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Mark A. Kahan
Marie B. Levine-West
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Introduction

Optical systems are used just about everywhere today, in systems that both image and illuminate. From eyeglasses to machine vision/robotics to automotive uses, from commercial reprographic equipment to medical instrumentation to the production of integrated circuits, and from telecommunications through Earth observations, space exploration, interferometers, nullers, and weaponry, optical systems are making a difference in our world. This conference is part of a sequence of similar conferences held in prior years that are dedicated to the optical modeling of these evolving imaging and non-imaging systems and the associated test-equipment needed to bring them forward with performance certainty. Note that models continue to be increasingly important as time-to-market pressures escalate and new missions are at times extending beyond the ability to accurately pre-test performance.

To predict performance over such a broad range of optical systems and engineering disciplines, there are a great many mathematical methods and tools that are needed. Some need to correctly model nano-scale systems with feature sizes comparable to the wavelengths of illumination, while others may need to address precise representations of controlled LED light leakage out of purposely-roughened fibers or the fluorescent behavior of specific phosphors. Still others need to contend with components ranging from meta-materials with negative refractive index and cloaking to quantum dots, to special prisms or gratings, to large deployable telescopes where accuracies are measured in picometers or at levels approaching 1/10,000th wave RMS WFE. When we add in wavelengths and configurations that range from X-Rays to THz, and environmental aspects spanning HEL through cryogenic in configurations from the laboratory to under-water and outer-space, the number of modeling developments needed to accurately predict optical performance is immense.

Electro-optical modeling and performance predictions also often require integrating many interdisciplinary techniques and mathematical methods with underlying physics that build-upon and/or utilize (arranged by similarity, of-sorts):

Optical Models, Methods, and Performance Estimates

- geometrical and physical optics
- diffractive optics and holographic systems
- beam propagation
- meta-materials (including negative index, photonic crystals, cloaking)
- plasmonics
- polarization
- adaptive optics
- radiometry
- narcissus
- fiber-optics and photonics
- interferometers and nullers
- image doubling

- illumination (including lasers, LEDs, OLEDS, solar)
- stray light/ghosts
- quantum dots
- optimization
- phase/prescription retrieval
- tolerancing and probabilistic design.

Electro-optical Models Including Relating Factors
- detector quantum efficiency
- charge diffusion
- EMI/EMC influences on E-O performance.

Optical Coating Performance
- filters
- laser damage resistance.

MEMS and MOEMS
- electrostatics; Casimir forces
- structures.

Structural and Opto-mechanical Modeling
- ultra-lightweight optics, nano-laminates, membrane mirrors
- mounting stresses, G-Release, and /or launch and deployment
- high impact/shock& pressure loadings
- influence functions
- vibration and damping
- micro-dynamics and influences of piece-part inertia; friction/stiction
- mechanical influences such as scanning deformations and special zoom/servo effects
- thermo-elastic effects
- stress birefringence
- fracture mechanics, and/or micro-yield
- proof testing models
- aspects such as lay-up anisotropy and material inhomogeneity
- nodal accuracy; meshing.

Thermal and Thermo-optical Modeling
- effects of energy absorption with depth in transmissive elements
- thermal run-away in IR elements
- aircraft/UAV/Instrument windows, missiles, and domes
- solar loading
- thermo-optical material characterizations over new wavelengths and/or temperatures
- system sterilization
- hole drilling, welding, and laser heat- treating
- HEL effects including survivability and hardening
- recursive models where thermo-elastic changes in-turn impact heating
- effects of joint resistance on conduction changes
- effects on LEDs
- meshing.

Integrated Models
- closely coupled thermal-structural- optical models
- optical control systems
- global optimizers
- acquisition, pointing, and tracking
- end-to-end simulations.

Space-borne (and/or Microlithographic) Factors
- contamination control
- particulate/NVR models
- photopolymerization
- radiative damage, atomic O2
- spacecraft charging
- micro-meteoroid modeling, including spalling.

Aero-optics
- boundary layer and shock wave effects
- convective effects and air-path conditioning/self-induced turbulence.

Modeling of Vision Systems

- HUDs
- HMDs.

Application-specific Unique Optical Models and Performance Predictions

- adaptive optics
- bio and medical optics/sensing
- lasers/laser communication systems
- LEDs/solid state lighting
- MEMs/nano technology
- existing/evolving photonic devices and systems
- photonic devices
- solar technology.

Other

- phenomenology
- reliability
- rules of thumb and scale factors of use to individual disciplines
- cost models of optical systems.

This conference brought forward new work in several of these areas. Our intent was to provide special attention to new methods of analysis that would help "anchor" various models and/or also provide parametric relationships to help correlate results with predictions. In this regard, several authors have helped to advance the state-of-the-art by contributing work that provides new insight into different aspects of optical modeling and predicting performance. Abstracts, some as originally submitted, are shown below; please note that some abstracts, authors, and titles were modified in the final version of the papers presented. Note also that some presentations were followed by a relatively lively discussion, so stay tuned, as further work in the areas noted may well be presented at a future date.

Session 1: Exoplanet Systems, Mirrors, and Structures/Materials

Using integrated modeling to assess performance of the Transiting Exoplanet Survey Satellite
(Paper 9577-1) Author(s): Gerhard P. Stoeckel, Keith B. Doyle, MIT Lincoln Lab. (United States)

The Transiting Exoplanet Survey Satellite (TESS) is an instrument consisting of four wide field-of-view CCD cameras dedicated to the discovery of exoplanets around the brightest stars, and understanding the diversity of planets and planetary systems in our galaxy. Using internally developed integrated modeling software, the point spread function is computed for multiple field points over the orbit and used to predict pointing errors for each of the four cameras. These errors are then compared against the requirement for the maximum allowable angular rate of change, and design modifications are implemented to ensure top-level performance requirements of the TESS instrument are met.

Advanced Mirror Technology Development (AMTD) thermal trade studies
(Paper 9577-2) Author(s): Thomas Brooks, H. Philip Stahl, NASA Marshall Space Flight Ctr. (United States); William R. Arnold, a.i. solutions, Inc. (United States); Brent Knight, Mike R. Effinger, W. Scott Smith, NASA Marshall Space Flight Ctr. (United States)

Advanced Mirror Technology Development (AMTD) is being done at Marshall Space Flight Center (MSFC) in preparation for the next Ultraviolet, Optical, Infrared (UVOIR) space observatory. A likely science mission of that observatory is the detection and characterization of 'Earth-like' exoplanets. Direct exoplanet observation requires a telescope to see a planet that is 10^{-10} times dimmer than its host star. To accomplish this using an internal coronagraph requires a telescope with an ultra-stable wavefront. This paper investigates two topics: 1) parametric relationships between a primary mirror's thermal parameters and wavefront stability, and 2) optimal temperature profiles in the telescope's shroud and heater plate that minimize static wavefront error (WFE) in the primary mirror.

AMTD: Advanced mirror technology development in mechanical stability
(Paper 9577-3) Author(s): J. Brent Knight, NASA Marshall Space Flight Ctr. (United States)

Analytical tools and processes are being developed at NASA Marshall Space Flight Center in support of the Advanced Mirror Technology Development (AMTD) project. One facet of optical performance is mechanical stability with respect to structural dynamics. Pertinent parameters are: (1) the spacecraft structural design, (2) the mechanical disturbances on-board the spacecraft (sources of vibratory/transient motion such as reaction wheels), (3) the vibration isolation systems (invariably required to meet future science needs), and (4) the dynamic characteristics of the optical system itself. With stability requirements of future large aperture space telescopes being in the lower Pico meter regime, it is paramount that all sources of mechanical excitation be considered in both feasibility studies and detailed analyses. The primary objective of this paper is to lay out a path to perform feasibility studies of future large aperture space telescope projects which require extreme stability. To get to that end, a high level overview of a structural dynamic analysis process to assess an integrated spacecraft and optical system is included.

Unified optomechanical modeling: Stabilizing the line-of-sight of an IR imager
(Paper 9577-4) Author(s): Alson E. Hatheway, Alson E. Hatheway Inc. (United States)

A common mechanical failure in optical systems is inadequate stiffness in the supporting structure. Stiffness is crucial for maintaining the alignment of the optical elements and achieving adequate optical performance. It is the responsibility of the mechanical engineer to provide adequate stiffness in the mechanical design.
Optical engineers assume that their large-displacement non-linear codes are required to analyze the perturbations caused by mechanical deflections. However, the permitted deflections of the optical elements are usually quite small, on the order of microns for structures of meter-sized dimensions. For perturbations of this magnitude it may be shown that a non-linear solver is not required for engineering accuracies. In fact, it can be argued that the optical functions are more linear than the solid mechanics functions, of which the finite element method itself is but a linear simplification.

Unified optomechanical modeling provides a vehicle for tracing offending image motions to particular optical elements and their supporting structure. The unified modeling method imports the optical elements' imaging properties into a finite element structural model of the optical system. It convolves the elements' motions and their optical properties in a single optomechanical modeling medium, unifying them. This provides the engineer with a tool that discloses each element's contribution to the offending motions of the image on the detector.

This paper presents the theory of unified optomechanical modeling as applied to the optical line-of-sight in a Nastran finite element model. The steps used in developing a unified optomechanical model are described in detail. Comparisons of the unified modeling technique to both analytical and empirical validation studies are shown.

Research on model identification of ultra-precision motion stage
(Paper 9577-5) Author(s): Sheng Qiang, Bin Wang, Harbin Institute of Technology (China)

Analyzing the structure of precision motion platform, building mathematical model of linear motors and voice coil motors, thereby macro-micro coupling theoretical models and mechanical model are established, which can reflect the combined effect of multiple motors motion characteristics. The unknown parameters of the macro-micro coupling theoretical model are identified by adaptive real-coded genetic algorithm. Validity of the precision motion platform model has been verified by simulations.

Integrated modeling: a look back
(Paper 9577-6) Author(s): Clark Briggs, ATA Engineering, Inc. (United States)

This paper discusses applications and implementation approaches used for integrated modeling of structural systems with optics over the past 30 years. While much of the development work focused on control system design, significant contributions were made in system modeling and computer-aided design (CAD) environments. Early work appended handmade line-of-sight models to traditional finite element models, such as the optical spacecraft concept from the ACOSS program. The IDEAS2 computational environment built in support of Space Station collected a wider variety of existing tools around a parametric database. Later, IMOS supported interferometer and large telescope mission studies at JPL with MATLAB modeling of structural dynamics, thermal analysis, and geometric optics. IMOS's predecessor was a simple FORTRAN command line interpreter for LQG controller design with additional functions that built state-space finite element models. Specialized language systems such as CAESY were formulated and prototyped to provide more complex object-oriented functions suited to control-structure interaction. A more recent example of optical modeling directly in mechanical CAD is used to illustrate possible future directions. While the value of directly posing the optical metric in system dynamics terms is well understood today, the potential payoff is illustrated briefly via project-based examples. It is quite likely that integrated structure thermal optical performance (STOP) modeling could be accomplished in a commercial off-the-shelf (COTS) tool set. The work flow could be adopted, for example, by a team developing a small high-performance optical or radio frequency (RF) instrument.

Session 2: Stray Light, Illumination, and DOEs

The different (yet similar) realms of illumination and stray light modeling
(Paper 9577-7) Author(s): Edward Freniere, Michael A. Gauvin, Lambda Research Corp. (United States); Richard N. Youngworth, Riyo LLC (United States)

The field of non-imaging optics is currently a diverse and fertile ground for innovation and analysis. Modeling systems for illumination and stray light effects influences a wide variety of electrical, optical, mechanical, material science, and system design decisions. Applications are also diverse in non-imaging including not only modeling these effects in imaging systems, but also important technologies such as solar energy, illumination, and projection systems, to name just a few areas of interest. Although design and analysis for illumination and stray light problems are both done in nonsequential ray-tracing programs, many practitioners only operate in one arena. Furthermore, the tasks associated with each of these types of problems have both similarities and distinct features. The goal of this paper is to provide a wide audience, including experts and people new to the field, an overview of the differences and similarities in modeling these two different (yet alike) types of problem.

Simulating the 2D PSF of multiple-reflection optical systems with rough surfaces
(Paper 9577-8) Author(s): Kashmira Tayabaly, INAF -Osservatorio Astronomico di Brera (Italy) and Politecnico di Milano (Italy); Daniele Spiga, Giorgia Sironi, Rodolfo Canestrari, Giovanni Pareschi, Paolo Conconni, INAF - Osservatorio Astronomico di Brera (Italy)

The Point Spread Function (PSF) is a key figure of merit for specifying the angular resolution of optical systems and, as the demand for higher and higher angular resolution increases, the problem of surface finishing must be taken seriously even in optical telescopes. From the optical design of the instrument, reliable ray-tracing routines allow computing and display of the PSF based on geometrical optics. However, such an approach does not directly account for the scattering caused by surface microroughness, which is interferential in nature. Although the scattering effect can be separately modeled, its inclusion in the ray-tracing routine requires assumptions that are difficult to verify. In that context, a purely physical optics approach is more appropriate as it remains valid regardless of the shape and size of the defects appearing on the optical surface. Such a computation, when performed in two-dimensional consideration, is memory and time consuming because it requires one to process a surface map with a few micron resolution, and the situation becomes even more complicated in case of optical systems characterized by more than one reflection. Fortunately, the computation is significantly simplified in far-field configuration, since the computation involves only a sequence of Fourier Transforms. In this paper, we provide validation of the PSF simulation with Physical Optics approach through comparison with real PSF measurement data in the case of ASTRI-SST M1 hexagonal segments. These results represent a first foundation stone for future development in a more advanced computation taking into account microroughness and multiple reflection in optical systems.

General physically-realistic BRDF models for computing stray-light from arbitrary isotropic surfaces

(Paper 9577-9) Author(s): Alan W. Greynolds, Consultant (United States)

Proposed twenty-five years ago specifically for stray light computations, a general BRDF model that automatically enforces continuity, positivity, reciprocity, and isotropic surface symmetry over all possible input/output directions has been implemented in commercial optical analysis codes. It was originally motivated by the need to fit (and possibly catalogue) measured BRDFs of everything from polished optical surfaces to rough diffuse blacks, reasonably extend in-plane only data to out-of-plane, reduce hundreds or thousands of measurement points to a relatively small number of parameters (like glass dispersion formulas), and cleanup "sloppy" data or models that violate physical constraints. However, there is little attempt to relate the BRDF to any actual surface structure or statistics (the inverse problem). As application examples, the model successfully fits several thousand measured data points on a "glossy" anodized Aluminum sample to a 100-coefficient form and several dozen measured data points on Aeroglaze Z306 diffuse black paint to a general 20-coefficient form then probably the simplest 2-parameter model. Variations and other general BRDF models are also proposed.

Optomechanical analysis of diffractive optical elements

(Paper 9577-10) Author(s): Gregory J. Michels, Victor L. Genberg, Sigmadyne, Inc. (United States)

Diffractive optical elements are important components to many high precision optical systems. When such systems are subjected to mechanical loading these optical components yield performance degradation contributions quite different from non-diffractive optical components. It is of interest to predict by analysis such performance degradations for the purposes of development of the optomechanical design for relevant optical systems. The developments of this paper are to characterize the changes in phase due to such deformations as predicted by the finite element method and represent them in optical analysis alongside characterizations of surface shape changes.

Session 3: Polarization, Telecom, and Microlithography

Minimize polarization aberrations to use all of the photons all of the time
(Paper 9577-11) Author(s): James B. Breckinridge, California Institute of Technology (United States) and The Univ. of Arizona (United States); Wal Sze T. Lam, College of Optical Sciences, The Univ. of Arizona (United States); Russell A. Chipman, The Univ. of Arizona (United States)

We analyze the polarization aberrations in a "typical" astronomical telescope to understand their effects on image quality for coronagraphic, photometric and astrometric applications. Polarization aberrations are just as important as geometric aberrations in high-performance ground and space astronomical systems, particularly in photon-starved situations that rely on high fidelity imaging. We show that the point spread function (PSF) for astronomical telescopes and instruments depends not only on geometric aberrations and scalar wave diffraction, but also on those wavefront errors introduced by the physical optics and the polarization properties of reflecting and transmitting surfaces within the optical system.

Simultaneous and independent optical impairments monitoring using singular spectrum analysis of asynchronously sampled signal amplitudes
(Paper 9577-12) Author(s): Latifa Guesmi, Mourad Menif, SUP'COM (Tunisia)

Optical performance monitoring (OPM) becomes an inviting topic in high speed optical communication networks. In this paper, a novel technique of OPM based on a new elaborated computation approach of singular spectrum analysis (SSA) for time series prediction is presented. Indeed, various optical impairments among chromatic dispersion (CD), polarization mode dispersion (PMD) and amplified spontaneous emission (ASE) noise are a major factors limiting quality of transmission data in the systems with data rates lager than 40 Gbit/s. This technique proposed an independent and simultaneous multi-impairments monitoring, where we used SSA of time series analysis and forecasting. It has proven their usefulness in the temporal analysis of short and noisy time series in several fields, that it is based on the singular value decomposition (SVD). Also, advanced optical modulation formats (100 Gbit/s non-return-to zero dual-polarization quadrature phase shift keying (NRZ-DP-QPSK) and 160 Gbit/s DP-16 quadrature amplitude modulation (DP-16QAM)) offering high spectral efficiencies have been successfully employed by analyzing their asynchronously sampled amplitude.

The simulated results proved that our method is efficient on CD, first-order PMD, Q-factor and OSNR monitoring, which enabled large monitoring ranges, the CD in the range of 170-1700 ps/nm.Km and 170-1110 ps/nm.Km for 100 Gbit/s NRZ-DP-QPSK and 160 Gbit/s DP-16QAM respectively, and also the DGD up to 20 ps is monitored. We could accurately monitor the OSNR in the range of 10-40 dB with monitoring error remains less than 1 dB in the presence of large accumulated CD.

Session 4: Fiber Optics in Testing and Radiation Sensing

System simulation method for fiber-based homodyne multiple target interferometers using short coherence length laser sources
(Paper 9577-14) Author(s): Maik Fox, Thorsten Beuth, Karlsruher Institut für Technologie (Germany); Andreas Streck, ELOVIS GmbH (Germany); Wilhelm Stork, Karlsruher Institut für Technologie (Germany)

Homodyne laser interferometers for velocimetry are well-known optical systems used in many applications. While the detector power output signal of such a system, using a long coherence length laser and a single target, is easily modelled using the Doppler shift, scenarios with a short coherence length source, e.g. an unstabilized semiconductor laser, and multiple weak targets demand a more elaborated approach for simulation. Especially when using fiber components, the actual setup is an important factor for system performance as effects like return losses and multiple way propagation have to be taken into account. If the power received from the targets is in the same region as stray light created in the fiber setup, a complete system simulation becomes a necessity.

In previous work, a phasor based signal simulation approach for interferometers based on short coherence length laser sources has been evaluated. To facilitate the use of the signal simulation, a fiber component ray tracer has since been developed that allows the creation of input files for the signal simulation environment. The software uses object oriented MATLAB code, simplifying the entry of different fiber setups and the extension of the ray tracer.

Thus, a seamless way from a system description based on arbitrarily interconnected fiber components to a signal simulation for different target scenarios has been established. The ray tracer and signal simulation are being used for the evaluation of interferometer concepts incorporating delay lines to compensate for short coherence length.

Calculation of detection efficiency of the fiber-optic sensor to measure radioactive contamination using MCNP simulation

(Paper 9577-15) Author(s): Hanyoung Joo, Arim Lee, Chan Hee Park, Rinah Kim, Joo Hyun Moon, Dongguk Univ. (Korea, Republic of)

In this paper, a fiber-optic radiation sensor (FORS) was developed to measure gamma rays from the radionuclides frequently found in radioactively contaminated soil. The sensing probe of the FORS was made of an inorganic $(Lu,Y)_2SiO_5$:Ce (LYSO:Ce) scintillator, a mixture of epoxy resin and hardener and a plastic fiber. The FORS was applied to measure gamma rays from Cs-137 source (1.1 μCi) in a disk shape. Also, MCNP simulation was performed for the same geometry as that in the experimental setup. Comparison between measurements by the FORS and MCNP simulation showed that the detection efficiency of the fiber-optic sensor was about 19.2%. The FORS is expected to be useful in measuring gamma rays from the radioactive soil at nuclear facility site.

Session 5: Gratings: Manufacturing, Beam Combining, and Temperature Sensing

Temperature sensing on tapered single-mode fibre using mechanically-induced long-period fibre gratings

(Paper 9577-19) Author(s): Sigifredo Marrujo-García, Ernesto González-Ocaña, Jesús Salvador Velázquez-González, Fernando Martínez-Piñón, María Guadalupe Pulido-Navarro, Ctr. de Investigación e Innovación Tecnológica (Mexico); Daniel Enrique Ceballos-Herrera, Univ. Autónoma de Nuevo León (Mexico)

The modeling of a temperature optical fiber sensor is proposed and experimentally demonstrated in this work. The suggested structure to obtain the sensing temperature characteristics is by the use of a mechanically induced Long Period Fiber Grating (LPFG) on a tapered single mode optical fiber. A biconical fiber optic taper is made by applying heat using an oxygen-propane flame burner while stretching the single mode fiber (SMF) whose coating has been removed. The resulting geometry of the device is important to analyze the coupling between the core mode to the cladding modes, and this will determine whether the optical taper is adiabatic or non-adiabatic. On the other hand, the mechanical LPFG is made up of two plates, one grooved and other flat, the grooved plate was done on an

acrylic slab with the help of a computerized numerical control machine (CNC). In addition to the experimental work, the supporting theory is also included.

Low-cost and high-resolution interrogation scheme for LPG temperature sensor
(Paper 9577-20) Author(s): Venkata Reddy Mamidi, Srimannarayana Kamineni, National Institute of Technology, Warangal (India)

A low-cost and high-resolution interrogation scheme for a long-period fiber grating (LPG) temperature sensor with adjustable temperature range has been designed, developed and tested. In general LPGs are widely used as optical sensors and can be used as optical edge filters to interrogate the wavelength encoded signal from sensors such as fiber Bragg grating (FBG) by converting it into intensity modulated signal. But the interrogation of LPG sensors using FBG is a bit novel and it is to be studied experimentally. The sensor works based on measurement of shift in attenuation band of LPG corresponding to the applied temperature. The wavelength shift of LPG attenuation band is monitored using an optical spectrum analyzer (OSA). Further the bulk and expensive OSA is replaced with a low-cost interrogation system that employ an FBG, photodiode and a transimpedance amplifier (TIA). The designed interrogation scheme makes the system low-cost, fast in response, and also enhances its resolution up to 0.1°C. The measurable temperature range using the proposed scheme is limited to 120 °C. However this range can be shifted within 15-450 °C by means of adjusting the Bragg wavelength of FBG.

Poster Session

Conference attendees were invited to attend the poster session on Monday evening.

Modeling of waveguide-couplers for the use in a micro-optical laser gyroscope
(Paper 9577-23) Author(s): Ingmar Leber, Thalke Niesel, Andreas H. Dietzel, Technische Univ. Braunschweig (Germany)

A new concept for the realization of a micro optical laser gyroscope was developed. This new concept consists of a passive free space ring resonator in which the light is circulating by reflections at three double mirrors. An external light source will be used to activate the resonator. To couple the light in and out of the resonator there will be waveguide-couplers used. This work reports on the modeling and simulation of waveguide-coupler structures. The simulation results are compared to experimental results of systematic examination of integrated waveguide-coupler structures for the use in the new micro optical resonator concept.

The full richness of application diversity and increasingly sophisticated operational requirements combine to make Optical Modeling and Performance Predictions an area where challenges abound. Clearly clever thinking can continue to return high intellectual rewards while significantly contributing to our collective ability to understand, enable, and improve the hardware of tomorrow.

Mark A. Kahan