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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 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):

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

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.

Optical Models, Methods, and Performance Estimates, Concluded

-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.

MEMS and MOEMS

-electrostatics; Casimir forces
-structures.

Structural and Opto-mechanical Modeling

-ultra-light-weight 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.

Application-specific Unique Optical Models and Performance Predictions
-adaptive optics
-bio and medical optics/sensing
-lasers/laser communication systems
-LEDs/solid state lighting
-MEMs/nanotechnology
-existing/evolving photonic devices and systems
-photonic devices
-solar technology.

Modeling of Vision Systems
-HUDs
-HMDs.

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

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.

Session 1: Mathematical Methods, Lasers, and Polarization

Paul K. Davis of NASA's Ames Research Center discussed hybrid fast Hankel transform implementations for optics simulation. He noted that the most compute intensive part of a full optics simulation, especially including diffraction effects, is often the Fourier transform between pupil and image spaces. This is usually performed as a two dimensional fast discrete transform. Paul noted that for a nearly radially symmetric system there are advantages to using polar coordinates, in which case the radial transform becomes a Hankel transform, using Bessel functions instead of circular functions. He presented a hybrid Hankel transform which divides the range, calculating a portion using Bessel function approximations but converting most of the range into a one dimensional Fourier transform which can be handled by standard methods. Audience discussions included comments and questions on measurements, etc.

Joseph P. Bebe Manga Lobe et al. of the III-V Lab. (France) presented a paper on frequency noise in the spectral line-shape of 780-nm GaAsP/GaInP quantum-well lasers for inertial sensor applications. Ultraprecise and stable gravimeters and gyrometers are highly demanded for various applications like fundamental physics, geophysics, and navigation systems. Interferometry of Rubidium cold atoms requires high power, narrow line-width, low frequency noise and highly reliable optical sources emitting at 780 nm. In this context, III-V developed basic bricks for realization of a distributed feedback (DFB) laser. Here audience discussions centered on selected aspects relating to the inclusion of noise in the models.

Rafael S. Lara and José Alfredo Alvarez-Chávez of the Center de Investigación e Innovación Tecnológica (Mexico) and Lelio de la Cruz May of the Universidad Autónoma del Carmen (Mexico) presented their paper via a pre-recorded briefing, as logistics prevented them from presenting their work in person. Their work involved Nth Stokes evolution due to SRS in single mode fibers. In this work, the evolution of the nth analytical solutions of traditional Raman equations was shown which included both numerical simulation and experimental results. In the experiment an 8.6 Km single mode fiber was pumped with an ytterbium doped fiber laser system (FL) in the CW regime at 1064-nm in a free running configuration. They showed that it is possible to obtain up to the nth power thresholds and maximum power for each Stokes by using compact analytical solutions such as first approximations in an arguably simple, quick process.

Young Uk Jung et al. of The City College of New York discussed the circulation and concentration of s- and p-polarized light in two-dimensional compound gratings. Both s-polarized and p-polarized phase resonances (PRs), and light circulation and concentration in two-dimensionally compound transmission gratings were modeled and numerically analyzed. The authors demonstrated that p- and s- polarized PRs of 2D compound gratings occur with similar characteristics of narrow bandwidths, high Q values, and highly concentrated fields as in one dimensional periodic gratings. The phase difference of Pi-radians between the fields in the coupled cavities produces light circulation and an inversion of the transmissivity/opacity of the structure. The dependencies of bandwidth and wavelength of the PRs on structural and material properties were described, as well as the way light flows in the structure when the phase resonances occur. Audience discussions involved other cases and model results which were stated as consistent.

Session 2: Stray Light and Scattering

Eunsong Oh et al. of the Korea Institute of Ocean Science & Technology presented work on a ray-tracing-based simulation of stray-light correction for the Geostationary Ocean Color Imager. The authors noted that ray tracing techniques are widely used to estimate the stray light effect inside optical systems. In this study they used these techniques to produce a stray light corrected image in the Geostationary Ocean Color Imager (GOCI) with simulated mosaic bias. After launching GOCI in 2010, a radiometric discrepancy among slot boundaries was noticed in the mosaic image. Stray light from slot boundaries was postulated as the cause, and ray tracing was used to figure out and quantify the effects of undesired ray paths. The authors' first step focused on a stray light analysis from an unwanted reflected bright source for GOCI, and their second step involved making a mosaicked bias image including the analyzed stray light pattern. Lastly, in their third step they corrected the acquired image by subtracting the weighted stray light pattern bias. Verification was performed by compare the difference among slot boundaries. Audience questions involved the number of rays traced (>100K), and the desire for color figures in the Proceedings.

Alan W. Greynolds of Ruda-Cardinal, Inc. presented work on the efficient automatic computation of veiling glare from scatter and ghosts by a simple modification to Monte-Carlo ray tracing. Alan noted that Veiling glare refers to stray light from an in-field extended source bleeding into adjacent dark regions of the image. Standard methods for calculating scattered light from out-of-field sources are cumbersome in this domain. On the other hand, basic Monte Carlo ray tracing is straightforward. However, a prohibitive number of rays are required to get accurate results. Instead of the standard ray-splitting and importance-sampling modifications to make it more efficient, a much simpler one was proposed and then applied to a representative lens system, resulting in a 100- to 1000-fold reduction in the number of rays required.

Salla G. Reddy et al. of the Physical Research Lab. (India) was unable to obtain a VISA to travel to the Conference, but this was not due to any fault of the PRL Team, and so this good/submitted work has been included in the Proceedings. The Team investigated the revival of the dark core in scattered optical vortices using a method that involved rotating a ground glass (RGG) plate. The scattered optical vortices were focused by a plano-convex lens, and it was shown that the dark core doesn't appear in near field, i.e. immediately after the RGG plate and the lens. The core presented itself only in the far-field. The diameter of the core increased with the increase in the order of the vortex. The diameter and the darkness of the core were shown to be independent of the speed of the RGG plate, i.e. the coherence of scattered light.

Session 3: Image Quality Measures and Methods

Ulas Kürüm of Roketsan Missiles Inc. (Turkey) presented a basic approach to define the signal-to-noise ratio for adjacent pixels in an uncooled micro-bolometer FPA detector. He noted that it is crucial for a system/optical designer to estimate the Signal to Noise value as it defines important system characteristics such as range performance and quality of the output signal. For uncooled micro-bolometer detectors used in imaging applications, system characteristics are also affected by signal to noise ratio of a particular pixel and noise characteristics of adjacent pixels. To define the ratio of the signal of the desired pixel and the noise of adjacent pixels, noise and signal sources were theoretically identified. While defining these values, atmospheric attenuation, losses at transmitting surfaces and wave characteristics of light were also considered. For presentation purposes, a standard NATO target was chosen as the source object. There was also brief audience discussions centered on OPD levels used in the models.

Greg Michels presented a paper on behalf of Victor L. Genberg of Sigmadyne, Inc., and a Team from MIT Lincoln Laboratory on methods that can be used to compute wavefront error due to aero-optic effects. Aero-optic effects can have deleterious effects on high performance airborne optical sensors that must view through turbulent flow fields created by the aerodynamic effects of windows and domes. An aero-optic analysis capability has been developed within the commercial software SigFit that couples CFD results with optical design tools. SigFit reads the CFD generated density profile using the CGNS file format. OPD maps are then created by converting the three-dimensional density field into an index of refraction field and then integrating along specified paths to compute OPD errors across the optical field. The OPD maps may be evaluated directly against system requirements or imported into commercial optical design software including Zemax® and CODE V® for a more detailed assessment of the impact on optical performance from which design trades may be performed. Audience discussions included comments on the treatment of temperature variations in the flow-field, as well as polychromatic effects, and the impacts on optical distortion as produced by field-dependent wavefront tilt.

Christoph A. Wächter et al. of the Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) discussed optical designs which included characteristics of manufactured nanostructures. The Team noted that micro- and nanostructures enable specific optical functionalities which rely on diffractive effects or effective medium features, depending on feature size and wavelength, but that actual manufactured nanostructures can deviate from their idealized geometry, and that these deviations influence the performance of the optical system. Thus, detailed optical characterization of the micro- or nanostructure functionality is prerequisite for accurate optical design and performance prediction. They reported on the incorporation of measurement results in corresponding models of planar optical components which are used within a ray-trace engine. The examples that were showed included grating structures and a meta-material with asymmetric transmission properties. Current modeling limitations were also discussed with the audience.

Session 4: STOP Models and Methods

Gregory J. Michels et al. of Sigmadyne, Inc. presented work on analyzing thermally-loaded transmissive optical elements. The performance metrics of many optical systems are affected by temperature changes in the system through different physical phenomena. Temperature disturbances cause changes in the refractive properties of transmissive optics. The resultant distributions of refractive index can be predicted by the finite element method. One current technique for representing such refractive index profiles is through the generation of OPD maps constructed from an integration along an on-axis ray-bundle, element-by-element.. While computationally efficient, the use of this method can have limitations in its ability to represent the effect of the index changes for rays associated with multiple field points and multiple wavelengths. A more complete representation of the thermo-optic refractive index profile may be passed to the optical analysis software through the use of a user defined gradient index material. The interface consists of a dynamic link library (DLL) which supplies indices of refraction to a user defined gradient index lens as ray tracing calculations are being performed. The DLL obtains its refractive index description from a database derived from the thermal analysis of the optics. This process allows optical analysis software to perform accurate ray tracing for an arbitrary refractive index profile induced by changes in temperature. This paper covers an update to work presented in a prior SPIE Conference Proceedings paper ("Improved integrated modeling of thermo-optic effects," Proceedings of SPIE Vol. 8127 (2011).

Gerhard P. Stoeckel et al. of MIT Lincoln Laboratory discussed the work underway at MIT Lincoln Laboratory that involves developing custom software to couple commercial software for STOP analysis. Here the need is to produce integrated opto-mechanical models that can be used to provide critical insights into the interdisciplinary behavior and dynamics of high performance optical systems operating in ground, air, and space environments. These integrated models serve as predictive test beds capturing complex environmental conditions and concurrent disturbances yielding deterministic performance predictions at any point in time. The Team is developing an enterprise framework for use during the design and testing stages of hardware programs that couples existing commercial thermal (Thermal Desktop), structural (Nastran), optical (Zemax), and control (Matlab) software tools that can then be used to inform architecture and system design decisions. Initial efforts have focused on development of a feature-rich software package configured to simplify STOP (structural-¬thermal-optical performance) analysis without sacrificing functionality or flexibility. This paper discussed the design of a framework and user interface for simple setup, execution and validation of STOP analyses on arbitrarily complex optical systems. Audience discussions covered how this architecture simplified the handling of Application Programing Interfaces (API's), tool-to-tool.

Lee D. Peterson et al. of NASA's Jet Propulsion Laboratory covered multi-physics modeling and uncertainty quantification for an active composite reflector. A multi-physics, high resolution simulation of an actively controlled, composite reflector panel was developed to extrapolate from ground test results to flight performance. The subject test article has previously demonstrated sub-micron corrected shape under a controlled laboratory thermal load. This paper presented the development of a model used to predict the on-orbit performance of the panel under realistic thermal loads, with an active heater control system, and it also presented how the model was used to perform a quantification of the uncertainty in the predicted response. The authors felt that the primary contribution of this paper would be the first reported application of the Sandia developed Sierra mechanics simulation tools to a spacecraft multi-physics simulation of a closed-loop system. The simulation was developed so as to have sufficient resolution to capture the residual panel shape error that remained after the thermal and mechanical control loops were closed. As such, the thermal mesh is converged to milli-kelvin scale resolution, and the structural mesh is converged to submicron scale resolution, both over millimeters of spatial wavelengths. An uncertainty quantification analysis was performed to assess the predicted tolerance of the closed-loop wavefront error. Key tools used for the uncertainty quantification were also described.

Alson E. Hatheway of Alson E. Hatheway Inc. discussed the modeling of diffraction gratings using Ivory optomechanical modeling tools. In imaging spectrometers it is important that both the image of the far-field object and the image of the spectra be stable on the detector plane. Lenses and mirrors contribute to the motions of these images but motions of the diffraction grating also have their own influences on these image motions. This paper develops the vector equations for the images (spectra) of the diffraction grating and derives their optomechanical influence coefficients from them. The Ivory Opto-mechanical Modeling Tools integrate the diffraction grating into the larger optical imaging system and format the whole system's influence coefficients suitably for both spread-sheet and finite element analysis methods. Their application was illustrated in an example of a spectrometer exposed to both static and dynamic disturbances.

Stephen C. Coy of Timelike Systems LLC discussed multidisciplinary Model-Based Engineering (MBE) for laser weapon systems, felt by the Office of the Director, Defense Science and Engineering, as one of several potentially "game-changing" technologies. Steve covered a system model that included concept formulation, the use of component libraries, R&D (physics level modeling & simulation), and engagement scenarios, through definitions of merit functions for effectiveness and the use of design parameters to optimize a design. The models were constructed so as to be able to be used at any (and/or multiple) level(s) of fidelity, and included both COTS and non-COTS tools, configured so as to allow use in a collaborative design and development environment that would enable configuration management & traceability, as well as full lifecycle support. The use of CometTM + TimeLikeTM + LightLikeTM tools was noted, as well as the potential tie-in to dozens of other software products. The pros and cons of unified (hub-and-spoke) vs. federated (point-to-point translators) processes was explained, as where white-box/black-box modeling concepts, and the benefits of the creation of re-usable modeling templates.

Session 5: Modeling Performance of Optical Systems

Bing Li et al. of the Beijing Institute of Technology (China) presented work on a method for measuring laser incident direction in a non-imaging mode, and laser-beam characteristics. One of the most crucial parameters that a laser warning system must provide is the direction of the laser threat. Because of the low resolution of a specific laser warning system that was based on an imaging mode, a new method for measuring laser incident direction which possessed that offered higher resolution. This novel method was based on the use of a cylindrical lens group and a linear IR FPA, and the laser incident direction was determined by measuring the offset of a" line-spot". The method allowed computation of the laser direction, and it also helped measure the details of incident laser beam.

Chia-Ray Chen et al., including Teammates from the Instrument Technology Research Centre) of the National Space Organization (Taiwan), discussed an integrated analysis of the FORMOSAT-5 remote sensing instrument in space. FORMOSAT-5 is the first space program fully developed by Taiwan's National Space Organization (NSPO). The Remote Sensing Instrument (RSI) is intended to provide spatial resolution of two meters in a panchromatic band and four meters in multi-spectral bands. The optical system is composed of two reflective aspheric mirrors and a spherical corrector lens set. Although the telescope system can be well aligned on the ground, the space thermal environment can result in thermal distortion of telescope system which impacts final image quality. Flight predictions were done and detailed studies were presented. Audience discussions included comments on materials used (CFRP & Zerodur®), reaction wheels, active focus, and the frequency at which MTF values were presented.

Branden Allen et al., including authors from MIT's Space Systems Lab. of the Harvard College Observatory, presented work on The REgolith X-Ray Imaging Spectrometer (REXIS) for NASA's OSIRIS-REx Mission, to be used in identifying regional elemental enrichment of an asteroid. The OSIRIS-REx Mission was selected under the NASA new frontiers program and is scheduled for launch in September of 2016 for a rendezvous with, and collection of a sample from the surface of asteroid Bennu in 2019; 101955 Bennu (previously 1999RQ36) is an Apollo (near-Earth) asteroid originally discovered by the LINEAR project in 1999 which has since been classified as a potentially hazardous near-Earth object. The REgolith X-Ray Imaging Spectrometer (REXIS) was proposed jointly by MIT and Harvard and was subsequently accepted as a student led instrument for the determination of the elemental composition of the asteroid's surface as well as the surface distribution of select elements through solar induced X-ray fluorescence. The REXIS was explained in this talk. It consists of a detector plane that contains four X-ray CCDs integrated into a wide field coded aperture telescope with a focal length of 20 cm for the detection of regions with enhanced abundance in key elements (Fe and Mg) at 20 m scales. Elemental surface distributions of approximately 100 m scales can be detected using the instrument as a simple collimator. An overview of the observation strategy of the REXIS instrument and expected performance were presented.

Azad Shademan et al. of the Children's National Medical Center discussed the feasibility of using near-infrared markers for guiding surgical robots. Automating surgery using robots requires robust visual tracking. The surgical field often has poor light conditions where several organs have similar visual appearances. In addition, the field of view may be occluded by blood or tissue. In this paper, the feasibility of near-infrared (NIR) fluorescent imaging for vision-based robot control was studied. The NIR region of the spectrum has several useful properties including deeper depth penetration. The Team studied the optical properties of a clinically-approved NIR fluorescent dye, indocyanine green (ICG), with different concentrations and used the dye to help quantify image positioning error of ICG markers when occluded by artificial tissue. The current status of the work was presented, and audience thoughts for further instrument improvements were solicited.

Posters

Lei Sun et al. of Zhejiang University (China) posted a paper on the mathematical modeling and analysis on a small/compact two-dimensional Cross Grating Lateral Shearing Interferometer (CGLSI) interference system. When using an interference wave front to detect a density field, the authors note that it is better to have an interference system which is small and compact so that different directions of wave fronts can be obtained to reconstruct the density field to be detected. A two-dimensional CGLSI which consists of a two-dimensional cross grating and a two-dimensional order-selecting window used as a filter was presented in this paper. Lateral shearing interferograms in two orthogonal directions (X and Y) can be obtained using this system. With the advantage of anti-vibration and no reference surface, lateral shearing interferometers inhibit external environmental disturbances. In this paper, analysis and simulations were shown on grating constants using both geometrical optics and physical optics (Fresnel approximation methods) for various lateral shearing rates and window distances (in two-dimensional order-selecting windows/ layouts) to determine what was the best option to use for a grating constant. The most optimized design of size and distance for windows in a two dimensional order-selecting configuration was established on the basis that the complex amplitude distribution can go through a filter so that there is no distortion on the wavefront. All designs shown went through computer simulations and met design requirements.

Last but not least, Yi-Chin Fang of the National Kaohsiung First University of Science and Technology (Taiwan) posted research on the optical design of non-image forming optical engine that used local-dimming effects produced by a liquid crystal and a laser light source. The work demonstrates a design which delivers an effect similar to that produced by dimming a backlight. In order to achieve high contrast similar to the local dimming effects produced in backlight designs, the author employed the primary colors of RGB laser lights mixed with an X-cube. With the assistance of a microscanning technique and a liquid optics array, varied contrasts could be presented on an illuminated plane. The configuration shown used special optical designs for each laser source array, and digital signal processing. It is a completely new design; it results in less heat interference, and it minimizes the volumetric size of the optical engine, but the simulations shown indicate it also provides up to 1:100 contrast if used in a Digital Light Processing (DLP) projector. The optical design provides light uniformity of

86.6 % and light energy efficiency near 40%. Local dimming produced by the liquid optical element was also discussed and is expected to significantly improve projector contrast (to ~70%).

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