PROCEEDINGS OF SPIE

Optical Modeling and Performance Predictions IV

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Editor

5–6 August 2009
San Diego, California, United States

Sponsored and Published by
SPIE

Volume 7427

Proceedings of SPIE, 0277-786X, v. 7427

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

Please use the following format to cite material from this book:
Author(s), "Title of Paper," in *Optical Modeling and Performance Predictions IV*, edited by Mark A. Kahan, Proceedings of SPIE Vol. 7427 (SPIE, Bellingham, WA, 2009) Article CID Number.

ISSN 0277-786X
ISBN 9780819477170

Published by
SPIE
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIEDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

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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 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 underwater and outerspace, 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):

Geometrical and Physical Optics
Fiber Optics
Interferometers and Nullers
Evolving Photonic & Plasmonic Models
Fluorescence & Scattering
Polarization
Stray Light/Ghosts
Adaptive Optical Models
Detector Quantum Efficiency & E-O Performance
Phase/Prescription Retrieval
EMI/EMC Influences
Material Removal, Heat Treating
Testing & Calibration Models
Laser and Laser Communication Models
Models of Vision Systems – incl. HUDs and HMDs
MEMS and MOEMS – Electrostatics & Structures
Mounting Stress, G-Release, Launch/Deployment
Vibration & Damping
Mechanical Influences/Scanning Deformations
Material Stability & Fracture Mechanics
Material Factors/Lay-Up Anisotropy; Inhomogeneity
Thermo-Elastic & Thermo-Optical Effects
Thermal Run-Away in IR Elements
T/O Material Characterization – New λ's/Temp's
System Sterilization
Solar Loading
Joint Resistance/Surf. Finish & Conduction Changes
Convective Effects & Air-Path Conditioning
Aero-Optics, Boundary Layers & Shock Waves
Integrated Models, Nodal Ties/Accuracies
Closely Coupled Thermal-Structural-Optical Models
Radiative Damage
Contamination Control
Particulate Models
S/C Charging; Photopolymerization, Atomic O_2 Phenomenology
Weight Models; Power Models
Rules of Thumb
Diffractive & Holographic Optics – incl. Coherence & Speckle
Illumination Design – incl. Lasers, LEDs, OLEDs, Solar, etc
Optimization & Global Optimizers
Meta-Materials – incl. Negative Index, Photonic Crystals, Cloaking
Beam Propagation
Radiometry
Narcissus
Influence Function Treatment
Charge Diffusion
Computational Optics
Tolerancing
Probabilistic Design
Optical Coating and Filters
Modeling of Bio/Medical Devices
Quantum Dots
Laser Damage Resistance
Ultra-Lightweight Optics/Nano-Laminates & Membrane Mirrors
High Impact/Shock Loading
Micro-Dynamics & Influences of Piece-Part Inertia
Special Zoom/Servo Effects
Stress Birefringence
Proof Testing Models
Energy Absorption With Depth in Transmissive Elements
Recursive Models Where T/S Changes Impact Heating
Sources – incl. THz, Fiber Lasers & Wall-Plug Efficiency Factors
Absorptive/Reflective Baffles/Structures
HEL Effects Including Survivability & Hardening
Hole Drilling, Welding, and Laser Heat Treating
Aircraft/UAV Windows, Missiles & Domes
Self-Induced Turbulence
Optical Control Systems
Acquisition, Pointing, and Tracking
Atmospheric Refraction & Scattering
NVR Models
Micro-Meteoroid Modeling – incl. Models of Spalling
Reliability
Schedule and Cost Models of Optical Systems
Scale Factors Of Use to Individual Disciplines

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.

Component Design

Alan Greynolds (Ruda-Cardinal, Inc.) presented new work on the space propagation of extreme NA polarized beams using a vector plane wave spectrum method. He noted that certain lasers have initial waists only a wavelength or less in size, requiring collection optics with extreme numerical apertures (NA). Though the design of these macro-optics using geometrical ray-tracing is trivial, Al noted that determining the exact vectorial field entering them is not. He presented the theory/implementation of Fourier, or Plane Wave Spectrum (PWS), based methods for near, intermediate, and far field applications. He also presented a real-world example where a 12 gigabyte two-dimensional fast Fourier transform (FFT) was required and where unexpected polarization effects were observed.

James Ryle (for John Healy & with John Sheridan of the University College Dublin) discussed a new sampling criterion for use in Linear Canonical Transform (LCT) analysis based on the consequences of sampling the LCT of a discrete signal. Previous LCT sampling work in the literature only considers sampling the LCT of continuous, band-limited signals. This analysis is important for numerical simulations of first order optical systems using the LCT, as these simulations must necessarily consider sampled input/output functions, and it also has significance in the analysis of periodic structures such as gratings. James discussed the consequences of this new work relative to analysis with fast LCT algorithms, and the use of the discrete Fresnel transform in digital holography, and he also presented numerical results which tested the analysis performed.

George Lawrence et. al. (Applied Optics Research; with NGC Electronic Systems/ Laser Systems & GSFC) covered a method of modeling a zigzag laser amplifier. In George's model a beam was injected at a large angle into a pair of reflecting side walls enclosing a gain medium. The optical beam then crisscrossed the gain in multiple passes increasing the gain length and averaging-out some of the effects of non-uniform gain. The paths overlapped at each sidewall reflection and swept out a complex zigzag path in the amplifier and to higher inversion depletion in selected regions. Ten reflections on the side walls resulted in a very complex three-dimensional gain distribution unlike a straight-through configuration where the gain might be represented in just a few axial steps and associated gain sheets, a full 3D solution would require the solution of ~ six differential equations at perhaps many millions of points in the 3D volume. Also, in a Q-switch laser, the variation of the optical field is extreme – covering many orders of magnitude. George described a method based on exact pixel matching and Franz-Nodvik theory that solved the full 3D gain problem in just a few seconds on an ordinary PC. This method of exact pixel matching eliminated the need for interpolations that would increase calculation time and reduce accuracy. The use of Franz-Nodvik theory gave a robust and rapid solution, even for the extremes of Q-switch operation. (The Editor notes this method should also help speed selected STOP evaluations where the perturbed laser's surfaces and paths can recursively impact subsequent paths/changes.)

Detectors (Including the Human Eye)

Ibrahima Djité (Institut Supérieur de l'Aéronautique et de l'Espace) shared his work on the theoretical evaluation of MTF and charge collection efficiency in CCD and CMOS image sensors. Classical models used to calculate the Modulation Transfer Function (MTF) of an image sensor generally solve the steady-state continuity equation in the case of a sinusoidal type of illumination to determine the MTF value using a contrast calculation. However, one of the major inconveniences of this approach is the impossibility of analytically evaluating crosstalk. Ibrahima described a new theoretical three-dimensional model of both the diffusion and the collection of photo-carriers, as created by point-source illumination on a image sensor array. Using his model one can accurately evaluate the crosstalk in, and the charge collection efficiency/MTF of, image sensors at all needed wavelengths.

Chong-Jhih Jiang et. al. (National Central University, Dept. of Optics and Photonics, Taiwan) related how she and her colleagues developed a human eye model for visual performance assessment – a powerful tool for the fields of ophthalmology, optics and vision science. Recent advances in metrology have resulted in improvements in ocular biometric data and this helped "Jean" and her colleagues develop an improved biometry-based human eye model in CODE V® and ASAP®. The non-homogeneous crystalline lens had its refractive index described by an index gradient, formulated with 2nd-order polynomials fit to empirical data and varied over wavelength according to a dispersive model. The chromatic dispersion model of the homogeneous ocular media was constructed by using Cauchy equations, and the chromatic optical power obtained from this model matched that of physiological eyes. Optical performance was evaluated using a point spread function (PSF) for an object at infinity and by a modulation transfer function (MTF) evaluated at single and multiple wavelengths. Preliminary contrast sensitivity tests of human observers validated the sagittal and tangential resolution differences in the monochromatic MTF. Light scatter occurs from the iris, ocular media and interfaces, cataracts, and normal aging. Due to the large size of protein particles in the human eye, Mie scattering dominates in the ocular media. The volumetric scatter in a cataractous lens was simulated with two variables: the mean size of the protein polymers and the obstruction area per unit volume. It was found that scattering caused a large energy loss at the fovea and increased veiling glare. Further model modifications were discussed, i.e. the need for including lens accommodation and age related factors. This evolving model has good potential for studying visual performance in general as well as the influence of glare inducing light sources. (Editor's note: This is a large problem in the appropriate design of street lighting.)

<u>Radiometry and Stray Light</u>

Leonard Hanssen (for/with Alexander Prokhorov, NIST) summarized their work on the application of the Monte Carlo method to the solution of computational problems in precision optical radiometry. Here, one would like to compute the spectral and total radiance, irradiance, and radiation flux with levels of relative uncertainty of several hundredths of percent or less so as to better characterize numerous devices such as stray radiation traps, blackbody cavity radiators, radiometers, integrating spheres of various designs and purposes, etc. It was noted that the model of reflection that is primarily employed is the diffuse (Lambertian) model, and in rare cases a simplified specular-diffuse model. However, there are materials for which such models cannot adequately simulate the real angular distributions of reflected radiation, and more importantly, applications and conditions for which the modeling results will not be sufficiently accurate. In this paper, the features and the methods of modeling for different kinds of reflection (from a rough surface, within a volume, and with the subsurface scattering), combined with the use of importance sampling, were considered, with a focus on the acceptance-rejection technique as well as on procedural methods. Monte Carlo algorithms for modeling non-Lambertian reflection were also discussed. Good agreement of the simulated and measured bi-directional reflectance distribution functions (BRDFs) for several materials was demonstrated. (Editor's note: Real-world factors that relate to material variations as well as changes in material characteristics with temperature and alternate ways of representing the various characteristics of materials, including some that might exhibit anomalous scatter from sub-surface structure, were also covered during the audience discussion.)

K. Scott Ellis (Photon Engineering LLC) presented a summary of the modeling work done to characterize the stray light characteristics of the Large Synoptic Survey Telescope (LSST), a proposed large, ground-based telescope that is intended to survey the entire visible sky every three nights. Stray light control is important for optimum sensitivity over decades of stellar magnitude. Scott showed how a critical / illuminated object study of the baseline design identified several stray light mechanisms that required unique baffling approaches. PST calculations (including the effects of diffraction) were run over multiple azimuth angles to quantify the stray light background levels and assess baffle effectiveness. Baffle design trades and their effect on stray light levels were also discussed.

Assembly and Test

Olena A. Protasova (for/with Volodymyr Borovytsky, National Technical University of Ukraine) presented a mathematical technique for calculating the three-dimensional intensity distribution near the focal point of a high aperture optical system for the case of quasi monochromatic partly polarized light. The technique used (Editor's note: which is at the mathematical formalism stage) is an extension of vector diffraction theory for high aperture optical systems, as based on Huygens-Fresnel principle, i.e. a spherical wave at the exit pupil is considered as a numerous set of elementary secondary partly polarized light sources. The total intensity is calculated as a superposition of complex wave amplitudes taking into account polarization orientation, the degree of polarization defined by Stokes parameters, the orientation of the detector aperture, and the coherence length of the quasi-monochromatic light. Cartesian (rectangular) angular coordinates were applied instead of polar coordinates to increase accuracy and to simplify digital integration. It was mathematically proven that the known expressions for calculating the intensity distribution near a focal point of an optical system formed by polarized and non-polarized light can be considered as a partial case of the proposed technique. A comparative analysis of three-dimensional intensity distributions for various degrees of polarization was outlined, and the influence of partial polarization and coherence length to the shape and dimensions of the intensity distribution at focus was discussed.

Bryan Stone (Optical Research Associates) discussed going beyond ray-based approaches to modeling interferometers with lens design software. Bryan showed that here are a number of aspects of interferometers that can be nicely modeled by using rays. For example, ray-based models allow one to make predictions regarding the changes to a measurement when aberrations are introduced into the input wave front, etc. [see Bryan D. Stone, "Modeling interferometers with lens design software", Opt Eng 39 1748-1759, July 2000 for a discussion of a ray-based approach to modeling interferometers]. However, there are other aspects that are more difficult (or impossible) to model well with ray-based approaches. For example, if a surface under test is not conjugate to the detector, the effects due to diffraction from the edge of the surface cannot be modeled with conventional ray-based approaches. Fortunately, modern lens design software generally includes tools for modeling beam propagation, and these tools can be used to go beyond conventional ray-based modeling of interferometers. Bryan discussed the use of this type of tool to model a variety of aspects of interferometer for which ray-based methods are not well-suited. This included issues like edge diffraction when a part is out of focus and how changes to the speed of the viewing optics can affect a measurement. (Editor's note: Bryan also covered sampling/beamlets, and the modeling of systems with large amounts of aberration, and departures from sphericity.)

Max Funck et. al. (RWTH Aachen, Lehrstuhl für Technologie Optischer Systeme) showed how they statistically simulated a selectively assembled optical system. Selective assembly is presently employed where fabrication of components to the required precision is either infeasible or exceedingly expensive or if extremely high system performance is required. However, even though these attributes frequently apply to optical systems, selective assembly is actually rarely applied in optics. A computer simulation approach was used to investigate the potential of selective assembly in optical systems taking optic-specific influences and quality criteria into account. The process of selecting randomly distributed components and finding the best matches was modeled and integrated in ray-tracing simulations, such that the development environment originally used to design the optical system could also be used for the analyses. Components with parameters varying randomly according to their tolerance distributions were generated with Monte Carlo analyses, and possible component combinations were created and entered in the ray-tracing simulation. Optimization steps could be employed at any point to account for alignment procedures or compensators. This procedure was repeated for sets of "n" components that were then combined into exactly "n" systems, so that no components would be left over at the end of the process. Out of all possible permutations resulting in sets of "n" systems the best set was chosen. Repetition of the experiment provided data for statistical analysis of the matching process and the probable benefits that could be achieved by using selectively assembly. The method was successfully applied to centration errors of a laser pump optic.

<u>Thermal</u>

Jose Suárez-Romero et. al. (Instituto Tecnológico de Querétaro, Mexico) addressed Fourier theory, and the modeling associated with temperature measurements. The best instruments in temperature measurements are double cavity pyrometers or radiometers, with or without imaging lenses. Accurate modeling requires knowledge of the function/scale of the instrument. In a previous work the authors covered the modeling of instruments without lenses, and they also considered partial coherence. However the resultant models had expressions that included four-fold integrals and which required several variable changes, both of which made it difficult to physically interpret the result. In this new work the authors generalize their results for instruments with lenses, and they use Fourier techniques to obtain an expression that is easier to manipulate and to interpret. The "instrument function" is evaluated numerically and physically interpretation for cases both with and without lenses. They applied this model to treat the case of plane filament lamps used in high temperature calibrations, and they also applied the theory to incandescent sources with different geometries and materials. Experimental verifications were shown which confirm their model.

Keith Doyle (MIT Lincoln Laboratory) presented antenna performance predictions for a radio telescope subject to thermal perturbations. The large ~ 120-foot (~ 35M) antenna's performance predictions and required calibration times were estimated using thermal-structural-optical modeling techniques. The telescope was designed to operate at frequencies up to 325 GHz with a one-way performance requirement of 1 dB loss in gain accounting for fabrication errors, alignment errors, gravity and thermal effects. Thermal degradations are principally due to temperature gradients acting over the antenna structure due to varying time constants of the structural members from daily air temperature changes and due to thermal air gradients within the raydome. Antenna performance predictions were made coupling thermal, structural, and optical modeling tools to evaluate performance as a function of time. Based on the results, design requirements were imposed on the radome thermal control system and the rate of calibration of the hexapod mounted subreflector. (Editor's note: Thermal control/AC within a diurnally heated fully enclosed dome can be a challenge, as can conductive "shunts" due to joint resistances. Athermalization and secondary focus adjustment may also come into play.)

Myung Cho et. al. (National Optical Astronomy Observatory AURA, together with the University of Arizona, and authors from the Thirty Meter Telescope Project) presented work on the thermal performance prediction of the Thirty Meter Telescope (TMT) telescope structure. (Editor's note: Here the dome is to be opened to the air at night, well before observations begin. See also the comments noted in the prior paper.) Thermal analysis of the TMT structure was performed using finite element analysis in ANSYS and I-DEAS. In the thermal analysis, the telescope structural parts, with simplified optical sub-systems, were modeled for various thermal conditions including air convection, conduction, heat flux loadings, and radiation. Thermal responses of the TMT telescope structure were predicted and the temperature distributions of the optical systems were calculated for sample thermal loading conditions. Thermo-elastic analysis was used to obtain the thermal deformations based on the resulting temperature distributions. Line of sight calculations were made using the thermally induced structural deformations. The goal of the thermal analysis was to establish FEA thermal models that could be used to establish the thermal responses of the TMT structure as well as an adequate thermal environment. It was noted that thermal performance predictions of the TMT structure will also help control and maintain acceptable system "seeing."

Adaptive Optics and Dynamics

Byoung-Joon Seo et. al. (Jet Propulsion Lab, together with authors from the Thirty Meter Telescope Project) discussed the modeling work they have done to assess the residual wavefront errors on the TMT's primary mirror segments. These residuals errors, after shape corrections with a warping harness have been applied, are the single largest error term in the Thirty Meter Telescope image quality error budget. In order to better understand the likely errors and how they will impact the telescope performance the team performed detailed simulations. They first generated primary mirror segment surface shapes that met TMT specifications. Then they used the predicted warping harness influence functions and a Shack-

Hartmann wavefront sensor model to determine estimates for the 492 corrected segment surfaces that make up the TMT primary mirror. Surface and control parameters, as well as the number of subapertures, were varied to explore the parameter space. The corrected segment shapes were then passed to an optical TMT model built using the Jet Propulsion Laboratory (JPL) developed Modeling and Analysis for Controlled Optical Systems (MACOS) ray-trace simulator. The generated exit pupil wavefront error maps provided RMS wavefront error and image-plane characteristics like the Normalized Point Source Sensitivity (PSSN). The results, which were discussed, have been used to optimize the segment shape correction and wavefront sensor designs as well as provide input to the TMT systems engineering error budgets. (Editor's note: Aspects relating to the inclusion/exclusion of a control loop to minimize bending moments and the effects of actuator angular tolerances were also discussed.)

Integrated Modeling

David Thomas (for/with Jason Geis and an Aerospace Corporation team) discussed a new software environment for the collaborative design and analysis of electro-optical sensors. David noted that over the past three years, a small engineering group at the Aerospace Corporation has been working with Comet Solutions, Inc. to develop a Simulation Driven Engineering (SDE) software tool that will enable Electro-Optical (EO) sensors to be designed and analyzed in a collaborative fashion across engineering discipline boundaries using the underlying COTS CAD and CAE engineering tools that the engineers already use to do their work. The initial application is Structural/Thermal/Optical (STOP) analysis, or the analysis of optical performance impacts arising from structural deformations to an opto-mechanical system due to quasi-static changes in instrument thermal environment. The Comet SDE STOP software was applied to the analysis of STOP effects in a sensitive lens subassembly that is a critical component in the visible channel of an EO sensor that has been developed for a government customer. The underlying CAD and CAE tools used for the analysis were ProE (mechanical CAD), Thermal Desktop (thermal analysis), Abaqus (structural analysis), SigFit (structures to optics conversion), and CODE V (optical analysis). The effects of lens retainer contact stresses and thermal gradients in the lens components and structure were included in the analysis. David's presentation began with an overview of the Comet software and its operation, and it concluded with a presentation of STOP analysis results for the specific optical system of interest. Dave also showed a comparison of model predictions to test data taken on the optical system during final thermal vacuum testing.

Posters

Jianping Wang et. al (University of Science and Technology of China) posted a paper on the physical distortion of a focal plane plate. The paper indicated that the multi-hole focal plate is one of the most important components of the LAMOST (Large Sky Area Multi-Object Fiber Spectroscopy Telescope), and its shape needs to be precisely centripetal and spherical. Hole-drilling can lead to residual stress and larger than desired distortion. Their paper covered a finite element simulation, as tied to the metal cutting principles. The distribution of residual surface stress was modeled using the FEM tool, ANSYS. The influence of cutting depth on the distortion of the focal plate was also investigated. Final CMM test results for distortion matched predicted deviations from a theoretical sphere to better than 0.066mm. The result showed that FEM analysis can be an effective method to predict focal plate machining distortion.

Last but not least, **Andrey Anisimov et. al. (St. Petersburg State University of ITMO)** posted a paper on the accuracy characteristics of the "shift control optical-electronic measurement system." Andrey walked visitors to his poster through his team's work. He noted that high accuracy shift control of large-size constructions (such as turbine or radio telescopes elements) involves an alignment task that can be solved with the help of an optical-electronic auto reflection measurement system. The paper describes such an alignment system based on an auto reflection optical scheme with a CCD-sensor, and its design, precision characteristics and testing were presented. This work included development of a point image's center detection algorithm with an accuracy within 0.05 pixel, as well as a coordinate system conversion method. Theoretical estimates of total system's accuracy were also described that used reflectors (corner-cube prism) and a couple of LEDs at specific locations. The main error sources were found to be the bending of the sighting points. Precision characteristics were established during the experiment, and total error did not exceed 0.05 mm at a distance of 20 M.

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 and improve the hardware of tomorrow.

Mark A. Kahan