Integrated modeling for stellar interferometry —motivation, development strategy and practical usage

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ABSTRACT

This article presents a software package for "integrated modeling" of single- and multi-aperture optical telescopes. Integrated modeling is aiming at time-dependent system analysis combining different technical disciplines such as optics, mechanical structure, control system with sensors and actuators. Various, environmental and internal disturbances can be taken into account. Software design and development is done in a joint effort by the European Southern Observatory (ESO), Astrium GmbH and the Institute of Lightweight Structures (LLB), Technical University of Munich. The architectures of the two most advanced modules generating dynamic models of the mechanical structure and the optical system are described. A "real-life" example related to the Very Large Telescope Interferometer (VLTI) illustrates the application in practice.

Keywords: stellar interferometry, optical telescopes, structural mechanics, linear optical model, Finite Element Modeling, Very Large Telescope Interferometer (VLTI), DARWIN

1. MOTIVATION

Research and development in the field of optical stellar interferometry combines several engineering disciplines such as actively controlled optics, structural mechanics, thermodynamics and control engineering. The mutual interaction between the subsystems of a stellar interferometer occurs under the influence of various environmental or internal disturbances. The relevance of a specific disturbance depends on the type of interferometer considered: For *Earth-based systems* (e.g., ESO's Very Large Telescope Interferometer (VLTI)) environmental disturbances, such as wind, seismic noise or atmospheric turbulence, play an important role. Massive support structures provide passive damping. *Spaceborne interferometers* allow operation in a nearly undisturbed environment. There are two basic types of spaceborne systems: (1) "single structure interferometers" with all subapertures mounted on a light weight "floppy" structure (e.g., Space Interferometry Mission (SIM)†), and (2) "formation-flying arrays" with their subapertures distributed on separated spacecraft (e.g., DARWIN‡). Both are exposed to pointing errors and optical pathlength fluctuations induced by their GN&C (Guidance, Navigation and Control) system. Their lightweight structures often require active damping to compensate for micro-vibrations induced by reaction wheels and on-board equipment.

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† URL: http://sim.jpl.nasa.gov/
‡ URL: http://sci.esa.int/home/darwin/

Integrated modeling is a numerical simulation technique for time-dependent system analysis combining different technical disciplines and disturbances. This does not include the subsystem design which is performed using specialized tools established in the respective disciplines (e.g., optical design and optimization software, control system identification software, structural Finite Element (FE) modeling software). Based on the detailed design of the subsystems simplified models of those are generated in the respective disciplines (e.g., optics, structure) and then integrated into a dynamic simulation environment. The results of such an "end-to-end" simulation can be used for feasibility assessment, design refinement and performance prediction.

2. THE INTEGRATED MODELING TOOLBOX

This article presents an "Integrated Modeling Toolbox" (IMT) which is being developed in a joint effort by ESO, Astrium GmbH and LLB. The design and development focuses on stellar interferometers with the VLTI representing a driving application. In addition, the generic structure of the toolbox allows its application to "classical" single-aperture telescopes too. The IMT is formed by a set of software tools written in ANSI C and Matlab® languages. Each software tool is responsible for model creation of a given subsystem (e.g. telescope, delay line, beam combiner) in the appropriate discipline (e.g., optics, structure). Presently, the two most advanced tools of the IMT are the optical modeling tool **BeamWarrior** and the "Structural Modeling Interface" **SMI** which are dedicated to the creation of optical and structural models, respectively. Figure 1 shows the simplified architecture of an integrated model. The two blocks generated by **BeamWarrior** and **SMI** are highlighted in gray.

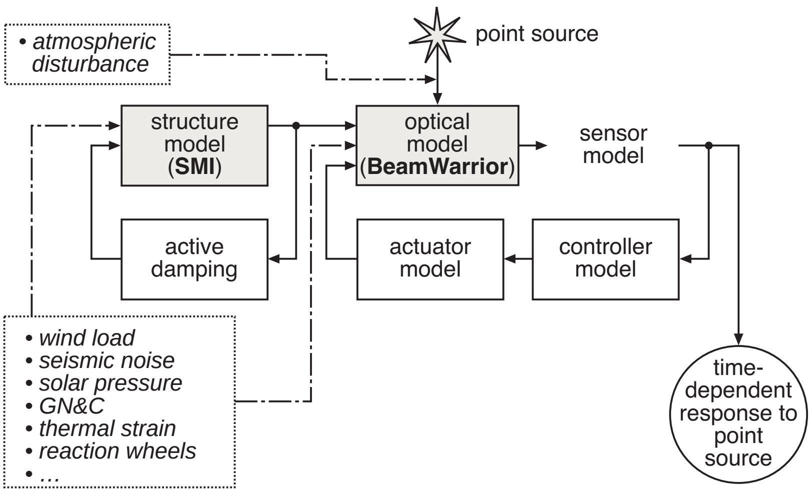

Fig. 1: Basic architecture of an integrated model

Some blocks appear optionally, depending on the respective system type (e.g., Earth- or space-based system). The main output of the dynamic simulation is the time-dependent response when observing a point source at a given angular position in celestial coordinates. This "impulse response" can be represented by the electric field pattern in an exit pupil, the point spread function (PSF) in an image plane or the complex visibility of a fringe pattern (in case of a stellar interferometer). Once the dynamic response to a point source is known, the observation of extended objects can be treated in the spatial frequency domain using two-dimensional signal theory (Fourier optics).[4] The diagram only shows a single closed loop of the controlled optical signal flow representative for several, partially nested loops in a practical implementation.

The model of the control loop(s) forms the comprehensive framework for integration of all subsystem models in different disciplines (optics, mechanical structure, sensors, actuators, disturbances). The control loop model is built making full use of the features of the block-oriented Simulink® —a widely used Matlab® toolbox for simulating dynamic systems.

2.1 Generating optical models using **BeamWarrior**

BeamWarrior is a software tool used to generate models of the optical signal flow influenced by perturbations. Its development has been initiated in 1997 driven by the non-availability of a powerful, open-architecture optical modeling code which can easily be customized to create models for integration into a control loop simulation. The institutions which have supported the development are Astrium GmbH, ESO and the German Aerospace Center (DLR). Present and future work is done in an ESO-Astrium team. The European Space Agency (ESA) has chosen **BeamWarrior** as a basis of the optical part of a system simulator for the planned spaceborne nulling interferometry mission DARWIN.

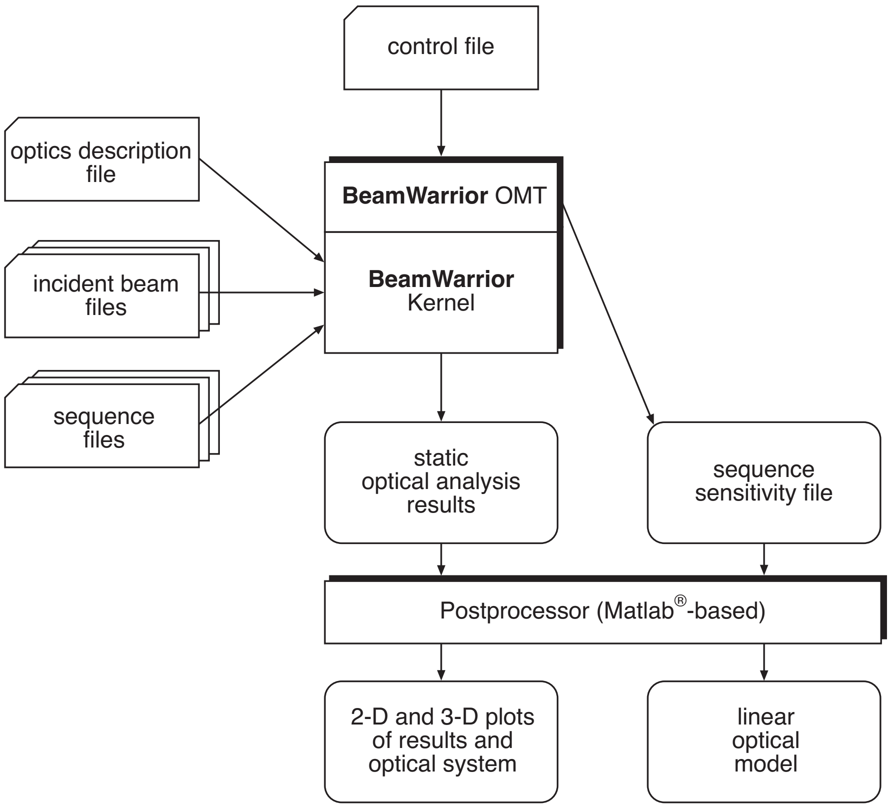

Fig. 2: Architecture of the ***BeamWarrior*** *Optical Modeling Tool*

Figure 2 shows the architecture of the tool. The **BeamWarrior** *Kernel* forms the core part of the package. It is a library of ANSI C functions for optical modeling. Light propagation is simulated by geometrical- or wave-optical methods which can be flexibly combined in a “hybrid propagation model”. The geometrical-optical domain is covered by a radiometric polarization ray tracing algorithm. Wave-optical (diffraction) propagation is handled by three alternative approaches, each being suitable for specific cases: (1) the “direct method” based on numerical approximation of the Rayleigh-Sommerfeld integral, (2) the “angular spectrum method” using a decomposition of the optical field into a set of homogeneous and evanescent plane waves, and (3) the powerful Gaussian beam decomposition technique which allows to simulate an "end-to-end" wave optical propagation —from the incident wavefront to the detector. All Kernel algorithms consider polarization effects and are radiometrically calibrated.[5,6]

The Kernel can be accessed in two different ways:

a) by writing a customized C application which calls the functions provided by the Kernel library, or

b) by using the **BeamWarrior** *Optical Modeling Tool* (OMT) which is an executable "general purpose application" reading in the sequence of computational steps to be performed and the results to be produced from a dedicated ASCII "control file" set up by the user (see Figure 2).

In both cases, **BeamWarrior** requires the same set of additional ASCII input files. The optical layout of the system is specified in an "optics description file". Sequential beam propagation can be modeled on different optical paths which are defined in "sequence files". The incident wavefronts can originate from various sources (e.g., stellar point source, laser beam for metrology). Their characteristics (geometry, frequency spectrum, intensity, polarization) are read from "incident beam files". The concept of using a *single* optics description together with a *multitude* of propagation sequences and incident beams is appropriate for modeling multi-aperture systems, such as stellar interferometers.

BeamWarrior allows creating two types of optical models: A *"linear optical model"* (LOM) is represented by a *"sensitivity matrix"* $\underline{\mathbf{M}}$ whose coefficients $M_{ij} = \partial x_i / \partial u_j$ describe the effect of a perturbation "j" on an output parameter "i". Examples for output parameters x_i are ray positions, ray directions, optical pathlength or a set of Zernike coefficients describing the shape of an optical wavefront. A LOM assumes that the perturbations u_j acting on the optical surfaces are small enough to ensure proportionality between the applied perturbation levels and the respective changes in optical output parameters. LOMs are built by accessing the Kernel via the OMT (method "b", see above). The coefficients M_{ij} are calculated as follows: Small perturbations ∂u_j are sequentially applied to the optical surfaces. In general, each surface is perturbed in its six degrees of freedom (DOFs). The matrix coefficients M_{ij} are computed from the resulting changes ∂x_i in the output parameters with respect to their static values. The magnitude of the "test perturbations" is chosen to match the order of magnitude expected during the simulation (typical values = 1 µm, 1 µrad). The OMT offers a large flexibility when specifying the perturbations. Translational and rotational DOFs, local coordinate systems and magnitudes of the perturbations can be freely chosen. Surfaces may be grouped before perturbation allowing two levels of hierarchy. The resulting matrix $\underline{\mathbf{M}}$ is written to a "sequence sensitivity file" (ASCII format) which, in addition, contains information on the chosen perturbation settings and a "linearity error matrix" $\underline{\boldsymbol{\varepsilon}}$ whose coefficients ε_{ij} are estimates of the expected deviations from linearity. A Matlab®-based *Postprocessor* converts the sequence sensitivity file into a LOM (sensitivity matrix) for usage within Simulink®.

The second, more general type of optical model is the *"non-linear optical model"* which is adequate if the changes in optical output parameters of interest are not proportional to the applied perturbations, e.g., in the case of large-scale perturbations. In such a case the **BeamWarrior** Kernel must be called *at every time step* of a dynamic simulation. It receives input data (e.g., perturbations), performs the computation of relevant beam propagations, and passes its output (e.g., a complex electric field distribution) back to the workspace memory of the dynamic simulation. Presently, this mode is not yet supported. However, in the future we intend to create a dynamically linked library (DLL) version of the OMT which then can be called within a Simulink® model. The structural architecture of **BeamWarrior** is designed to cope with this intention.

Besides its main purpose, i.e., the creation of optical models for integration into a control loop model, **BeamWarrior** can also be used for a large variety of "stand-alone" sophisticated optical analysis tasks. Typical examples are diffraction / polarization analysis, finding pupil locations and tolerancing analysis.[5,6]

Results created by the Kernel (e.g. graphical representation of the optical system including the beam trains, spot diagrams, electric field amplitude and phase / intensity distributions) are stored in binary format. The Matlab®-based Postprocessor provides a set of commands for graphical visualization of result data.

2.2 Generating structural models using **SMI**

The "Structural Modeling Interface" (**SMI**) is used to generate a linear state-space model of the telescope structure to be integrated within a dynamic Simulink® model. Model creation within **SMI** relies on the results of a modal analysis performed by an "external" FE code. An interface to the output data format of the commercial FE software ANSYS® is provided. Data obtained with any other FE software has to be pre-processed into a Matlab®-readable format which then can be interpreted by **SMI**.

The development of the Matlab®-based **SMI** started in 2000 within the scope of a collaboration between ESO and the Institute of Lightweight Structures (LLB), Technical University of Munich. The basic architecture of the tool is depicted in Figure 3

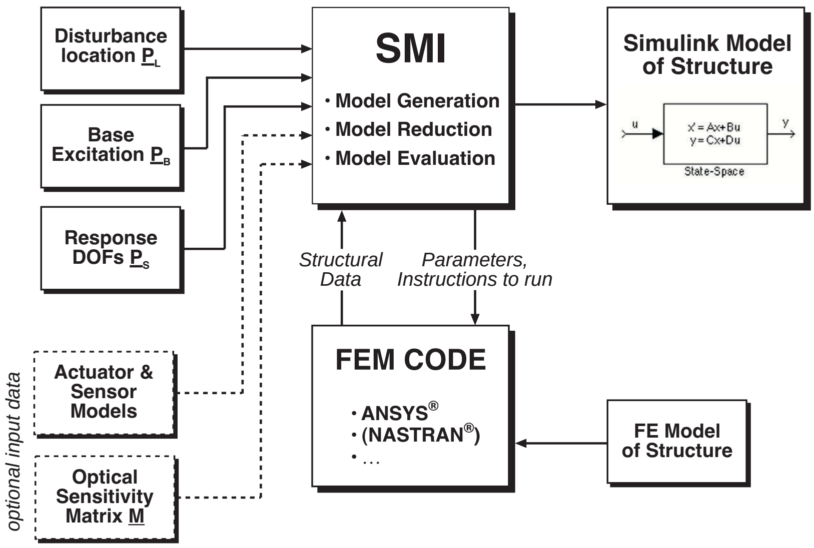

Fig. 3: Architecture of the Structural Modeling Interface ***SMI***

A clearly structured graphical user interface is guiding the user through the following steps of generating a dynamic model of the structure:

1. Loading the results of a structural analysis (eigenvectors and eigenfrequencies and / or mass- and stiffness matrix) performed by an "external" FE software (e.g. ANSYS®)
2. Loading the matrices $\underline{\mathbf{P}}_\mathbf{L}$ or $\underline{\mathbf{P}}_\mathbf{B}$ defining the points of applications and directions of input disturbances; One distinguishes between a "force excitation" (e.g., by wind load) ($\Rightarrow \underline{\mathbf{P}}_\mathbf{L}$) and a "base excitation", i.e., ground acceleration due to seismic noise ($\Rightarrow \underline{\mathbf{P}}_\mathbf{B}$).
3. Loading the matrix $\underline{\mathbf{P}}_\mathbf{S}$ which specifies the output DOFs (nodal translations and / or rotations)
4. Creating a linear state-space model of the structure
5. Reducing the structural model by removing eigenmodes and / or states; A key feature of **SMI** are its quality-criteria based tools for manual and automatic model reduction.[3] For evaluation of the "quality" of a condensed model an optical sensitivity matrix $\underline{\mathbf{M}}$ created by **BeamWarrior** and / or linear models of an

actuator or sensor can be included. This allows to study the effect of the model condensation onto the power spectral density (PSD) of an output of interest (e.g., the optical pathlength in a single interferometer arm) for a given PSD of the input disturbance (e.g., wind force).

6. Creating a Simulink® block representing the (condensed) linear state-space structural model —for usage in an integrated model

In addition to the above listed features, **SMI** offers the possibility to remotely command a modal analysis performed in ANSYS®. If the FE model of the structure is available in a parametrized way, such a remote control can include variations of parameters (e.g., stiffness).

3. APPLICATION EXAMPLE: WIND LOAD-INDUCED FLUCTUATIONS OF THE OPTICAL PATH IN A VLT UNIT TELESCOPE

This section presents an example of an integrated model based on models created with **SMI** and **BeamWarrior**. We consider the VLTI which is formed by the coherent combination of two or more Unit Telescopes.[1] The optical path difference (OPD) between two interferometer arms is a critical quantity for interferometric observations. Among other environmental disturbances wind load is causing random fluctuations of the optical pathlength (OP) in each telescope, i.e., in each interferometer arm. Integrated modeling allows to assess this effect —both, in time and frequency domain. Furthermore, it allows to include the effect in a time-dependent "end-to-end" simulation.

The first component of our example integrated model is a dynamic model of the telescope structure. Based on a simplified 6378 nodes FE model of the telescope structure (see Figure 4) a modal analysis is performed in ANSYS®. 600 eigenmodes are extracted. Using these modal data as input, **SMI** generates a linear state-space model with 1200 states, four inputs and 24 outputs. The four inputs correspond to four different wind forces ("load cases") —each being applied to a group of structural elements. The 24 outputs represent the three translational DOFs of each of the eight mirrors (M1…M8, see Figure 6). These will serve as inputs for the optical model (see below). All mirrors except M1 are represented by single nodes in the FE model. For the primary mirror M1 modeled by 800 nodes the translational DOFs are computed by a simple averaging procedure. Using its built-in "balanced realization" method, **SMI** reduces the size of the structural model to 400 states. This is justified since the resulting standard deviation (rms) value of the OP does not change significantly.[3]

As an example, Figure 5 shows the amplitude of one of the $4 \times 24 = 96$ "force → displacement" transfer functions "contained" in the state-space model.

The second component of the integrated model is a linear optical model (LOM) in form of a 24×1 sensitivity matrix. Its 24 inputs are linked to the 24 outputs of the structural model, i.e., the translational DOFs of the 8 mirrors. The single output represents the change in OP (in units of m) of the "chief ray"¶ measured from the incident wavefront up to the Coudé focal plane. Rotational DOFs are not taken into account since they have no influence on the selected output. Figure 6 shows the optical layout of the telescope. Table 1 holds the values of the 24 coefficients of the sensitivity matrix computed by the **BeamWarrior** OMT assuming a unit perturbation level of 1.e–05 m.

¶ The term "chief ray" denotes the ray which passes through the center of the aperture stop (= M2 for the Unit Telescope).

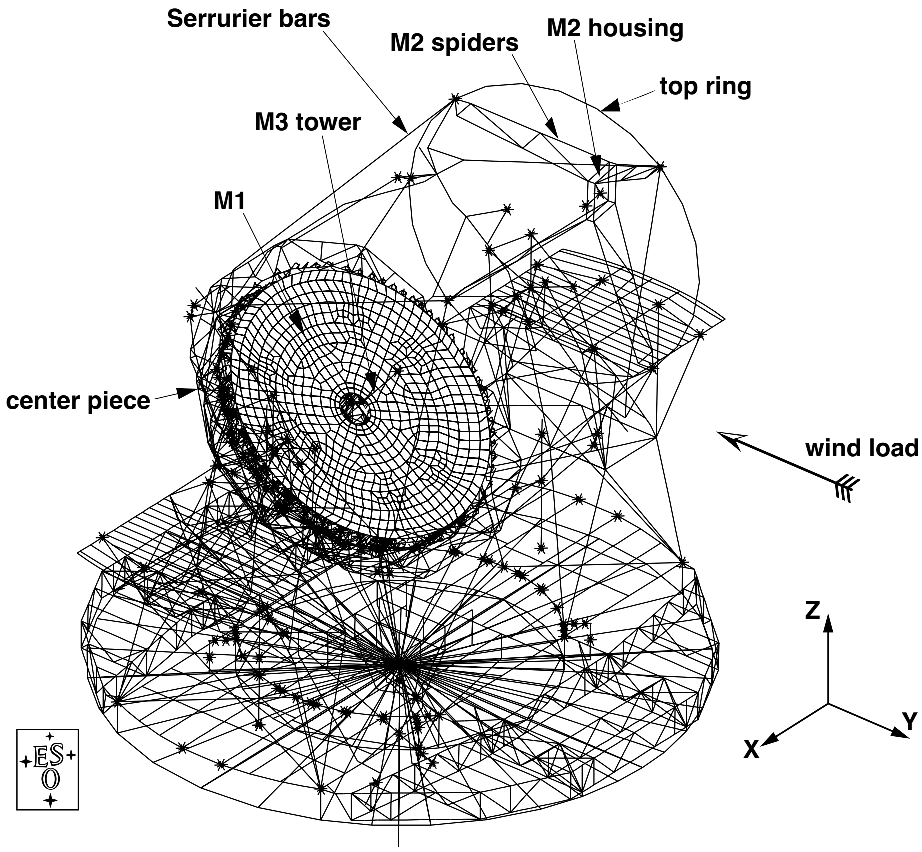

Fig. 4: Finite Element model of the VLT Unit Telescope used for the calculations; The model was set up in ANSYS®. The telescope points to an altitude angle of 50 degrees. The wind direction is parallel to the negative Y-axis.

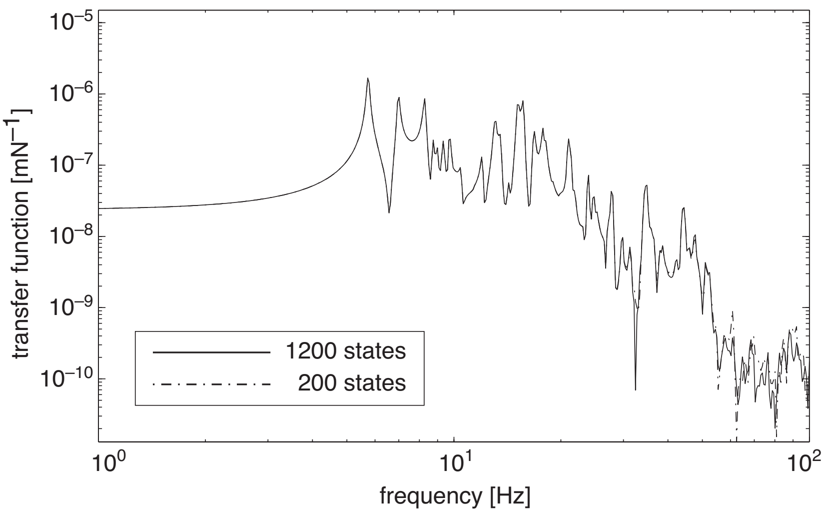

Fig. 5: Amplitude of the transfer function [mN^{-1}] from a wind force on M1 to the x-displacement of M1; The transfer function is plotted against frequency for two different model sizes.

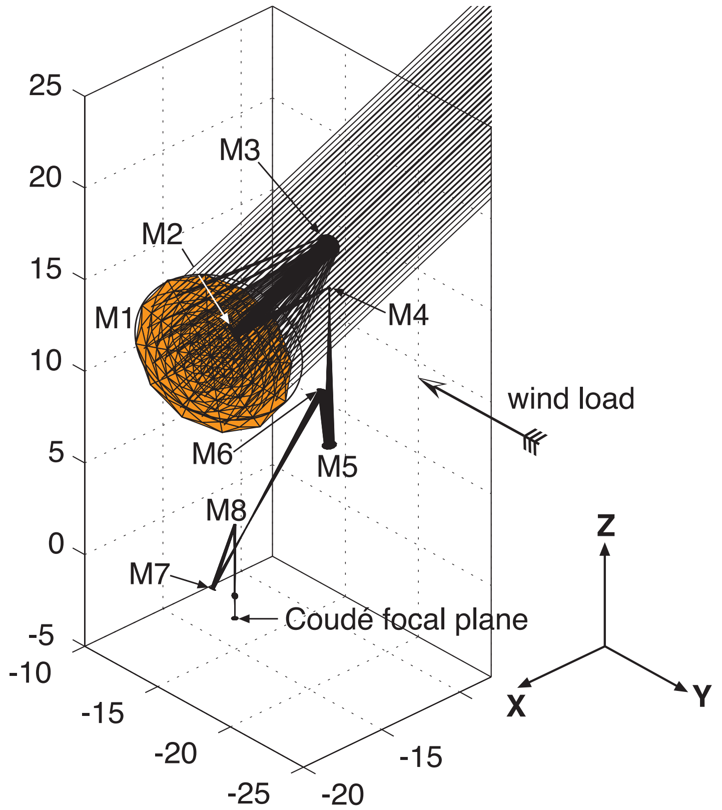

Fig. 6: Optical model of the VLT Unit Telescope consisting of the "telescope optics" (M1…M3) and the "Coudé train" (M4…M8); The model was extracted from a ***BeamWarrior*** *model of the complete VLTI array.*

Table 1: Sensitivity matrix for the optical pathlength variation of the chief ray versus mirror displacements; The coefficients are given in units of mm^{-1} = 1 (unitless).

	∂OP/∂x	∂OP/∂y	∂OP/∂z
M1	2.20907e–03	–1.28600e+00	–1.53100e+00
M2	–5.97501e–04	1.28674e+00	1.53169e+00
M3	9.99844e–01	–6.42675e–01	–7.65909e–01
M4	–9.99770e–01	0.00000e+00	9.99792e–01
M5	–1.52598e–01	3.18565e–05	–1.98832e+00
M6	–5.14499e–01	0.00000e+00	1.73346e+00
M7	1.11343e+00	5.55929e–06	–1.63991e+00
M8	–4.46527e–01	0.00000e+00	1.89477e+00

The four input wind forces are applied to four groups of structural elements, respectively. For example, the primary mirror M1 (consisting of 800 nodes) forms one of these groups. For each load case a PSD of the aerodynamic wind force (unit N^2Hz^{-1}) is calculated using an analytic expression (von Kármán model). Required parameters such as mean wind speed, drag coefficients, turbulence intensity, outer scale of turbulence and effective cross-section area are estimated by "rule-of-thumb calculations" or derived from measurements. Details can be found in *Koehler & Koch 1995*[2]. The four wind force PSDs are then converted into random time series F(t) for usage in the dynamic simulation.

Finally, both, the structural and the optical model are linked together in a dynamic Simulink® model. The architecture of the resulting integrated model is illustrated in Figure 7 (compare to the general architecture shown in Figure 1). Figure 8 shows the result of a simulation with a total duration of 10 sec. The standard deviation (rms) σ_{OP} equals roughly 800 nm. Table 2 summarizes standard deviation values obtained at three typical exposure times of the VLTI corresponding to the three observation wavelengths 600 nm, 2.2 µm and 10 µm.¶

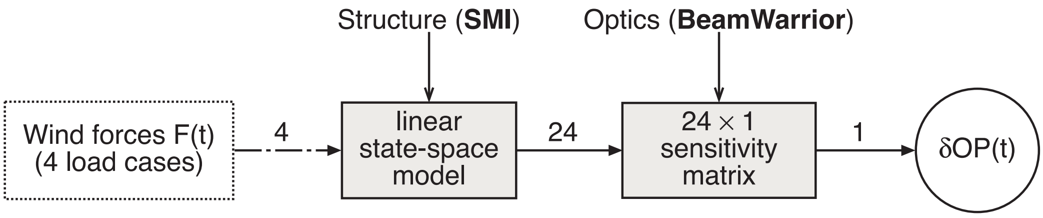

*Fig. 7: Integrated model for the calculation of the dynamic fluctuation of the optical path δOP(t) induced by wind load; The model is formed by linking the structural (**SMI**) and optical (**BeamWarrior**) models,*

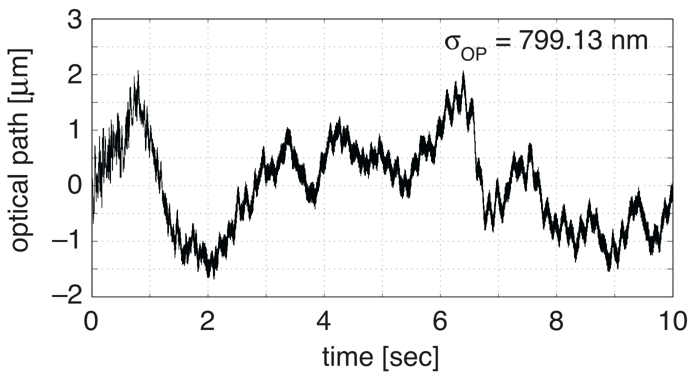

Fig. 8: Temporal fluctuation of the optical path δOP(t) in a Unit Telescope induced by wind load; The standard deviation (rms value) for an exposure time of 10 sec is given by σ_{OP} = 799.13 nm.

Table 2: Standard deviation (rms) σ_{OP} of the optical path fluctuation δOP(t) measured at the Coudé focal plane for three typical exposure times used for the VLTI

Exposure time [ms]	10	48	290
rms σ_{OP} [nm]	18.3	77.8	251.8

¶ The exposure time for a given observation wavelength (e.g. T = 48 ms for λ = 2.2 µm) is chosen to match the atmospheric coherence time at this wavelength.

4. CONCLUSION

An "Integrated Modeling Toolbox" (IMT) is under development. It aims at time-dependent multidisciplinary system analysis of controlled optical systems. The IMT is designed for modeling of Earth- and space-based stellar interferometers with the VLTI being a "driving application". Due to its generic architecture the IMT can also be applied to a wide variety of single aperture telescopes. Possible applications of the IMT are performance prediction, design refinement or feasibility assessment.

The IMT is formed by a set of software tools —each being responsible for generating a dynamic model of a given technical subsystem (e.g., telescope, delay line, beam combiner) in different disciplines (e.g., optics, mechanical structure). All subsystem models are integrated into the Matlab / Simulink® environment for dynamic control system simulation. At present, the two most advanced tools of the IMT are **BeamWarrior** and **SMI**. These are used for creating optical and mechanical structure models, respectively. Design and architecture of both tools are presented. The integrated modeling concept is illustrated by a practical example related to VLTI system engineering: The effect of wind disturbances on optical path fluctuations in a Unit Telescope is computed by a dynamic opto-mechanical simulation.

Future development of the IMT will be driven by its application to the VLTI including the dual-feed facility PRIMA, as well as the spaceborne nulling interferometry mission DARWIN and its ground-based demonstrator GENIE (a nulling beam combiner instrument for the VLTI).

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