STOP ANALYSIS FOR THE CLIM INSTRUMENT; APPLICATION AND LESSONS LEARNED

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ABSTRACT

As part of the CO2M mission, OIP has been developing the Cloud Imager Instrument (CLIM). The CLIM instrument serves to detect the presence and position of the clouds in the CO2I (Main CO2M instrument) field of view, with the aim to support the data screening and line of sight (LoS) analysis. The instrument development is currently in phase D. As part of instrument verification, ATG has provided thermal and mechanical engineering support to OIP, including end to end structural-thermal-optical (STOP) analysis.

Very strict LoS stability requirements for the CLIM instrument resulted in the need for a robust and well optimized thermal control system (TCS). By integrating the STOP verification as part of nominal thermal analysis iterations, it was possible to very efficiently characterise the main drivers of LoS perturbations and optimize the TCS accordingly.

In this paper, the STOP verification process is further explained focussing on two aspects;

- Practical implementations and applications of a TE classification and TCS optimization process for CLIM
- General lessons learned and experiences of applying methods outlined in the European Guidelines for Thermo-elastic Verification, STM-285 [1], which was developed in parallel to CLIM verification and to which ATG also contributed.

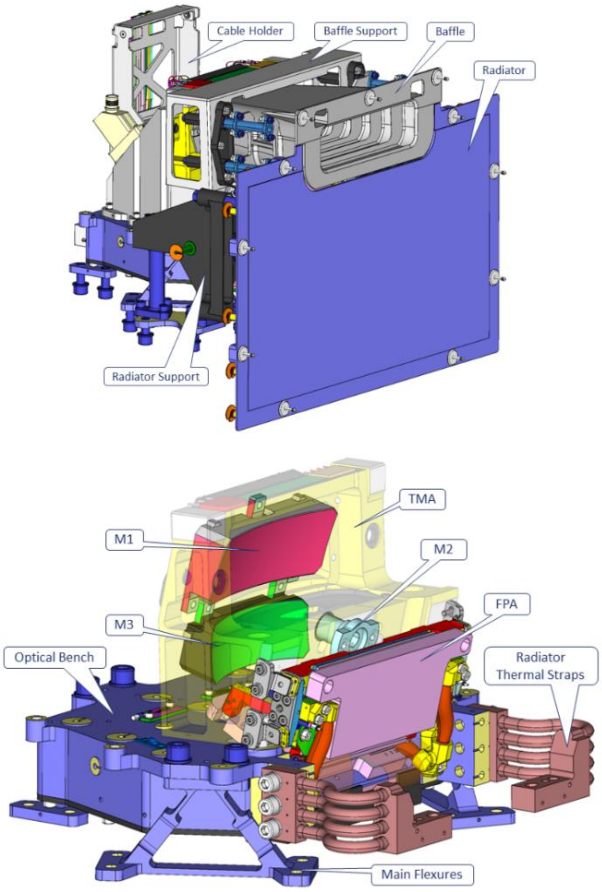

Figure 1: CLIM Instrument general architecture

THE CLIM INSTRUMENT

The CLIM instrument is a compact optical instrument developed by OIP for the CO2M mission. It operates at two different wavelengths (VNIR and SWIR) and serves to detect the presence and position of the clouds in the CO2I (Main CO2M instrument) field of view, with the aim to support the data screening and line of sight (LoS) analysis.

A schematic overview of the instrument is provided in Figure 1.

The CLIM Optical Unit (OU) is composed of a single monolithic optical bench and a cover that are bolted together and form a closed aluminium structure. On the optical bench, the Spectral Imager (SI) unit, the baffle, and its corresponding baffle holder are mounted. The Spectral Imager (SI) unit is composed of the Three Mirror Anastigmat (TMA) assembly and the Focal Plane Array (FPA) structure that contains the Visible and Near-InfraRed (VNIR) and Short-Wave InfraRed (SWIR) detectors. The OU features three A-shaped titanium flexures that serve as the main interface to the spacecraft. An earth-pointing radiator, that is thermally connected through two thermal straps to the optical bench, is mounted on the spacecraft in front of the instrument. This radiator has its own supporting structure and is thermally decoupled from the spacecraft through four titanium insulators. The earth pointing radiator provides the basis and as well a part of the challenges of the TCS, as heat loads over the orbit can vary significantly whereas the instrument requires strict temperature stability.

The TMA assembly is based on existing heritage from OIP on the Proba V instrument which has been operating successfully for many years. Even though the mechanical design of the TMA is mostly identical, stricter LoS requirements impose also stricter requirements on the thermal control system of CLIM.

GUIDELINES FOR THERMO-ELASTIC VERIFICATION & RELEVANCE ON CLIM

Parallel to the phase B2 development of the CLIM instrument, in addition to supporting OIP in the thermal and mechanical verification of the CLIM instrument, ATG was also involved in the development of European Guidelines for Thermo-elastic Verification, STM-285 [1]. As such, CLIM has (informally) served as one of the earlier test cases for the developed guidelines. The main Thermo-Elastic Verification (TEV) process is summarized into four steps: (1) Identification, (2) Modelling, (3) Classification and (4) Final performance verification.

In the context of this paper, focus is laid on the classification system and how that has helped with the analytical verification of the system. However, some short notes are provided on the other steps of the process.

Identification:

- Purpose: establishing which performance parameters are relevant for the problem, and which thermo-mechanical deformation mechanisms may critically affect these performance parameters. A performance parameter is defined as any output supporting the verification of the compliance to a TE performance requirement. It can be either a direct TE output, or some form of derived magnitude obtained by post-processing a direct TE output.
- Application on CLIM: For CLIM the optical performance has been the primary driver (LoS, mirror deformations) as well as survival of the item.

Modelling:

- Purpose: best practices to capture all relevant thermo-mechanical deformation mechanisms and establish mathematical adequacy of the modelling.
- Application on CLIM: As the design of CLIM was partially based on the existing heritage, already from phase B2 a high detail thermal model was implemented. In addition, a large part of the TMM was generated using FE model & (py)Sinas, yielding highly accurate conductors and capacitance. In phase C the models were updated according to the relevant design changes. In addition, details were added in the model for regions that were found to have a high TE relevance in the previous phase. A figure of the thermal model is provided in the next section.

Classification:

- Purpose: establish which thermal cases, thermal features, mechanical features, and thermo-mechanical features of the design are critical for ensuring positive margins on these performance parameters. The term feature is used to describe any potential aspect in the mathematical model, physical model or design, which may affect the magnitude of the TE (Thermo-Elastic) responses. Some features can be quantified, but others cannot. Material properties, mesh density or the representation of a certain part are examples of features.
- Application on CLIM: As the CLIM instrument is high CTE design, the primary focus of the classification was to consider the thermal and thermo-mechanical features. More details on this can be found in the subsequent section as it is the focus of this paper. In particular the following types of assessment are discussed in this paper:
    - A thermo-mechanical classification, highlighting the key contributors of TE deformation in a structure (method also explained in the TEV guidelines)
    - An extension of this thermo-mechanical classification to show how it can be used to deconstruct much more complex problems (extension not covered in TEV guidelines).
    - A set of different sensitivity studies (method also explained in the TEV guidelines)

Final performance compliance verification:

- Purpose: once a model is deemed fit for purpose the formal verification against requirements can be performed.
- Application on CLIM: For the case of CLIM the primary parameter of interest LoS and this will be the focus of this paper. Other parameters (e.g. mirror surface deformation) were also assessed directly by OIP using the output from the thermal and TE and analysis but won't be covered here.

For more details on the guidelines one can refer to STM-285 [1], or to one of the previous ECSSMET proceedings.

As previously noted, the emphasis on this paper is primarily on the classification methods and how these were used in CLIM and some of the conclusions and lessons learned that can be extracted from these.

APPLICATION OF CLASSICATION PROCESSES ON CLIM

This paper covers three different iterative loops; one in phase B2 and two in phase C of the projects. The focus of the iterations of the Phase B2 analysis initial sizing of the TCS system, including positioning of the heaters and sensors. In phase C, the focus was shifted to (re)-verifying the design after the design was detailed and looking in more depth at the margins and sensitivity of the design.

As noted previously, the primary concern of the CLIM instrument from a TE-perspective is the LoS stability. To facilitate the direct assessment of the LoS, dedicated transfer matrices were setup to evaluate the LoS with every iteration of the TCS and the corresponding updated thermal node temperatures $\{\boldsymbol{T_{Thermal\ Node}}\}$ according to the following equations:

$$\begin{bmatrix} x_{LoS} \\ y_{LoS} \end{bmatrix} = \begin{bmatrix} \mathtt{Optical} \\ \mathtt{Transfer} \\ \mathtt{Matrix} \end{bmatrix} \{\delta_{optical}\},$$

$$\{\delta_{optical}\} = \begin{bmatrix} \mathtt{TE} \\ \mathtt{Transfer} \\ \mathtt{Matrix} \end{bmatrix} \{T_{Thermal\ Node} - 20.0\}$$

The optical transfer matrix accounts for all the displacement/rotations of the three mirrors.

The primary LoS requirement of concern was the stability of the LoS, which needs to be stable between calibration windows. Therefore, the stability did not just need to be assessed within an orbit, but also between the different pointing modes and seasons (inter-orbit):

- Season: Hot Case (HC; Winter) & Cold Cases (CC; Summer)
- Pointing: Nadir & sun glinting modes

An overview of the thermal model can be found in the following figure.

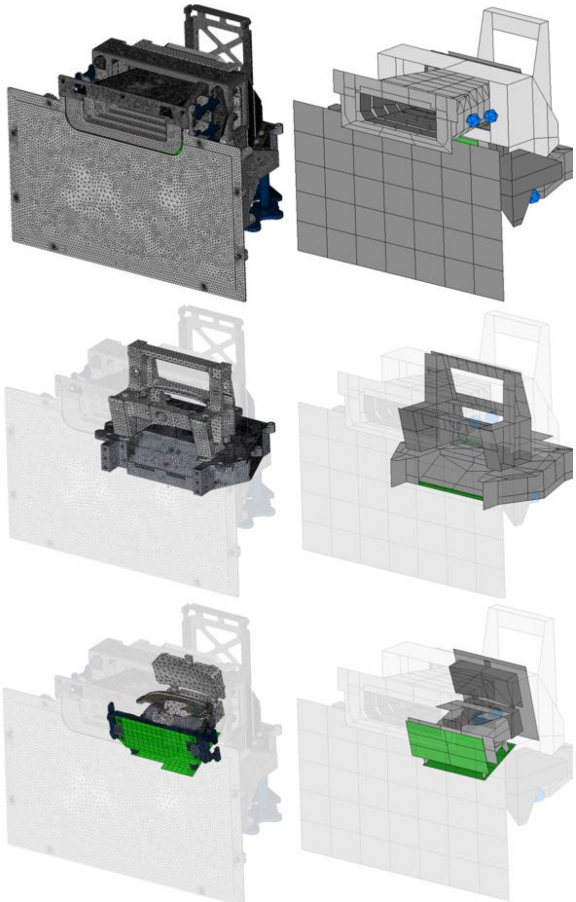

Figure 2 CLIM Structural and thermal model

Phase B2 - Architecture and initial sizing of the TCS: using a basic classification approach

The TCS architecture for the CLIM instrument was initially foreseeing, results permitting, a simple form of thermal control. A single on/off heater line was foreseen on the optical bench, near the attachment point of the thermal straps. This heater line serves to ensure that a consistent heat load was received through the earth facing radiator. Combined with the thermal mass of the optical bench it was hoped that this would provide sufficient LoS stability.

In the following figure the CLIM LoS results are provided for the nominal cases corresponding to the baseline thermal control. The effect of heater switching (on/off logic) is clearly noticeable. More importantly, this basic form of thermal control did not meet performance requirements for the LoS, due to the large difference between the different orbits. The overall LoS performance is driven by two different effects: Seasonal effects, driven by different season and/or orbits, which is primarily driven by the average temperature of the instrument. In addition, there are the orbital effects, resulting from (a lack off) temperature stability within the orbit.

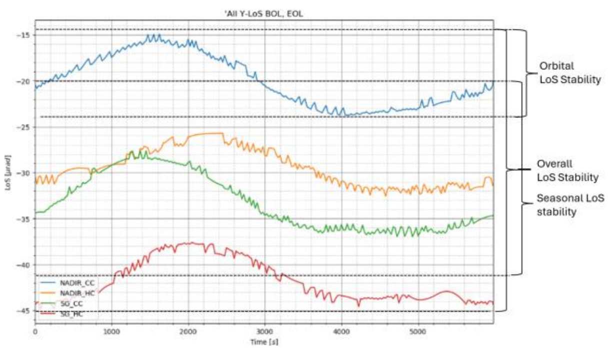

*Figure 3 Initial LoS results, with a single heater line (OB) and on/off heater logic (PDR Phase)**

With these unsatisfactory baseline results started the process of better understanding and improving the LoS performance.

A useful way to better understand the contributors to the LoS, is by plotting its individual contributors. These contributors provide a useful indication to the source of the LoS stability. By using linear superposition the LoS equation can be decomposed as follows:

$$\begin{bmatrix} x_{LoS} \\ y_{LoS} \end{bmatrix} = \begin{bmatrix} x_{LoS} \\ y_{LoS} \end{bmatrix}_{group\ 1} + \cdots + \begin{bmatrix} x_{LoS} \\ y_{LoS} \end{bmatrix}_{group\ n} + \cdots + \begin{bmatrix} x_{LoS} \\ y_{LoS} \end{bmatrix}_{group\ N}$$

with

$$\begin{bmatrix} x_{LoS} \\ y_{LoS} \end{bmatrix}_{group\ n} = \begin{bmatrix} \mathit{Optical} \\ \mathit{Transfer} \\ \mathit{Matrix} \end{bmatrix} \{\delta_{optical}\}_{group\ n}$$

and

$$\{\delta_{optical}\}_{group\ n} = \begin{bmatrix} \mathit{TE} \\ \mathit{Transfer} \\ \mathit{Matrix} \end{bmatrix} \begin{bmatrix} \{0\}_{group\ 1} \\ \cdots \\ \{T_{Thermal\ Node} - 20.0\}_{group\ n} \\ \cdots \\ \{0\ \}_{group\ N} \end{bmatrix}$$

Where $group\ n$ represents a group of thermal nodes belonging to a single thermomechanical feature.

In Figure 4 these individual contributors are plotted. It is noted that results in the figure are presented for the Nadir Pointing Hot Case, but similar trends can be observed for the other cases.

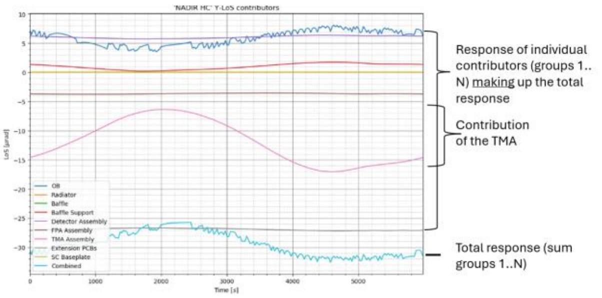

*Figure 4 LoS contributors with a single heater line (OB) and on/off heater logic (PDR Phase) **

It can be clearly observed that the largest variations within the LoS of an orbit are caused by perturbations in the TMA frame. A more stable temperature field for this part is therefore expected, and confirmed, to have the biggest impact on the LoS stability.

In Figure 5 an additional heater line was implemented to improve the temperature stability of the TMA. This additional heater line on the TMA was then able to significantly improve the LoS stability. Due to the (re)positioning of the heaters, the simple on/off heater logic has become even more problematic though, with very high frequency oscillation clearly visible.

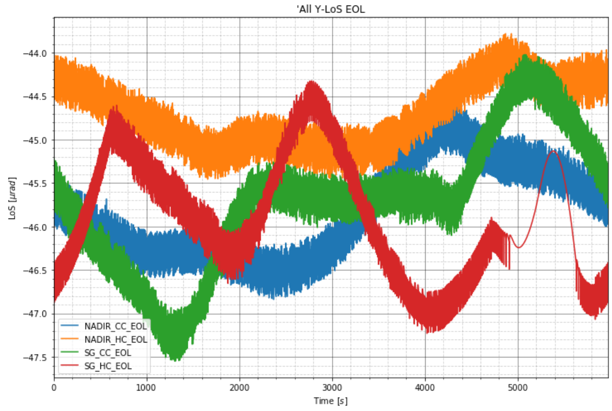

*Figure 5 LoS results, with a two heater lines (OB+TMA) and on/off heater logic (PDR Phase) **

As a final step to improve the LoS, PI control was added, instead of on/off heater logic. These results are provided in Figure 6.

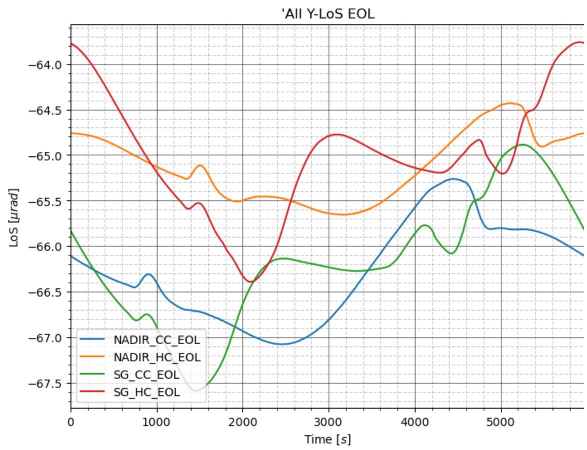

*Figure 6 LoS results, with a two heater lines (OB+TMA) and PI heater logic (PDR Phase) **

The approach as shown in the previous graphs was found to be highly advantageous. It also aligns well with part of the philosophy of the classification step in the aforementioned thermo-elastic verification guidelines, by focusing the engineering effort on those aspects that are found to be most important. In particular the **following advantages were noted:**

- The approach is rather direct or “linear”, meaning that limited to no guessing is involved to understand the TE problem.
- Iterations were found to be very efficient. There is initial effort associated with setting up the Thermo-Elastic Transfer matrices but any iterations after this can be performed very efficiently. Iteration on the thermal control system -including a full assessment of the LoS - happened in a matter of minutes, rather

than days or even weeks if the analyses are performed independently.
- A deeper physical understanding of what is happening is also provided, ensuring that the attention is focused on those parts that matter most.

**Note that absolute LoS results vary between all different plots. This is the result of different set-point of the TCS to improve the heater/power budget margins. These iterations are outside the scope of this paper.*

Phase C – Design updates: extending the classification approach

Whereas the primary focus during PDR was the general feasibility of the TCS, in the CDR additional attention was put on the following aspects.

- Effect of design updates (post PDR)
- Design sensitivity, TCS sizing and system margins.

Design updates had been made after PDR was closed. These updates were implemented in the new CDR structural and thermal models, which after analysis showed a decrease in performance. At the end of PDR a LoS stability of 4 µrad was achieved, which degraded to 20 µrad in the early CDR model. Although the fundamental design concept had not changed, many smaller design changes had been implemented. An overview of the new LoS can be found in Figure 8.

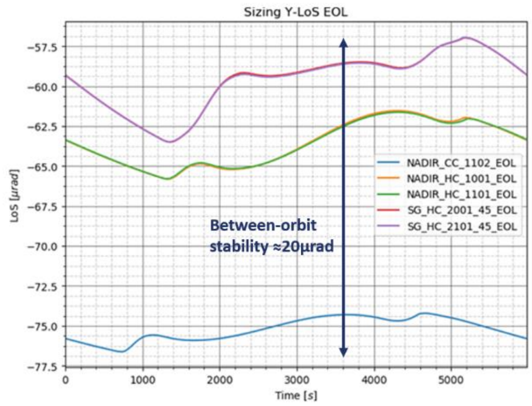

Figure 8 LoS results, with two heater lines (OB+TMA) and PI control heater logic (after first CDR release)

The process of decomposing the LoS stability into its contributors, as explained in the section for Phase B2, has been used and extended to identify the main changes and drivers that caused the decrease in performance. As with the examples shown in phase B2, this approach is based on the concept of linear superposition.

In the updated model the LoS stability was primarily driven by the variations between the hot and cold case, rather than the variations within a single case (i.e. orbit). The LoS stability can be decomposed into its contributors for both the hot and the cold case (i.e. seasons). Inspecting the difference between the hot and cold case contributors reveals the main contributors to the between-orbit stability, i.e. the main driver of the LoS

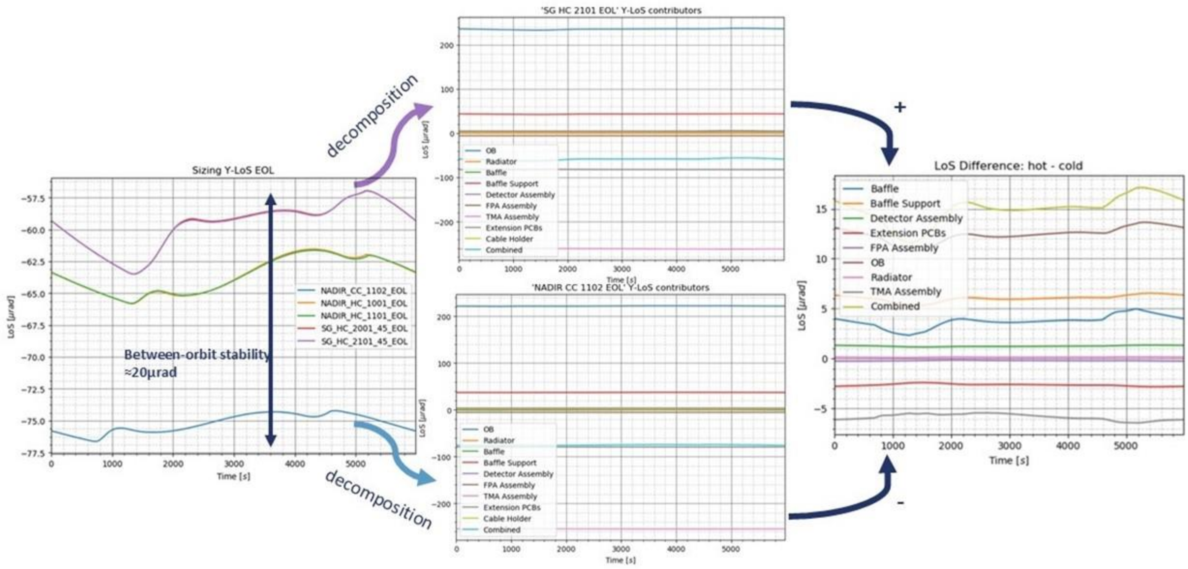

Figure 7 Schematic visualizing the process used to identify the main contributors to the between-orbit stability of the early CDR model. The left graph shows the LoS stability of a selection of orbits. In the middle two graphs the worst cases have been decomposed

stability, which is visualised in Figure 9. The complete process is visualised in Figure 7.

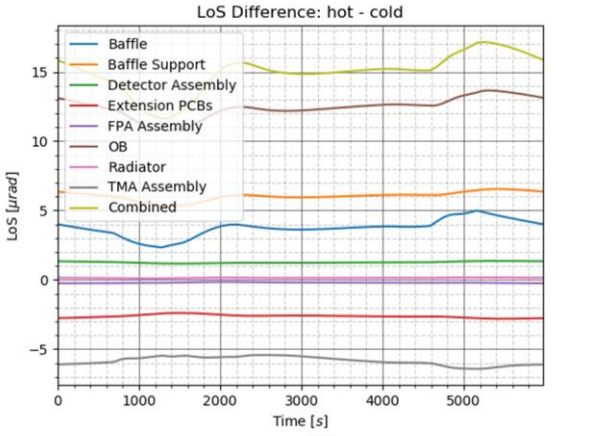

Figure 9 Contributors to the difference in LoS results between the hot and the cold cases from Figure 8.

This process, visualised in Figure 7, was performed for both the PDR and CDR models and the contributors to the between-orbit stability of the two models are compared. Figure 10 shows the differences in the contributors to the between-orbit stability between the PDR and CDR models. It enables the identification and understanding of the changes in the model that caused the decrease in performance.

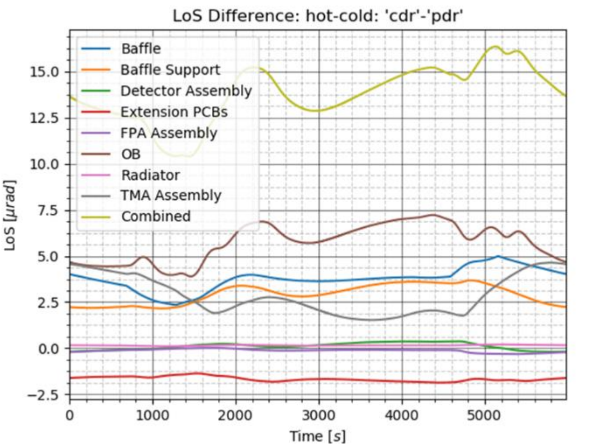

Figure 10 Comparison of the contributors to the between-orbit stability of the CDR model with respect to the PDR model. The contributors of PDR were subtracted from those of CDR.

The described process led to the discovery of three factors that could explain the decrease in performance for the largest part. This was also later confirmed in a dedicated sensitivity analysis.

- The first factor was an increased radiative coupling of the baffle and radiator with the OB, due to the removal of the dedicated MLI around the baffle and behind the radiator. Since the radiator and baffle directly receive environmental heat fluxes, the OB temperature, and thus its LoS contribution, becomes more susceptible to environmental heat fluxes.
  The issue was later resolved by reintroducing the MLI around the baffle and behind the radiator. The analysis process was repeated, and it showed a performance increase of around 6 μrad.
- Secondly, the material of the baffle was changed from CFRP to aluminium. The accompanying increase in CTE is clearly visible in the LoS contributor data, and accounts for around 3 μrad in the between-orbit LoS stability.
- Lastly, the material change in the baffle from CFRP to aluminium also brought an increase in thermal conductivity. The increased conductivity allowed heat to penetrate further into the baffle and radiate towards the TMA and the OB.
  This explanation was tested by observing the results of the CDR model after changing the thermal properties of the baffle back to that of CFRP, which showed another LoS stability improvement of around 4 μrad.

By extending the classification approach that was already previously used in phase B (which is also one of the key components of the TEV Guidelines), a wealth of additional information can be obtained.

Although there definitely is a level of complexity and mathematical trickery required, the method is quite flexible and can be extended to many different kinds of comparisons and assessments, not just the example provided here. One of the key benefits of the approach is that it can be applied in a very systematic manner and allows for a large complex problem to be broken down into more manageable smaller sub-problems. Moreover, contrary to a traditional sensitivity analysis, the approach requires no additional thermal analyses. Rather, it exploits the results of analyses that were already performed.

More traditionally such comparisons might have been done solely by means of sensitivity studies on individual parameters, similar to the studies in Phase B2. However, complex interactions were encountered during Phase C in CLIM, which will be described in the next section. Due to this complexity, it was found that such a traditional approach (on its own) might not always work well as it may trigger multiple effects at the same time, making it difficult to draw useful conclusions.

Phase C – Model sensitivity

As part of later assessments in phase C a detailed sensitivity study was performed to further investigate the LoS stability. This study had multiple purposes:

- To better understand -and confirm- the design changes that cause the aforementioned reduction in LoS performance
- Provide system margins
- Identify possible ways to improve the LoS performance (TCS Layout)
- To perform more detailed sizing of the TCS (TCS margins)

Already in Phase B a dedicated sensitivity study was used both for sizing and to assess the overall system margins. This was feasible because the transfer matrices (TE, Optical) allowed for the efficient evaluation of the LoS after each thermal iteration.

The basic sensitivity analysis was done in a very traditional sense, where key variables in the model (contact conductance's, MLI properties, bulk properties, etc.) were increased and decreased sequentially and the response was recorded. While such an approach can be great if all variables are fully independent, this is only partially applicable for CLIM and would only hold if there was no saturation** of the thermal control system. However, a "worst case" scenario in terms of parameter uncertainty, might very well cause such a loss of thermal control. On this front the CLIM instrument had multiple challenges:

- In many cases this problem can be solved by oversizing the TCS to fully prevent such situations from happening in the first place. Again, the case of CLIM was slightly special. In addition to typical limitations on mass and power budgets, etc., there were also limits on the radiator size driven by performance. As CLIM has an earth pointing radiator, an oversized TCS, with a correspondingly oversized radiator, may actually reduce performance as the system becomes more exposed to the unstable thermal environment.
- The two different heater lines can interact with each other. It may be possible that the overall TCS system is unsaturated, whereas the individual heater lines are.
- The contact conductance of the interface between M1 and the TMA showed high sensitivity with respect to LoS stability, as the actively controlled heaters of the TMA were placed close to this interface. This discovery led to the decision to move the heaters further away from the interface. The relocation improved LoS stability significantly, indicating a high sensitivity to the heater location.
- The sensitivities of different interfaces affect the LoS performance differently. An increase in contact conductance in one interface may decrease LoS stability, while an increased contact conductance in another interface may increase LoS stability. Consequently, when during a sensitivity study all contact conductances are increased, it can represent the worst-case scenario from a thermal perspective and TCS sizing perspective, but it likely does not from a thermoelastic perspective.

*** saturation was considered as the heater power exceeding 90% or dropping below 10% of installed power.*

In the case of CLIM these challenges resulted in a tailored approach for margin philosophy. In particular, there was some flexibility in the operating temperature, and correspondingly the set-points of the TCS. In fact, the set-point of the TCS were among the key parameters to prevent the saturation of the TCS, in particular to manage the interaction between the OB and TMA heaters. The heat of the TMA heaters flows into the optical bench, which can cause the optical bench heaters to saturate at zero power, and vice versa. Even though it was possible to avoid saturation with careful tuning of the setpoints, saturation was again observed in the uncertainty study. The balance between both heaters is shifted by the uncertainties in the model, to such an extent that the setpoints must be retuned to avoid saturation. Consequently, no single combination of setpoints prevented saturation for all uncertainty cases.

A (further) revision of the margin philosophy provides additional justification why this may not be an issue. In the physical reality, only one configuration exists, and it is not strictly necessary to avoid saturation for all uncertainty cases. Since it is possible to adjust the heaters' setpoints after a model correlation (or even in-orbit), demonstrating during testing that the setpoints can be tuned such that saturation is avoided provides confidence that saturation can be avoided. Proving that such an adjustment is possible and may be sufficient.

After all assessments and following updates, the LoS performance has improved substantially. While the performance reported during PDR could not be reobtained, it was possible to decrease the LoS stability to within requirements, with a nominally predicted between-orbit stability of 7.8 µrad as shown in Figure 11.

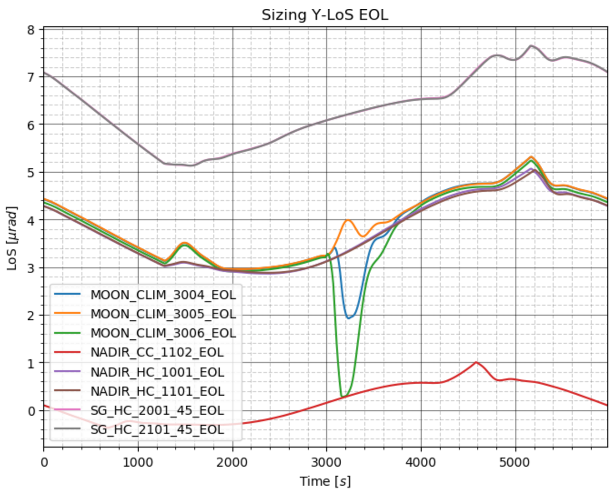

Figure 11 LoS results, with updated for the heater lines (OB+TMA) and PI control heater logic (after second CDR release)

The results of CLIM highlight again the necessity that, for all except the simplest of systems, a sensitivity analysis is needed. In the case of CLIM the sensitivity analysis highlighted very strong non-linear behaviour, mostly driven by interactions with the TCS. It also further indicates the need for testing which is foreseen as part of the upcoming work in Q1 2025.

CONCLUSION AND OUTLOOK

In this paper three different parts of the thermo-mechanical verification process of the CLIM instrument were shown:

- A thermo-mechanical classification, highlighting the key contributors of TE deformation in a structure.
- An extension of this thermo-mechanical classification to show how it can be used to deconstruct much more complex problems.
- A reflection of the key observation in the sensitivity study and resulting TCS margins approach. In particular the dangers of a high non-linearity in the sensitivity analysis, as a results of a saturated TCS and inappropriately chosen sensitivity parameters, were highlighted.

The experience of CLIM reiterates the need of a thorough understanding of the TE problem to effectively solve the right problem. The methodology applied on CLIM therefore also aligns well with the philosophy of the TE verification guidelines [1]. In practical application, the guidelines are really only that - guidelines - and a form of tailoring may often be needed.

In the context of TE guidelines the experiences of CLIM can be generalized to the following lessons learned:

- For critical systems, whenever possible, ensure that you are looking at the true output-variables that determine performance (the LoS for CLIM)
- Automation of processes is needed in one way-or another to effectively do such assessments
- Differences in approach for a high CTE design (like CLIM) and low CTE design can be significant
    - High CTE design, thermal uncertainty is important
    - Low CTE design, mech uncertainty is important
- A basic sensitivity analysis in which parameters are updated one by one, may hide complex issues. In particular, the presence of active thermal control can create strong nonlinearities in the response and a dedicated margin approach may be needed.
    - Grouping of sensitivity study parameters may be needed to trigger a “worst case” scenario for the sizing of the TCS
    - … while simultaneously that grouping of the same parameters may not be the worst case scenario when the TCS system is adequately sized, and not saturated.

  Ideally, both these assessments are decoupled and done independently, but in cases with tight margins and/or strong interactions (as was the case for CLIM) this may not always be possible.

Finally, given all the complexities highlighted above the need for testing is also highlighted. Testing was not covered in this paper but will be the next verification step for the CLIM instrument.

ACKNOWLEDGEMENTS

The CLIM instrument is currently being developed by OIP sensor systems with ATG supporting in the thermal and mechanical verification.

REFERENCES

[1] European Guidelines for Thermo-Elastic Verification (May 2023), ESA STM-285 1st ed.