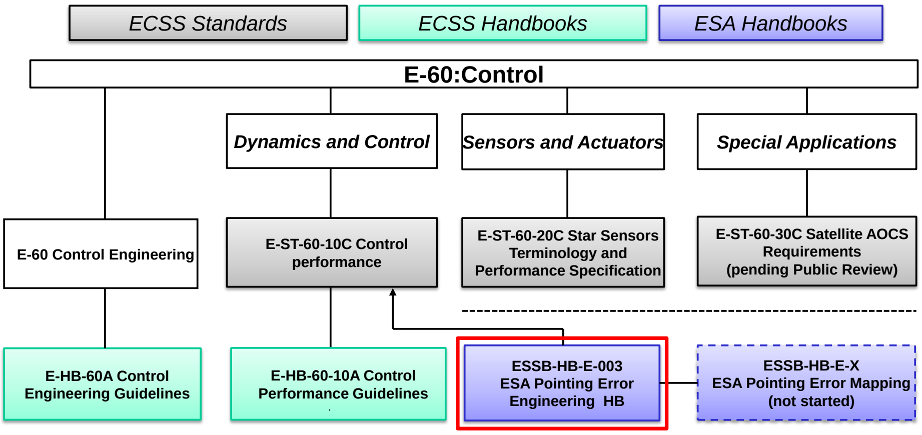


Fig. 1: *handbook application framework*

Full attention has been devoted during the ESA PEE Handbook preparation to be consistent with and fully refer to the ECSS standard, without introducing normative clauses, which are to be found solely in the ECSS standard. As usual, specific and quantitative performance pointing requirements shall be expressed in the ESA Mission Requirement Document and System Requirement Document, and further broken down and engineered by prime contractor in the various project phases.
It shall be noted that the ECSS standards and handbooks are available at the following website: http://www.ecss.nl.

III. PRELIMINARIES

In this section essential nomenclature and definitions are introduced in order to lay the basis for summarizing the main elements of the ESA PEE Handbook [2] in the following sections. To begin with, the handbook distinguishes between where pointing errors are described in the system. Physical phenomena ultimately affecting pointing performance, but being described before entering a system, will be referred to as *pointing error source* (PES) and denoted as e_s. A PES is either constant in time (time-constant), random in time (time-random) and/or random in its realization (ensemble-random). A *pointing error contributor* (PEC), denoted as e_c, represents the actual contribution of one or more PES on the overall pointing error e after system transfer.
The overall pointing error is not only of interest with respect to instantaneous time t behaviour, but also in terms window time Δt and stability time Δt_s behaviour as illustrated in Fig. 2. The window time and stability time criteria have their origin in actual satellite payload requirements. For example to keep a camera stable during CCD integration, a pointing requirement is specified with respect to instantaneous time and window time, where the window time usually corresponds to the CCD integration time.

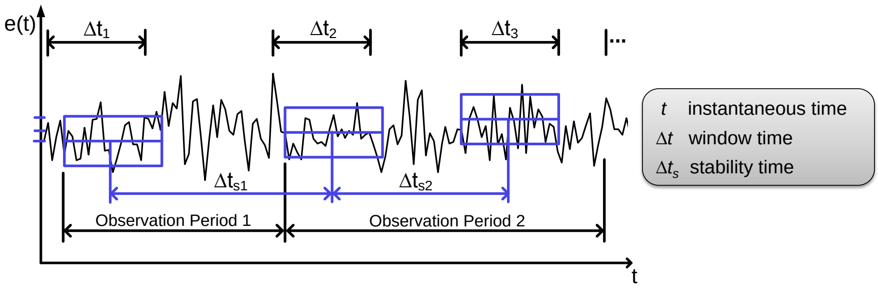


Fig. 2: *time-windowed pointing error properties*

A pointing error *e* as shown in Fig. 2 can be formulated as stationary random process $\{e_k(t)\}$ with time *t* and *k* being the sample function index of an ensemble of process realizations. With this formulation ensemble-random and time-random properties of a PES are captured. In terms of PES characterisation in line with stationary random process formulation, time-series PES data is described by its ensemble PDF *p(e)*. In practice most stationary random processes have a Gaussian PDF and thus are completely defined by their mean value and covariance respectively:

$$\mu_e = E[e_k(t)] = \int_{-\infty}^{\infty} e \;\; p(e)de \tag{1}$$

$$C_{ee}(\tau) = E[(e_k(t)e_k(t+\tau)] - \mu_e^2 = R_{ee}(\tau) - \mu_e^2 \tag{2}$$

where the autocorrelation is defined as:

$$R_{ee}(\tau) = E[(e_k(t)e_k(t+\tau)] = \int_{-\infty}^{\infty}\int e_1 e_2 \;\; p(e_1, e_2) \;\; de_1 de_2 \tag{3}$$

with $e_1 = e_k(t)$ and $e_2 = e_k(t+\tau)$. Note that the statistics are independent of *t* and that the covariance function $C_{ee}(\tau)$ represents the variance of the random process for $\tau = 0$.

A description of the pointing error by a stationary random process is not foreseen in the ECSS standard [1]. However, in the ESA PEE Handbook it is considered to be useful because the double-sided power spectral density (PSD):

$$S_{ee}(\omega) = \Im\{R_{ee}(\tau)\}\big|_{\tau=0} \tag{4}$$

of a stationary random process contains additional pointing error characteristics with respect to the window time Δt and stability Δt_s as will be shown in section V. The single-sided PSD, used in this paper, is defined as $G_{ee} = 2S_{ee}$ in $[unit^2/(rad\, s^{-1})]$.

In the ECSS standard pointing error indices are defined that signify different instantaneous time, window time and stability time properties of a pointing error process as shown in Fig. 2. Any type of pointing requirement is usually classified in one of these pointing error indices: APE, AKE, MPE, MKE, RPE, RKE, PDE, KDE, PRE, and KRE.

Table 1: *ECSS standard pointing error indices*

Pointing Error Indices	
index	***instantaneous***
$e_{APE}(t)$	$= e_P(t)$
$e_{AKE}(t)$	$= e_K(t)$
$e_{MPE}(t, \Delta t)$	$= \overline{e_P}(t, \Delta t)$
$e_{MKE}(t, \Delta t)$	$= \overline{e_K}(t, \Delta t)$
$e_{RPE}(t, \Delta t)$	$= e_P(t) - \overline{e_P}(t, \Delta t)$
$e_{RKE}(t, \Delta t)$	$= e_K(t) - \overline{e_K}(t, \Delta t)$
$e_{PDE}(t, \Delta t_1, \Delta t_2, \Delta t_s)$ $e_{PRE}(t, \Delta t_1, \Delta t_2, \Delta t_s)$	$= \overline{e_P}(t, \Delta t_1) - \overline{e_P}(t - \Delta t_s, \Delta t_2)$
$e_{KDE}(t, \Delta t_1, \Delta t_2, \Delta t_s)$ $e_{KRE}(t, \Delta t_1, \Delta t_2, \Delta t_s)$	$= \overline{e_K}(t, \Delta t_1) - \overline{e_K}(t - \Delta t_s, \Delta t_2)$
Δt_s *stability time* Δt *window time*	e_{index} *instantaneous error* $e_K(t)$ *knowledge error signal* $e_P(t)$ *performance error signal*
time average:	$\bar{e}(t, \Delta t) = \langle e(t) \rangle_{\Delta t} = \frac{1}{\Delta t}\int_{t-\Delta t/2}^{t+\Delta t/2} e(t) \;\; dt$

instantaneous time

window time

stability time

IV. SCOPE

The PEE Handbook [2] covers the engineering process 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. Meaning that for specification of pointing error requirements relevant analysis and verification methods have to be identified and vice versa. The handbook provides guidelines and recommendations in this context.

A. POINTING ERROR ENGINEERING CYCLE

The ESA PEE Handbook [2] focuses on the formulation of a consistent methodology for performing pointing error engineering on system and subsystem (SS) level in line with the definitions in the ECSS standard [1], thus enabling systematic requirements engineering and system design as illustrated in Fig. 3. The mapping of application requirements into system pointing error requirements by means of ECSS pointing error indices is not treated in the handbook because the mapping is application specific.

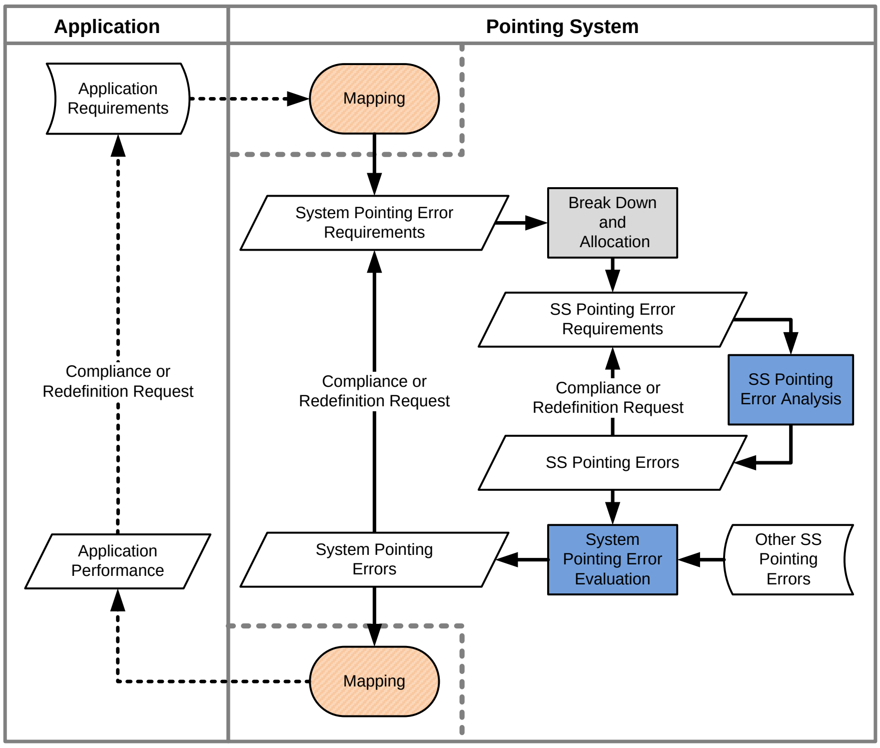


Fig. 3: *pointing error engineering cycle*

B. POINTING ERROR ANALYSIS METHODOLOGY

Pointing error analysis in the ESA PEE Handbook [2] is a step-by-step process from PES characterization to system pointing performance, as shown in Fig. 4 for the example of an AOCS subsystem.

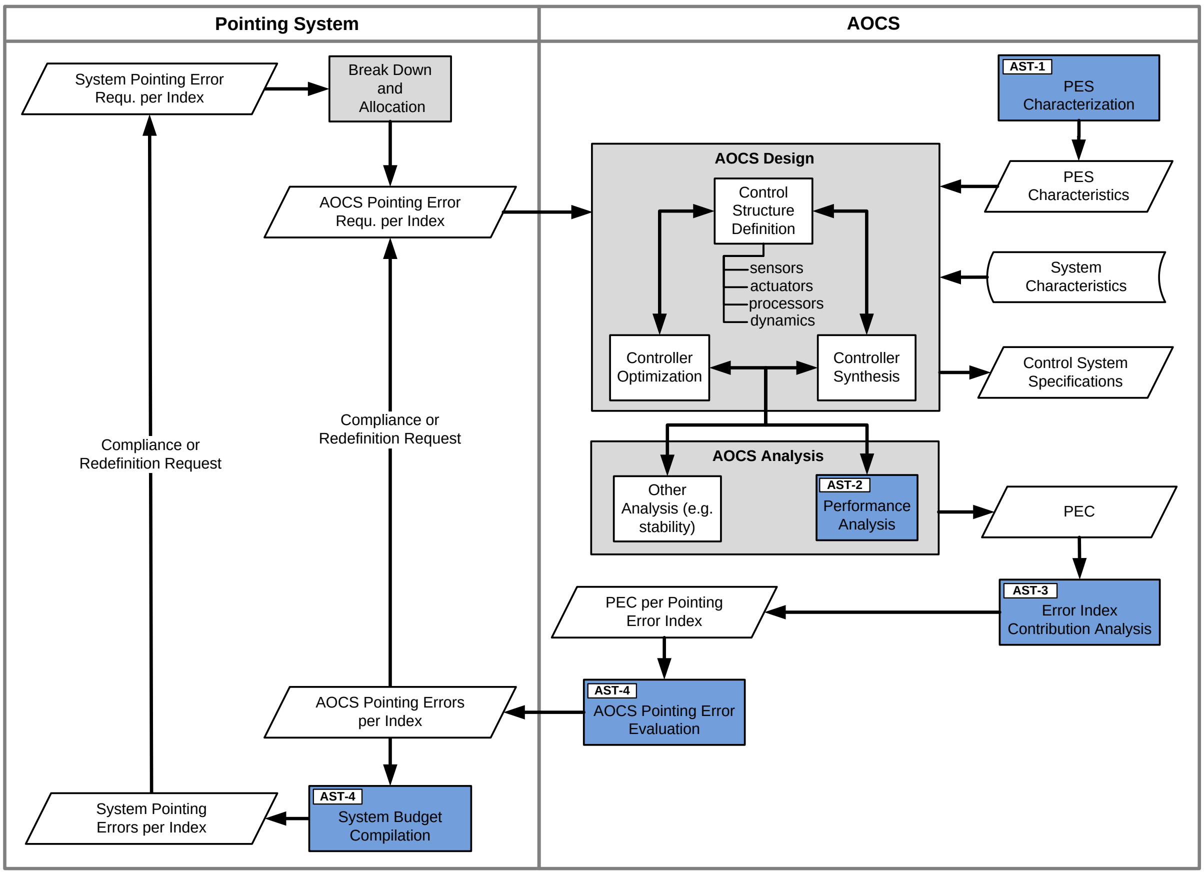


Fig. 4: *pointing error analysis methodology*

Pointing error analysis consists of the following steps with clearly defined interfaces as shown in Fig. 4 and further broken down in Fig. 5:

AST-1: PES Characterization

AST-2: Transfer Analysis

AST-3: PEC error index contribution

AST-4: Pointing Error Evaluation

Due to the fact that the analysis process is set-up in a generic manner with well-defined interfaces for each step, it can be tailored to any mission type and design phase. In this regard, the ESA PEE handbook provides recommendations for tailoring the process to specific pointing error analysis needs.

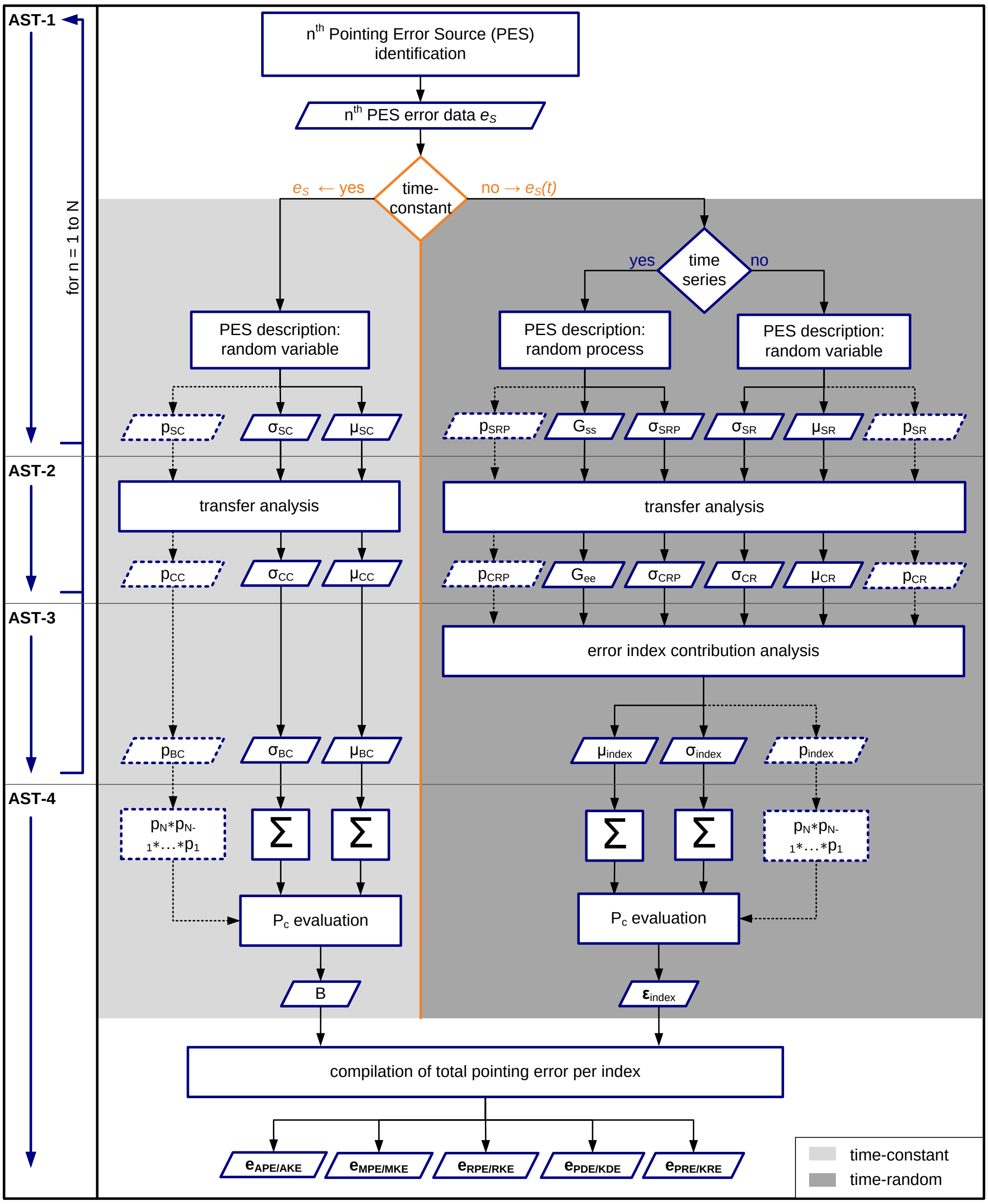


Fig. 5: *pointing error analysis flow-chart with input/output data*

V. POINTING ERROR ANALYSIS

Pointing error analysis in the ESA PEE Handbook [2] consists of two methods:

- **simplified statistical method:** evaluation via variance, σ, and mean, μ, summation per error index under the assumption of the central limit theorem.
- **advanced statistical method:** joint PDF characterization via convolution of different error PDF, $p_{...}(e)$.

In Fig. 5 the simplified statistical method is depicted with solid lines whereas the advanced method is depicted with dashed lines. Depending on the available data for the individual steps one or the other method or a combination is suggested by the handbook.

The main elements of analysis steps AST-1 to AST-4 are introduced in the following paragraphs of this section.

A. CHARACTERIZATION OF POINTING ERROR SOURCE

The ESA PEE Handbook [2] provides guidelines for the characterization of PES based on the PES nature and the available PES error data. The guidelines are expressed in form of classification criteria that make up the decision tree in Fig. 6. However, before the decision tree criteria are applied the PES error data is categorized in signal classes (random, periodic, bias, etc.), analogous to the classes in the ECSS standard [1].

In the decision tree, the first criterion categorizes a PES in time-random and time-constant. Time-constant PES do not vary randomly with time, but in their ensemble of realizations. On the other hand, time-random PES have a magnitude that varies randomly in time and/or in its ensemble. A time-constant PES is described as a random variable according to the rules in [1]. A time-random PES is ideally described as a stationary random process if time-series data is available and stationary random process theory is applicable. Therefore guidelines for a stationary random process description are given in the ESA PEE handbook. If time series data is not available the ESA PEE handbook refers to the rules in [1]. Note that describing a PES as stationary random process and also characterizing its PSD has the advantage that exact time window and stability time properties of the PES, as shown in paragraph C of this section, are described.

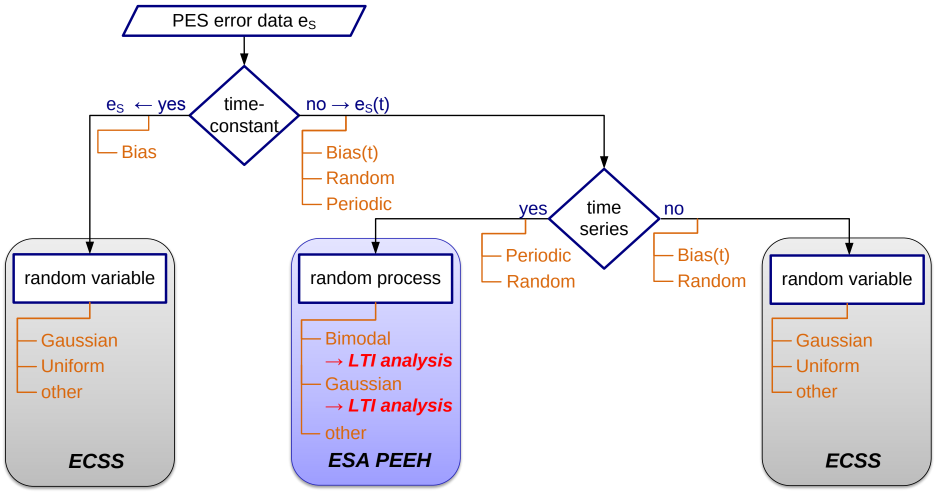


Fig. 6: *decision tree for PES characterization*

In Table 2 an example is given for the characterization of two PES following different branches of the decision tree. The Star Tracker (STR) - Payload misalignment error example is a time-constant PES, for which the guidelines provided by the ECSS standard [1] are applicable. The Gyro-Stellar Estimator (GSE) noise is a time-random PES with available time-series error data. Thus the ESA PEE Handbook guidelines apply for describing the PES. The decision tree in Fig. 6 precisely defines and thus simplifies the characterization of PES. In the ESA PEE Handbook further PES characterization examples are provided.

Table 2: *PES characterization examples*

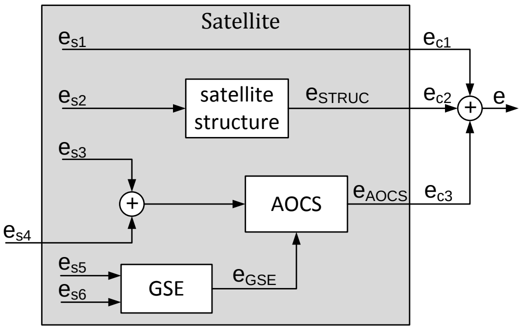
characterization steps	**STR-Payload misalignment error**	**Gyro-Stellar Estimator (GSE) noise**
temporal behavior	time-constant	time-random
signal class	bias	random
description	random variable	random process
reference document	***ECSS***	***ESA PEE Handbook***
characteristic data	$U(0, e_{max})$	$G(0, \sigma_G)$, G_{ee}
temporal interpretation	$p(e)=\delta(e_{max})$	$G(0, \sigma_G)$
AST-1 output data	$\mu(e)=e_{max}$, $\sigma(e)=0$	$\mu(e)=0$, $\sigma(e)=\sigma_G$, G_{ee}

B. TRANSFER ANALYSIS

The description of PES is given with respect to its point of origin. In order to evaluate a pointing error requirement the transfer of a PES from its origin to the point of interest has to be analysed to determine the pointing error contribution of a PES. In this context transfer analysis refers to:

- coordinate frame,
- closed-loop control system,
- structural,

transformations. In order to analyse system transfer, a pointing system can be broken down into subsystems with individually controlled (active or passive) transfer properties as in Fig. 7. Then the overall pointing error is the sum of the different PEC. The exemplary satellite system contains PES with different characteristics, which are classified according to paragraph A of this section.



	PES
e_{s1}	STR-Pay. misalignment
e_{s2}	µVibrations
e_{s3}	thruster noise
e_{s4}	solar pressure noise
e_{s5}	*STR noise*
e_{s6}	*gyro noise*

Fig. 7: *transformations in a satellite pointing system*

The ESA PEE Handbook [2] concentrates on system transformations because standards and handbooks exist for other transformations, e.g. on reference frame transformations. In particular, the handbook suggests an analytical approach for transfer analysis with linear time-invariant (LTI) systems. This approach relies on the PSD transfer relation in LTI-systems:

$$G_{ee}(\omega) = |H(j\omega)|^2 G_{ss}(\omega) \tag{5}$$

with G_{ss} being the PSD of the PES and G_{ee} being the PSD of the PEC at the output of the system H. This transfer can be analysed by various methods as summarized in [5] and applied in [6].

The advantage of the analytical approach is that it can be used in order to tune the system transfer function H based on signal and system norms. Then in the ESA PEE handbook signal and system norms are summarized in a condensed manner to provide an overview. In [7] pointing error index signal norms are introduced based on [8], [9], and [10] in order to tune closed loop system transfer functions in control design based on system norms. This control design approach has been applied in the AOCS design of the ESA mission study Euclid in [11].

Guidelines for other transfer analysis approaches based on simulations and experimental results are provided in the ECSS standard [1].

C. POINTING ERROR INDEX CONTRIBUTION

Depending on the description of the PES in AST-1 the analysis of time-windowed pointing error index contribution in line with the definitions in Table 1 is required or not. Meaning that if a PES is described as time-constant the resulting PEC only contributes to the pointing error bias, and thus time-windowed analysis is not required. On the other hand time-random PEC contribute differently to the pointing error indices subject to the window time and stability time and thus contribution needs to be analysed. In this context the ESA PEE Handbook [2] suggests either to use stationary random process description guidelines, if possible, or alternatively refers to the ECSS standard [1] guidelines. In the following paragraphs analysis in line with stationary random process description is summarized, because it is different compared to the ECSS standard.

ECSS STANDARD ↔ POINTING METRIC

If a PEC is described as stationary random process with the PSD G_{ee} exact metrics exist to determine the contribution of a PEC to an ECSS standard pointing error index, defined in Table 1. The metrics are given in the ESA PEE Handbook for the time-domain and frequency-domain based on the results in [8] and [9]. Time-domain metrics and frequency-domain metrics, summarized in Table 3, are exact and equivalent.

Table 3: *pointing error metrics*

Pointing Error Metrics		
$\sigma^2_{index} := \sigma^2_{metric}$	***time domain***	***frequency domain***
APE, AKE:= *Absolute (ABS) Metric*	$\sigma^2_{ABS} = E\left[(e(t)-\mu_{ABS})^2\right]$	$=\frac{1}{2\pi}\int_0^\infty G_{ee}(\omega)d\omega$
MPE, MKE:= *Windowed Mean (WM) Metric*	$\sigma^2_{WM}(\Delta t) = E\left[\left(\langle e(t)\rangle_{\Delta t} - \mu_{ABS}\right)^2\right]$	$=\frac{1}{2\pi}\int_0^\infty G_{ee}(\omega)\ F_{WM}(\omega,\Delta t)d\omega$
RPE, RKE:= *Windowed Variance (WV) Metric*	$\sigma^2_{WV}(\Delta t) = E\left[\left\langle\left(e(t)-\langle e(t)\rangle_{\Delta t}\right)^2\right\rangle_{\Delta t}\right]$	$=\frac{1}{2\pi}\int_0^\infty G_{ee}(\omega)\ F_{WV}(\omega,\Delta t)d\omega$
PDE, PRD, KDE, KRE:= *Windowed Mean Stability (WMS) Metric*	$\sigma^2_{WMS}(\Delta t,\Delta t_s) = E\left[\left(\langle e(t)\rangle_{\Delta t} - \langle e(t-\Delta t_s)\rangle_{\Delta t}\right)^2\right]$ $\Delta t=\Delta t_1=\Delta t_2$	$=\frac{1}{2\pi}\int_0^\infty G_{ee}(\omega)\ F_{WMS}(\omega,\Delta t,\Delta t_s)d\omega$
PDE, PRD, KDE, KRE:= *Stability (STA) Metric*	$\sigma^2_{STA}(\Delta t_s) = E\left[\left(e(t)-e(t-\Delta t_s)\right)^2\right]$	$=\frac{1}{2\pi}\int_0^\infty G_{ee}(\omega)\ F_{STA}(\omega,\Delta t_s)d\omega$

σ^2	*variance*	$e(t)=e_K(t)$	*knowledge error signal*
μ	*mean*	$e(t)=e_P(t)$	*performance error signal*
Δt_s	*stability time*	$E[\ldots]$	*expected value*
Δt	*window time*	F_{metric}	*spectral weighting filter*
$\langle e(t)\rangle_{\Delta t} = \frac{1}{\Delta t}\int_{t-\Delta t/2}^{t+\Delta t/2} e(t)dt$	*time average*	G_{ee}	*single-sided PSD in [(unit)^2/(rad s^{-1})]*
		$\mu_{ABS} = E[e(t)] = 0$	*mean value*

POINTING ERROR INDEX CONTRIBUTION EXAMPLE

In order to illustrate the application of the frequency-domain metrics an example is given in this paragraph. Assuming that a PEC is, among others, described by its PSD G_{ee}, plotted in Fig. 8, its variance is determined by:

$$\sigma_e^2 = \frac{1}{2\pi}\int_0^\infty G_{ee}(\omega)d\omega \tag{6}$$

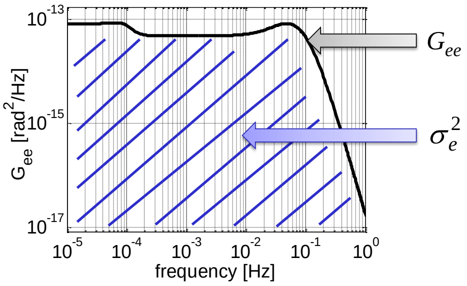


Fig. 8: *PEC power spectral density*

In order to analyse the contribution of the PEC to a certain pointing error index the metric weighting function $F_{metric}(\omega)$ has to be multiplied with the PSD before integration. If performing LTI-system analysis it is convenient to use rational approximations of the weighting functions, derived in [9], such that:

$$F_{metric}(\omega) \cong \left|\tilde{F}_{metric}(j\omega)\right|^2 \tag{7}$$

The metric weighting function and its rational approximation are shown in Fig. 9 for the pointing error index RPE. It is a high-pass with the corner frequency at about $(2\Delta t)^{-1}$, which is reasonable because we are only interested in the magnitude deviations within a window Δt.

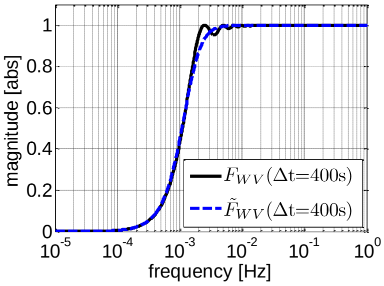


Fig. 9: *RPE weighting function*

Multiplying G_{ee} with the windowed-variance weighting function F_{WV} in Fig. 9 results in the PSD of the RPE in Fig. 10, from which the RPE-variance can be calculated by:

$$\sigma_{RPE}^2(\Delta t) = \frac{1}{2\pi}\int_0^\infty G_{ee}F_{WV}(\Delta t)d\omega \tag{8}$$

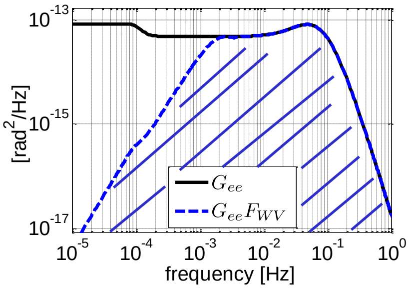


Fig. 10: RPE power spectral density

D. POINTING ERROR EVALUATION

The ECSS standard [1] and the ESA PEE Handbook [2] suggest two methods for analysing pointing performance, the simplified statistical method and the advanced statistical method. In early development phases, when detailed control design and hardware specifications are not yet available, the performance can be analysed by the simplified statistical method. This method is based on the summation of variances and mean values by assuming the applicability of the central limit theorem. However, at the end the pointing performance analysis process is a combination of the simplified and advanced statistical method, which is adapted throughout the development process.

In terms of the simplified statistical method, which is treated in detail in the ESA PEE Handbook, time-constant and time-random error contributors are summed separately before evaluating the confidence level as shown in Fig. 11. In this respect the handbook provides guidelines for summation based on cross-correlation properties of the pointing errors. Thereafter, the total pointing error is computed per pointing error index from both intermediate results before compilation of the total pointing error budget per system or subsystem. The individual steps with corresponding guidelines are given in detail in the ESA PEE Handbook.

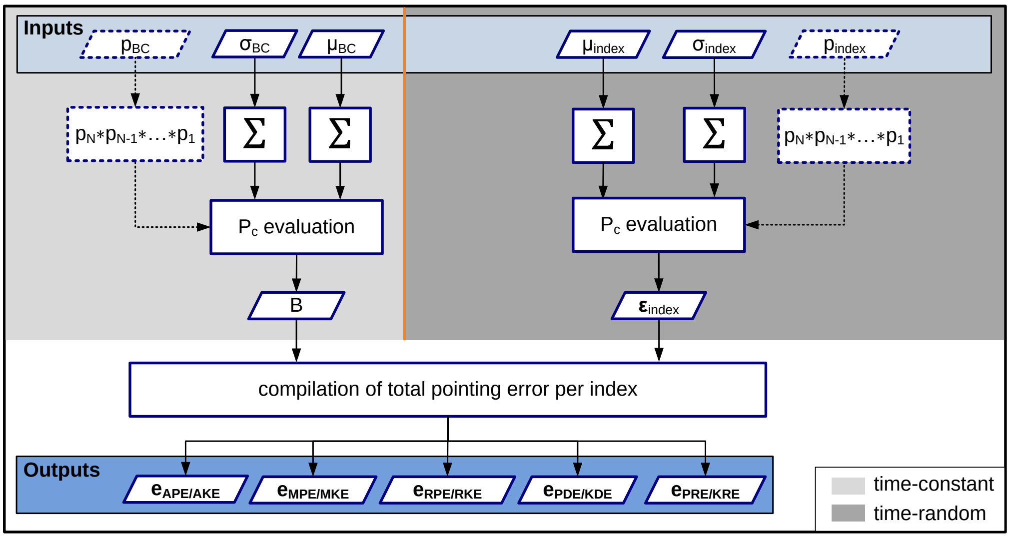


Fig. 11: *pointing error evaluation per system or subsystem*

VI. CONCLUSIONS

The ESA PEE Handbook [2] provides an engineering step-by-step process ranging from the formulation of system pointing error requirements, to systematic pointing error analysis, and eventually to the compilation of pointing error budgets for compliance verification. The process is consistent with *ECSS-E-ST-60-10C* standard [1] and complements it with additional elements like the PSD characterization and the pointing error metrics. Moreover, it defines an interface for the unambiguous formulation of pointing error requirements and provides guidelines, recommendations and examples for specific case of satellite pointing error engineering. As the process has clearly separated steps with defined input and output data it is quite generic and thus applicable to any mission type and design phase.

After publication, the ESA PEE Handbook together with the ECSS standard will replace the ESA Pointing Error Handbook [3]. Furthermore, it is intended to complete the ESA PEE Handbook in the future by one or several documents providing guidelines for the mapping process, i.e. the flow-down of application requirements (e.g. from the ESA MRD) to pointing error requirements.

However, it must be noted that the ESA PEE Handbook overlaps in some topics with the ECSS standard [1] and the ECSS Control Performance Guidelines Handbook [4]. It was found preferable not to add additional delays in the release of these two useful handbooks, and to postpone their streamlining and possible harmonisation to future updates. The users of the handbooks are encouraged to give comments and recommendations.

ACKNOWLEDGEMENTS

The results obtained and presented in this paper have been developed under the ESA Network/Partnering Initiative with the title “Precision Pointing Control Design Under Agility Constraints“. Partners are the Institute of Flight Mechanics and Control of Universität Stuttgart, AOCS/GNC and Flight Dynamics Department of Astrium Satellites, Germany, and the Control Systems Division of ESA/ESTEC. In this context, the authors thank Jens Levenhagen of Astrium Satellites, Germany, to support this extracurricular activity.
Moreover, this ESA PEE Handbook would not have been possible without the precursor work performed by ECSS Control Performance Working Groups and thus special thanks are expressed to their convenor, Mr Philippe Laurens of Astrium Satellites, France. Useful coordination between ECSS E60 branch and this activity was also facilitated by the E60 Discipline Convenor, Mr Christophe Rabejac of Astrium Satellites, France.

REFERENCES

[1] ECSS, “Control Performance Standard ECSS-E-ST-60-10C”, *ESA-ESTEC Requirements & Standards Division*, 2008.
[2] ESA Engineering Standardisation Board, “Pointing Error Engineering Handbook ESSB-HB-E-003”, ESA-*ESTEC Requirements & Standards Division*, 2011.
[3] VEGA Space Systems Engineering, "ESA Pointing Error Handbook”, *ESA Contract No.7760/88/NL/MAC*, 1993.
[4] ECSS, “Control Performance Guidelines ECSS-E-HB-60-10”, *ESA-ESTEC Requirements & Standards Division*, 2011.
[5] Bayard D. S., “A State-Space Approach to Computing Spacecraft Pointing Jitter”, *AIAA Journal of Guidance, Control, and Dynamics, vol.27 no.3*, May-June 2004.
[6] Bayard D. S., Neat G., “Performance Characterization of a Stellar Interferometer”, *IEEE Control Systems Magazine*, October 2007.
[7] T. Ott, W. Fichter, S. Bennani, S. Winkler, “Coherent Precision Pointing Control Design based on H_∞-Closed Loop Shaping”, *8th International ESA Conference on Guidance, Navigation & Control Systems*, Karlovy Vary CZ, June 2011.
[8] Lucke R.L., Sirlin S.W., San Martin A.M., “New Definition of Pointing Stability: AC and DC Effects”, *The Journal of the Astronautical Sciences*, Vol. 40, No. 4, p. 557-576, 1992.
[9] Pittelkau, M.E., “Pointing Error Definitions, Metrics, and Algorithms”, *American Astronautical Society*, AAS 03-559, p. 901, 2003.
[10] Boyd, S. P., & Barratt, C. H., “Linear controller design: Limits of performance”, *Prentice-Hall*, 1991.
[11] Winkler S., F. Cirillo, Ergenzinger K., Ott T., Wilhelm, R., Zaunick, E., “High-Precision Attitude Determination and Control of the EUCLID Spacecraft: Challenges and Solutions”, *8th International ESA Conference on Guidance, Navigation & Control Systems*, Karlovy Vary CZ, June 2011