EUROPEAN GUIDELINES FOR THERMO ELASTIC VERIFICATION

DE CILLIA (1), VAN OOSTRUM (2), PEMAN (2), GONZALEZ-LLANA (2), RAPP (3), MESCHENMOSER (3)), MARESCHI (4), DE PALO (4), PERACHINO (4), APPEL (5),

(1) Thales Alenia Space, 5 allée des Gabians - BP 99 - 06156 Cannes La Bocca cedex (France), Email : Mathieu.Decillia@thalesaleniaspace.com
(2) ATG europe, Space Business Park, Huygensstraat 34, 2201 DK Noordwijk (The Netherlands), Email: Alexander.Vanoostrum@atg-europe.com
(3) OHB System AG,Manfred-Fuchs-Str. 1, D-82234 Wessling (Germany), Email: Stephan.Rapp@ohb.de
(4) Thales Alenia Space, Strada Antica di Collegno, 253 – 10146 Torino (Italy), Email: Vincenzo.Mareschi@thalesaleniaspace.com
(5) European Space Agency, Keplerlaan 1, PO Box 299 NL-2200 AG Noordwijk (The Netherlands), Email : Simon.Appel@ext.esa.int

KEYWORDS

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ABSTRACT

Almost every Scientific and Earth Observation mission is faced with the need for thermo-elastic verification.

The European Space community has been, despite all previous activities to date, lacking commonly accepted guidelines for performing the end-to-end thermo-elastic verification.

To solve this issue, ESA emitted an invitation to tender, in 2020, to the European Community to work for European Methods for Thermo-Elastic Verification (briefly TEV). This project was aiming at supporting the European space community to establish Europe wide accepted and validated methods for thermo-elastic verification and at consolidating these in guidelines.

Since 2021, a consortium of the core partners Thales Alenia Space France and Italia, ATG Europe BV and OHB system AG has worked on the TEV project under ESA contract. A wide variety of topics supporting the guidelines have been covered, such as thermo-elastic terminology, temperature mapping methods, exchange of model and test data. The main achievement however is the establishment of a thermo-elastic verification process, which is the main subject of this article.

This article has the intention to act as a summary of the completed first issue of the European Guidelines of Thermo-Elastic Verification [1]. It is recommended to read this article together with [5] which contains an application of the guidelines to a test item.

1 INTRODUCTION

1.1 Multi-disciplinary nature

In most spacecraft projects thermal analyses are self-contained and executed in isolation from other disciplines: the thermal simulation of the space environment provides thermal output (e.g. for thermal control verification). The same appears for the majority of the structural analyses to verify the structure’s capability to sustain launcher environment (e.g. modal behaviour, sine and random analyses).

However, thermo-elastic verification (TEV) deals with prediction of stresses and deformations (structural analyses output) due to thermal loading of a structure (thermal analyses output). In many cases the thermo-elastic (TE) analysis is there to support the operational performance verification of a system. In such a case the output of the thermo-elastic analysis is input to the optical, Radio Frequency (RF) or other performance verification. Therefore, thermo-elastic verification is a multi-disciplinary activity of thermal and structural discipline in collaboration with system engineering and the respective performance engineering discipline(s).

1.2 No existing standard for performing Thermo-Elastic Verification (TEV)

Current ECSS standards and handbooks provide valuable requirements, guidelines, and best practices for the different subsystems and processes occurring within the frame of a space project. These technical standards provide such information in general from a monodisciplinary perspective. These appear not to cover the interaction with other disciplines and the need for TEV.

There have been several activities on the topic of improvement of methods for thermo-elastic prediction and verification. However, the dissemination of the results of these activities has been limited mostly due to a combination of IPR issues and the fact that parties were making their development in isolation from the rest of the European space community. Despite all previous activities till today, the European Space community has been lacking commonly accepted guidelines for performing the end-to-end thermo-elastic verification.

Because of the missing generally accepted TEV guidelines, quite some time is spent in each space project to reach consensus within the full customer chain about the way the TEV must be performed. The need to have accepted guidelines is also from this perspective clear.

In conclusion, there was no standard recommended way to perform a TEV within the European community, but there was a consensus on the need to have these. This need is well confirmed by the European space community. They expressed their interest in such guidelines through the well-attended meetings of the European Working Group on Thermo-Elastics [2]. One of the objectives of this working group is to establish an ECSS style standard or handbook for thermo-elastic verification. The interest for these guidelines is also demonstrated through the active contribution of many working group members to the first version of the guidelines through thorough reviewing of the draft version.

1.3 The guidelines are not a TEV cookbook

The document, “European Guidelines for Thermo-Elastic Verification” [1], tries to formulate a recommended way for approaching thermo-elastic problems in spacecraft engineering.

Due to the diversity of the thermo-elastic problems, the guidelines cannot and do not intend to be a cookbook for thermo-elastic verification. In other words, the guidelines do not dictate in detail how models should be built, how load cases should be selected or any step-by-step execution of analyses. Instead, the guidelines in this document try to guide the thermal and structural engineer through a process that supports them to develop an understanding of the critical thermo-elastic deformation mechanisms and to identify the parts of the structure having the highest contribution to the degradation of the performance or are the sources of the highest stresses.

The intended benefit is that this process directs the engineers to the parts of the models where model enhancements have the highest likelihood to make a difference for the quality of the predictions.

As is also expressed in the conclusion, experience with the guidelines will show whether the way these are formulated is adequate and cover sufficiently all relevant topics as well as identify additional topics to be covered. These experiences form a basis for future further development of the guidelines.

2 SUMMARY OF THE TEV GUIDELINES

2.1 Guidelines on this article and introduction of terminology

A wide variety of topics supporting the guidelines have been covered in the European Guidelines of Thermo-Elastic Verification [1]., such as thermo-elastic terminology, temperature mapping methods, exchange of model and test data. The main achievement however is the establishment of a thermo-elastic verification process. This chapter deals specifically with this thermo-elastic verification process.

An important part of the explanation of the guidelines is devoted to a systematic numerical process. To allow the explanation to be generic enough to be useful for an as wide as possible range of thermo-elastic problems, the terminology also needs to be to some extent generic. These terms may be considered abstract and might limit the intended appreciation of the guidelines. Here, a few terms will be introduced with the intention to simplify the understanding of this chapter.

One main purpose of doing analysis is to verify that a system is compliant to the needs that are put down in the requirements. In the context of thermo-elastic problems for spacecraft applications one of the important requirements is related to the operational performances of one or more instruments on a spacecraft. However, the thermo-elastic sizing can also be a major point of interested for an instrument, as for example in the case of infra-red space instruments.

The design of the spacecraft and its instruments have the objective to limit the effects of the environments in space on the performance. To express the effects of the environment on the performances a quantity called “performance parameter” is introduced to assess the level of degradation of the performance. An example of a performance parameter is the rotation angle of the line of sight (LoS) of an optical instrument. It could also be a safety margin for stress level in a component.

When the thermal and structural model are going to be built, it is important, before the start of the modelling, to investigate which deformations of the structure could reduce the performance and thus increase the response of the performance parameter. The mechanisms behind these deformations are called “deformation mechanisms”. The physical origin of these mechanisms is, not surprisingly, the form of temperature fields, the coefficient of thermal expansion (CTE) of the materials used in the structure in combination with the constraints and the relative stiffness of the various components. It is important that the combination of thermal and structural models can capture these deformation mechanisms to simulate the deformation fields that could affect the performance.

For various reasons it can be important to understand the contribution of the different parts with their inherent deformation mechanism to the predicted degradation of the performance. Then the term "feature" is introduced in this article to describe any potential aspect in the mathematical model, physical model or design, which may affect the magnitude of the TE responses. Some features can be quantified, but others cannot. Material properties, mesh density or the representation of a certain part are examples of features. Understanding the effect of the uncertainties these features have on the response of the performance parameters is essential for confidence in the quality of the models and their final results.

2.2 Definition of the steps in the TEV process

To verify that the response of the performance parameters of a structure remains within specification during a mission, it is fundamental to understand the deformation mechanism and the associated contribution of certain features to the structure's response under the applicable thermal environment. For this purpose, a thermo-elastic (TE) classification process is introduced through which the criticalities of the various features of a structure can be identified by using thermal and structural models. The TEV process is based on four main steps:

1. Identification: helping to create a design and identifying which performance parameters are relevant for the performance verification, and which deformation mechanisms may potentially be important for the responses of the performance parameters.
2. Modelling: best practices to capture all relevant deformation mechanisms and establish mathematical sanity of the modelling.
3. Classification: establish insight in which thermal cases, thermal features, mechanical features, and thermo-mechanical features of the design are critical for ensuring positive margins on these performance parameters.
4. Final performance compliance verification: once a model is deemed fit for purpose the formal verification against requirements can be performed.

Although the steps above are presented as a linear sequential process, in general the creation of a design concept and its validation is an iterative process that is potentially leading to various updates of the design. This iterative process is schematically presented in Fig. 1.

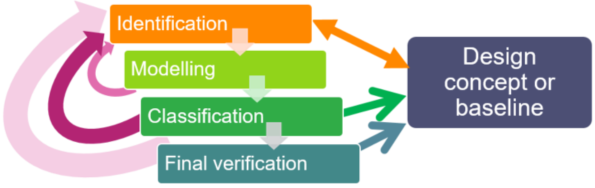

Figure 1: TEV process and interaction with the design

2.3 Step 1: Identification

The identification step is the initialisation of the TEV process (Fig. 1).

The objectives of this step are to:

- establish the TEV team with colleagues of the structural, thermal and systems engineering disciplines (including specialists in the relevant domains: optics, RF, …).
- Identify the TE needs for the design concept or familiarise the TEV team with the provided design concept
- identify which performance parameters are relevant for the system (i.e., what is the key output of the models?).
- identify which deformation mechanisms and phenomena affect the performance parameters (i.e., what physics, model features, etc. affect the most relevant responses of the system?).

During this identification step no modelling of the system under evaluation is needed. Of course, it is not prohibited to support the identification process with some elementary modelling exercises.

The quality of the result of this step is decisive for the success of the TEV process. Depending on the project phase, the identification step can support the development of the concept or confirm a sound baseline principle. It is then followed by a more detailed identification of the performance parameters in relation to the performance requirements.

It is good to point out at this stage that each performance parameter must be accompanied by deformation mechanisms that may have the potential to be responsible for the responses of the performance parameter.

2.3.1 TEV team

The TEV team is established with at least colleagues of the design, structural, thermal and systems engineering disciplines.

Above all, it is considered essential that performance engineers are involved especially in the identification process. There are at least two reasons for that:

- It is crucial to ensure the TE engineers have a good understanding of the high-level design choices that lead to the distortion budgets

  available for TE. The TE engineers need the performance engineer to translate performance requirements into TE requirements.
- It allows the TE team to produce the most appropriate information for the performance evaluation for which the TE results are used as input. The performance engineer can guide the TE engineers to provide the right data in the right format.

2.3.2 Design concept or baseline

Depending on the phase of the project, the experience of the company or the chosen use of a recurrent design, there can be roughly two possibilities identified as starting point for the identification step:

1. A design is needed to be built from scratch.
2. A design is already defined.

In the 1st case, the TEV team must identify the TE needs for the design concept. This part of the identification step aims at implementing where possible the needs from TE perspective in the design: Sizing need (eg, CTE mismatch or high gradient) or stability needs often linked to the operational performance needs (eg, high or low and local or global). As indicated by Fig.1, the definition of the design baseline is expected to be iterative within the identification step. However, thermo-elastic requirements are not the only possibly driving requirements for the design during the full lifetime of the spacecraft.

In the second case, the design was prepared without involvement of the current TEV team. The team must familiarise themselves with the provided design concept.

2.3.3 Identification of performance parameters and physics to be simulated

Now a design concept or baseline is available, the essence of the identification step is to develop a good understanding of the thermal and structural physics that must be simulated during the next modelling step.

Two closely linked identification processes must be executed by the TEV team, being:

- Identification of performance parameters from the performance requirements for the system under study.
- Identification of deformation mechanisms having the potential to affect the response of the performance parameters and their associated needed features

With the help of the performance engineer, the thermal and structures engineer must translate system operational performance requirements into performance parameters, often as mathematical expressions linking the deformations of the structure to quantities relevant for the performance evaluation.

Also, locations in the structure that are critical in terms of potential high mechanical stress levels need to be identified.

Thermo-elastic deformations are governed by the interaction of:

- Temperature field
- CTE
- State of constraints: this is the interaction between stiffness constraints and thermally imposed deformation.

It is considered crucial to generate a sound understanding of all three aspects and their potential interaction to be able to identify all the relevant thermo-elastic deformation mechanisms. As shown in Fig 2., the three aspects cannot be assessed separately but need to be considered in combination.

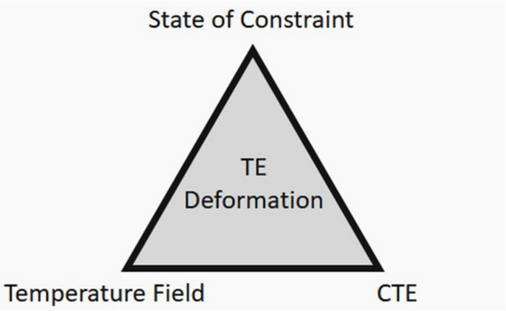

Figure 2: Governing aspects of thermo-elastic deformations

2.4 Step 2: Modelling

The modelling step focuses on best practices to capture all relevant thermo-mechanical deformation mechanisms, their associated needed features and establish mathematical sanity of the modelling. (Fig. 1.).

The objectives of this step are to prepare thermal and structural models that:

- Can produce the responses of the performance parameters.
- Can translate the performance parameter into numerical value (stress, or LoS etc)
- Can simulate adequately deformation mechanisms identified to be potentially important for the responses of the deformation mechanisms and their associated needed features.
- Have an adequate initial mesh resolution for representing the relevant physics
- Are verified on mathematical adequacy and sanity.

An alignment between CAD, thermal and structural model is needed to avoid inconsistencies in the configuration of different models to prevent simulation errors due difference in representation of the structure.

In industry, there is a wide range of modelling techniques for the different aspects of S/C structures. It is not the intention of this guideline to dictate a certain way of modelling, simply because there is not enough information available to promote one way of modelling over another for any given project, application, design, etc. However, certain modelling aspects are highlighted which are important in thermo-elastics as the ability to capture the deformation mechanisms and features, the potential re-use of an existing models and the collaboration between disciplines.

2.4.1 Capturing the deformation mechanisms and features

After the performance parameters and their driving deformation mechanisms have been identified, the structural and thermal models are being developed. It is recalled that the structural model needs to be suitable for the application of the temperature fields responsible for the identified deformation mechanisms. At the same time the thermal model needs to be able to generate these temperature fields to be used as loading for the structural model.

In the process of building the thermal and structural models, care must be taken that the features identified to have a role in the deformation mechanisms are being represented in the models. Some of these features are mandatory input data such as material and geometrical properties (e.g. shell thickness values) others relate to the level of detail of representation.

If the important features are explicitly modelled, they can be used as design parameters in potential subsequent steps for sensitivity analysis to investigate their impact on the performance.

In general, it cannot be decided at this stage which level of detail and mesh resolution is needed. This will be identified in a later stage, after performing the classification. It is therefore recommended in this step to have the models with sufficiently high level of detail to capture the basic physics, which is in this context the relevant deformation mechanisms.

2.4.2 Re-use of existing model

In many cases the thermal model has been developed for thermal control purposes and likewise the structural model has been developed for dynamic analyses. These models are often more or less directly used for thermo-elastic analyses, as well. While this may be appropriate in some cases it is important to verify whether the identified relevant deformation mechanisms can be simulated jointly in the thermal and structural model. If this is not the case, the models must be modified to become useful for the purpose of thermo-elastics verification. The ultimate objective is to adequately capture the relevant thermo-elastic deformation mechanisms to simulate the performance parameter responses. This will allow the models to be used as starting point for the numerical classification for screening the level of contribution to the performance parameter responses of the individual features of the structure.

2.5 Step 3: Classification

The classification step focuses on screening of thermal cases, thermal-, mechanical-, and thermo-mechanical features of the design and model on their contribution to the response of performance parameters. It is much recommended to read this theoretical section together with example provided on the [5].

This step integrates all the TE simulations to be performed at thermal and structural level.

The classification step is using the initial models that were developed in the previous step with the objective of being able to simulate the deformation mechanisms.

The classification of TE relevant features is based on three main aspects:

- Initially predicted overall margin in a nominal model, for each individual performance parameter (see §2.5.1)
- The relative contribution of a model features to the response of a performance parameter (see §2.5.2)
- The uncertainty of response of the performance parameters due to the uncertainties in the feature (modelling and/or physical properties) §2.5.3

In all cases the objective is to end up with thermal and structural models that can be declared to be adequate, i.e. good enough, for their purpose. Essential is that the resulting models will be supported by a substantiated confirmation of their adequacy.

However, during all the classification, the process can lead to the conclusion that a design modification is needed.

2.5.1 Setup of analysis and first runs

The objective of this part of the work is to obtain an initial familiarisation with the thermo-elastic behaviour of the structure, represented by the current set of models.

It may be tempting to complete this step as quickly as possible and focus on the full detailed classification instead. However, since the results from this step will feed into all subsequent steps, a thorough initial assessment will pave the way to the most efficient course of action in the complete numerical classification.

Selection of thermal verification case

First an initial selection of representative TE cases is made. The purpose of this initial selection is twofold:

- Provide representative thermal cases to verify the (mathematical) correctness of the mapped temperature field. Especially when using automated processes and when analysing many thermal cases, it is recommended to focus on a small set of cases and verify these in detail.
- Provide thermal cases which can be used for the assessment of initial margins. This is the leading purpose.

Having representative initial margins of the system allows for a more efficient classification process. Based on the initial margins it can be justified to reduce the classification effort by skipping some steps or, the opposite, to go for a detailed classification exercise.

Preparation of temperature mapping process with corresponding validation runs

In this step the temperature mapping processes is prepared. The specific work required here depends on the tools available and the temperature mapping method that is used. An overview on the considerations related to this aspect can be found in [1].

Using the initially selected thermal cases, the first analysis results are obtained. The main purpose of this step is to ensure the mathematical correctness of both the thermal and structural models and correct transfer of temperatures between the models through temperature mapping. This is typically done by checking:

- temperature fields mapped on the structural model
- deformation fields
- stress fields

for unexpected and unphysical values.

Setup of (automated) analysis chain and determination of initial/preliminary performance margins

The thermo-elastic analysis process involves large amounts of data. An automated analysis chain supports the process and allows efficient verification of many cases. This is essential for TEV.

Using the initial selection of thermal cases, margins for the performance parameters can be computed after the setup of (automated) analysis chain. These initial margins determine the extent of the subsequent numerical classification.

Although this computation of margins is not the final performance verification, it is highly advised to already consider and apply, as much as is possible at this stage, the considerations of the final performance compliance verifications as discussed in §2.6.

The preliminary margin should confirm that the deformation mechanisms identified during the identification step are well simulated. As consequence, the performance parameter margin associated to these deformation mechanisms should also be well simulated.

It must be stressed here that the initial margins are based on a sub-set of thermal cases. During the course of the TEV process other cases need to be assessed or, with justification, being considered as not driving the performance.

Performance parameter, feature and thermal case down-selection.

The initial margins determine the further approach for the TE verification, by application of the numerical methods and classification.

The basic premise is that a down-selection (of features, thermal cases, performance parameters etc.) is done only on the basis of a complete numerical justification. Practical limitations however do not always make it feasible or desired to do a complete classification. In such a case, if well justified, the initial margins can be used to justify a tailored classification approach. The initial margins can then be used to sub-select, the features, thermal cases and performance parameters that then are to be assessed in more detail. Here it is important to consider the following:

- When an extensive down-selection is performed (i.e. small amount of features etc. is left to be assessed), then the numerical classification can be performed comparatively quickly. However, uncertainty in the model will be larger and it might not be possible or at least difficult to declare the model fit for purpose. In that case an iterative loop might be needed where the classification is performed multiple times. In these additional iterations part of the model may (for instance) be detailed further to reduce the uncertainty.
- If the final classification is performed without any down-selection, then this will become a very extensive and time-consuming process. Potentially, significant more time is spent than is needed. For instance, already through a quick assessment it can be determined that the model would need to be updated or even more fundamentally, that the design concept won’t work as indicated by the overall too low margins.

2.5.2 Thermo-mechanical classification methods

Now the down-selection on the performance parameter is achieved, the objective of the thermo-mechanical classification methods is to determine the absolute and relative contribution of the different thermo-mechanical features of the structure to the responses of the performance parameters.

Thermo-mechanical classification methods are based on the different ways to use the TE transfer matrix. This matrix_defines the translation from the thermal node temperatures to performance parameter outputs.

$$\{u\} = \begin{bmatrix} TE \\ Transfer \\ Matrix \end{bmatrix} \{\Delta T\} \qquad (1)$$

The basic idea of the used of the TE transfer matrix already exists for a long time. For instance, in [3] Airbus DS presents a process that follows a similar logic, using unitary temperature increase methodologies to highlight the main thermal and mechanical contributors to the stability.

These methods will confirm also that the identified TE deformation mechanisms are well simulated, and that the TEV team has well understood the design concept.

This category of methods is characterised by the fact that the methods are using the initial thermal and structural models assuming that these have been set up to adequately to represent the identified deformation mechanisms. In general, these methods therefore do not require any modification of the models for the objective of determining the contributions of the different thermo-mechanical features. The fact that models are not changed allows for introducing an efficient way to represent the relation between temperature fields from the thermal model and deformations or even performance parameter responses determined with the structural model.

Depending on a high or low value of the performance margin, it can be decided to what level of detail the contributions of the individual features need to be determined.

2.5.3 Thermal and structural model impact assessment

At this stage the features linked to the selected performance parameter are classified.

The objective of the impact assessment of the thermal and structural model is then to determine if changing the representation of features in the model makes a difference, thus have an impact, for the responses of the performance parameters. This category of numerical methods does require changes to the models.

Depending on the feature variation, thus changes to the models, some of transfer matrices used for the thermo-mechanical classification can still be used. Complementary knowledge of possible consequences of the uncertainties of the different features on the performance degradation, can justify to either consider further enhancement not worth the effort, or, the contrary, to consider it essential to spend time on further enhancements.

2.5.4 Conclusion of adequacy of thermal and structural TE models

The underlying decisions to potentially select features of the models for further work or re-design, is relying on the following inputs:

- The performance margins relative to the required performance
- The contribution of the individual features of the structure to the degradation of the performances
- The uncertainties in the individual features and their impact on the degradation of the performances

In early project phases, it can also highlight a need of extending the set of verified thermal cases and down-selection of them for a future phases in which both the design and the verification levels are mature.

2.6 Step 4: Final Performance Compliance Verification

Now the models are considered “fit for purpose”, the last step is to run all the cases that are considered relevant and determine the performance parameter values and their corresponding margins relative to the required values.

In thermo-elastic analysis, as in most of other engineering analyses, engineers study the behaviour of the real technical systems by means of mathematical representations of the physics and subsequent simulations under certain fixed conditions. The mathematical models for this purpose are based on thermal and mechanical parameters that are affected by inaccuracies. Those inaccuracies translate into uncertainties of the analysis results and consequently uncertainties in the performance of the thermo-elastic design. The uncertainties can affect the performance parameter in a positive or negative way. It is not always trivial to establish this level of uncertainty and what it means for the expected range of the response of the performance parameter.

There are in general two approaches applied to cover the uncertainties, also for thermo-elastic problems. The most common one is application of a factor of safety which is also a standard approach for strength verification as for instance is reported in the ECSS standard “Structural factors of safety for spaceflight hardware” [6]. The second well known approach is the use of stochastic methods.

The applicable thermo-elastic factor of safety, K_{TE}, can be produced through accumulation of the factors of safety covering the uncertainties in the thermal model (K_{MT}), the thermal environment (K_{ET}), the temperature mapping process (K_{MAP}) and finally the structural finite element model (K_{MS}) [7].

$$K_{TE} = K_{MT} K_{ET} K_{MAP} K_{MS} \qquad (2)$$

In case the use of factors of safety is selected, the applicable value of the thermo-elastic factor of safety must be agreed at the beginning of the project.

The second one is the application of stochastic methods. Results of stochastic simulation give a good indication of the potential spread of TE output due to spread of model parameters. The knowledge of this spread will allow to increase the confidence on the minimum performance that can be achieved.

Traditional stochastic methods, like Monte Carlo Simulation (MCS), are time consuming and require significant computational resources. Promising alternatives based on the Rosenblueth 2k+1 method [8] and the Univariate Uncertainty Quadrature (URQ) [9] can produce comparable results with a fraction of the computational effort. These methods do however have some limitations, but when handled with care the methods can provide good insight in the impact of the uncertainties on the performance parameter responses.

With the completion of the performance compliance verification the full TEV analysis campaign is concluded and allows to produce the reporting.

3 CONCLUSIONS, OUTCOMES AND WAY FORWARD

The first version of the European Guidelines on Thermo-Elastic Verification has been issued and is available from the website of the European Working Group on Thermo-Elastics [2] as well as via the ESA Technical publications page [4]. Many aspects are touched upon. Aspects that were collected from papers presented in the past by several Working Group members. Obviously, also the experience of the authors is shared with the reader as good as possible.

Due to the need to have the guidelines applicable to as many thermo-elastic problems as possible, the terminology may be considered abstract.

The authors are aware, that despite their efforts, these guidelines are not complete. The valuable feedback from the members of the European Working Group on Thermo-Elastic is as good as possible implemented. However, there were points raised that could be properly treated in the remaining budget of the guidelines development project or needed a complementary study. These topics are collected in the appendix of the guidelines document.

Hopefully the guidelines are considered beneficial for the upcoming projects. The use of the guidelines will for sure reveal shortcomings and limitations. Users of the guidelines are encouraged to report any problems encountered to thermoelastic@esa.int. These experiences will then be combined with the untreated review points, collected in the appendix, to form a basis for a future activity for further development of the guidelines.

4 ABBREVIATIONS AND ACRONYMS

TEV	Thermo-Elastic Verification
TE	Thermo-Elastic
RF	Radio Frequency
LoS	Line of sight
CTE	Coefficient of Thermal Expansion
MCS	Monte Carlo Simulation
URQ	Univariate Uncertainty Quadrature

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