Combined Opto-mechanical analysis for modern optical instruments

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ABSTRACT

Today several methods are developed and used to integrate structural FEA and optical analyses results, enabling detailed prediction of our instrument performance. This publication gives an overview of some of these developments and the choices and challenges that currently exist without claiming to be complete. The focus is on the combination of Structural, Thermal and Optical Performance analyses, also known as 'STOP'. These analysis solutions are available for projects large or small and can be combined with existing analysis packages.

Challenges identified related to start using STOP analysis are related to knowing which S/W solutions are available, and secondly how to define the integrated analysis process that fits with existing 'design and analyses' experience.

These challenges and implementation options are listed in this publication with the aim to encourage the integration of engineering analysis. By applying this integrated analysis process, the risk of finding mistakes and design flaws late in the project are reduced, avoiding delays and additional costs.

Keywords: STOP, integrated analysis, tolerancing, error-budgeting, opto-mechanics, thermo-mechanics, thermal deformation, optical performance

1. INTRODUCTION

The highly sensitive optical instruments and telescopes that are developed today require thorough analyses to prove the design meets the demanding requirements. The performance must be known for a range of environmental or load conditions that are experienced operationally and during the development and verification phases. Rather than analyzing the nominal load case and allowing for adjustments during the development, modern analysis software can predict the performance for many and complex situations.

Where the thermal, mechanical and optical analyses were typically performed separately, a challenge remains in the interpretation of the results and communicating these with the team and the users.

Even though this analysis process is not new to many larger corporations and space projects (e.g.Herschel and JWST ref.[1][2]), it has now also become more widely available to the smaller projects and developments in the form of commercial and research S/W.

While mechanical design and analysis are well integrated nowadays, the integration of optical and mechanical design and analysis is not widely applied. This publication presents on overview of the possibilities and latest developments found within the SPIE community and with some of the commercial S/W developers.

Two examples are described of integrated analyses for ESO telescopes and instruments; The VISTA telescope has been analysed with the inhouse S/W named 'Sensitizer' and the second example is on the integration and simulation of the ELT to a more extensive level.

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2. THE DEVELOPMENT PROCESS AND THE ANALYSIS OPTIONS

2.1 Generic Design and Analysis approach

The following steps can be identified to describe the typical development of an optical system. The fourth step is the proposed activity where the optical and mechanical design can be analysed together, labelled STOP analysis.

1. Optical design model
2. Sensitivities
3. Tolerancing
4. STOP analyses

Optical design model

The first step in the development is the 'conceptual optical design' that can meet the requested performance given certain budgets for size, mass and effort. The 'performance criteria' such as spot size, PSF, MTF and many others can be set in a 'function' and monitored throughout the design and development process. The optical programs (e.g. Zemax®, CodeV®, OSLO® or others) allow for exporting the optical design parameters to the mechanical design CAD S/W, typically in STEP-file format or simply as a list of geometrical parameters. The CAD model may use only the optical surface definitions and locations or use the 3D-model of the optical components, for the basis of the structural design. Agreement needs to be made on the 'global Coordinate System' but also the 'local CS' and 'vertices'. The defined apertures and footprints from the optical design helps to define the mechanical structure.

Sensitivities

Only briefly mentioned is the step of "sensitivity analysis". This exercise helps to clarify the performance sensitivity to the alignment degrees of freedom, (DoF). As a result the 'high tolerance components' are ranked and next "compensators" can be selected that allow for correction by post-alignment. Though primarily used to iterate the optical design, the 'sensitivity matrix' also enables a broader optical performance analysis to positioning tolerances.

Tolerancing

Just briefly mentioned is the step of "tolerance analysis" performed typically by the optical designer or -analysist. For a generalized set of tolerances on alignment (position, orientation) and/or optical surface quality, a stochastic prediction can be made on the optical performance. For the many alignment DoF and surfaces a system may have, these values are typically combined statistically (Monte Carlo) to get a prediction of the performance with a certain probability. Feedback of the workshop can be taken into account to set realistic tolerances. How well this represents the actual system depends highly on the size of the product-series and if the tolerances are actually random and not systematic in nature.

Secondly, or often later in the project a 'deterministic' tolerance exercise can be performed where measured, directional, position errors are evaluated, typically after a Coordinate Measurement Machine, CMM or laser tracker measurement.

2.2 STOP Analyses Process and Options

Detailed thermal and structural analyses are performed based on the CAD model. The 'load cases' that are analysed are typically:

1. Temperature distribution or dimensions and shapes at different temperatures, (e.g. operational or laboratory environment, room temperature or at cold (cryogenic) conditions or heating by a localized heat source (e.g. motor));

2. Gravity deflection that varies with its orientation (of the telescope);

3.Pressure variations or vacuum pressure, (e.g. vessel and window).

Rather than ending an individual analysis with a report, the STOP analysis process feeds the simulated temperature map or deformations for a specific load case to the next analysis program. For the case that starts with a standalone thermal analysis, this means feeding the temperature distribution into the FEA program that may combine this with other load cases such as gravity loading and (vacuum)pressure. The combined structural deformation is than fed back into the optical analysis program to quantify the optical performance. However, as the generated mesh of an FEA program does-not feed directly into an optical ray trace program, a conversion must take place. The latter is the enabler for STOP analysis and the method separates the different proposed solutions.

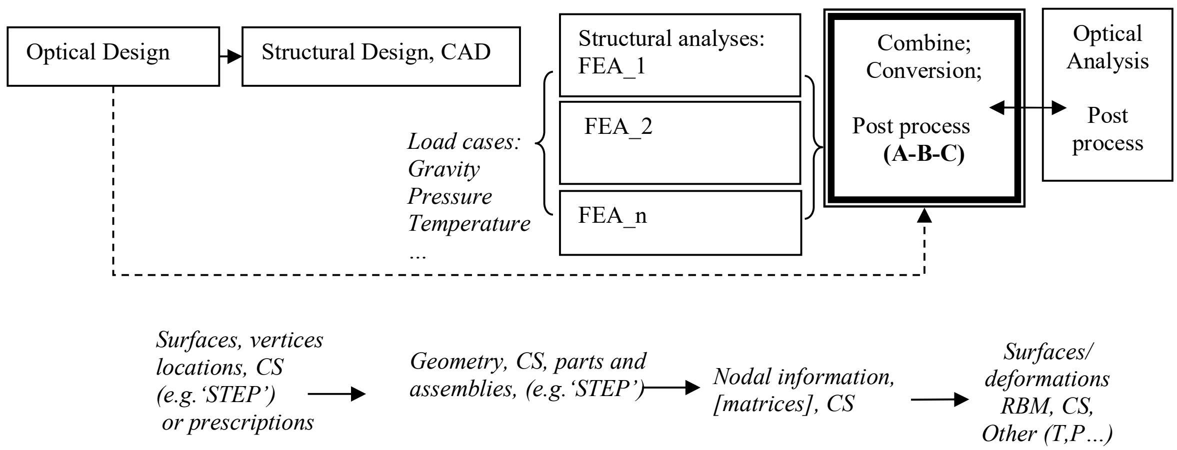

Figure 1: Generalized STOP process steps between S/W programs and below this, the type of information shared (CS : Coordinate System, RBM : Rigid Body Motion)

The following options exist when sharing and converting analysis results between different S/W programs:

A-Import the deformed optical surfaces, locations and other data into the optical analysis program, (e.g. Step file, ref.[3])

B-Import the changes only and add these to the original optical design, (e.g. polynomials, Zernike coefficients.)

C-Import the FEA results *and* the optical design and sensitivities into a third program for post processing

Because different analysis will likely require separate (FEA) models there is a need for multiple imports and the combination and integration of the results. For example the 'rigid body motions'(RBM) of the optical components in a large structure will be modelled differently from a glue mount or local stress concentration.

Note that this approach also allows for inclusion of other specific tolerances to create a more complete picture of the system performance, ref.[4]. Though for now this is omitted in this overview that focusses on a limited version of STOP analysis.

3. AVAILABLE SOFTWARE

Some of the software solutions that exist are listed in the following table and briefly described below listing compatibility, analysis options and post processing.

Table 1: Summary table of a (selective)list of programs and some published features related to STOP analysis

	FEA capabilities within	**Ray trace capabilities within**	**Post processing within**	**Refractive index dn(dP,dT)**	**Active Optics**	**Compatibility w. Zemax®**	**Licensing**
OOFELIE, Open Engineering	Yes through OOFELIE	No	Yes	Yes	Yes	Supported	Commercial S/W
Sigfit, Sigmadyne	No	No	Yes	Yes	Yes	Supported	Commercial S/W
Ray Optics w. COMSOL	Through COMSOL	Yes	Yes	Yes		No	Commercial S/W
Lensmechanix, Zemax OpticStudio	No	Yes	Yes			Directly	Commercial S/W
Tracepro +Rayviz, OSLO	No	Yes	Yes	Yes		No	Commercial S/W, educational licenses exist
APEX w.Solidworks	Through Solidworks	Yes	Yes	Only with ASAP		No, ASAP based	Commercial S/W
TOP RWTC,	No	No	Yes	Yes		Supported	proprietary research S/W
NRCIM	No	No	Yes	No		Supported	proprietary research S/W
Sensitizer	No	No	Yes	No	Yes	Supported	Open source

OOFELIE® by Open Engineering works with the optical design and analysis program Zemax® and CAD programs such as Siemens NX®. OOFELIE::Multiphysics performs FEA analyses. Simulation results can be evaluated in OOFELIE and exported to Zemax in different formats sequential or non-sequential, (Grid Sag, Zernike Sags). Analyses capabilities include refractive index gradient as a function of temperature and stress, (GRIN) and Active Optics. A schematic representation of the analysis process is shown below, ref [5].

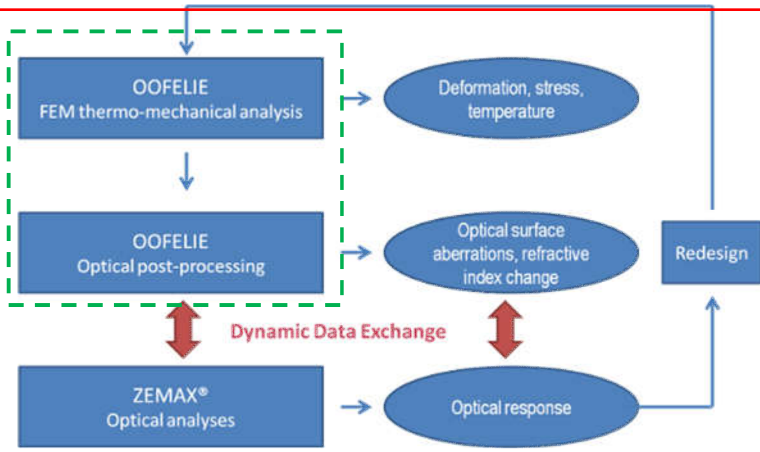

Figure 2: Analysis process graph, source: http://www.open-engineering.com

Sigfit®, by Sigmadyne.

SigFit can interface with Solidworks®, ANSYS®, NASTRAN®, ABAQUS® and CodeV®, OSLO®, Zemax®. It also has capabilities for importing measurement data and exporting to Matlab®.

Postprocessing can be done in SigFit and by exporting to optical programs. Analyses capabilities include refractive index gradients as a function of temperature and stress, ref. [6][7][8]. Active Optics performance analysis and tolerance analysis. A schematic representation of the analysis process is shown below.

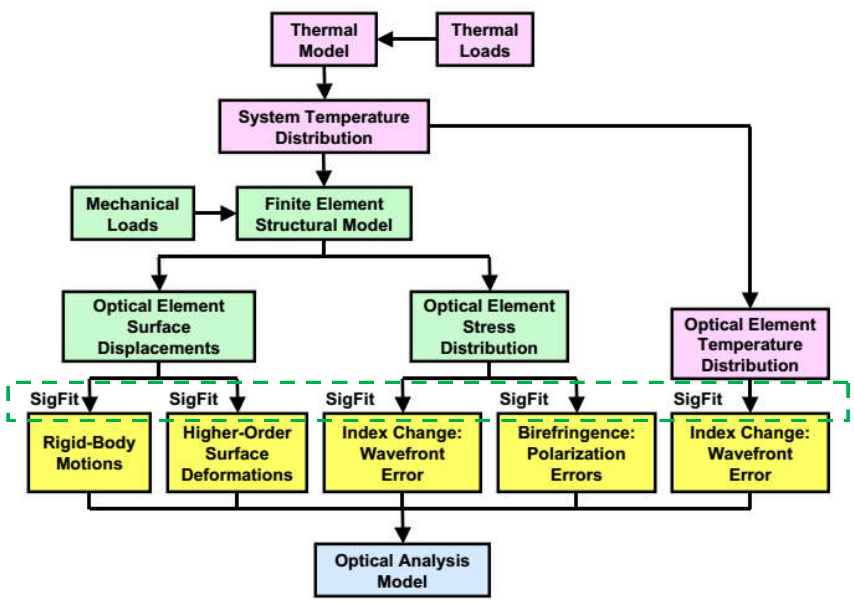

Figure 3: SigFit process graph, source ref.[7]

COMSOL® with Ray Optics module

This basically provides an "all in one package" that allows CAD, FEA and Ray tracing. It also has capabilities in "Wave Optics (e.g. micro and nano-sized optical systems) and (cryogenic) thermal analyses and "multi-physics type of analyses, including simulation of inhomogeneities in refractive index. Limitations exist in capabilities for optical design analysis and optimization, ref [9].

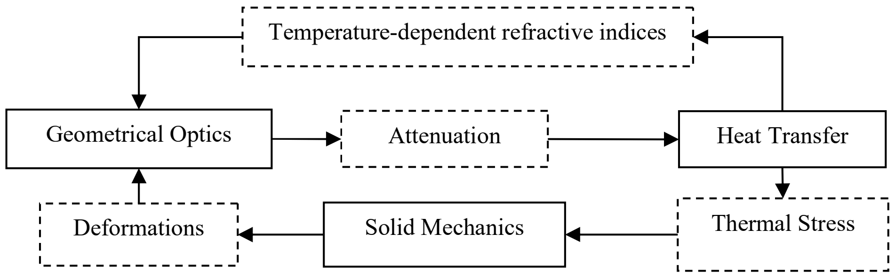

Figure 4: Ray Optics COMSOL Ray trace process graph, source ref [10].

Lensmechanix® from Opticstudio (ZOS). The development named "Virtual Prototyping" enables improved interaction with the mechanical / structural analyst and improves the accessibility and interaction with the Zemax model. Export and import using STEP or IGES files are no longer needed for Solidworks, PTC CREO® and Autodesk Inventor® with the use of "Dynamic CAD Link". The inclusion of STOP analysis capabilities has been announced and is to be released in the near future, ref [11].

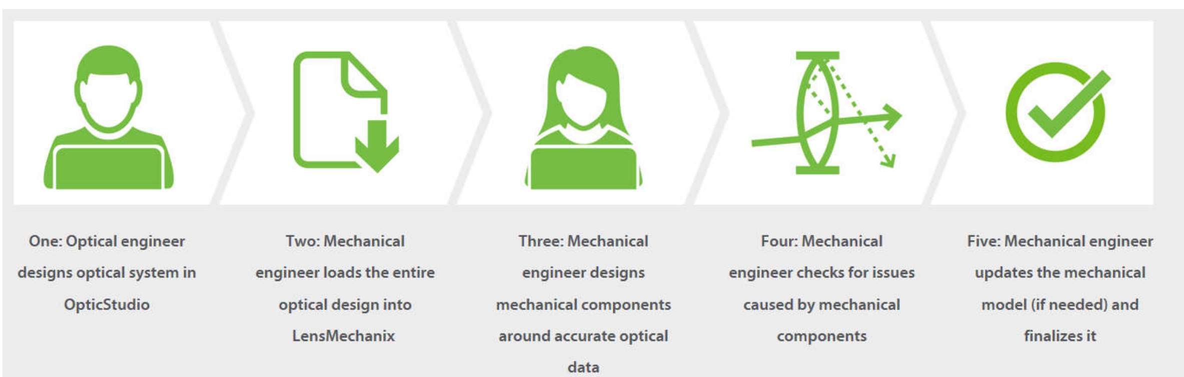

Figure 5: Lensmechanix process graph, source: Zemax.com

APEX®, from Breault Research works within Solidworks as a ray trace program. It is based on BRO's ASAP® kernel technology. It allows ray tracing of imaging and illumination systems and can perform scatter light predictions, ref. [12]. APEX is capable of ray tracing deformed optical surfaces from Solidworks FEA. The optical analysis S/W ASAP can in addition analyse inhomogeneities in refractive index and can deal with deformed surfaces either as Zernike polynomials or as deviation from the original surfaces.

Lambda Research Corporation developed the programs 'OSLO®', 'Tracepro®' and 'RayViz®'. The latter works directly within Solidworks and enables basic ray tracing within the module. Tracepro is the ray trace and optical analysis program that interfaces with RayViz to get direct access to the shared CAD geometry. As standalone S/W it can import and export CAD models. OSLO (Optics Software for Layout and Optimization) is their advanced optical design, optimization and ray trace program. In OSLO three options exist for analyzing deformations, as .INT file wavefront, as

Zernike type surfaces or as bi-cubic spline surfaces defining points/node location in coordinates. Inhomogeneities in refractive index can also be modelled and analysed in different ways, ref[13].

CodeV from Synopsis provides supporting Macros that enable importing nodal information from FEA models, ref[14] [15]. Code V has a partnership with ANSYS to improve design optimisation.

Besides the commercially available S/W several research programs have developed their own STOP process for large projects or optical research. At ESO different processes for 'integrated analyses' are applied as will be discussed in the next paragraph. A selection of the many examples that can be found in the literature, are:

At the RWTH University of Aachen together with Fraunhofer institute (ILT) an analysis process for high power laser applications has been developed with an interface between FEA and Zemax. This enables analysis of surface deformations and for inhomogeneous temperature variation and refractive index profiles. The process for integrated (S)TOP, ray tracing and "wave optical" analysis is described in the following reference [16]. The program that transforms discrete finite element data into functions that can be continuously differentiated, can be found in the following ref [17].

NRCIM, 'National Research Council Canada Integrated Modelling' has developed a STOP analysis process based around ANSYS and Zemax through an interface programmed in Matlab. Special attention is given to automated Coordinate System definitions and post processing through Zemax or by using a Linear Optics Model, (LOM), this matrix is generated via ray tracing, see the figure 6 below. This process has been applied to the TMT, the instrument NFIRAOS and several other projects, ref[18]. For the optical performance prediction of the TMT, partners JPL and Caltech use the Modeling and Analysis for Controlled Optical Systems (MACOS), ref[19].

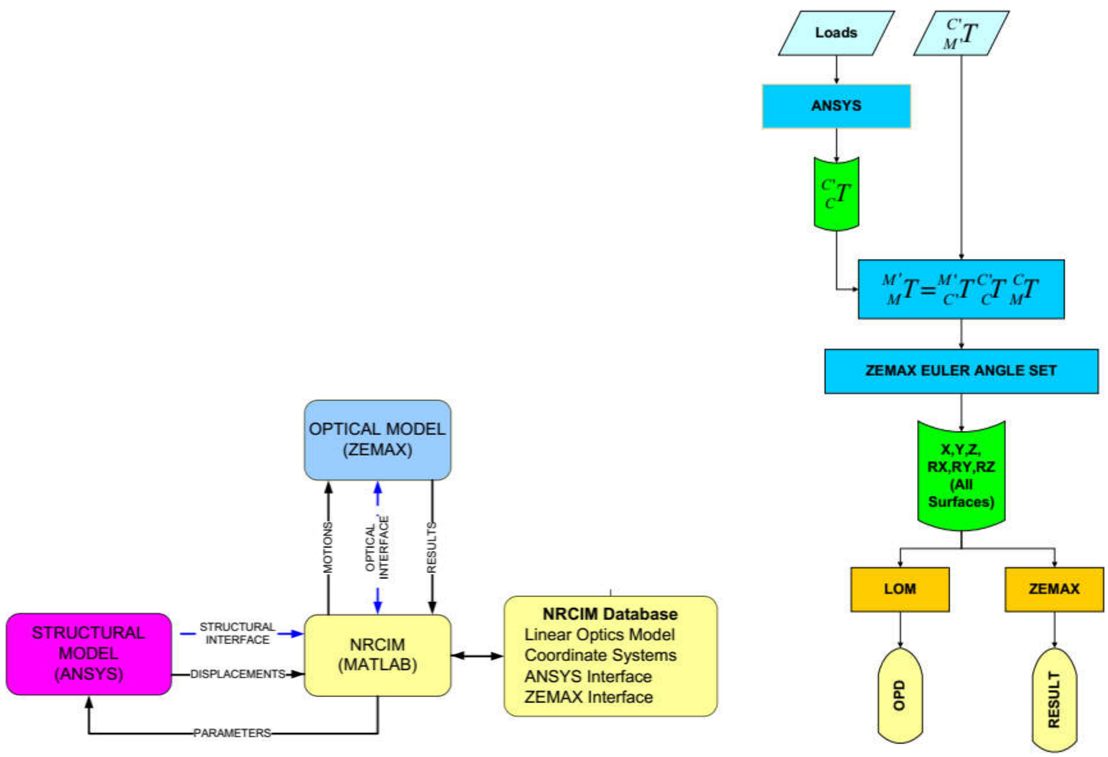

Figure 6: NRCIM process graphs (L) S/W interfaces (R) Split post processing FEA (C,M are Coordinate Systems) source ref[18].

The STOP development has been successfully applied in many projects for a long time as is shown by this publication from a 'Cryogenic Infrared sensor developed by Honeywell Radiation Center in 1977, ref[20]. The modern process hasn't changed but the current interface issues with specialized S/W requires matching solutions for exchanging analysis results. Post processing can be done in the optical analysis S/W but can also be performed in 'third party S/W'.

As can be seen from this overview several different solutions have been developed over the past years. Choosing a process may depend on the expertise of the engineer or sticking to a preferred analysis program.

In evaluating the options, criteria are:

-Cost and Learning curve

-Level of Support

-Compatibility with specific analysis S/W

-Verification and validation

-Expandability beyond STOP analysis to simulate 'Systems Performance' for other contributions as described in paragraph 'Future Developments'.

From the perspective of the 'customer', it is of importance to have a transparent process and an analysis that can deal with all the dominant load cases.

4. ESO INTEGRATED ANALYSES FOR TELESCOPES AND INSTRUMENTS

4.1 Sensitizer

SENSITIZER is an ESO software toolset written in Matlab and Mathematica aiming at automating some aspects of STOP and sensitivity analyses with Zemax OpticStudio. The core code of SENSITIZER runs in MATLAB and drives Zemax in the background through the Zemax-API interface, based on .NET (superseding the obsolete DDE interface). The output is saved in the MATLAB file format and can be post-processed using MATLAB and/or Mathematica routines. The optical system under analysis is defined in a Zemax lens file.

The core data structure of SENSITIZER is an optical group which can be any optical surface in the lens file or a set of subsequent surfaces. These groups will be perturbed by varying their positions relative to the rest of the system (rigid-body-motions, RBM) and/or by adding Zernike shape deformations on their front surface, ref.[21]. After a certain perturbation is applied, Zemax runs (sequential) raytracing to compute the optical performance such as centroid displacement or wavefront error.

SENSITIZER can run in two different modes: Either by applying perturbations separately to each group and each degree of freedom, or else by perturbing all groups in all degrees of freedom at the same time. The first mode is used to compute sensitivity matrices, the second to evaluate specific compound perturbations. Perturbations can be defined in Zemax surface coordinates or in global coordinates, e.g. for modeling perturbations provided by a finite-element simulation. The tool is available to the public as open-source software (GPL v.3 license), ref [22].

4.2 ELT System Performance model

A performance model of the ELT has been produced some years ago, ref[23] and has recently undertaken an in-depth update to convert it into an end-to-end model. The purpose is to be able to run simulations of the performance of the complete system from the atmosphere to the telescope focal plane. Simulations of the system performance in seeing-limited and SCAO mode are now possible. Extending the model to other AO cases (e.g., Multi-Conjugated Adaptive Optics) has also began but this requires the integration of models that would be delivered by instrument consortia.

The performance model integrates and connects the following sub-models:

• A ray-tracing tool

• The FE model of the telescope structure

• A model of the telescope control system

• the SCAO wavefront sensor and the control loops with M4 and M5 units

• the perturbation introduced by the atmosphere

• the perturbation introduced by windshake

The positions and shapes of the optical elements can be perturbed and controlled. In particular, a complete model of the M1 unit with the segments, edge sensors, positioning actuators and control loops are included.

The ELT performance model will allow running simulations to assess the top level 'L1' requirements on AO wavefront control performance under the specified conditions. This is the main goal regarding the ELT system verification. In addition, the model serves as a key tool to analyze the potential impact at system level of changes (changes requests, waivers) on the subsystem requirements.

5. IMPLEMENTATION CHALLENGES

To implement STOP analysis as a step towards realistic performance prediction, more than conformity to the right file formats is required. Besides increased team work, several other implementation challenges exist.

- Definition of a transparent approach that is accepted by all analysts and possibly the stake holders too.
- Standardizing the approach that enables results to be re-producible and consistency over multiple projects

On the practical side;

- Large models and fine meshes can make analysis slow and inefficient to set up and run. This leads to separating analyses that need to be imported and integrated individually to one integrated solution.
- Defining the global and local coordinate systems and their orientation and the vertex of the optical surfaces is critical when FEA results need to be fed back in to the Optical design and analysis S/W. This requires unambiguous definitions.
- Analysis settings such as meshing size and "number of digits" in the calculated solution to achieve the (sub)nanometer accuracy that may be needed.
- Verification of the results. The optical performance prediction should be done in such a way that it can be compared with an actual test setup, ref[24]. Secondly, cross checking the direction and order of magnitude of the solution such as can be done by using the (linearized) sensitivity matrix and multiplying these to the analysed RBM.

6. FUTURE DEVELOPMENTS

In this publication the focus has been on STOP analysis and on dimensional changes. However, increased capabilities such as stress or temperature related refractive index changes are already available in several programs.

This process is also useful to organize and evaluate measurement reports of manufactured parts and assemblies. In this case rather than using it to specify parts and assemblies it provides feedback and evaluates the impact of deviations or changes on the system performance. Other aspects to include in 'Integrated Analyses' are dynamical performance prediction for Active- and Adaptive Optics (AO), and evaluation of dynamic loading (wind and vibration).

Having a more accurate prediction of the optical performance and data-product will allow the customer or user to prepare and act before the instrument is fully build. For calibration- and verification activities it could mean better defined and directed effort during the project rather than after the instrument delivery.

Optical performance analysis has valuable input in the 'system level performance analysis', ref[29]. This next level performance analysis may include atmospheric conditions, scatter light, coating performance and noise levels. These types of analyses are also known as 'End to end' (E2E) simulations. Some examples of these are: [25][26][27][28].

At ESO integrated analyses are an important tool in the development of our telescopes and facilities.

The program named Sensitizer has been one of the most recent developments that is also made available to the community. For the ELT the integrated modeling is an ongoing effort where modeling will change from design specification to an evaluation tool.

An increase in the number of publications on STOP analysis has appeared over the recent years and this is expected only to increase further with the trend of commercial S/W enabling integrated design and simulations, standardizing interfaces and data format.

7. CONCLUSIONS

STOP analysis is a first essential step into a more integrated development approach and better team work. Integrating analysis enables a more realistic performance prediction as it does not need to be 'evaluated and simplified' in each step of the process, as is the case when treating each analysis separately. Avoiding the step of interpretation and communication of results, in person and by hand, reduces the effort and the possibility to make mistakes.

By applying an integrated analysis process early in the project, the risk of finding surprises and design flaws in the hardware are reduced, avoiding delays and additional costs, or failure.

The general process for STOP analysis is clear but varies depending on the scope and complexity of the project. It also depends if post processing is done within the 'optical analysis program' or by other S/W which is related to the decision to use STOP analysis only for 'optical performance evaluation' or as input to the broader 'system performance'.

The basic but critical step of the conversion of node displacements coming from an FE-Analysis into 'rigid body motions' and 'deformed optical surfaces' also varies between the listed solutions.

Because the process and the outcome affect everyone, the motivation to start using this process does not only lay with the engineers but should also come from the systems engineer, the project manager and the project investigator.

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