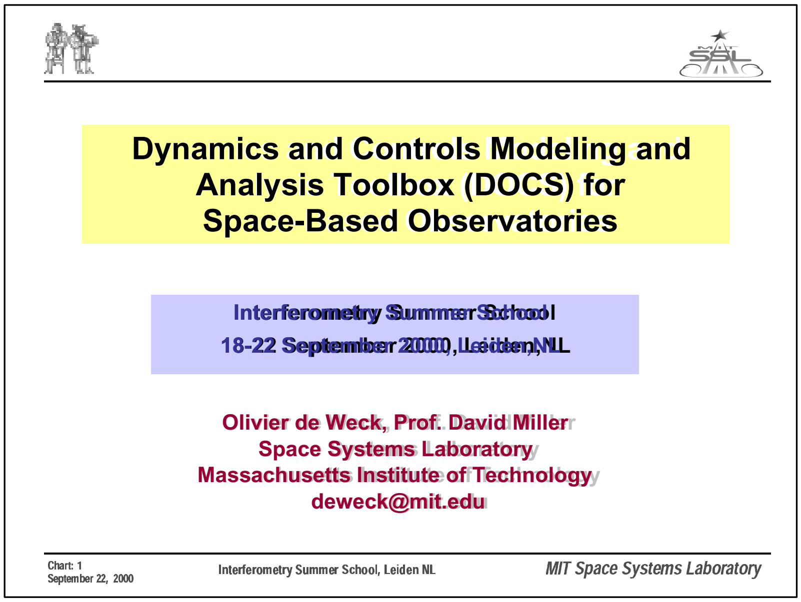
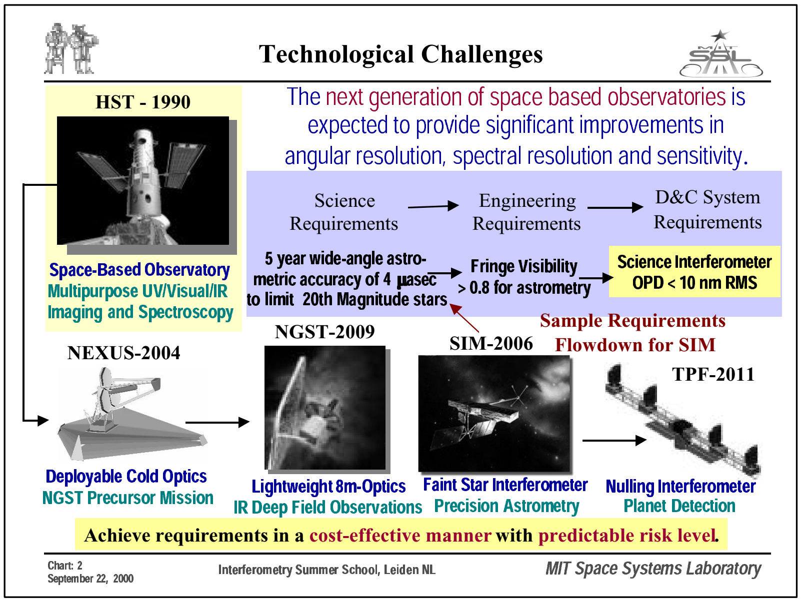
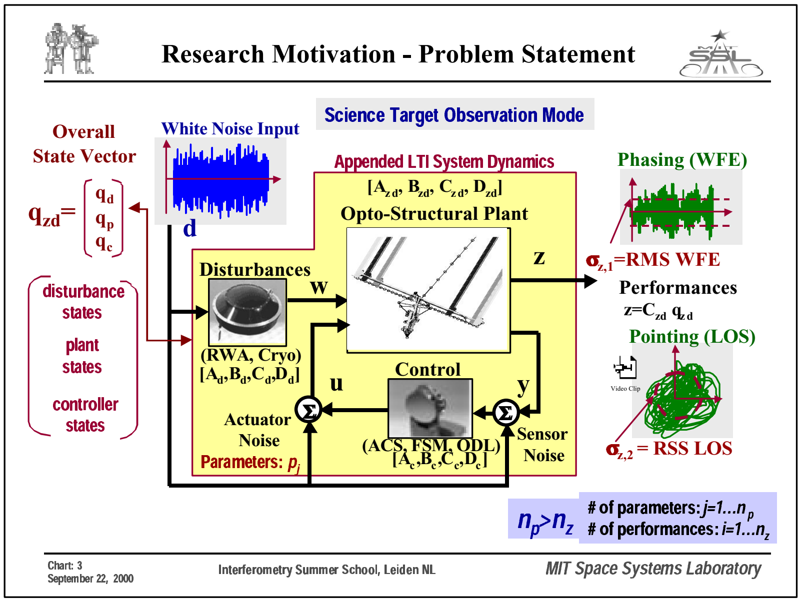


Abstract

The DOCS (Dynamics-Optics-Controls-Structures) framework presented here is a powerful toolbox for the modeling and analysis of precision opto-mechanical systems such as interferometers. Within the MATLAB environment a model of the system can be created, which simulates the dynamic behavior of the structure, the optical train, the control systems and the expected disturbance sources in an integrated fashion. This modeling is critical in order to identify important modal and physical parameters of the system that drive the opto-mechanical performance. Other uses are the development and tuning of attitude and optical controllers, uncertainty analysis, model updating with test data, the development of error budgets and the flowdown of subsystem requirements. This presentation outlines the technical challenges faced by precision telescopes and gives an overview of how the DOCS framework can assist in solving observatory design problems. Two specific analysis examples are presented. First the derivation of an error budget for NGST with two performance metrics and three error sources is shown. Secondly the effect of reaction wheel disturbances and OPD control bandwidth on the transmissivity function of TPF is presented. Experimental validations of the toolbox are carried out with telescope testbeds in 1g. Preliminary versions of the framework have been successfully applied to conceptual designs of SIM, NGST, TPF and Nexus.

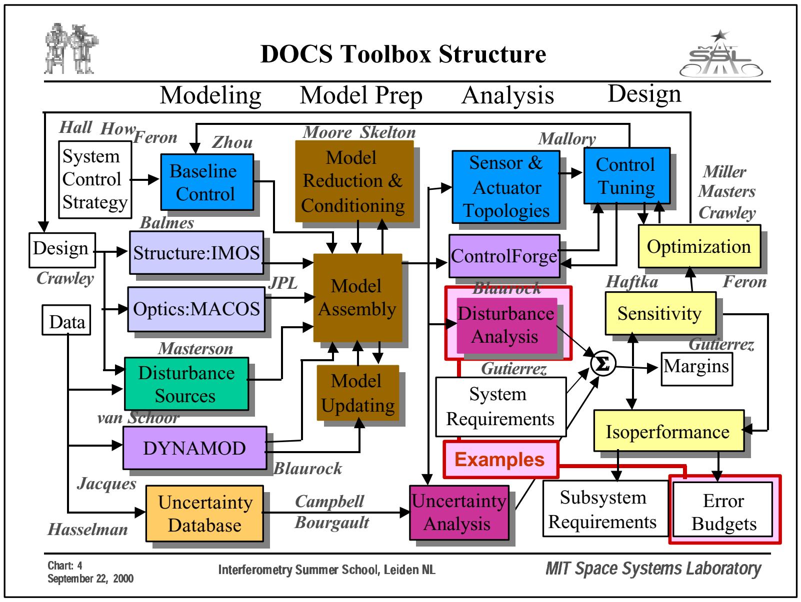


The Hubble Space Telescope (HST) has celebrated it's 10th year of on-orbit operation in 2000. Hubble has broken technological ground for space based astronomy as a multi-purpose UV/visual and IR observatory. The main science objectives for Hubble are multi-purpose astrophysical imaging and spectroscopy. The next generation of space based observatories, including interferometers is being designed at this time and is expected to provide significant improvements in angular resolution, spectral resolution and sensitivity. In spaceborne interferometry SIM will provide precision astrometry for faint stars and TPF (and DARWIN) will work as a nulling (Bracewell) interferometer for direct plant detection in the IR. In designing these ambitious missions a requirements flowdown is taking place from the science requirements, to the engineering requirements to sub-discipline requirements such as dynamics and controls (D&C). Thus phasing and pointing requirements for the metrology-, guide- and science-light can be postulated in terms of wavefront error (WFE), optical pathlength difference (OPD), wavefront tilt (WFT), line-of-sight(LOS) jitter, beam shear (BS) and others. The primary objective of DOCS is to address these dynamic system requirements. This can be done for the various telescope modes such as science light integration, tracking, retargeting and slewing.

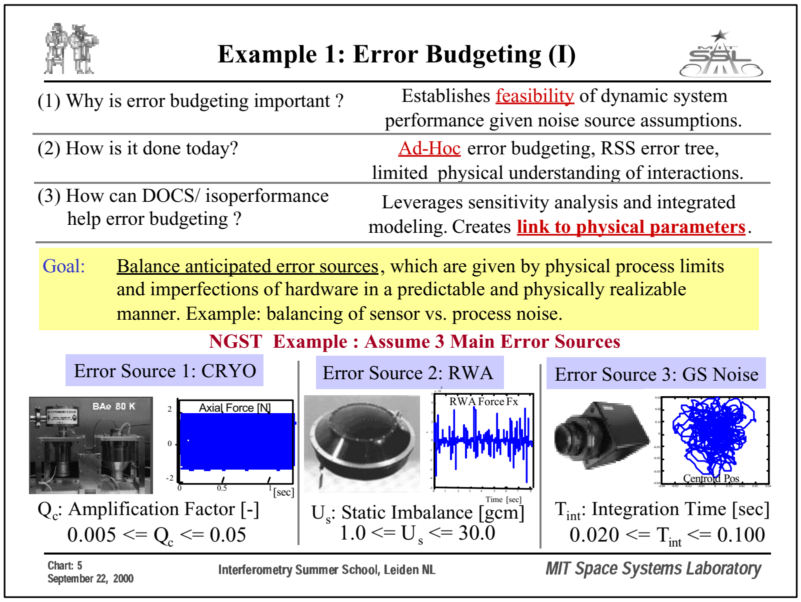


The present work is motivated by the need to simulate the dynamic behavior of the future generation of space interferometers during the conceptual and preliminary design phases. In order for these space or ground-based telescopes to meet their stringent phasing (e.g. OPD) and pointing requirements (e.g. LOS jitter), the path from disturbances to the performance metrics of interest ,z , must be modeled in detail. It is assumed that the systems are linear and time-invariant (LTI). The premise is that a number of disturbances sources (reaction wheel assembly (RWA), cryocooler, guide star noise etc.) are acting during the various operational modes of interest as zero-mean random stochastic processes. Their effect is captured with the help of state space shaping filters $[A_d,B_d,C_d,D_d]$, such that the input to the appended system dynamics $[A_{zd},B_{zd},C_{zd},D_{zd}]$ is assumed to be unit-intensity white noise d, which is uncorrelated for each disturbance source. The shaped disturbances w are propagated through the opto-structural plant dynamics $[A_p,B_p,C_p,D_p]$, which include the structural dynamics of the spacecraft and the linear optics matrices. A compensator $[A_c,B_c,C_c,D_c]$ is often present in order to stabilize the observable rigid body modes (ACS) and to improve the disturbance rejection capability (ODL, FSM). The sensor outputs y and actuator inputs u might be subject to noise. One of the goals of the DOCS framework is to accurately predict the root-mean-square (RMS) values and sensitivities of the performances z under the above assumptions.

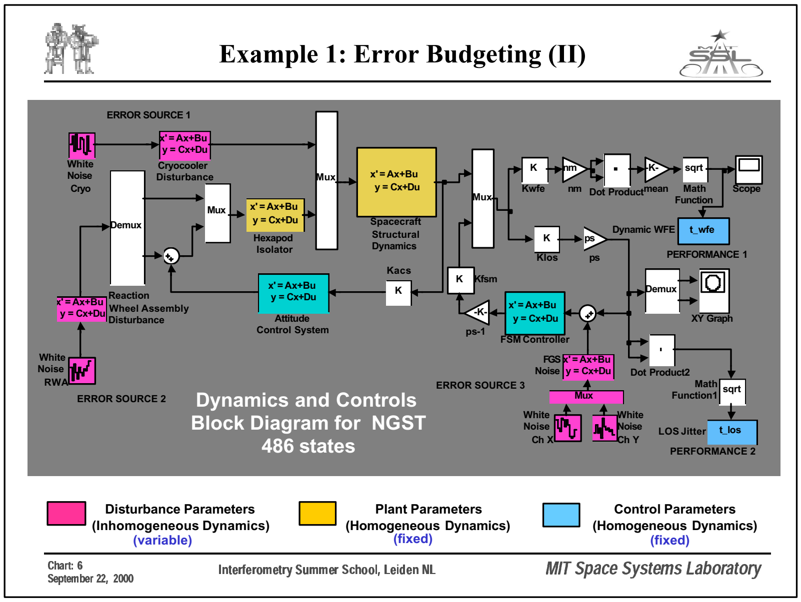
Reaction Wheel Picture: http://www.ithaco.com/T-Wheel.html, FSM picture: http://www.lefthand.com/prod_fsm.html, SIM Picture: http://sim.jpl.nasa.gov



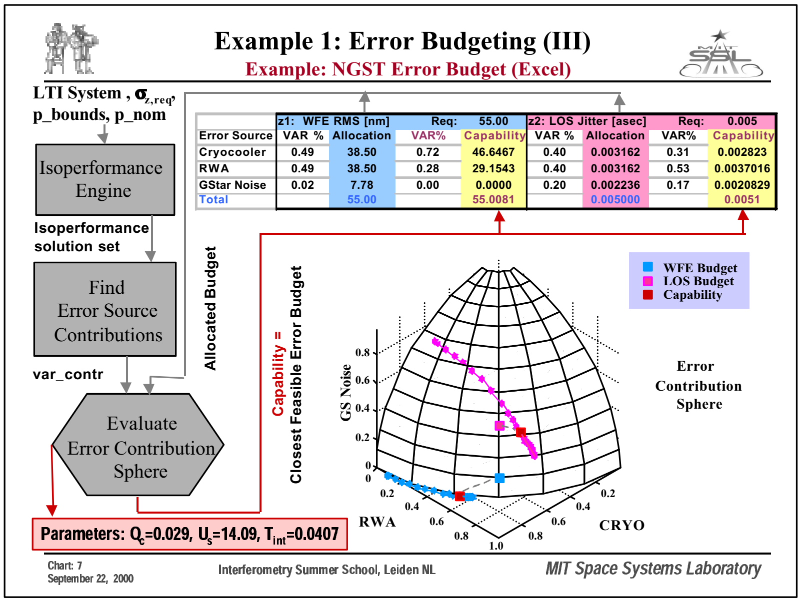
This block diagram shows an overview of the DOCS framework. The existing toolboxes are compatible with IMOS (version 4.0), MSC/NASTRAN as well as DynaMod® and ControlForge®. Once an initial model has been created and numerically conditioned, the root-mean-square (RMS) values of scientific and opto-mechanical performance metrics of the system (e.g. pathlength difference, pointing jitter, fringe visibility, null depth) can be predicted. The exact sensitivities of the RMS with respect to modal or physical design parameters can be computed. These sensitivities are essential for conducting gradient-based optimization, redesign or uncertainty analyses. The goal of the uncertainty analysis is to associate error bars with the predicted RMS values, which are based on an uncertainty database resulting from past ground and flight experience. The actuator-sensor topology of the system can be analyzed numerically to ensure that the control system uses the actuator-sensor pairs that will ensure maximum disturbance rejection or tracking performance. Once a design has been found that meets all requirements with sufficient margins, an isoperformance analysis can be conducted. Treating the performance as a constraint the expected error sources (error budgeting) or key design parameters (subsystems requirements definition) can be traded with respect to each other. If hardware exists, the experimental transfer functions can be used to update the structural, avionics and uncertainty models throughout the life of the program to achieve a convergent design that will achieve mission success.



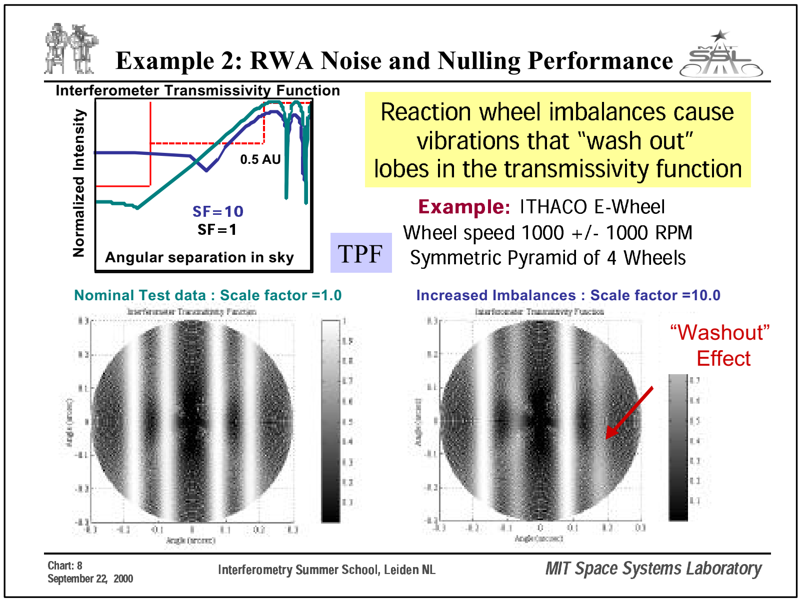
The first example for the usefulness of the DOCS toolbox is error budgeting. Error budgeting is the process of capturing and allocating allowable contributions to all potential dynamic error sources of the opto-mechanical system. Typically error budgeting is done in an RSS fashion and in a tree structure, where the total error for the system, e.g. 10 nm OPD RMS is subdivided among the expected error sources. The problem with this traditional approach is that an allocation of a subportion of the allowable error to a particular error source is not in the same units as the modal or physical parameters, which directly describe the error source. (E.g. How does a 5 nm OPD RMS error allocation to the reaction wheels relate to allowable static imbalances Us of the wheels ?). The Isoperformance module of the DOCS framework can assist in the error budgeting process by leveraging the integrated model and sensitivity analysis to yield an error budget (capability), which is as close as possible to the desired budget (allocation), but takes into account the limitations/feasibility on the physical parameters, which describe the error sources. In this example for NGST we assume three main error sources. The cryocooler is located in the integrated science instrument module (ISIM) and produces tonal mechanical vibrations to to a linear compressor-expander (Physical parameter: Qc). The reaction wheel assembly in the spacecraft support module (SSM) produces attitude command torques and superimposed disturbance forces and torques due to static and dynamic imbalances (Physical parameter: Us). Guide star noise is introduced as a NEA (noise equivalent angle) due to photon noise in the detector (Physical parameter: Tint). The module assumes a 16.5 Mag guide star in the K-band.



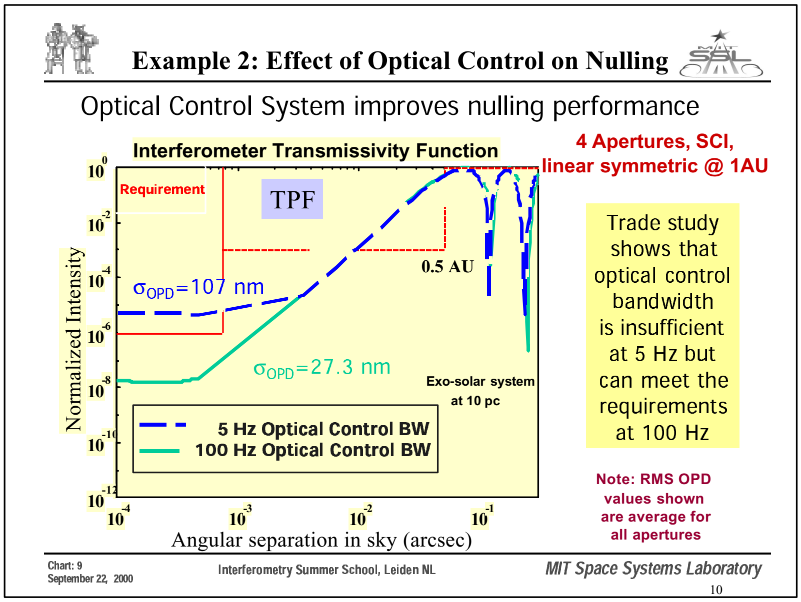
This slide presents the dynamics block diagram (Simulink®) for NGST used in the error budgeting example. The dynamics of the disturbance sources (CRYO, RWA, FGS) are shown in magenta. The assumption is that these disturbances act as random, zero-mean processes which can be represented as colored (filtered) white noise such that the PSD's of experimentally measured noise processes can be reproduced. These processes represent the inhomogeneous dynamics of the system. There are two performance metrics z_1 (Dynamic WFE RMMS) and z_2 (LOS Jitter). The requirements that have to be met by the system are 55nm at λ=2.2 mm (λ/40) and σ_{LOS}=5 mas respectively. The cryocooler disturbance acts directly onto the structure of the ISIM. The RWA forces and torques are low-pass filtered by a mechanical hexapod isolator. The displacements and rotations of the attachment points of optical elements (primary mirror, secondary mirror, detector etc…) on the structure are converted to optical quantities via linear sensitivity matrices. There are two independent control loops in the model. The Attitude Control System (ACS) uses measured attitude angles (star tracker) and rates (gyros) to command torques in order to stabilize the rotational rigid body modes of the observatory (bandwidth ~ 0.02 Hz). The LOS stabilization loop senses the guide star position with the science camera with a frequency of $1/T_{int}$ and commands two angles of the fast steering mirror (FSM) gimbal. The plant and controller parameters are assumed to be fixed during the error budgeting computations. These are the homogenous dynamics of the system.



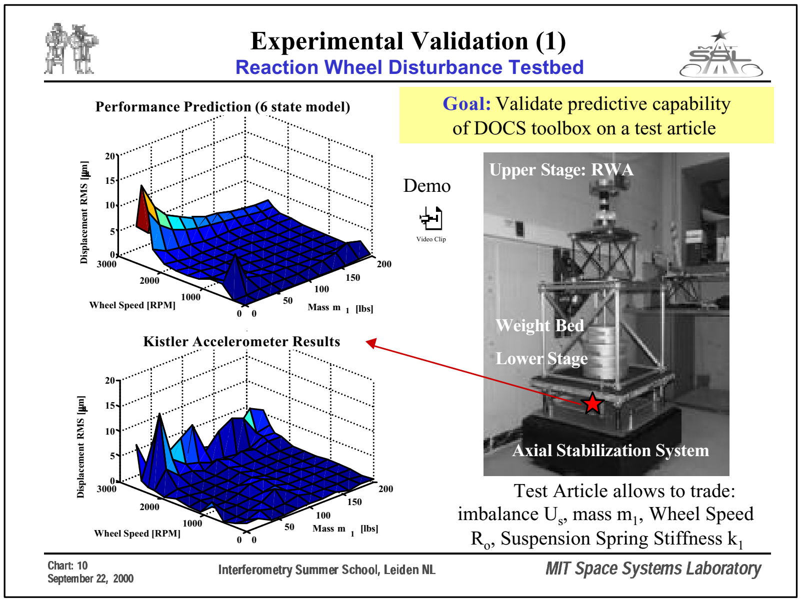
This slide presents the results of the error budgeting exercise. The Excel spreadsheet in the upper right corner shows the error allocation (blue) for the three error sources as a percentage of the total variance for both performances. This allocation is done apriori based on empirical experience. This desired error budget is fed into the isoperformance engine of DOCS together with a LTI model of the system dynamics, the system requirements and upper and lower bounds on the physical parameters, which describe the error sources. An isoperformance solution set is computed. This set contains all combinations of solutions, which produce the required performance levels and do not violate any constraints. For this set of solutions the error contributions are computed and plotted on an error contribution sphere. The error budget, which comes closest to the desired budget (allocation) on this sphere is computed. This is called the capability budget, which is then returned to the error budgeting spreadsheet (yellow columns). It is also possible to assign a weighting factor to the performances, while finding the capability error budget. Another useful result are the physical (error source) parameters, which correspond to the capability error budget. In this case these parameters are Q_c=0.029, I.e. the cryocooler disturbances have to be reduced to 2.9% of the (uncompensated) experimental levels, U_s=14.09 gcm, i.e. the static imbalance of the reaction wheels should not exceed 14.09 gcm and the integration time T_{int} of the fine guidance sensor should be set to 40 msec. We see that the WFE is dominated by the cryocooler disturbance, whereas the pointing performance (LOS jitter) is mainly determined by the RWA imbalances.



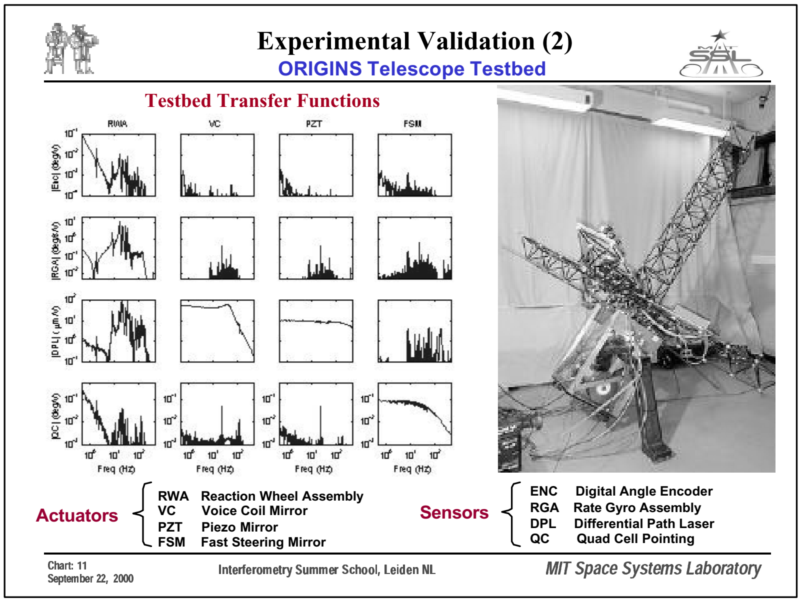
The second example shows a performance prediction analysis conducted for the TPF mission. This chart shows the effect that reaction wheel imbalances can have on the transmissivity function of the nulling interferometer and ultimately the signal to noise ratio. The reaction wheel disturbance data was obtained from a test of the ITHACO E-Wheel conducted at NASA GSFC in 1998. The wheel speed distribution was assumed to be uniform between 0 and 2000 RPM. The combined effect of 4 wheels in a pyramidal configuration is taken into account. The left subplot shows the effect of the reaction wheel imbalances that where obtained from the test without any modification to the test data. We see that the transmissivity for a linear symmetric array with four apertures (1-2-2-1) has four symmetric lobes (areas of peak intensity) and that the suppression of starlight meets the specification (upper left plot) of 10^{-6} out to the star diameter. The right subplot however demonstrates the effect if the wheel imbalances are scaled up by a factor of 10. This could occur if the wheels are poorly balanced or if a ball bearing failure occurs during operations. The effect on the transmissivity is dramatic. Firstly we notice that a pair of lobes is now being washed out by the vibrations, secondly the nulling no longer meets requirements. In the nominal case the σ_{OPD} (average) is 76 nm, where it is 762 nm in the second case, which corresponds to roughly $\lambda/16$. At 12 microns. For non-interferometric systems such a wavefront error might be acceptable. Thorough analysis and testing of reaction wheel imbalances before launch is paramount.



This chart shows the level to which the dynamics and controls can be captured in a systems analysis (such as TPF) with the DOCS toolbox. The effect of optical control on the system is modeled using a high-pass filter approach, where each OPD channel is attenuated by the optical control at low frequencies but not at high frequencies due to the limited sensor and actuator bandwidths. The sensor is the internal and external metrology system and the actuators are the multi-stage optical delay lines (ODL's). The chart shows the effect of changing the optical control bandwidth on the transmissivity function of TPF assuming λ=12 μm. If the optical control bandwidth is too low, the optical pathlength differences between the apertures creates a time-varying phase difference ϕ_i between the light beams at the combiner. This phase shift disturbs the +/- 180 degree phase shift required for perfect nulling. A simplifying assumption is that the OPD's which are the square roots of the variance of a stochastic random signal are added to the phase shift used to compute the transmissivity function as if they were deterministic. Thus the perturbations from the perfect transmissivity shown above are to be understood in a 1 sigma sense. The preliminary results indicate that the science requirements for TPF cannot be met with an optical bandwidth of 5 Hz, but increasing the bandwidth to 100 Hz leads to sufficient suppression of the dynamic onboard disturbance sources. In this sense the DOCS toolbox can be used to design and size important components (controllers, sensors, actuators) of the observatory prior to manufacturing, integration and test.



This chart shows the Reaction Wheel Disturbance Testbed (RWDTB) at MIT's Space Systems Laboratory. This testbed is being designed with two purposes in mind. First it serves as a platform to investigate coupling and impedance effects, which occur when a dynamic disturbance source such as a reaction wheel drives a flexible mechanical structure. Secondly it enables an experimental verification of other elements of the DOCS toolbox such as the isoperformance module. This is achieved by allowing variable parameters (wheel speed, imbalance, spacecraft mass, base stiffness) and several operational modes. The right side shows the testbed, which is comprised of an upper stage (reaction wheel, DC motor, load cell, coupling plate, optics truss), a lower stage (spacecraft truss, weight bed) and an axial stabilization system. The instrumentation consists of three accelerometers, a laser displacement sensor, an inductive proximitor, a six axis load cell and an analog tachometer. The left side shows a comparison between a numerical prediction with a simple 6 state DOCS-model (top) and initial experimental measurements (bottom). It can be seen that the general trends are captured such as an increase in accelerometer response with wheel speed and the occurrence of two resonances including the suspension mode. The maximum predicted and measured displacement RMS of the lower stage is 15 microns. A possible extension to this testbed is to add a Michelson interferometer in the upper stage and to predict and measure the impact of reaction wheel imbalances on fringe visibility.



This chart shows the second ground based testbed, which is being used for experimental validation of the DOCS toolbox. The ORIGINS Telescope Testbed is able to slew by +/- 40 degrees about one axis and simulates the main operational modes of a spaceborne imaging or interferometric telescope such as slewing, target acquisition and tracking. It contains reaction wheels, a gimbal connecting it to the floor structure, a voice coil and piezo stage for pathlength control and a fast steering mirror for pointing control as actuators. The sensors are a digital angle encoder and rate gyro for attitude determination, a heterodyne laser measuring differential pathlength with a resolution of 10 nm and a CCD or quad cell for pointing. The left side of the chart shows the experimentally determined transfer function matrix from all actuators to all sensors. It can be seen that the first flexible mode of the testbed occurs at 2 Hz and corresponds to a flexible appendage simulating solar panels. A non-dimensionalization and scaling analysis ensures traceability of the results to full-size observatories. The testbed has been used to validate several modules of the DOCS toolset such as DynaMod (obtaining measurement models from test data), Sensor-Actuator topologies and Controller tuning.

Conclusions

- **Integrated modeling and simulation** are critical for space and ground-based interferometry before committing to a particular system architecture
- A MATLAB based analysis **toolbox** has been developed and is integrated into the IMOS and MACOS environments. Can work with numerical models or component test data
- **Experimental validation** using laboratory testbeds in 1g has been conducted
- Supports **dynamics and controls analysis**: performance prediction, uncertainty analysis, error budgeting, subsystem requirements definition, controller development

Further information contact: **deweck@mit.edu**

Chart: 12
September 22, 2000 Interferometry Summer School, Leiden NL *MIT Space Systems Laboratory*

The DOCS toolset is in a continuous flux of development. With each new program (SIM, NGST, TPF, Nexus) the tools are becoming more robust and user-friendly. The components MACOS and IMOS are available for academic licensing from JPL. The components DynaMod and ControlForge are available from Mide Technology Corporation (www.mide.com) for commercial licensing. Other components might be available upon request from MIT or will be transitioned to commercial products in the future.